INTRUSION INFLUENCE ON CHILD OCCUPANT BEHAVIOUR IN THE CASE OF A SIDE IMPACT MADYMO SIMULATION

Marius-Dorin Surcel
Michel Gou
École Polytechnique de Montreal
Canada
Paper Number 05-0050

ABSTRACT

The effectiveness of child restraint systems has been very well proven in the case of frontal collision but the performance of the protective devices in side-impact situation were not, as yet, clearly demonstrated.

This research was aimed at the development of a numerical method to simulate the behavior of a child passenger restrained in a protective device in the case of a vehicle side impact, considering vehicle body deformation. The model was mainly based on a multi-body method. However the side wings of the child restraint system and the vehicle body have been modeled by the finite-element technique, to allow for a better representation of the contacts between the child dummy, the restraining device and the structure of the vehicle and to make possible the simulation of the vehicle body deformation, based on available side impact test data. The model had been validated for side impact and we have used it to study the influence of the intrusion against the child dummy behavior in the case of side impact.

The intrusion influence is most important for the head injury criteria, being proportional with the impact speed. The study of various installation configurations showed that the usage of ISOFIX lower anchorages offers the best protection for the head, followed by the lower flexible anchorages and vehicle belt installation. The intrusion influence is most important when the child restraint system is installed using the vehicle safety belts, the results being much higher than for the case where the intrusion is not considered. Chest deceleration is less influenced by the intrusion and the three considered installation configuration give similar results. Although the results of the project successfully responded to the initial objectives, the model is offering a lot of possibilities of improvement, development and exploitation.

INTRODUCTION

Children are the most innocent victims of road accidents and therefore their protection is a major issue for all involved in automotive safety.

The effectiveness of the specialized child restraint systems was well proved in the case of frontal collision, where regulations, standards and test procedures are available. As a result of educational campaigns, most child restraint systems are now installed on the rear seat of the vehicle so that vehicle body deformation influence for the child occupant injuries was considerably reduced in the case of frontal impact. Table 1 illustrates the trend of the gradually increasing rear seat placement of the child restraint system (Stern, 1998).

Table 1.
Child Seat Distribution by Row
(from Stern, 1998)

Year	88 – 90	91 – 93	94 - 96	Total
Front	40 %	41 %	34 %	38 %
Rear	59 %	59 %	66 %	62 %

However, the performances of these protective devices in side-impact situation were not, as yet, clearly demonstrated. The applicable regulations are only stipulating that the child passenger should be not ejected from the car in the case of a side impact and crash data shows that they are side impact situations when the child restraint system is unable to offer sufficient protection, resulting in serious injuries or even the death of the child occupant. The FARS data shows that in U.S.A., 1,317 children between the ages of zero to twelve have been killed in motor vehicle crashes in 1999 and 31.89 percent of them were involved in side impact crashes. Of these, children seated on the side nearest to the impact represent 55 percent of the fatalities (NHTSA, 2002). Canadian statistics side impact accident data confirms that this is the most dangerous position in the vehicle. Moreover, the vehicle body intrusion is very important especially when the child restraint system is positioned on the outboard nearside to the impact place (Howard, Rothman, Moses McKeag, Pazmino – Canizares et al., 2003).

Thus this project was aimed at the development of a numerical method to evaluate the influence of the intrusion on the behavior of a child passenger restrained in a protective device placed on the nearside to the impact place, in the case of a vehicle lateral collision, considering different installation possibilities and impact speeds.

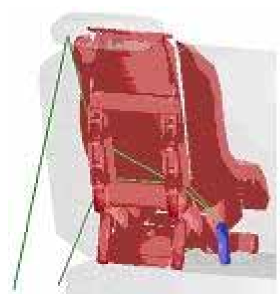
METHODOLOGY

General Approach

Child restraint system, vehicle body vehicle, child dummy, belts and anchorages models have been built using finite element and multi-body techniques. The MADYMO software was chosen to build the model because it reduces the computational time and the related cost, allows the use of already validated dummy models from the MADYMO library and makes possible the comparison with other simulations created with the same software. The side wings of the child restraint system and the vehicle body have been modeled by the finite-element technique, to allow for a better representation of the contacts between the child dummy and the restraining device and the structure of the vehicle and to make possible the simulation of the vehicle body deformation, based on available side impact test data.
The reverse engineering method (Monclus-Gonzales, Eskandarian, Takatori et al., 2001; Zaouk, Marzougui and Kan, 1998) was used to obtain the necessary constructive data, because the manufacturer information is generally proprietary.
The model was then evaluated for side impact against available similar test data.
Finally model exploitation was conducted to assess side impact simulation with and without considering the intrusion and for different installation configurations and impact speeds.
Because the majority of tests and studies have been done using three years old dummies and moreover, the available test results to evaluate the model being obtained for the Hybrid III three years old child dummy, this model was chosen for the comparative study.

