Occupant Response in Rollover Crashworthiness Assessment of Cutaway Bus

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Abstract

The objective of this study is to assess the injury risk and rollover mechanism of the cutaway bus during two rollover crash tests using finite element method. Based on two well-established test procedures, ECE-R66 and SAEJ2114, different rollover scenarios were conducted. The full finite element (FE) model of the cutaway bus which was verified by previous studies, and Hybrid III 50th male Anthropomorphic Test Device (ATD) were deployed to conduct the rollover test and calculating the severity of injuries. The computational analyses were carried out with using the LS-DYNA® nonlinear finite element code. Several simulations were performed with considering different initial conditions. The effects of drop height and initial velocity of rollover mechanism and passenger responses were measured. In addition, the interaction of the occupants and structural parts were quantified quantitatively and qualitatively.

The capability of two test procedures to predict the injury risk was discussed. Results show that the initial condition of the rollover test procedures has the significant influence on occupant response. For instance, the results of the dolly rollover test indicate that the occupant response and rollover mechanism were highly affected by the initial velocity rather than drop heights. The outcomes of this study also provide a better understanding of kinematics of occupants and cause of the injuries during the rollover crash of buses. The results also showed that the head, neck and chest injuries are the most common type of injuries that occupants experienced. Partial ejection due to broken side windows and direct impact between head, chest, and shoulder with the ground was found the main causes of injuries. Furthermore, it is recommended that to improve the countermeasures of rollover safety assessment the interaction of the occupants and structural components should be considered.

Keyword: Injury Assessment, Rollover Test, Hybrid III ATD, Cutaway Bus, LS-DYNA

Introduction

Rollover crashes for bus seemed to be rare events but when they occur they may cause a number of severe injuries. Moreover, rollover accidents are the most complicated accidents mode among traffic crashes because they usually happen with multiple impacts. In order to decrease the complexity of this event, researchers divided rollover accidents into three phases: tripping phase (roll initiation phase), airborne phase, and ground impact phase [1].

Many studies have been conducted to replicate the rollover phases in the laboratory condition. Researchers have been utilized different experimental and numerical methodologies to assess the kinematics of the vehicle and occupants during the rollover crashes. Among the current rollover test procedures, the Tilt table and dolly rollover test have been found to be more applicable and available for heavy vehicles such as a cutaway bus. In Figure 1, the overall motion of the vehicle in these two tests are shown. The important difference between these test procedures is that dolly rollover test is able to simulate the entire rollover event while the tilt table test only can present the first ground impact phase (dash line in Figure 1).

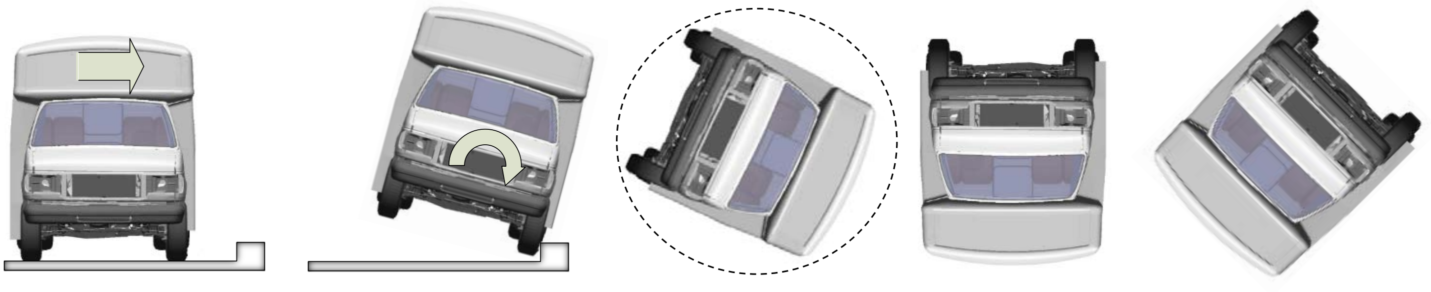


Figure 1: Dolly rollover test sequences vs tilt table test

In an attempt to quantify the occupant response, researchers have been utilized different types of numerical models of ATDs to illustrate the pattern and causes of the injuries during the rollover crashes [2]. In this paper, the FE model of Hybrid III 50th male was selected to address the injury mechanism. Preprocessing FE modeling was conducted using LS-DYNA and Hypermesh, and FE analysis was performed with selecting nonlinear explicit dynamic code. The purpose of this study is to provide the better understanding of occupant response during the two rollover test procedures. Furthermore, some recommendations have been suggested in order to improve the countermeasure of rollover safety assessment.

Finite Element Development

Cutaway Bus FE Model

The full FE model of the cutaway bus was simulated in LS-DYNA. The FE model was developed in two different stages. First, the FE model of bus's chassis and driver cab, suspension, transmission, and engine system were selected and modified from a public domain FE model of the Ford Econoline Van which developed by the National Crash Center Analysis Center (NCAC) at George Washington University. The components of engine and suspension systems were simplified by changing their materials to rigid with keeping the inertial properties in order to decrease the computational time. In the next stage, the passenger compartment which includes the steel cage, skin, seats, windows and doors were modeled with using the information given by the manufacturer. Then, the passenger compartments were attached to the chassis using proper bolt and welding connections [3-5].

The validation and verification process were performed in three levels by previous researchers [3-6]. The unit level where the material properties of skin, steel hollow sections, and side wall windows were determined. Next level was component tests, where two test procedures were defined to assess the characteristics of the roof to wall and roof to floor connections. At the final level, the center of gravity was measured by using the real bus and finally, the full rollover crash test was conducted experimentally and numerically to achieve the more reliable FE results [3-6].

Occupant FE Model

The FE model of Hybrid III-50th male, which was developed by National Crash Analysis Center (NCAC), was used to measure the kinematics of occupants. It should be noted that however, until now, there is no ATD that has been developed specifically for rollover testing [7], Hybrid III is considered to be the most widely used ATD and available human surrogate to address the kinematics of occupants in experimental and numerical analyses [8-11]. The ATD was seated in the first row close to the impacted side wall and belted with using 2-points seatbelt. The seatbelt was modeled with using "Seatbelt Fitting" option. Other passengers were modeled by water ballasts which they belted with a similar 2-point seatbelt.

The kinematics of ATD were calculated in terms of forces and accelerations to quantify the injuries that occupant may experience during the rollover crash test. Several injury criteria have been developed to predict the severity of injuries [10]. The well-established Injury Assessment Reference Values (IRAV) was used to measure the severity of the injuries [12]. Based on the IRAV which was defined as a lower bound of injury threshold level, if measured injury criteria are above the specific value injury will occur for that part of the body. In Table 1, the injury criteria with corresponded reference values are shown.

