ASSESSMENT OF A DYNAMIC TEST DEVICE TO EVALUATE VEHICLE ROLLOVER SAFETY

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ABSTRACT

The objective of the Guided Rollover Propensity (GRP) test device is to subject vehicles and occupants to dynamic rollover accident conditions and to assess the performance of some of the active and the majority of the passive safety systems. The purpose of this study is to determine the characteristics of the rollovers produced by the GRP test device.

This study uses computer models to evaluate the GRP device's performance. The GRP device attempts to subject vehicles to repeatable initial conditions using a guided maneuver of a forward motion followed by a gradually increasing curvature sufficient to roll most vehicles. The decreasing radius of turn causes a gradual increase in lateral acceleration to a point where the vehicle rolls over. This motion is similar to a J-turn induced rollover with the exception of the increase of the turn curvature angle. The test vehicle is carried on a cart with a tripping edge to eliminate the possibility of the vehicle slipping off and to remove the influence of vehicle and road characteristics such as tire properties or road-surface friction during rollover initiation. The cart follows a guided track. The vehicle is subjected to its own roll characteristics that define the dynamics and consequently the roof-to-ground contact.

Finite element (FE) simulation results for different vehicles, subjected to GRP induced motion, show promising dynamic responses and rollover initiation consistency. The passive safety systems, such as roof structure and occupant containment systems (including airbag deployments), and vehicle mechanical systems, such as the vehicle suspension, were assessed under dynamic rollover loading. The dummies were subjected to rollover kinematics similar to a J-Turn and were used to assess injury protection and ejection mitigation during the dynamic rollover test. The study results indicate that the test device is practicable and offers reasonable rollover conditions.

BACKGROUND

Rollover accidents make up only 2.4% of all vehicle crashes, but account for a disproportionate 33% of passenger vehicle occupant fatalities [1]. The Crashworthiness Data System (CDS), a database of the National Automotive Sampling System (NASS), years 1995 through 2005, shows that for belted front seat occupants, 33% of injuries scoring 3 or higher on the maximum abbreviated injury scale, including fatalities (MAIS3+F) occur in single vehicle rollovers without planar impact, while the remaining 67% occur in rollovers with a minor or moderate planar impact [2]. The data shows that the percentage of MAIS3+F injuries by body region with severe damage from planar impacts excluded is 33% to the Head, Face, Neck and Spine, 37% to the Chest and Abdomen, and 30% to the Pelvic, Upper and Lower Extremities [2]. Additionally, rollover data taken from the Crash Injury Research Engineering Network (CIREN) database over 10 years suggests that rollovers need to be disaggregated based on number of crash events in order to understand how to describe the scenario that led to the injury [3]. Thoracic injury, not just head and neck injury, and cervical spine injury mechanisms need to be considered in order to understand the injury causation during multiple event rollover crashes [3]. More recent data from years 2000 to 2009 of NASS-CDS for belted occupants in pure rollover crash accidents reveals serious injuries by Abbreviated Injury Scale (AIS) body region as follows: 36% to the spine, 23% to the thorax, 20% to the head, and the remaining to the upper and lower extremities, abdomen, face, and neck [4].

This injury list highlights that the roof crush is not solely responsible for all the injury mechanisms in a rollover; therefore a traditional dynamic rollover test device might not solve this complicated phenomena. Protection in a rollover should be a priority even if rollover is not the most frequent crash type since rollover injuries are so diverse and occupant

protection would benefit in other crash modes that are not included in the common planar tests (front, offset, oblique, and side impacts).

Existing Dynamic Rollover Test Devices

The National Highway Traffice Safety Administration (NHTSA) considers the development of a dynamic rollover test to be a priority [5]. Recent research has focused on understanding rollover accidents and their resulting occupant injuries. To date no dynamic rollover test method has been adopted to evaluate rollover safety and rollover occupant protection either in government safety standards or in consumer ratings. However, several dynamic rollover test devices have been used to address this topic. The most popular dynamic tests that have been widely used are: Federal Motor Vehicle Safety Standard (FMVSS) No. 208 Dolly Rollover test, Decelerated Rollover Sled (DRS) test, NHTSA Fishhook test, Corkscrew test, Inverted Vehicle Drop test, Controlled Rollover Impact System (CRIS) test, and Jordan Rollover System (JRS) test. Selected dynamic test systems are briefly mentioned herein with their operational details along with NHTSA observations on each one.

The FMVSS No. 208 dolly rollover test rolls a vehicle laterally off a moving inclined platform at 23 degrees. This test has been used extensively by the automotive industry. NHTSA mentioned that this test was originally developed only as an occupant containment test and not to evaluate the loads on specified vehicle roof components [5]. Additionally, after conducting many tests, NHTSA determined that the test conditions were so severe that it was difficult to identify which vehicles had better performing roofs [5]. The Decelerated Rollover Sled (DRS) test is another variation of the FMVSS No. 208 where the vehicle is placed horizontally on a cart, which decelerates it laterally to a specific pulse. The DRS can generate repeatable test conditions but the responses are highly sensitive to variations in the test conditions [6].