Models

The Hybrid III 3-years-old child dummy numerical model is available in MADYMO Data Base (TNO Automotive, 2003) and has been validated by TNO for frontal loading. The model consists of 28 ellipsoids while certain head regions are built using the finite elements method. The contact between head and thorax is defined by default but additional contacts have been defined: between both femurs; between each femur and the abdomen, the thorax, the neck and the head; between both tibias; between each tibia and the neck and the head; between both arms; between each arm and the neck and the head. The child dummies were positioned in the child restraint system by applying the gravitational force on the dummy, which allowed for an equilibrium state.
In agreement with the chosen child dummy model, the required child seat is the convertible restraint system designed for use by infants and toddlers. The Cosco Touriva child seat was chosen, for which test results and a specimen were available for analysis.
The central region of the child seat was built using multi-body technique and the child seat side wings have been reconstructed using finite elements, to allow for a better representation of the contacts between the child dummy and the restraining device and between the side wings of the child restraint system and the vehicle interior.
The child restraint system was placed on the outboard nearside to the impact place and the following installation configurations were considered: vehicle safety belts, lower anchorage belt system and ISOFIX system. A supplementary top tether was also used (figure 1).



a. Vehicle safety belts

b. Lower anchorages belt system

c. ISOFIX anchorages

d. Top tether

Figure 1. Child restraint system installation.

The child restraint system harness, lower anchorage belt system straps and vehicle safety belt characteristics have been measured or adapted from the available literature data (TNO Automotive, 2003). The straps were represented using MADYMO belt segments. The child restraint system attachments (release button and the harness retainer clip), vehicle safety belt anchorages and ISOFIX anchorages were built by ellipsoids.

The available test results (vehicle side impact test and child restraint system test) were obtained from a Pontiac Grand Am 1999, so this vehicle model was chosen for the simulation. Vehicle body dimensional characteristics and constitutive material properties were measured or experimentally determined on a similar vehicle and its components. The rear bench and the front seats were represented using ellipsoids and were linked to the reference space using point restraints (a combination of three mutually perpendicular parallel springs and dampers), to allow their displacement for the case of the side impact. Vehicle side frame, rear doors, rear panel, rear shelf, rear glasses and rear doors glasses were built by finite element, to allow for a better representation of the contacts between the vehicle interior and child dummy and child restraint system side wings and to make possible the simulation of the vehicle body deformation, based on available test data (figure 2).

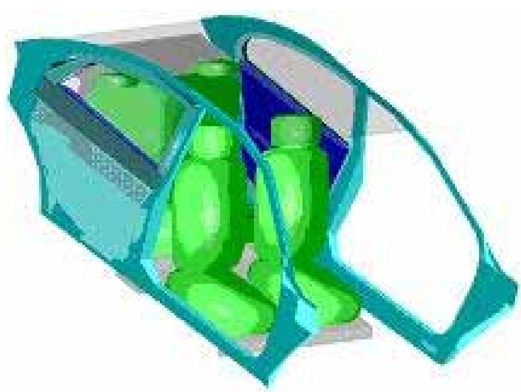


Figure 2. Vehicle model.

Simulation

To simulate the side impact, a lateral acceleration field (figure 3) and the gravity field were applied to the child dummy and to the child restraint system. The lateral acceleration field complies with SNCAP (Side impact – New Car Assessment Program) specifications and had been used during the tests performed by NHTSA in 2001 (Sullivan, Willke and Brunner, 2001). The lateral acceleration field corresponds to an impact speed of 33,8 km/h (21 mph), with a peak acceleration of 26 g (255 m/s^2). The simulation results are compared with the results of the above-mentioned tests, performed with a Hybrid III 3-years-old child dummy seated on a Cosco Touriva child seat installed on a Pontiac Grand Am 1999, using the vehicle safety belts.