Table 1: Injury measurements reference values for Hybrid III-50th-male [13]

Injury metric	Injury Assessment Reference Values (IRAV)
Head injury criterion (HIC15)	700
Neck injury criteria (Nij)	See appendix 1
Chest 3ms (Clip3m)	60g
pelvis accelerations	130g

The head injury criteria are defined by the equation (1). The magnitude of linear acceleration observed at the center of the head is denoted by a(t) and the HIC15 indicates the maximum HIC that head experienced during15 milliseconds in the arbitrary time frame (t2-t1=15).

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

3-millisecond clip value (often known as the “3ms clip”) is defined to calculate the maximum chest acceleration within the 3 milliseconds time frame and calculating the corresponded injuries [14].

Rollover Test Procedures

Tilt Table Test (ECE R66)

The first rollover test procedure is ECE-R66 which is also known as a tilt table test. This rollover test was specifically developed to evaluate the structural behavior of passenger compartment of the bus during the rollover accident [15]. As it is shown in Figure 2, the bus was placed on the flat table and slowly titled to its unstable equilibrium position. Then, the bus fell under its own weight from 800mm (h) above the smooth concrete ditch.

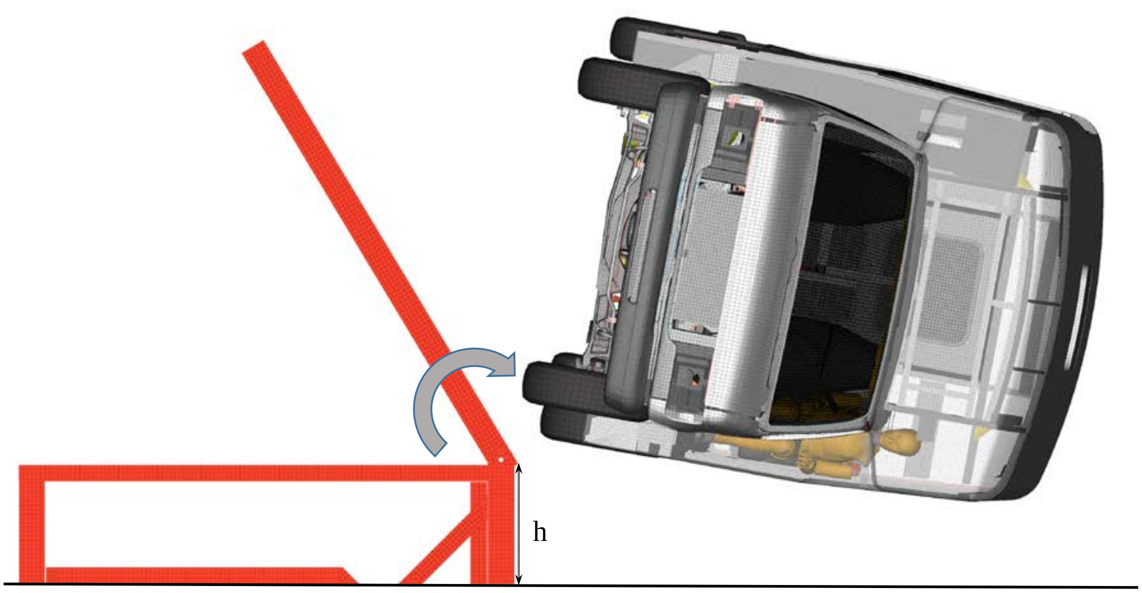


Figure 2: Schematic of tilt table test and position of the ATD inside the bus

The ATD was seated close to the side impacted wall to create the high- risk scenarios (Figure 2). According to the test procedure, suspension systems were locked. The coefficient of friction between roof and concrete was assumed around 0.7 [16].

Dolly Rollover Test (SAEJ2114)

Dolly rollover test is one of the most widely used dynamic rollover test procedure that can simulate the entire rollover event. Based on The common test procedure, a vehicle is seated on the cart (dolly) with an initial angle (23 degrees form ground), then the cart is accelerated and when it reaches the desired speed it stops suddenly. It should be noted that however this test guarantees a rollover, the main criticism of dolly rollover test is that it does not represent the most real-world rollover accidents. Because the initial position of the vehicle produces the high kinetic energy which usually does not occur in real-world rollover crashes. To solve this issue, customized test platform was designed for passenger cars [17], and specifically for vehicles heavier than 5000kg [18]. The platform designed to keep the vehicle straight and without initial roll angle which has a significant effect on reducing the roll rate and consequently decreasing the crash energy. In Figure 3 the test configurations of customized dolly rollover test are shown.