Other dynamic rollover systems closely examine the roof-to-ground event. The Controlled Rollover Impact System (CRIS) suspends a vehicle and rotates it laterally from the back of a semi-trailer equipped with a hanging fixture travelling at a fixed speed. CRIS was developed to produce repeatable vehicle and occupant kinematics for the initial vehicle-to-ground contact. Additional evaluation to the test procedure and further assessment of the repeatability following the initial contact are needed [5].

Other promising dynamic rollover test devices are being evaluated in the United States [7, 8] and Australia [9] based on the Jordan Rollover System (JRS) concept. The JRS mounts a vehicle on an axis that permits it to roll as it is dropped. The constraints with this mounting are in the longitudinal and lateral directions. As the vehicle is rotated, a roadway segment runs underneath so that the vehicle's roof strikes the road as it would in an actual rollover. After both sides of the roof have struck the roadway, the vehicle is caught so that it will sustain no further damage. The JRS is a versatile and repeatable rollover test system developed to evaluate the performance of roof structure and occupant restraint system during rollover. The CRIS and JRS test devices primarily control the roof crush in a dynamic way.

NHTSA believes that there is a large number of unresolved technical issues related to the JRS as performed by the Center for Injury Research. These issues are with respect to whether it would be suitable as a potential test procedure to replicate real-world crash damage patterns for a safety standard evaluating vehicle roof crush structural integrity. These issues include lack of real-world data to feed into the test parameters and dummies biofidelity [5].

NHTSA has initiated research toward achieving a dynamic test standard that provides a sufficiently repeatable test environment [5, 8]. NHTSA's principal research contractor for developing a dynamic rollover test is the University of Virginia. A Dynamic Rollover Test Device (DRoTS) as described by Kerrigan [10] has been installed and is now being operated by NHTSA's research contractor. This rollover test device employs concepts that were patented in the Jordan Rollover System (JRS) [11]. Additionally, the Australian government is funding the Dynamic Rollover Occupant Protection (DROP) project that uses an updated version of the initial JRS test device [9]. These two test devices are being evaluated. Some of the current research is focused on identifying the test parameters: initial roll rate, roll angle, drop height, road surface speed, and a test dummy to replicate some real world injuries.

NHTSA has also performed dynamic rollover tests based on selected maneuvers. NHTSA experimentally examined on-road untripped light vehicle rollovers [12]. These were vehicle characterization maneuvers (Pulse Steer, Sinusoidal Sweep, Slowly Increasing Steer, and Slowly Increasing Speed) and rollover propensity maneuvers (J-Turn, J-Turn with Pulse Braking, Fishhook # 1 and

2, and Resonant Steer). The repeatability of the steering controller handwheel inputs were found to be good for all maneuvers studied. Other measurements were also analyzed in this study [12].

Need for a New Rollover Test Device

Recognizing the shortcomings of the existing methods of testing occupant protection in a realistic dynamic rollover situation, this study combines the concepts addressed above and proposes a Guided Rollover Propensity (GRP) test device. The GRP test device enables a test vehicle to behave in a fashion similar to a real-life rollover, exposing the (dummy) occupant to realistic kinematics, loading the roof structure dynamically, and assessing the full- and partial-ejection and injuries of the occupants.

The GRP device consists of a railed track that is maneuvered similar to a specific forward J-turn with a carrying cart. The carrying cart has a tripping edge that eliminates the possibility of the vehicle slipping off prematurely. The GRP device removes the influence of any contaminating factors in the rollover, like vehicle and road characteristics such as tire properties or road-surface friction. As a result, the test will involve only rollover specific properties of the vehicles – for example, center of gravity, inertias, and suspension design – while subjecting all vehicles to similar rollover initial conditions. Therefore, the GRP device assesses the following parameters: vehicle rollover propensity, dynamic roof structure loading, occupant safety restraint systems, ejection epidemic, and dummy injuries.

METHOD

Vehicle Dynamic Analysis (VDA) software was used to evaluate variations in rollover initiation among different vehicles. Different vehicles follow different tracks and roll at different times and locations. The vehicle's suspension and inertia characteristics affect rollover initiation. The GRP test device was based on vehicle dynamic analysis and assessments. Then, a finite element (FE) model of the GRP test device was created, followed by a sensitivity study and an evaluation of three vehicle FE models.

The test development concept is addressed in this section. A dynamic vehicle handling simulation was performed using VDA software, the Human Vehicle Environment (HVE) by Engineering Dynamics Corporation. Several passenger vehicles were randomly selected and were subjected to the same speed and steering inputs (a linear acceleration followed by an increasing turn radius with respect to time). The results showed that each vehicle traced a different curvature. The findings are not surprising since each vehicle has a unique weight, center of gravity (CG), inertia, tire characteristics, steering-rack ratio, suspension geometry, and design that influence the vehicle dynamics motion. HVE is capable of showing the tires' traces on the ground surface. The different traces' curvatures are shown in Figure 1. The vehicles with low CG heights, small wheel bases, and well designed suspensions had small curvatures while the vehicles with higher CG heights and longer wheel bases had larger curvatures.

