

Subsystem Rollover Tests for the Evaluation of ATD Kinematics and Restraints

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ABSTRACT

The development of a repeatable dynamic rollover test methodology with meaningful occupant protection performance objectives has been a longstanding and unmet challenge. Numerous studies have identified the random and chaotic nature of rollover crashes, and the difficulty associated with simulating these events in a laboratory setting. Previous work addressed vehicle level testing attempting to simulate an entire rollover event but it was determined that this test methodology could not be used for development of occupant protection restraint performance objectives due to the unpredictable behavior of the vehicle during the entire rollover event. More recent efforts have focused on subsystem tests that simulate distinct phases of a rollover event, up to and including the first roof-to-ground impact. This paper explores two subsystem rollover test methods up to the first roof-to-ground impact, and highlights the importance of simulating the lateral vehicle acceleration that occurs during the pre-trip/trip phase of a rollover event in order to provide more realistic trailing-side Anthropomorphic Test Device (ATD) kinematics and enable more meaningful restraint evaluations.

INTRODUCTION

In 2007 there were over 6 million police reported crashes in the United States. Only 2.4 percent of those crashes involved vehicle rollovers, however, this crash type represented 11.2 percent of the fatalities that occurred [1]. This data is consistent with previous field data which indicates that while rollover crashes are an infrequent collision type, they can be severe events with a considerable potential for harm.

As acknowledged by the National Highway Traffic Safety Administration (NHTSA) in their final rulemaking on Federal Motor Vehicle Safety Standard (FMVSS) 216a:

Rollover crashes are complex and chaotic events. Rollovers can range from a single quarter turn to eight or more quarter turns, with the duration of the rollover crash lasting from one to several seconds. The wide range of rollover conditions occurs because these crashes largely occur off road where the vehicle motion is highly influenced by roadside conditions. Also, rollover crashes tend to occur at higher speeds than other crash types due to the energy required to initiate the rollover motion. [2]

Fundamental to the development of occupant protection safety systems for rollover crashes is the ability to recreate a controlled and repeatable rollover event in the laboratory. Due to the random and chaotic nature of rollover crashes this has posed a significant challenge to the automotive industry. Considerable advancements have been made in recent years regarding test methodologies for the development of rollover sensors [3]. This body of work has been instrumental to the development of sensors that predict rollover crashes and deploy curtain airbags and safety belt pretensioners.

A still unmet challenge in the automotive industry however, is the development of a repeatable dynamic rollover test that can be used to evaluate the performance of various occupant protection technologies. Key elements to assessing these technologies are the occupant kinematics resulting from the vehicle deceleration at trip, vehicle roll rate during the free flight, and the roll angle and acceleration during a ground impact. This paper reports on two subsystem test series that explored a test methodology to produce more realistic rollover ATD kinematics and enable more meaningful restraint evaluations for a trailing-side occupant.

BACKGROUND

VEHICLE TESTS

Vehicle rollover testing has been conducted at General Motors (GM) since the 1930s [4]. A variety of full scale vehicle rollover tests were proposed and evaluated in the subsequent decades. These efforts ranged from rolling vehicles down hills to more current tests involving the use of a deceleration sled. The earlier vehicle rollover tests were focused on developing an understanding of the mechanisms needed to initiate a vehicle roll with subsequent observations of the vehicle rollover dynamics whereas more recent efforts have been focused on rollover sensor calibration development.

SAE J2114 Dolly Rollover Test

Beginning in 1971 the SAE J2114 Dolly Rollover Test Procedure was incorporated into the FMVSS 208 final rule [5]. The SAE J2114 procedure is conducted with a complete vehicle mounted on an inclined dolly designed to trip a vehicle and convert its translational energy into translational and rotational energy as is shown in Figure 1.

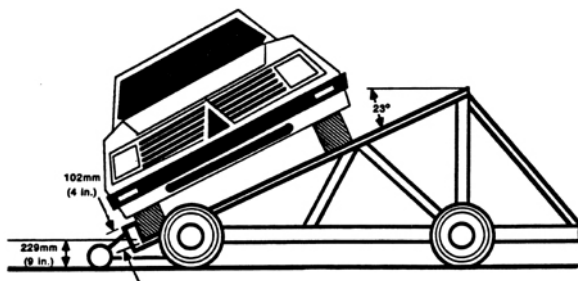


Figure 1. SAE J2114 Dolly Rollover Fixture

A consistent observation of the SAEJ2114 Dolly Rollover Test procedure is the lack of repeatable test results. As stated by James et. al.:

The dolly rollover procedure developed for FMVSS 208 is most often used because it provides a measure of control over the trip location and the vehicle roll direction. It does not, unfortunately, simulate the occupant motion prior to and during the trip phase. In spite of the controlled initial conditions and trip mechanism, the timing and location of specific vehicle/ground contacts and the resulting roll motion of the vehicle during staged testing are not repeatable. [6]

The dolly rollover test procedure has been used in numerous studies for observations regarding items such as occupant kinematics [7], roof crush, and injury mechanisms [8, 9], as well as safety belts with and without pretensioners [10]. Although helpful as a test method for making observations, as noted by James, et.al., it is not repeatable, nor does it provide a realistic pre-trip/trip phase of a rollover event.

Rollover Sensor Signature Tests

More recently a suite of laboratory full scale vehicle rollover tests have been utilized for the development of rollover sensors (O'Brien-Mitchell, et. al., 2007). The tests focused on repeatable rollover initiations that reflected the most common types of rollover initiations in the field and included curb trip-overs, soil trip-overs, ditch fall-overs, a corkscrew ramp flip-over and a SAE J2114 dolly rollover. The curb and soil trip-over tests were incorporated into this test matrix with the objective of subjecting the vehicle to repeatable decelerations on a deceleration sled to distinguish between a vehicle tipping up and continuing to roll versus a vehicle falling back onto its wheels. These laboratory tests proved to be an effective method of controlling the trip initiation, trip deceleration pulse, and vehicle roll direction for the purpose of developing a predictive rollover sensor.

Since the intent of this testing was to develop rollover sensors that are engineered to react to the early phases of a rollover crash, the free flight and ground impact phases were not of interest. Tethers were used in the majority of tests to mitigate vehicle free flight and eliminate vehicle-to-ground impacts (Figure 2). This allowed the vehicles to be used for multiple tests.



Figure 2. Tethered Vehicle on Sled

In tests such as the ditch fall-over and corkscrew ramp flip-over it was not practical to tether the vehicle and in these tests the vehicle was allowed to impact the ground. As experienced with other full scale vehicle rollover test methods, once the vehicle experienced the ground impact, the vehicle motion became chaotic and unrepeatable, precluding the use of the test for assessment of occupant protection performance.

Controlled Rollover Impact System (CRIS)

In recognition of the difficulty of achieving a controlled repeatable test methodology for an entire rollover event, Cooper, et. al. [11] introduced a new test procedure in 2001

called, “Controlled Rollover Impact System” commonly referred to as CRIS. For this test procedure a vehicle was mounted to a fixture that is attached to a tractor trailer. The tractor trailer was driven along the test track to provide a prescribed lateral translational velocity. The fixture to which the vehicle was attached allowed pitch, yaw, drop height, roll rate and roll angle at impact to be controlled. As the tractor trailer travelled along the test track to the impact location, the test vehicle was rotating at a prescribed constant angular velocity. Once the impact location was reached, the vehicle was released from the fixture and impacted the ground from a prescribed height with a pre-determined translational velocity, roll angle, and roll rate. [Figure 3](#) shows the overall setup of the CRIS test.



Figure 3. Controlled Rollover Impact System

In CRIS testing performed by GM in 2003, this test methodology demonstrated acceptable repeatability in terms of vehicle characteristics at ground impact. [Table 1](#) shows a comparison of the targeted test parameters to those achieved. Two 1996 Chevrolet Blazer SUVs were tested to evaluate axial neck loads in a prescribed roof-to-ground impact with a production and a reinforced roof.

Table 1. Blazer CRIS Test Parameters

Test Descr.	Roll Ang at Impact [deg]	Roll Rate [deg/s]	Horiz. Speed [mph]	Drop Height [in]
Target	185	220	8.0	10.0
Reinf. Roof	185	226	8.1	9.7
Prod. Roof	185	226	7.9	9.7

Each Blazer was tested with a belted Hybrid III 50th percentile male ATD, with a seated pelvis in the driver (trailing) position. The CRIS method used ATD positioning cables to minimize dummy motion as the vehicle rotated while translating down the test track to the impact point. When the tractor trailer approached the impact point, the test vehicle was released from the fixture and at ground contact

the cables on the ATD were released to allow the ATD to freely rotate and translate.

The CRIS test methodology was found to be repeatable however, it is focused on the input and output parameters surrounding a single vehicle-to-ground impact. This testing was helpful for understanding occupant kinematics at the time of impact but it did not allow for an assessment of occupant kinematics that resulted from the lateral deceleration, vehicle trip and free flight phases of a rollover.

