NUMERICAL SIMULATION FOR EVALUATING CHILD OCCUPANT BEHAVIOUR IN THE CASE OF A REAR IMPACT

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ABSTRACT

This project uses dynamic simulations to assess the effectiveness of child restraint systems in the case of rear impact, in various installation configurations and for different acceleration pulses.
The model was mainly based on a multi-body method, using the MADYMO software. However, the side wings of the child restraint system have been modelled by the finite-element technique, to ensure a better representation of the contacts between the child dummy and the restraining device.
The study shows that the neck is the most exposed part of the body and in some situations the neck injury criteria overpass the limit values. Thus, the case of the neck injury criteria in tension-extension for the installation using vehicle safety belts, when the result is more than double than the limit value.
The simulations employed two triangular pulses, with speed variation of 16 km/h and 25 km/h, and one trapezoidal pulse, with speed variation of 25 km/h. In all cases, the results are proportional with the speed variation. Furthermore, the two triangular pulses give higher values for injury criteria than the trapezoidal pulse.
Installation of a child restraint using rigid anchorages and lower straps offers the best protection for the child passenger in the case of rear-end collision. The acceleration pulse is a crucial factor for the accuracy of tests and the realism of simulations.
The principal limitation of the study refers to the injury criteria that are not yet well defined and for which does not exist a consensus in the case of a rear impact.
The paper presents an approach for simulating rear-end collision involving child passengers, which could be used for comparative studies of different rear-impact scenarios, such as different acceleration pulses or installations.

INTRODUCTION

Real life accident data are showing that the slow-speed rear-impact can produce neck injury causing invalidity and long-term disability. These injuries, abbreviated WAD (Whiplash Associated Disorders) are usually classified as AIS 1 (Hynd and van Ratingen, 2005). AIS – Abbreviated Injury Scale, created by The Association for the Advancement of Automotive Medicine (AAAM), is the most used injury classification scale, where 0 signifies that there is no injury and 6 designates unsurvivable injuries.
A study conducted in Japan and presented by Sawada and Hasegawa (2005) showed that neck injury represent around eighty percent from the total injuries caused by rear-end accidents. According to Fatality Analysis Reporting System - FARS (NHTSA, 2002), in the USA in 1999, 8 % of the children (101 children) killed in road accidents were involved in rear-end accidents. Between 1991 and 2000, in USA, 662 children were killed in rear-end accidents, representing 7 % of the total number of the children dead in traffic accidents in the considered period. More than 30 % of these victims (214) were seated in a child restraint system during the accident (NHTSA, 2004).
In Quebec in 1987, $18 millions was paid for damages caused by this type of accident, which determined La Société d'Assurance d'Automobile du Québec (SAAQ) to form a special workgroup, Quebec Task Force, with a view to studying the injuries produced by whiplash (Spitzer et al., 1995). This study is considered the reference for similar research (Freeman et al., 1998 and Versteegen et al., 2001).
Boyd et al. (2008) present a study performed in England for eight months in emergency rooms, which used the Québec Task Force methodology. The study identified 101 child passengers victims of rear-end accidents, from which 49 (47 %) were presenting WAD symptoms. The average duration of the symptoms was 8.8 days, showing more important incidence than in similar studies.
In order to assess the emergency of having rear impact regulatory stipulations for child passenger protection, NHTSA performed some dynamic sled tests at both 17.5 and 30.5 km/h impact speeds using a CRABI 12-month-old dummy. The dummy, seated in an Evenflo On My Way rear-facing infant seat, was installed on the rear seat of a 1999 Dodge

Intreprid vehicle body. Because the measured injury parameters did not exceed the limits stipulated by FMVSS 208 and considering that a 7 % fatality is low, it was concluded that it is not necessary yet to stipulate special requirements for the child passenger protection in the case of rear impact (NHTSA, 2004). According to Croft (2000), the risk for a child passenger represents two-thirds of the risk for an adult occupant but despite this high risk, less than 2 % of rear-end impact studies are dedicated to child passenger protection.