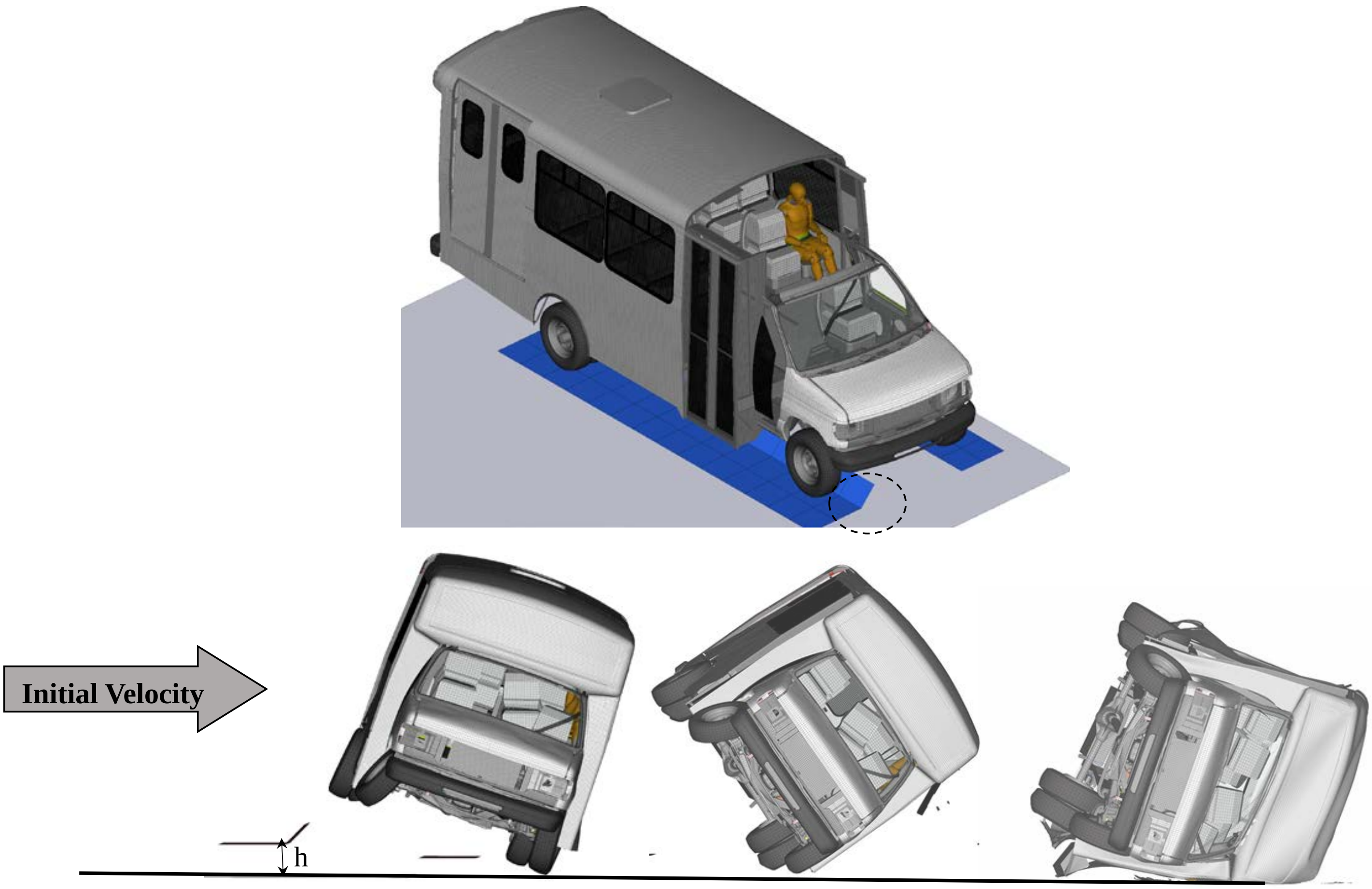


Figure 3: Customized dolly rollover test configurations and position of the ATD inside the bus

The platform was modeled with two simple rigid shell surfaces with very low friction. Based on normal test procedure, the top surface of the cart was approximately 200mm above the ground and the small tilted surface (dashed line in Figure 3) was used increase the roll rate and making sure that a rollover occurs [18]. The belted ATD was placed close to the side wall impacted the same as tilt table test. Simulation time was started when the bus reached the desired velocity which the cart stopped suddenly (no initial acceleration were applied).

Rollover Test Parameters

Since the occupant responses highly depend on the particular rollover scenario used for the test, the effects of test parameters on the severity of injuries need to be quantified. Hence, different initial conditions were selected to find the influence of rollover mechanism and test procedure on the severity of injuries. In this study, among parameters of tilt table test, drop height and from dolly rollover test, velocity and drop height were selected. The range of velocities and drop heights for both test procedures are shown in Table 2. Three rollover scenarios for each test procedure were conducted with using LS-DYNA software.

Table 2: Initial values for rollover crash tests

Test procedure	Variables	
	Drop height (h) (mm)	**Initial Velocity (m/s)**
Tilt table test	800	N/A
	1000	N/A
	1500	N/A
Dolly rollover test	150	8
	200*	11.2*
	500	8

* Recommended values based on customized dolly rollover test for heavy vehicles [18].

Results and Discussion

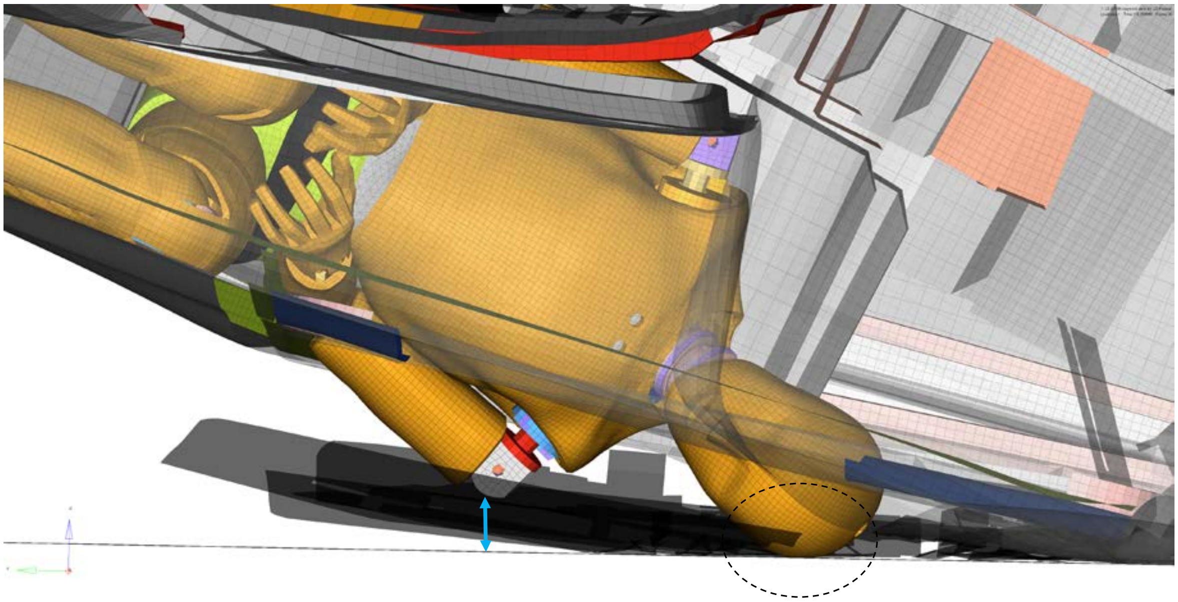
The results of numerical analyses from both test procedures were shown that the rollover mechanism of bus significantly affects the injury outcomes. The injury mechanism and severity of injuries that ATD experienced during airborne phase and impact phase are discussed and evaluated. In Table 3, the overall response of the ATD during all rollover crash tests are shown. The values that severe injuries were highlighted. It can be observed that in both rollover tests, the occupants experienced the severe injuries to the neck parts. This occurred by direct impact with either ground or window's frame. The details of injury measurements can be found in Appendix 2. In the following sections, the details of occupant's motion in both rollover test procedures were discussed.

Table 3. Injury measurements for ATD in rollover tests

Injury parameters	Tilt Table Test			Dolly Rollover Test			Injury Assessment Reference Values (IARV)
	h=800 mm	h=1000 mm	h=1500 mm	h=150mm, V=8m/s	h=200mm, V=11.2m/s	h=500mm, V=8m/s	
HIC15	1847	2737	3657	206	4132	158	700
Clip3ms (g)	25	25.5	30.7	88	160	47	60
max Pelvic Acceleration (g)	27	32	36	30	38	40	130
Nij*	1.6	1.9	2.2	1.1	2.5	1.3	1

* The severe combination is shown (see appendix 1).

Tilt Table Test-Due to the different drop heights, the roof structure hits the ground in different angles and it affects the impact mechanism of ATD to the ground. The overall results indicated that with increasing the drop height the occupant experienced the severe injuries. In Figure 4 the position of the ATD in right before the impact is shown. The results of injury measurements showed that the in tilt table test, regardless of the drop heights the amount of chest and pelvic injury are negligible.



