DETERMINING DRIVERS' INJURIES DUE TO ROLLOVER CRASHES – A COMPUTATIONAL METHOD

Anderson de Lima, andersonkaipers.lima@gm.com
Rogério José Marczak, rato@mecanica.ufrgs.br
Mechanical Engeneering Dept. – Federal University of Rio Grande do Sul

Abstract. *Rollover crashes are responsible for more than 20% of total passengers deaths in vehicular accidents. Every year a higher number of consumers have been critically injured in rollovers, which translates into hundreds of millions of dollars of unnecessary health care cost. Efforts to reduce the incidence of death and catastrophic injuries associated with rollover crashes have increased the importance of both, prototype testing and computational simulations. Automotive industry and individual researchers have performed numerous rollover tests using instrumented anthropomorphic test devices (ATD), with the objective of predicting possible head, neck, and cervical spine injuries. Some of these works measured accelerations, forces and moments on head, neck and cervical spines, which can cause several other injuries according to medical traumas databases. The objective of the present work is to present finite element computational models used to simulate rollover crashes and the associated methodology to determine possible injuries in drivers. ATDs were considered in the computational models in order to estimate the severity of the injuries. The proposed methodology is also used to compare different standards and procedures. Finally, it is shown that the FMVSS 216 procedure is not able to estimate the real loads found during a rollover event.*

Keywords*: rollover, crashes, computational, injury, methodology*

1. INTRODUCTION

Although the rollover crash is not the most frequent type of accident, it is of great significance with respect to injuries caused to the vehicle occupants. Vehicular safety is a very important topic in the automotive industry today, considering the great increase in the automotive market and thereby the number of automobile accidents.

The injuries and trauma are the result of the inability of a vehicle to protect its occupants in case of rollover events. Although countermeasures to prevent injuries due to ejection of the occupants are well established, there is still much debate on the mechanism of trauma and injuries to occupants in the interior of the vehicle during the rollover event therefore countermeasures are necessary to prevent these injuries (Young *et al*., 2006).

Even though many studies have already been developed and continue to be performed, the role of roof crush upon the injuries in the occupant during the rollover accidents is still an area of research with respect to type of injury mechanism.

Among the different types of vehicular accidents rollover crashes have a higher rate of fatalities. Of millions of vehicle accidents involving passenger cars, SUV, vans and pick-ups in 2005, only 3.3% involved in rollover. However, rollover crashes are responsible for more than 20% of total passenger deaths in vehicular accidents.

The objective of this study is to develop numerical models to simulate different standards and procedures in the literature, which evaluate the structures and vehicles to prevent deaths and injuries caused by incidents involving rollover.

The existing standards and procedures to test rollover crashworthiness are still not suitable to computer simulation because of the huge computational effort required, and the need of faithful/overly complex representation of the aspects involved in real crashes.

2. METHOD

Roof structure performance is regulated by FMVSS 216, Roof Crush Resistance (NHTSA, 2005). FMVSS 216 is the most used procedure to evaluate the roof crush strength. However this procedure provides a poor emulation of the conditions of actual rollovers that result in serious injury. Despite extensive evidence of the need for a stronger standard, it has never been amended except to broaden its coverage to light trucks and vans (Friedman and Nash, 2001).

FMVSS 216 requires that each side of the vehicle's roof deforms with no more than 127 mm of crush under an applied load of 1.5 times the vehicle's weight. The force is applied at a 5^o pitch and 25^o roll angle at the region where the A-pillar meets the roof panel.

Inverted drop testing of vehicles is also a destructive method to evaluate the roof strength used by automotive industry. This procedure evaluates the structural integrity of roofs under loadings similar to those seen in real world rollovers. The vehicle is inverted and dropped from a determined height and at the same orientation as the load plate applied in the static test FMVSS 216.

Both of these tests do not consider the vehicle's dynamic during the rollover. Also, it is not required using dummy and thus is not possible to determine injury in occupants.

SAE J2114 rollover test is the most representative of real-world loading rates of roof structures in a rollover collision, figure 1 shows the test device. The vehicle test is placed on a device inclined of 23 degrees from the horizontal, and the lower flange is 102 mm, which trips the tires of the test vehicle. The intersection of the inner side of the flange and the top inclined surface should be 229 mm above the concrete roll surface.

