Effectiveness of the Child Restraint System with a Special Airbag and Smart Seatbelt Pretensioner in Frontal Collisions

Edyta Rola, Cezary Rzymkowski

Abstract Currently, child restraint systems do not provide good enough protection to the child's head although it is the most frequently injured region in motor vehicle crashes. Children need a safety device which accommodates their size, weight and differences from adult's relative proportions and stages of their body development. Most of the modern vehicle safety systems are designed for adults and may lead to injuries among children. The aim of the study was to investigate whether the redesign of selected safety systems could reduce the risk of serious and fatal injuries to a child. The three-year-old child travelling in a forward-facing child restraint systems in the rear seat of a passenger car was considered. A series of numerical simulations were carried out with the use of MADYMO v7.5.1 software. Scaled industrial characteristics of the airbag inflator and scaled characteristics of adult seat belt systems were used. During the simulations, fourteen injury criteria connected with the head, neck and chest were controlled. In this study, the Q3 dummy model kinematic behaviour and the serious injury risk of each case were compared. This paper shows the potential of forward-facing child restraint systems combined with a special airbag and smart belt pretensioner to protect child occupants.

Keywords belt slack, child airbag, frontal crash, smart pretensioner, Q3 dummy model

I. INTRODUCTION

The effectiveness of child restraint systems (CRSs) in reducing injury is shown in [1-3]. CRSs can reduce deaths among young children (1 to 4 years) by as much as 54% [4]. The CRS performance mainly depends on proper installation and use. Examples of critical missuses are described in [5]. The references [6-7] indicate internal harness slack as one of them. The type of CRS attachment to the vehicle is also important. The CRS with ISOFIX attachment has a possibility of relative vehicle movement. This relative movement can be eliminated by the use of a top tether or support leg. The risk of injury to small children seated in the rear seat in a passenger car is about 30% lower than to children seated in the front seat [8] because there is further from any potential collision point. Several studies found out that the position of a child which is different from a standard dummy position [9-11] may have significantly influenced the kinematics and passive safety of a child [5]. In the research [10], mathematical simulations with Q1.5 and Q3 dummy models were conducted to explore the effect of the posture of a child in a CRS on the injury potential in a typical car crash. The investigation based on the photo-study with 10 vulnerable children (aged from one to three years) seated in ECE-R44 Group I seats. Most children did not sit in the standard position. Mathematical simulation was stated to be a valuable tool to predict trends in automotive safety. In the case of severe crashes, despite proper CRS usage and the correct position of the child without belt slack, a serious injury risk exists.

In the event of a crash, the most common body regions of injury (AIS3+ and limbs fractures) for children in forward-facing (FF) CRS are the extremities, followed by the head, neck, chest and abdomen [5][9].

The anatomy of a child differs to that of an adult and undergoes changes until maturity [12-13]. The injury patterns in children differ as well. During a crash, a child's torso is held by seatbelts while the disproportionately large head of a child (yet it is the most frequently injured child's body part during motor vehicle crashes) supported by a weak neck is not completely protected even during a minor frontal crash. Despite the fact that adult bodies are stronger than children's, front seat adults have additional devices such as frontal airbags, belts retractors, pretensioners and load limiters to protect them from injuries. Hence, children do require particular specific protection.

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A few published studies have presented evaluations of the effect for children of advanced vehicle restraint systems such pretensioners and load limiters. [14] investigated the effect of these safety systems for 3-years-old children by tests with the P3 dummy. This research showed that using load limiters with boosters have marginal effect on acceleration. The later study [15] also included an evaluation of belt pretensioners and load limiters for children (6-years-olds). In this research, mathematical simulations with HIII 6YO dummy model was conducted. The potential of the combination of safety pretensioner and load limiter to reduce head, chest and neck injury responses was found. [16] indicated that these findings are valid for 3-year-olds. The Q3 dummy model validated to sled tests was used. A factorial design of experiments method to evaluate restraint parameters was used. The research showed that mathematical simulations are able to predict child dummy kinematic and injury response. It was also indicated that the greatest influence on the child dummy responses have the lap belt angle, following by upper belt anchor position, the retractor pretensioner and the load limiter. In these publications the influence of belt pretensioner and load limiter on child safety was considered, but no such publications regarding the use of advanced vehicle restraints integrated with internal harness of CRS have been found.

Retractors allow changing the active length of the webbing. Seatbelts can be equipped with load limiters to prevent high chest loads. Pre-crash child occupant parameters have an impact on child safety [5]. If the load limiter was used the child's head would contact the front seats. However, CRS can be enhanced by a special airbag to slow the child occupant's forward motion as evenly as possible to reduce the severity of injuries. Smart pretensioner could tighten the belts prior to a crash (during sudden braking) and improve the initial position of the child, reducing the likelihood of the occurrence of out-of-position situations. This is especially important when an airbag is applied. Moreover, sensing devices can determine the child's seated position and potential crash severity to decide whether the airbag will be deployed (and how aggressively) or not.

Adult restraints are not designed for children's height, weight, different relative proportions and different stages of their development but may be redesigned to improve child occupant safety. The objective of this study was to investigate the effect of a combination of a special airbag, a retractor, a load limiter and a smart pretensioner on the child injury response. The other objective of this study was to compare the child occupant safety with and without belt slack. The research presented in this paper focuses on the frontal impact which is the most frequent type of crash. A three-year-old child traveling in the FF CRS in the rear seat of a passenger car was considered.