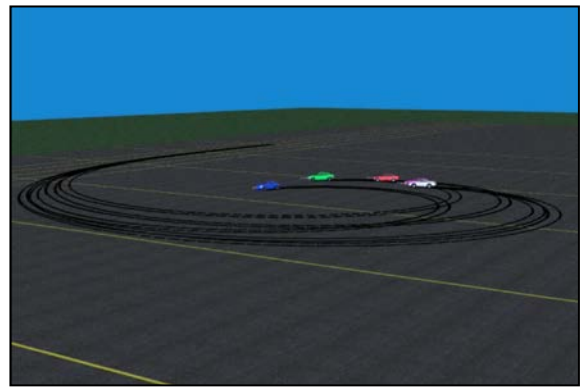


Figure1. Multiple vehicles with different characteristics do not follow similar curvatures when subjected to motion similar to a J-turn maneuver.

The vehicle motion is similar to a J-Turn and the different traces shown in Figure 1 were expected. Two comparable vehicles were needed in order to achieve a similar path. The two vehicles selected from the HVE database were the Audi TT and the Mercedes-Benz C230. The TT and C230 models have similar weights, 1321.3 kg (2913 lbs) and 1416.6 kg (3123 lbs), and CG heights, 562 mm (22.16 in) and 572 mm (22.54 in), respectively. The same speed and steering input maneuver were performed and the tires' traces were tracked. Figure 2 shows the trace curvatures for each vehicle. Both curvatures are similar. It is observed that the C230 rolled sooner than the TT. The vehicle characteristics played a crucial part in determining when each vehicle rolled from the similar paths.

Therefore, if different vehicles were positioned on a carrying cart with an imposed track path, then the vehicles are subjected to the same input and the vehicles' abilities to resist rolling (i.e. leaving the track) and to protect the occupants can be tested. The GRP test device concept is shown in Figure 3. The

carrying cart subjects each vehicle to the same initial conditions. The track path has a gradually increasing curvature that is sufficient to roll most vehicles.

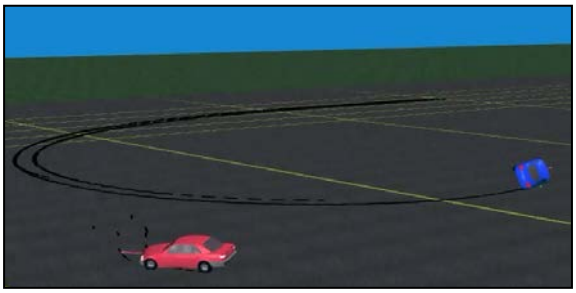


Figure2. Audi TT and Mercedes-Benz C230 have similar weight and CG height, follow similar curvature, but one rolls before the other.

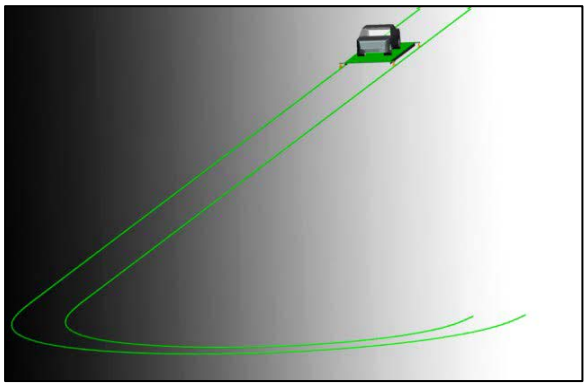


Figure3. GRP test device concept: track and cart design.

DISCUSSION

In order to evaluate the concept, FE analysis was performed. The commercial LS-DYNA software by Livermore Software Technology Corporation (LSTC) was used. The GRP test device concept was modeled initially with a simplified generic vehicle. Then three full scale FE models were analyzed. Finally, a Hybrid III dummy was incorporated in one of the full scale models.

Concept Simulation

The track curvature was taken from the HVE output based on similar vehicle characteristic simulation traces. The track is made of 3 sections. The first is a straight section, which allows the cart and the vehicle to accelerate and reach the designed test speed as the dummies remain seated in a natural position. The second section is a gradually increasing curvature. The third is a straight section sufficient to allow cart braking after the vehicle rolls off it.

The cart is a simple platform, big enough to carry common passenger vehicles and Sport Utility Vehicles (SUV). The cart wheels follow the track curvature. The cart has a tripping edge, which has two benefits. First, it prevents the vehicle from falling off the cart during the acceleration phase of the test. Second, it prevents the vehicle from skidding off the cart while turning begins, reducing contaminating motions prior to the rollover of the vehicle, and improving the test device repeatability.

The simplified vehicle shown is based on a generic vehicle shape and property. The baseline model weighs 2392 kg (5273 lbs) and has a 2900 mm (114 in) wheel base, a 1550 mm (61 in) track width, and a 623 mm (24.5 in) CG height. The tires are made of elastic material and were rigidly connected to the vehicle body in order to eliminate suspension effects on the roll initiation. Figure 4 shows the FE assembly of the simplified vehicle, cart and the straight section of track. Figure 5 shows the FE assembly of the cart on the track alone. The cart assembly can be designed and installed at ground level to simulate a vehicle losing control on a horizontal plane or above ground level to simulate a vehicle losing control and rolling over in a ditch. The GRP test device parameters (the decreasing radius of curvature, cart height, and other specifications) will be addressed in future work to correlate to real-world crashes [13].