Another element of importance for studying WAD associated to child occupant, presented by Klinich et al. (1996), is the fact that the weight of the head of the child is proportionally more important with respect to the rest of the body than for the adult, one forth compared with one seventh, thus favouring the lesions of the spine.

While the efficiency of child restraint systems was very well proven in frontal collisions, and studies regarding side impact collisions are continually increasing, the performances of these devices in the case of a rear-end collision were not yet sufficiently demonstrated. The objective of the project presented in this paper was to study by simulation the behaviour of the child dummy in the case of a rear-end impact, for various acceleration pulses and in different installation configurations of the child restraint system.

METHODOLOGY

General Approach

The first step of the project stands for the development of the model. The study is based on multi-body method but the side wings of the child restraint system have been modelled by the finite-element technique. This modelling allows for a better representation of the contacts between the child dummy and the restraining device. The second step, consisting in model exploitation, presents rear-end impact simulations for different acceleration pulses and in various installation configurations of the child restraint system.

Child Dummy

The majority of the studies on the effect of the impact on child passengers use three-years-old child dummies. Adult rear-impact dummy models are available in MADYMO Data Base, such are Hybrid III – TRID Neck (Hybrid III dummy with the neck model adapted for rear impact), RID II and BioRid II, but there is not yet any child dummy specially destined for the study of rear impact. The model on which this study is based uses the Hybrid III – 3-years-old child dummy (Surcel, 2004). The Hybrid III series was designed for front impact studies, thus the accuracy of the evaluation of the risk in the case of a rear impact was not yet verified by experimental studies. According to European Vehicle Passive Safety Network 2 (2004), because their neck mimics human bending response in flexion and extension, these dummies can be used in rear as well as frontal collision evaluations.

In spite of the above mentioned limitations, we have chosen for our model a Hybrid III – 3-years-old child dummy model, consisting of 28 ellipsoids while certain head regions are built using finite elements. The contact between head and thorax is defined by default. Additional contacts have been defined to consider the interactions between different parts of the model: between femurs; between each femur and the abdomen, the thorax, the neck and the head; between tibias; between each tibia, the neck, and the head; between arms; between each arm, the neck and the head.

Models

For the chosen child dummy model, the required child seat is the convertible restraint system designed for use by infants and toddlers. The child seat model described by Surcel and Gou (2005) was used. It is made of a shell and its support that is in contact with the vehicle bench cushion. A padding that satisfies energy absorption requirements covers the inside of the shell. A contact stiffness function was defined for the padding of the child restraint system. The seat is also equipped with a tilting adjustment button, a rear support and a harness.

The central region of the child seat, consisting of sixty-eight ellipsoids and four cylinders, has been assembled with the side wings, modelled using finite elements in order to allow for a better representation of the contacts between the child dummy and the restraining device (Figure 1).

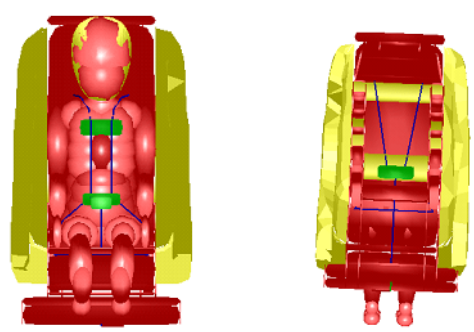

Figure 1. Installation of child restraint system harness.

The child restraint system can be installed using vehicle safety belts or the lower rigid anchorages and straps. The upper part of the seat back is attached to the vehicle's structure with a top tether.
The material properties for the child seat and the belts and straps characteristics are those used by Surcel (2004). All the straps were represented using MADYMO belt segments. The child restraint system attachments, vehicle safety belt anchorages and rigid anchorages were built by ellipsoids. Figure 2 present child seat installations.