II. **METHODS**

For this study, the MADYMO v7.5.1 software package for numerical calculations was used. Simulations with an ellipsoid child dummy model of the Q-series representing a 3-year-old child were performed. This model consist of 72 rigid bodies and was developed and validated using component and complete dummy tests [17-18]. Predefined contact properties for the Q3 model were used. A facet CRS model described using surface elements was taken from previous research [19]. This model was designed using HyperWorks. New integral five-point hybrid belts were modelled. The safety belt webbing was modelled by finite elements, other parts by rigid bodies. This seat belt webbing was modelled using 1mm thick membrane elements. A dummy model was seated in a CRS in pre-simulation with only gravity load included. The Q3 dummy model seated in FF CRS is shown in Figure 1.

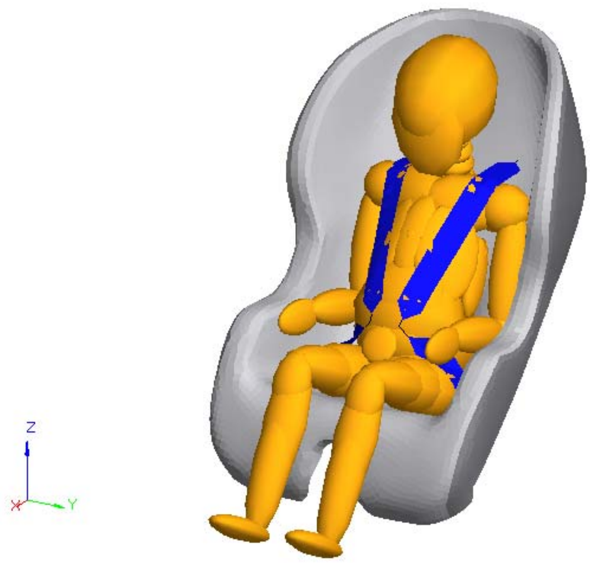

Fig. 1. The Q3 dummy model seated in FF CRS in the reference configuration.

Firstly, the simulation reflected braking during which smart pretensioner began to work. Pre-impact braking was simulated by applying an acceleration of 0.7 g for 200ms before the impact pulse begins. This part of the study is not presented in this article. Next, a simulation with a child dummy model in reference configuration (without any additional safety device) was conducted. Subsequently, a series of numerical simulations (which took into account belt slack, the application of a retractor, load limiter and an airbag with a variety of properties) were carried out, but only significant are presented. The impact pulse representing a frontal collision was configured according to European regulation ECE R129 (with a test speed of 50 km/h and maximum acceleration about 25g). The acceleration pulse is shown in Figure A in Appendix. Only symmetrical loading condition was taken into account.

In this study, the following cases were investigated:

- Reference case (Case A)

Analysis of slack in the CRS harness:

- 50 mm slack (Case B)
- 75 mm slack (Case C)
- 100 mm slack (Case D)

Analysis of CRS with additional safety devices:

- Retractor+ pretensioner + load limiter fixed CRS – PT+LL (Case E)
- Retractor+ pretensioner + load limiter + pivoted CRS – PT+LL+pCRS (Case F)
- Retractor+ pretensioner + load limiter + airbag PT+LL+airbag (Case G)

The last case is shown in Figure B in Appendix.

Pyrotechnical inflation of an airbag was simulated. The characteristics of an inflator were based on scaled industrial data. The aggressiveness of the airbag was reduced in order to minimize the risk of fatality among children. The airbag was deployed after 14ms (after the impact pulse begins) from the front seat. The maximum volume of airbag chamber was about 40 liters. The maximum pressure of the airbag chamber was about 1.5bar. The gas was able to escape through vent holes in the fabric. The child dummy model came into contact with the airbag after it had been fully inflated. The belt pretensioners was fired at 15ms. Standard belt webbing elongation and retractor functions were used.

During the simulations, head resultant accelerations and chest resultant accelerations were the most important responses (based on injury frequency of moderate or higher injuries according Abbreviated Injury Scale – AIS2+) chosen to represents injuries to the head and the chest. The various injury criteria were also controlled to evaluate the performance of CRSs in each configuration. In total, 14 injury criteria concerning head, chest and neck injuries were proposed. To make the evaluation more robust, more than one injury criterion for each body region was considered. These injury criteria were based on the parameters that may directly interact with the Q3 measurements.

The defined injury criteria for the head were:

- *the highest center of gravity of head acceleration that is exceeded during at least 3ms - Cumulative 3ms Head Injury Criterion (CUM_H)*
- *the Head Injury Criterion with the time interval of 36ms (HIC_36)*

Injury criteria connected to the chest were:

- *Cumulative 3ms Thorax Injury Criterion (CUM_T)*
- *Chest Deflection (CD)*

Particular attention was paid on the neck injury criteria. Injury criteria related to neck were:

- Neck Injury Predictor - Tension-Extension (*N_TE)* and Tension-Flexion *(N_TF)*
- Neck Injury Predictor - Compression-Extension *(N_CE)* and Compression-Flexion *(N_CF)*
- Neck Injury Criterion - Tension Negative *(NIC_TN)* and Tension Positive *(NIC_T_P)*
- Neck Injury Criterion - Shear Negative *(NIC_S_N)* and Shear Positive *(NIC_S_P)*
- Neck Injury Criterion - Bending Negative *(NIC_B_N)* and Positive *(NIC_B_P)*

The Injury critical values (reference value at which injury may occur) for a 3-year-old child are shown in Table 1. Some of these values were defined in regulations [20], some were the proposed by Świetlik while others were adapted from [21-22].

