

ANALYSIS OF CHILD DUMMY RESPONSES AND CRS PERFORMANCE IN FRONTAL NCAP TESTS

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ABSTRACT

The new car assessment program (NCAP) conducted 95 frontal crashes with child dummies in child restraint systems (CRS) in the rear seat. In addition to the two mid-size male dummies in the front seat, there were one or two child dummies in the rear seat area. The child dummies were (1) 12-month-old, (2) 3-year-old, and (3) 6-year-old. The child dummies were restrained in a CRS or a booster. This research focused on comparing the response of the child dummies with the adult dummy. The study examined the dynamic readings of the head acceleration, chest acceleration, chest deflection, and upper neck loading.

In terms of the customary injury assessment reference values (IARVs) for the adult and child dummies, the adult dummy had an easier time going under the IARVs than the child dummies. The passing rate for the adult was almost 100% while the passing rate was 60 - 70% for the child dummies. In short, the different dummy sizes in their respective seating location do not show the same relative level of protection as measured by body motion and instrumentation inside the dummy occupant.

The 3-year-old and 6-year-old child dummies show relatively elevated head response because their heads are not restrained in the sense that the adult's head is cushioned by the airbag. Some device or concept is needed to reduce the rotational motion of the head for the forward-facing child. The child dummies do not take advantage of the ride down (connecting the occupant to the initial crushing of the vehicle structure to slow down the occupant) as capably as the adult dummy. Some device or concept - such as the pre-tensioner for the adult in the front seat - is needed to reduce the free motion of the forward-facing child. The motion and response of the 6-year-old child dummy appear to vary more than the other crash test dummies.

INTRODUCTION

Recent investigations (of frontal laboratory crashes) have found that adult-size dummies in the rear seat

had much higher head and neck injury-assessment values than adult-size dummies in the front seat. Generally, the rear seat dummy had higher chest acceleration readings than the front seat dummy. [1-3]

In investigating real-world field data in 2009, Kent *et al.* [5] observed that, "the relative effectiveness (to mitigate serious injury and death) of rear seats with respect to front seats for restrained adult occupants in newer vehicle models is less than it is in older models, presumably due to the advances in restraint technology that have been incorporated into the front seat position." Other studies have examined real-world data and suggested similar findings. [5-7]

A 2005 report by Starnes [8], which was based on the analysis of the fatality analysis reporting system (FARS) and the national automotive sampling system crashworthiness data system (NASS CDS) data, focused on child passenger injuries in different crash configurations. For all crash configurations, a child occupant, whether restrained or unrestrained, was safer when travelling in the second row of the vehicle as opposed to the front passenger seat. It was also found that in non-fatal crashes, unrestrained passengers were much more likely to have been injured than restrained passengers.

In 2008, Hong *et al.* [9,10] investigated frontal crashes conducted by NCAP. All crashes had two 50th % male Hybrid III dummies in the front-seat area and a total of twenty-eight 10-year-old (10YO) child Hybrid III dummies in the rear-seat area. Hong compared the 10YO Hybrid III dummy with the adult dummy in the front seat. In these NCAP tests, almost all the front-seat adults had low IARVs. In contrast, many of the rear-seat 10YO child dummies saw violent head motion, high head injury criterion (HIC), high tension or compression in the neck, and high chest accelerations. In a few vehicles, the 10YO child dummy saw much smoother head motion, lower HIC, lower tension, and lower chest acceleration.

In this paper, an analysis of child dummies (1 through 6-years-old) was conducted to determine crash conditions that involved rear-seat injuries that

are not currently being directly addressed by vehicle safety standards or by consumer information test protocols. Analysis of US NCAP tests were conducted to determine the relative safety provided by seating position and by vehicle model year. Opportunities for reducing IARVs [11] in the child dummies were determined by examining current laboratory safety testing. Areas of opportunities include improved occupant restraint to reduce the dynamic readings of the children relative to their IARVs.

METHODOLOGY

This study examines the responses of child dummies and the performance of CRS in frontal NCAP tests. There are 95 cases of the frontal NCAP test performed from 2001 to 2005 with child dummies on rear seats of a vehicle as shown in Table 1 [12]. The vehicles are classified into 3 types: a passenger car, a sport utility vehicle (SUV) and a van, and a light truck. Generally there are two adult dummies on a driver and a passenger seats, and one or two child dummies on the rear seat. The adult dummy is the Hybrid III 50th percentile male dummy. Three child dummies, such as the Hybrid III 6-year-old (6YO) child dummy, Hybrid III 3-year-old (3YO) child dummy, or child restraint airbag interaction (CRABI) 12-month-old (12MO) child dummy, are used. The child dummies are seated on the rear seat with a CRS or a booster. The 12MO child dummy is restrained by a 5 points belt on a rear facing CRS (RFCRS) and the RFCRS is affixed to the vehicle by using the 3 points seatbelt system. The 3YO child dummy is restrained by a 5 points belt on a forward facing CRS (FFCRS), which is affixed to the vehicle by using the 3 points seatbelt system and the top tether or the lower anchors and tethers for children (LATCH) system.

The 6YO child dummy is restrained by the 3 points seatbelt system on a booster.

