

A Study of Occupant Ejection Mitigation During Rollovers for Front Row Occupants

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ABSTRACT

As a part of its ejection mitigation research, the National Highway Traffic Safety Administration (NHTSA) has proposed a linear impact test that uses a featureless head-form to impact a vehicle's side windows' daylight opening at various positions. The test measures the excursion of the head-form beyond the plane of the window glazing. The intention is to evaluate the ability of a vehicle's ejection mitigation countermeasures, such as the curtain airbag or other vehicle features, to manage the impactor energy and limit excursion. However, at this time NHTSA has not yet established the performance criteria for the excursion. Additionally, there is no clear agreement on the energy level to be used for ejection mitigation testing. The agency has considered three energy levels for the head-form impact: 178, 280, and 400 Joules [9]. This paper discusses the results from computer modeling used to study an ejection representative energy level that can be employed for evaluating ejection mitigation systems. Additionally, the authors will present a parameter study in which the stiffness of a curtain airbag has been optimized considering both the NHTSA's ejection mitigation research test method as well as side impact performance.

INTRODUCTION

Rollover crashes continue to have a significant impact on occupant injuries. In 2007, rollover crashes accounted for approximately 35% of the 28,933 passenger vehicle occupant fatalities [1]. Rollovers are complex events characterized by

unpredictable vehicle and occupant kinematics. They can be influenced by a variety of factors including occupant behavior before the event, vehicle parameters, roadway design, and other environmental conditions.

EJECTION

In 2005, 4,606 people were killed as a result of being completely ejected during a rollover, accounting for roughly half of all occupants killed in crashes where rollover was the most harmful event [5].

Many studies have concluded that restraint use reduces the injury risk in rollovers primarily by reducing the risk of ejection. Unbelted occupants run the highest risk of being ejected, and this risk increases with number of rolls. In studying NASS/CDS field data from 1995-2003, Moore et al. determined that for crashes involving less than one roll, the risk of ejection for unbelted occupants is less than 20%, but the risk increases to over 80% in rollovers involving three or more rolls [6]. By comparison, the risk of ejection for belted occupants is less than 10% and less than 5% for 3+ rolls and 1 roll, respectively.

BELT USE

In rollover crashes, the occurrence of serious or fatal injuries is heavily influenced by belt use. Padmanaban et al. studied various driver and vehicle factors to estimate their influence (explanatory power) of front seat occupants receiving fatal or serious injuries in single-vehicle rollovers [11]. In analyzing 93,823 crashes, driver belt use explained 67% of the variation

in the odds of fatality. They also presented that of 2,570 fatal injuries from over 100,000 rollover crashes; approximately 77% were sustained by unbelted front seat occupants. Parker et al. summarized 1988-2004 NASS/CDS data to show that approximately 10% of all crash-involved occupants are involved in rollovers [4]. Of that 10%, 0.6% of the occupants were involved in crashes with 8 or more quarter turns. Of that 0.6%, 0.2% of the occupants were unbelted. Even though a small percentage of all crash-involved occupants were unbelted during a rollover, they make up a disproportionate number of fatalities. Although this data suggests that seatbelts are the most effective countermeasure for rollovers, NHTSA has indicated that any ejection mitigation rulemaking would consider unbelted occupants in an effort to help further reduce ejection fatalities. It is recognized that if an ejection mitigation countermeasure such as a curtain airbag is developed to protect unbelted occupants, there may be injury trade offs for the belted occupants, particularly with regards to side impact protection.

EJECTION MITIGATION COMPONENT TEST DEVELOPMENT

The National Highway Traffic Safety Administration (NHTSA) has been studying rollovers for a number of years. In 2003, NHTSA published the report “Initiatives to Address the Mitigation of Vehicle Rollover” [7] which outlined vehicle, roadway, and behavioral strategies to help mitigate rollover crashes. Several of the proposed strategies have resulted in the application of new regulatory requirements subsequent to the report. However, a component level test and criteria to evaluate ejection mitigation countermeasures are still under consideration. The work presented here was performed to contribute to the ongoing research for an ejection mitigation test procedure.

Linear Impactor Test Procedure

NHTSA has identified the need for a component level ejection mitigation test procedure due to their observed variability in vehicle and occupant kinematics in full vehicle rollover tests, noting that “[f]or a test to be acceptable, it must show that good (or poor) performance in the laboratory test correlates to good (or poor) performance in the real world” [12]. The agency has studied the use of a linear impactor test for this purpose dating back to their advanced glazing research [8].