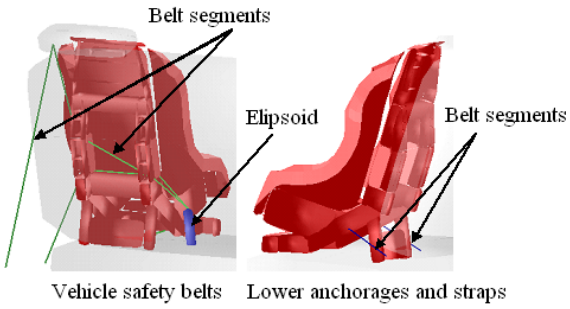

Figure 2. Child restraint system installation.

The test sled was modelled using ellipsoids, based on the description given in test method 213 (Transport Canada, 2001).). The contact stiffness for the sled bench cushion and sled bench back was defined by force-deflection curves. Figure 3 presents the model of the test sled.

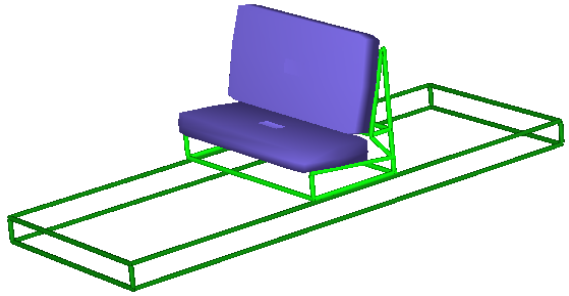

Figure 3. Test sled model.

The model on which is based this study was evaluated for side and frontal impact against similar test data. The simulation results were generally very close to experimental data (Surcel, 2004; Surcel and Gou, 2005). There are not enough accidentology studies and experimental data are practically inexistent for child passengers involved in a rear impact. Thus, validation of the model for rear impact or, at least, comparing the results of the simulations with test results was not possible.

Injury Criteria

Injury criteria are necessary in order to evaluate the risk for the passenger in case of an accident and for correlating the loading conditions during impact with the injury scales.
WAD-RAP (Whiplash Associated Disorders - Risk Assessment Parameters) is intended to replace injury criteria when the actual cause of the Whiplash Associated Disorders is not known. According to Hynd and Ratingen (2005), from the regulatory point of view, it is necessary to have a good correlation between WAD-RAP and the risk. This condition is fulfilled by the neck injury criteria (NIC) and by the Nkm criteria, which is based on a combination of shearing forces and bending moments in the upper neck (Schmitt et al., 2001). Another proposed combined criteria for evaluating neck injury in the case of a rear impact is LNL (Lower Neck Load), a combination of lower neck loading in shearing, tension and extension (Heitplatz et al., 2003).
Head Injury Criteria (HIC) is the most used criteria for evaluating the severity of the head injuries and it gives the necessary information to differentiate the contact impact response from the non-contact impact response. HIC is calculated based on « Wayne State Tolerance Curve » (WSTC) and it was established only for the front – to rear direction impact. In our case, contacts are defined between the head of the child dummy and the child seat back with the loading applied in a longitudinal direction. Therefore, we consider that the usage of HIC is appropriate for our study.
Other studies have shown that the neck forces and moments, as well as the head and the thorax acceleration, might not have an adequate biofidelty for the study of the rear impact. Consequently, the neck injury criteria NIC and Nij, which computation are based on the above mentioned parameters, might be also inadequate for the rear impact study (Kuppa et al., 2005).
The European Automobile Manufacturers' Association (ACEA) has carried out a study looking at the repeatability and reproducibility of the proposed test procedures and injury criteria for rear impact, using 16 km/h and 25 km/h – delta-V (ΔV) pulses (Adalian et al. 2005). The injury criteria used for the BioRID adult dummy were head, spine and pelvis accelerations, lower and upper neck forces and moments as well as the combined criteria LNL, Nkm and NIC, and the contacts between the seat and the dummy. The repeatability of most of the injury criteria at 16 km/h was acceptable but reproducibility was poor, with variations of up to 40% for some of the criteria. The situation worsened at 25 km/h, with some criteria yielding variations of over 100%. The

