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INJURY PERFORMANCE EVALUATION OF THE CHILD RESTRAINT SYSTEMS

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ABSTRACT−The new FMVSS 208, 213, 225 regulations include automatic suppression of airbags to prevent low-risk airbag deployment and the use of child seats with a rigid-bar anchor system. The regulations mean that children must sit in the rear seat, but do not include other specific safety measures for their protection. In the rear, restraint equipment consists of three-point shoulder/lap belts for the outside seats and a static two-point lap belt in the middle, with no additional devices such as pretensioners or load limiters; this is far from optimal for children. This study investigated injury rates using a 3-year-old-child dummy. ECE R44 sled tests used a booster, a speed of 48 km/h, and a 26- to 32-g rectangular deceleration pulse. While seated on a booster, the dummies were restrained by an adult shoulder/lap three-point belt. HIC_15 msec, Chest G and Nij were somewhat lower with an emergency locking retractor (ELR)+ pretensioner+load limiter than with only an ELR or with ELR+pretensioner. However, the current seat-belt system results in injury rates that exceed the limit for OOP performance under the new FMVSS 208 regulations.

KEY WORDS : Emergency locking retractor (ELR), Child restraint system (CRS)

1. INTRODUCTION

The National Highway Traffic Safety Administration (NHTSA) concluded that child restraint systems (CRSs) could reduce infant mortality rates by up to 71%, and were the most effective safety measure, if properly used. Nevertheless, in America, where CRSs are built in, about 230 children under the age of six years die annually, and 66,000 are injured. The NHTSA study on child-seat mountings and CRS standards for children found that 230 deaths and 875 injuries in the accidents studied could have been prevented if the CRS had been worn correctly (NHTSA, 1998).

The final economic assessment, related to FMVSS Nos. 213 and 225, issued in February 1999, was that adoption of child seats with rigid-bar anchor systems and tethers was desirable, so the revised FMVSS Nos. 213 and 225 were adopted in September 1999, but boosters were excluded (NHTSA, 1999).

In May 2000, FMVSS No. 208 was revised, with the intention of decreasing the risk of injury from airbags, to stipulate that the injury regulation criteria for "Out of Position (OOP)", shown in Table 1, should be achieved in low-risk airbag deployment tests through automatic suppression of the airbag, with rear seat positioning and the rear seat belt as the means of restraint for child seats or infant carriers.

However, the current FMVSS No. 213 requires that CRSs are tested using a 30-mph sled test, with injury limits of a Head Injury Criteria (HIC) value of 1,000 and 60 g on the chest with forward movement of the head and knees. HIC and Chest G values are the same as those of 50th-percentile adult dummies prior to the revision of FMVSS No. 208, so the effectiveness of the measures has been questioned, since they are not based on biomechanical data (Janssen *et al.*, 1993; Rattenbury and Gloyns, 1993).

The results of an NHTSA study of how to reduce HIC values in side impacts and the performance of boosters were announced in November 2001, but no changes were made to protect children seated on boosters in the event of a frontal collision. Therefore, this study compared the revised FMVSS No. 208 regulations for HIC values in a 30-mph sled test, using a booster and child dummy, to examine the effects on restraint performance of changes in the positioning of the seat belt attachment according to

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Table 1. FMVSS 208 occupant protection performance requirements.

	50th% HIII	5th% HIII		6 year HIII	3 year HIII
	FRM	FRM		FRM	FRM
	Dynamic	Dynamic	OOP	OOP	OOP
HIC	$700_{(15)}$	$700_{(15)}$	$700_{(15)}$	$700_{(15)}$	$570_{(15)}$
Neck: N_{ij} method (Linear Combination of Moment/Axial Forces)					
N_{ij}	1.0	1.0	1.0	1.0	1.0
N_{ij} critical values					
Tension (N)	6,806	4,287	3,880	2,800	2,120
Compression (N)	6,160	3,880	3,880	2,800	2,120
Flexion (N-m)	310	155	155	93	68
Extension (N-m)	135	67	61	37	27
Peak tension (N)	4,170	2,620	2,070	1,490	1,130
Peak compression (N)	4,000	2,520	2,520	1,820	1,380
Chest acceleration (3 msec)	60g	60g	60g	60g	55g
Chest deflection (mm)	63	52	52	40	34
Femur load (N)	10,000	6,805	6,805	N/A	N/A

the specifications for emergency locking retractors (ELRs) (Henderson *et al.*, 1997; Czernakowski and Bell, 1997).