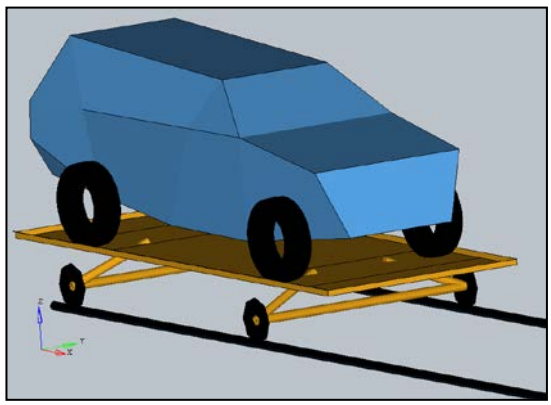


Figure4. GRP test device with a simplified vehicle.

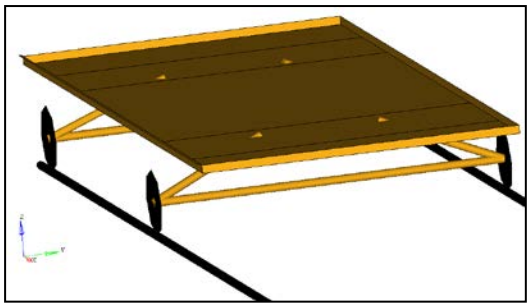


Figure5. GRP cart with the wheels following the straight section of the track.

The cart is 203.4 mm (8 in) above the ground. The cart and vehicle were given an initial velocity of 20.1 m/s (45 mph, 72.42 km/h). The system starts to accelerate along the straight section of the rails until the initial speed is reached (only constant speed is simulated in FE). Thereafter, the system starts to travel on the curved rail section. The system longitudinal velocity starts to decrease while the lateral velocity starts to increase. Since the cart is only allowed to follow the prescribed track rails, the cart does not experience any vertical separation from the rails and its initial total speed is maintained throughout its motion. Since the vehicle is not attached to the cart, it starts to experience different kinematics. Additional to the longitudinal and lateral velocity changes, the vehicle starts to have an angular velocity component that eventually allows it to roll over the tripping edge of the cart. The vehicle and cart motions at different positions and times are shown in Figure 6. The simplified vehicle model starts to gain some lift off the cart starting at 1.5 seconds. At around 2 seconds, the vehicle completely separates from the cart and is in a free rollover motion.

Sensitivity Simulation

In order to illustrate the GRP test device sensitivity, the vehicle CG characteristics were changed from the simplified vehicle model used in the concept simulation. The CG height variations should affect the position on the curved section of the track at which the vehicle departs the cart. This location of departure is indicative of the vehicle's rollover propensity as it would be expected in real life. Two variations of CG heights were addressed by computer simulations. The first variation has a 152.3 mm (6 in) CG height lower than the original height position. The second variation has a 152.4 mm (6 in) CG height higher than the original height position.

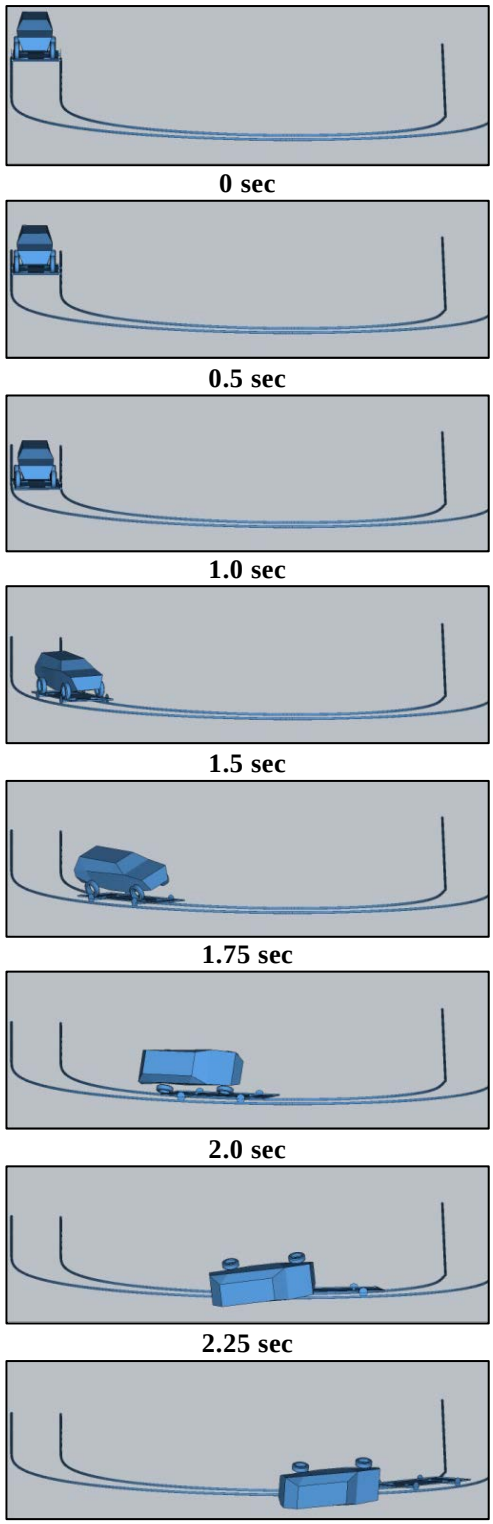


Figure6. Simplified vehicle motion subjected to the GRP test device conditions up to 2.5 sec (note the additional pictures at the critical time between 1.5 seconds and 2.5 seconds).