Table 1. Cases of the frontal NCAP test with child dummies on rear seats of a vehicle (performed from 2001 to 2005)

Type of Vehicle	Number of Tests	Type of Child Dummy	Number of Dummies
Passenger Car	46	6YO Child	7
		3YO Child	56
		12MO Child	13
SUV & Van	39	6YO Child	6
		3YO Child	62
		12MO Child	9
Light Truck	10	6YO Child	2
		3YO Child	17
		12MO Child	1
Total	95	6YO Child	15
		3YO Child	135
		12MO Child	23

The pass rates of HIC15, maximum chest G's and peak chest deflection of dummies in frontal NCAP tests are summarized in Table 2. Table 2 shows that the pass rates of HIC15 and chest G's of adult dummies are almost 100%, which means that drivers will be well protected in frontal vehicle crash environment. The pass rates of HIC15 and chest G's of child dummies are not as good as the adult dummies even though they need to be. The injury pass rates of child dummies are around 50 – 70% and especially the pass rate of HIC15 of 6YO child dummies is as low as 21%. In other words, a child on rear seat might be expected to suffer much more severely from impact than an adult on driver seat during frontal vehicle collisions even though a child is supposed to be as well protected as an adult. Interestingly, the chest deflection of the adult and the child dummies is passed the injury criterion in all

Table 2. Pass Rates of HIC15, chest max G's and chest peak deflection of dummies

Type of dummy	Type of vehicle	Pass rate of HIC15	Pass rate of chest G's	Pass rate of chest deflection
50th Percentile (Driver) (HIC15 < 700) (Chest G's < 60 G's) (Chest Deflection < 52mm)	Passenger Car	100.0 % (45/45)	100.0 % (45/45)	100.0 % (45)
	SUV	100.0 % (39/39)	92.3 % (36/39)	100.0 % (38)
	Light Truck	100.0 % (10/10)	90.0 % (9/10)	100.0 % (10)
	Total	100.0 % (94/94)	95.7 % (90/94)	100.0 % (93)
6YO Child (HIC15 < 700) (Chest G's < 60 G's) (Chest Deflection < 40mm)	Passenger Car	0.0 % (0/6)	42.9 % (3/7)	100.0 % (6)
	SUV	33.3 % (2/6)	50.0 % (3/6)	100.0 % (5)
	Light Truck	50.0 % (1/2)	100.0 % (2/2)	100.0 % (1)
	Total	21.4 % (3/14)	53.3 % (8/15)	100.0 % (12)
3YO Child (HIC15 < 570) (Chest G's < 55 G's) (Chest Deflection < 34mm)	Passenger Car	74.5 % (41/55)	67.3 % (37/55)	100.0 % (56)
	SUV	69.5 % (41/59)	77.0 % (47/61)	100.0 % (62)
	Light Truck	64.7 % (11/17)	76.5 % (13/17)	100.0 % (17)
	Total	71.0 % (93/131)	72.9 % (97/133)	100.0 % (135)
12MO Child (HIC15 < 390) (Chest G's < 50 G's)	Passenger Car	50.0 % (6/12)	41.7 % (5/12)	N/A
	SUV	88.9 % (8/9)	100.0 % (7/7)	
	Light Truck	0.0 % (0/1)	0.0 % (0/1)	
	Total	63.6 % (14/22)	60.0 % (12/20)	

cases.

ANALYSIS OF HEAD ACCELERATION

In Table 2, the pass rate of HIC15 of adult dummies is 100%, but the passing of 12MO and 3YO child dummies is around 65-70% and the passing of 6YO child dummy is as low as 20%. To understand this, the head response of adult dummies is compared with one of child dummies. Table 3 summarizes the cases that HIC15 of the child dummies is higher than one of adult dummies. In the 76% of the cases, child dummies experience higher head acceleration than adult dummies during the vehicle crash. The data points of HIC15 of adult dummies vs. HIC15 of child dummies are plotted in Figure 1. It shows that the data points of the 12MO child dummies are distributed around a diagonal dot-line, but most of the data points of 6YO and 3YO child dummies are spread far over the diagonal dot-line. HIC15 of all adult dummies is less than 700, but one of many child dummies, especially 3YO and 6YO child dummies, are much greater than 700. In other words, child dummies experience higher HIC15 values relative to IARVs than adult dummy during crash.

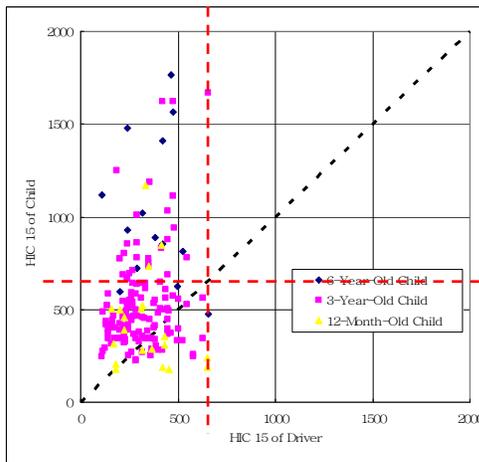


Figure 1. HIC15 of the driver vs. HIC15 of the child

Table 3. Cases of [(HIC15 of the child) > (HIC15 of the driver)]

Type of child dummy		Cases of [(HIC15 of child) > (HIC15 of driver)]		
6YO Child	Forward Facing	93%	85%	76%
(13/14)		(131/145)		
3YO Child	82%	(108/131)	(123/165)	
12MO Child	Rear Facing	60%		
		(12/20)		



(a) Adult dummy (Test 5130)



(b) 6YO child dummy (Test 5130)



(c) 3YO child dummy (Test 5130)



(d) 12MO child dummy (Test 4242)