study concluded that the injury criteria must be very carefully selected, and the high severity pulses might be inadequate for neck injury assessment.
The linear and angular head accelerations and the head displacement are also used during the rear impact tests performed by insurance companies (GDV- Alianz-Germany) and research institutes (JARI - Japan Automobile Research Institute and TRI - Transport Research Institute – United Kingdom).
The actual injury, causing the typical WAD symptoms, and the injury mechanism are still unknown, though hypotheses exist. The evaluation of the currently proposed injury criteria, such as LNL, Nkm and NIC, is statistically derived from field accident data and reconstructions of real world accident situations (Hynd et van Ratingen, 2005). An important validation work is still necessary, and especially for the child passengers.
The fore mentioned considerations as well as the MADYMO output data availability, guide us on the choice of the parameters for evaluating the behaviour of the child dummy response in the case of the rear impact simulation. Table 1 presents these parameters.

Table 1.
Evaluation parameters

N°	Description	Symbol
1	Head Injury Criteria – 15 ms	HIC 15
2	Head Injury Criteria – 36 ms	HIC 36
3	Head Injury Criteria – unlimited	HIC
4	Thorax deflection	DT
5	Head linear acceleration in the centre of gravity, m/s^2	HCG_acc
6	Head angular acceleration, rad/s^2	Hang_acc
7	Thorax deceleration - 3ms, m/s^2	T3ms
8	Neck injury criteria in tension – extension	Nij TE
9	Neck injury criteria in tension – flexion	Nij TF
10	Neck injury criteria in compression – extension	Nij CE
11	Neck injury criteria in compression – flexion	Nij CF
12	Rearward neck injury criteria, m/s^2	NIC Rr
13	Resultant force in the lower neck, N	NLow_F
14	Resultant force in the upper neck, N	NUp_F
15	Resultant moment in lower neck, Nm	NLow_M
16	Resultant moment in upper neck, Nm	NUp_M

Acceleration Pulses and Simulations

WG20 working group has been set-up within EEVC (European Enhanced Vehicle Safety Committee) for studying the rear impact test procedures and rear impact neck injuries.
WG task is to develop sled test procedures in order to define acceleration pulses, installation and test dummies. Based on accident data records from several countries, WG20 reported that the majority of these types of injuries occur in medium impact severity crashes consisting in change of velocity (ΔV), between 10 and 15 km/h, and deceleration less than 4 g. These are short-term injury and the patients recover within a couple of weeks. Long-term injuries, with consequences lasting more than one month, are produced by impacts with ΔV greater than 20 km/h and deceleration more than 5 g (Hynd et van Ratingen, 2005). Consequently, the low severity accidents are well reproduced by using acceleration pulses with $\Delta V < 20$ km/h, while the impacts with more severe consequences are corresponding to acceleration pulses with $\Delta V \geq 20$ km/h. In order to study both situations, we chose one acceleration pulse with $\Delta V = 16$ km/h and two acceleration pulses with $\Delta V = 25$ km/h. Figure 4 presents these pulses, adapted from Sawada and Hasegawa (2005).
The acceleration pulse no. 1, used by IIWPG (International Insurance Whiplash Prevention) and ADAC (Allgemeiner Deutscher Automobil-Club e.V.), corresponds to $\Delta V = 16$ km/h. For $\Delta V = 25$ km/h we used the triangular acceleration pulse no. 2, also proposed by ADAC, and the trapezoidal acceleration pulse no. 3, adopted by the Swedish insurance company Folksam.

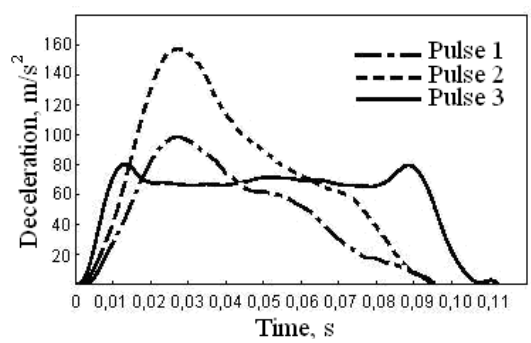

Figure 4. Acceleration pulses for rear impact, adapted from Sawada and Hasegawa (2005).