The three models were given the same initial conditions as prescribed in the previous section. The models are overlaid and shown in red, blue, and green for the higher, the original, and the lower CG height positions respectively, as shown in Figures 7 and 8.

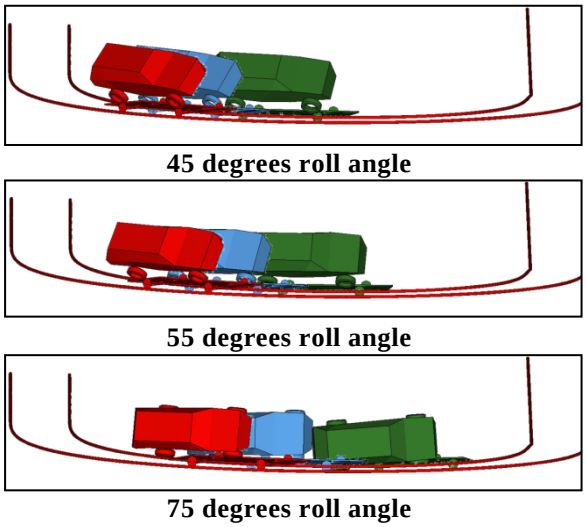


Figure7. Selected simplified vehicle positions overlay horizontal view at vehicle roll angles of 45º, 55º, and 75º.

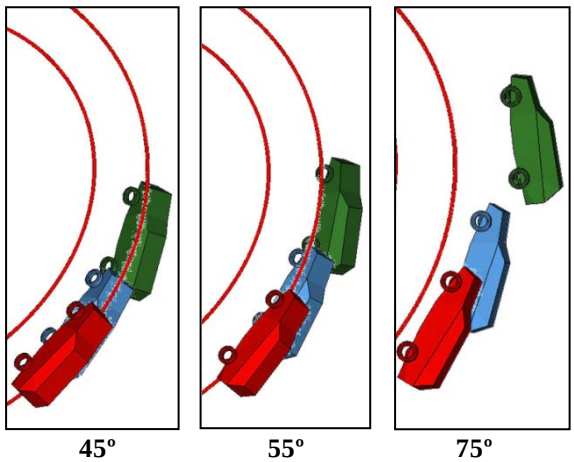


Figure8. Selected simplified vehicle positions overlay top view at vehicle roll angles of 45º, 55º and 75º.

These figures show the models leaving the cart at the curvature section of the track with horizontal and top views. Three different roll angles are shown in order to distinguish the important vehicle positions. The first roll angle is 45º in, which shows the pre-roll position. The second roll angle is 55º, which shows that the CG position of the original model is vertically above the near side tripping point. The third roll angle is 75º, which shows the models rolling over. The results shown in Figures 7 and 8 are based on roll angles rather than time since the 3 different vehicles have different CG heights and the roll angle is a good rollover prediction.

The different CG height models clearly show a distinction when each model leaves the cart. The longer the vehicle model stays on the cart, the better the stability performance is for the vehicle.

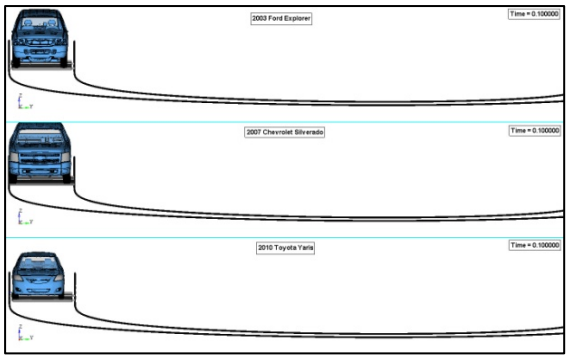
Full-Scale Simulation

The same test setup was used to perform the rollover analysis using full-scale FE vehicle models. Three models were selected: a 2003 Ford Explorer, a 2007 Chevrolet Silverado, and a 2010 Toyota Yaris. These models were developed for the Federal Highway Administration (FHWA) and the National Highway Traffic Safety Administration (NHTSA) by the National Crash Analysis Center (NCAC), the George Washington University. The models are available publicly on the NCAC website [14].

Since these models were validated to multiple planar crashes with rigid barriers, deformable barriers, movable deformable barriers, and roadside hardware barriers, the vehicle behaviors were assumed adequate for the GRP test conditions.

The three models are compared at the same time in Figure 9. The top section of each figure shows the Explorer model, the middle section shows the Silverado model and the lower section shows the Yaris model. Different timing was considered in Figure 9 in order to highlight the far side lift off from the cart, the vehicles completely leaving the cart, and several roof contact conditions.