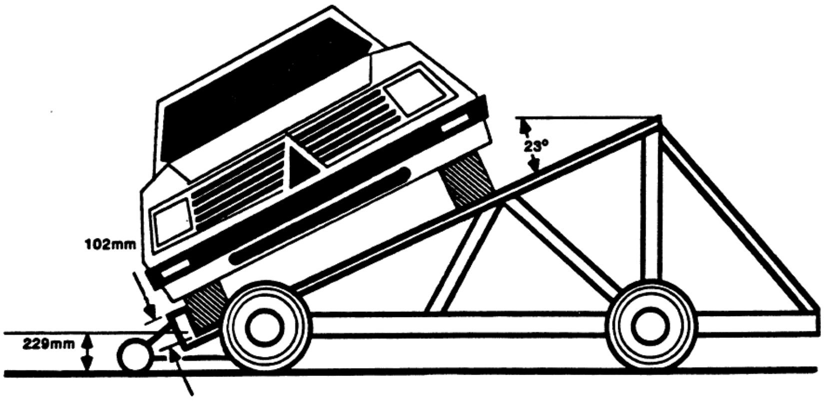

Figure 1. Dolly rollover test setup.

The vehicle and device are accelerated to a constant velocity of 48 km/h and the device is then stopped in a distance of not more than 914 mm without transverse or rotational movement. The device deceleration must be at least 20 g's for a minimum of 40 ms.

This procedure also does not require using dummy during of the test, however the vehicle with belted and unbelted dummy was simulated. Dolly rollover simulation enables to get the following accelerations, deflections and loads on the dummy:

- Head acceleration;
- Neck axial load;
- Neck moments;
- Neck shear load;
- Thorax acceleration;
- Thorax deflection.

3. INJURY MECHANISMS AND CRITERIA

The effects of mechanical loads, in particular impact loads, on the human body are dealt with biomechanics. Due to these mechanical loads some regions of the body can undergo mechanical o psychological changes. These changes are called biomechanical response (Deshmukh, 2006).

3.1. Head injury criteria

The head is a particularly vulnerable body part both due to its exposed position on the flexible neck and the sensitivity of the face and brain to impact injuries. HIC is used to measure the head injury resulting of the linear accelerations.

Although a great deal has been learned regarding head injuries, the only injury criterion in wide usage is the Head Injury Criterion (HIC), which was adopted over twenty-five years ago. HIC was first introduced as a curve fit to the Wayne State Tolerance Curve (WSTC). The WSTC was first presented by Lissner (1960). HIC criterion is calculated by the following expression:

$$HIC=\left\{\left(t_2-t_1\right)\left[\frac{1}{t_2-t_1}\left\{\int_{t_1}^{t_2} a\left(t\right)dt\right\}\right]^{2.5}\right\}_{max} \quad (1)$$

Some researchers use the time interval of 36 ms and 15 ms in the calculation of HIC. Table 1 shows the limits for HIC according to dummy size. Potential passenger safety issues may occur in case these limits are exceeded..

Table 1. Head Injury Criterion for Various Dummy Sizes.

	Hybrid III 50th Male	Hybrid III 50th Female	Hybrid III 6 years	Hybrid III 3 years	12 months CRABI
HIC36	1000	1000	1000	900	660
HIC15	700	700	700	570	390

The probability of head injury depends of the severity level, AIS3 level predicts a serious injury and can be calculated by the equation:

$$AIS3=\left[1+exp\left(\left(3.39+\frac{200}{HIC}\right)-0.00372HIC\right)\right]^{-1}-\left[1+exp\left(\left(4.9+\frac{200}{HIC}\right)-0.00351HIC\right)\right]^{-1} \quad (2)$$

3.2. Neck injury criteria

Neck is a flexible connection between head and torso, the majority of neck injuries are caused by indirect loading, because the loads are transferred from the torso to the head or head to the torso through the neck.