Recently, some advanced seats were introduced to improve ride comfort (Yoo *et al.*, 2005; Yoo *et al.*, 2006), but injury performance should be examined with the various restraint systems.

The study used a child dummy to evaluate passenger restraint performance, using a pretensioner and load limiter adapted to an optimal seat belt path, which was decided by experiment, and considered improvements that might reduce injury rates.

2. SLED TEST

2.1. Summary of the Test

The sled test was executed to verify seat belt performance for children, while excluding the effects of performance differences of the vehicle seat belts. The test conditions followed ECE R44 regulations, and a Hybrid III 3-year-old dummy was used (Anderson, 1991).

2.2. Specification of the Seat Belt

The tests were performed using three different seat-belt configurations: ELR, ELR+pretensioner, and ELR+pretensioner+load limiter. Figure 1 shows the seat belt configuration with a pretensioner. The pretensioner specifications were a shoulder belt load of less than 2,500 N for twelve seconds and rewind of more than 120 mm in a static state without slackening with respect to a seated 50th-percentile adult dummy. Load limiter transformation section of 150 mm under 4,500 N and an extension rate of 7% for the seat-belt webbing were adopted. The seat-belt anchor points were positioned according to the

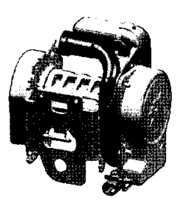


Figure 1. Seat belt assembly with pretensioner.

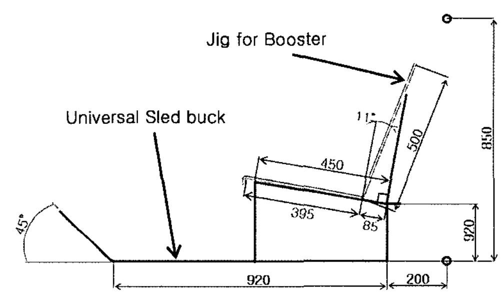


Figure 2. ECE R44 universal sled buck.

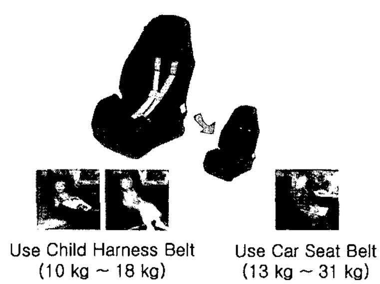


Figure 3. Method of booster use.

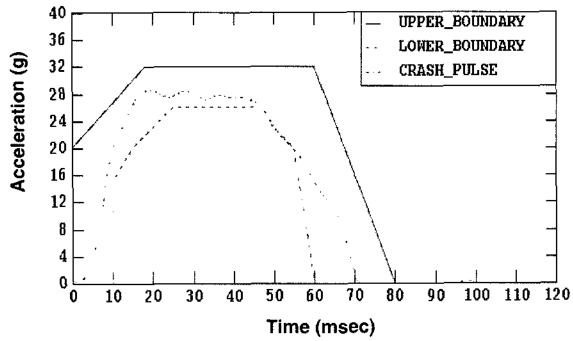


Figure 4. ECE R44 curve of trolley's deceleration.

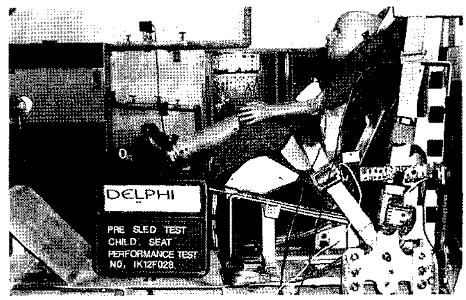


Figure 5. Test set-up for ECE R44 30-mph frontal sled test using a dummy 3-year-old.

