SAE International

SURFACE VEHICLE INFORMATION REPORT

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Rollover Testing Methods

RATIONALE

Inquiries from industry have been received requesting information on rollover testing procedures and approaches that have been utilized. This document provides background as to the techniques that have been utilized for rollover testing and evaluation of rollover protection systems at the vehicle and component levels.

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INTRODUCTION

At SAE there have been inquiries regarding the common techniques being used for evaluation of rollover crashworthiness. This report contains a brief description of the methods being utilized for rollover crashworthiness evaluation, as well as references for additional follow-up. The materials are organized to reflect:

- Full vehicle testing methods (Section 3)
- Component testing methods (Section 4)
- Computer Aided Engineering (CAE) testing methods (Section 5)

Our work was facilitated by the literature created by Chou, McCoy and Leigh at Ford Motor Company, who graciously have provided their work to us (Chou, 2005b). The literature has been revised to reflect information that has been published or become available since that time. The authors wish to acknowledge our appreciation to the previous authors for sharing their document, which allowed us to expand upon their initial work. The present document cannot include all test methodologies that have been used in the past and does not refer to all published papers that have been written on the subject. Omission of a paper or particular methodology should not be construed as invalidating any work not included, nor is the inclusion of a method intended to endorse or authenticate the use of any particular method. This document is intended to be a living document that evolves as new methodologies are developed.

It is hoped that the current document provides some additional insight into the current state of methods available for use in the development of improved vehicle rollover crashworthiness.

By way of background, there are numerous rollover configurations that occur in the accident environment. For example, Obrien-Mitchell (2007) reported that more than 60% of rollover initiations were tripped as shown in Figure A and Digges (1991) reported that more than 90% of vehicle rollovers occur about the vehicle longitudinal axis.

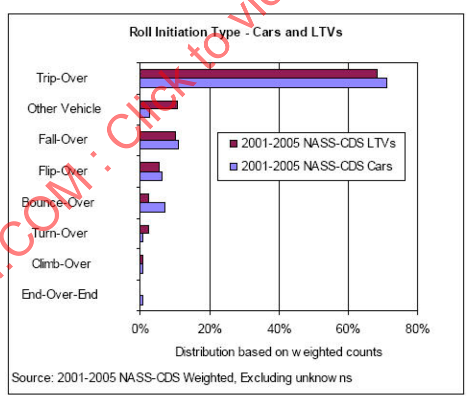


FIGURE A - DISTRIBUTION OF ROLLOVER INITIATION TYPE IN THE 2001-2005 NASS-CDS

Viano (2004) reported on a breakdown of test types and their relationship with rollover crashes as shown in Figure B. The study of field crashes involved analysis of databases from crashes in the United States, United Kingdom, Australia and Germany (Parenteau et al. 2001a, 2003). This work provided a global perspective on the relevant rollover crashes. As shown in Figure B, nine laboratory tests cover 93% of the field incidence of rollover crashes for passenger cars and 89% for LTVs. This addressed 84% of serious injury rollovers. Details on the methodology used to determine these fractions are covered in the paper by Parenteau et al. (2001a). The data shown in Figure B involve three columns of frequency percentages. The left represents the NASS-CDS rollover categories used to classify rollover crashes and their field prevalence. The middle column represents the type of laboratory rollover crashes considered. The analysis method determined the fraction of real-world rollovers that would be addressed by these laboratory tests. The right column is the final fraction of field relevance of the laboratory tests. This includes the frequency of rollover crashes and serious injury of belted occupants. The results have been updated with newer NASS-CDS data, but the main conclusion was that a series of rollover tests is needed to cover the majority of real-world injuries in field rollover crashes.

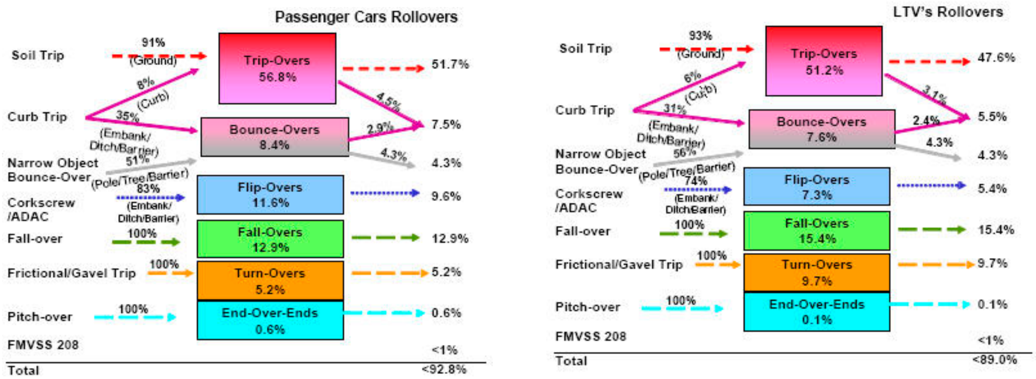


FIGURE B - ANALYSIS OF TEST TYPES WITH ROLLOVER CRASH TYPES FOR PASSENGER CARS AND LTVS

Numerous papers exist with regard to rollover crash characterization where examination of various aspects of interest has been conducted.

DEFINITIONS

For ease of discussion the following terms are identified in terms of general usage and in the context of rollover testing:

Leading Side (sometimes referred to as Near Side) - The side of the vehicle that is initially going into the roll; so a driver side leading roll describes an orientation that in the initial part of the rollover the driver side is starting to move toward the ground (while the passenger side would be moving upward).

Trailing Side (sometimes referred to as Far Side) - The side of the vehicle that is following the leading side going into the roll; so in driver side leading roll the passenger side would be the trailing side.

Curb Trip - A rollover that occurs when a vehicle moving laterally slides into a length of raised curb; the rollover is initiated by the impact of the wheels with a raised curb.

Pitch-over - An end-over-end type of rollover, such as might occur when a vehicle with a longitudinal velocity goes over a drop off.

Soil Trip - A rollover that initiates as a result of the furrowing forces from the buildup of soil by the wheels as the vehicle moves laterally on a dirt surface.

On-road Rollover - A rollover that initiates on the road surface.

Un-tripped Rollover - A rollover that initiates on the road surface as a result of friction forces between the tires and the road surface.

Corkscrew - A rollover test where the rollover motion is initiated by a vehicle moving with one side of its wheels on an inclined ramp, resulting in a spiraling-type motion during the rollover.

Trip-over - When the lateral motion of the vehicle is suddenly slowed or stopped inducing a rollover. The opposing force may be produced by a curb, pothole or pavement that the vehicle wheels dig into.

Turn-over - When centrifugal forces from a sharp turn or vehicle rotation are resisted by normal surface friction (most common for vehicle with higher cg). The surface includes pavement surface and gravel, grass, dirt and there is no furrowing, gouging at the point of impact. If rotation and/or surface friction causes a trip, the rollover is classified as a turn-over.

Fall-over - When the surface on which the vehicle is traveling slopes downward in the direction of vehicle movement so that the center of gravity (cg) becomes outboard of its wheels. The distinction between this code and turn-over is a negative slope.

Flip-over - When a vehicle is rotated around its longitudinal axis by a ramp-like object such as a turned-down guardrail or the back slope of a ditch. The vehicle may be in yaw when it comes in contact with a ramp-like object.

Bounce-over - When a vehicle rebounds off of a fixed object and overturns as a consequence. The rollover must occur in close proximity to the object from which it is deflected.

1. SCOPE

The scope of this document is to provide an overview of the techniques found in the published literature for rollover testing and rollover crashworthiness evaluation at the vehicle and component levels. It is not a comprehensive literature review, but rather illustrates the techniques that are in use or have been used to evaluate rollover crashworthiness-related issues.

2. REFERENCES

Appendix A contains a list of references and other literature on the subject.

3. TEST METHODS FOR FULL VEHICLE TESTING

3.1 Dolly Rollover Test Procedure

3.1.1 Background

According to Wilson and Gannon (1972), the Dolly Rollover Test Procedure was introduced by Mercedes-Benz in a presentation to the SAE Impact and Rollover Subcommittee in 1970. The dolly rollover test was incorporated into FMVSS 208 in 1971. SAE Recommended Practice SAE J2114 "Dolly Test Procedure" was adopted in 1993. The SAE J2114 rollover test procedure is shown in Figure 1. A close up of the dolly fixture is shown in Figure 1A. Based on literature review SAE J2114 has been used in evaluation of the following:

- Restraint system performance
- Rollover occupant protection system performance
- Occupant kinematics and ejection
- Vehicle structural integrity such as roof crush performance
- Vehicle rollover kinematics

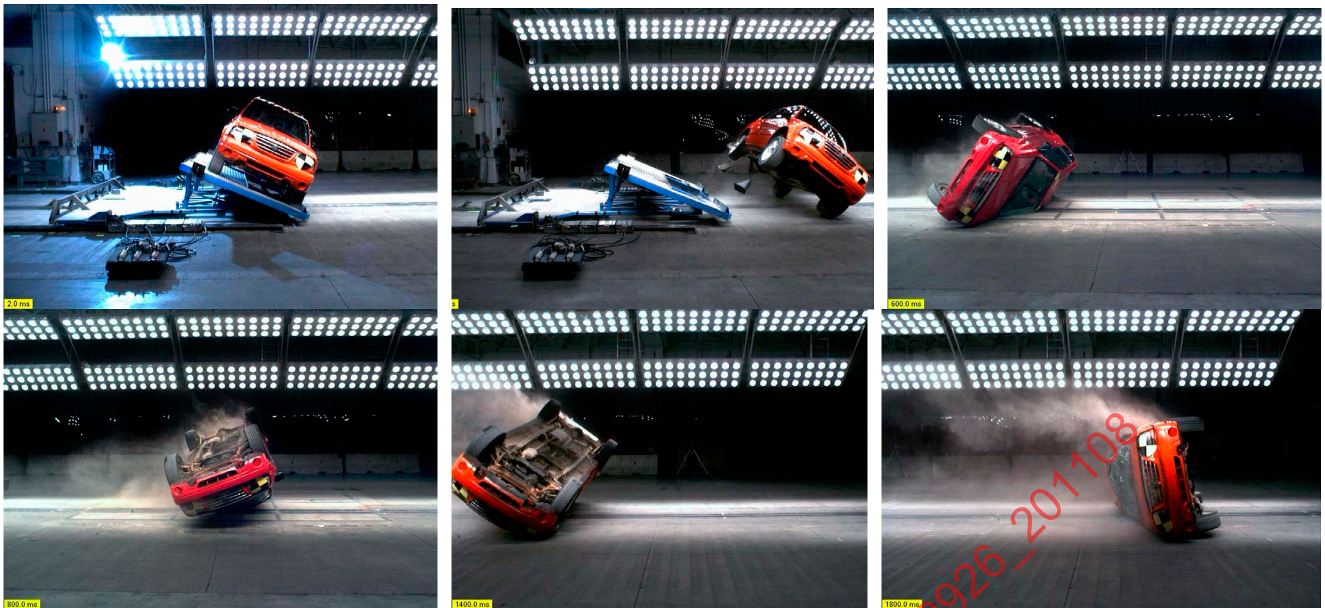


FIGURE 1 - SAE J2114 ROLLOVER TEST MODE (COURTESY OF AUTOLIV)

FIGURE 1A - CLOSE UP OF J2114 DOLLY ROLLOVER FIXTURE (COURTESY OF EXPONENT)

James et al. (1997) reported that the SAE J2114 rollover test procedure is one of the most widely used rollover test methodologies because it provides a measure of control over the trip location and the vehicle roll direction. In spite of a measure of control over the trip location and vehicle roll direction, they noted that the timing and location of specific vehicle/ground contacts and the resulting roll motion of the vehicle during staged testing are not repeatable. According to James et al., the procedure also does not appear to simulate the occupant motion prior to and during the trip phase.

3.1.2 Test Procedure

The test vehicle is oriented laterally on a rolling cart with a platform at a roll angle of 23 degrees from the horizontal and with the leading side tires against a 4-in (10.16-cm) high rigid flange. The lower-side tires are to be 9 in (22.86 cm) above the ground. The vehicle and rolling cart are accelerated to a constant velocity (30 mph is given as an example in the SAE J2114 procedure, but is required in FMVSS 208) and the cart then is stopped at a distance of not more than 3 ft (0.914 m) without transverse or rotational movement of the platform during its deceleration. The cart deceleration must be at least 20 g's for a minimum of 40 ms. The tire support flange will induce an initial roll velocity of the vehicle, and the leading side tires will most likely impact the ground first, after which the vehicle will continue to roll.