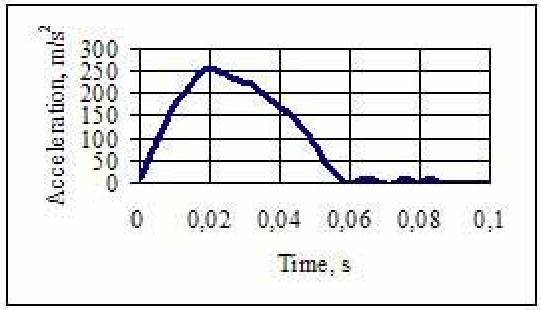


Figure 3. Side impact pulse (adapted from Sullivan, Willke et Brunner, 2001).

Model Exploitation

The model exploitation was conducted to compare the behavior of the child dummy model in the case of the side impact both with and without considering the intrusion, based on the available test data (the intrusion profiles measured as a result of the NCAP side impact tests at a 90^0 angle and 62.1 km/h actual test speed, NHTSA, 1999).
Because full finite element models are large in terms of CPU time consumption, the vehicle deformation was simulated using the MADYMO's prescribed structural motion feature.
The project considered three impact situations:

- 90^0 side impact at 33.8 km/h without intrusion.
- 90^0 side impact at 33.8 km/h with the intrusion profiles recalculated based on 62.1 km/h available intrusion profiles (using the simplified energetic balance between deformation energy and kinetic energy).
- 90^0 side impact at 62.1 km/h with the acceleration pulse recalculated based on 33.8 km/h available pulse (using the equations of motion and considering the same impact duration).

The following installation configurations were taken into account:

- Vehicle safety belt installation, with and without top tether.
- Lower anchorages belt system.
- ISOFIX system.

EVALUATION RESULTS

The simulation results were compared with the results of the above-mentioned tests, performed by NHTSA in 2001 and with the Injury Assessment Reference Values (IARV), stipulated by FMVSS 208 and FMVSS 213. These injury parameters are for frontal impact and may not accurately reflect the risk of injury in side impact and the corresponding Injury

Assessment Reference Values should be used for reference purposes only. Figures 4 and 5 illustrate the comparisons of the variation of head acceleration and thorax acceleration. Test variations were calculated based on the available test signals (NHTSA Vehicle Crash Test Database).

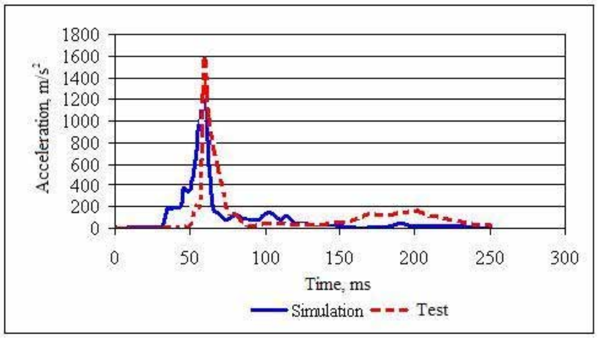


Figure 4. Comparison of head acceleration variation.

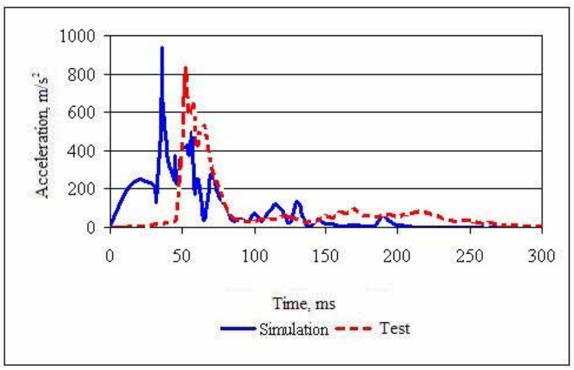


Figure 5. Comparison of thorax acceleration variation.

The comparison of head acceleration curves shows good reproduction of the experimental data. However, the comparison of the thorax acceleration curves shows a time lag between the two peaks and a less progressive variation at the beginning, for the simulation curve. These discrepancies are the results of using standard MADYMO belt model for both harness straps and vehicle safety belts straps because MADYMO standard belt model has fixed attachments points and cannot reproduce the effects of slip on the dummy model. As a result, some differences between the tested belt and harness and the belt and harness model behaviour are possible. The effect is not important for the head acceleration since the peak is related here to the contact between the dummy head and the door panel and the two curves coincide at this point. For the thorax acceleration, the peak is given by the brutal stop of chest movement caused by the restraint forces in the harness and in the belts and thus detail of belt and harness model is very important for this value. Table 2 presents the maximal values of some injury parameters. The maximal head acceleration was calculated based on the available test signals (NHTSA Vehicle Crash Test Database). The simulation results were generally very close to the experimental data.