TABLE I
PROPOSED INJURY CRITERIA AND CRITICAL VALUES OF INJURY CRITERIA

Injury Criterion Symbol	Units	Critical Value	Injury Indicator Symbol
Head_3ms	g	80	*1*
HIC_36	-	800	*2*
N_TE	-	1	*3*
N_TF	-	1	*4*
N_CE	-	1	*5*
N_CF	-	1	*6*
NIC_TN	*N*	1130	*7*
NIC_T_P	*N*	1130	*8*
NIC_S_N	*N*	500	*9*
NIC_S_P	*N*	500	*10*
NIC_B_N	*Nm*	16	*11*
NIC_B_P	*Nm*	16	*12*
Chest_3ms	*g*	55	*13*
CD	*m*	0,034	*14*

In order to indicate a potential increase of injury risk in different cases the normalized value (NV) of each injury criterion – injury indicator - was defined as follows:

$$NV = \frac{response}{critical\ value}, \quad (1)$$

where *NV* is the normalized value of injury criterion (-), response is the resulting value of injury criterion and *critical value* is taken from Table 1. The effectiveness of configurations was estimated by comparing the sum of normalized values (SNV) of all injury indicators.

The kinematics of the child occupant model, as well as appropriate injury criteria, were monitored for 145ms from the initiation of the impact pulse. All signals were filtered according to the SAE J211-1 (CFC filters).

III. **RESULTS**

The head resultant acceleration for all cases is shown in Figures 2 and 3. All the cases with belt slack had a similar peak value of head acceleration. Even if the occurrence of slack slightly modified the trajectory of the head, it did not cause substantial changes in the magnitude of the head accelerations. However for cases with additional safety devices this peak was lower in magnitude and longer in duration.

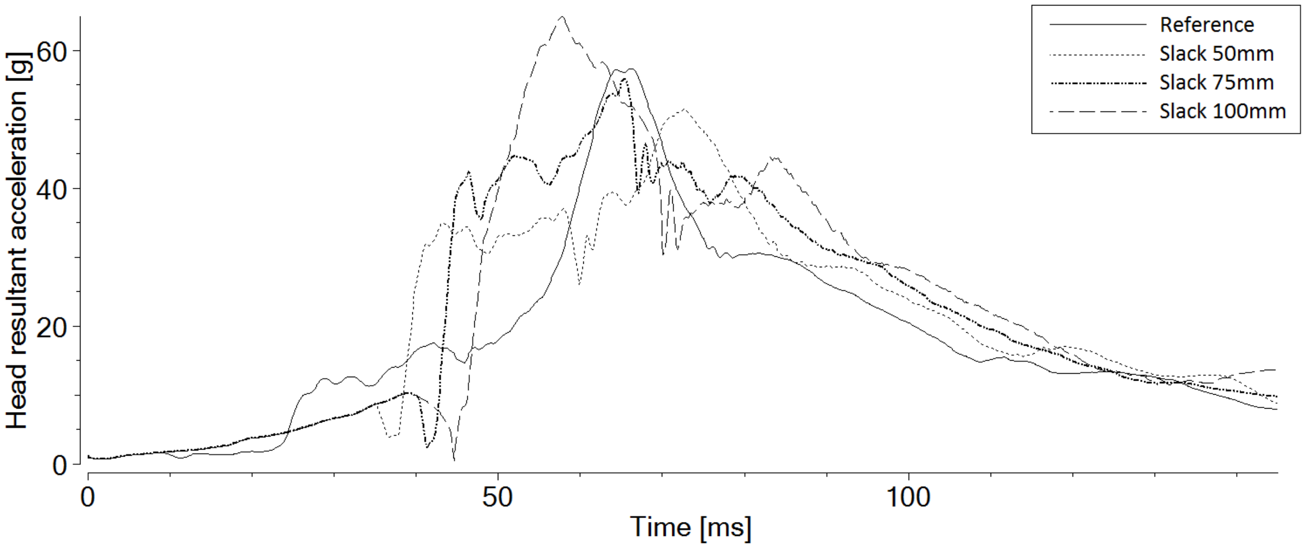

Fig. 2. Time histories of center of gravity of the head resultant acceleration - Cases A-D.

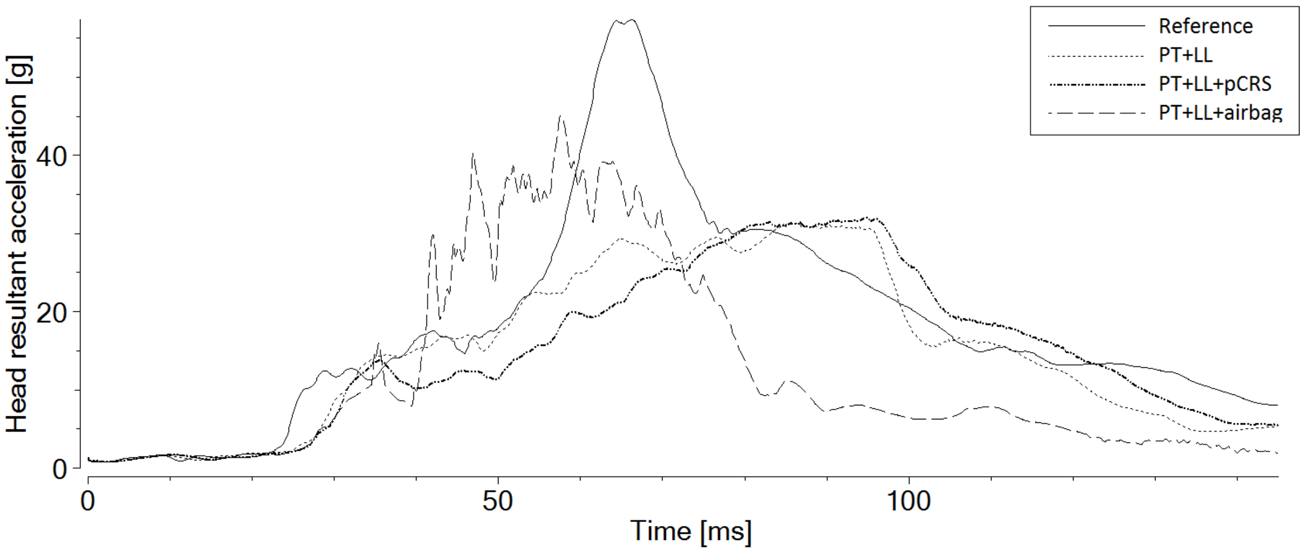

Fig. 3. Time histories of center of gravity of the head resultant acceleration - Cases A,E-G.