NHTSA has published details of the current test set up and parameters being used for research [9]. The linear impactor is a guided impactor that projects an 18 kg impacting mass in the shape of a featureless head-form. This 18 kg mass is designed to be representative of the impacting mass of an AM50 occupant. In the NHTSA procedure, four impact locations are tested on each of the daylight openings to which the evaluated countermeasure is applied. Using a

potentiometer, the impactor measures the excursion of the head-form beyond the inside glazing surface of the daylight opening. NHTSA has researched the proposals summarized in Table 1. Both proposals consist of two test conditions: the first test is conducted at a 1.5 second delay (time after curtain deployment time); the second test is conducted at a 6 second delay. For the first test, there are currently two energy levels NHTSA has considered, 280 Joules or 400 Joules. The proposed impact energy for the second test (6 second delay) is 178 Joules. These test conditions were determined on the basis of dummy pendulum testing, video analysis of full scale rollover tests, and sled testing outlined by NHTSA in the Advanced Glazing First Status Report [8]. Figure 1 shows a typical test setup, and it outlines the method for determining the impact locations for each daylight opening.

Table 1. NHTSA R&D Linear Impactor Test Conditions.

	Impact Mass	Test Energy	
		1.5 second delay	6.0 second delay
Proposal 1	18 kg	400 Joules Test Speed = 24 km/h	178 Joules Test Speed = 16 km/h
Proposal 2		280 Joules Test Speed = 20 km/h	

<figure 1 here>

Linear Impactor Test Energy

In order to accurately evaluate ejection mitigation countermeasures in terms of expected effectiveness, a test procedure should simulate conditions indicative of ejection producing conditions in the real world. However, collecting directly relevant data such as ejection energy in real world rollover crashes is not possible.

A 2007 study by O'Brien et al. used a series of rollover sensor development tests to identify the load and energy absorption characteristics that could be used in the development of ejection countermeasures [2]. They used several rollover test conditions, including the Curb Trip and Dolly, as well as Soil, Corkscrew, and Ditch tests to conduct a total of 57 tests. Using data from load cells positioned at the mounting locations of membranes placed over the front side windows and accelerometers mounted at various locations on the vehicle, they calculated the kinetic energy of Anthropomorphic Test Devices (ATD) in the front seat that were restrained by the membrane. They used this kinetic energy calculation to analyze data from tests which were conducted with both belted and unbelted ATD's. Tests with unbelted ATD's resulted in low head velocities but large effective mass while belted tests resulted in higher head velocities but lower effective mass. In all cases, the calculated kinetic energy was less than 180 Joules. In the paper, emphasis is placed on, "...the need to focus on energy requirements for an ejection mitigation countermeasure as opposed to choosing mass and velocity values independent of kinetic energy levels." Thus, for their component tests, they

selected impactor parameters based on the calculated kinetic energy levels. While using the same 18 kg impactor mass as in NHTSA's proposed procedure, they suggest a velocity of 16 km/h, which produces a kinetic energy of 182 Joules.

Linear Impactor Excursion Criteria

At this time NHTSA has proposed a possible excursion requirement of not more than 100mm beyond the plane of the side window, however, the justification and relevance of this value is unclear. Shilliday and Mowry studied the influence of changes in air bag characteristics on head-form excursion measured using the linear impactor test and compared the results to occupant retention ability of the air bag [13]. A series of guided impactor tests were performed on a single air bag design where inflation pressure was varied from test to test and head excursion measured. MADYMO simulations were also performed at each air bag inflation pressure to simulate an AF05 occupant in a NHTSA Dynamic Rollover Fixture (DRF) test with a maximum roll rate of 360 degrees per second. The excursions measured in the linear impactor tests were then compared with the occupant retention observations in the DRF simulations.

Shilliday and Mowry observed that the ejection/retention threshold in the DRF simulation corresponded to small changes in excursion measured in the linear impactor test. Additionally, large differences in excursion were identified depending on the location of the linear impactor test point. The authors concluded that “[t]hese discrepant results make it difficult to define an allowable excursion criterion.”

It is unclear whether changing other air bag parameters in conjunction with air bag pressure would have resulted in occupant containment in the DRF simulations with the same or similar measured excursion in the linear impactor test. However, the Shilliday and Mowry study suggests that the ability of a given excursion measurement in the linear impactor test to predict ejection or non-ejection of an occupant in a rollover may be limited. As such it is not clear what excursion criterion is appropriate, and care should be taken in deciding this value. For the purposes of this study, the NHTSA proposal of 100 mm will be used; however, the authors believe additional research is necessary to set an appropriate criterion.

METHOD

Curtain airbags developed for ejection mitigation must serve two purposes: to help mitigate the risk of ejection in rollovers while also providing occupant protection in side impacts. As such, care should be taken to balance the performance requirements for both purposes when developing the restraint systems. The purpose of this research was to study this balance in the development of curtain airbags. To accomplish this, this study was divided into two portions:

- Occupant Containment Energy Case Study

- Curtain Airbag Pressure Parameter Study

OCCUPANT CONTAINMENT ENERGY CASE STUDY

The purpose of this study was to analyze a severe rollover test and estimate a representative occupant containment energy level that a curtain airbag may experience. The findings for this test case were then compared with each of the agency's two proposals.