Table 2.
Evaluation results

Injury parameter	Simulation	Test	IARV
HIC 15	1001	1085	570
HIC unlimited	1001	1085	1000
Thorax deflection, mm	6,14	3,56	34
Thorax acceleration, 3 ms, m/s2	639	646	540 589
Head acceleration, m/s2	1193	1582	-

INTRUSION INFLUENCE ASSESSMENT

Safety belts installation without top tether

Figure 6 illustrates the model during the simulation of the side impact at 62.1 km/h with intrusion when the child restraint system is installed using vehicle safety belts.

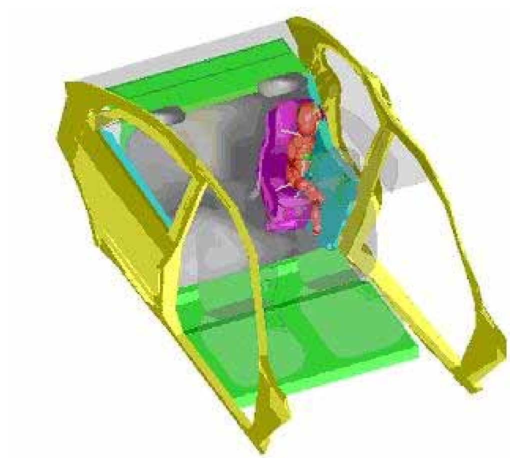


Figure 6. Side impact simulation at 62.1 km/h with intrusion.

The compared parameters were:

- Head injury criteria: HIC15 and HIC unlimited,

- Maximal head acceleration and head acceleration variation, a_H,
- Maximal thorax acceleration with a duration of at least 3 ms, a_T , thorax acceleration variation and chest deflection, d_T,
- Neck axial forces, F_Z (compression and tension) and flexion and extension moments about the occipital condyles, M_Y,
- Biomechanical neck injury predictors (tension-extension NIJ TE, tension-flexion NIJ TF, compression-extension NIJ CE and compression-flexion NIJ CF).

Table 3 and figures 7 and 8 illustrate the comparisons when the child restraint system is installed using vehicle safety belts but without top tether.

Table 3.
Injury parameters comparison, safety belt installation, no top tether

Parameter	No intrusion	With intrusion		IARV
	33.8 km/h	33.8 km/h	62.1 km/h	-
HIC 15	1001	2271	7450	500
HIC	1001	2271	7450	1000
Nij TE	1.615	1.885	1.439	1
Nij TF	0.242	0.294	0.760	1
Nij CE	0.625	0.300	1.168	1
Nij CF	0.706	0.422	0.338	1
F_z , N	1251	1721	1591	2340
$-F_z$, N	1276	558	514	2120
M_y , Nm	13.8	13.7	28.9	-
$-M_y$, Nm	29.0	29.3	29.4	-
d_T, mm	6.14	11.81	19.04	34
a_T, m/s^2	639	678	969	540 / 589
a_H, m/s^2	1193	1925	3577	-

The intrusion influence is very important for the head injury parameters, the results being much higher than seen in the case when the intrusion is not considered (up to 600 % for HIC15 and HIC unlimited and near to 200 % for head maximal acceleration) and they are proportional to the impact speed. The IARV's are largely exceeded when the intrusion is considered. The peak is reached sooner when the intrusion is considered, being related to the moment when child dummy's head hits the door panel (figure 7).
Thorax deceleration is also influenced by intrusion but here the differences are smaller, up to 60 % when the impact at 62.1 km/h is simulated. The results are greater than the IARV. The peak is reached almost at the same time when the intrusion is considered, compared to the collision without intrusion, because it is more related to the restraint forces in belts and harness than to the impact between the child dummy and the vehicle body (figure 8). Thorax deflexion is also proportional to the impact speed but the IARV is not exceeded. Neck injury parameters are not clearly influenced by intrusion but the IARV for neck predictors is exceeded in tension-extension in all the cases while the neck forces are under the limits.