The expression to calculate the neck injury criteria caused by axial load and longitudinal moment is:

$$N_{ij}=\frac{F_z}{F_{zc}}+\frac{M_{ocy}}{M_{yc}} \quad (3)$$

Where F_Z is the axial load, F_{ZC} is the critical intercept value of load used for normalization, M_{OCY} is the flexion/extension bending moment, and M_{YC} is the critical intercept value for moment used for normalization. The values for calculating the N_{ij} are uniquely specified for each dummy. In the present work hybrid III 50th male dummy is used and for these we have the following values: F_{ZC} is equal to 6806 N and 6160 N, for tension and compression respectively, M_{OCY} is equal to 310 Nm and 135 Nm, for bending and extension respectively. Besides these values the peaks of each load must be verified. Equation 4 shows the probability of serious injuries (AIS3) in the neck.

$$AIS3=\frac{1}{1+exp(3.227-1.969N_{ij})} \quad (4)$$

3.3. Thorax injury criteria

The human torso is normally divided into 2 main areas divided by the diaphragm: thoracic cavity with its lower boundary defined by the diaphragm and abdominal cavity which is separated in upper and lower abdominal cavity with the diaphragm as the upper boundary and pelvis the lower. Unfortunately the majority of biomechanical researches have either concentrated on the thorax injuries.

The current criterion for compression of the thorax accepted by FMVSS 208 is based on recommendations from Neathery *et al.* (1975), whereby a compression of 76 mm results in a severity AIS3 for a hybrid III 50th male dummy, so this value must not be exceeded and as an acceleration of 60 g's cannot be exceeded.

Combined thoracic index (CTI) that consider the acceleration and deflection in the thorax is expressed by the following equation:

$$CTI=\frac{A_{max}}{A_{int}}+\frac{D_{max}}{A_{int}} \quad (5)$$

Where A_{max} is the maximum thorax acceleration, D_{max} is the maximum value of the thorax deflection, and A_{int} and D_{int} are respectively 85 g’s and 102 mm. The probability of a serious injury can be calculated by three different ways, considering only maximum acceleration, only maximum deflection or combined thorax index, respectively:

$$AIS3=\left[1/\left(1+exp\left(3.1493-0.0630A_C\right)\right)\right]x100\% \quad (6)$$

$$AIS3 = \left[1/\left(1 + exp\left(3.7124 - 0.0475 D_C\right)\right) \right] x100\% \quad (7)$$

$$AIS3 = \left[1/\left(1 + exp\left(8.224 - 7.125 CTI\right)\right) \right] x100\% \quad (8)$$

Equations for other levels of the injury can be found in the recent work by Lima (2009).

4. NUMERICAL SIMULATION RESULTS

The passenger car roof must withstand the 1,5 times the vehicle's weight, as shown in Figure 2. The intrusion must not exceed 127 mm for 1.5 times the vehicle's weight, considering that the vehicle's weight is 991 kg, therefore the roof structure is approved by the requirement according to FMVSS 216 procedure. Even though vehicle being approved in this requirement maybe cannot prevent occupant injuries.