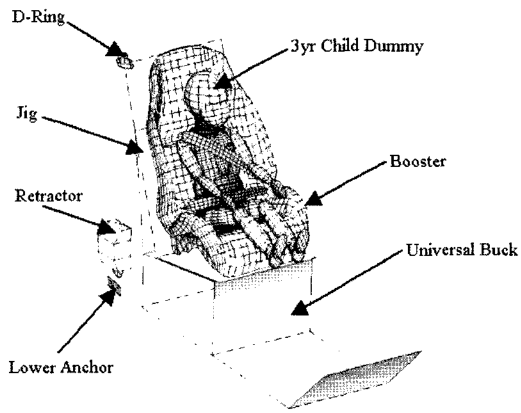


Figure 6. 3-year-old-child dummy sled test model.

coordinates of a small car.

2.3. Sled Test Conditions

As a test jig, a universal sled buck was used as indicated in ECE R44, and a separate jig was added so as to mount the booster (Figure 2). The booster was a High Back 02-442 made by Costco Company, one of the child seats listed in Advanced Regulations-FMVSS208 Final Rule Appendix A, which came into effect in May 2000. The booster is provided with a child harness belt for children weighing 10~8 kg; however, since the 3-year-old-child dummy weighed 16 kg, the test was performed using an adult seat belt, as shown in Figure 3 (Pincemaille *et al.*, 1993).

Figure 4 shows a half sine graph for an ECE R44 frontal collision at a speed of 30 mph with the crash pulse in the sled test. Figure 5 is a photograph of the dummy before the sled test.

2.4. Test Results

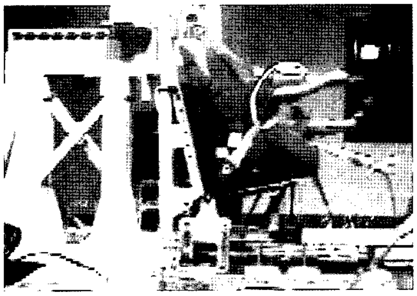
The test was performed three times using seat belts adopting ELR, ELR+pretensioner, and ELR+pretensioner+load limiter to obtain basic data and evaluate the model. The results are presented in Table 2, in which HIC and Chest G values exceed regulation values; the tension load and the compression load applied to the neck are compared. The HIC and regulation values following the OOP standardization of New FMVSS208 are not a suitable reference for a dynamic crash event but are of value in understanding the HIC of the dummy.

It was found that most OOP injury standards were exceeded. In the case of N_{ij}, newly added to FMVSS 208, the dummy 3-year-old was subject to the complex load of

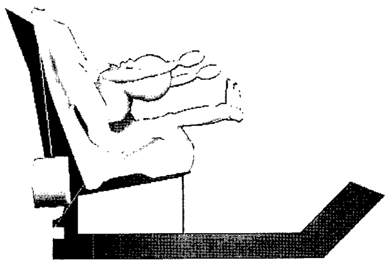
Table 2. Sled test results (TTF: 11 msec).

Injury type		Limit	Test mode		
			ELR	ELR+P/T	*ELR+P/T+L/L
HIC_15 msec		570	975.82	592.22	782.80
Chest G		55	68.64	56.93	71.07
Neck tension (N)		1,130	1,977.48	1,875.06	1,873.43
Neck compression (N)		1,380	665.88	429.69	632.27
Neck	N_{TF}	1.0	1.31	0.97	1.12
	N_{TE}	1.0	1.47	1.29	1.53
	N_{CF}	1.0	0.32	0.25	0.27
	N_{CE}	1.0	0.38	0.07	0.34

*Pretensioner TTF: 15 msec



(a) Sled test



(b) Analysis model

Figure 7. Movement of the dummy 3-year-old at 80 msec in the 30-mph sled test.

"tension-flexion" and "tension-extension", and some problems were detected in N_{TF} and N_{TE}. HIC and Chest G values at 15 msec were lower when ELR+pretensioner was applied.