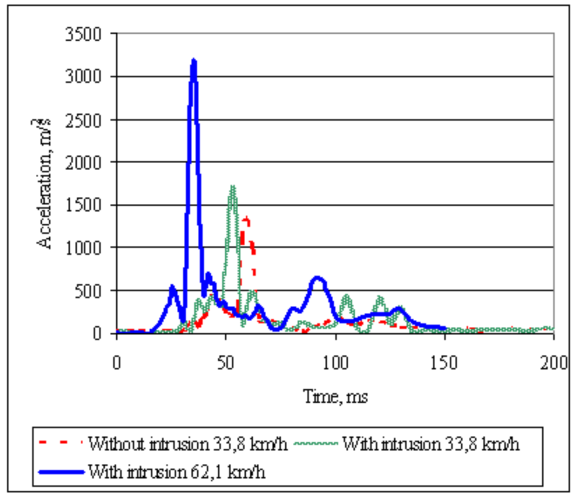


Figure 7. Safety belt installation, no top tether: head acceleration variation.

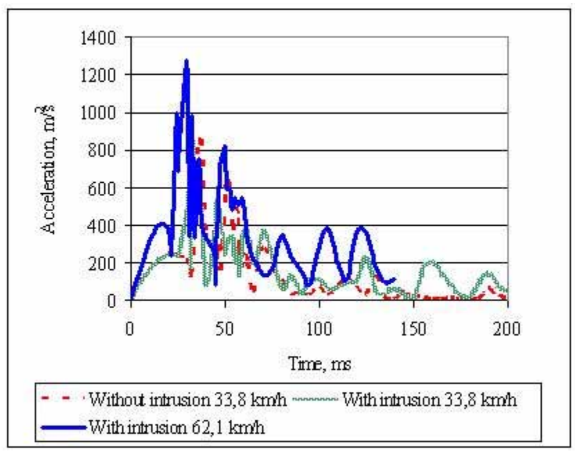


Figure 8. Safety belt installation, no top tether: thorax acceleration variation.

Safety belts installation with top tether

The vehicle safety belt installation with top tether is analyzed in table 4 and figures 9 and 10.
The same trends noticed before can be observed in this case too for the head injury criteria, being much higher than in the case when the intrusion is not considered (up to 700 % for HIC15 and HIC

unlimited and more than 200 % for head maximal acceleration) and they are proportional to the impact speed. The IARV's are exceeded in all the cases for HIC15 and for HIC unlimited when the intrusion is considered.

Table 4.
Injury parameters comparison, safety belt installation, with top tether

Parameter	No intrusion	With intrusion		IARV
	33.8 km/h	33.8 km/h	62.1 km/h	-
HIC 15	848	1454	6584	500
HIC	848	1454	6584	1000
Nij TE	0.704	1.330	2.740	1
Nij TF	0.431	0.413	0.667	1
Nij CE	0.390	0.681	2.618	1
Nij CF	0.205	0.203	0.217	1
F_z , N	863	1005	1834	2340
$-F_z$, N	380	971	420	2120
M_y , Nm	6.9	15.1	19.7	-
$-M_y$, Nm	13.0	23.8	68.9	-
d_T, mm	9.03	13.45	21.53	34
a_T, m/s^2	605	586	1007	540 / 589
a_H, m/s^2	1337	1704	3220	-

The maximum for the head acceleration is again reached sooner when the intrusion is considered, being again related to the moment when child dummy's head hits the door panel (figure 9).

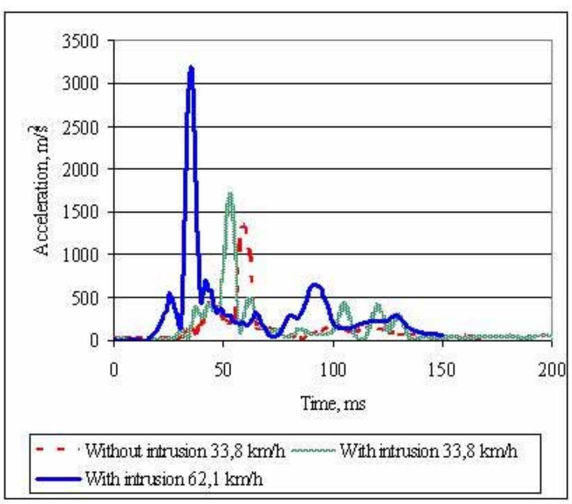


Figure 9. Safety belt installation, with top tether: head acceleration variation.