This test procedure was used by NHTSA during the early 1980s for testing numerous passenger cars and trucks, and evaluated by many researchers from the 1970s to the present (Ennos, 1971; Segal and Kamhilz, 1983; Wilson and Gannon, 1972; Cooperrider, 1990). The specified test conditions of 23 degree angle and 30 mph velocity were chosen to ensure that most vehicles would roll on concrete roadways subjected to the aforementioned deceleration pulses. It also has been used for developing, testing and evaluating rollover occupant protection systems. This test method has been used to research rollover mechanics on surfaces other than concrete, including dirt (Croteau 2010).

3.2 Rollover Impact Test Systems Designed for Initial Impact Control

There are at least two rollover test systems designed to control initial impact conditions. The CRIS (Controlled Rollover Impact System) test device utilizes a semi-trailer to deliver a rotating and translating test vehicle onto an outdoor test surface. The JRS (Jordan Rollover System) test device enables control of the vehicle initial rollover impact conditions and the number of impacts with a moving impact surface driven by a pneumatic sled system. The JRS rollover system is suitable for use in a laboratory setting. These systems are described in 3.2.1 (CRIS) and 3.2.2 (JRS).

3.2.1 Controlled Rollover Impact System (CRIS) Test

Cooper et al. (2001) reported on a dynamic rollover test procedure with controlled roof impact, thus the method is referred to as the Controlled Rollover Impact System (CRIS) and is covered by US Patent 6,651,482 assigned to Exponent, Inc. (Moffatt, 2003). This test method releases a rotating vehicle onto the ground from the back of a moving semi-trailer. By controlling the roll, pitch and yaw angles, translation and vertical velocities, and roll velocity of the vehicle, the first roof-to-ground interaction is found to be controllable from test to test. However, the subsequent vehicle dynamics may not be repeatable as the vehicle rolls to rest.

3.2.1.1 CRIS Test Procedure

To achieve this goal, the CRIS procedure involves a moving semi-trailer with a drop fixture that has adjustable-height support pins designed to spin and drop the vehicle at a given roll rate and orientation (see Figures 2 and 3). The towed semi-trailer supports a U-shaped fixture used to allow dropping the vehicle directly onto the ground. This test methodology assures a controllable initial roof-to-ground impact at a given combination of translational, vertical and roll velocities. The fixture is equipped with a motor drive system for rotating the vehicle about its center of gravity (CG), and also is versatile enough to allow testing of different vehicles with identical roof-to-ground impacts. The fixture is movable to allow testing on flat surfaces such as asphalt, dirt, sod, etc., and on other facility locations. Cameras can be mounted on-board and off-board the fixture to cover filming of the event. This methodology can be used with ATDs for research such as occupant excursion and airbag curtain evaluation; the methodology for positioning dummies in the test vehicle was reported by Moffatt et al. (2003). Carter et al. (2002) compared some CRIS test results with SAE J2114 dolly tests and concluded that the dolly and CRIS tests produced two significantly different results, in terms of vehicle dynamics.

FIGURE 2 - TEST VEHICLE AND FIXTURE FOR CRIS PROCEDURE TEST

The fixture accommodates pitch angles of ±15 degrees and yaw angles of ±15 degrees. Test conditions have been reported from 13 to 80 kph (8 to 50 mph) translation velocity, 25 cm (10 in) and larger drop heights, roll rates of 220 to 450 degrees/s, with the yaw angle typically at 90 degrees and the pitch angle typically at 5 degrees.

3.2.2 Jordan Rollover System (JRS)

3.2.2.1 Background

The Jordan Rollover System (JRS) is a physical test apparatus which evaluates vehicle-rollover-protection performance by dropping a rotating vehicle with a horizontally stationary CG position onto a moving road bed and is covered by US Patent 7,373,801 assigned to Safety Testing International. This test configuration permits control and monitoring of the rollover impact conditions, and allows the rollover test to be conducted in a limited space.

3.2.2.2 Test Procedure

A pictorial sequence of a JRS test is shown in Figure 3. The system consists of a pneumatic dynamic impact sled that is mounted a platform, which represents an impacted road surface. The pneumatic system propels two pistons connected to cables that pull the platform, which is mechanically coupled to a driveshaft that rotates the test vehicle. The pistons are disconnected from the rotational drive system before impact, allowing the vehicle to roll freely during impact. The initial impact conditions are controlled by mechanical adjustments in the rotational drive system and the pneumatic system. The vehicle initially is positioned to have the desired vertical velocity at impact and is suspended by a fixture as illustrated. The vehicle release is electromechanically controlled to ensure that the desired impact location and angle are obtained. The translational impacting velocity is controlled through the pneumatic sled system. During the impact event, the vehicle remains connected to the fixture via the cradle and its rotating axis, and the vehicle is free to move vertically and to rotate about its rotational axis and in the plane of the fixture. Once the vehicle impacts the platform and the platform passes out from under the vehicle, the vehicle is kept from falling onto the tracks by a built-in arresting system, thus preventing any further contacts with the vehicle roof.

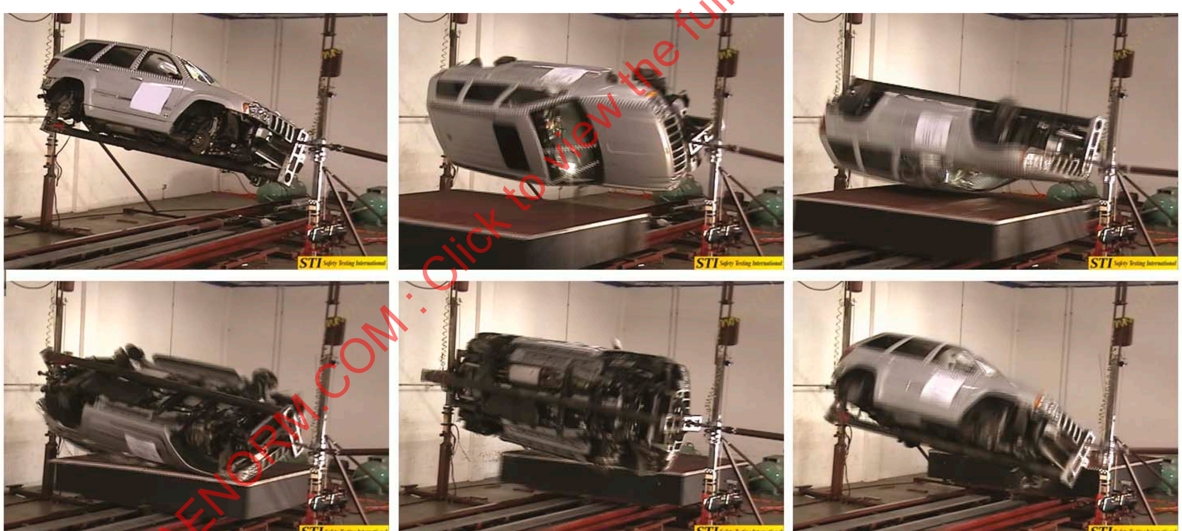


FIGURE 3 - JORDAN ROLLOVER SYSTEM TEST (COURTESY SAFETY TESTING INTERNATIONAL)

The sequence above shows a vehicle in a pitched and yawed orientation rotating and falling against a moving surface, allowing a controlled initial impact of the vehicle. The vehicle impacts the surface and the surface then moves out of the way to preserve the resulting damage. Subsequent impacts can be run on the same vehicle under controlled impact conditions to continue evaluation of the effects of interest. The moving surface is instrumented to provide measurement of impact loads, and instrumentation on the test device provides measurements of the impact conditions, including rotational and vertical velocity, and velocity of the impacted surface. Instrumentation and video on-board the vehicle record the metrics of interest associated with a given study. Anthropometric dummies routinely are incorporated for evaluation of restraint and structural performance evaluations.

A number of sensors provide data of the actual impact conditions. For example, direct recording of the velocity at the front and back of the vehicle is provided by potentiometers mounted on the vertical rails. The rotational velocity of the vehicle is measured directly with an angular rate sensor mounted inside the vehicle. A roll encoder mounted to the cable drive system measures the roadway velocity at impact.

The system design approach can accommodate yaw attitudes of at least ±30 degrees, and the vehicle can be pitched at selectable angles ranging from 0 to 10 degrees. The JRS has a provision for recording the loads on the roof through load cells mounted between the moving platform and the carrier system mounted on the rails (Jordan 2010). The JRS design approach supports various road platform sizes and provides for vehicles weighing up to 2727 kg (6000 lb). The JRS can control the number of impacts that occur during a given test by adjusting the length of the platform and the initial contact location (Jordan 2010).

Impact velocity control is provided through two mechanisms. The translational impacting velocity is controlled through a pneumatic sled system. The drop height of the vehicle is positioned to produce the desired impact velocity.

Variability analyses of the system with regard to initial impact conditions have been reported (Bish, 2008; Chirwa, 2010; Friedman, 2010).

Test conditions typically reported in the literature are translation velocities from 24 to 34 kph (15 to 21 mph), 5 or 10 degrees pitch, 80 degrees yaw, 10 to 15 cm (4 to 6 in) drop height and 180 to 270 degrees/s at first side contact.

3.3 Ramped Rollover Tests

3.3.1 Background

Unlike the SAE J2114 test methodology where a vehicle is moving laterally at the initiation of the test, ramp or corkscrew tests take a portion of a vehicle's forward (longitudinal) momentum and translate it into roll motion. This typically produces a rollover with significant longitudinal velocity and relatively low roll rates. Depending on the vehicle's forward velocity and ramp configuration, both roll and non-roll cases can be generated, thus providing roll rate data in both roll and non-roll for rollover sensing algorithm development. In Europe, Allgemeiner Deutscher Automobil Club (ADAC) developed this test mode as a consumer information test, thus it sometimes is referred to as "ADAC Corkscrew" or "ADAC ramp test" in the literature (Viano and Parenteau, 2004). Figure 4 shows various ramp configurations with different height, width and length that have appeared in the literature. One type shown in Figure 4 is a straight-up-flat-surface ramp, while the other is a curved surface (sometimes referred to as a spiral ramp). These are described in 3.3.1.1 and 3.3.1.2.

3.3.1.1 Straight-Up-Flat-Surface Ramp

The straight-up-flat-surface ramp is designed in such a way that the bottom of the test vehicle does not contact the side edge of the ramp. This eliminates one source of possible test variations, but as ramp height increases the risk of vehicle underbody interaction increases. Switching to a curved-surface corkscrew ramp alleviates this condition (3.3.1.2). A ramp that is designed to serve this purpose for testing vehicles ranging from small-sized cars to light trucks and SUVs is shown in Figure 4(d).

An early straight ramp test was incorporated into SAE Recommended Practice J857 (now canceled). According to Wilson and Gannon (1972), this procedure, developed by Chrysler, uses a curved guide-rail to direct the test vehicle up the ramp (see Figure 5) high enough to initiate vehicle roll. Sakurai et al. (1991) used the SAE J857 ramp for their rollover study by conducting a series of 12 ramp rollover tests at 50 km/h (31 mph) as shown in Figure 6. The roll motion was developed by driving the right-side tires onto the ramp while quickly turning the steering wheel to the right, resulting in a left-side-leading vehicle rollover.

During a straight ramp test, a vehicle with longitudinal velocity runs over a ramp; initially wheels from one side of the vehicle contact the ramp, while wheels on the other side are in contact with the ground. As the vehicle continues to move up the ramp, it experiences a high asymmetric acceleration from the z-direction causing it to rotate along its longitudinal axis. When it leaves the ramp, the vehicle continues to rotate along its longitudinal axis until it contacts the ground.

Issues pertaining to this test mode may include: (1) getting the test vehicle on the ramp in the same manner every time, and (2) whether or not the steering wheel on the test vehicle should be locked in position during the test. The ramps shown in Figures 4(b) and 4(c) were used by TUVRheinland. Figure 4(b) shows a corkscrew ramp and test. The ramp shown in Figure 4(c) consists of four segments: The first three segments of lower heights are an integral part (referred to as a three-segment ramp), while the fourth segment can be separated from the entire fixture (referred to as a four-segment system). Given a forward velocity, the three-segment ramp can be used for non-roll tests, while the four-segment ramp can be used for roll cases. A ramped test from the 1930s is shown in Figure 7.