3. FINITE ELEMENT MODEL

The finite element model for the parametric study using the data for the dummy and the sled test conditions was made by coupling PAM-CRASH, an explicit code and Madymo. The universal buck, seat belt, and booster were modeled using PAM-CRASH, and the dummy 3-year-old was modeled using the Hybrid III Dummy from the Madymo dummy database (Hoffmann *et al.*, 1990; PSI, 2000; TNO, 1999).

As shown in Figure 4, acceleration was applied to the child dummy and booster, and corrected using the weight ratio of the physical parts of the Madymo dummy model to compensate for the weight difference between the test and the Madymo dummies. In Figure 6, the booster and the universal buck are defined as a robust body. The contact conditions between the dummy and the booster given by the load-parameter curve are shown.

Comparison and verification of the test and the FE model used the ELR specification. Figure 7 shows a comparison of the movement of the dummy 3-year-old in the sled test in (a) with the analysis model in (b) at 80 msec. Figures 8 and 9 show the profile of the head and chest resultant accelerations for the 3-year-old dummy.

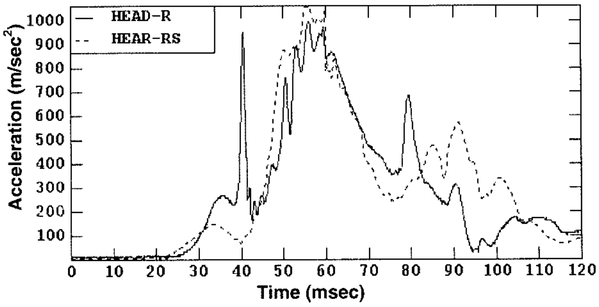


Figure 8. Model correlation – 3-year-old child dummy (head resultant acceleration).

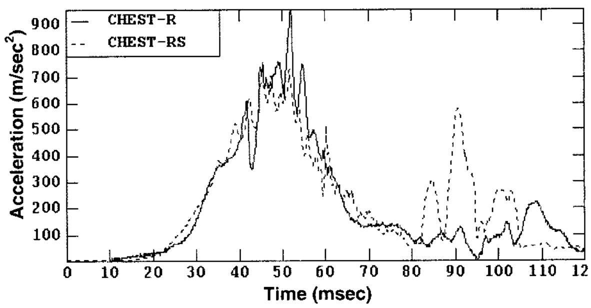


Figure 9. Model correlation – 3-year-old child dummy (chest resultant acceleration).

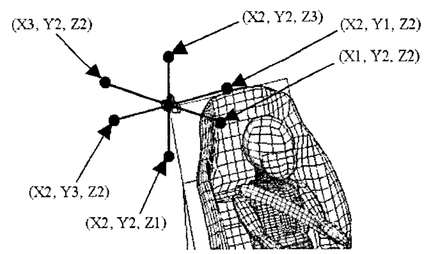


Figure 10. D-ring location.

Table 3. D-ring-location coordinate table (ref. H-point, unit: mm).

Parameter	X	Y	Z	Remarks
1	173.25	212.10	517.70	
2	301.00	240.00	572.00	
3	428.75	267.90	626.30	

4. OPTIMIZATION OF SEAT BELT ROUTING

4.1. Design Parameters

Most rear seat belts use only an ELR, and the anchor points that determine the path of the seat belt are located with reference to an adult. Therefore, the seat-belt anchor point was selected as a parameter to study. In particular, the effect of the position of the D-ring on injury to the dummy was examined.

Table 4. Matrix experiment and simulation results (for a 3-year-old child).

No	X	Y	Z	HIC	Chest G	N_{TF}	N_{TE}	N_{CF}	N_{CE}	Neck ten.	Neck comp.	IC
1	X1	Y1	Z1	1,003.9	58.31	1.61	1.27	0.26	0.27	2,850.59	506.81	3,912.80
2	X1	Y2	Z2	1,238.6	60.46	1.82	1.24	0.23	0.35	3,250.74	463.76	4,549.80
3	X1	Y3	Z3	1,301.9	62.64	1.84	1.45	0.19	0.39	3,170.86	479.72	4,535.40
4	X2	Y1	Z2	1,025.3	58.01	1.68	1.46	0.26	1.54	2,920.20	519.98	4,003.51
5	X2	Y2	Z3	1,134.1	62.05	1.73	1.62	0.24	1.47	3,265.16	474.62	4,461.31
6	X2	Y3	Z1	967.2	56.20	1.71	1.41	0.25	1.44	2,928.80	524.25	3,952.20
7	X3	Y1	Z3	1,104.8	63.55	1.70	1.67	0.21	1.90	3,099.61	484.41	4,267.96
8	X3	Y2	Z1	1,016.5	60.58	1.67	1.56	0.25	1.83	3,014.40	518.98	4,091.48
9	X3	Y3	Z2	1,073.6	62.67	1.67	1.67	0.23	1.87	3,176.42	499.06	4,312.69
Test result				975.80	68.64	1.31	1.47	0.32	0.38	1,873.43	632.27	

