



Experimental assessment of vehicle performance and injury risk for cutaway buses using tilt table and modified dolly rollover tests



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ABSTRACT

Background: Rollover crashes of buses occur less frequently than do those involving passenger cars; however, they are associated with higher fatality rates. During rollover crashes, a vehicle experiences multidirectional acceleration and multiple impacts, yielding a complex interaction between structural components and its occupants. A better understanding of vehicle and occupant's motion, structural deformation, and vehicle and road interactions are necessary to improve the safety of the occupants during this event. One of the key factors in rollover crashworthiness assessment is to investigate the relationship between the strength of the vehicle's structure and the risk of injury outcomes. However, rollover crashes involving buses have received less research attention than have those involving passenger cars. Experimental studies in bus rollover safety have mainly focused on the structural integrity of the passenger compartment without considering the occupant responses. The main goal of this research is to evaluate the rollover mechanism and associated injury risk during two experimental rollover tests for a paratransit cutaway bus that is commonly used by transit agencies.

Methods: The modified dolly rollover (MDR) and tilt table (TT) tests were conducted using a similar bus and anthropomorphic test device (ATD) configurations. In each test, a 2-point and 3-point belted Hybrid III 50th percent male ATDs were used to quantify the kinematics of the occupants. The deformation index (DI), accelerations and angular velocities of the bus's CG were measured as vehicle responses. The collected data were then calibrated and filtered to assess the effects of the test procedure on kinematic responses of the vehicle and occupants. Next, the effectiveness of the 2-point vs 3-point seatbelt to reduce or prevent the injuries, the vulnerable body regions and corresponded injury risk were evaluated.

Results: The residual space remained intact ($DI < 1$) during both rollover tests, however, the ATD responses were quite different. The results of the injury assessment indicate that the risk of the injuries in the MDR test was significantly higher than the TT test. The highest risk of injuries was identified for the head, neck, and shoulder of 2-point belted ATD during the MDR test. Also, the main source of injuries during the MDR test was partial ejection due to the shattered side window, whereas for the TT test impacts between the ATDs and the side window and/or window frame were the injury causes. From the vehicle point of view, the total energy produced in the MDR was 3.5 times higher than the TT test, but the overall structural deformation in the TT test was higher than MDR test. Overall, the tilt table test provides a more severe scenario compared to the MDR test for the assessment of structural strength. Considering the limited real-world injury data in rollover crashes of buses, the MDR test presented the more realistic occupant responses.

1. Introduction

Rollover crashes constitute the most severe crashes in terms of fatality rate (NHTSA, 2018). They are associated with multidirectional accelerations that create complex interactions between the occupants and vehicle. Rollover crashes typically have three phases – the trip, airborne, and ground impact phases (i.e., the first major impact between vehicle and ground) from a vehicle's point of view (Parenteau

and Shah, 2000). However, instead of having an airborne phase, bus rollovers often involve sliding of the vehicle along the road, due to the different geometrical and inertial properties (Botto and Got, 1996). Other differences with passenger car rollovers involve their frequency and severity: Although bus rollovers occur less frequently, they have higher fatality rates (Albertsson, 2005; Björnstig et al., 2005).

To examine the mechanisms involved in bus rollovers, researchers have been using field data analysis (Botto and Got, 1996; Albertsson

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et al., 2003; Martínez et al., 2003; Albertsson, 2005; Albertsson and Falkner, 2005; Albertsson et al., 2006) and experimental or computational methods to characterize rollover crashes of buses (Belingardi et al., 2005; Guler et al., 2007; Kang et al., 2012; Gepner et al., 2014; Karliński et al., 2014). Field data analyses were mainly focused on identifying the injury mechanisms and injury patterns of occupants during the real rollover crashes. Based on their results, the injury mechanisms can be classified into the following four types: projection, full ejection, partial ejection, and intrusion. Experimental and numerical studies have been conducted primarily to address the integrity of the passenger compartment (Nii and Nakagawa, 1996; Honiball and Van Niekerk, 2001; Belingardi et al., 2005; Guler et al., 2007; Tech et al., 2007; Li et al., 2012; Seyedi et al., 2019) and enhancing the crash-worthy parameters of bus structure (Friedman et al., 2006; Gürsel and Gürseli, 2010; Liang and Le, 2010b; Su et al., 2011; Kang et al., 2012). However, few numerical studies have investigated the occupant responses with considering different variables such as the position of occupants inside the bus, type of restraint systems, and occupant size (Ferrer, 2001; Belingardi et al., 2003; Martínez et al., 2003; Jongpradist et al., 2018; Seyedi et al., 2018). Current study provides some insights into the occupant response during two experimental rollover tests.

In the literature, the following test procedures have been found to replicate either the entire or specific phase of rollover event (Seyedi, 2019). The FMVSS 220 (Federal Motor Vehicle Safety Standard) test method is a quasi-static test procedure and has been used to measure the strength of the bus's roof (Liang and Le, 2010b). The concept of this test is to apply a vertical force on the bus's roof using a flat rigid rectangular plate. In spite of its high repeatability, FMVSS 220 test cannot reflect real-world loads applied to the bus's structure during the rollover (Liang and Le, 2010a; Gepner et al., 2014). The ECE R66 tilt table rollover test (TT) has been widely used to evaluate the superstructure of a bus (Belingardi et al., 2003; Martínez et al., 2003; Gürsel and Gürseli, 2010; Karliński et al., 2014). In this test procedure, a test bus, with locked suspension, is placed on the table 800 mm above the ground. A bus is slowly tilted until it reaches its unstable position and falls under its own weight (see Fig. 1-a). This test only replicates the roof-to-ground impact phase of a rollover crash. It has yet to be established whether the tilt table test can represent the real-world kinematics of the bus and occupants. A dolly rollover test, specified as Federal Motor Vehicle Safety Standard (FMVSS) 208, was designed for passenger cars and has been used to reconstruct the entire rollover crash event. In this test, a cart carrying a test vehicle is accelerated to the desired velocity and

then the cart is stopped suddenly, causing the vehicle to roll laterally. This test is one of the most widely used rollover tests for passenger cars (SAE, 1999). However, related findings showed that this test produces very high crash energy (due to the tilted vehicle's body) and it is not repeatable particularly for the initial roof-to-ground contact (Cooperrider et al., 1990). To overcome these issues, several studies have been conducted using the same test procedure with the modified cart (Hughes et al., 2002; Kerrigan et al., 2011). The modified dolly rollover test (MDR) was developed for testing the vehicles heavier than 5000 kg (Hu et al., 2017). The difference between the standard dolly rollover and the MDR test is that in the standard dolly rollover test, the vehicle is placed on the tilted fixture with initial 23° roll angle, while in MDR test the cart is redesigned with zero-degree roll angle. Fig. 1-(b) shows the overall motion of the bus during the MDR test.

The results of an experimental test can be divided into rollover outcomes (vehicle responses) and injury outcomes (occupant responses). Generally, rollover outcomes include structural deformation, roll distance, number of quarter turns, deceleration rate, and the maximum height of the center of gravity (CG) (Grzebieta et al., 2010). The occupant responses include the kinetic and kinematic parameters (e.g., force, acceleration, and displacement) measured using an anthropomorphic test device (ATD) (force, acceleration, and displacement). The results were then compared with corresponding human tolerances to assess the injury risk (Mertz and Irwin, 2015). The main goal of the current study is to provide a detailed assessment of the vehicle and occupant responses in two experimental rollover test (the MDR and TT tests). In this study, a paratransit cutaway bus with the same configurations was used in both tests (more details about bus structure can be found in Gepner (2014)). To capture the occupant responses, in each test, two instrumented Hybrid III 50th male ATDs with different restraint systems (2-point and 3-point seatbelt) were placed on the same seat position.

2. Test setup

2.1. Test procedures

Two full-scale MDR and TT rollover tests were conducted in this study. The bus was placed in a left-side leading configuration on the cart/table and the driver seat was removed. In the MDR test, because the cart was non-adjustable, the bus was slightly leaned on its left side (initial roll angle was 4°). A layer of Teflon was installed in their contact

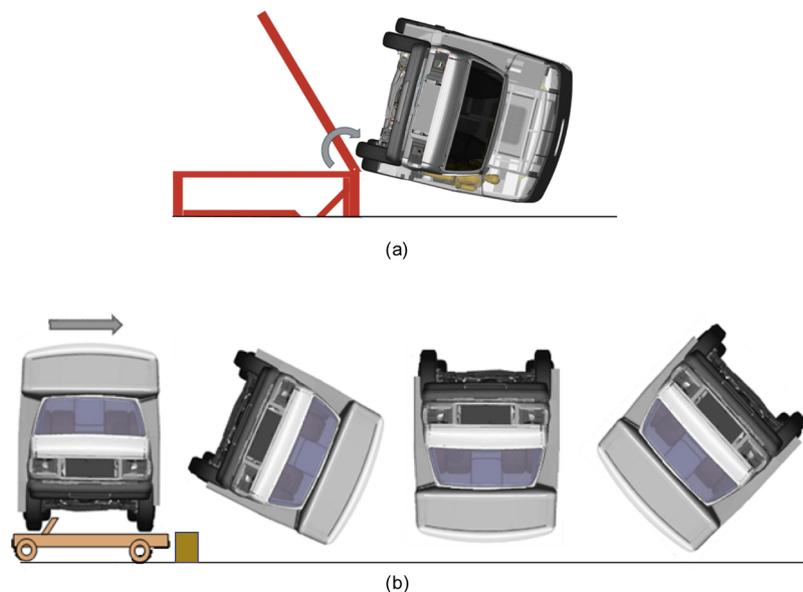


Fig. 1. a) tilt table test (TT); b) modified dolly rollover test (MDR).