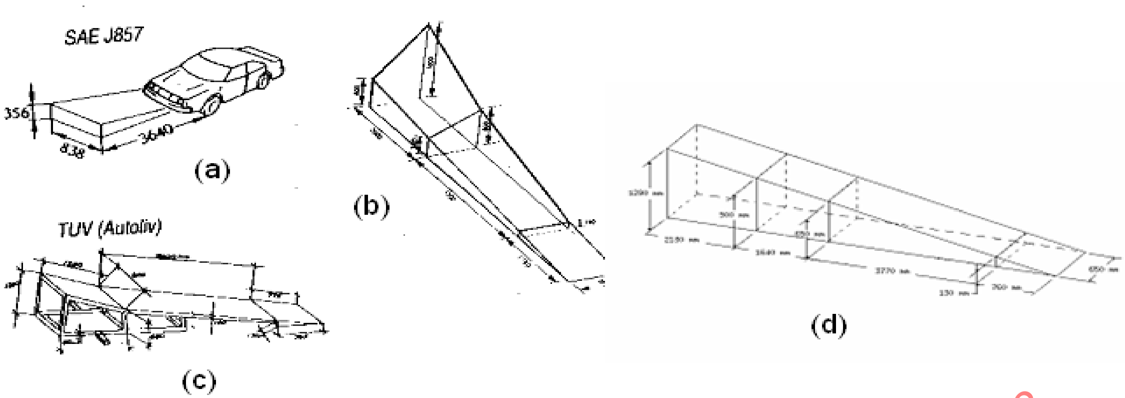


FIGURE 4A - 4D - VARIOUS RAMP CONFIGURATIONS

FIGURE 5 - USE OF SAE J857 RAMP (NOW CANCELED)

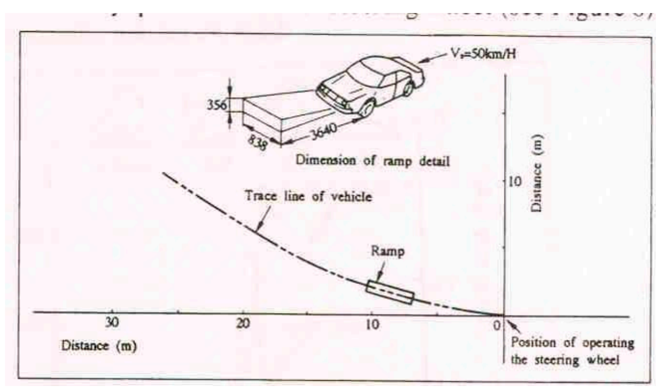


FIGURE 6 - CORKSCREW RAMP TESTS (SAKURAI ET AL., 1991)

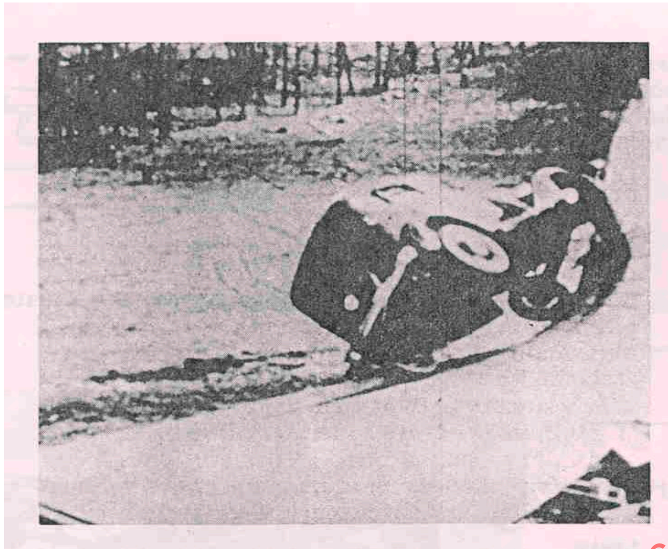


FIGURE 7 - GM TEST IN EARLY 1930s

3.3.1.2 Curved-Surface (Corkscrew) Ramp

Another type of test ramp is a curved or spiral ramp, which provides the ability to introduce an inclination angle as the vehicle travels up the ramp. Figure 7 shows an early corkscrew rollover test done at General Motors (GM) in the 1930s. The test, as reported by Wilson and Gannon (1972), was done by driving a vehicle onto a spiral ramp located at the top of a hill. Figure 8 shows a spiral ramp used for corkscrew tests conducted by DEKRA as reported by Berg et al. (2002). Typically, a corkscrew test produces one or two quarter-turn vehicle rolls; i.e., 90 degrees and 180 degrees, respectively.

Vehicle roll and non-roll conditions can be generated using different ramp configurations, such as:

- Ramp length
- Ramp height
- Ramp surfaces: flat versus spiral
- Longitudinal velocity
- Entrance: straight-in versus curved-in

FIGURE 8 - CORKSCREW TEST MODE USING SPIRAL RAMP

3.4 Curb Trip Methodologies

3.4.1 Critical Sliding Velocity Mode

The Critical Sliding Velocity Mode (CSVM) test method, shown in Figure 9, has been reported by Chou (2005a). The CSVM test is a quasi-static test condition, and is relatively easy to perform. In this test mode, the test vehicle is placed at the top of a ramp, which can be adjusted to any angle smaller than the angle that the vehicle will roll over by itself under static conditions. The wheels of the vehicle sit on a "frictionless pad" and are guided on the ramp. The vehicle slides laterally down the ramp when released and initiates rollover when the tires impact the flange located at the bottom of the ramp, provided that the speed and angle are sufficient, as shown. This test mode has been shown to be capable of generating low to midrange lateral acceleration levels depending on the ramp angle (for a given ramp length and curb height) for both roll and non-roll conditions. Some sensor suppliers and test institutions have adapted this test methodology as a means to generate low lateral g's and vehicle roll rates for rollover sensor/algorithm development. However, signals generated from this mode may pose some difficulty to sensor engineers in discriminating rolls from non-roll conditions.

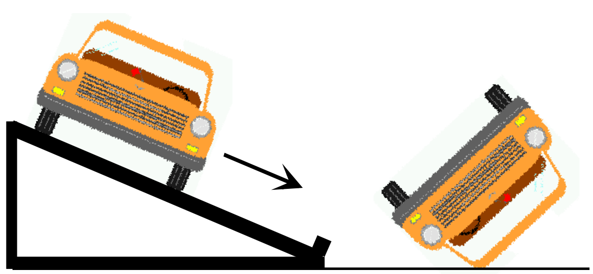


FIGURE 9 - RAMP CURB IMPACT TEST MODE

3.4.2 Lateral Curb Tripping

A Lateral Curb Trip test involves propelling a vehicle sideways, with no longitudinal velocity, into a curb-type structure. In a pure lateral side curb test mode, as shown in Figure 10A, the vehicle is placed on a sled against a curb of about 6 in (15 cm) high, or high enough to allow rim interaction with the curb. The sled is then towed to a predetermined velocity (which can be determined by a CAE rollover model of the specific vehicle or via trial-and-error method) and released from the tow device prior to impact with the curb. In general, the vehicle will experience a lateral acceleration of approximately 7 to 12 g, thus producing high roll rate and high lateral acceleration signals (Chou, 2005b). Another method used for conducting this type of test is to tow the vehicle sliding sideways on a low-friction surface into the curb, such as utilizing a layer of soap to allow the vehicle to slide sideways. The curb height and lateral velocity are parameters that affect the roll condition in a lateral curb impact. It has been reported that curb trip tests generate occupant head lateral movement that is the fastest to close the gap between the occupant head and the side glass, thus requiring an earlier time-to-fire for a rollover occupant protection system (Werner, 2002). Thomas and Cooperrider (1989, 1990, and 1998) presented this test procedure using passenger cars and utility vehicles; analyzed vehicle kinematics results including time histories of displacement, velocity and energy; and compared results with those from dolly tests at similar speeds with a similar vehicle.

Hare et al. (2002) and Hughes et al. (2002) presented a lateral curb trip test methodology that utilized an SAE J2114 dolly, but with the vehicle support platform horizontal, to launch the vehicle into an aluminum honeycomb-cushioned curb (honeycomb often is utilized to ensure a rollover occurs rather than have the vehicle wheel/axle separate without a rollover occurring) Figure 10B. In this testing the vehicle came off the dolly platform 18.5 in (47 cm) above the ground and impacted a 6 in (15 cm) tall curb that was placed approximately 13 ft (4 m) downrange from the launch point. The authors noted that this methodology provided an alternative to the FMVSS 208 rollover dolly procedure in a limited area of evaluating dummy kinematics and restraint performance. Dummy head movement in response to the trip differed from that shown in FMVSS 208 rollover dolly testing.

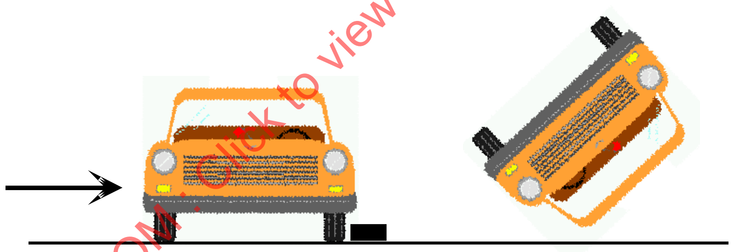


FIGURE 10A - PERPENDICULAR SIDE CURB TRIPPING

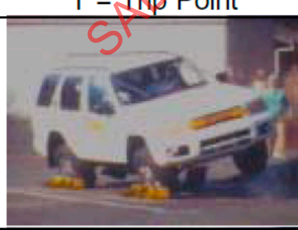
T = Trip Point	T = 1.0 second	T = 3.0 seconds
		

FIGURE 10B - EXAMPLE OF TRIPPED ROLLOVER PROCEDURE RUNS

3.4.3 Oblique Curb Trip

Curb trip tests alternatively can be run in an oblique configuration, as shown in Figure 11, in which the vehicle has a forward velocity component, with and without a yaw rate, impacting the curb with a prescribed incident angle. The benefit to this type of procedure could be to more closely replicate the configuration of a specific accident scenario, but the cost would be in the repeatability of the resulting vehicle behavior. The pure lateral variation sometimes is referred to as an "aggressive" side curb trip, and could be considered for some research to be a worst-case condition. In addition to curb height and lateral velocity, forward velocity and side-slip angle is a controlling factor in an oblique mode. An example of oblique curb trip testing is the test series conducted by the University of Missouri Columbia where vehicles were driven via remote control into a curb in three different ways: driving straight, cornering, and cornering and spinning (Nalecz 1994).

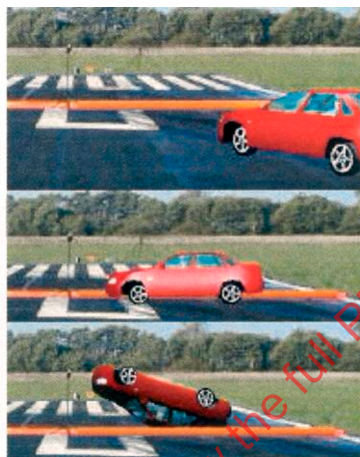


FIGURE 11 - OBLIQUE SIDE CURB TRIPPING

3.5 Deceleration Rollover Sleds

The deceleration sled test is a methodology developed to allow for controlled 90-degree tip-up events. The methodology was developed as the Deceleration Rollover Sled (DRS) Patent 6,622,541 is described by Stein (2003) for use in occupant protection development (Rossey, 2001) and as the Dynamic Rollover Test (DRT) for use in rollover resistance measurement (Larson, 2001). This methodology consists of a sled that runs on a rail and a method of applying a deceleration force in the range of lateral tire friction or furrowing forces. The DRS method uses a series of pulse-generating brakes to provide the deceleration force, as shown in Figure 12, and the DRT method uses a linear brake fin that is mounted to the ground, to which brake pads on the sled clamp. A test vehicle can be positioned laterally on the platform of the sled. On the leading side of the platform, a set of tire stops are bolted to the surface of the platform. The wheels are placed against the edge of the stops. The sled accelerates in the direction of the sled track until it reaches a constant predetermined velocity; brakes are used in such a manner as to decelerate the sled to a desired "g" level. A system of tether straps can be used to stop the vehicle from rolling onto its side or traveling off of the sled. The vehicle then can be saved for reuse in subsequent tests. Examples of the DRS and DRT are shown in Figures 13A and 13B respectively.

The DRS can provide a wide range of “g” levels from slow (1 to 2 g) to fast roll (8 to 10 g), so it can be adapted for furrow-type and aggressive curb-trip-type simulations. Stopping distance, deceleration velocity and deceleration g's are parameters that affect the performance of this test mode.