An interesting observation is seen in Figure 9 at 1.3 seconds. The three different vehicles have their own rollover characteristics that initiated the roll and that affected each model contact with the ground. The Explorer model contacts the ground at a low positive pitch angle while the other two models contact the ground at negative pitch angles. This observation is seen in some NASS-CDS cases in pure rollovers where vehicles have extended rear roof damage [15].



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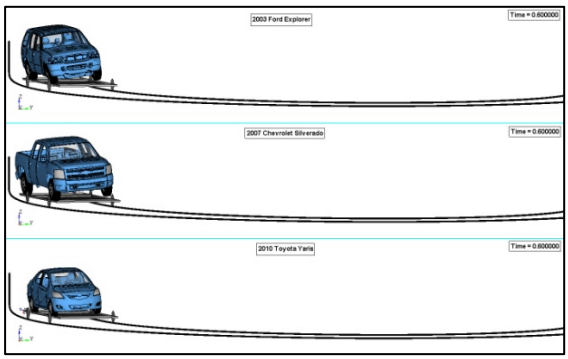

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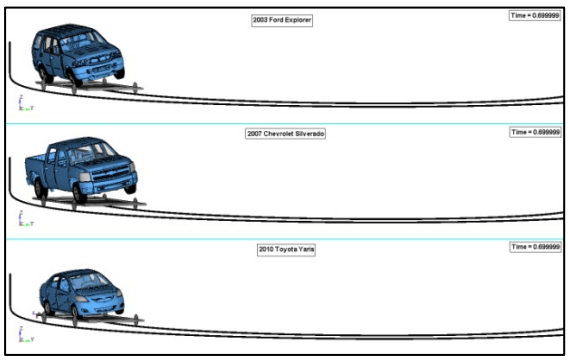

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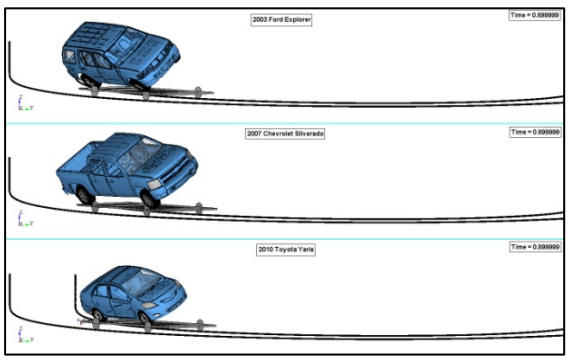
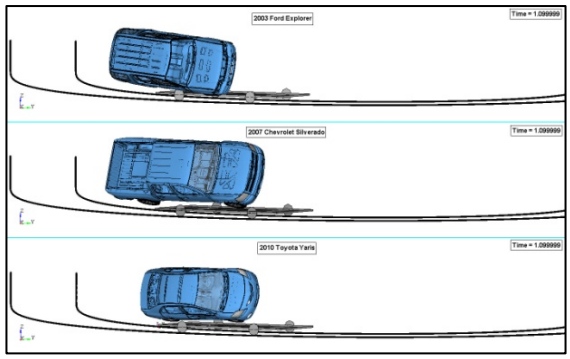


0.90 sec

Figure9. Selected GRP simulations of a 2003 Ford Explorer, 2007 Chevrolet Silverado, and 2010 Toyota Yaris between 0.1 -0.9 sec.



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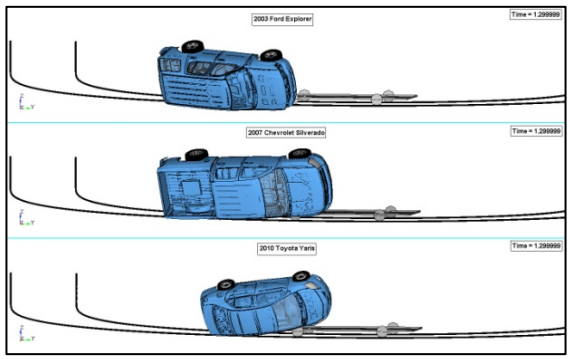

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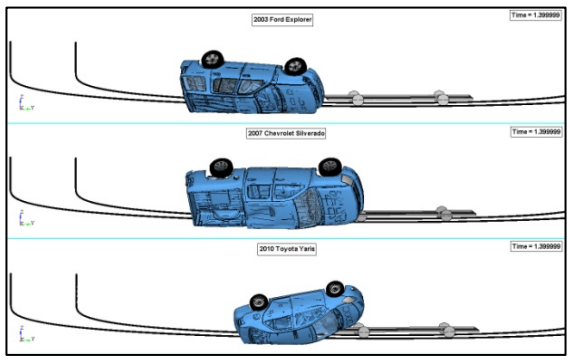
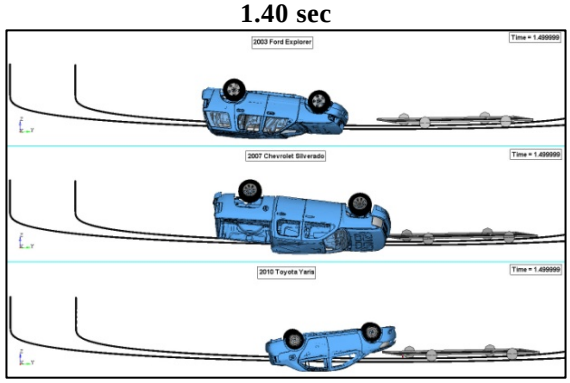
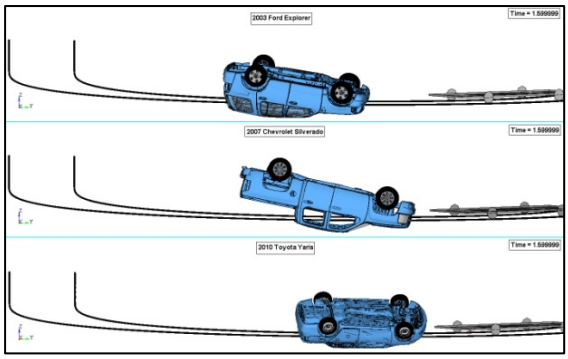