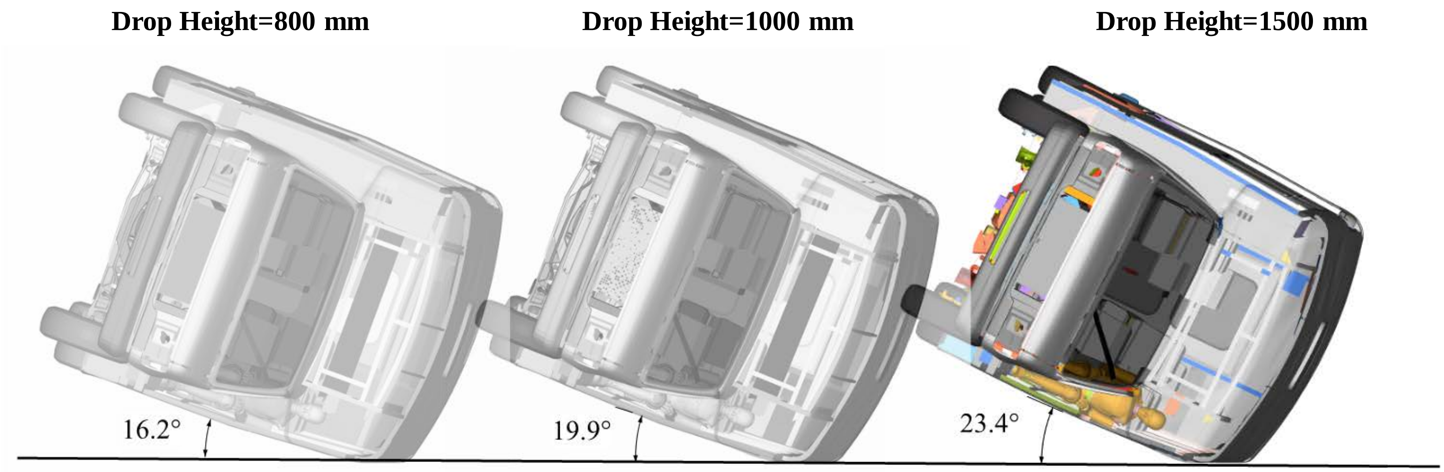


Figure 4: The position of the bus and ATD at the moment of impact with the ground in three tilt table test

As it is shown in Figure 4, the corner of the roof's bus hits the ground with different angles respect to the drop height. In all three cases, the side windows were shattered and the upper part of the ATD partially ejected. Additionally, the first part of the body that hits the ground is head and consequently, the value of the HIC15 was above the human tolerance. At the highest drop height (h=1500mm), the ATD experienced the most severe head injury and the lowest chest injury. This can be explained by analyzing the position of the ATD at the moment of the impact with the ground. With increasing the impact angle the distance between shoulder and ground is increased (blue arrow in Figure 4), so, the portion of the energy that is transferred to the head would be much higher than shoulder and chest.

Dolly Rollover Test- The rollover mechanism in this test procedure was significantly different from tilt table test. However, in all three dolly tests, the bus rolled less than 180 degrees, the roll distance and impact mechanism were considerably different. As it is expected, for the higher initial velocity, the bus traveled a longer distance. It should be noted that the rollover mechanism and occupant responses (as they are shown in

Table 4) for the two dolly tests with an initial velocity equal to the 8m/s were found very similar. Therefore, the comparison was made between the results of two tests. For the test procedures with the initial velocity equal to 8m/s, the ground impact phase occurred with the angle close to zero. This means that the whole side of the bus touched the ground simultaneously at the moment of impact. For the initial velocity equal to 11.2m/s, the bus experienced the longer airborne phase and the corner of the roof was the first part of the structural components that hit the ground (similar to the tilt table test but with less impact angle).

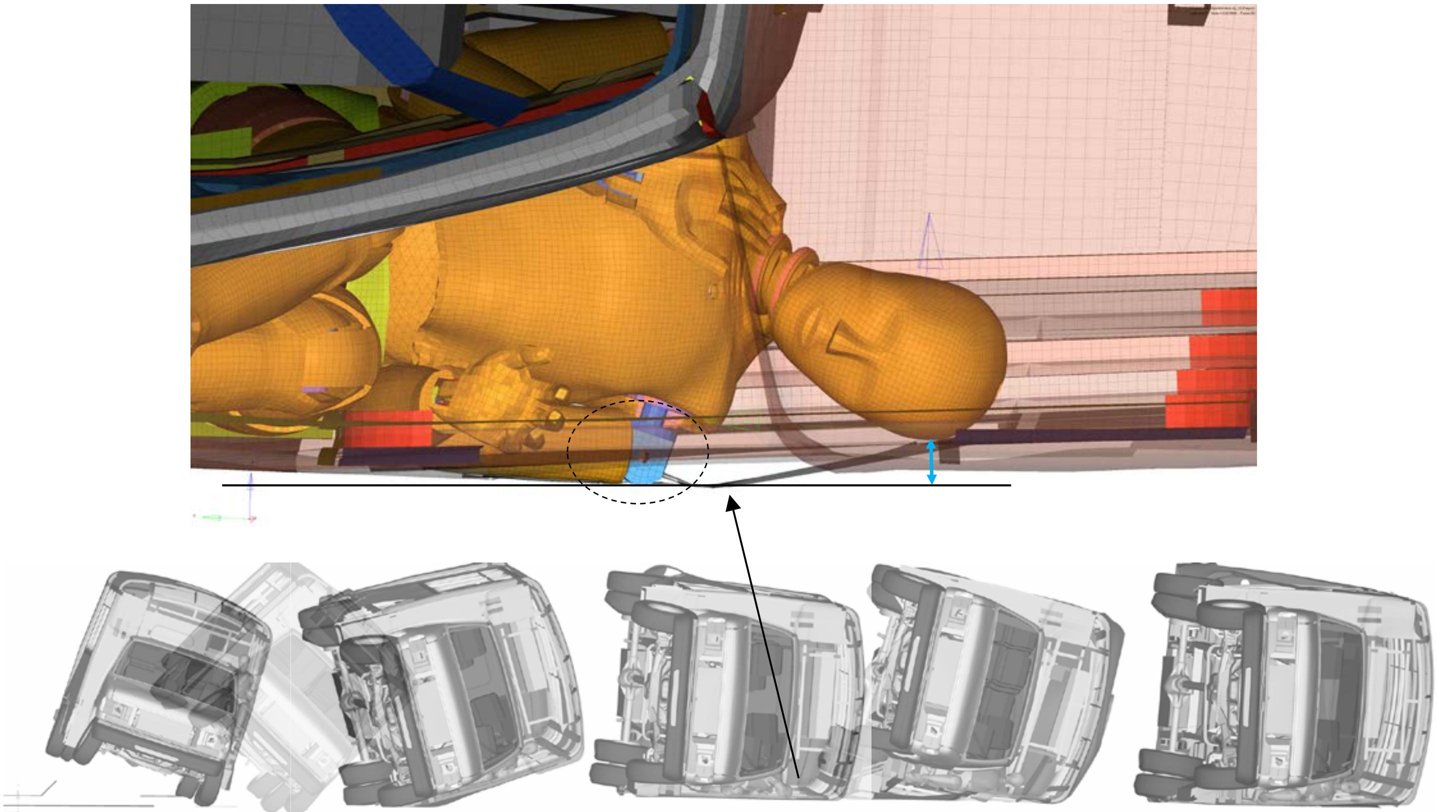


Figure 5: Dolly rollover sequences and the position of the ATD at the moment of impact for V=8m/s