Times histories of center of gravity of the chest resultant acceleration for cases A to D are shown in Figure 4. The lowest value of these accelerations can be observed for the reference case (without slack in the belt harness). A comparison of model response in terms of chest resultant acceleration between all cases with proposed improvements, as shown in Figure 5, indicated that both timing and maximum value of the chest resultant acceleration were similar in E and F cases and occurred earlier than in case A and had a lower maximum value. For case G, the maximum value of the acceleration applied in a similar time as in case A. The value was significantly lower, but higher than in cases E and F. It can be concluded that the occurrence of slack in belts increases the chest resultant acceleration, and by applying the proposed safety devices it can be reduced.

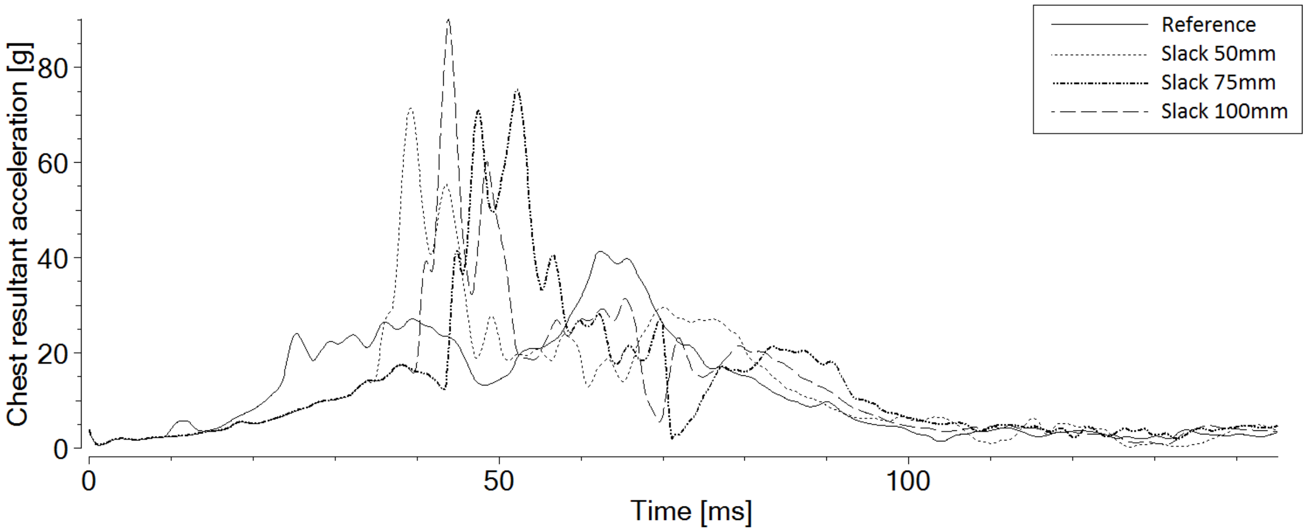

Fig. 4. Times histories of center of gravity of the chest resultant acceleration - Cases A-D.

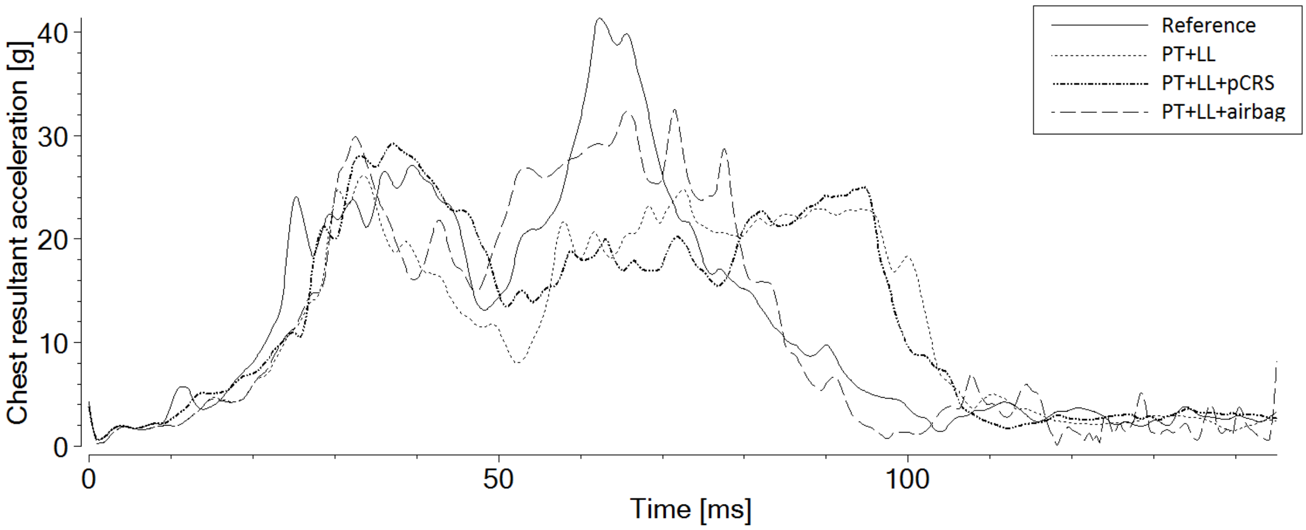

Fig. 5. Time histories of center of gravity of chest resultant acceleration - Cases A, E-G.