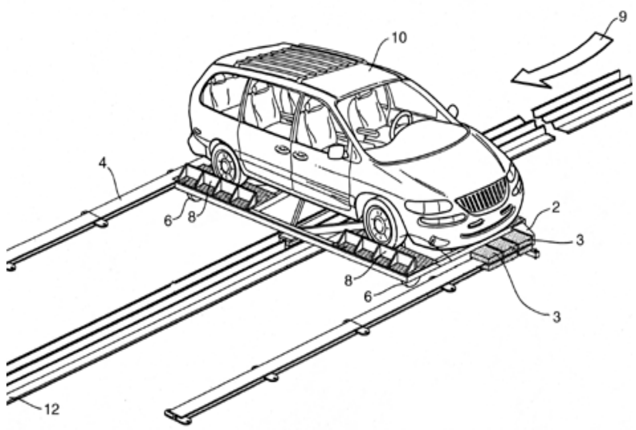


FIGURE 12 - DECELERATION ROLLOVER TEST SLED (LEADING SIDE)

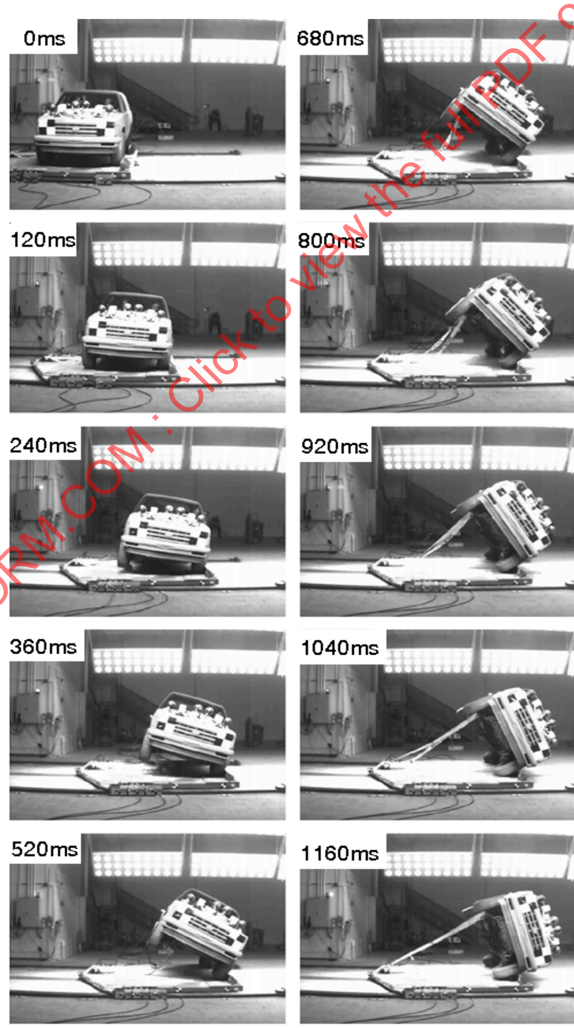


FIGURE 13A - VEHICLE ROLLOVER SEQUENCE USING THE AUTOLIV DRS DECEL-SLED TEST

FIGURE 13B - EXAMPLE OF EXPONENT DRT TIP UP TEST

A third system reported by Bostrom (2005) consists of a sled with a rigid compartment assembly that simulates full-scale tripped rollovers along the longitudinal axis during the tripping phase, the airborne phase and the initial ground contact. The roof is assumed to be able to absorb the first ground impact. The test device is shown in Figure 14 during the three phases corresponding to the tripping phase 14A, the airborne phase 14B, and the first ground impact phase 14C.

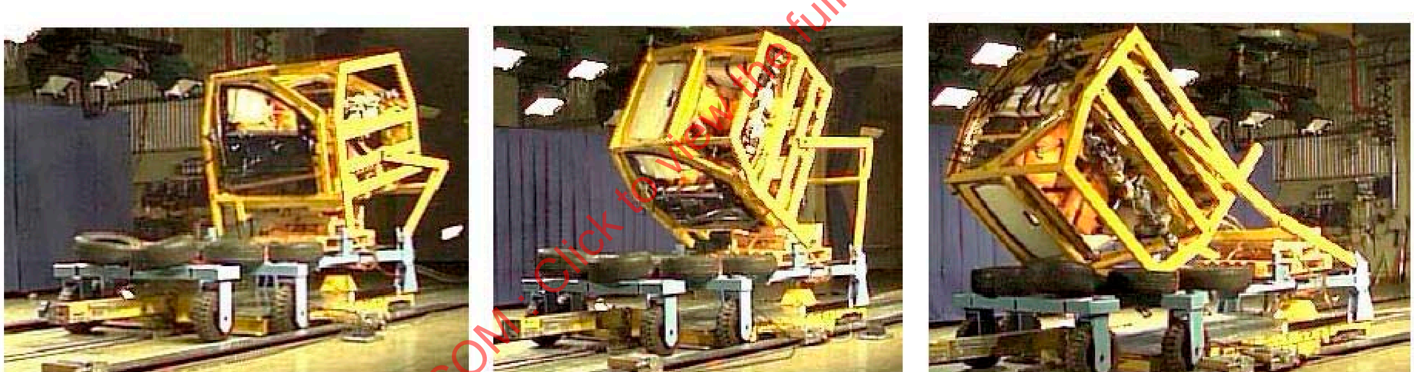


FIGURE 14A - 14C - EXAMPLE OF AUTOLIV SLED COMPARTMENT ROTATION SYSTEM

3.6 Ditch/Embankment

An Embankment rollover test involves causing a vehicle to roll laterally down an embankment or slope of a ditch. In the early 1930s GM conducted such tests by pushing crawler tractors down an embankment to evaluate their roll-cages as shown in Figure 15. In the 1980s, this type of test was carried out more systematically by DEKRA (see Figures 16A and 16B) for accident reconstruction of rollover crashes (Berg et al., 1992, 2002). The DEKRA tests were conducted as part of an effort to study vehicle behavior under given off-road circumstances, such as when a vehicle leaves the road and travels into an embankment. Various slopes, "incident" angles, and steering profiles were considered. Millbrook Test Center was reported to have an outdoor test facility that simulates sideways roll down an embankment via a calibrated gradient (Birch, 2002). A ditch test facility was developed by Autoliv that allows tests to be done at 15 mph with a ditch angle ranging from 35 to 50 degrees.

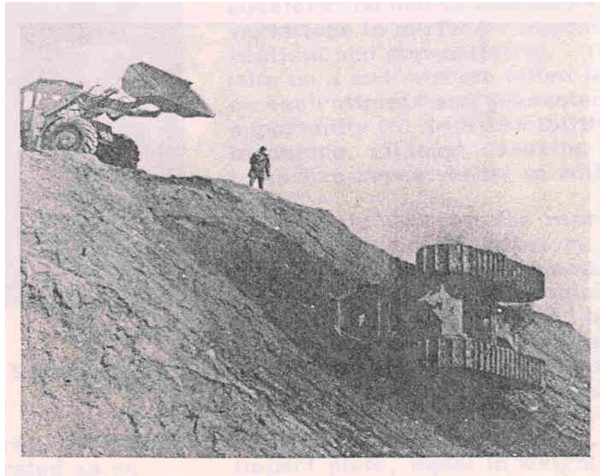


FIGURE 15 - CRAWLER TRACTOR ROLLOVER BY GM IN EARLY 1930S (WILSON AND GANNON, 1972)

FIGURE 16A

FIGURE 16B

FIGURE 16 - VEHICLE GUIDANCE AND 16B EMBANKMENT TEST

3.7 Soil Trip Testing

As reported by Wilson and Gannon (1972), the earliest recorded soil tripping rollover tests with automobiles took place at the GM Proving Ground in the early 1930s. Figure 17 shows their method for inducing ground level rollovers by driving the car into a skid on a sod field. Wilson et al. mentioned that deliberate spinouts of a vehicle on a sod surface failed to assure a roll on each attempt and lacked reproducibility. This 1930 rollover test was to demonstrate the benefit of a car with full steel roof structure and occupant compartment as reported by Yanik in his article addressing the first 100 years of transportation safety (Yanik, 1996). Other soil trip test methods developed by DEKRA (Berg et al, 2002) and Cooperrider et al. (1998) are shown in Figures 18 and 19, respectively.

The soil trip is a type of off-road rollover most likely caused by a trip mechanism created by vehicle sideslip through soil or sod. As with curb trip testing, the vehicle can be accelerated up to speed either by installing it on a cart or dolly, or by towing it on a low-friction surface, such as a soap-covered surface. The soil test section reported by Cooperrider (1998) was about 40 ft long and 20 ft wide to allow the entire rollover event to occur on the soil surface. Depending on lateral velocity and sand density, a vehicle will roll over when the force of the tires furrowing, or plowing, through the soil is large enough.

FIGURE 17 - INDUCED GROUND LEVEL ROLLOVER BY GM IN THE EARLY 1930S (WILSON AND GANNON, 1972 AND YANIK, 1996)

FIGURE 18 - SOIL TRIP TEST FACILITY AT DEKRA (BERG ET AL., 2002)

FIGURE 19 - A SOIL TEST CONFIGURATION (COOPERRIDER ET AL, 1990)

3.7.1 Roller Coaster Dolly (RCD)

Larson et al. (2000) developed a Roller Coaster Dolly (RCD) for vehicle rollover testing as a methodology in re-creating soil-tripped rollover collisions. Figure 20 shows the test fixture of RCD, with which a vehicle can be released at a predetermined speed onto flat or sloping terrain with any desired initial yaw angle.

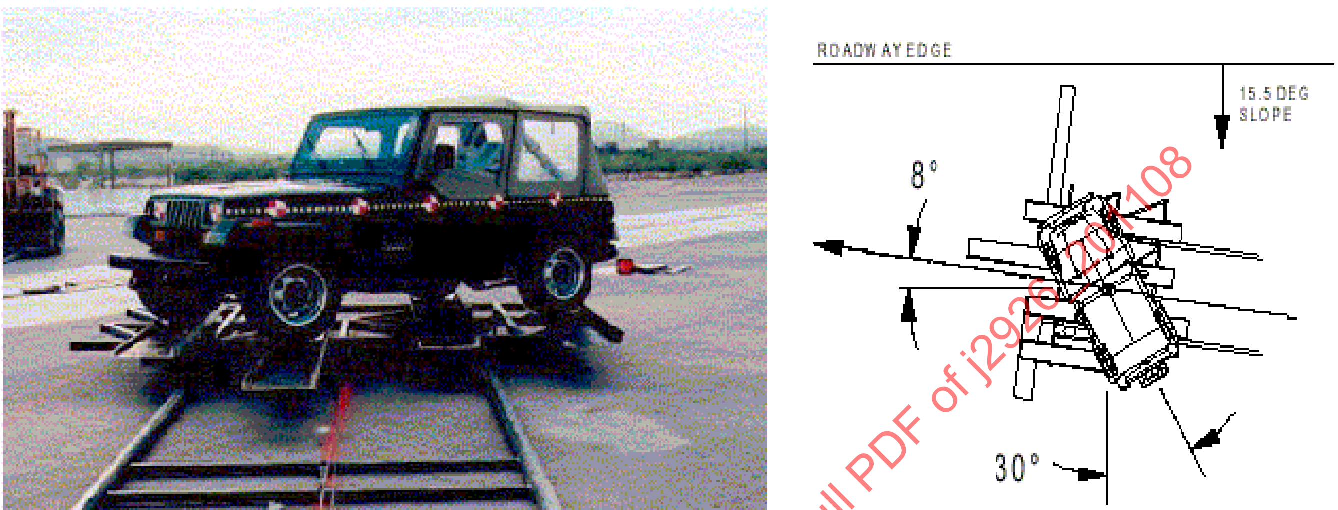


FIGURE 20 - TEST FIXTURE OF RCD (LARSON ET AL., 2000)

3.8 Maneuver Induced Rollover Testing

Maneuver induced rollover testing consists of using a programmable steering machine to input steering into an unmanned vehicle traveling at speed on a test surface. An example of this method is presented by Nalecz (2004), where vehicles were tipped-up onto outriggers on both an asphalt and soil surface. Nalecz used a system that followed a predetermined path with an optical system. An example of this methodology used for a full vehicle rollover is given by Larson (2000), where a vehicle was towed with a crash rail system up to test speed and steered with an automatic steering controller to induce an on-pavement rollover. Testing by Gilbert utilized remote control (Figure 21) of the vehicle's accelerator, brake and steering to accelerate a test vehicle up to speed prior to an open-loop steering input (Gilbert 2007). Asay (2009, 2010) also reported on a method that towed the test vehicle up to speed behind another vehicle, which was then released and a preprogrammed robotic control then provided the subsequent steering inputs.

FIGURE 21 - GILBERT ENGINEERING REMOTE CONTROL SYSTEM PROVIDING FOR ACCELERATOR, BRAKE, AND STEERING CONTROL

4. COMPONENT TEST METHODOLOGIES

Component Test Methodology is an approach to simulate/replicate only a certain portion of a rollover event. Many methods reported in the literature are quasi-static tests involving rotating or "inverting" the occupant in a test fixture around a stationary axis, thus addressing the rotational phase of a vehicle motion without taking the lateral translational motion into consideration. More recent additional methods have been introduced to address various other phases of rollover such as pre-trip, trip, and rotational motion up to first ground contact. Table 1 lists various component level tests addressing the phases of vehicle rollover such as pre-trip, trip and rotational motion used in evaluating occupant motion and developing restraint countermeasures in rollover accidents.