Figure 2. Snapshots of the dummies' behavior

Figure 2 shows snapshots of the dummies' behavior during impact. After the vehicle impacts the barrier, the forward facing occupant starts moving forward. Since the torso of the occupant is restrained by the seatbelt, the head of the occupant starts rotating and then X- and Z- head accelerations occur as shown in Figure 3. In the case of the occupants in front seats, the rotational head motion is restrained by an airbag, like in Figure 2(a). Thus the airbag contributes to reduce the head acceleration of front occupants and leads the high pass rate of HIC15 in Table 2. However, in the rear seat, the occupant's head is not restrained. Therefore the heads of the forward facing 6YO and 3YO child dummies are fully rotated around the axis of the shoulder like Figure 2(b) and 2(c). Figure 3(a) shows that X- accelerations are not much different among all dummies, but Z- accelerations of the 6YO and 3YO child dummies are much higher than one of the adult dummy. The head of 12MO child, who is restrained with the RFCRS like Figure 2(d), does not rotate since the head is

supported by RFCRS. However, the RFCRS itself is rotating and produces considerable head accelerations as shown in Figure 3(b).

The head resultant accelerations of 6YO and the 3YO dummies in some tests are shown in Figure 4. It can be seen that there are two peaks in the head resultant acceleration. The 1st peak is due to the forward movement of the head like Figure 5(a) and the 2nd peak is due to the rear seat contact with the back of the head like Figure 5(b). In some cases, the 2nd peaks of the head acceleration are considerable high, or even higher than the 1st one of 3YO child dummies in Figure 4(b). In Table 4, the cases that the 2nd peak of head acceleration is higher than its 1st one are 28% in 3YO child dummies and 20% in 6YO child dummies. Also, the cases that HIC15 around the 2nd peak of head acceleration is higher than 570 G's, which is the head injury criteria of 3YO child, are 5%. It seems that the 2nd peak of head acceleration of 3YO child dummies is considerable.

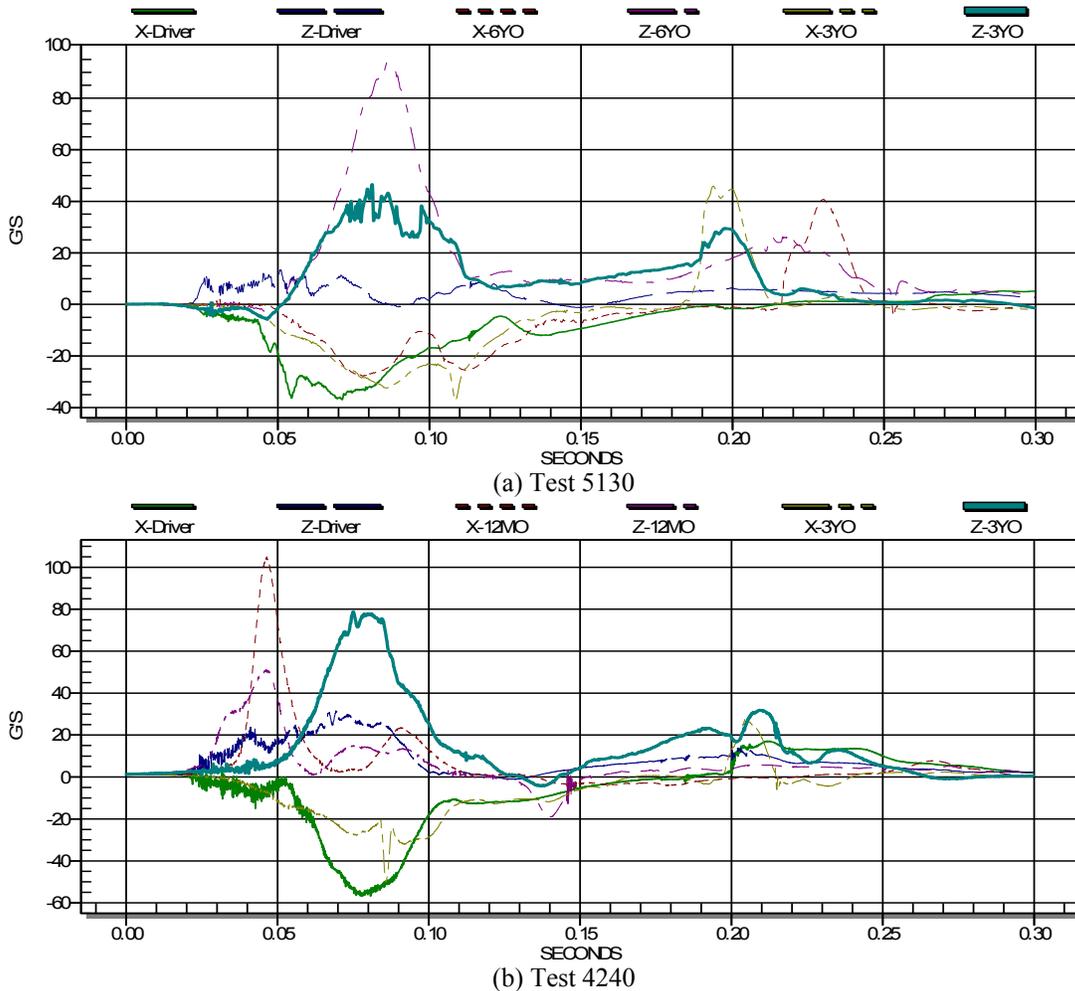
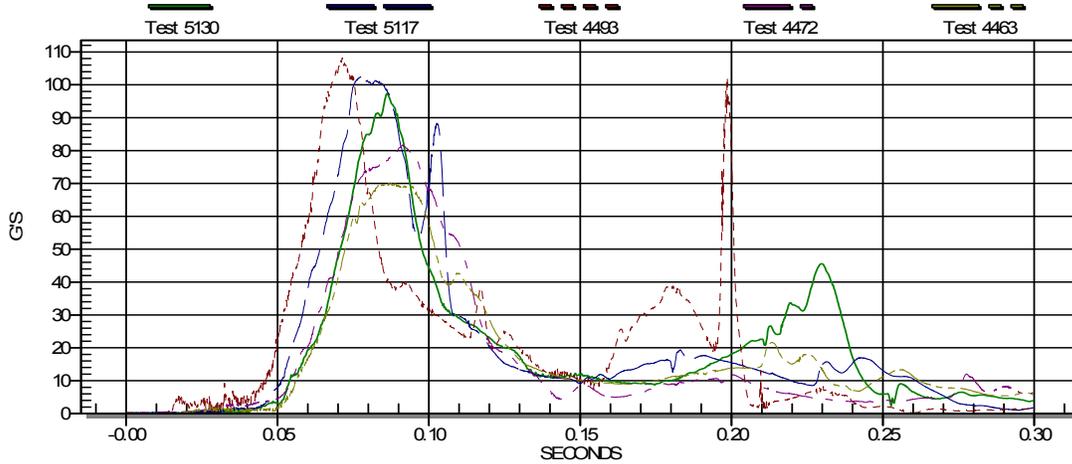
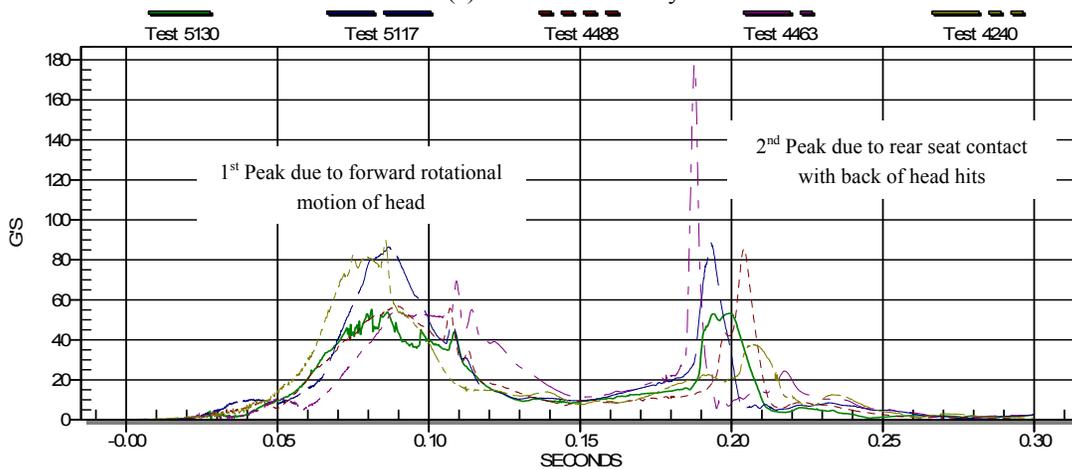