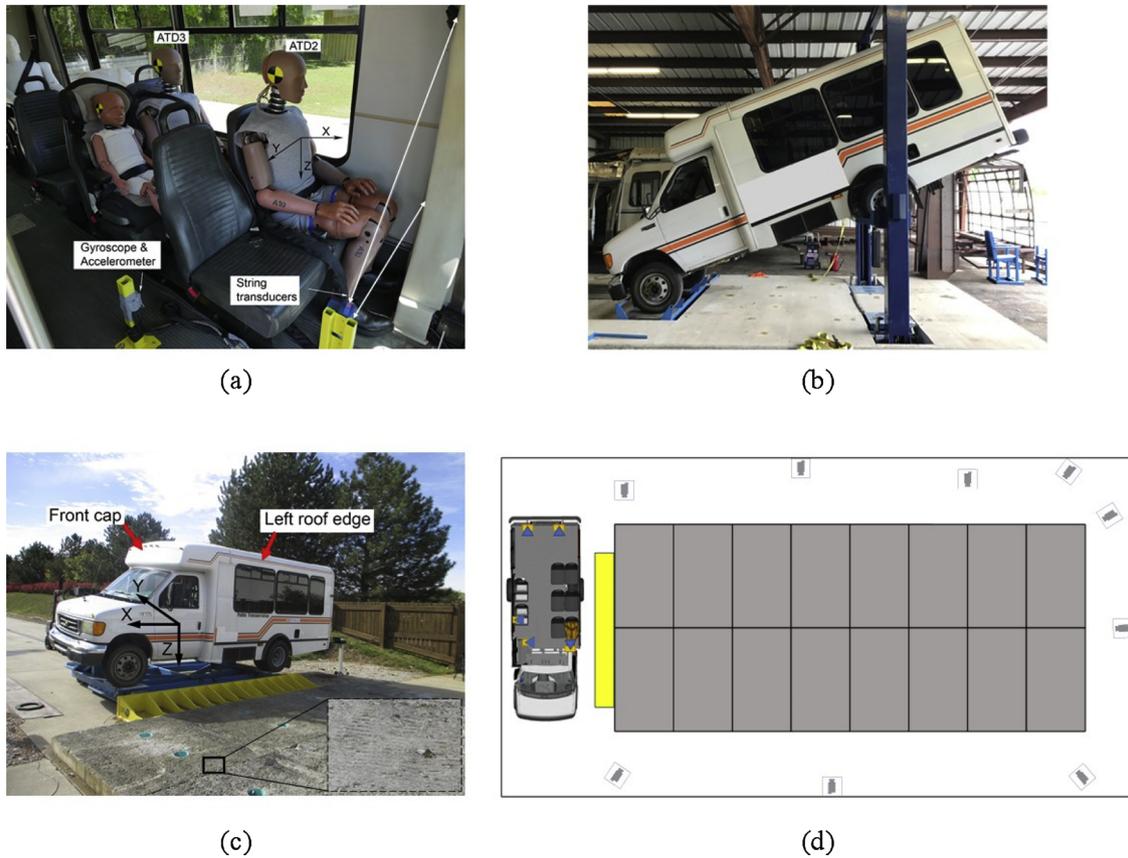


Fig. 2. The bus and ATD's configurations: (a) Position of ATDs and sensors; (b) Bus's CG measurement; (c) Bus's coordinate system and concrete surface; (d) Location of cameras.

area between the tires and cart to reduce the friction (see more details of the test procedure in Hu et al. (2017)). The cart was accelerated by pulling a cable to a target speed of 11.2 m/s (25 mph). Then it was stopped by striking two honeycomb blocks (200 mm × 250 mm × 250 mm Hexcel rated at 5.5 MPa) with approximately the deceleration rate of 50 g. This allowed the bus to translate and roll laterally onto the test surface. The test surface was prepared by raked concrete pads with a rough surface that can provide a high surface friction (see Fig. 2-c). According to the TT test procedure, the front and rear suspension systems of the bus were locked, and the fuel tank was drained. The bus was placed on the table in the upright position 800 mm above the ground and slowly tilted (0.4 deg/s) to reach its unstable equilibrium. Then the bus started to rotate about its left tires and fell on dried smooth concrete. In both tests, fixtures were also installed inside the bus to mount the cameras, transducers, and sensors.

2.2. Vehicle and ATD instrumentation

Two identical cutaway buses manufactured in 2005, equipped with eight seats, tempered side windows, and one wheelchair, were used. Table 1 shows details of the bus configurations. For each bus, the center of gravity (CG) was measured based on the R66 test procedure (UN/ECE, 2006) for the unloaded and loaded configuration (see Fig. 2-b). The loaded condition was when a water ballast was placed on all the seats and the unloaded condition was without any passenger load and extra equipment. All the doors and windows were closed at the

Table 1
Summary of bus configurations.

Kinematic parameter	TT tested bus	MDR tested bus
Base Curb Weight (Kg)		
Total	3916	3854
Front axle	1202	1211
Rear axle	2714	2643
Loaded Weight (Kg)		
Total	4331	4269
Front axle	1254	1265
Rear axle	3077	3004
Overall Dimensions (m)		
Length	6.63	6.63
Height (from the ground)	2.84	2.84
Width (exterior)	2.23	2.23
Wheelbase	3.5	3.5
CG location-unloaded (m)		
L (distance from a front axle toward rear axle)	2.43	2.4
W (distance from the center line toward a left side)	0.06	0.07
H (above the ground)	0.89	0.88
CG location-loaded (m)		
L	2.48	2.46
W	0.03	0.03
H	0.94	0.95

beginning of each test. Each bus was instrumented with a three-axis digital accelerometer (35200B) and a three-axis gyro (31206B, Summit Instruments, Toronto, Canada). In each test, the accelerometer and gyro

cubes were mounted close to the bus's CG location. Additionally, a total of 8 string transducers was used to measure the deformation of the front and rear section of the bus and calculate the Deformation Index (DI). The residual space was determined based on the geometry of the passenger compartment (JASIC, 2006). The DI values greater than one implies that the elements of passenger compartment intrude into the residual space (see more details in Gepner et al. (2014)).

In each test, the two instrumented Hybrid III 50th percentile male ATDs were placed in the first and second rows, close to the left side wall, and restrained with a 2-point and 3-point seatbelt respectively (ATD2 and ATD3 in Fig. 2). An uninstrumented Hybrid II (only in the MDR test) and a 3-years old Hybrid III (in both tests) were also used for objectives that are out of the scope of this paper. The seats close to the ATDs remained empty to prevent any interruption with ATDs movement and the rest of the seats were filled with water ballasts (each had approximately 80 kg weight). Measured kinematic responses of the ATDs included: the acceleration of the head, chest, and pelvis along with neck forces and moments. The results were compared with the corresponding injury assessment reference values (IARVs) to evaluate the risk of the injuries (Mertz, 2002). If the values did not exceed the IARVs, then the probability of severe injuries would be less than 5%. However, this should not be interpreted as no injury. In fact, depending on ATD measurements, the risks of serious injuries could remain high. For the Hybrid III 50th male ATD, according to the IARVs, the values of 700 for the head injury criterion (15 ms HIC), one for the neck injury criteria (N_{ij}), 60 g for the 3 ms clip chest acceleration, and 130 g for the pelvic acceleration were used (Mertz and Irwin, 2015).

The coordinate systems that were used for kinematic responses of vehicle/occupants in both tests are shown in Fig. 2-a. The left and right side of a bus are defined as the -Y and + Y direction respectively. The recorded data of four seconds for the MDR test were presented, began when the cart touched the honeycomb block ($t = 0$ s) until the rest position of the bus ($t = 4$ s). For the TT test, the data duration was three seconds, starting from two seconds before the roof edge-to-ground contact until one second after the impact. All the data were acquired at 20 kHz and filtered according to the SAE J211 (SAE, 2007) channel filtering class (CFC). The filtered vehicle acceleration data were de-biased and transformed from the vehicle-fixed coordinate into the global references using the quaternion method (Diebel, 2006). The results were integrated to extract the velocity and position of the bus's CG in the global coordinate system throughout the rollover event. This allowed us to analyze the vehicle motion (position and orientation, linear and rotational velocities, and linear accelerations) and energy exchange (Croteau et al., 2010; Larson et al., 2015). Additionally, the vehicle motion was recorded by four off-board high-speed cameras, which were time synchronized with the cart release trigger. The five real-time cameras were also used to capture the ATDs motion inside the bus (see Fig. 2-d).