Figure 6 and 7 show the Q3 model chest deflection responses in each configuration. It may be noted that by increasing the slack in the belts the resultant deflection of the chest increases and after adding the next safety device the maximum deflection of the chest significantly decreases.

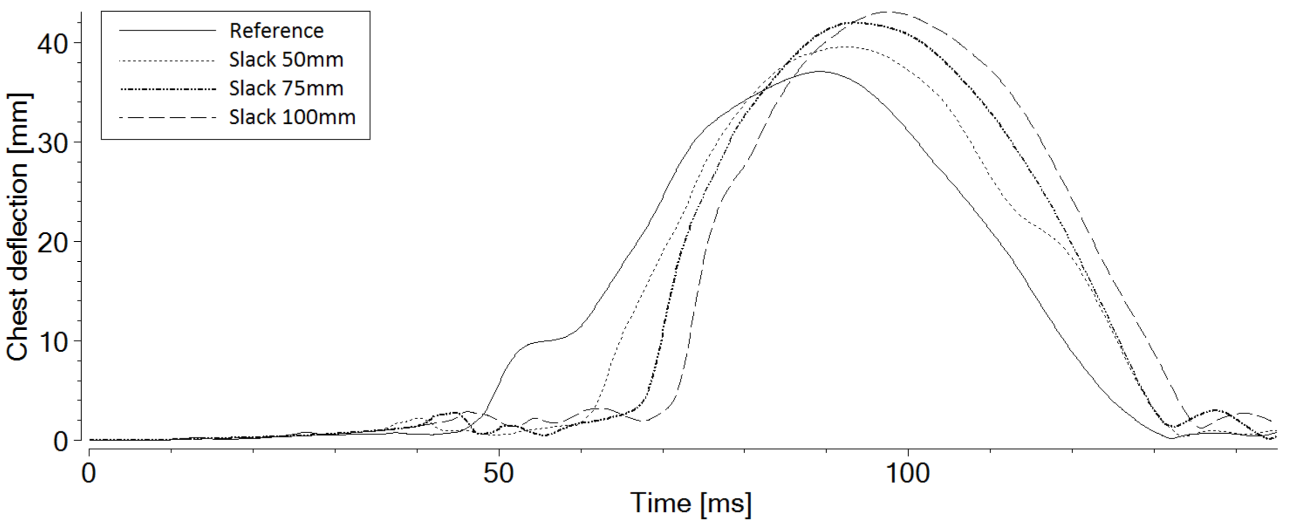

Fig. 6. Time histories of chest deflection - Cases A-D.

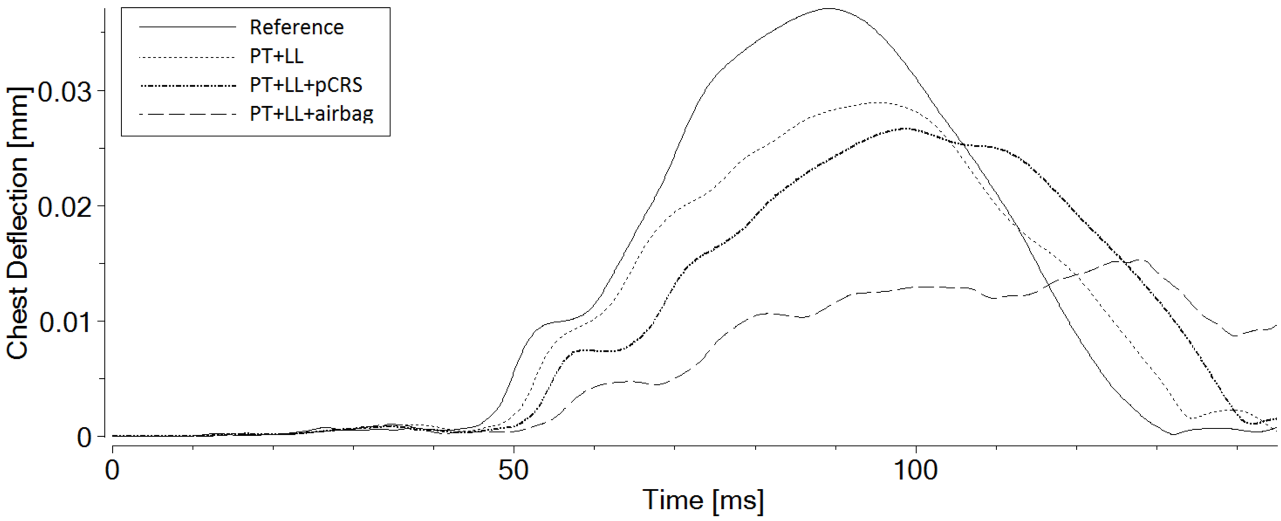

Fig. 7. Time histories of chest deflection - Cases A-D.

During the simulations, the injury criteria of each configuration were observed. All injury criteria values for the presented simulations are shown in Appendix [Table A1-B2]. In the case of the reference configuration (A), four of the injury criteria referring to the neck and one referring to the chest exceeded their limits. In the configurations with the slack, five or six injury criteria reached critical values, while in the cases E and F only one did. In case G, where the special airbag was involved, the normalized values of all injury criteria (injury indicators) were smaller than the unity.

Figure 8 shows Sum of Normalized Value of Injury Criteria (SNV). Cases with the belt slack as compared to the reference case resulted in an increase in SNV even by around 40%. The case with special safety devices as compared to the reference case resulted in a significant decrease in SNV (29%, 32%, 54% for case E, F, G respectively). In fact, the obtained results look very promising.