To simulate the rear impact, the rear acceleration field and the gravity field were applied to the child dummy and to the child restraint system. The study compared the results obtained with the three different acceleration pulses described above, and considered

the two different installation configurations - vehicle seat belts and lower anchorages and straps.
The results of the simulation were also compared with the Injury Assessment Reference Values (IARV), stipulated by FMVSS 208 and FMVSS 213, and with the reference values proposed by Klinch et al. (2006). These injury parameters are for frontal impact and may not accurately reflect the risk of injury in rear impact. The corresponding Injury Assessment Reference Values should be used for reference purposes only. For thorax acceleration, the two standards stipulate different values: 540 m/s^2 (FMVSS 208) and 589 m/s^2 (FMVSS 213).

RESULTS AND DISCUSSIONS

Comparison Study for Different Acceleration Pulses

This section presents the results of the simulations performed with the three different acceleration pulses with the child restraint system installed using the lower anchorages and straps. In all cases, the upper part of the child restraint system is attached to the vehicle body with a top tether while the child is attached with the harness provided by the child restraint system. Similar simulations have been conducted with CRS installed using vehicle's safety belts.
The simulation results show that both the child dummy and the child restraint system moved rearward under the action of the acceleration field. The vehicle safety belts and the child restrain harness were stressed and the child dummy entered into contact with the child seat back. The child dummy was pushed to the front by the reaction forces due to the impact with the back of the CRS and by the elastic forces in the harness and in the straps. Figure 5 illustrates the model during the simulation of the rear impact and Table 2 presents the results of the simulation.

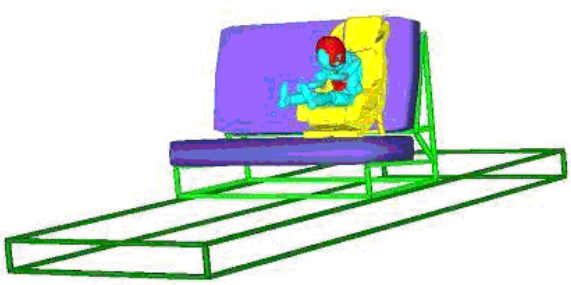

Figure 5. Rear impact simulation.

It can be observed that the acceleration pulse no. 2 (ΔV=25 km/h, triangular) generally gives higher values for the injury criteria than the two other pulses. The result for the neck injury criteria in tension – extension (Nij TE) is the only one exceeding the admissible value, with 12 %.

Table 2.
Injury criteria comparison for the simulations using the three acceleration pulses and the CRS installed with lower anchorages and straps

N^o	Parameter	Acceleration pulse			Ref. value
		1	2	3	
1	HIC 15	34	44	25	570
2	HIC 36	34	48	25	1000
3	HIC	49	84	37	1000
4	DT, mm	24	26	18	34
5	HCG_acc, m/s^2	354	501	325	785
6	Hang_acc, rad/s^2	4214	3470	3897	2200
7	T3ms, m/s^2	161	156	134	540 / 589
8	Nij TE	0.959	1.123	0.801	1
9	Nij TF	0.336	0.020	0.020	1
10	Nij CE	0.569	0.486	0.518	1
11	Nij CF	0.255	0.234	0.225	1
12	NIC Rr , m/s^2	77	62	67	-
13	NLow_F, N	1278	1960	1115	2500
14	NUp_F, N	1016	1569	965	2500
15	NLow_M, Nm	75	95	69	-
16	NUp_M, Nm	14	18	13	-

The variation curves for head accelerations are presented in Figure 6 and Figure 7.