3. Test results

The kinematic responses of the vehicle and occupants from each rollover test are presented in this section. The vehicle responses include the kinematics of the bus's CG, structural deformation, and overall motion of the bus during each test. The occupant responses contain the measurements of the head, neck, chest, and pelvis for ATD2 and ATD3. The results of kinematic analysis provided insight into the bus dynamics and mechanism that caused the injuries which will be discussed in Section 4. Additionally, summaries of the vehicle kinematic responses collected from both tests are presented in Appendix A.

3.1. MDR test results

In the MDR test, the bus was released at 40 km/h from the cart. The bus rolled 5.1 quarter turns (460 degrees) and traveled the 16.5 m distance from the releasing point to the rest position over four seconds. Fig. 3 shows the time history of roll rate and overall motion of the bus. During the first 0.33 s of the test, the bus moved laterally with both left tires on the concrete surface (tripping phase). The frictional forces caused a decrease in the translational speed and an increase in the roll rate. Following the trip, the rear left wheel rims dug into the concrete slab which caused a 150% increase in the roll rate (100–250 deg/s) at $t = 0.33$ s. Up to this moment, the two ATDs did not move significantly and still remained in their seats. Then, the airborne phase started and the first impact between a left portion of the front cap and the ground occurred in the second quarter turn. The impact caused a minor deformation and slightly increased the roll rate (to 270 deg/s at $t = 0.7$ s). As the bus continued to rotate, it turned upside down and only the front cap touched the ground. The bus's CG reached to its maximum height above the ground at $t = 1.08$ s ($h = 2.8$ m). Due to the inertial effects during this time, the ATD2 moved upward and hit the window frame.

Fig. 4 shows the impact times between the bus and ground during the MDR test and corresponding resultant acceleration. The first major impact between the bus structure and ground occurred at the end of third quarter turns (roll angle = 280°) where the right lower portion behind the rear axle, hit the concrete slab at $t = 1.53$ s. The peak value for resultant acceleration was recorded at this moment (14.7 g) and the roll rate suddenly decreased from 220 deg/s to 108 deg/s. The rear side door was partially opened because of this impact. No significant changes were observed in the head, neck, and chest responses and only the pelvic resultant acceleration for ATD3 reached its first peak (15.4 g). The second major impact occurred when the bus was rolling in the fourth quarter turn (270–360 degrees) and its front left tire severely hit the ground and blew out at $t = 2.18$ s. The roll rate substantially changed at this time from 220 to 60 deg/s. During this impact, ATD2 experienced multiple peaks in the neck's forces (F_x and F_y) and moments (M_y and M_z) and experienced the maximum pelvic acceleration of 17.4 g.

During the last turn (roll angle between 360–460 degrees), the motion of the bus was associated with the upward movement caused by the reaction between the suspension and ground (at $t = 2.18$ s). The third major impact occurred between the left roof edge of the bus and the ground. Subsequently, the side window was shattered, and the bus slipped until it reached to its rest position. During this impact, the maximum DI value for the front section (left side) was recorded (DI = 0.3 at $t = 2.85$ s) and the roll rate dropped from 110 deg/s to zero. Unfortunately, due to the transducer malfunction, the DIs of other sections were not measured. However, the measurements of residual deformation in post-crash analysis indicated that the residual space remained intact and the DI values were less than one. Due to the broken side window, the ATD2 was partially ejected and direct contact between its upper parts and ground occurred. In contrast, the ATD3 did not eject and had only minor impacts with interior parts of the bus. The highest peak of 207 g and 26 g was recorded for head acceleration of ATD2 and ATD3 respectively. Table 2 summarizes kinematic responses of ATDs during the MDR test.

3.2. TT test results

Fig. 5 shows the overall motion and corresponding resultant acceleration and roll rate of the bus during the TT test. The rollover started ($t = 0$ s) when the CG of the bus reached its maximum height above the ground ($h = 2.6$ m and initial roll angle = 47 degrees) and the bus

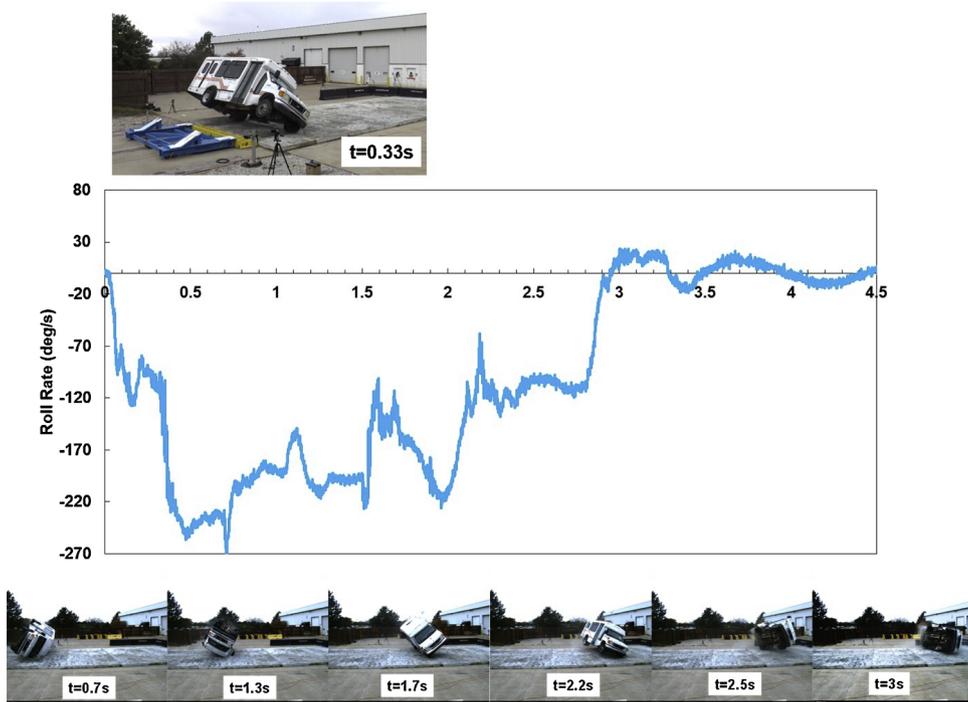


Fig. 3. The roll rate, orientation of the bus at the end of tripping phase, and its overall motion during the test.

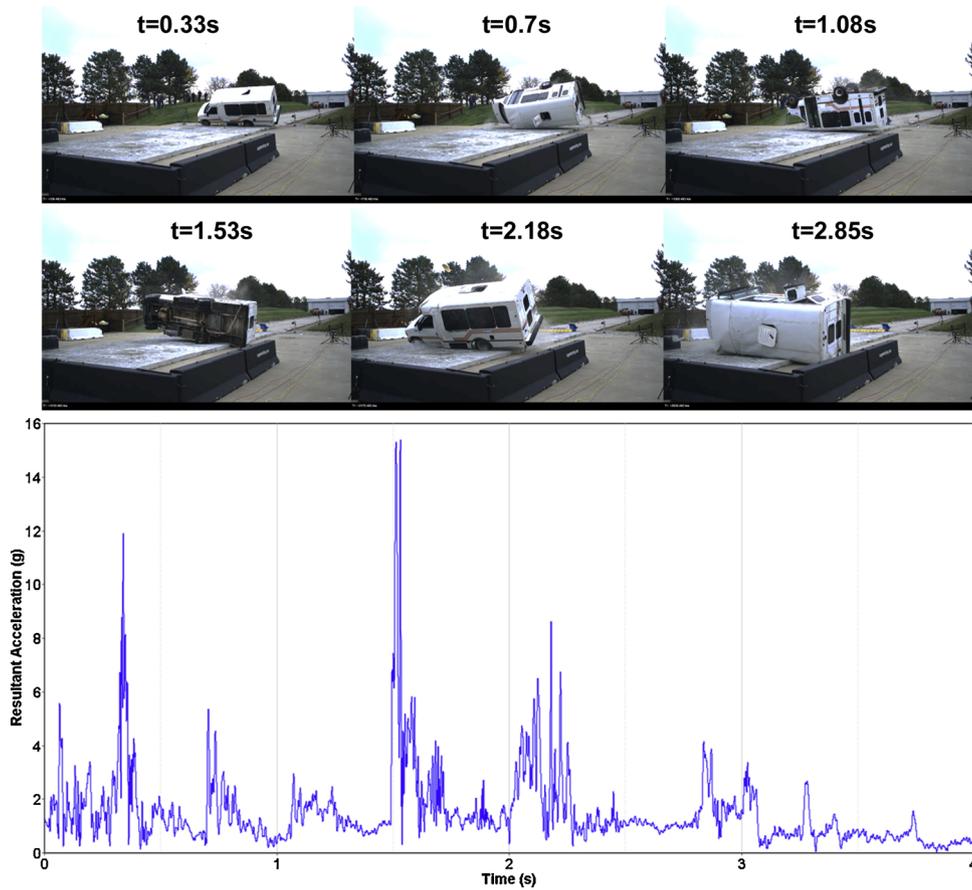


Fig. 4. The resultant acceleration of the bus's CG and its position during different impacts.