Thorax acceleration variations show a larger time lag between peaks in this case, probably induced by top tether's supplementary restraint forces and moment of rotation (figure 10).

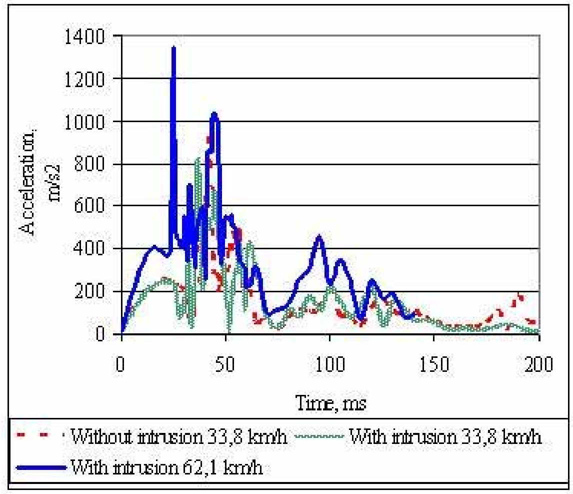


Figure 10. Safety belt installation, with top tether: thorax acceleration variation.

Practically the intrusion has no influence on the thorax deceleration at lower impact speed but an increase of about 40 % can be observed when the impact speed is higher. Thorax deflexion is also proportional to the impact speed but the IARV is not exceeded.
Intrusion generally gives now an increase of all neck injury parameters, probably caused by the top tether which induces supplementary restraint forces that make possible a larger head rebound. The IARV is exceeded especially for the extension neck predictors in the case of 62.1 km/h side impact.
In conclusion, when the child restraint is installed using vehicle safety belts, the intrusion causes lethal head injuries to the child occupant and serious injuries for the chest and the neck.

Lower anchorage belt system and rigid ISOFIX installations

The comparative results of the simulations at 33.8 km/h side impact speed, without and with intrusion, when the child restraint system is installed using lower belts and rigid ISOFIX system, are presented in table 5 and 6 and figures 11 to 14.
The intrusion influence is very important for the head injury criteria, especially for lower belt anchorages The IARV's is exceeded for lower belt anchorages with 200% increase for the HIC unlimited and a 500 % increase for the HIC15. When ISOFIX anchorages are used, only the HIC15 is higher than the allowed limit. Head maximal acceleration is almost double for lower belts anchorages when intrusion is simulated

but the influence is not important in the case of ISOFIX anchorages.

Table 5.
Injury parameters comparison, lower anchorage belt system installation, 33.8 km/h impact speed

Parameter	No intrusion	With intrusion	IARV
HIC 15	899	3042	500
HIC	899	3042	1000
Nij TE	1.320	1.657	1
Nij TF	0.475	0.223	1
Nij CE	0.569	0.489	1
Nij CF	0.037	0.196	1
F_z , N	1138	1670	2340
$-F_z$, N	262	619	2120
M_y , Nm	11.3	9.7	-
$-M_y$, Nm	23.7	24.0	-
d_T, mm	10.00	11.38	34
a_T, m/s^2	578	696	540 / 589
a_H, m/s^2	1266	2239	-

Table 6.
Injury parameters comparison, rigid ISOFIX installation, 33.8 km/h impact speed

Parameter	No intrusion	With intrusion	IARV
HIC 15	379	859	500
HIC	379	915	1000
Nij TE	1747	1.849	1
Nij TF	0.370	0.552	1
Nij CE	0.197	0.738	1
Nij CF	0.199	0.400	1
F_z , N	1059	1783	2340
$-F_z$, N	106	835	2120
M_y , Nm	13.7	9.9	-
$-M_y$, Nm	37.6	35.7	-
d_T, mm	12.75	14.96	34
a_T, m/s^2	848	728	540 / 589
a_H, m/s^2	919	1149	-

The head acceleration variations show a small time lag for the case of lower belts installation (figure 11). The main peaks coincide for ISOFIX installation but the intrusion gives a second pronounced peak that corresponds to the second impact between dummy head and the door panel. The first peak is related to the primary contact between dummy head and door panel surface. The second impact is caused by the rigidity of the ISOFIX anchorages that forces the child dummy to remain in the vicinity of the deformed door panel and to bend forward, entering into contact again with the deformed door panel front surface (figure 12).