Figure 3. X- and Z- head accelerations of adult, 6YO child and 3YO child dummies



(a) 6YO child dummy



(b) 3YO child dummy

Figure 4. Resultant head acceleration curves

Table 4. Relationship between 1st Peak and 2nd Peak of Head Resultant Acceleration

		Cases of [2nd Peak > 1st Peak]	Cases of [HIC15 at 2nd Peak > 570 G's]
3YO Child	Passenger Car	19.6 % (9/46)	6.5 % (3/46)
	SUV	35.2 % (19/54)	5.6 % (3/54)
	Light Truck	28.6 % (4/14)	0.0 % (0/14)
	Total	28.1 % (32/114)	5.3 % (6/114)
6YO Child	Total	20.0 % (1/5)	0.0 % (0/5)



(a) at 1st peak time of head acceleration



(b) at 2nd peak time of head acceleration

Figure 5. Behavior of 3YO child dummy (Test 4901)

ANALYSIS OF HEAD VELOCITY

The velocity histories of dummies are helpful to understand the initial behavior of occupants and the interaction between the vehicle and the occupant during crash. The velocity curves are obtained by integrating the acceleration curves and only X-velocity (longitudinal) is utilized here. Figure 6 shows the typical X-velocity curves of a vehicle and dummy head in frontal NCAP test. In general, the vehicle velocity starts to decrease right after vehicle impact barrier, but the deceleration of occupant velocity is not occurred until time t_1 , which is the required time for the restraint system to fully work on occupants because of initial space between restraint and occupant. Figure 7, which is cited from reference [13], gives the good physical interpretation of the velocity profiles in frontal crash of vehicle. In Figure 7(a), the area under the vehicle velocity curve represents the crush of the vehicle. The area between the vehicle velocity curve and the occupant velocity curve, up to time t_1 , represents the initial restraint to occupant spacing (e.g., the spacing from occupant to an airbag or the longitudinal slack in a lap and shoulder belt). The area between the vehicle velocity curve and the occupant velocity curve, after time t_1 , represents the stroking of the restraint system. A lot of time (up to t_1) is wasted in bringing the occupant to rest. The area not wasted is the stroke of the restraint system and the vehicle crush after the restraint picks up the occupant in Figure 7(b). The area labeled “vehicle crush after the restraint picks up the occupant” in Figure 7(b) is commonly referred to as *ridedown*, which is the important part to reduce the stroke of the restraint system.