In Figure 5 and Figure 6, the rollover mechanism and occupant's motion in two different test procedures are shown. In the rollover tests with the V=8m/s, the ATD experienced the severe chest injury. Because as it is shown in Figure 5, the first part of the body that hits the ground is shoulder and chest. Thus, the higher amount of crash energy transferred to these parts of the body.

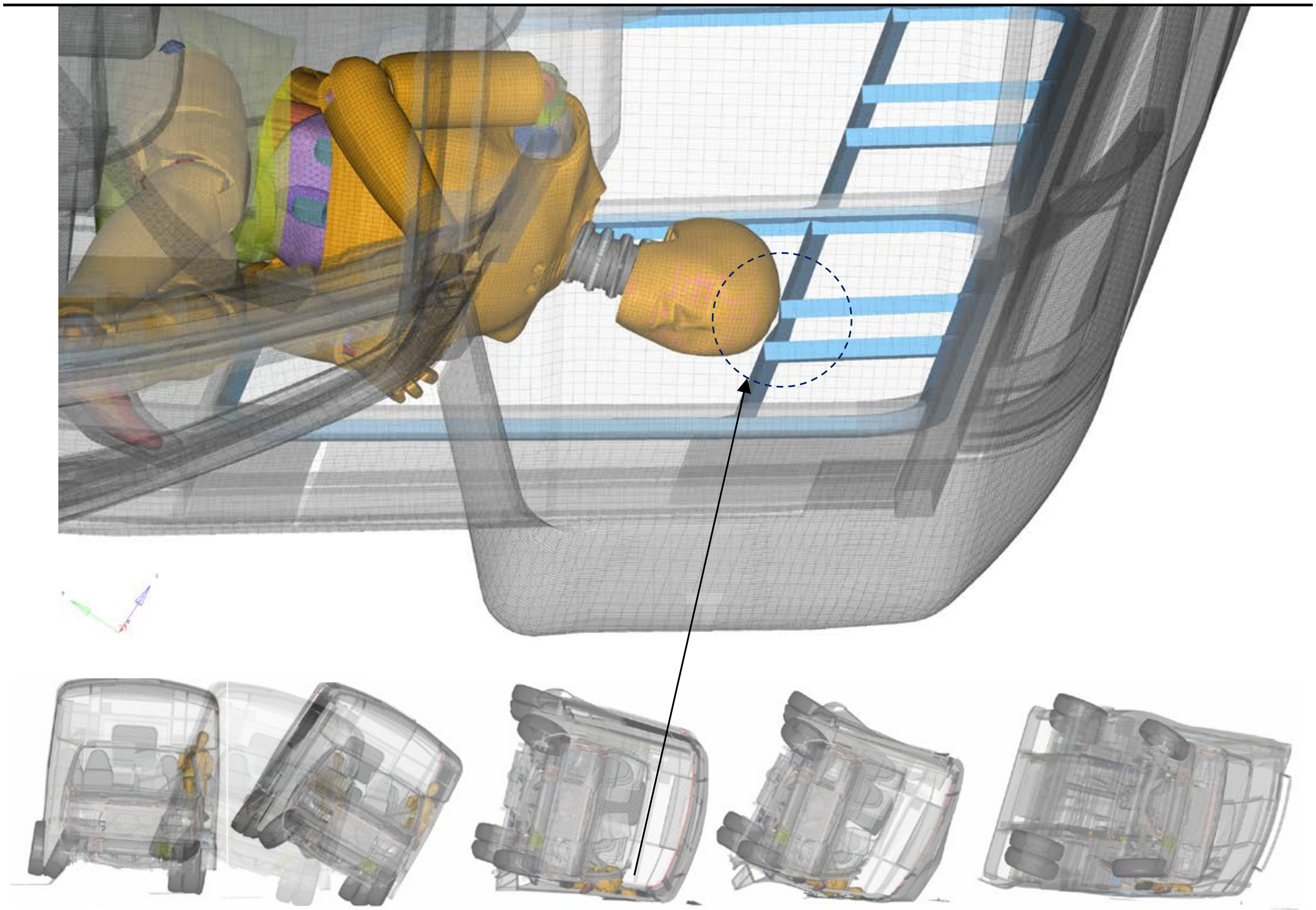


Figure 6: Rollover mechanism of the bus in dolly rollover test with V=11.2m/s and position of the ATD at the moment of impact with window's frame

Figure 6 shows that during the airborne phase, the head has an impact with the window's frame. This occurred only for the initial velocity equal to 11.2 m/s. The most likely explanation for this impact is that the tendency of the ATD to move upward is much higher than lower velocity. Because the eccentric force that occupants experienced during the dolly rollover will significantly increase when the roll rate goes up.
The overall assessment of the ATDs' responses during the two rollover test procedures shows that the upper parts of the body are more exposed to the injuries than lower parts. This is in agreement with the research findings that was performed by [19]. The author believes that further researches on occupant response should be carried out to improve the safety of the passengers and corresponded countermeasures for rollover accidents.

Limitation- The current study has some limitations that should be noted. Due to the lack of available statistical information about real-world injury data during the rollover accidents and also limited biomechanical studies on rollover accidents for buses, the severity of injuries may differ from what happened in real-world rollover crashes. Moreover, head injury criteria that are used in this study are based on maximum linear acceleration which is not sensitive to the direction of impact and also it is unable to predict the injury due to the angular motion [20]. Furthermore, one of the important challenges in rollover safety assessment of all types of vehicles is to choose scenarios that have broad applicability, with the understanding that the results do not cover all situations that could lead to rollover. So, definitely, further research needs to be carried out to define and extract the more realistic and applicable rollover test parameters for buses with considering the human response.