Table 2
Summary of the kinematic results of ATDs in the MDR test.

Kinematic parameter	ATD2 (time)	ATD3 (time)
Maximum Head Acceleration (g)		
A _{hx}	30.6 (2.84s)	15.7 (3.08s)
A _{hy}	201.3 (2.84s)	18.4 (3.08s)
A _{hz}	64.8 (2.84s)	25.3 (3.08s)
Maximum Neck Force^a (N)		
+F _x /-F _x	255 (1.64s)/-198 (2.84s)	218 (1.55s)/-127 (1.71s)
+F _y /-F _y	706 (2.06s)/-130 (0.76s)	566 (2.83s)/-177 (1.65s)
+F _z /-F _z	1101 (2.84s)/-2193 (2.84s)	1044 (2.83)/-311 (1.57s)
Maximum Neck Moment^b (N.m)		
+M _x /-M _x	36 (2.85s)/-24 (2.85s)	39.5 (2.84s)/-11.7 (1.61s)
+M _y /-M _y	15.5 (0.79s)/-14.5 (1.66s)	16.4 (1.70s)/-16.8 (1.63s)
+M _z /-M _z	8.5 (2.85s)/-7.5 (2.07s)	8.7 (2.86s)/-4.5 (1.64s)
Maximum Chest Acceleration (g)		
A _{cx}	8.3 (2.83s)	NA
A _{cy}	20.2 (2.83s)	45.7 (2.83s)
A _{cz}	48.8 (2.83s)	8.7 (2.83s)
Maximum Pelvic Acceleration (g)		
A _{px}	8 (1.57s)	13 (1.57s)
A _{py}	16.6 (2.07s)	13.2 (2.84s)
A _{pz}	14.1 (2.84s)	6 (2.84s)

a: + Tension / - Compression.
b: + Extension / -Flexion.

Table 3
Summary of the kinematic results of ATDs in the TT test.

Kinematic parameter	ATD2 (time)	ATD3 (time)
Maximum Head Acceleration (g)		
A _{hx}	6.8 (2.33s)	15.5 (2.52s)
A _{hy}	37.5 (2.33s)	26.4 (2.52s)
A _{hz}	18.4 (2.45s)	6.4 (2.37s)
Maximum Neck Force^a (N)		
+F _x /-F _x	170 (2.35s)/-63 (2.16s)	12 (2.26s)/-319 (2.42s)
+F _y /-F _y	76 (2.29s)/-244 (2.33s)	33 (2.48s)/-170 (2.31s)
+F _z /-F _z	719 (2.45s)/-1119 (2.36s)	194 (2.53s)/-573 (2.54s)
Maximum Neck Moment^b (N.m)		
+M _x /-M _x	12.2 (2.60s)/-27.4 (0.32s)	5.6 (2.51)/-18.7 (2.61s)
+M _y /-M _y	5.8 (2.17s)/-6.2 (2.96s)	11.9 (2.67)/-21.5 (2.41s)
+M _z /-M _z	1.8 (2.61s)/-3.8 (2.55s)	16.2 (2.51)/-6.4 (2.11s)
Maximum Chest Acceleration (g)		
A _{cx}	7 (2.29s)	3.8 (2.49s)
A _{cy}	6.8 (2.29s)	15.7 (2.49s)
A _{cz}	14.5 (2.29s)	5 (2.49s)
Maximum Pelvic Acceleration (g)		
A _{px}	4.5 (2.61s)	4.3 (2.12s)
A _{py}	7.6 (2.65s)	7.5 (2.79s)
A _{pz}	5.9 (2.31s)	4.3 (2.55s)

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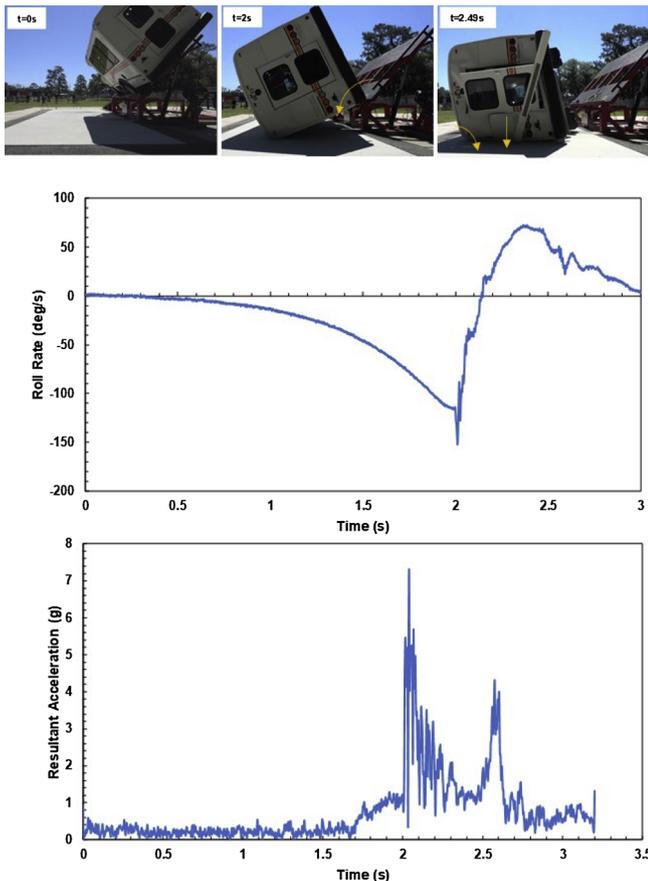


Fig. 5. The overall motion of the bus and resulted roll rate and resultant acceleration during the TT test.

rotated about its left side tires. Due to gravity, the roll rate increased smoothly up to the impact with the ground (t = 2 s). No significant relative movement between ATDs and bus was observed before the first touch. The bus experienced two main impacts. The directions of the impacts are illustrated in Fig. 5. The first impact occurred when the left roof edge hit the ground (t = 2 s) and the second impact occurred when the left side tires separated from the table (t = 2.49 s).

At the first impact (t = 2 s), the upper part of ATD2 struck the side window, while the ATD3 did not move significantly and only its head hit the window frame. Both ATDs experienced the highest values for head acceleration and neck forces and moments during this impact. Table 3 summarizes kinematic responses of ATDs and the time of the occurrence. Since the side windows remained intact during this impact, no partial ejection of ATD was observed. The maximum angular velocity of 155 deg/s and resultant acceleration of 7.3 g were obtained during the first impact (Fig. 5). The bus's CG reached its minimum height above the ground after 0.3 s and the maximum DI value of 0.5 and 0.1 was measured for front-left and rear-left sections respectively. This means that the structural components did not intrude into the residual space. The second impact happened when the bus started to slip on the ground (t = 2.3 s), the elastic properties of passenger compartment caused also backward rotation (from 114° to 84°) and upward movement. As a result, the left side of the bus rotated in the opposite direction and hit the ground (Fig. 5). The rear door was detached from the body and side windows were shattered. The ATD2 was partially ejected, but since most of the crash energy was absorbed in the first impact, no significant peaks for occupant responses were observed during the second impact.

4. Discussion

Kinematic responses of the vehicle and ATDs in each rollover test were quantified in the previous section. Here, the crash outcomes are discussed with emphasis on the energy dissipation and injury risk

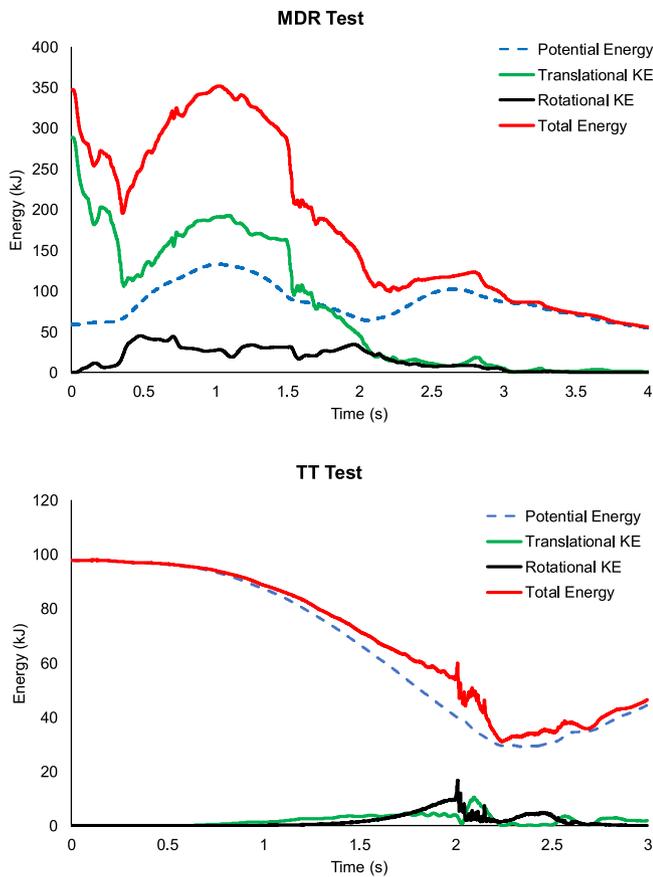


Fig. 6. Energy distribution as a function of time for two rollover tests.

assessment. First, the mechanical energy and its components including translational and rotational kinetic, and potential energies were calculated for each test. It provides some insights into the bus structural performance and its capability to dissipate the kinetic energy. Then, the injury risks were assessed based on the IARVs values and the sources and causes of those injuries were identified based on synchronization of video data and ATD responses.