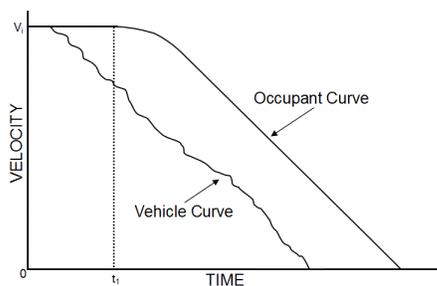


Figure 6. Typical head X-velocity curve

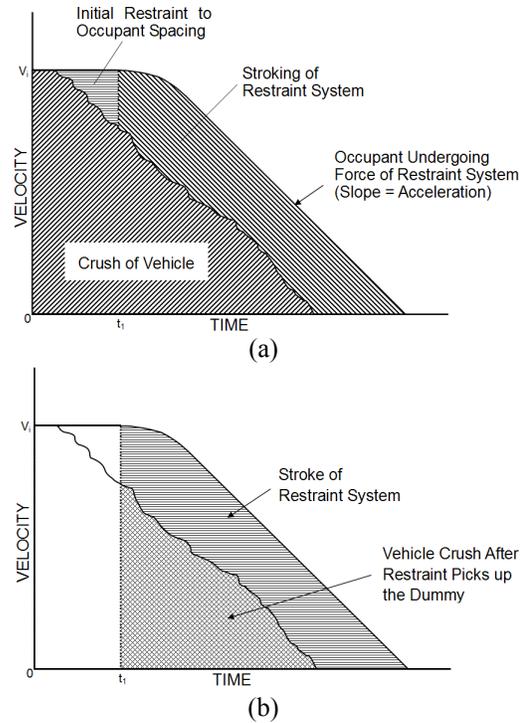


Figure 7. Interpretation of head X-velocity curve [13]

Figure 8 shows the X-velocity curves of some cases. It can be seen that the time t_2 , the initial restraint space of the 6YO and the 3YO child dummies in rear seat, is much longer than the time t_1 , the initial restraint space of the adult dummy in driver seat. This means that even though the child dummies are well seated and secured by CRS or booster with seatbelt, there is still a lot of initial space and slack between occupant and restraint system and between CRS or booster and rear seat. Therefore the child is supposed to have a small *ridedown*, which is unfavorable for the child.

Fundamentally, the *ridedown* contributes for occupants to reduce the stroke of the restraint system, which is the impact force on the head and chest. The *ridedown* is also related with the vehicle crush. Figure 9 shows the relationship between chest and head of dummy and vehicle. Statistical linear regression curves shows that the maximum chest acceleration and the maximum upper neck force of the 3YO and 6YO child dummies decrease respectively when the vehicle crush increases.

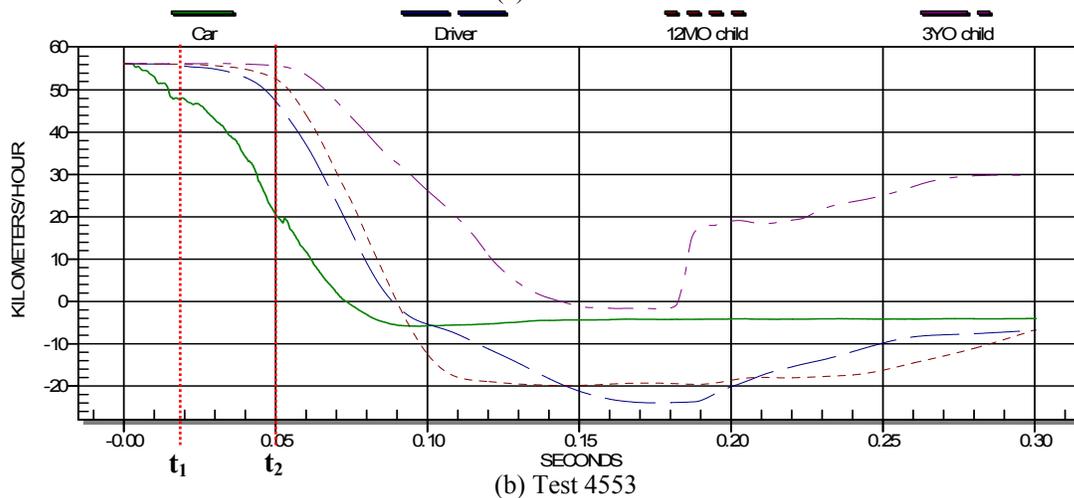
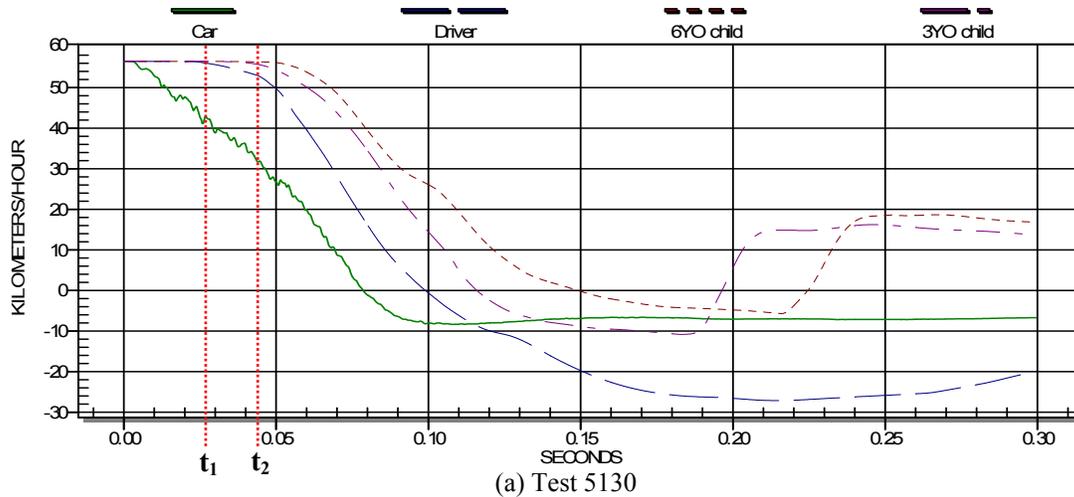