TABLE 1 - COMPONENT TEST METHODOLOGIES

Paragraph No.	Test Method	Seatbelt Restraint	Sensor	Curtain	Occupant Kinematics	Glazing	Structure	Heavy Truck
4.1	Rollover Restraint Tester (RRT)	X			X			
4.2	Key Safety Devise	X			X			
4.3	Delphi Test Bench	X						
4.4	Dynamic Rollover Fixture (DRF)	X		X		X		
4.5	Rollover Component Sled (ROCS)	X	X	X	X			
4.6	Lateral Rollover Simulator (LRS)	X			X			X
4.7	Spin Fixture	X			X			
4.8	Linear Impactor			X		X		
4.9	FMVSS 216 Type Testing						X	
4.10	Drop Tests	X					X	

4.1 Rollover Restraint Tester (RRT)

A component test device called the Rollover Restraint Tester (RRT) (Rains et al., 1998) that was developed by NHTSA is shown in Figure 22. This is a "Spit Test" type device that is capable of generating the free-flight motion in the airborne phase of a rollover event. The driving force for the RRT is provided by the drop tower and free-weight system. The angular velocity of RRT, ranging from 180 to 290 degrees/s can be generated by various combinations of drop weight and drop height. The main features of the RRT consist of a supporting framework, a counterbalanced test platform with a pivot axle, a free-weight and drop tower assembly, and a shock tower. The dummy's head movement can be digitized by tracing tape markers on the head with respect to a reference grid behind the dummy's head. In 1997, Moffatt et al. (1997) developed a very similar device called Head Excursion Test Device for studying head excursion during seated cadaver, volunteer and Hybrid III tests.

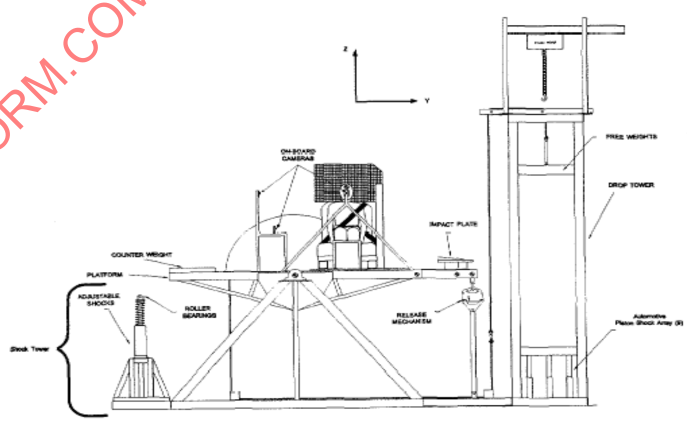


FIGURE 22 - ROLLOVER RESTRAINT TESTER (RRT), A NHTSA COMPONENT TEST DEVICE (RAINS ET AL., 1998)

4.2 Key Safety Inc. Device

This fixture, as shown in Figure 23, is developed by Key Safety Inc. (formerly Breed), which includes only a portion of the occupant compartment to simulate a quarter-turn roll with no free-flight motion. The fixture is accelerated using a HYGE sled to reach the desired lateral velocity, and the "compartment" is pushed outward by hydraulic pistons at the bottom, causing the compartment fixture to rotate clockwise about the pivot at the top of the compartment fixture. In this fashion, the dummy will experience vehicle rotation. The device is covered by US Patent is 6,256,601 and is described by Wipasuramonton (2001).

FIGURE 23 - KEY SAFETY INC. (FORMERLY BREED) TEST DEVICE

4.3 Rotational Test Benches

Shown in Figure 24A is a simple fixture developed by Pywell et al. (1997) to simulate different quasi-static vehicle rollover conditions for characterizing various belt restraint systems in terms of dummy's excursion. This device generally can achieve a peak roll rate from 240 degrees/s with a rotation up to 180 degrees. The device rotates about an axis from a given starting angle. It attempts to replicate the occupant's potential trajectory and displacement on a driver-side-leading roll, simulating a road shoulder step off type roll event. The effects of occupant kinematics by modifying the vehicle seat, belt restraint system and belt geometry can be monitored easily. The system consisted of two 2.5 m tri-mount stanchions, a 3.25 m axle straddling the stanchions, and a rectangular cage that housed the simulated vehicle environment. However, there was no indication of the power source.

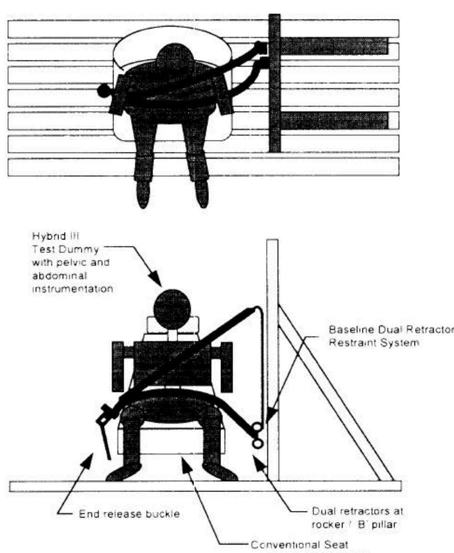


FIGURE 24A - TEST BENCH BY PYWELL ET AL. 1997

An updated version of the system reported by Kumar (2009) and Safety Research Institute includes an AC motor drive system and the ability to rotate up to 480 degrees per second with multiple rolls. Figure 24B illustrates the Safety Research Institute system from an end view.

FIGURE 24B - TEST BENCH BY SAFETY RESEARCH INSTITUTE

4.4 Dynamic Rollover Fixture (DRF)

The Dynamic Rollover Fixture was developed by NHTSA as a research tool to produce full dummy ejections repeatedly at less cost than full vehicle tests. As described by Willke et al. (2003), the DRF is modified from the previous NHTSA test device known as the Rollover Restraint Tester (RRT), described in 4.3 Paragraph 1. The test fixture simulates only the rotational component of the rollover event and is limited in evaluating rollover sensor performance due to the lack of simulating the pre-trip phase of the event. In addition, influences due to roof contact cannot be evaluated. The DRF has similar components to the RRT (Figure 25). The angular velocity generated on the DRF is tailored by varying the mass (force generating the acceleration) and the drop height of the free weight (duration of acceleration pulse). Angular velocities up to 360 degrees/s can be generated. A test buck is secured to the platform and a generic seat is used to allow variation in initial seated position relative to the side window. The buck position relative to the axle pivot, as well as the yaw angle between the test buck and platform, can be adjusted to obtain various dummy trajectories.

FIGURE 25 - DYNAMIC ROLLOVER FIXTURE (DRF)

4.5 Rollover Component Sled (ROCS) Fixture

The Rollover Component Sled fixture (US Patent 7,380,436 B2) is a component test device that simulates both the rotation and lateral translational motion to represent tripped rollover events (McCoy and Chou, 2005). This device, as shown in Figure 26, is comprised of several components and mounted on an existing rollover sled test device (Rossey, 2001). The major components of the fixture are the carriage, the occupant compartment, the roof shell, and a landing surface with devices designed to provide roof-to-ground contact forces. The fixture is able to provide representative vehicle roll rates, angles, velocities and accelerations, and associated occupant motion for lateral tripped rollover crashes. The test fixture is placed on the Rollover Sled Test Fixture and a choice of lateral velocity and deceleration is made. The Sled Test Fixture then is accelerated to the constant velocity chosen and the sled's brakes are activated to achieve the desired lateral deceleration. The test fixture then experiences lateral decelerations, free rotations and eventually ground contact. Figures 27A and 27B illustrate the beginning and an airborne phase during a test event. This component test device and procedure is controllable and flexible for different vehicle programs for occupant protection system development as described by McCoy et al. (2006). Under combined variations of the sled velocity, suspension characteristics and BIW (body-in-white), a rollover restraint system can be developed and evaluated.

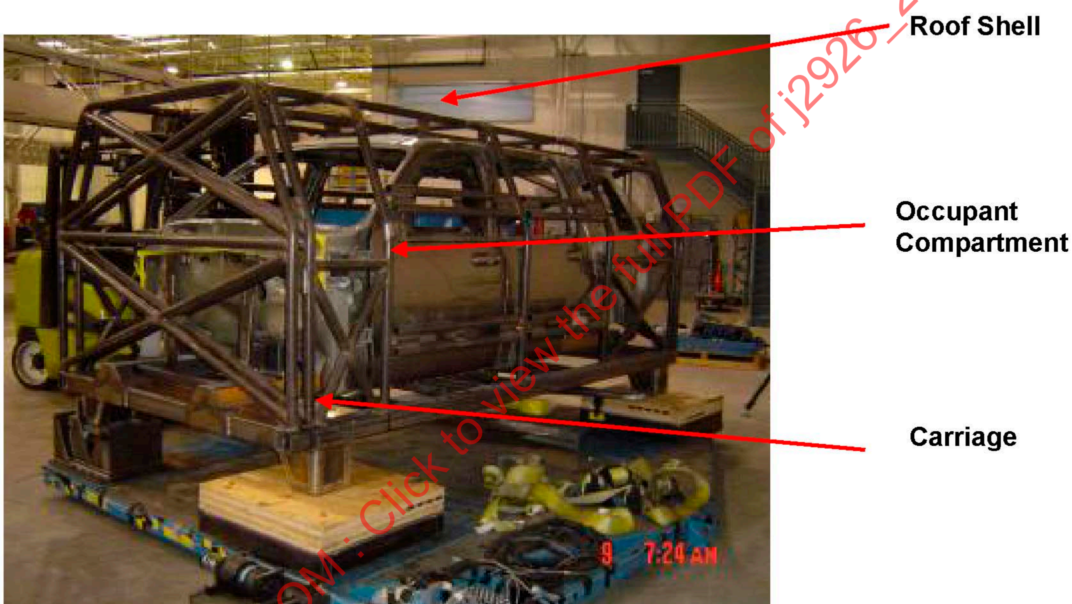


FIGURE 26 - ASSEMBLED COMPONENT FIXTURE MOUNTED ON THE ROLLOVER SLED DEVICE

McCoy et al. (2007) utilized the ROCS to evaluate the effects of activating pyro-mechanical buckle pretensioners and electronic retractor pretensioners on 5th to 95th driver and right-front passenger head and pelvis excursion. The ROCS allowed for replication of key vehicle responses for the trip, roll and free-flight phases of a full vehicle curb trip test. However, since the ROCS does not deform during ground impact and allow for energy absorption, more energy is generated by the vehicle to ground-contact transfers to the occupants and restraint system than expected in real-world rollovers.

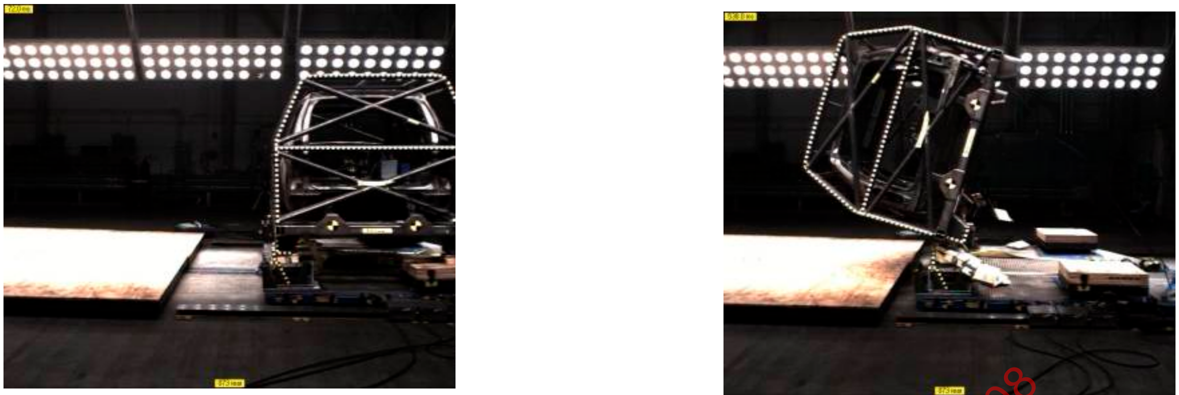


FIGURE 27A - 27B - FIXTURE ENGAGES BRAKES OF ROLLOVER SLED DEVICE FOLLOWED BEGINNING OF FREE FLIGHT

4.6 Lateral Rollover Simulator (LRS)

Heavy truck crashes consist of comparatively low deceleration over a longer duration compared to passenger cars. Moving heavy trucks possess more mass and momentum than do passenger cars, resulting in lower decelerations. Investigation into heavy truck rollover crashworthiness led to the development of the Lateral Rollover Simulator (Werner et al., 2000) pictured in Figure 28. The fixture and procedure were developed to evaluate occupant restraint systems and cab structure in 90 degree rollover conditions for heavy trucks. A tractor cab is mounted to the LRS platform and rotated about a pivot point representing the leading-side outboard-edge tractor tires. The rotational energy is initiated with hydraulic cylinders and continues due to gravity. The fixture impacts a honeycomb wedge at 90 degrees of rotation. The pulse shape is determined by a honeycomb wedge approximating the impact of the cab to the ground. The LRS research led to an SAE Recommended Practice: "Occupant Restraint System Evaluation – Lateral Rollover System – Level Heavy Trucks, SAE Recommended Practice," SAE J2426.