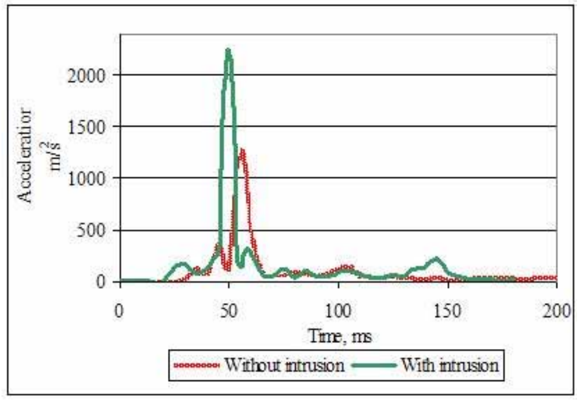


Figure 11. Lower anchorage belt system installation: head acceleration variation.

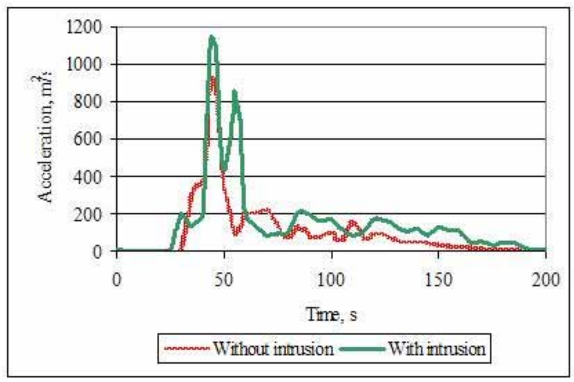


Figure 12. Rigid ISOFIX installation: head acceleration variation.

Thorax acceleration variation curves show some time lag, especially for the case of lower belts installation, and some fluctuations occur too (figure 13 and 14).

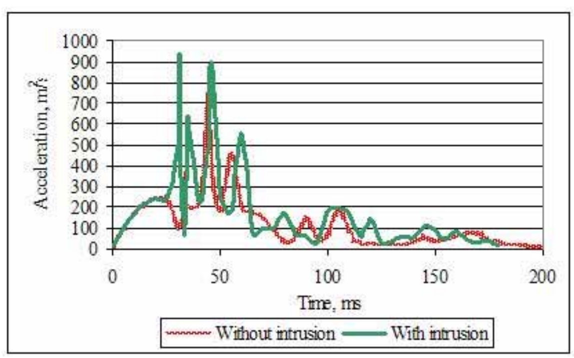


Figure 13. Lower anchorage belt system installation: thorax acceleration variation.

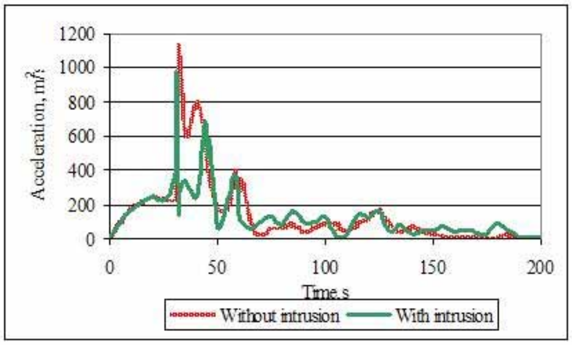


Figure 14. Rigid ISOFIX installation: thorax acceleration variation.

Thorax deceleration is less influenced by the intrusion but the IARV's are almost always exceeded. The increase in thorax deflection when the intrusion is considered is minor and the IARV is not exceeded.
Intrusion causes increase of neck forces, which are very important in the case of ISOFIX anchorages installation but the results are still within the allowed limits. Neck moments are not clearly influenced by the intrusion. Neck biomechanical injury predictors are larger for the ISOFIX installation when intrusion is considered but the trend is not clear for lower belts anchorages installations and the IARV is exceeded only in tension-extension.
In conclusion, when the child restraint is installed using lower belts anchorages or ISOFIX anchorages, the intrusion causes large increase of the head injury criteria, more pronounced for lower belts installation. Thorax and neck injury parameters are less influenced by intrusion.