Figure 8. X-velocity curves

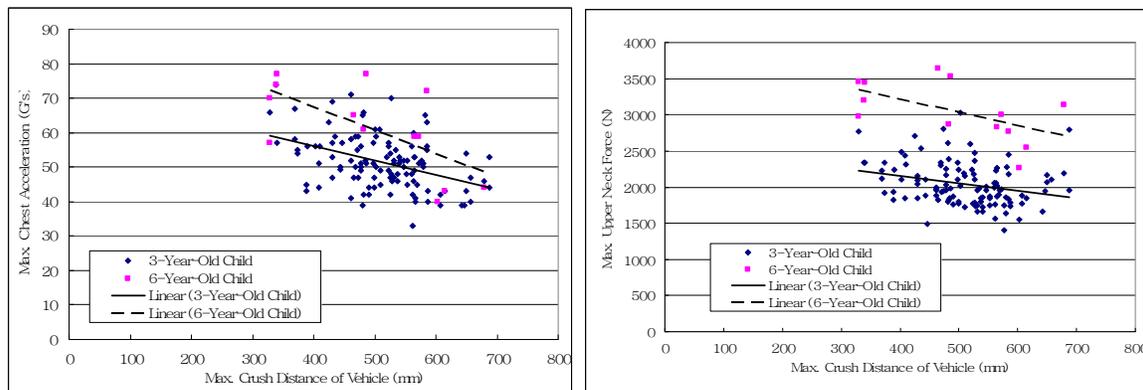


Figure 9. Vehicle crush vs. max. chest acceleration and max. upper neck force

ANALYSIS OF UPPER NECK FORCE

In general, the upper neck force (tension) is linked with the head acceleration. The data points of the upper neck force vs. the head acceleration are plotted in Figure 10. It shows that the upper neck force is

proportional to HIC15. In addition, it can be seen that the upper neck force and HIC15 of the 3YO and 6YO child dummies is much higher than the responses of adult dummies.

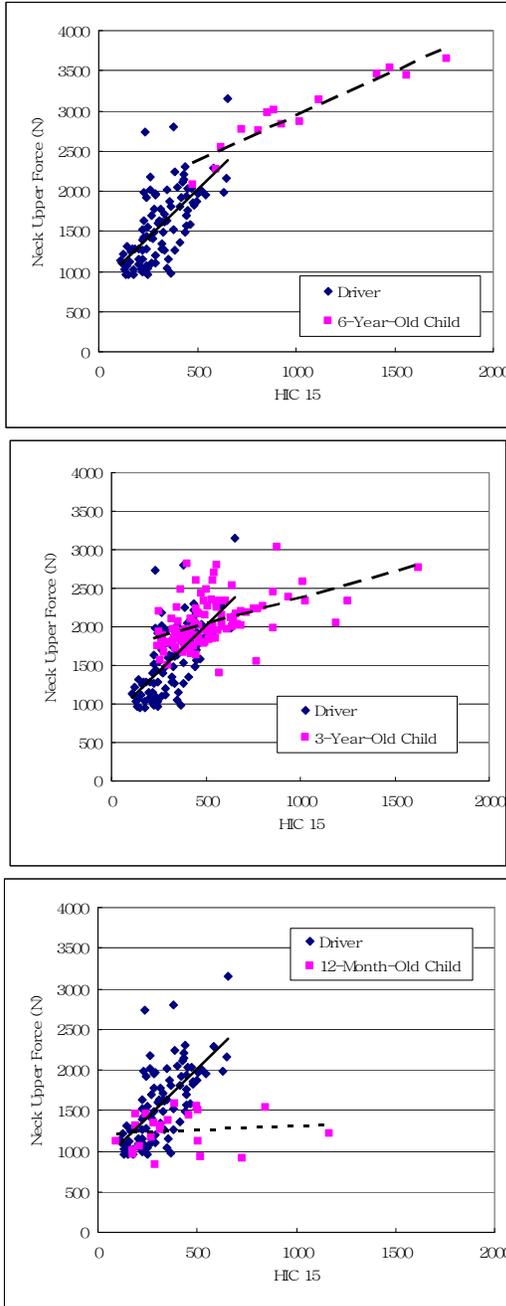


Figure 10. Data distribution plots of Neck Upper Force vs. HIC15

As mentioned in the previous section, the rotational motion of the dummy head during impact produces the Z-acceleration (a_z), the centripetal acceleration. According to Newton's law, multiplying the Z-acceleration by the mass of dummy head should equal to the Z-upper neck force (F_{neck}) if there is no external force ($F_{external}$), in other words,