1.40 sec



1.50 sec

Figure9. Selected GRP simulations of a 2003 Ford Explorer, 2007 Chevrolet Silverado, and 2010 Toyota Yaris between 1.1 -1.5 sec. (Cont.).



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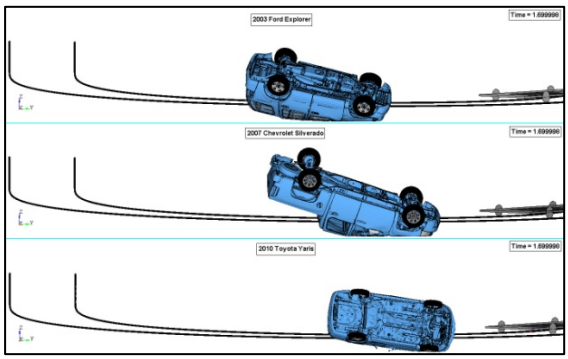


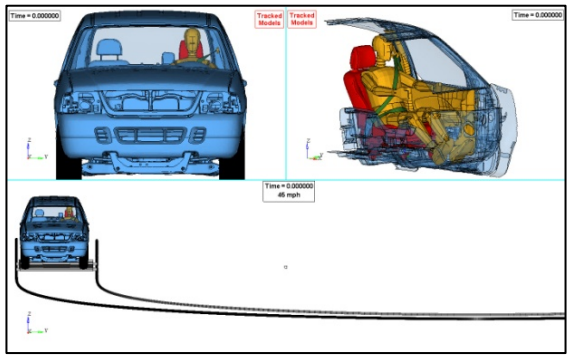
1.70 sec

Figure9. Selected GRP simulations of a 2003 Ford Explorer, 2007 Chevrolet Silverado, and 2010 Toyota Yaris between 1.6 - 1.7 sec. (Cont.).

Dummy Simulation

The Explorer model was selected to simulate a rollover with a Hybrid III Anthropomorphic Test Device (ATD) dummy, since the SUV has been validated to two different roof crush tests (NHTSA C0139 and C0140) and has been extensively used in full-scale rollover simulations [16, 17]. The simplified Hybrid III model from LSTC was used since it is numerically stable for extended computational time and it was considered adequate to provide a first look at the overall dummy kinematics under the GRP test conditions.

The Hybrid III GRP simulation is shown in Figure 10. The images show the progressive motion of the vehicle and dummy at different intervals of the simulation. Three images appear in the selected time steps. The upper left image shows the dummy in the vehicle, in the vehicle coordinate system. The upper right image shows the dummy (at an angle view) with partial vehicle components, in the vehicle coordinate system. The lower image shows the vehicle and dummy in the earth based inertial coordinate system.



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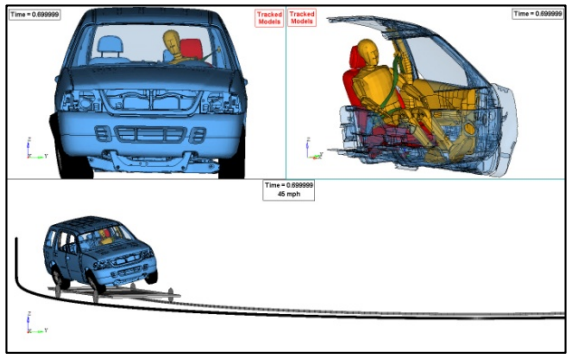

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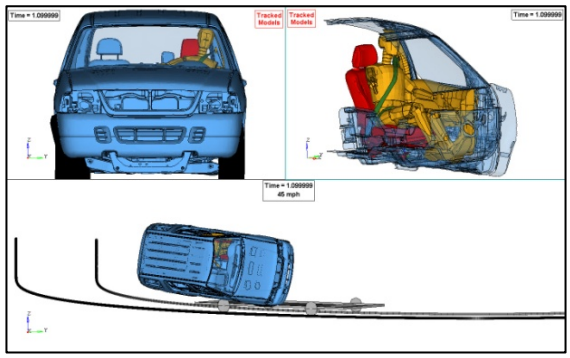