Summary and Conclusions

In this study, the occupant responses during the specific rollover tests were measured quantitatively and qualitatively. Although the number of simulations and selected variables is relatively small, the results of computational analyses provide a better understanding of human response during the rollover. The tilt table and dolly rollover test procedures were selected to evaluate the kinematics of occupant. The FE model of hybrid III ATD was placed close to the side impacted wall to create the high-risk scenarios. The ATD was belted with using a 2-point seatbelt. Then different drop height and initial velocity were chosen to assess the effects of them on the injury mechanism and severity of injuries.

Initial computational analyses indicate that the upper parts of the body include head, neck, and chest are more prone to experience the severe injuries due to partial ejection, broken side windows, the direct impact between head, chest, and shoulder with the ground. So, proper design of windows and their frames can reduce or even prevent some of the injuries. Moreover, the kinematics of the ATD highly depends on the rollover test procedure and the initial condition of the test. This factor was more obvious in dolly rollover test which slight change in initial velocity and drop height can lead to significantly different injury outcomes. it is also recommended that to improve the countermeasure of rollover safety assessment, the comprehensive studies on dynamic parameters of the bus to extract the more realistic initial condition should be carried out.

References

[1] C. S. Parenteau, and M. Shah, "Driver injuries in US single-event rollovers," *SAE Technical Paper*, 2000.
[2] K. H. Yang, J. Hu, N. A. White, and A. I. King, "Development of numerical models for injury biomechanics research: a review of 50 years of publications in the Stapp Car Crash Conference," *Stapp car crash journal*, vol. 50, pp. 429, 2006.
[3] C. Bojanowski, "Verification, validation and optimization of finite element model of bus structure for rollover test," The Florida State University, 2009.
[4] C. Bojanowski, and R. F. Kulak, "Multi-objective optimisation and sensitivity analysis of a paratransit bus structure for rollover and side impact tests," *International journal of crashworthiness*, vol. 16, no. 6, pp. 665-676, 2011.
[5] B. Gepner, C. Bojanowski, L. Kwasniewski, and J. Wekezer, "Effectiveness of ECE R66 and FMVSS 220 standards in rollover crashworthiness assessment of paratransit buses," *International Journal of Automotive Technology*, vol. 15, no. 4, pp. 581-591, 2014.
[6] L. Kwasniewski, C. Bojanowski, J. Siervogel, J. W. Wekezer, and K. Cichocki, "Crash and safety assessment program for paratransit buses," *International Journal of Impact Engineering*, vol. 36, no. 2, pp. 235-242, 2009.
[7] C. C. Chou, C. D. Wagner, K. H. Yang, A. I. King, J. Hu, K. Hope, and S. Arepally, "A review of math-based CAE tools for rollover simulations," *International journal of vehicle safety*, vol. 3, no. 3, pp. 236-275, 2008.
[8] J. Croteau, J. Zolock, R. Larson, C. Bare, D. Peterson, and D. Parker, "Dynamic response of vehicle roof structure and ATD neck loading during dolly rollover tests," *SAE International Journal of Passenger Cars-Mechanical Systems*, vol. 3, no. 2010-01-0515, pp. 407-449, 2010.
[9] D. Friedman, and K. Friedman, "Upper interior head, face and neck injury experiments."
[10] H. J. Mertz, and A. L. Irwin, "Anthropomorphic Test Devices and Injury Risk Assessments," *Accidental Injury*, pp. 83-112: Springer, 2015.
[11] R. Piziali, R. Hopper, D. Girvan, and R. Merala, *Injury causation in rollover accidents and the biofidelity of Hybrid III data in rollover tests*, 0148-7191, SAE Technical Paper, 1998.
[12] R. Eppinger, E. Sun, F. Bandak, M. Haffner, N. Khaewpong, M. Maltese, S. Kuppa, T. Nguyen, E. Takhounts, and R. Tannous, "Development of improved injury criteria for the assessment of advanced automotive restraint systems–II," *National Highway Traffic Safety Administration*, pp. 1-70, 1999.
[13] H. J. Mertz, A. L. Irwin, and P. Prasad, *Biomechanical and scaling basis for frontal and side impact injury assessment reference values*, SAE Technical Paper, 2016.
[14] D. Gabauer, and R. Thomson, "Correlation of vehicle and roadside crash test injury criteria." pp. 6-9.
[15] C.-C. Liang, and G.-N. Le, "Optimization of bus rollover strength by consideration of the energy absorption ability," *International Journal of Automotive Technology*, vol. 11, no. 2, pp. 173-185, 2010.
[16] M. Gleba, "Effect of friction on vehicle crashworthiness during rollover," The Florida State University, 2015.
[17] J. R. Kerrigan, N. J. Dennis, D. P. Parent, S. Purtsezov, J. H. Ash, J. R. Crandall, and D. Stein, "Test system, vehicle and occupant response repeatability evaluation in rollover crash tests: the deceleration rollover sled test," *International Journal of Crashworthiness*, vol. 16, no. 6, pp. 583-605, 2011.
[18] J. Hu, N. R. Orton, R. Gruber, R. Hoover, K. Tribbett, J. Rupp, D. Clark, R. Scherer, and M. Reed, *Development of A New Dynamic Rollover Test Methodology for Heavy Vehicles*, 0148-7191, SAE Technical Paper, 2017.

[19] P. Albertsson, and T. Falkmer, "Is there a pattern in European bus and coach incidents? A literature analysis with special focus on injury causation and injury mechanisms," *Accident Analysis & Prevention*, vol. 37, no. 2, pp. 225-233, 2005.

[20] P. Thesis, "Characteristics of serious head injuries in pure rollover crashes and an evaluation of their replication in a dynamic rollover test," *University of New South Wales*, 2015.

[21] S. Abrate, "Modeling of impacts on composite structures," *Composite structures*, vol. 51, no. 2, pp. 129-138, 2001.

Appendix 1

IARVs have been considered the internal reactions of junctions between head to neck and neck to torso, to quantify the possible neck injuries. The peaks of reactions for linear combinations of axial forces and bending moments known as Nij. This index represents the Normalized Neck Injury Criterion (equation 2). This criterion considers four loading combinations which are summarized in Table 4 and the threshold value for Nij is 1.0.

$Nij=(Fz/Fzc)+(Mocy/Myc)$ (2)

Where:

- F_z – Axial force at the upper neck load cell,
- F_{zc} – Critical axial force,
- M_{ocy} – Total occupant condyle moment along y-axis, and
- M_{yc} – Critical moment along y-axis.