$$F_{external} = ma_z - F_{neck} \quad (1)$$

and $F_{external}$ is zero. Figure 11 shows the data points of maximum Z-upper neck force vs. maximum Z-head acceleration. The diagonal line indicates the $F_{neck} = ma_z$ line, where the masses of dummy head (m) are 3.47 kg in 6YO child dummy and 2.73 kg in 3YO child dummy [14]. The data points of 6YO child dummy in Figure 11(a) are distributed close to the diagonal line, which means that the external is zero, in other words, Eq (1) is zero. However, the data points of 3YO child dummy in Figure 11(b) are quite scattered over the diagonal line, which means any external force exists on dummy head during crash, in other words, Eq. (1) is not zero. Figure 12 is the snapshots of the behavior of the 3YO child dummy in test 3554. The child is restrained by FFCRS. Basically FFCRS has a chest clip, which is a stiff material and located on the middle of the dummy chest shown in Figure 12(a). Figure 12(b) shows that the chin of the child dummy hits the chest clip during crash. Thus $F_{external}$ is the force caused by that the chin of 3YO child dummy hits the chest clip or chest. Also, the reference [11] looks into the external force by dummy chin contact with chest clip. Probably, this external force produces a high reverse X-velocity of the head of 3YO child dummy and induces the high 2nd peak of head acceleration of 3YO child dummy in Figure 4(b). On the other hand, the 6YO child is restrained by 3-points rear seat belt on the booster. During crash, the head of 6YO child dummy is fully rotating without any external force as shown in Figure 2(b). This head motion of 6YO child dummy produces high acceleration and upper neck force and makes pass rate of HIC15 as low as 21.4% in Table 2.

According to references [11] and [15], real world crash analysis suggests that neck trauma corresponds to only a small fraction of the injuries found in children in passenger vehicles crashes. In Figure 10, however, the upper neck tensions exceed the injury criteria (6YO:1890N, 3YO:1430N, 12MO:780N [11]) in most of the cases, which suggests that there is a possibility that the neck force of child dummies is over-predicting neck injury and that further study is needed.

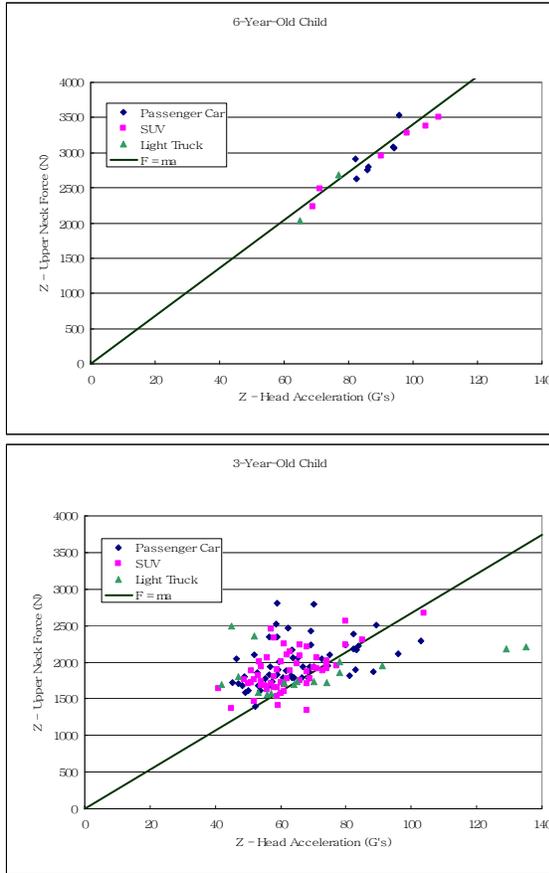


Figure 11. Max Z-upper neck force(F_{Neck}) vs. Max Z-head acceleration



(a) before impact



(b) moment that chin hits chest clip

Figure 12. Behavior of 3YO child dummy (Test 3554)