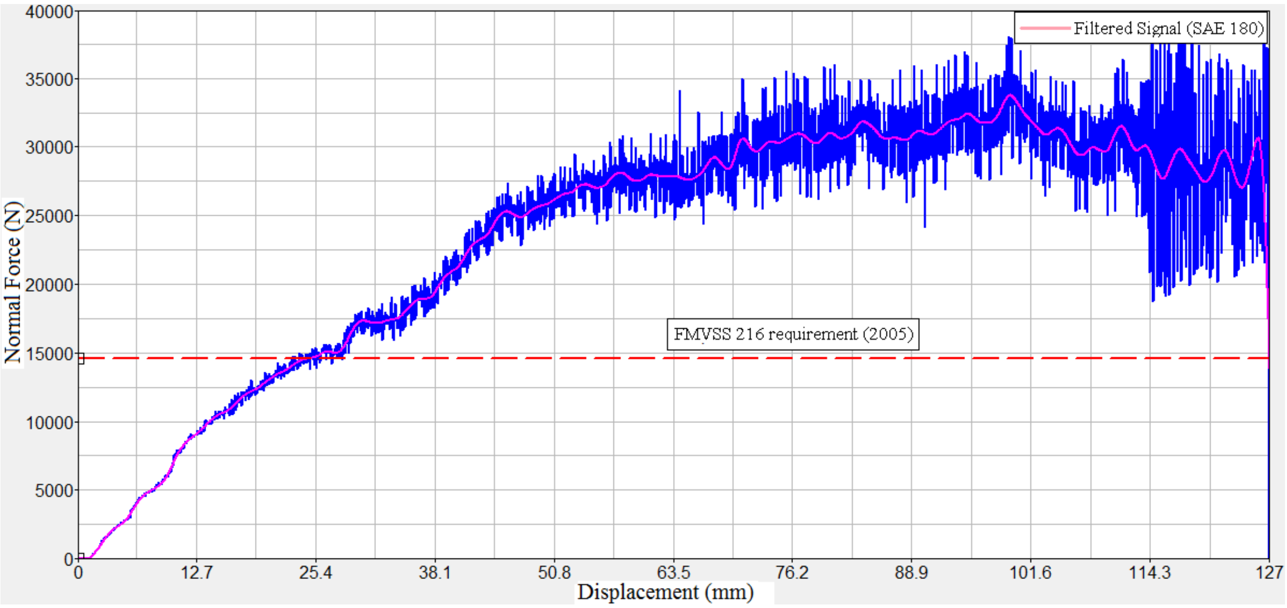

Figure 2. Normal force on the rigid device versus applied displacement.

The suspension has a great importance in the rollover event due to loading transfer between the sides of the vehicle. In the case of dolly rollover test is more evident because of the contact between tire and flange platform, the C.G. height, roll axle of the suspension and other parameters which influence directly in the dynamics of rollover. Figure 3 shows the suspension model which considered springs, shock absorbers, stabilizer bars and axles.

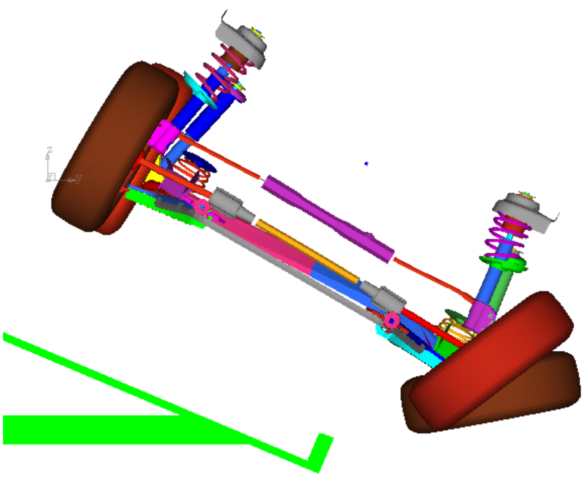

Figure 3. Suspension model.

The present study focuses in the first contact between roof and ground, according to some researchers in the real-world most of fatal injury due to rollover accidents occur in this time. Figure 4 shows the full vehicle model used to simulate the dolly rollover test.

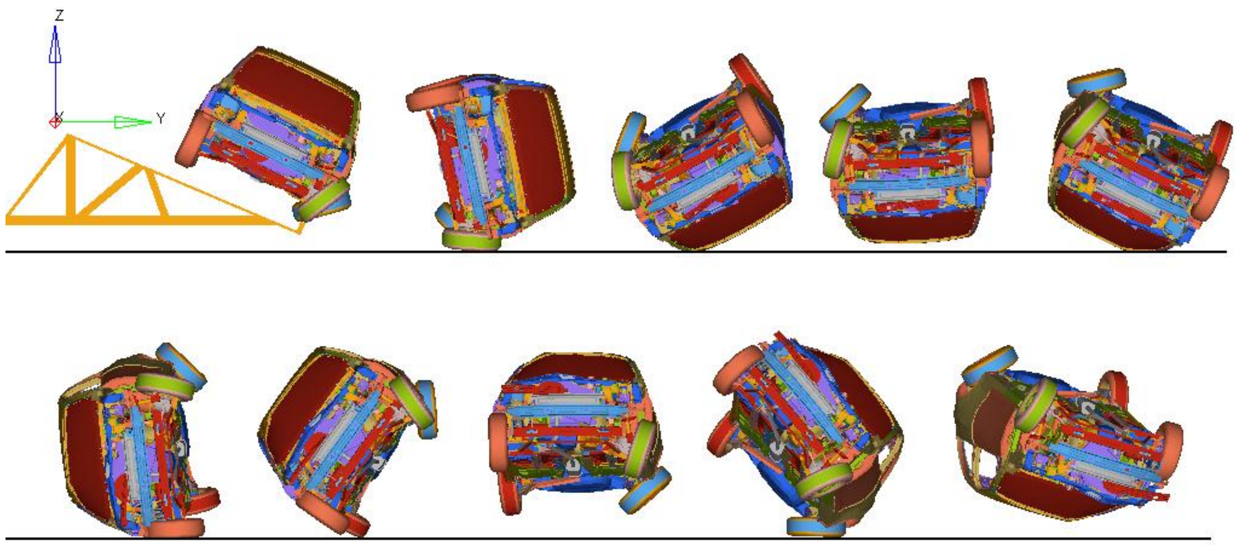

Figure 4. Computational simulation results of the dolly rollover test.