4.1. Energy analysis

The results of energy analysis can be used to improve either the safety of the vehicle structure (Gürsel and Gürseli, 2010) or countermeasures (Liang and Le, 2010a). The total mechanical energy is a known quantity at the beginning of each test. During the test, the energy dissipated through different mechanisms such as structural deformation (strain energy), sliding (heat due to the friction between vehicle and ground), and ground disturbance. The measured angular velocities were used to calculate the rotational kinetic energy. The global velocity of the vehicle in Y and Z direction was used to calculate the translational kinetic energy. For the potential energy, the ground level was used as a reference. Fig. 6 presents the energy distribution from each rollover test. The total initial energy in MDR and TT test was equal to 347.4 kJ (translational kinetic energy plus potential energy) and 97.7 kJ (only potential energy) respectively.

In the MDR test, the dominant energy component was the linear kinetic energy. During the trip phase (between 0 s and 0.4 s), 42% of the initial energy was dissipated through the tire-to-ground interaction.

During the airborne phase (0.35 s–1.48 s), the bus's CG reached its maximum height above the ground (at $t = 1.08$ s) and it was associated with increasing roll rate. As a result, the total energy went up and reached 350 kJ. Although during the airborne the front cap touched the ground (between $t = 0.7$ s–1.34 s), the energy loss due to the structural deformation or friction was small. During the first major impact at $t = 1.59$ s, the total energy decreased from 350 kJ to 207 kJ. The highest drop in energy occurred during the second major impact (1.7 s–2.2 s) when the front left tire struck the ground and it blew out (from 207 kJ to 101 kJ). During the last major impact between left roof edge and ground (2.8 s to 3 s), the bus reached to its rest position and the kinetic energy dropped to zero. The total energy loss from beginning to rest position in MDR test was equal to 292.5 kJ which mostly dissipated during the tire-to-ground contact (more than 50% of initial energy). Considering a rigid ground, the energy loss due to the ground disturbance was negligible. Therefore, the total energy dissipated by the structural deformation and sliding was approximately equal to 38 kJ. The contribution of the passenger compartment in energy dissipation can be estimated as 40% and 11% of total initial energy during the first and last major touchdowns ($t = 1.53$ s and $t = 2.85$ s) respectively. This amount of energy was absorbed by the deformation of the side wall and roof edge (assuming the small amount of ground plane friction). It should be noted that since the first impact was between the lower portion of the right-side wall and ground, the DI measurements did not reflect the amount of the deformation.

In the TT test, the dominant term of the energy component was potential energy which was calculated from the height of the bus's CG above the ground. Both components of the kinetic energy represented a small portion of the total energy. As the vehicle impacts the ground ($t = 2$ s), a portion of the vehicle kinetic and/or potential energy was converted to elastic or "spring" energy in the bus's structure. Therefore, an increase in the total energy (after 2.2 s) was a result of the converting elastic energy into kinetic and/or potential energy and raising up the bus's CG in the final stage of the test. The total energy loss during the TT test was 51.4 kJ and since there was no tire-to-ground contact and a distortion of the ground, most of the energy was dissipated by structural deformation and sliding friction.

One of the key factors in rollover crashworthiness assessment of the vehicle is to investigate the relationship between the strength of the vehicle's structure and injury risk during the rollover crashes. To do that, several experimental test procedures have been developed to replicate the entire or part of the rollover event. In this study, the ability of MDR and TT rollover tests (which replicates the entire and ground impact phase of rollover event respectively), to address the structural and occupant responses were assessed. A noticeable difference in vehicle dynamics and structural performance were observed between the MDR and TT tests. Compared with the initial energy that produced in the TT test (98 kJ), the MDR test still represented a very high-energy event (347 kJ). In contrast, the deformation of the front and rear section (DI) resulted in the TT test was higher than the corresponded measurements in the MDR test. This can be explained by the smaller portion of crash energy that was dissipated through the impacts between the passenger compartment and ground in the MDR test (38 kJ vs 51 kJ in the TT test). Different orientation and velocity of the vehicle during the major impacts influenced the deformation of the passenger compartment which is also consistent with the research findings of Friedman and Grzebieta (2009). Furthermore, despite using similar tempered glass for side windows in both buses, they behaved differently. Therefore, different initial impact conditions between sidewall and ground (e.g., orientation and velocity of the bus) and different types of ground surfaces (e.g., rough and smooth concrete surfaces) caused different vehicle responses. In the TT test, the side window remained intact after

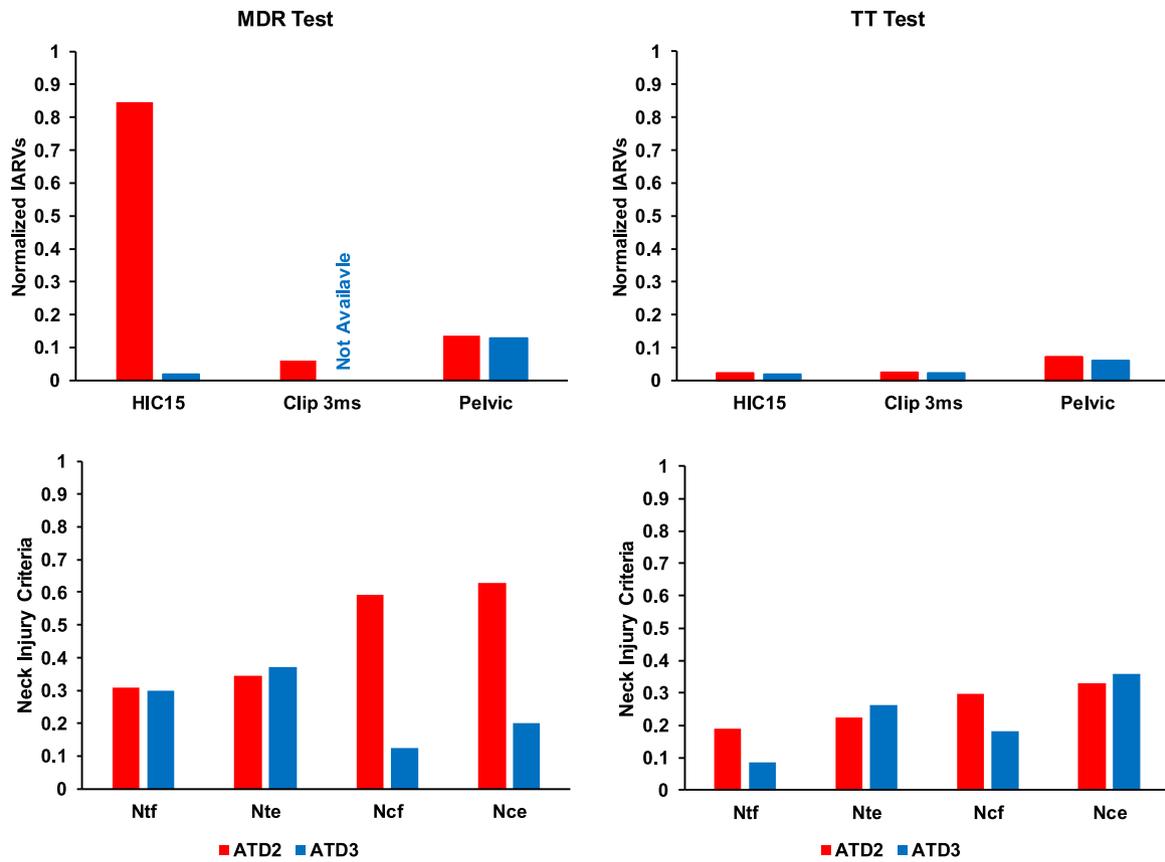


Fig. 7. Summary of injury assessment for ATDs: left column) Modified dolly rollover test; right column) Tilt table test.

the first major impact, while in MDR test, it was shattered right after the last touchdown. Overall, the amount of structural deformation and its pattern (location and crush mechanism) differed for each test.