Table 5. Results of D-ring location optimization for the dummy 3-year-old.

Injury type		Limit	Results		
			Test	Initial model	Optimized model
HIC_15 msec		570	975.8	1301.9	927.5
Chest G		55	68.6	62.6	57.3
Neck tension (N)		1,130	1,873.4	3,170.9	2,781.39
Neck compression (N)		1380	632.3	479.7	533.30
Neck	N_{TF}	1.0	1.31	1.84	1.49
	N_{TE}	1.0	1.47	1.45	0.81
	N_{CF}	1.0	0.32	0.19	0.30
	N_{CE}	1.0	0.38	0.39	0.75

The seat-belt anchor-points are shown in Table 3, where coordinates are relative to the reference H-Point following the ECE R44 test conditions to give three parameter coordinates in the X, Y, and Z axes. For the purposes of the parameter study, each coordinate was arranged as indicated in Table 4 using an orthogonal arrangement table with a three-level L3(34) based on the experimental planning method.

The injury criteria (IC) introduced for the adoption of the experimental planning method were combined, as follows:

IC=HIC_15 msec+Chest G+Neck Tension Load

The sled test and the analysis model described above used the combination X1, Y3 and Z3 in Table 3.

4.2. Parameteric Study Results

A rear seat belt with only an ELR was adopted. Changes in IC values with different D-ring positions were identified by examining the parameters based on the orthogonal arrangement in Table 4, as shown in Figure 11. The X2 position corresponding to the dummy's mid-position with respect to the X-axis was selected as optimal for the D-ring. IC values were reduced near the center of Y2 of the Y-coordinate. In the case of the Z-coordinate, IC values decreased as the path of the seat belt approached the shoulder of the dummy. Table 5 shows the test results for the initial and optimized models.

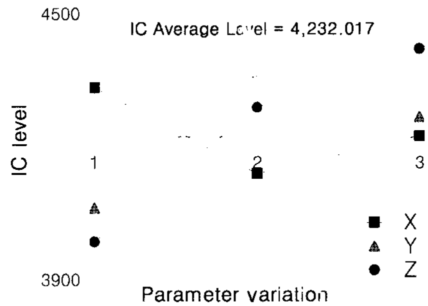


Figure 11. Graph of average IC values of 3-year-old according to anchor location.

5. STUDY TO IMPROVE IC VALUES

To further improve IC values, in case they were still too high even after optimizing the seat belt path, the effects of a pretensioner and a load limiter were reviewed. The pretensioner adopted was the same as used in the test, and the load limit was specified as 4,000 N, 3,000 N, and 2,000 N, to reflect a child's weight.

Table 6 shows the effect on IC I-value improvement IC values were improved more at 13 msec than at 11 msec, and the results at 15 msec were little different from those at 13 msec. Table 7 shows results with operating loads of 2,000 N, 3,000 N and 4,000 N when the TTF of the pretensioner was set at 15 msec. The HIC was 645.9, at 4,000 N and 466.7 at 2,000 N, which meet the OOP regulation criterion of 570.

Chest G was a little lower at 3000 N and increased again at 2,000 N, closely approaching the regulation criteria. Neck tension was reduced slightly with adoption of a pretensioner, but was still more than double the

Table 6. Comparison of the pretensioner TTF for a dummy 3-year-old.