CONCLUSIONS

This project was aimed at the development of a numerical method to evaluate the intrusion influence in the case of the simulation of vehicle side impact. Child restraint system and vehicle body model have been built using multi-body technique combined with the finite element method, to allow for a better representation of the contacts between the child dummy, the restraining device and the structure of the vehicle and to make possible the simulation of the vehicle body deformation, based on available side impact test data. The model was evaluated against similar test results and simulations results were generally in agreement with the experimental data. When the child restraint system is installed using vehicle safety belts, the intrusion influence is very important for the head injury parameters, the results being much higher than in the case when the intrusion is not considered. The peak is reached sooner when the intrusion is considered, being related to the moment when the child dummy's head hits the door panel. Thorax deceleration is also influenced by intrusion but here the differences are smaller, especially when the top tether is used. The time lag for thorax acceleration is less pronounced than for head acceleration, because it is more related to the restraint forces in the belts and harness than to the impact between the child dummy and the vehicle body. However, when the top tether is used, the time lag between peaks is larger, probably because of the top tether's supplementary restraint forces and supplementary induced moment of rotation. Thorax deflexion is also proportional to the impact speed.
Neck injury parameters are increased when the top tether is used and the intrusion is considered, probably due to the supplementary restraint forces that make possible a larger head rebound.
In the case of lower belts and ISOFIX installation, intrusion increases the head injury criteria, more pronounced for lower belts installation. Head maximal acceleration is almost double for lower belts anchorages when intrusion is considered but the influence is not important for the case of ISOFIX anchorages. The head acceleration variations show a small time lag in the case of lower belts installation. The main peaks coincide for ISOFIX installation but the intrusion causes a second pronounced peak that corresponds to the second impact between dummy head and the door panel. Thorax deceleration and thorax deflection are less influenced by the intrusion. Thorax acceleration variation curves show some time lag, especially for the case of lower belts installation, and the curves also show some fluctuations when the intrusion is considered. Intrusion also increases neck forces, which are very important in the case of ISOFIX anchorages installation. Neck biomechanical injury predictors are higher for the ISOFIX installation when intrusion is considered.
The model is now offering a lot of possibilities of improvement, development and exploitation and other developments aim to evaluate different child dummies responses in the case of various side impact and frontal collision configurations.

REFERENCES

Howard, A., Rothman, L., Moses McKeag, A., Pazmino – Canizares, J., German, A., Monk, B., Comeau, J.L., Hale, I., Mills, D. and Blazeski, S. 2003. "Children in Side Impact Motor Vehicle Crashes: Seating Position and Injury Mechanism." Proceedings of the Canadian Multidisciplinary Road Safety Conference XIII, Banff, Canada

Monclus-Gonzales, J., Eskandarian, A., Takatori, O. and Morimoto, J. 2001. “Development of Detailed Finite Element Models of Child Restraint System for Occupant Protection.” Paper Number 126, 17th International Technical Conference on the Enhanced Safety of Vehicles, Amsterdam, Netherlands

National Highway Traffic Safety Administration. 1999. “New Car Assessment Program Side Impact Test Pontiac Grand AM 1999 Final Report. Report number SNCAP-CAL-99-03.” http://www-nrd.nhtsa.dot.gov/database/nrd-11/asp/VehicleInfo.asp

National Highway Traffic Safety Administration, Office of Regulatory Analysis and Evaluation Plans and Policy. 2002. “Preliminary Economic Assessment, Advanced Notice of Proposed Rulemaking (ANPRM) To Add A Side Impact Test to FMVSS No. 213.” http://www.nhtsa.dot.gov/cars/rules/rulings/CPSUpgrade/CPSSide/PEA/tocI

NHTSA Vehicle Crash Test Database, http://www-nrd.nhtsa.dot.gov/database/nrd-11/asp/TestTableDetails.asp?LJC=3629

Stern, S.D. 1998. “Child Restraint Information in the National Automotive Sampling System Crashworthiness Data System.” Paper No. 98-S10-O-21, p. 2306-2309, 16th International Technical Conference on the Enhanced Safety of Vehicles, Windsor, Canada

Sullivan, L.K., Willke, D.T., Brunner, J. 2001. “Comparison of European and U.S. Child Restraints in Lateral Grand AM Sled Tests.” National Highway Traffic Safety Administration Vehicle Research and Test Center http://dmses.dot.gov/docimages/pdf81/ 165824_ web .pdf

TNO Automotive. 2003. “MADYMO Application Manual Version 6.1." Delft, Netherlands

TNO Automotive. 2003. “MADYMO Database Manual Version 6.1.” Delft, Netherlands

Zaouk, A., Marzougui, D. and Kan C.D. 1998. “Development of a Detailed Vehicle Finite Element Model, Part I: Model Development.” The 1st International Conference for the IJC, Detroit, MI, USA