Jordan Rollover System

Although its repeatability has been questioned [[12](#), [13](#)], another recently developed test methodology is the Jordan Rollover System (JRS) developed by Acen Jordan of Jordan & Co. and illustrated in [Figure 4](#). This test procedure uses a complete or partial vehicle mounted to two vertical drop towers along its longitudinal roll axis. The drop towers span a set of rails upon which a moving road bed section is mounted. The vehicle is rotated and lowered onto the moving road section to simulate a ground impact. Like the CRIS test methodology, this procedure focuses on the vehicle-to-ground impact phase of the rollover event and does not address the vehicle lateral deceleration, vehicle trip or the free flight phases of a vehicle rollover.



Figure 4. Jordan Rollover System with Vehicle Mounted and Ready for Testing

SUBSYSTEM TESTS

Rotating Platform with Subsystem Analysis

In 1997, Pywell, et. al. [[14](#)] reported on a quasi-static test procedure used to characterize belt restraints. In this test procedure the fixture was propelled by gravity and was able to achieve a peak rotational velocity of 240 degrees/sec with an average velocity of 140 degrees/sec through 290 degrees of rotation. This procedure focused on the free flight phase of a rollover and did not address the lateral deceleration, vehicle trip and vehicle impact phases.

Head Excursion Test Device

A similar quasi-static test procedure was used by Moffatt, et. al. [15] in 1997 to evaluate the head excursion of belted human volunteers, cadavers, and ATDs. This test procedure utilized counterweights and a rotating platform shown in Figure 5 with an occupant compartment environment that rotated about an approximation of a vehicle center of gravity. The fixture was called a Head Excursion Test Device and was capable of achieving a maximum roll rate of 280 degrees/sec. This quasi-static rollover test fixture also focused only on the free flight phase of a rollover and did not address the other two phases. Nevertheless, using this test procedure to evaluate belted occupant excursion the authors noted that early application of pretensioners could reduce excursion.

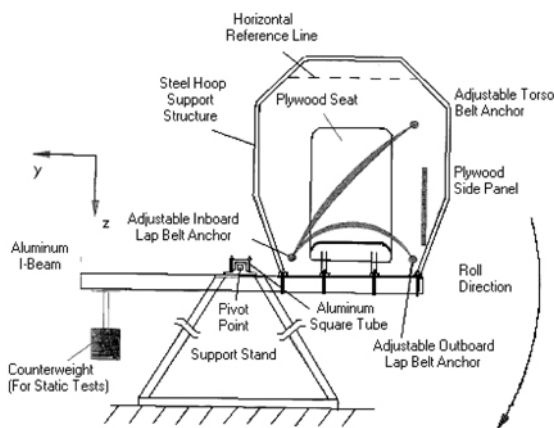


Figure 5. Head Excursion Test Device Fixture

Rollover Restraints Tester

In 1998 Raines et.al. [16] conducted a series of tests to evaluate the effectiveness of safety belt restraints in reducing occupant excursion in rollovers. The tests were conducted with a device called the rollover restraint tester (RRT). This device, shown in Figure 6, was a quasi-static device that utilized a free weight and drop tower assembly, a rotating platform and shock tower assembly. The platform was rotated 180 degrees and its motion was arrested by the shock tower, simulating a roof-to-ground impact. A typical 3-point safety belt and an inflatable tubular torso restraint (ITTR) were tested and found that in this limited test series, the ITTR was able to reduce occupant excursion.

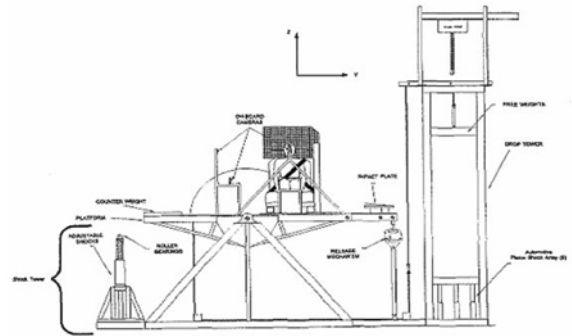


Figure 6. Rollover Restraint Tester (RRT)

In 2007 Sword et. al. [17] conducted additional testing using the RRT where additional restraint systems were evaluated including pretensioners deployed at 45 degrees of table rotation. The authors concluded that for the configurations tested, pretensioners reduced dummy motion in the lateral and vertical directions.