Injury type		Limit	Pretensioner Time to Fire (TTF)		
			11 msec	13 msec	15 msec
HIC_15 msec		570	664.5	525.9	523.8
Chest G		55	55.29	51.67	51.67
Neck tension		1,130	2,686.69	2,429.88	2,326.50
Neck compression		1,380	868.11	557.53	559.10
Neck	N_{TF}	1.0	1.59	1.45	1.39
	N_{TE}	1.0	0.73	0.74	0.89
	N_{CF}	1.0	0.25	0.28	0.33
	N_{CE}	1.0	1.42	0.98	0.62

Table 7. Comparison of the load limit levels with a pretensioner for a dummy 3-year-old.

Injury type		Limit	Load limit		
			2000 N	3000 N	4000 N
HIC_15 msec		570	466.4	596.2	645.9
Chest G		55	54.55	51.30	53.30
Neck tension		1,130	2,259.31	2,416.78	2,533.07
Neck compression		1,380	537.46	574.30	547.72
Neck	N_{TF}	1.0	1.32	1.47	1.49
	N_{TE}	1.0	1.09	0.78	0.81
	N_{CF}	1.0	0.28	0.30	0.30
	N_{CE}	1.0	0.28	0.66	0.75

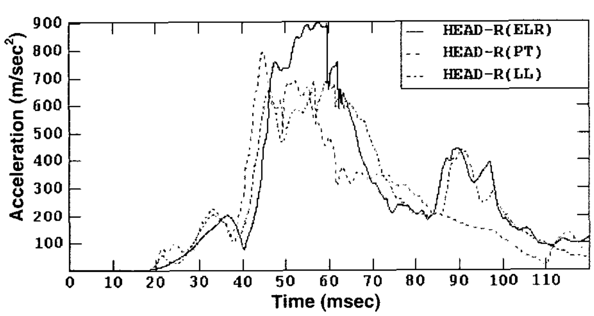


Figure 12. Head resultant acceleration – 3-year-old child dummy.

regulation criteria. Tables 6 and 7 show higher IC values with adoption of load limits of 3,000 N or 4,000 N than with a pretensioner alone. This is because the shoulder belt load does not increase by the load necessary for the load limiter to operate. On the contrary, when a load limit of 2,000 N was adopted, a better reduction in injury was evident.

Figures 12 and 13 show the acceleration of the head

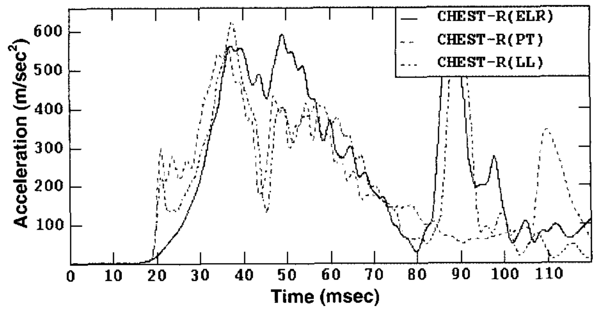


Figure 13. Chest resultant acceleration – 3-year-old child dummy.

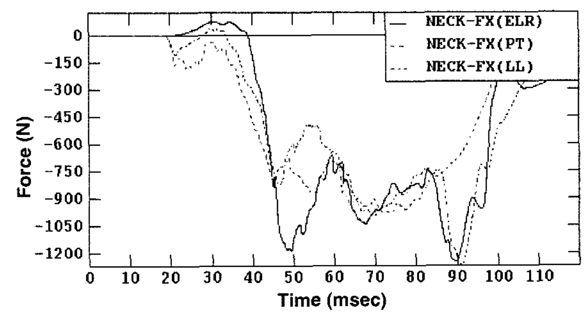


Figure 14. Neck load Fx – 3-year-old child dummy.

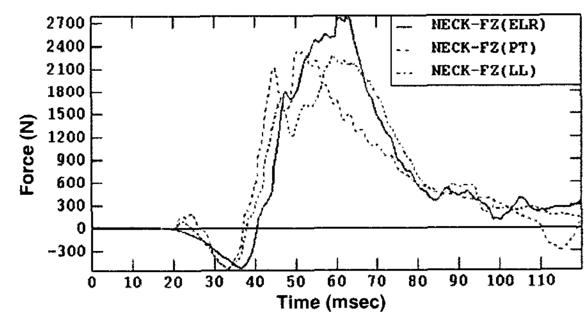


Figure 15. Neck load Fz – 3-year-old child dummy.