4.2. Injury assessment

Fig. 7 summarizes the injury measurements of ATDs in both tests. The injury criteria for each part of the body were normalized with the corresponding IARVs. The results of injury risk assessment show that in

both tests, compare to the injury measurements of ATD3, the ATD2 predicted the higher risk of head, neck and chest injuries. As mentioned in Section 2.2, although none of those injury measurements exceeded the IARVs, the results identified the vulnerable body regions that experienced high injury risk during the rollover crashes. Fig. 7 also shows that for all body regions, the level of the injuries in the MDR test was significantly higher than similar injury outcomes in the TT test. The 3 ms clip value of resultant chest acceleration for ATD3 in MDR test was not available because of the sensor malfunction in the X direction. In

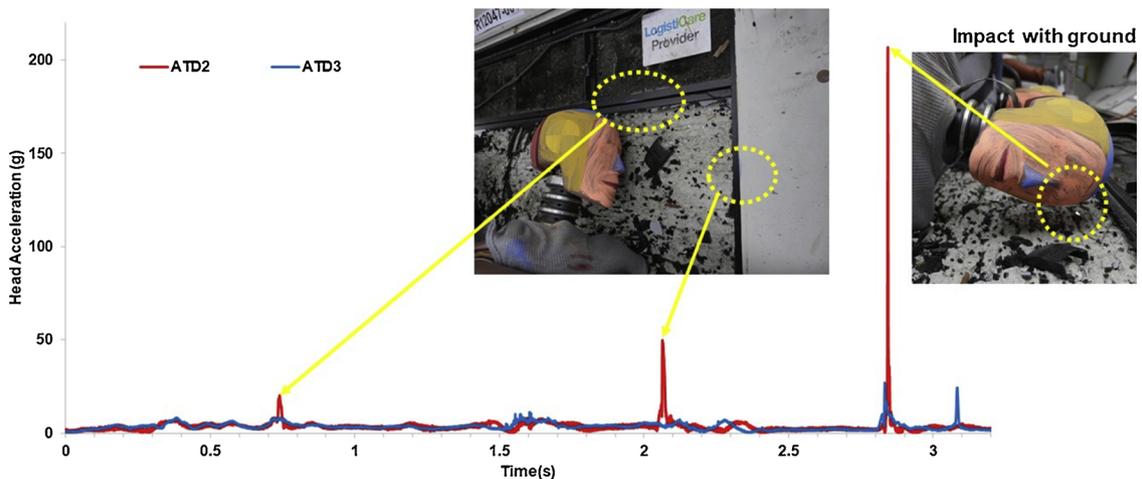


Fig. 8. Impact locations of the ATD2's head and corresponding head resultant acceleration in the MDR test.

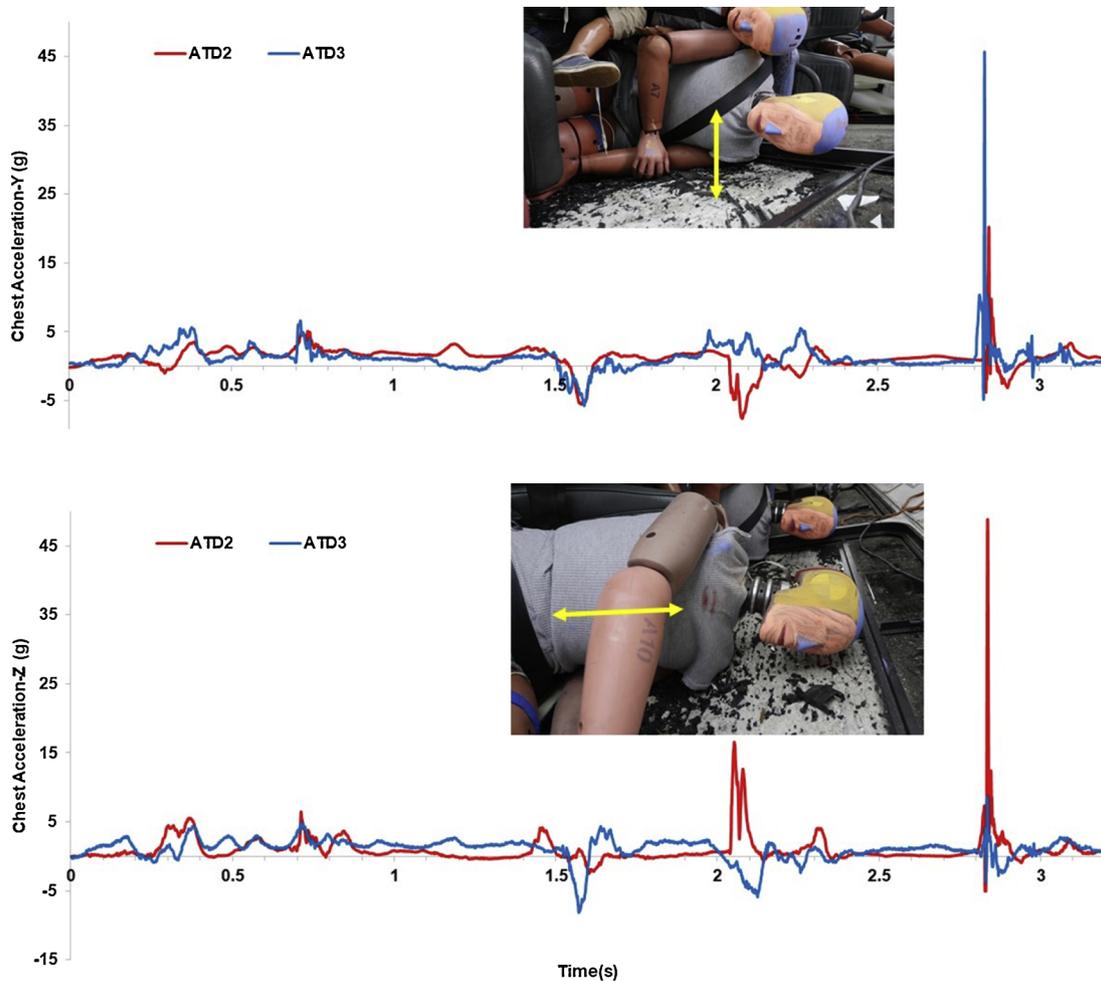


Fig. 9. Chest acceleration resulted in the MDR test and the direction of the chest movement for the ATD3 (top) and ATD2 (bottom).

both tests, the results of neck injury criteria for four load combinations indicated that the ATD2 predicted the higher compressive neck load and the ATD3 predicted the higher extension moment (relevant details can be found in Mertz and Irwin (2015)). Further assessment of the ATD’s motion using synchronized video frames, painted ATD’s head and shoulder are provided in the next paragraphs.

Due to the dynamic nature of the MDR test, the ATD’s motion and its interaction with bus components were different than those in the TT test. During the MDR test, as the bus rolled over, the ATD2’s head experienced multiple impacts with interior parts. The highest peaks in the head acceleration occurred during the last impact when the side windows shattered and the ATDs were partially ejected. The yellow lines in Fig. 8 illustrate the time and location of contact points with corresponded head resultant acceleration. The partial ejection due to the shattered side window and impacts between the head and window frame were identified as the main causes of the those peaks during the MDR test. It should also be noted that although the lap seatbelt kept the ATD2 on the seat and prevented the projection during the rollover, it was not effective to prevent the partial ejection or movement of upper body parts.

Fig. 9 illustrates the direction of the torso movement in each ATD during the last impact of MDR test and corresponding accelerations in

the Y and Z direction (yellow arrows). For the ATD3, the peak value of chest acceleration was recorded in the Y direction which indicated a partial ejection of the torso and direct contact between the shoulder and ground. The peak chest acceleration for the ATD2 was measured in the Z direction which implies the upward movement of the torso towards the roof. Furthermore, erosion and abrasion in the upper extremities of ATD2 were also observed due to the side movement of the roof panel as the bus slid over the ground during the last impact.