The study has focused in the first complete roll, Hughes *et al.* (2002) showed that 85% of the rollover crashes involves only one roll or less. Due to the occupant dives toward the roof and the roof crush, as shown in Figure 5, the dummy's neck has a lateral moment. This occurs after the dummy's head strikes the roof and causes an increase in the neck load. Figure 6 shows the head position up to first contact between roof and ground.

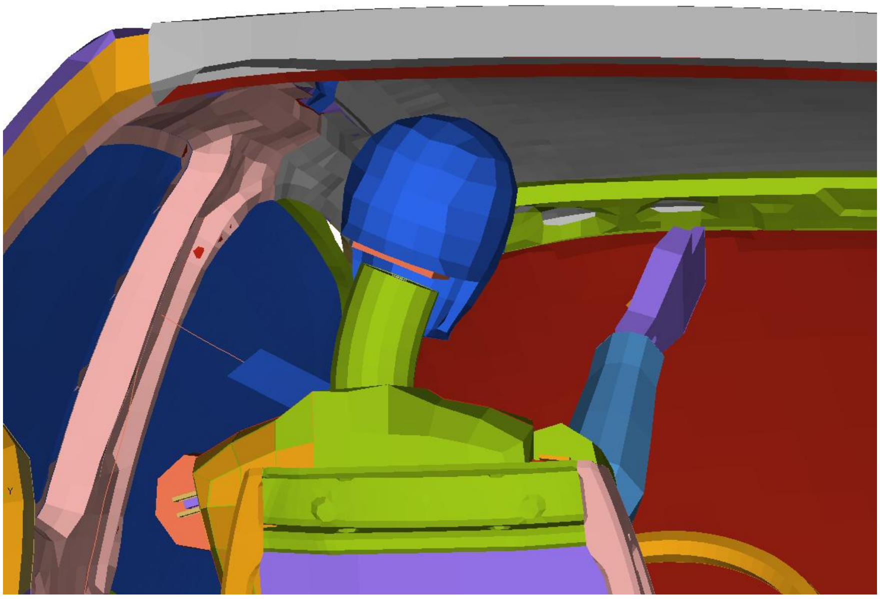

Figure 5. Head position and neck flexion during contact between roof and ground.

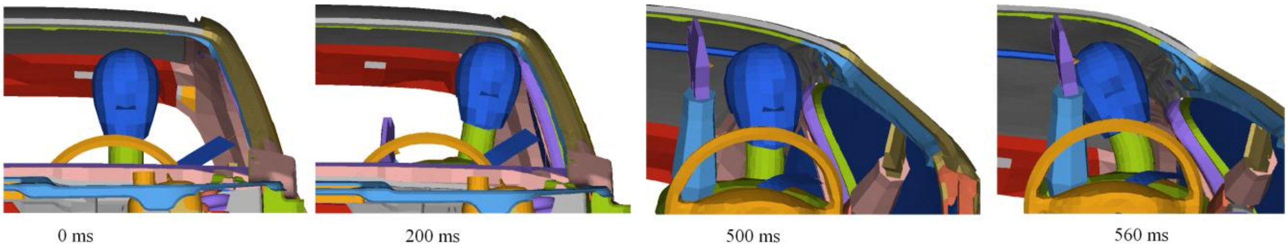

Figure 6. Head position up to first contact roof/ground.

Dolly rollover test produces a contact force of 22 kN between the roof and the ground which gives a relationship with the vehicle's weight of 2,2 times. FMVSS 216 procedure requires a force 1,5 times the vehicle's weight for validation, than the roof crush into the occupant survival space is higher than calculated by FMVSS 216.

Table 2 shows the parameter values used to determine the injury criteria and to evaluate the probability of serious injury in drivers.

Table 2. Peak values considering belted and unbelted dummy.