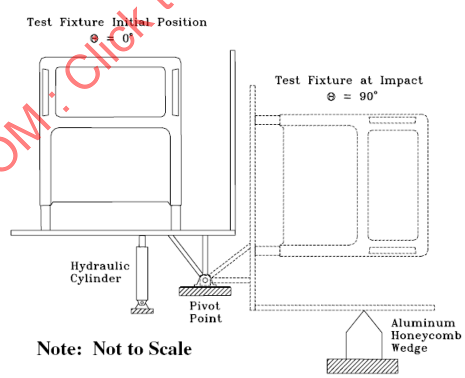


FIGURE 28 - SCHEMATIC OF LATERAL ROLLOVER SYSTEM

4.7 Spin Fixture Testing

Moffatt et al. (2003) used a controlled, multi-revolution rotation of a complete vehicle about a fixed, longitudinal axis through the vehicle center of mass to compare the vertical excursion of the head of restrained test dummies and human subjects. The vehicle was rotated about its longitudinal roll axis at roll rates from 180 to 360 degrees/s providing occupant information during the airborne phase of a rollover. Both far- and near-side roll directions were used to evaluate excursion on leading- and trailing-side occupants. In addition to head excursion dimensions, the movement of the seat belt webbing through the latch plate also was analyzed. The spin fixture was developed as a stationary laboratory fixture to dynamically balance a vehicle in preparation for a CRIS rollover test (Cooper et al, 2001). The spin fixture does not address vehicle-to-ground impacts that cause additional relative movement between the vehicle and the occupant.

4.8 Linear Impactor Testing

Willke et al. (2003) used data generated from DRF testing to reduce the test method in evaluating ejection mitigation countermeasures to a smaller subsystem-level test that is more viable for compliance or regulatory purposes. NHTSA began the development of a guided impactor test in 1995 during advanced glazing research. The guided impactor, pictured in Figure 29, utilizes an 18 kg mass.

A featureless head form covered by head skin, originally developed for the upper interior head protection research program, is mounted on the end of the impactor. The dimensional and inertial characteristics of the form were averaged from the frontal and lateral regions of the head. The head form is designed to replicate the loading of an occupant's head and shoulder into a single form. The guided impactor measures only uni-axial motion and is capable of measuring dynamic deflection during an impact.

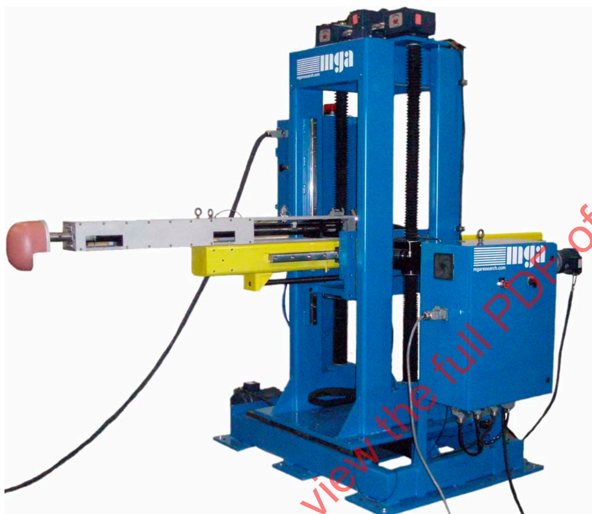


FIGURE 29 - NHTSA TYPE GUIDED IMPACTOR (COURTESY OF MGA)

One of the agency's crashworthiness efforts to reduce rollover fatalities and injuries is to focus on mitigating occupant ejection through side window portals. Summers et al. (2005) continued research using a guided linear impactor with the objective of developing test parameters such as test speed, impact location and performance criteria. Shilliday et al. (2005) studied the comparison of linear impactor excursion results compared to DRF excursion results. Using a correlated airbag model, impactor excursion responses to variations in airbag pressure were compared with DRF responses. The results highlighted testing challenges in creating a unidirectional component test to evaluate a subsystem response. In November 2006, NHTSA published a testing procedure to use as a guideline, outlining their test method used to research performance of ejection mitigation countermeasures. The memorandum that contained the procedure was published to aid manufacturers and suppliers in replicating NHTSA's research. O'Brien-Mitchell et al. (2007) developed a component-level test utilizing a linear impactor to evaluate ejection mitigation. The study consisted of evaluating various impact points and occupant-impact-energy data collected through sensor development tests. On December 2, 2009, NHTSA published a notice of proposed rulemaking establishing a new FMVSS, No. 226, to reduce the partial and complete ejection of vehicle occupant through side windows, particularly targeting rollover crashes. Within the proposed rule, the procedure for evaluating ejection mitigation is defined using a linear impacting device.

4.9 Vehicle Roof Strength Test Procedure

In 1968, SAE introduced a quasi-static test procedure, SAE J374, to assess roof strength of passenger cars under loading conditions simulating vehicle rollover. The procedure consists of a loading device having a flat, rigid surface with minimal dimensions of 1800 mm x 750 mm. The device is orientated over the front passenger area of the vehicle such that the edges are not contacting the vehicle during the test. The plane of the loading device is oriented to simulate a vehicle roll angle of 25 degrees ± 1 degree from fully inverted and a pitch angle of 5 degrees ± 1 degree. The bottom of the rocker panel on the vehicle defines the reference plane from which to measure the roll and pitch angles. The procedure can be conducted on a complete vehicle, a vehicle body or a body mounted on a chassis frame. Components shall be installed that affect load or deformation such as doors, roof panels and fixed glass.

In 1971, NHTSA adapted the SAE procedure into the FMVSS 216 Roof Crush Resistance requirement. The 2009 FMVSS 216 rule adds head forms placed within the vehicle to simulate vehicle occupant positions in the front row of seating. The 2009 amended rule requires the roof strength of a vehicle with a GVWR of less than 6000 lb to be 3.0 times the unloaded vehicle weight within 5 in of platen displacement and with less than 50 lb of loading onto a head form. Two tests are performed on a single vehicle at each front corner of the roof. For vehicles with a GVWR between 6001 and 10 000 lb the roof strength requirement is 1.5 times unloaded vehicle weight within 5 in of platen displacement and with less than 50 lb of loading onto the head form.

4.10 Inverted Drop Test

SAE published a recommended practice for an inverted vehicle drop test procedure known as SAE J996. The intent of the procedure was to produce as closely as possible “deformation of a vehicle roof or roll bar structure which occurs in a vehicle rollover.” The procedure consisted of positioning an inverted vehicle to free fall under conditions of roll and pitch angle onto a somewhat controlled surface. The orientation positioned the vehicle at a longitudinal pitch angle of 5 degrees ± 0.5 degree from the horizontal and a lateral roll angle of 25 degrees ± 0.5 degree form the horizontal. The vehicle was lifted to the desired drop height, which was measured between the impacted surface and the lowest point on the vehicle roof, pillar or roll bar. The drop test was considered severe since the majority of the kinetic energy is applied to one area of the roof structure unlike real-world rollovers where there is a progressive dissipation of energy by various parts of the vehicle. The SAE procedure eventually was canceled in 1994 as an active SAE procedure.

In 1990, Bahling et al. (1990) utilized the inverted drop test to assess neck loads on restrained and unrestrained dummies placed in roll-caged and production vehicles. In their procedure they suspended the vehicle 12 in above a concrete floor with 0 degrees pitch and 20 degrees roll angle between the plane of the inverted roof and the ground. The study discussed the drop test results on vehicle kinematics, occupant kinematics, the effects of roof crush and the effects of safety belts.

Although the SAE procedure is no longer active, the method still is in use. For example, Herbst et al. (2001) utilized an inverted drop test to research roof integrity. The objective of their study was to simulate roof deformation that incurred by a real-world rollover accident. More recently, NHTSA reported on drop testing results in docket NHTSA-2005-22143.

5. CAE TESTING METHODS

To study the vehicle and/or occupant kinematics during rollover crashes, mathematical models are useful tools for understanding essential rollover mechanics and evaluating restraint system performance in mitigating occupant ejection. Tools available for such analyses include vehicle dynamic handling models, occupant gross-motion simulators (Fleck and Butler, 1981; Obergefell et al., 1988; TNO, 1996) and finite element (FE) analysis programs.

Methodologies have been developed to model a rollover prospectively as well as retrospectively. Depending on the objectives of interest, various approaches are available to assess the performance of any vehicle system using virtual testing methods.

With regard to crashworthiness occupant protection, two general approaches – rigid body simulations and finite element methods – have been utilized during the past thirty years.

Simplified approaches using rigid body assumptions are used by some when effects of intrusion or occupant compartment deformation are not of interest and an impact pulse can be characterized.

The state-of-the-art CAE techniques in vehicle crashworthiness and rollover occupant protection involve finite element methods. Models are created of a portion of the vehicle of interest (or the complete vehicle), as well as the restraint system and occupant. Prescribed vehicle motions or motions in response to initial impact conditions can be utilized. Hybrid methods involving both finite element and rigid-body techniques have been combined as well.

5.1 Rigid Body Based Simulations (e.g. MADYMO, ATB, DYNAMAN)

Examples of general packages that have been utilized with rigid body simulations include MADYMO, ATB and DYNAMAN.

Rollover models of varying degrees of complexity based on rigid-body assumptions have been utilized. In 1995, computer simulations using ATB were reported by Cheng to predict passenger ejection and minimal driver impacts for a rollover accident (Cheng, 1995a, 1995b). In 1998, Renfroe used MADYMO to model a rollover crash test with dummies, reporting good agreement between simulation and test (Renfroe, 1998). In 1998, Yaniv reported research including MADYMO simulations to demonstrate rollover ejection mitigation under rollover conditions (Yaniv, 1998). In 2000, engineers at Siemens describe using ADAMS and MADYMO for rollover simulation and analysis including both vehicle and occupant motions (Frimberger, 2000). In 2001, engineers at Delphi and Saab reported using computer simulations and MADYMO to characterize rollovers, occupant kinematics and injury measures in rollovers (Parenteau, 2001b). In 2001, Ward utilized MADYMO to evaluate occupant motions and injury measures under inverted impact conditions (Ward, 2001).

The analytical studies and model simulations are useful methods for determining the influence of vehicle parameters on vehicle response. MADYMO-based models for simulating vehicle kinematics in SAE J2114, side-curb trip, critical sliding velocity and corkscrew ramp were developed and reported by Chou (2002). The rigid-body based MADYMO models are easier than finite element models to run in order to provide trend analysis and design direction for rollover sensing system and restraint system development. Gopal et al. (2004) used MADYMO and PC-Crash as analytical tools for simulation and testing of a suite of field-relevant rollovers.

The CAE methodologies can be developed along with the test methodologies. Experimental data obtained from testing can be used for developing rollover CAE models that replicate vehicle motion under similar test conditions. Analyses of simulated results provide valuable feedback to help enhance the test procedures. Testing with enhanced procedures can provide additional data for continued model refinements. MADYMO-based CAE tools can provide high quality models with better simulated and/or predicted results. MADYMO rollover models consist of sprung and un-sprung masses, suspension systems and tires, whose characteristics may be extracted from an ADAMS-based vehicle handling model. In addition, MADYMO has a large selection of occupant models available. Use of the MADYMO-based models to support rollover testing, rollover sensing algorithm development, and rollover protection system development will be described, and many issues associated with rollover CAE simulations are given by Chou (2002). Wu, Chou and Amin (2002) used MADYMO models of four different rollover test modes in selecting vehicle configuration for sensor calibration tests.