Table 4: Nij loading criterion

Criterion Nij	Forces	Moments
NCF	Compression (compression force) F<0	Flexion (forwards bending) M>0
NCE		Extension (backwards extension) M<0
NTF	Tension (tensile force) F>0	Flexion (forwards bending) M>0
NTE		Extension (backwards extension) M<0

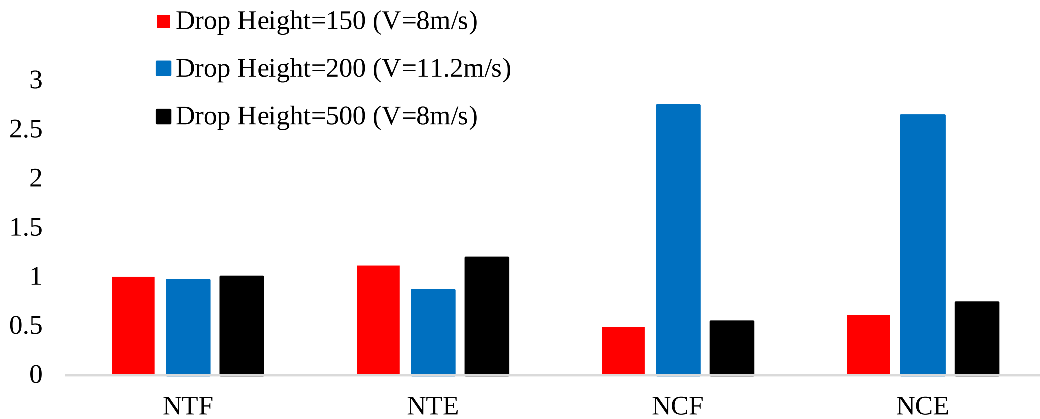
Corresponded critical forces and moments values for Hybrid III 50th male are also presented in the Table 5.

Table 5: Proposed Critical Intercept Values for neck injury calculation [12]

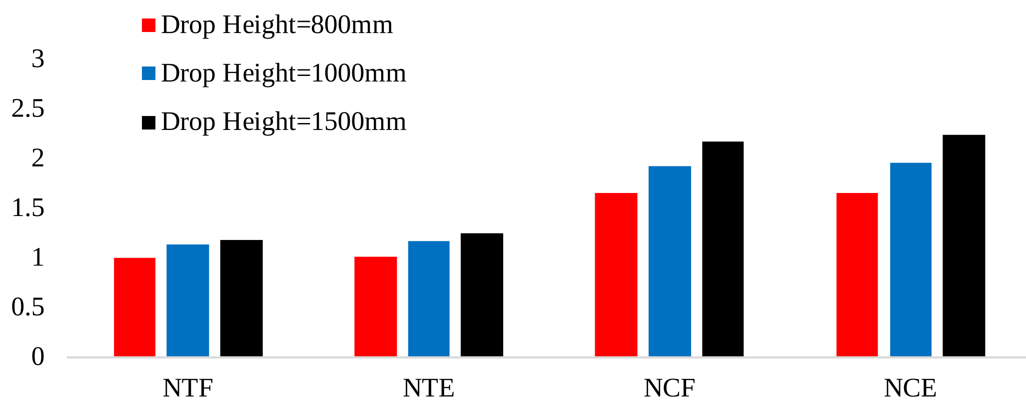
ATD Type	F_{zc} [N] Tension	F_{zc} [N] Compression	M_{yc} [Nm] Flexion	M_{yc} [Nm] Extension
Hybrid III- male 50%	4500	-4500	310	-125

Appendix 2

The details of ATD response are shown in below Figures.



(a)



(b)

Figure 7: Neck injury criteria for different load combination; a)tilt table test, b) dolly rollover test

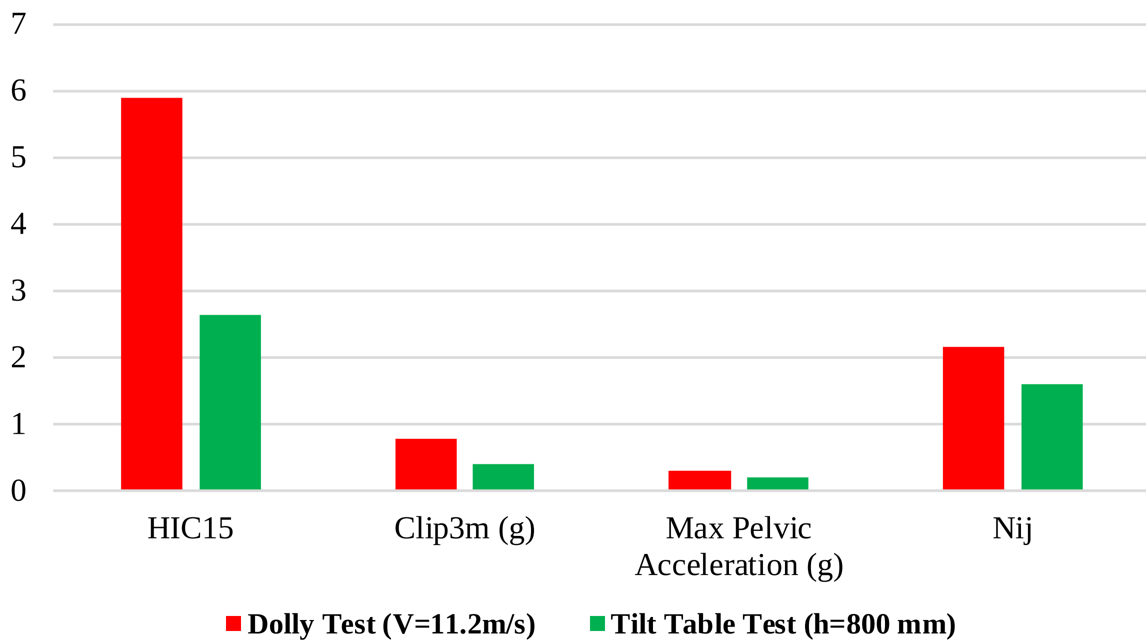


Figure 8: Comparison of normalized injury outcomes for two rollover tests (standard initial conditions)