During the TT test, the ATD2 leaned against the side window before the first touch, which decreased the range of motion for its torso and head. Fig. 10 shows the position of two ATDs right before and during the first impact. The distance between the ATD3’s head and the side window was larger than those for the ATD2. As a result, the ATD3’s head traveled a long distance and the peak head acceleration occurred 3 ms later than the ATD2. More importantly, the head of ATD2 and ATD3 have made a contact point with window and window frame respectively. The corresponding head injury of $HIC_{15} = 25.2$ and $HIC_{15} = 64$ measured for the ATD2 and ATD3 respectively. Since the ATDs remained inside the bus without being ejected during the first impact, the injury outcomes were significantly lower than those observed in the MDR test. During the second impact that occurred at $t = 2.4$ s, the side window was shattered and only the ATD’s shoulder

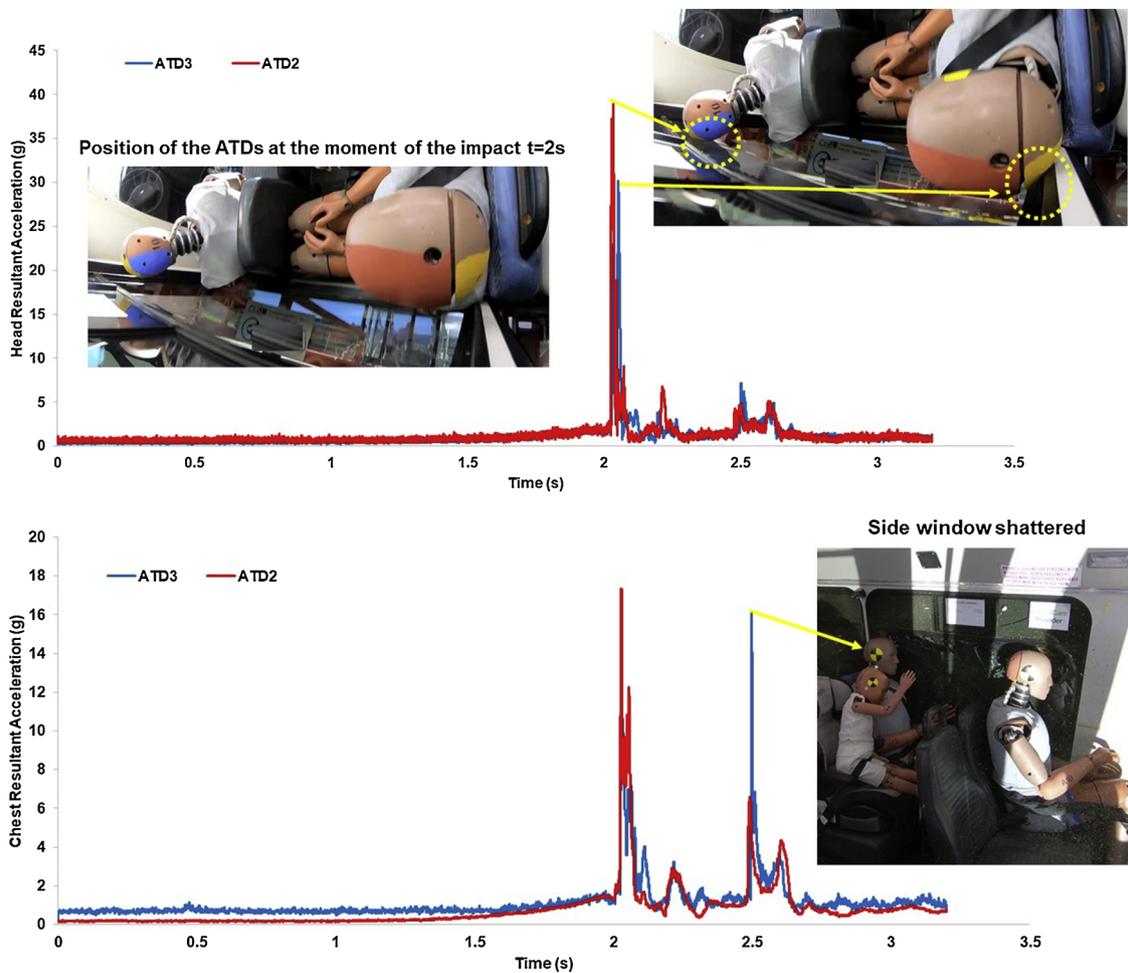


Fig. 10. The ATD's final position and corresponding head and chest resultant accelerations during the TT test.

made a contact with the ground. Fig. 10 shows the corresponding chest acceleration for each ATD and their final position inside the bus.

The results from this study demonstrate that the structural performance of the bus has substantial effects on the occupant's injuries. In both tests, the impact between the side wall and the ground was identified as the most dangerous event sequence that substantially increases the risk of the serious injuries for occupants who seated close to the impacted side wall. This was supported by earlier studies that have been conducted on data from real-world bus rollover crashes (Albertsson et al., 2003; Lapner et al., 2003; Martínez et al., 2003; Albertsson et al., 2006). Additionally, the results of the MDR test indicated that the 3-point seatbelt can reduce the risk of the head injuries by 80%. However, in the TT test, the ATD2 and ATD3 predicted very similar injury outcomes which were below the IARVs. In terms of the injury risk, the results of the TT test do not seem consistent with the findings of the numerical study that was conducted by Belingardi et al. (2005). In their numerical analysis, they predicted the higher injury risk for 2-point and 3-point belted passengers who were seated next to the impacted wall. Whereas, the results of current study showed that for a similar test procedure, the risk of the injury outcomes for ATD2 and ATD3 was very low. The most likely explanation of these differences is that they used the rigid multibody EuroSID 50th male model which were not validated against experimental data. Additionally, they used

only a bay section of the passenger compartment which may cause different kinematic responses for the bus and occupants.

The highest risk of injuries observed for the head, neck, and shoulder in each test. They were consistent with the findings from 128 injured occupants from real-world rollover crashes that have been reported earlier by Albertsson et al. (2006). Although the residual space remained intact during both rollover tests, the risk of the partial ejection was still remained high. Because the residual space was designed to prevent the injuries caused by the structural intrusion, not ejection (also to provide enough space for emergency evacuation). Therefore, the safety of occupants can be significantly improved by considering the interaction of the occupants and passenger compartment (mostly side walls and not the roof) in determining the residual space. Researchers have also recommended using retentive glazing (considered in conflict with the need to use a side window as a potential emergency exit), higher side window panels, an impact absorbing material for the window frame, and side airbags to prevent the ejection risk and reducing the severity of the injuries (Albertsson and Falkmer, 2005). The side curtain airbags provide cushioning between the occupants and side wall components and ground which can reduce the risk of partial ejection.

To date, in most of the studies, a TT test was used to assess the bus's rollover safety. From the vehicle point of view, a TT test can replicate

the impact between side wall and ground seems more effective and available for representing the real-world rollover crashes (Liang and Le, 2010a; Gepner et al., 2014). However, it has yet to be determined whether this test can adequately address the occupant responses during the real-rollover crashes. Presented work showed that different rollover and injury outcomes resulted from each rollover test procedures. The important parameters that have effects on the kinematics of the vehicle and occupant were identified. It also showed that the orientation and position of the bus during the impact can significantly change the vehicle performance and injury outcomes.

Promising data have been provided by this research which allows researchers to develop rollover countermeasures in the safety assessment of the buses or similar vehicle types. Some important insights into the relationship between the structural strength and injury outcomes during the rollover crash have been brought. Furthermore, the results of this study demonstrate the effectiveness of the seatbelt to prevent and reduce the injuries. Future works can study the effects of the occupant body posture, side window characteristics, and impact conditions on severity of injury outcomes during the controlled rollover test.

4.3. Limitations

This study has some limitations that should be mentioned. First, although the Hybrid III is one of the most widely used ATD in rollover studies, the biofidelity of this ATD kinematic responses has not been confirmed in rollover crash tests (Lessley et al., 2014; Zhang et al., 2014). Secondly, it has remained unclear whether the specified locations of transducers to measure the bus deformation are the best representative of the maximum structural deformation of the passenger compartment. For instance, If the maximum deformation occurred somewhere between the front and rear section on roof or side wall, then the DI measurement may not be able to identify that. A more feasible way is to use more transducers along the side wall and between the front and rear sections of the passenger compartment or use new methods such as digital image correlation (DIC) technique which also has its own limitations. Finally, this study was conducted only for two positions inside the bus, whereas to improve the injury prevention systems, it is important to investigate the risk of injuries for other passengers who seated in different locations.

5. Summary and conclusion

The rollover safety of the cutaway bus and its occupants were assessed using the same bus's configurations during the modified dolly rollover (MDR) and tilt table (TT) tests. For each test, the kinematic parameters (linear accelerations and angular velocities) of the bus's CG and the structural deformation of the frontal and rear section of the passenger compartment were measured as vehicle responses. The kinematic responses were transferred to a global frame to calculate the mechanical energies and energy dissipation of the bus structure. The instrumented Hybrid III 50th percent male ATDs were placed next to the impacted side wall in the same seating position. The ATDs were restrained using a 2-point and 3-point seatbelts (ATD2 and ATD3

respectively). The occupant kinematics were then quantified and compared to corresponding IARVs in order to evaluate the risk of injuries. Lastly, the vehicle and occupant motion were analyzed using interior and exterior cameras to investigate the impact mechanism and sources of injuries.

From the vehicle perspective, the residual space remained intact ($DI < 1$) in both tests, but the energy dissipation mechanism and structural deformation were quite different. The results of this study showed that the initial mechanical energy of the bus in the MDR test was significantly higher (347 kJ) than the corresponding values (98 kJ) in the TT test, whereas the energy dissipation by the passenger compartment varied (approximately 38 kJ in the MDR test versus 51 kJ in the TT test). The results of structural deformation showed that the higher deformation occurred for the bus during the TT test. Also, the deformation pattern, direction, and velocity of two buses at the moment of the major impacts differed considerably.