Review of mathematical models indicated that analytical tools are good for many functions, including, for example:

- Providing test conditions for roll and non-rollover events for a given test mode.
- Supporting countermeasures development
- Trend analysis

5.2 Finite Element Methods (e.g. LS-DYNA, RADIOSS, PAMCRASH)

Finite element modeling has been utilized in the automotive industry since the 1950s (Friedman, 1998). Finite element modeling of rollovers has been conducted for many years. In 1991, Mitsubishi reported studying rollover impacts with Hybrid III dummies to analyze roof crush and head and neck injury prediction utilizing finite element modeling (Sakurai, 1991). In 1991, a project sponsored by NHTSA reported results of finite element analysis showing the effects of design modifications on a pickup under rollover impact conditions; this was followed by further extension of the work in 1993 (Tyan, 1993). In 1994, Kumagi reported on the use of finite element modeling using LS-DYNA to evaluate the rollover strength of bus structures (Kumagi, 1994). In 1998, Friedman reported using finite element modeling with optimization to demonstrate improved roof strength (Friedman, 1998). In 2001, Friedman reported finite element analyses using LS-DYNA to study roof-intrusion velocities during rollover impacts, as well as effects of roof strength and restraints on injury potential during rollovers (Friedman, 2001a, 2001b). In 2004, Mao described finite element modeling of static and dynamic roof crush analyses (Mao, 2004).

Since then, numerous studies have reported on the use of finite element modeling related to rollover protection. Today, finite element modeling of rollovers is conducted on a regular basis to study vehicle structural deformation and occupant kinematics interacting with the restraint system and vehicle interior.

Finite element methods also are being accepted as a basis for certification by manufacturers to meet European bus rollover crashworthiness requirements.

Table 2 lists examples of various applications of CAE methods used to evaluate rollover related problems, ranging from structural performance and occupant protection to developing restraint and structure countermeasures.

TABLE 2 - EXAMPLES OF CAE ROLLOVER APPLICATIONS

Section Number	Seatbelt Restraint	Structure	Sensor	Curtain	Occupant Kinematics	Padding	Heavy Truck	Test Conditions	Crash Conditions	Bus	Mining Vehicles
5.3								X			
5.4			X		X						
5.5	X	X									
5.6		X							X		
5.7	X		X	X	X			X			
5.8	X	X			X						
5.9										X	
5.10	X				X			X	X		
5.11				X							
5.12											X
5.13							X				
5.14						X					
5.15	X	X									

5.3 Test Conditions Selection and Adjustment

Gopal (2004) at Delphi used PC-Crash and MADYMO to aid in the development of new field representative rollover laboratory tests. (Figure 30) The tools were used to identify and adjust test conditions for impacts of interest and to explore effects of changing items like track width and initial velocity variations for gravel and friction tests. They found that once the models were correlated, they were useful for what-if type scenarios and identifying robust test conditions. However, neither MADYMO nor PC-Crash were found to provide effective solutions for impacts requiring the incorporation of complex suspension models that need to be detailed enough to capture some specific high-severity rollover conditions (curb trip). They also found that the laboratory tests being conducted were not very repeatable, adding to the limitations in using these math tools. The simplified representation of loose soil and gravel also was found to be a problem area for these models. PC-Crash was reported as useful to help narrow down the choice of vehicle kinematics from a variety of potential choices. It was found that MADYMO-type solutions have good potential, but still need further development to be useful as a correlative tool.

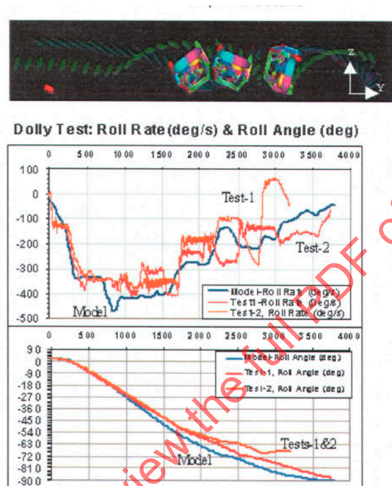


FIGURE 30 - DOLLY TEST USING PC-CRASH AND MADYMO

5.4 Sensor Testing

McCoy (2007b) at Ford reported on the use of MADYMO to model suspension and tire characteristics. (Figure 31) It was reported that the model utilizing the Delft-Tyre magic formula description enabled correlation of the model by simulating a vehicle suspension kinematics and compliance test. The model then was used to simulate a J-turn vehicle dynamics test maneuver, a roll and non-roll ditch test, a corkscrew ramp, and a lateral trip test. Rigid masses were attached to the vehicle body to represent the occupants. A mesh representation of a tire and wheel was made for the curb impact because the MF-Tyre model does not provide for lateral contact characteristics. McCoy found that MADYMO was able to reasonably predict the vehicle and occupant responses in these applications and potentially is a tool to help set up a suite of vehicle configurations and test conditions for rollover sensor testing.

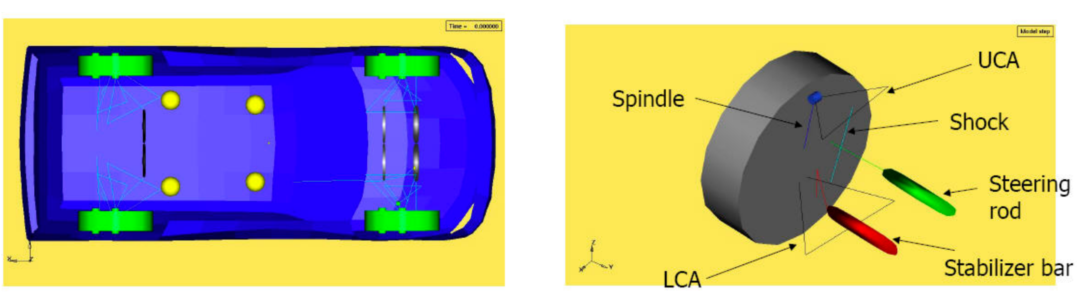


FIGURE 31 - SENSOR TESTING USING MADYMO

Bardini (1999) at University of Duisburg for Bosch used FASIM_C++ to evaluate vehicle motions of a car falling down an embankment until the car body hits the ground. (Figure 32) The inputs were used by MADYMO for occupant simulations. It was found that because of the plastic deformations occurring in the curb-impact case, the rigid-body modeling of the curb event was not suitable, and therefore they used crash test vehicle results for vehicle motions as input to MADYMO.

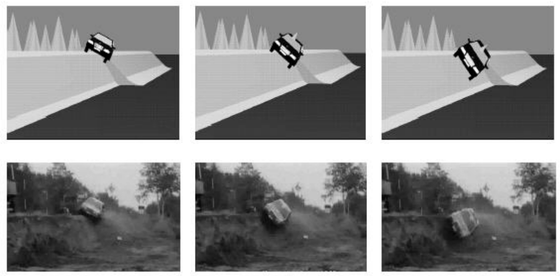


FIGURE 32 - EVALUATION OF VEHICLE MOTION WHILE FALLING USING FASIM_C++

5.5 Restraint and Structure Development

Friedman Research Corporation (Friedman, 2008) demonstrated the ability to model rollover laboratory impacts with a baseline and modified vehicle, Hybrid III dummy and restraint system using LS-DYNA. (Figure 33) The reported head and neck responses from rollover tests using the CRIS test fixture with production and modified vehicles were shown to match the simulation results well.

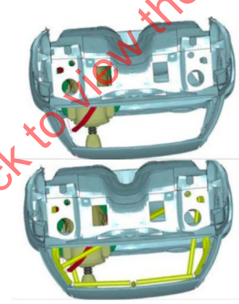


FIGURE 33 - ROLLOVER TEST USING LS-DYNA

Friedman Research (Friedman, 2007) also reported the use of LS-DYNA for the development of a seat-based rollover occupant system design as shown in Figure 34. The restrained-occupant-protection performance under rollover conditions using an intelligent rollover protection subsystem was reported. In this system, a roll-activated integrated seat and seat belt system was evaluated under published CRIS impact conditions. LS-DYNA was used to evaluate the effect of the system's ability to move the occupant's head away from the roof structure prior to far-side roof contact, and the effect on head and neck injury measures.

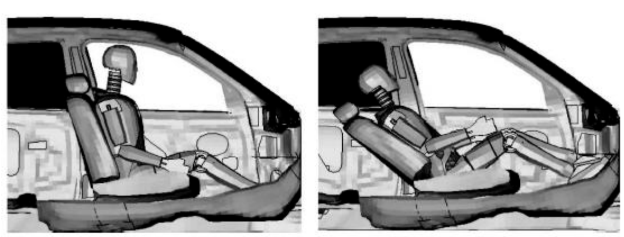


FIGURE 34 - SEAT-BASED ROLLOVER OCCUPANT SYSTEM DESIGN USING LS-DYNA

Friedman Research (Friedman, 2001c) also reported on the use of LS-DYNA to evaluate the effects of restraint and structure conditions using a model of the human head and spinal column under rollover conditions (Figure 35). Effects of representing the head and neck with a fixed lumbar spine T1 compared with the entire spinal column were evaluated. In addition, effects of improved restraint, roof structure and head clearance were evaluated.

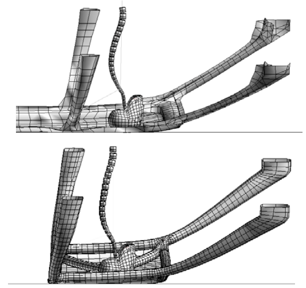


FIGURE 35 - RESTRAINT/STRUCTURE EFFECTS ON HEAD/SPINE DURING ROLLOVER USING LS-DYNA

5.6 Impact Conditions and Roof Structure

Friedman Research (Friedman, 2005) reported the use of LS-DYNA to examine the effect of automotive roof buckling on the intrusion velocity in the vertical direction under rollover conditions. A finite element model of a vehicle structure was created and provided with conditions representative of an automotive rollover event. The model was validated based on test and observational data. The impact conditions of the roof structure in the vertical direction were compared with the intrusion velocity with and without the presence of a buckle (Figure 36). It was found that the vertical intrusion velocity amplification could be in the range of two-to-three times the corresponding vertical impact velocity in the area of a buckle.

FIGURE 36 - ROOF BUCKLING - INTRUSION VELOCITY IN VERTICAL DIRECTION DURING ROLLOVER USING LS-DYNA

Parent (2010) at the University of Virginia performed a sensitivity study using the NCAC 2003 Ford Explorer model in the LS-DYNA. This study evaluated the sensitivity of roof crush and vehicle kinematic response to variations in roof strength, roll angle, pitch angle, yaw angle, roll velocity, translational velocity, and drop height during the roof-to-ground interaction phase of the rollover event. A full-factorial design of experiments (DOE) array made up of three levels for each of the seven parameters was sub-sampled to a total of 129 simulations. Peak roof crush ranged from 9 to 66 cm with a mean of 44 cm, while vertical acceleration ranged from 0.85 to 5.96 g with a mean of 3.3 g. Stepwise linear regression indicated drop height was a predictor for both structural and kinematic response, as drop height alone described approximately 70% of the variation in both peak roof crush and vertical acceleration. (Figure 37)

FIGURE 37 - SIMULATION OF ROOF-TO-GROUND PORTION OF ROLLOVER EVENT USING LS-DYNA

5.7 Vehicle Rollover Sequence Modeling Including the Effects of the Suspension

Hu (2007) and his team from Wayne State University, China, and Ford reported on development of a finite element model for simulation of rollover crashes using LS-DYNA. (Figure 38) The model refined the suspension characteristics of an NCAC model and modeled the first roll of several rollover test conditions, such as a dolly rollover, curb trip and corkscrew test. The results obtained were reported as having good-to-excellent agreement with observed physical test results in vehicle kinematics in terms of roll angular velocity, and lateral and vertical accelerations at the vehicle center of gravity.

FIGURE 38 - FINITE ELEMENT MODELING FOR SIMULATION OF ROLLOVER USING LS-DYNA

In addition, restraints (seat belt and side curtain airbag) and a Hybrid III dummy were incorporated for a dolly rollover to examine occupant kinematics as shown in Figure 39. The interior was developed based on estimated geometry of a production vehicle, with the seat and dash being represented as rigid structures. It was reported that timing and location of the most severe impact to the dummy's head compared well with the experimental results

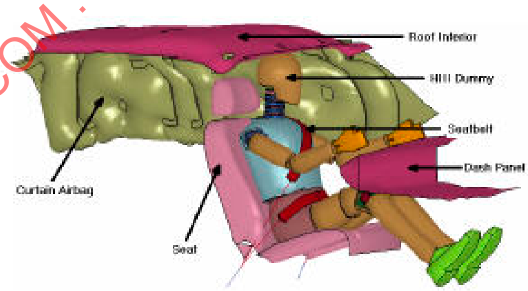


FIGURE 39 - MODELING OF DOLLY ROLLOVER TO EXAMINE OCCUPANT IMPACT USING LS-DYNA

Viano (2009), Delphi, and Collision Safety used PC-Crash and MADYMO (Figure 40) to augment the results from rollover crash tests and concluded that an approach to reducing diving injuries in rollovers was to recline the occupant and minimize their outboard and upward movement before the first far-side roof impact. By reclining the occupant, the clearance between the head and roof increases and the torso kinetic energy is directed less through the neck. Impact with the roof would involve the face rather than the top of the head and the torso would move more toward the roof, not the neck. Upper body recline also would move the head rearward of the frontal areas of the passenger compartment where intrusion in a rollover usually is greatest. Such an approach directly would address the issue of torso augmentation with an upright-seated occupant who is inverted and moving toward the ground. The PC-Crash outputs were used to prescribe the motion in MADYMO.