Dynamic Rollover Component Test System

In 2006 McCoy, et. al. [18] described a test method that utilized the same deceleration sled as used by O'Brien-Mitchell et. al. The sled laterally translated a rigid vehicle fixture shown in Figure 7. A series of six pneumatic brakes produced a deceleration pulse to simulate a curb trip rollover event. The rigid vehicle fixture became airborne and rotated in free flight until its roof impacted a landing platform. The test method provided a simulation of the lateral deceleration, vehicle trip, free flight rotation, and the first vehicle-to-ground impact of a tripped rollover event. Utilizing this deceleration sled, in 2007 McCoy, et. al. [19] reported on a series of 15 tests which utilized a dynamic rollover component test system (ROC) to evaluate ATD kinematics restrained by safety belts incorporating pretensioning devices. In this study the author concluded the "...ROC system was able to consistently generate vehicle roll rates in all 15 tests and replicate the key vehicle responses for the trip, roll and free flight phases of the full vehicle curb trip test reasonably well."



Figure 7. Rollover Component Test System (ROC)

The authors observed that the ability of the safety belt restraint pretensioning devices to reduce vertical ATD excursion was limited primarily to the free flight phase of the rollover. They concluded “...that in order to reduce relative occupant vertical head displacements during the free flight phase, the pre-tensioning devices must be activated prior to the vehicles roll initiation phase”.

PHASES OF A TRIPPED ROLLOVER

This study evaluated two dynamic rollover test methods to assess their effectiveness to evaluate the performance of safety belt restraints. A goal of the study was to identify a test method that replicates the phases of the rollover event which influence occupant kinematics. The tripped rollover (where the vehicle rotates primarily about its longitudinal axis) is the most common rollover initiation type [20] and in these events there are generally four phases associated with the rollover: pre-trip, trip, free flight and impact. For the purposes of this study, the tripped rollover event was separated into three phases by combining the pre-trip and trip phases. The three phases used in this study are illustrated in [Figure 8](#) and are defined as follows:

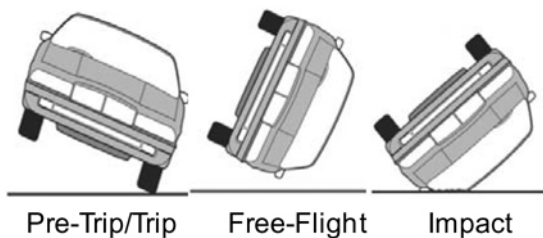


Figure 8. Three Phases of a Tripped Rollover Event

Pre-trip/Trip: This phase includes all vehicle dynamics and occupant kinematics associated with the lateral deceleration of the vehicle. Throughout this phase there remains some tire/wheel contact with the ground and it includes the transition from translation to translation/rotation of the vehicle. All tripped rollover events include this phase.

Free flight: This phase begins at the point where there is no vehicle or tire/wheel contact with the ground and the vehicle and occupant are subject to predominately rotational motion. This phase of the rollover event may occur several times or not at all.

Impact: This phase occurs at any time after the vehicle has tripped where there is vehicle-to-ground contact. In a tripped rollover event this phase will occur at least once and may occur several times.

EVALUATION OF TWO EXISTING TEST METHODS TO ASSESS ROLLOVER OCCUPANT KINEMATICS

This study compares two existing test methodologies intended to provide a means for evaluating safety belt restraints in a rollover simulation. The comparison focuses on the ability of the two methods to replicate the trailing-side ATD and vehicle motion seen in a given tripped vehicle rollover test. The study also evaluates the influence of simulating the three previously described phases of a rollover event versus just one or two selected phases. The first method utilized a rotating platform to simulate free flight and vehicle-to-ground impact and the second method simulated lateral deceleration, vehicle trip, free flight and vehicle-to-ground impact. Safety belt restraints with various combinations of pretensioning devices were used to evaluate the effects of deployment timing relative to occupant motion. The results from these two test methodologies were then compared to a vehicle rollover test to assess test to test correlation. The methods and details of the associated test series are described below.

ROTATING PLATFORM TEST

A rotating platform does not simulate the lateral deceleration and trip phase of a vehicle rollover. To understand how this influences the evaluation of restraint performance, a series of rotating platform tests was conducted. A rollover platform fixture similar in concept to the rollover restraint test device described by Raines et. al. was constructed to assess this test methodology. The fixture consisted of a large frame structure that included a drop tower and a rotating 76-inch by 78-inch platform. The platform was propelled by drop weights and a pulley system. The platform pivoted on bushings located at the front and rear. It was arrested by a pair of shock absorbers in order to simulate a roof-to-ground impact at a roll angle of approximately 180 degrees. A photo of the fixture is provided in [Figure 9](#).