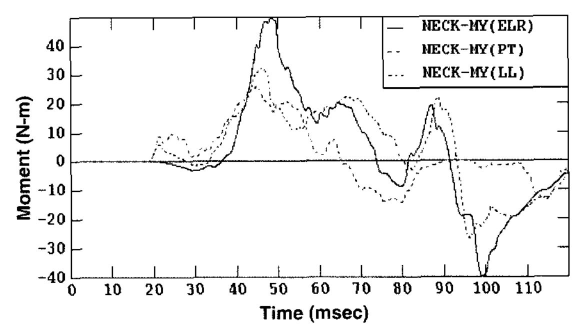


Figure 16. Neck moment My – 3-year-old child dummy.

and the chest, respectively. Figures 14, 15 and 16 are graphs of the loads and the moments used for the calculation of Nij. Figures 17 and 18 show the uniform load section that occurs with a load limiter.

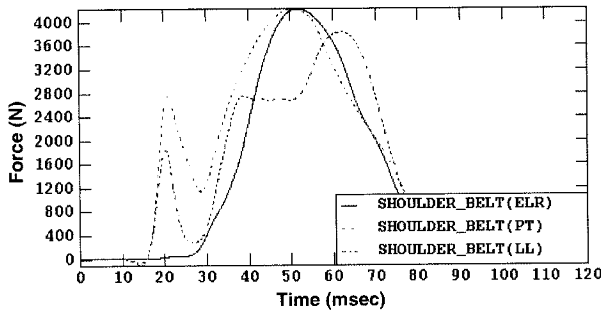


Figure 17. Shoulder belt load – 3-year-old child dummy.

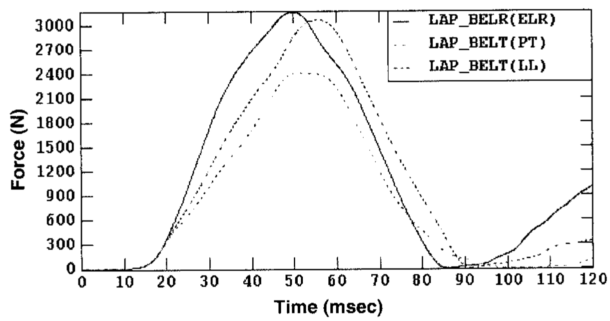


Figure 18. Lap belt load – 3-year-old child dummy.

6. CONCLUSIONS

This study evaluated child safety in a crash situation with conventional passenger protection equipment. The results are as follows:

(1) The sled test executed with a booster and a 3-year-old child dummy adopted the OOP standardization of the revised FMVSS 208 regulation. Use of an ELR, ELR+Pretensioner, and ELR+Pretensioner+Load Limiter did not meet the OOP regulations for the child dummy. The neck load of the child dummy wearing the seat belt was identified as a composite load of "tension-flexion" and "tension-extension".

(2) The study showed how the seat belt path could be improved with respect to the child dummy, adopting an experimental planning method related to optimization of the position of the seat belt D-ring with the ELR specification, using a verified FE model. Namely, IC values decrease as the D-ring anchor point approaches the shoulder area from the Y-coordinate to the Z-coordinate. However, the results did not meet the OOP HIC_15 msec, Chest G, Neck Tension, NTF and NTE regulations for a 3-year-old dummy.

(3) Analysis of the use of a pretensioner and load limiter as IC reduction countermeasures showed them to be effective in reducing HIC and Chest G values. The greatest improvement was in the extension load generated in the neck region of the child dummy and the NTF and NTE, but it was difficult to meet the OOP regulation criteria with the load characteristics of the dummy and the seat belt.

(4) The study identified a better reduction in IC values with a load limit of 2,000 N. However, as this might be detrimental to the restraint capability of the seat belt for an adult, adoption of multi-level load limiters that allow limits of 2,000 N and 4,000 N will be required.

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