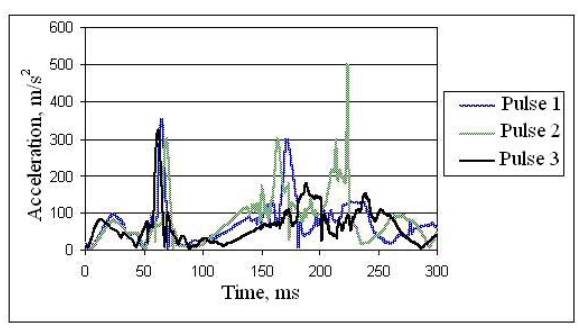

Figure 6. Acceleration pulses, installation with lower anchorages and straps: variation of head linear acceleration.

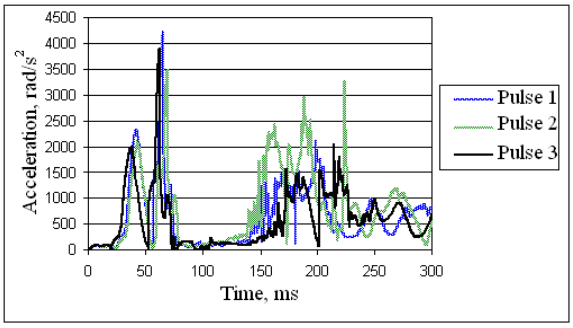

Figure 7. Acceleration pulses, installation with lower anchorages and straps: variation of head angular acceleration.

Figure 8 presents the comparison between the variation curves according to rearward neck injury criteria.

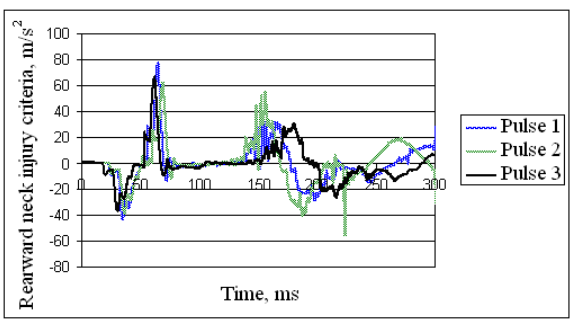

Figure 8. Acceleration pulses, installation with lower anchorages and straps: variation of rearward neck injury criteria.

These comparisons are showing similar variations, except during the last part of the simulations. For head accelerations, two peaks can be observed: the first maximum is toward 60 ms and the second maximum around 220 ms, when the acceleration pulse no. 2 gives the peak for the linear acceleration of the head. The first maximum corresponds to the impact between dummy's head and the child seat back. The second maximum occurred when the head had the greatest displacement and started the backward movement. Its duration is very limited and it was not produced by contact. Consequently, it does not give a significant increase of the HIC.

Comparisons between Installation Configurations

This section presents the simulations' results of the child restraint system when installed using the lower anchors and straps compared to using the vehicle's safety belts. For both installations, the upper part of the child seat back is attached to the vehicle body with a top tether and the child is attached with the harness of the child restraint system. Table 3 presents the comparison between different parameters for the two considered installation configurations, when the rear impact is simulated by the acceleration pulse no. 2 (ΔV=25 km/h, triangular).

Table 3.
Injury criteria comparison for different installation configurations (pulse no. 2)

N°	Parameter	Installation		Ref. value
		Lower anchorages	Safety belts	
1	HIC 15	44	141	570
2	HIC 36	48	154	1000
3	HIC	84	180	1000
4	DT, mm	26	37	34
5	HCG_acc, , m/s^2	501	717	785
6	Hang_acc, rad/s^2	3470	4980	2200
7	T3ms, , m/s^2	156	354	540 / 589
8	Nij TE	1,123	2,229	1
9	Nij TF	0,020	0,746	1
10	Nij CE	0,486	0,444	1
11	Nij CF	0,234	0,272	1
12	NIC Rr , m/s^2	62	249	-
13	NLow_F, N	1960	2792	2500
14	NUp_F, N	1569	2798	2500
15	NLow_M, Nm	95	155	-
16	NUp_M, Nm	18	28	-

Similar simulations have been performed for the other two acceleration pulses.
The variation curves for head accelerations are presented in Figure 9 and Figure 10.