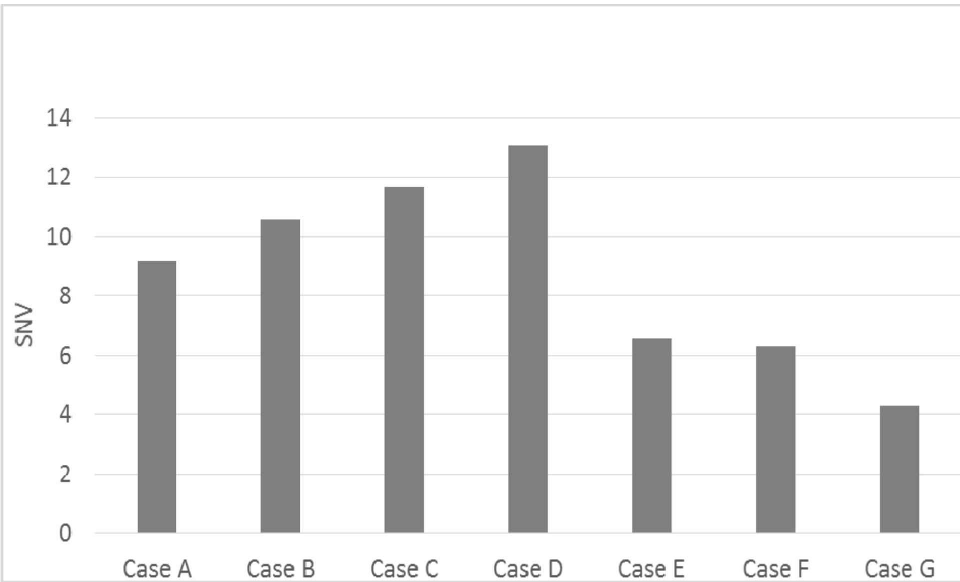

Fig. 8. Sum of Normalized Value of Injury Criteria (SNV) for A-G cases.

IV. DISCUSSION

In this study different injury mitigation systems were proposed: the belt retractor pretensioner, load limiter (integrated with internal harness of CRS), pivoted CRS and special airbag. The obtained results suggest that the use of a supplemental restraint (belt retractor pretensioner, load limiter, pivoted CRS and airbag) by a child occupant could reduce the likelihood of a serious injury. In fact, this additional equipment protects the child during a frontal collision by distributing the forces over a wider area of the body and limiting the relative motion between the head and the thorax in a controlled way.

The retractor pretensioner and load limiter showed a reduction of head and chest accelerations and chest deflection of the Q3 model. Furthermore, the airbag have a potential to reduce neck injury measurements. The special airbag is also effective in reducing head and chest accelerations (although these values were slightly higher than in the case with retractor pretensioner and load limiter used). The retractor pretensioner made less difference in chest deflection than the special airbag.

Only in the case where the special airbag was used, all injury indicators were smaller than the unity. The injury indicators were based on selected biomechanical injury criteria for the chest, head and neck and their critical values for 3-year-old children were assumed (based on the literature data), which can suggest that they can reduce the risk of fatal injury and the severity of injury that a child occupant may have sustained.

It is widely known that airbags make travel safer for adults, but several children have been reported to have died due to airbag deployment [23]. Nevertheless, a “second-generation airbag” can reduce the risk of fatal injury in older children (6-12 years) [24]. In this study the airbag was used for younger children, but the “second-generation airbag” was depowered and redesigned. Previous research showed the protection potential of an airbag while a child is travelling in a car equipped with a special airbag system [25].

Belts slack is considered to increase head excursion and resultant accelerations [28]. The effect of increasing head excursions and resultant chest accelerations were evident also in this study. In contrast, higher resultant head acceleration due to belts slack was not found. In the present research pre-impact braking was considered, but the child dummy model was not developed for this conditions. However, this initial condition was considered not to significantly influence the injury criteria.

In the reference case, chest deflection exceeded its critical value. This was reduced by using a load limiter and distributing the crash forces over a larger body area in the case with a special airbag. In contrast, using a load limiter might potentially induce injury because it allows for more head excursion (especially for taller and heavier children). However, during the simulations the head excursion did not exceed its limit. The belt pretensioners with a level set to 0.75kN, load limiters with a level of 1.5kN and retractors with 5cm pull in were indicated as the most effective.

Head injuries are the most common serious injuries sustained by a child occupant. In this study low head injury criteria values were noticed. These low values could be caused by dismissing angular head motion – proposed head injury criteria based only on linear accelerations [18].

It was indicated that in many cases the critical value of neck injury criteria was exceeded - high neck loads occurred. Presumably they were caused by too high stiffness of the neck model and were not representative of the injury potential. Further study is needed to confirm or reject this assumption. According to the current state of knowledge, cervical spine injuries remain unclear [26]. In fact, neck injuries are not common but in the case of small children they seem to be serious due to the tendency to occur in the upper part. Furthermore, it was reported that noncontact injuries are also possible [27].

As far as leg injuries are concerned, the injuries below knee are the most common [29] and mostly occurred due to contact with the front seat. The special airbag could also protect the child's legs.

It can be concluded that the ECE-R129 regulation includes simplified test configurations and insufficient number of injury criteria which are significantly different from the real crashes in which children are injured.

Child dummy models are not accurate representations of child dummies and child dummies are not ideal representations of children but previous studies indicated that the use of ellipsoid dummy models drastically reduces computation time while preserving acceptable accuracy for kinematic responses [17-19]. Another limitation in this research is the quantification of injury. Injury criteria rely on displacements, force and acceleration signals to indicate injury risk. To predict injury risks from child dummy model, simulations need to be correlated with signals from sled tests and signals from sled tests need to be correlated with real child injuries in crash. Determining a good correlation between observed real injury and dummy model (especially in the case of child models) responses has numerous restrictions. Some simplifications and assumptions must be made when dealing with human body modeling. It remains uncertain whether the model is able to predict all child dummy model measurements accurately, but this study, as the comparative study (not only values was taken into account but also the trends), should be still valuable for improving child safety. Moreover, the trends were similar for the different comparison criteria (not only for the sum of normalized values (SNV) of all injury indicators which was presented but also for grouping by the body regions). The model used in this study is robust and give a reasonable kinematics results for a variety of input conditions which was showed in previous research [19].