From the occupant perspective, the ATDs predicted the significantly low risk of the injuries in the TT test compare to the results in the MDR test. This can be explained by the different injury mechanism that was identified for each test. The main cause of injuries during the MDR test was a partial ejection and direct contact with the ground due to the shattered side window, whereas for the TT test the impacts between the ATDs and the side window and/or window frame were the causes of injuries. Also, the 2-point belted ATD predicted the highest risk of injuries for its head, neck, and chest in each test. Overall, the tilt table test provides a more severe scenario compared to the MDR test for the assessment of structural strength. Considering the limited real-world injury data in rollover crashes of buses, the MDR test presented the more realistic occupant responses. It is also concluded that injury assessment using the tilt table test will not reflect the majority of injuries that occupant experiences during the real-world rollover crash. To develop effective injury countermeasures further studies are required to fully understand the kinematics of the occupant (using an appropriately biofidelic ATD) and the vehicle performance in the full dynamic rollover procedure.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

The details of the vehicle response are summarized in Table A1. Additionally, the time history curves of acceleration and angular velocities for the bus's CG, resulted in each test, are shown in Fig. A1 and Fig. A2

Table A1
rollover outcomes resulted in each rollover test.

Items	TT test (time)	MDR test (time)
Maximum Global Linear Acceleration (g)		
A _x	-2.1 (2.08s)	-2.3 (2.12s)
A _y	4.3 (2.02s)	-13.2 (1.51s)
A _z	6.6 (2.03s)	-14.2 (1.53s)
Maximum Rotational Velocities (deg/s)		
Roll rate	-152 (2.01s)	-271 (0.71s)
Pitch rate	-36 (2.15s)	-88 (1.53s)
Yaw rate	23 (2.12s)	53 (2.19s)
Maximum DI		
FR	0.4	NA
FL	0,5	0.3
RR	0,3	NA
RL	0,1	NA
Maximum height of CG (m)	2.6 (0s)	2.8 (1.08s)
Number of quarter turns	Less than 1	5.1
Roll distance(m)	1.55	15

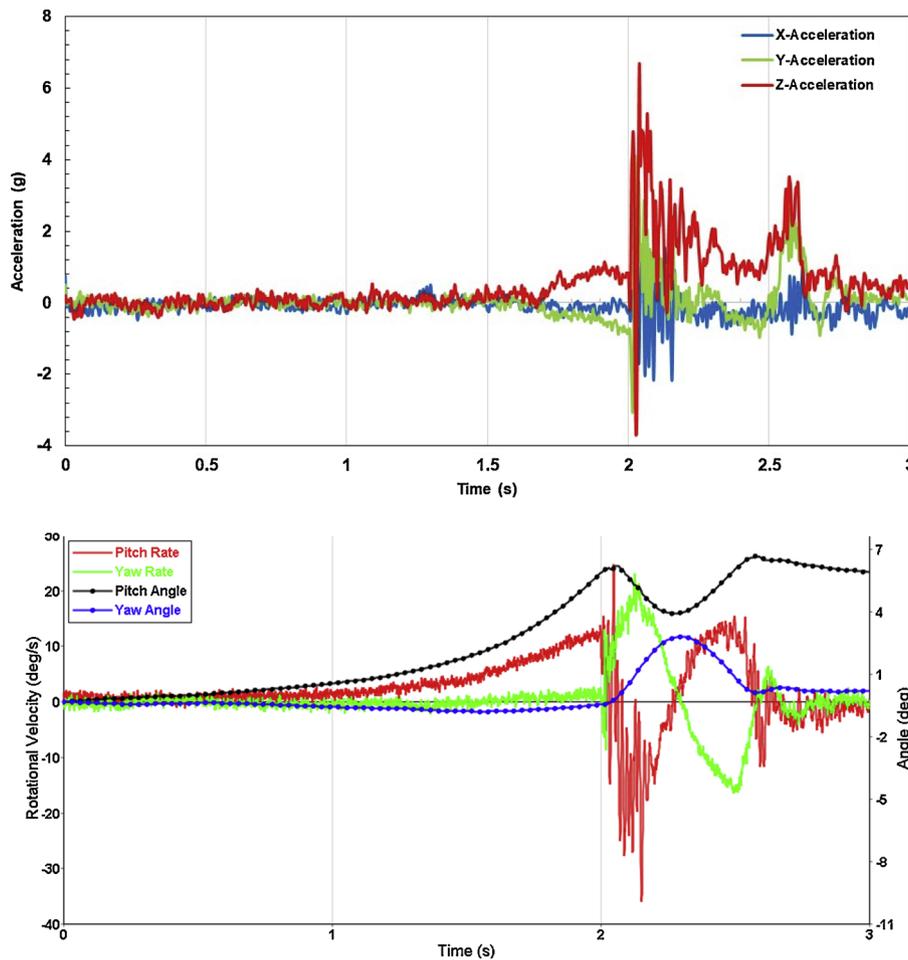


Fig. A1. Three-component accelerations, pitch and yaw rates, and corresponding bus's CG angles during the TT test.

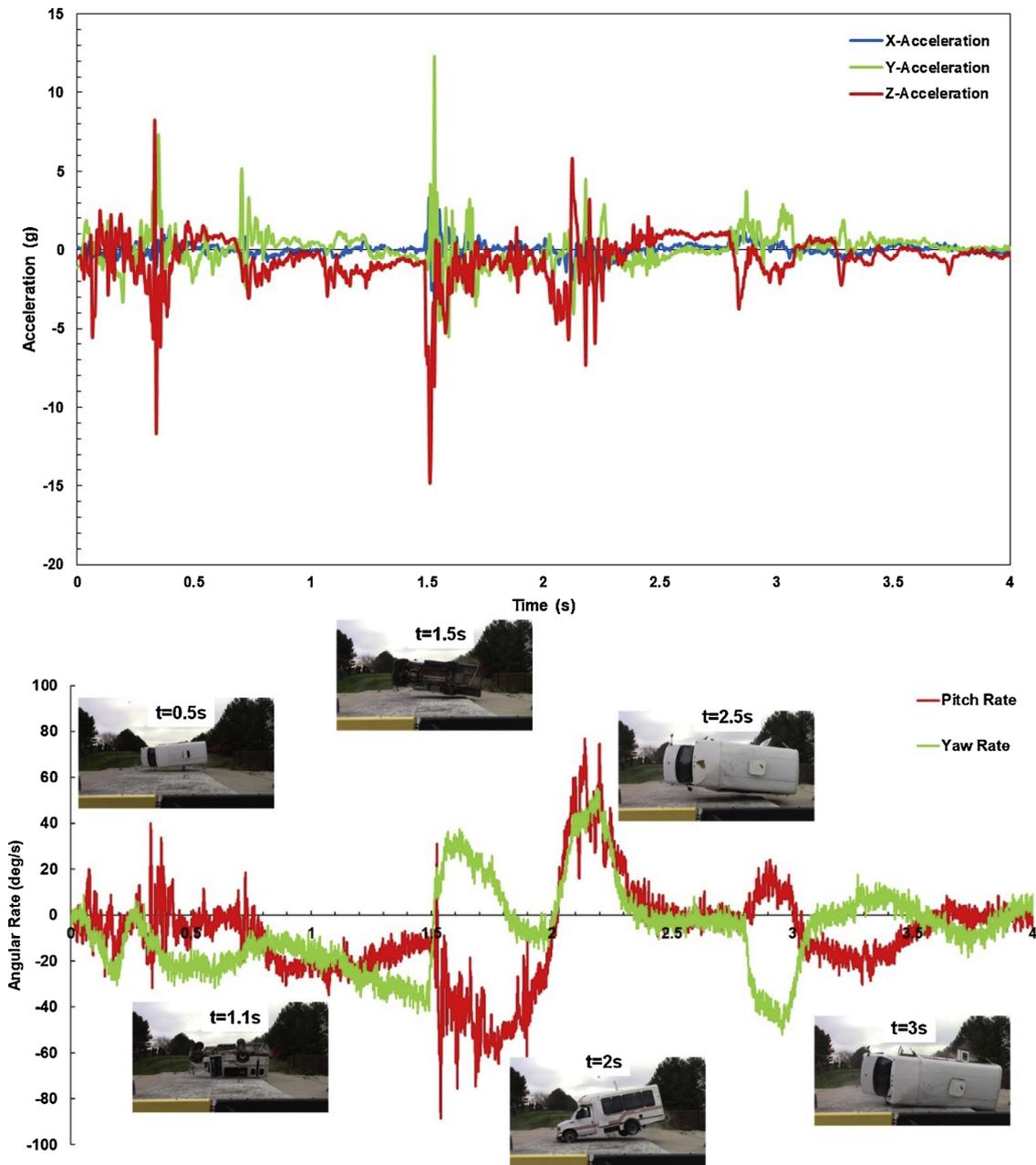


Fig. A2. Three component accelerations, pitch and yaw rates, and corresponding bus's CG angles during the MDR test.

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