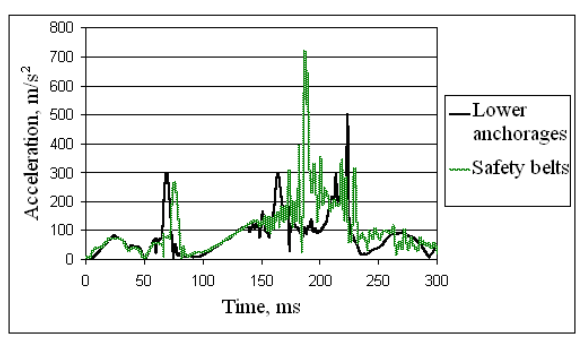

Figure 9. Installations, acceleration pulse no. 2: variation of head linear acceleration.

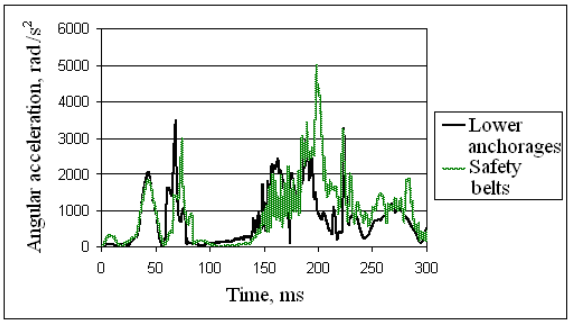

Figure 10. Installations, acceleration pulse no. 2: variation of head angular acceleration.

Figure 11 presents the comparison between the variation curves according to the rearward neck injury criteria.

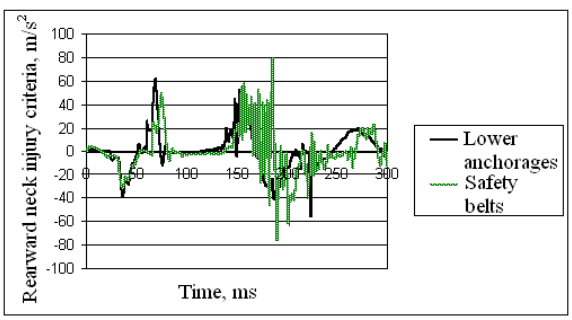

Figure 11. Installations, acceleration pulse no. 2: variation of rearward neck injury criteria.

Table 3 yields also that the admissible values are exceeded only for the neck injury criteria in tension – extension (Nij TE), and this with more than 220 %. For all the parameters, the results for the vehicle safety belt installation are greater than the corresponding results obtained for lower anchorages and straps.
The comparisons of plots shows similar trends but some differences are observed. The curves corresponding to the vehicle safety belts installation are showing more amplitude than the curves obtained with lower anchorages and straps installation. The maximal values in the last part of the simulation are higher for the vehicle safety belt installation, when the head of the dummy reached its maximum displacement and started the backward movement. The linkage is less stiffer and the safety belt segments generate elastic forces producing additional acceleration during the backward movement.
The results show that lower anchorages and straps provide the best protection for the child passenger.