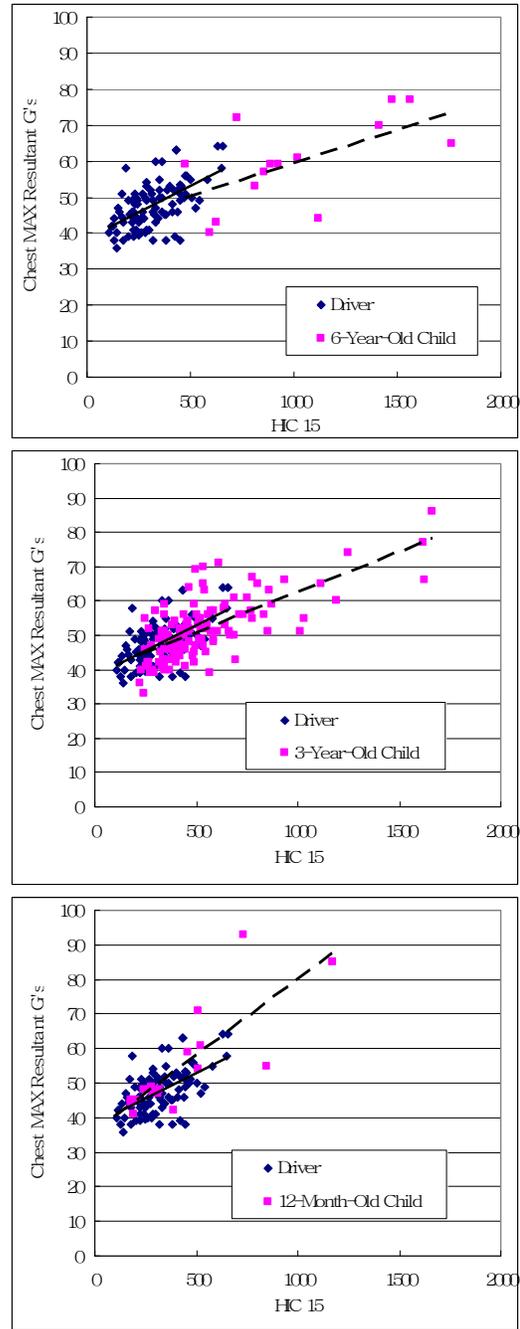


Figure 13. Maximum chest resultant G's vs. HIC15

ANALYSIS OF CHEST ACCELERATION AND DEFLECTION

In Table 2, the pass rate of chest G's of the child dummies is about 60%, while the pass rate of the adult dummies is about 96%. The data distribution of the maximum chest resultant G's vs. HIC15 is plotted in Figure 13. It shows that the maximum chest G's is proportional to HIC15. In addition, Figure 9 shows

that the maximum chest acceleration is inversely proportional to the vehicle crush. The pass rate of the chest deflection is 100% for all dummies in Table 2. The data distribution of the maximum chest deflection vs. HIC15 is plotted in Figure 14. It shows that, in the cases of the 3YO child dummy, the chest deflection is much lower than the driver in spite of the fact that the chest acceleration is similar with the driver in Figure 13. It is because the 3YO child dummy is restrained by the 5-point CRS, which has two harnesses on the child chest like Figure 12(a). These two harnesses make the force be dispersed around the chest.

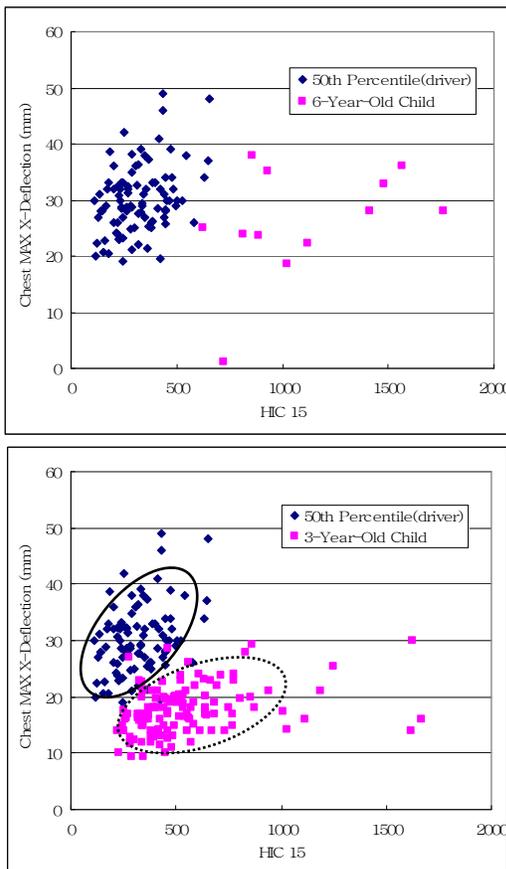


Figure 14. Maximum chest X-deflection vs. HIC15

CONCLUSIONS

The objective of this study is to examine the responses of child dummies and the performance of CRS in the frontal NCAP tests. The responses of head, upper neck and chest of adult and child dummies in 95 NCAP tests are analyzed.

Head Acceleration

- Pass rate of HIC15: Driver - 100%, 6YO child - 21.4%, 3YO child - 71%, and 12MO child - 63.6%
- Child dummies experience higher HIC15 values relative to IARVs than adult dummy during crash
- HIC15 around the 2nd peak of the head acceleration of the 3YO child is considerable.

Head Velocity

- The head X-velocity is helpful for understanding the initial occupant behavior and the relationship between the vehicle and the occupants during impact.
- The much space between the restraint systems and the child makes the “ridedown” area small, which is unfavorable for the child.

Upper Neck Force

- The upper neck tension forces of the child dummies are exceed the criteria in the most of the cases.
- As HIC15 increases, the upper neck force increases.

Chest Acceleration and Deflection

- Pass rate of chest maximum acceleration : Driver - 95.7%, 6YO child - 53.3%, 3YO child - 72.9%, and 12MO child - 60%
- Pass rate of chest maximum deflection : all occupants - 100%

This study suggests that the performance of the CRS could better protect the child in the rear seat during frontal crash. Based on the study, a couple of countermeasures can be recommended. Firstly, a forward facing child experiences severe head acceleration and neck force because of rotational head motion. Thus, during frontal crash, child head needs to be restrained by some means like airbags in front seats. Secondly, child on CRS or booster in rear seat has a lot of initial slack and gap between child and CRS and between CRS or booster and rear seat, which make ridedown small. The ideal countermeasure is to make the crash performance of vehicles improved. In practice, some devices are needed to reduce the initial slack, for example, a pretensioner or an air-belt in the rear-seat area.

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