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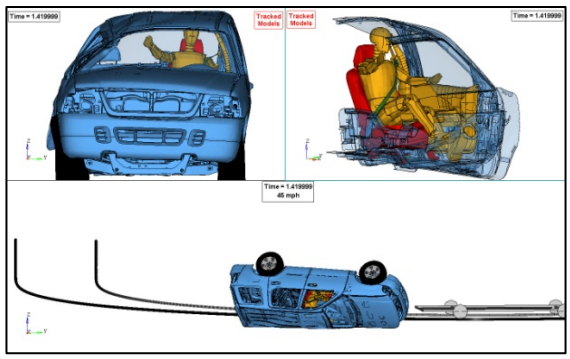
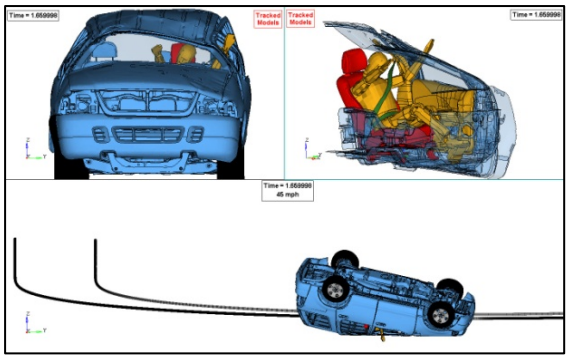


1.42 sec

Figure10. GRP simulation of a 2003 Ford Explorer with a Hybrid III Dummy between 0.0 - 1.42 sec.



1.66 sec

Figure10. GRP simulation of a 2003 Ford Explorer with a Hybrid III Dummy at 1.66 sec. (cont.).

The dummy at 0.7 seconds, as shown in Figure 10, moves inboard inside the vehicle when the far side of the vehicle starts to lift off the cart. At 1.1 seconds, the dummy moves upward off the seat and outboard into the B-pillar. When the vehicle contacts the ground at its near side at 1.42 seconds, the dummy is at its highest position with respect to the driver seat. When the vehicle continues its roll and contacts the ground at its far side at 1.66 seconds, the dummy slams into the back of the seat. The dummy motion and impacts with the vehicle interiors correspond to real rollover accidents. This simulation demonstrates multiple injury potentials during rollovers.

Potential Rating System

The GRP test device can be used to produce a rollover rating score for vehicles similar to the Static Stability Factor (SSF) that is currently used by the New Car Assessment Program (NCAP) rollover star rating and the roof crush rating by the Insurance Institute for Highway Safety (IIHS). The GRP can produce a similar rating to the SSF. Figure 11 suggests that a vehicle should be rated based on the position that it leaves the track.

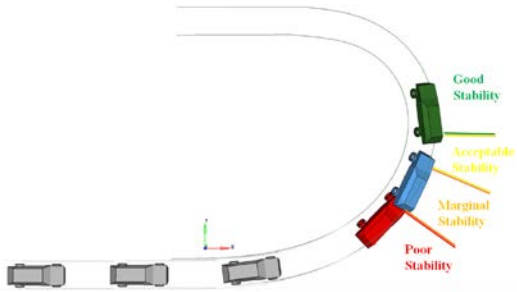


Figure11. GRP test device rating proposal.

A rating system similar to the rating system used by the IIHS is recommended. Poor, Marginal, Acceptable, and Good stabilities are proposed based on when the vehicle leaves the cart and track system. In order to distinguish between SUV and passenger cars, two GRP rating systems should be created since the vehicles belong to different categories. Additionally, dummy injuries and ejection mitigation can also be assessed dynamically and rated. Finally, a comprehensive rollover rating can be based on all the ratings listed above in order to create an easy vehicle comparison score rating. Such a rating system should be thoroughly assessed in future work.

CONCLUSIONS

The Guided Rollover Propensity (GRP) test device subjects the vehicle to a forward motion followed by a gradually increasing curvature on a guided track that is sufficient to roll most vehicles. The forward motion is similar to pre-roll conditions in real world rollovers. The vehicle is positioned on a cart that follows the track and the vehicle is free to roll based on its roll inertial and other design properties. Computer simulations show that the initial conditions for rollover from the test cart are repeatable and the GRP test device is designed to eliminate conditions that would bias the rollover outcome.

Finite element methods used in this paper simulate the test device and the results show repeatable tests and promising rollover behavior of both vehicles and occupant kinematics.

Since pure rollover injuries are divided into three main categories (injury to the head and neck, to the spine, and to the thorax), rollover assessment should not only be based on roof strength (static or dynamic). Dynamic rollover assessment should be a comprehensive approach of the restraint system with the vehicle interiors during a realistic one full roll scenario additional to the dynamic roof crush. The proposed rating is an evaluation of multiple rollover characteristics in order to give a score to each vehicle.

The main limitation of the GRP test device is assessing the performance of the Electronic Stability Control (ESC). ESC is a notable rollover risk-reducer that can only be evaluated by driving maneuvers. Nevertheless, the GRP device may encourage manufacturers to produce better handling vehicles regardless of ESC.

The GRP test device has the advantage over several dynamic rollover test devices. It is a research tool that assesses the vehicle roof structure and occupant injuries at the same time in a dynamic rollover scenario. The GRP device can be used to evaluate all passive safety systems. An overall rating system is suggested.

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