Discussion

This project aimed at the development of a numerical method, using multi-body and finite elements methods, to simulate the behaviour of a child passenger restrained in a protective device while involved in a vehicle rear impact. Simulations have been performed in order to compare the influence of installation configurations and to evaluate the effects of different acceleration pulses.
One of the general limitations of the model is the utilisation of MADYMO belt segments for modelling vehicle safety belts and child seat harness. This type of modelling duplicates very well the geometry of the safety belts and the geometry of the harness, and correctly represents the unidirectional sliding of the belt on dummy's body. Despite these advantages, MADYMO belt segments have fixed attachment points and consequently they do not accurately reproduce the multi-directional sliding
Another category of objective limitations refers to the injury criteria that are not yet well defined and for which does not exist a consensus in the case of a rear impact. We had to use the same criteria normally employed for frontal impact, and available in MADYMO as output data. There are not enough accidentology studies and experimental data are practically inexistent for child passengers involved in a rear impact. Thus, validation of the model for rear impact or, at least, comparing the results of the simulations with test results was not possible. Moreover, there is not yet a child dummy specially destined for the study of rear impact. The Hybrid III dummy was designed for the study of frontal impact and therefore the evaluation of the risk in the case of a rear impact might be also questionable. There are studies showing that the neck of the Hybrid III dummy reproduces well the human response in bending and extension, thus these dummies can be considered for rear as well as for frontal collision evaluations.
A similar situation is met when choosing the acceleration pulses, which are not yet standardized. We used three different acceleration pulses: one acceleration pulse with ΔV = 16 km/h to reproduce low severity accidents, and two acceleration pulses with ΔV = 25 km/h to simulate impacts with more severe consequences.
The comparisons of the simulations results obtained with the three different acceleration pulses show that the acceleration pulse no. 2 (ΔV=25 km/h, triangular) generally gives higher values for the injury criteria than the two other pulses. The result for the neck injury criteria in tension – extension (Nij TE) is the only one exceeding the admissible value, with 12 %. The variation curves for head accelerations are

showing similar variations, excepting the last part of the simulations. For head accelerations, two maximum can be observed: the first is toward 60 ms and the second around 220 ms, when the acceleration pulse no. 2, triangular, with a more abrupt variation of the speed and with the highest amplitude, gives the peak for the linear acceleration for the centre of gravity of the head. The first maximum corresponds to the impact between dummy's head and the child seat back. The second maximum, which has a short duration and not produced by contact, occurred when the head had the greatest displacement and started the backward movement, and it did not significantly increase the HIC.

The comparison of the installation configurations, lower anchorages with straps and vehicle's safety belts, shows that the admissible values are exceeded only for the neck injury criteria in tension – extension (Nij TE). For all the parameters, the results for lower anchorages and straps are less than the corresponding results obtained when the vehicle safety belts were used.

The comparisons of plots shows similar trends but some differences are present. The curves corresponding to the vehicle safety belts installation are showing more variation than the curves obtained with lower anchorages and straps installation. The maximal values in the last part of the simulation are greater for the vehicle safety belt installation, when the head of the dummy reached its maximum displacement before starting the backward movement. The explanation resides in the increased mobility of the installation. Furthermore, the generation of the elastic forces in safety belt segments produce additional acceleration during the backward movement. These considerations entitle preference of the lower anchorages for a better protection of the child passenger.

CONCLUSIONS

The simulations performed with the three acceleration pulses have shown that the neck is the most exposed part of the body. This result is confirmed by the actual preoccupations in the design of the whiplash protection systems. The injury criteria exceed the limit value in certain situations, as in the case of the neck injury criteria in tension-extension with the child restraint system installed using vehicle's safety belts. The result probed is more than double of the limit value.

The acceleration pulse is very important for the accuracy and the realism of the simulations. The simulations were performed under two triangular pulses, with speed variation of 16 km/h and 25 km/h, and one trapezoidal pulse, with speed variation of 25 km/h. In all cases, the results are proportional with the speed variation. Furthermore, the two triangular pulses, with speed variation of 16 km/h and 25 km/h, give higher values for injury criteria than the trapezoidal pulse with speed variation of 25 km/h. The triangular pulse with speed variation of 25 km/h is the most appropriate for a conservative approach.

The comparison of the installation configurations showed that the installation using vehicle's safety belts allows a bigger displacement of the child seat and, consequently of the child dummy.

The rebound caused by the elastic forces is more important, which generates supplementary loads in the neck. Finally, the installation using rigid anchorages and lower straps offers the best protection for the child passenger in the case of rear-end collision.

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