	Peak values		**Tolerable Values**	**Coefficient: Belted / Unbelted**
	Dummy belted	**Dummy unbelted**		
Head Acceleration (g's)	45,6	62,6	80	1,373
HIC	33,9	75,8	700	2,236
Neck axial load (N)	-396,6	-1362,6	$3300^{(t)}$ / $4000^{(c)}$	3,436
Longitudinal moment (Nm)	88,8	238,9	$57^{(e)}$ / $190^{(f)}$	2,690
Lateral moment (Nm)	-111,2	-120,4	-	1,083
Neck shear load (N)	-223,8	939,9	3100	-4,200
Thorax acceleration (g's)	14,0	14,4	60	1,029
Thorax deflection (mm)	-5,2	-1,3	76	0,250

$^{(t)}$: tension, $^{(c)}$: compression, $^{(e)}$: extension, $^{(f)}$: flexion

These values can change because the size, posture and position of the dummy. The significance of the initial cervical spine position at the time of axial impact loadings was studied by Hodgson and Thomas (1980) in their cadaver impact tests for various neck and thorax positions and also for differing directions of loading. Of the varying positions of load application, axial loading at the vertex with the cervical spine neutral demonstrated the highest vertebral body strains, in comparison to more anterior force application positions.

According to computational simulation results the belt occupant does not suffer injury, as shown in Table 3, however if the occupant does not use seat belt there is a 21,8% probability a serious injury on the neck will occur, consequently the occupant can have a injury in the cervical spine. If an occupant does not use seat belt during a rollover the probability a serious injury will occur is 3 times higher.

Table 3. Injury AIS3 level probability to different body regions for belted and unbelted dummy.

Region	**Parameter**	**Probability of AIS3**	
		Dummy belted	**Dummy unbelted**
Head	HIC	0,0082	0,249
Neck	N_{ij}	7,3	21,8
Thorax	A_{max}	9,4	9,6
	D_{max}	3,0	2,5
	CTI	0,2	0,1

Moffatt (1975) set forth the theory that occupant injury in rollovers was the result of diving into the roof rather than from the consequences of roof collapse or buckling. Subsequently other investigators have shown that these conclusions had been manipulated. Other crashworthiness experts state that roof crush is linked to fatal and serious head and neck injuries resulting from rollover crashes (Friedman and Nash, 2001; Grzebieta *et al.*, 2007).

Then, in order to investigate the influence or not of the roof crush in the increase of injuries and fractures of the neck, a passenger car with roof smaller resistance was simulated. Loads obtained through the neck of the dummy compared the results with the original model, without changing the structure of the roof, and found that the resistance of the roof, especially the side of the roof structure has great influence on the compression of the neck of the occupant. The comparison was between the original model of passenger car and a model with roof and side structure with reduced thickness as shown in Figure 7.