Relatively few studies have dealt with child biomechanics and thus there are a great number of uncertainties connected with the child's body tolerances and the effective representation of the population. These conclusions are consistent with the studies carried out by [30]. In that research it was stated that: "*Future pediatric biomechanics research must focus on defining anthropometrics, age-dependent injury tolerance and material and whole body response across the entire pediatric age*".

In addition to the limits of the model itself, in this study nearly no interior vehicle structures were modeled. The effectiveness of forward-facing restraints varies with the methods of installation in the vehicle, vehicle type, various material and contact parameters, a variety of the CRSs and seatback angles (static and their changes during moving) [23] as well as the distance from the airbag (the interior space varies depending on the position of the front seat). However, these variables were not considered.

This research did not represent all possible frontal crash conditions (the crash severity and direction). The aim was to model most common frontal crash conditions. To provide a real life safety effect, the injury mitigation systems should provide appropriate protection in a range of pre-crash sitting position (not only the nominal dummy position) and natural variation between individuals in a population (weight and height of a child). Such analysis was beyond the scope of this study, yet it may be considered in future work.

V. CONCLUSIONS

It was found that the slack in the CRS harness can cause a significant increase of injury criteria values. The obtained results indicate that removing the seatbelt slack would be beneficial for child occupants. It can be achieved through the use of smart pretensioner. The smart pretensioner can start working prior to impact so it can protect out-of-position child occupants during the crash. Belt slack can also result in an increase in head excursion and consequently an increase in the probability of colliding against the front passenger seat. On the other hand, the controlled excursion increase may lead to the severity reduction of injuries sustained. Furthermore, applying the retractor with pretensioner and load limiter resulted in reduction of the injury response of the Q3. Application of the special airbag slightly increased head and chest accelerations but significantly reduced neck injury measures.

The obtained results would seem to indicate that the considered safety system may improve child occupant safety in frontal crashes. In the future, an improved version of this type of safety device may cope with the unique needs of children in automotive safety. However, children who are seated near the front seat or are improperly restrained may be at high risk of serious injury. In addition, the results depend on many variables such as the acceleration pulse waveform, vehicle type, the crash severity and direction, harness tightness, seatbelt webbing width, various material and contact parameters, as well as injury rating method. The research deals with uncertainties which are common in car accident analyses. Further research is essential both for numerical simulations and experiments.

It should be emphasized that a special airbag, a retractor and a smart pretensioner are supplemental restraints and only work effectively in combination with a properly selected child restraint system which accommodates size, weight and stages of child's body development.

VI. ACKNOWLEDGEMENT

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VIII. APPENDIX

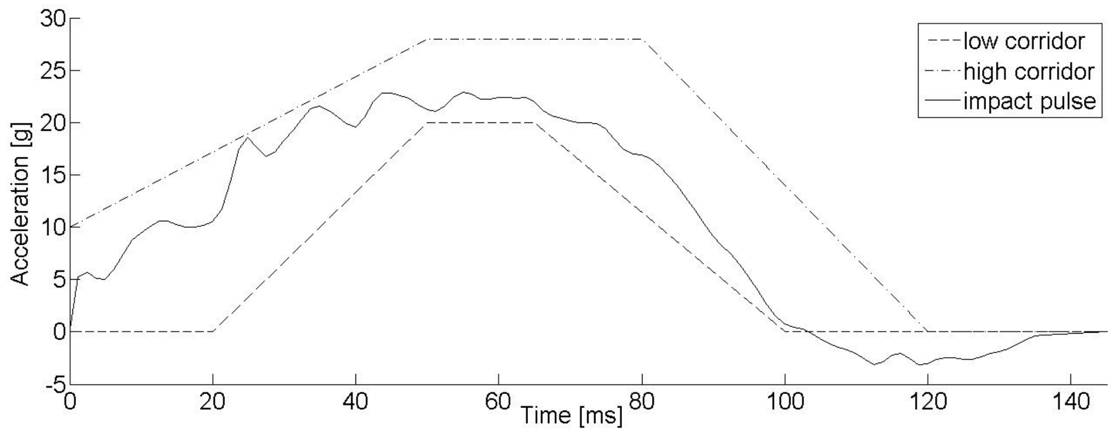

FIG. A. THE IMPACT PULSE APPLIED TO THE MODEL.