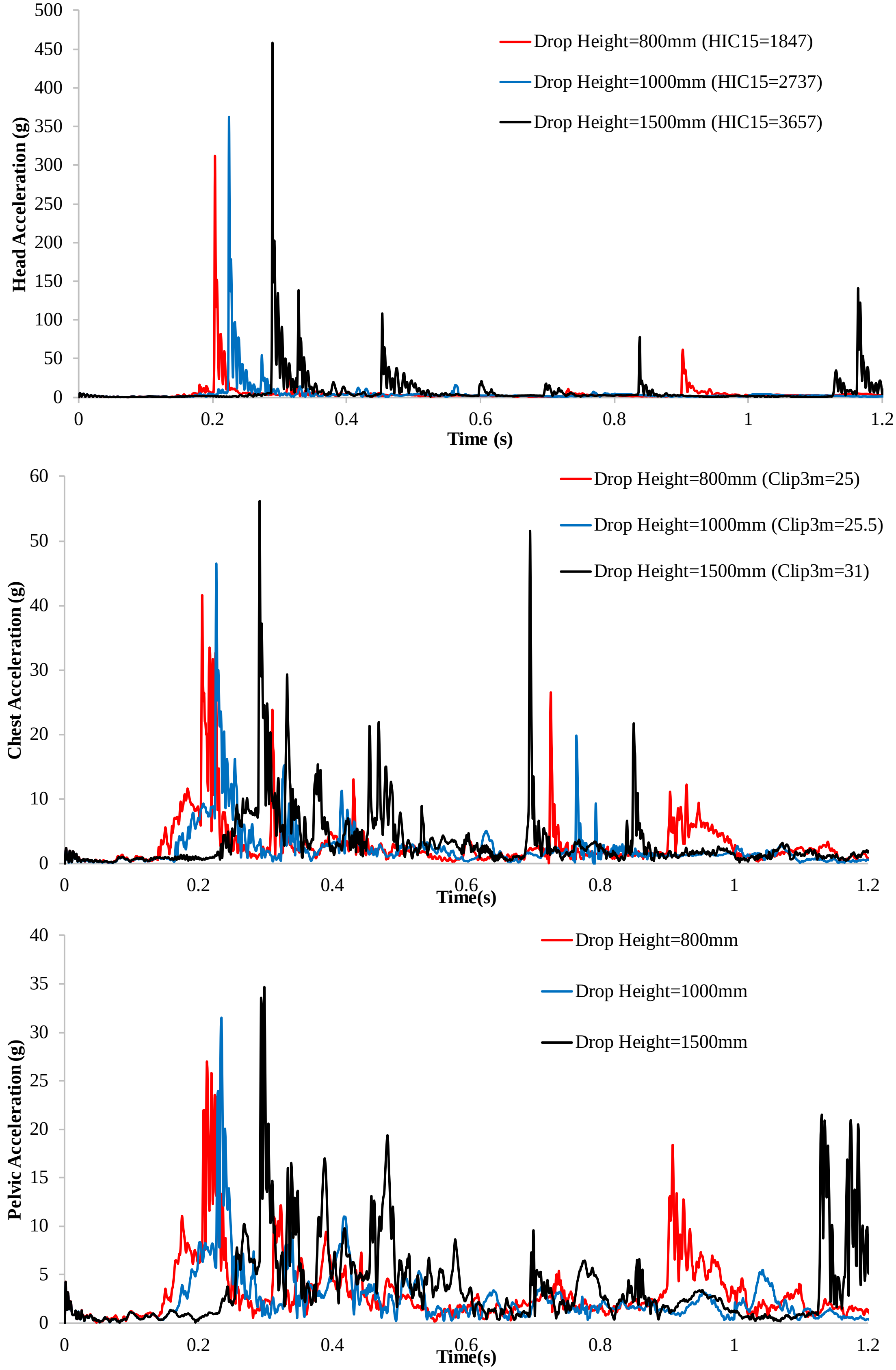


Figure 9: Injury measurements of ATD in tilt table test for different drop heights

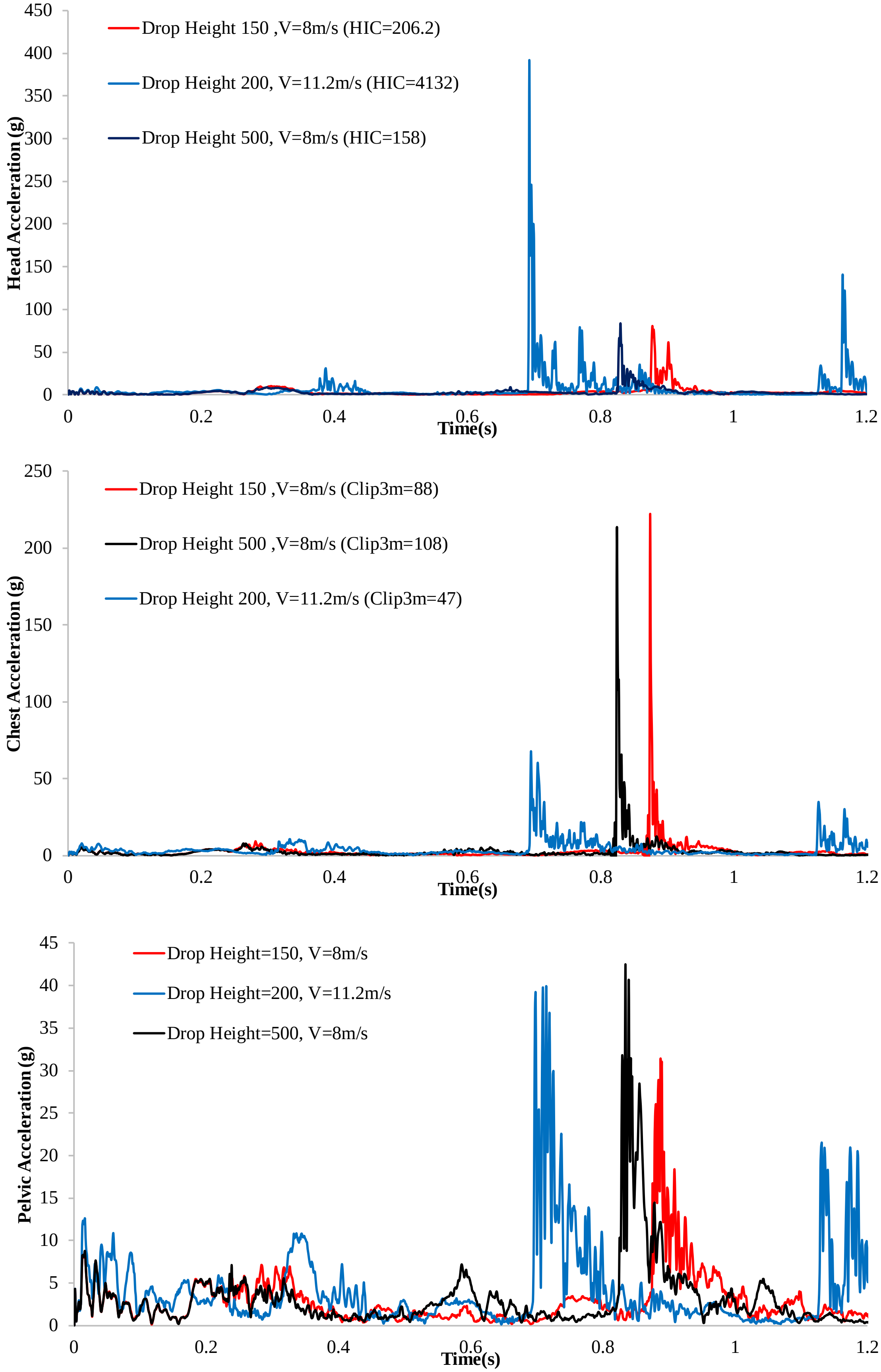


Figure 10: ATD responses in dolly rollover test for different initial condition