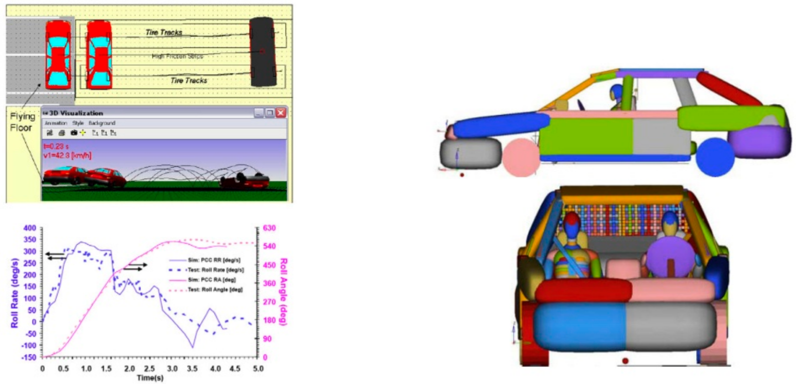


FIGURE 40 - MODELING OF REDUCING INJURIES IN ROLLOVERS USING PC-CRASH AND MADYMO

Chou (2008) reported on a literature review of math-based CAE tools used primarily for evaluation of vehicle dynamics from a normal driving condition to rollover initiation. (Figure 41) This sequence was characterized as consisting of three phases: the control region, transition region and out-of-control region. It was reported that there were no mature CAE tools for simulating the vehicle motion in the transition region although some existing rigid body tools were available. Many ADAMS-like models may claim that they are capable of simulating vehicular motion in this phase, with or without some limited validation. Chou reports that ADAMS-like models such as HVE, PC-Crash and others need to be investigated. For the out-of-control region prior to impact, rigid body dynamic models such as MADYMO, ATB and CVS were reported as being used, as well as deformable-body-based models using LS-DYNA, Pam-Crash and RADIOSS. Finite element tools like PAM-CRASH, RADIOSS and LS-DYNA were reported to be required for modeling the vehicle-deformation portion of a rollover event.

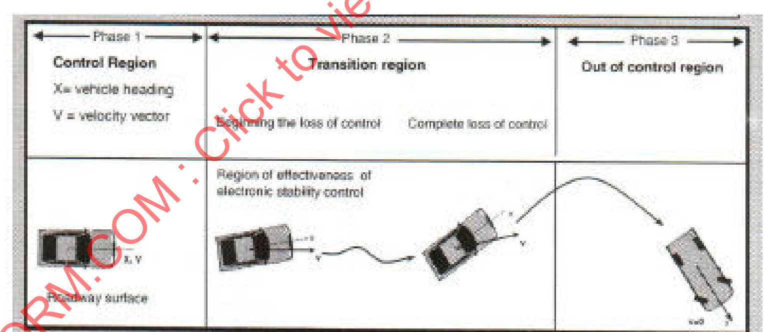


FIGURE 41 - NORMAL DRIVING CONDITION TO ROLLOVER SIMULATION USING CAE TOOLS

5.8 Restraint Evaluation

Hu (2009) at University of Michigan reported using finite element modeling to evaluate the effect of restraint variations on excursion during rollover. LS-DYNA was utilized for this work. A rigid seat and interior based on the estimated geometry associated with an existing SUV were utilized in conjunction with a Hybrid III dummy model and a THUMS human body model. A selected set of belt restraint characteristics were utilized, as shown in Figure 42.

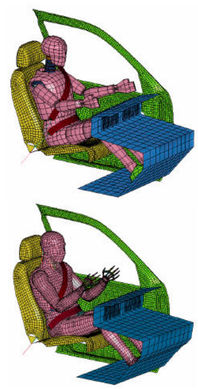


FIGURE 42 - MODELING RESTRAINT VARIATIONS ON EXCURSION DURING ROLLOVER USING LS-DYNA

Newberry (2006) from Exponent reported on the use of MADYMO version 6.1 to simulate the performance of pretensioners with seat belts in rollovers (Figure 43). PC-Crash was utilized to extend previous vehicle tests past the point of outrigger contacts. It was reported that the pretensioner model available in MADYMO is appropriate for well-defined systems but may be of limited use without appropriate testing to determine the amount of webbing that is retracted for an uncertain loading scenario. An incremental improvement is described to incorporate a transient force function that characterizes the maximum force that can be generated by a particular pretensioning retractor.

FIGURE 43 - SIMULATION OF SEAT BELT PRETENSIONERS DURING ROLLOVERS USING MADYMO

5.9 Bus Rollover Simulations

Tech (2007) from Italy utilized LS-DYNA to model the ECE R66 bus rollover crashworthiness requirements. (Figure 44) The ECE R66 allows a simulation of a bus rollover to determine the minimal structure rigidity of the bus in a rollover. The bus model was built with beam elements and some plastic hinges in several unions where the bus structure might experience plastic behavior during rollover. To determine the force-deflection curve of those plastic hinges, experimental and theoretical predictions of the collapse of basic bus-structure-union elements were performed. Although LS-DYNA was used to simulate the elements, a more complex finite element model, using shell elements, was developed to capture the plastic hinge behavior.

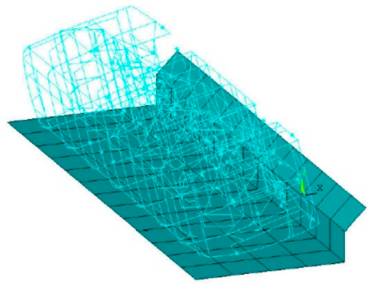


FIGURE 44 - SIMULATION OF BUS STRUCTURE UNION ELEMENTS USING LS-DYNA

Friedman Research (Friedman, 2007b) reported on the use of LS-DYNA for the evaluation of bus structure performance under rollover conditions (Figure 45). Evaluation of the effects of alternative structural materials and designs using enhanced steel and composite materials on rollover performance was reported.

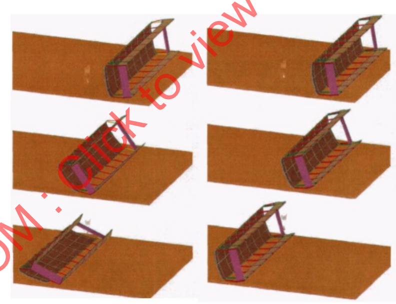
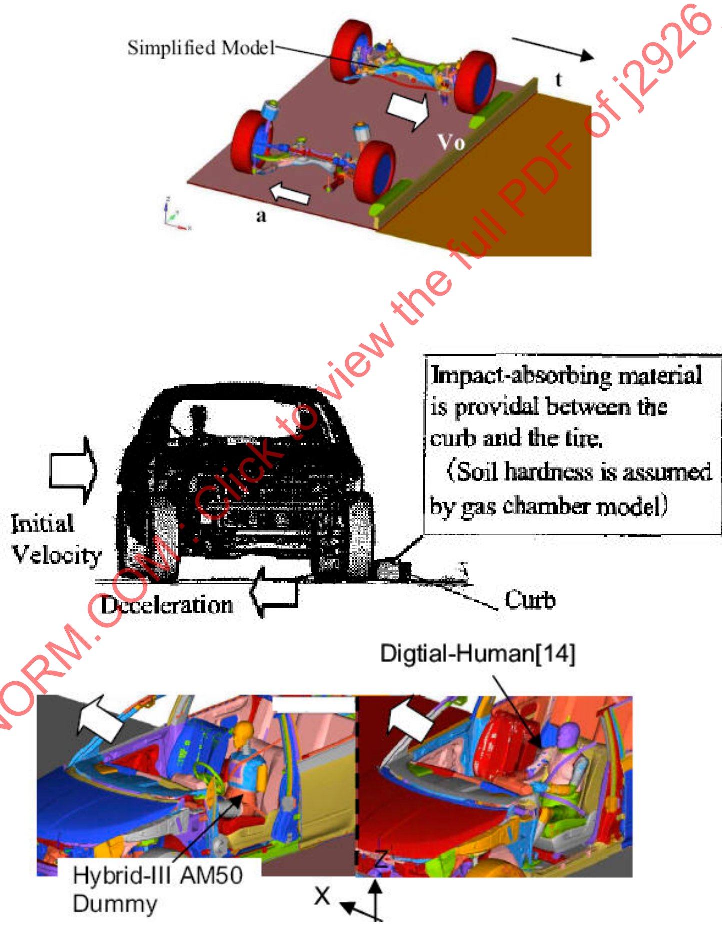


FIGURE 45 - EVALUATION OF BUS STRUCTURE PERFORMANCE DURING ROLLOVER USING LS-DYNA

5.10 Curb and Soil Trip Rollover

Ootani (2007a, 2007b) of Nissan utilized PC-Crash and RADIOSS in modeling curb and soil trip rollovers. (Figures 46A, B, C) It was found that an FE model was needed to properly represent the deformation energy associated with the curb impact. A full FE model of the vehicle and a dummy were utilized for the curb impact and subsequent rollover. FMVSS 216-type testing was used to validate the RADIOSS model. Comparisons were made with a vehicle of similar weight, cg height and moments of inertia. For the soil trip case, PC-Crash was utilized to characterize initial conditions about 1 s prior to a simulated roll. For soil rollover, it was found that FE analysis will be very helpful and sometimes necessary for more accurate investigation of rollover accident reconstruction. However, a simplified representation of the soil buildup using a simple air-bag-type cushion mechanism and a curb were used here. It was concluded that a proper combination of PC-Crash and finite element analysis can be a very useful tool to reconstruct and analyze complex real-world rollover phenomena. It also was concluded that this combination can help design engineers select proper parameters for experimental setup to evaluate and check the performance of existing or new occupant restraint systems under consideration.



FIGURES 46A - 46C - MODELING CURB AND SOIL TRIP ROLLOVER USING PC-CRASH & RADIOSS

5.11 Side Curtain Development

Narayanasamy (2005) from Delphi reported on the use of CAE methods in the development of side curtain airbags. (Figure 47) The use of a Free Motion Head form impacting a pole with a pillow-shaped airbag is reported. The influences of the curtain airbag design parameters such as pressure, chamber width, impact speed and hit location were evaluated. Comparisons with physical tests showed good correlation.

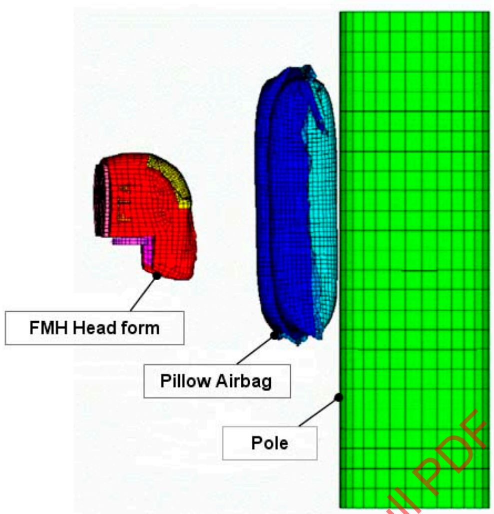


FIGURE 47 - USE OF CAE METHODS AID IN DEVELOPMENT OF SIDE CURTAIN AIRBAGS

Zhang (2004) from Delphi reported on CAE methods and the use of uniform pressure and CFD methods in the development of a side curtain airbag. (Figure 48) He also found that CAE methods have great potential to reduce the material cost and time duration of the airbag design process. He reported that with CAE models, especially the CFD simulations, deeper understanding and insights into the physics of the design problems, which are very hard to obtain through physical tests, can be achieved. With a CAE-based approach, Design of Experiments (DOE) and other numerical optimization tools can be used to optimize a design. Further, the CAE experience that was learned from previous designs can be transferred easily to new products. Zhang evaluated the use of LS-DYNA's ALE capability, MADYMO's gas generator model, and Pam-Crash's FMP capabilities. He reported that all tools had something to offer depending on the priorities of the user.

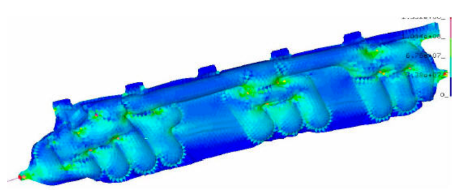


FIGURE 48 - DESIGN PROCESSES ARE OPTIMIZED USING CAE-BASED APPROACHES