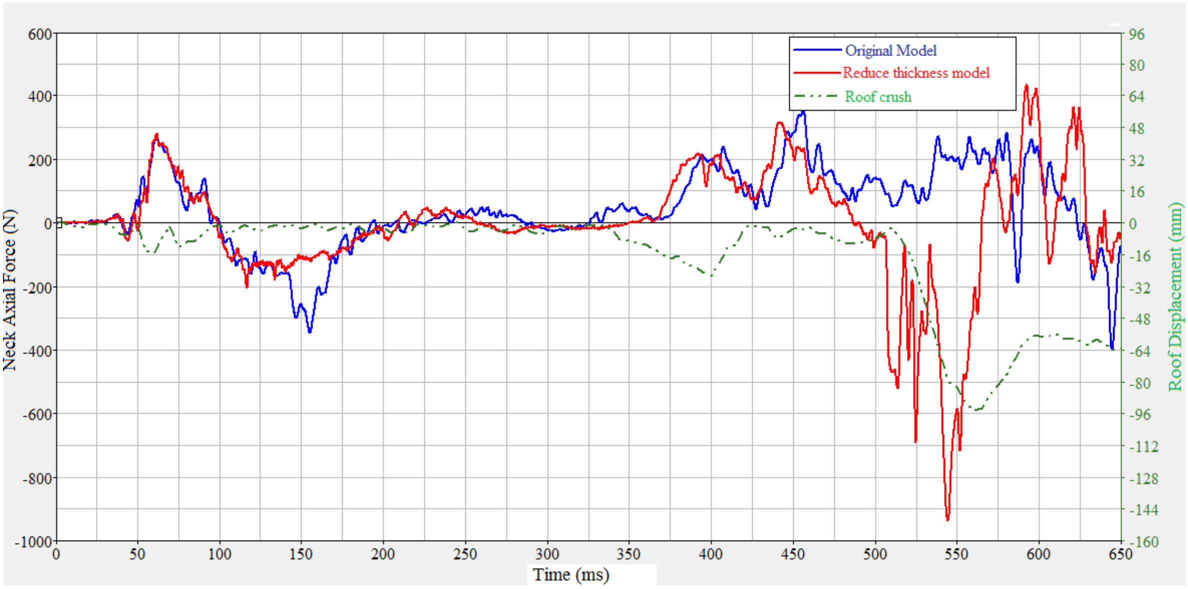

Figure 7. Influence of the roof resistance in the neck force.

From Figure 7, reducing the roof strength causes a high increase of the neck load, hence the conclusion is that the rigidity of the roof has a large influence on the probability of occurrence of injuries in the neck and consequently in the cervical spine.

Current, we are performing rollover test simulations using SUV, to verify the possible injury in occupants and the injury severity in comparison with passenger cars, and also analyzing the loads results of entire rollover event.

5. CONCLUSIONS

FMVSS 216 load application is not representative of real-world loading rates of roof structures in rollover accidents. Even though vehicle being approved in the FMVSS 216 requirement may not prevent occupant injuries. Roof crush combined with the dive of the dummy toward the roof direction cause neck axial load during the rollover test. This axial neck load can cause serious injuries.

Computational simulation results present that the belt occupant does not suffer injury, however if the occupant does not use seat belt there is a 21,8% probability of a serious injury on the neck will occur, consequently the occupant can have a injury in the cervical spine. During the first complete roll of the vehicle if a driver does not use seat belt the probability a serious injury will occur is 3 times higher than using seat belt.

Roof crush has a great influence in the axial neck load.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

Deshmukh, P.S., 2006, “Rollover and Roof Crush Analysis of Low-Floor Mass Transit Bus”, Master of Science Dissertation, Wichita State University.

Friedman, D. and Nash, C. E., 2001, “Advanced Roof Design for Rollover Protection. 17th International Technical Conference on the Enhance Safety of Vehicles”, Amsterdam, The Netherlands.

Grzebieta, R.H., Young, D., Bambach, M. and McIntosh, A., 2007, “Rollover Crashes: Diving Versus Roof Crush”, 20th International Technical Conference on the Enhanced Safety of Vehicles (ESV), Lyon, France.

Hodgson, V. R. and Thomas, L. M., 1980, "Mechanisms of Cervical Spine Injury During impact to The Protected Head”, SAE Paper # 801300.

Huges, R., *et al.*, 2002, "A Dynamic Test Procedure for Evaluation of Tripped Rollover Crashes", SAE Paper No. 2002-01-0693.

Lima, A., 2009, “, Numerical Simulation of Vehicular Rollover – Comparison Among Standards and Evaluation of Driver’s Injury Risk”, M.Sc. thesis (in Portuguese), Mechanical Engeneering Dept., Federal University of Rio Grande do Sul.

Lissner, H.R., Lebow, M., and Evans, F.G., "Experimental Studies on the Relation Between Acceleration and Intracranial Pressure Changes in Man", Surgery, Gynecology, and Obstetrics, Volume III, p. 329-338, 1960.

Moffatt, E. A., 1975, “Occupant motion in rollover collisions”, Proceedings of the 19th Conference of American Association for Automotive Medicine.

Neathery, R.F., *et al*., 1975, “Prediction of Thoracic Injury from Dummy Responses”, Proceedings of the Nineteenth Stapp Car Crash Conference, pp. 295 - 316, SAE Paper No. 751151.

NHTSA, 2005, National Highway Traffic Safety Administration, Federal Motor Vehicle Safety Standards: Roof Crush Resistance. FMVSS 571.216. Standard No. 216.

Young, D., *et al*., 2006, “Diving vs Roof Intrusion: A Review of Rollover Injury Causation”, International Journal of Crashworthiness , Vol. 12 No. 6 pp. 609–628.

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