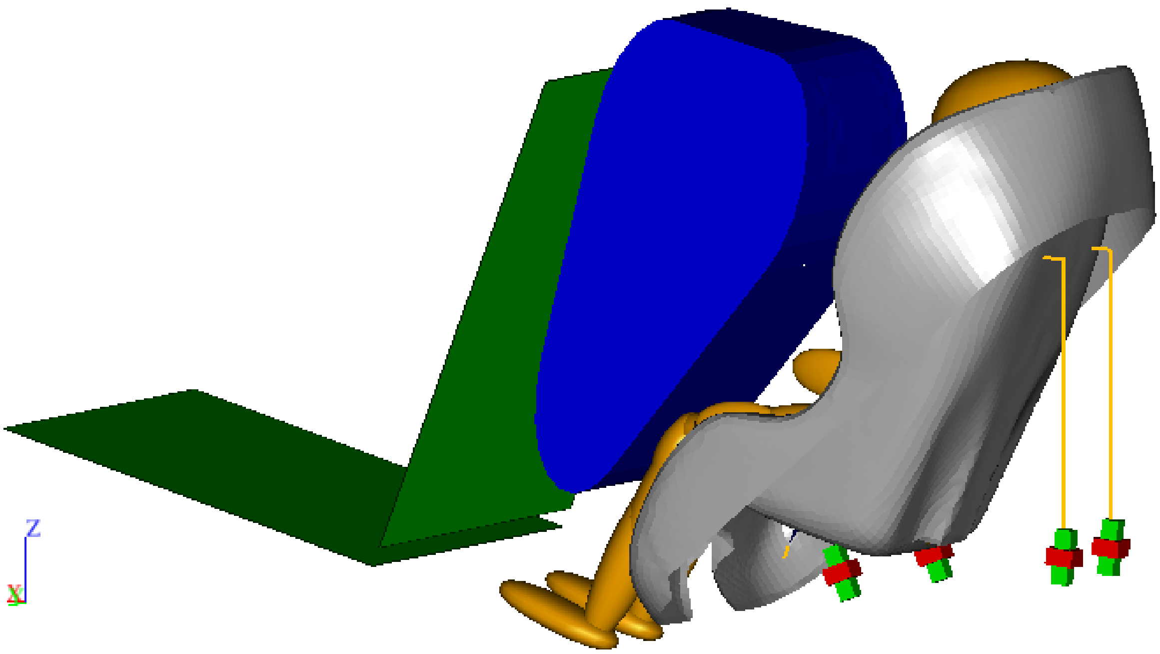

FIG. B. THE Q3 DUMMY MODEL SEATED IN FF CRS IN THE CASE G.

TABLE AI

VALUES OF INJURY CRITERIA

Injury Criterion	Injury Criterion Value			
	Case A	Case B	Case C	Case D
CUM_H	555,770	492,650	516,240	603,260
HIC_36	305,480	336,160	451,570	561,940
N_TE	**1,343**	**1,314**	**1,646**	1,599
N_TF	0,255	0,567	0,530	0,895
N_CE	0,067	0,267	0,205	0,155
N_CF	0,024	0,053	0,053	0,053
NIC_TN	41,334	216,840	255,920	255,920
NIC_T_P	**1788,100**	**1671,300**	**1886,500**	**1814,900**
NIC_S_N	**722,280**	**722,530**	**702,350**	**704,730**
NIC_S_P	12,957	12,957	12,957	27,848
NIC_B_N	**18,079**	**27,095**	**33,131**	**31,131**
NIC_B_P	6,252	5,166	4,701	5,928
CUM_T	392,350	545,430	**596,270**	**649,440**

TABLE AII

NORMALIZED VALUES OF INJURY CRITERIA AND SUM OF NORMALIZED VALUES (SNV)

Injury Indicator	Injury Indicator Value			
	Case A	Case B	Case C	Case D
1	0,695	0,616	0,645	0,754
2	0,38	0,420	0,564	**0,702**
3	**1,343**	**1,314**	**1,646**	**1,599**
4	0,255	0,567	0,530	0,895
5	0,067	0,267	0,205	0,895
6	0,024	0,053	0,053	0,155
7	0,037	0,192	0,226	0,226
8	**1,582**	**1,479**	**1,669**	**1,606**
9	**1,445**	**1,445**	**1,405**	**1,409**
10	0,026	0,026	0,026	0,056
11	**1,130**	**1,693**	**2,071**	**1,946**
12	0,391	0,323	0,294	0,370
13	0,713	0,992	**1,084**	**1,181**
14	**1,090**	**1,162**	**1,233**	**1,265**
SNV	*8,483*	*10,549*	*11,652*	13,061
Loss	*reference*	*14%*	*26%*	42%

TABLE BI
VALUES OF INJURY CRITERIA

Injury Criterion	Injury Criterion Value			
	Case A	Case E	Case F	Case G
CUM_H	555,770	303,630	309,890	382,030
HIC_36	305,480	163,540	160,610	186,700
N_TE	**1,343**	0,856	0,778	0,344
N_TF	0,255	0,476	0,297	0,253
N_CE	0,067	0,071	0,082	0,084
N_CF	0,024	0,024	0,024	0,069
NIC_TN	41,334	41,467	41,513	37,471
NIC_T_P	**1788,100**	1093,400	1059,800	388,940
NIC_S_N	**722,280**	**531,460**	**570,800**	284,540
NIC_S_P	12,957	12,957	12,605	41,558
NIC_B_N	**18,079**	12,779	13,925	6,617
NIC_B_P	6,252	4,745	4,920	9,518
CUM_T	392,350	276,190	249,680	292,700
CD	**0,037**	0,029	0,026	0,008

TABLE BII
NORMALIZED VALUES OF INJURY CRITERIA AND SUM OF NORMALIZED VALUES (SNV)

Injury Indicator	Injury Indicator Value			
	Case A	Case E	Case F	Case G
1	0,695	0,380	0,387	0,478
2	0,382	0,204	0,201	0,233
3	**1,343**	0,856	0,778	0,344
4	0,255	0,476	0,297	0,253
5	0,067	0,071	0,082	0,084
6	0,024	0,024	0,024	0,069
7	0,037	0,037	0,037	0,033
8	**1,582**	0,968	0,938	0,344
9	**1,445**	**1,063**	**1,142**	0,569
10	0,026	0,026	0,025	0,083
11	**1,130**	0,799	0,870	0,414
12	0,391	0,297	0,307	0,595
13	0,713	0,502	0,454	0,532
14	**1,090**	0,844	0,775	0,244
SNV	**9,178**	**6,545**	**6,318**	**4,275**
Profit	*reference*	*29%*	*32%*	54%