Four rollover tests were considered for analysis (reference Table 2). For the purposes of this study, the authors chose to use the number of quarter-turns as a comparative metric for rollover severity. This was deemed to be reasonable given Moore's finding that the risk of ejection increases from 5% and 20% for less than 4 quarter-turns to 10% and 80% for greater than 12 quarter-turns for belted and unbelted occupants, respectively [6]. Thus, as the number of quarter-turns increases so does the risk of ejection. Of the four tests considered, the FMVSS 208 Dolly rollover had the highest number of quarter-turns with a total of 12. Furthermore, the 12 quarter-turns value represents over 98% of field incidents with a MAIS 3 or greater injury (Figure 2). Therefore, it was concluded that the dolly rollover was the most severe of the tests considered, and while not a repeatable, it provides a reasonable representation of a severe rollover.

<table 2 here>

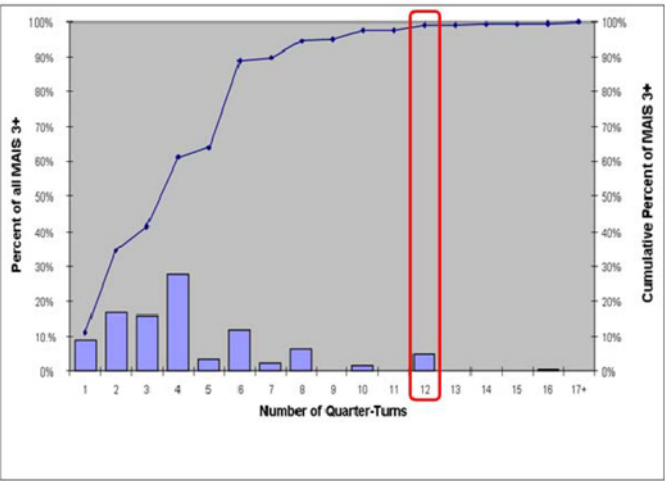


Figure 2. MAIS 3+ Injuries vs. Number of Quarter Turns [3].

The test vehicle was instrumented to measure the X, Y, and Z accelerations as well as angular velocities in the vehicle's local coordinate system. This data was then used as inputs for a MADYMO model using a prescribed motion technique as proposed by Yu, et al. [10]. The following conditions were used for the analysis:

1. AM50 occupants were used in the front outboard seating positions.
2. All modeling was conducted with unbelted occupants given that they would represent a more severe case for the curtain airbag, as well as NHTSA's intention to consider unbelted occupants in their rule making.
3. It was not necessary to model the entire vehicle including the suspension since a prescribed motion technique was utilized for this study. Therefore, only the components which the dummy interacted with were included in the model (Figure 3).

Figure 4 shows the occupant kinematics from the MADYMO model. The vehicle orientation relative to the global coordinate system is also shown for reference (reference appendix for information of simulation correlation). To estimate the maximum energy with which an occupant may impact an ejection mitigation countermeasure, the energy transfer between the interior components and the dummy was measured in the simulation. In a rollover, occupants tend to move outward and upward interacting with the side window glazing and the headliner. The balance in the energy sharing between these two components will vary depending on the vehicle layout and occupant position. Therefore, it is difficult to predict an appropriate energy considering only the impact with the window glazing for this one vehicle layout. For this reason, the sum of the energy transfers between the occupant and both the window glazing as well as the headliner was used.

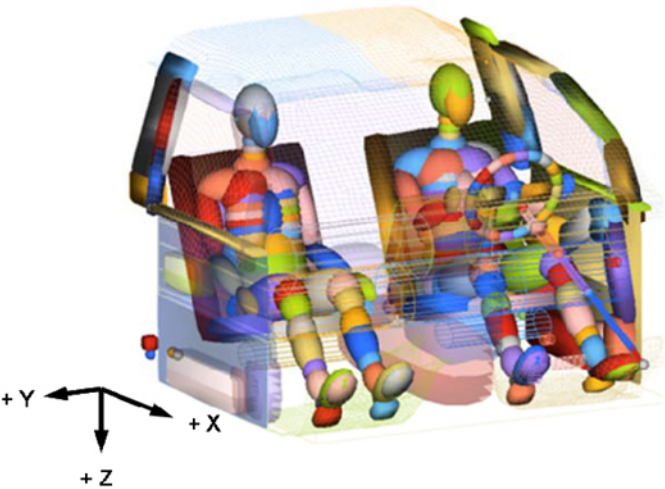


Figure 3. MADYMO model with unbelted occupants.

<figure 4 here>

CURTAIN AIRBAG PRESSURE PARAMETER STUDY

The next portion of this study concentrated on examining the balance between ejection mitigation and side impact. Figure 5

shows an overlay of the dummy head locations for AF05 and AM50 occupants seated per Federal Motor Vehicle Safety Standard (FMVSS) No. 214, “Side Impact Protection” [14], and the impact points proposed for the ejection mitigation component test. The curtain airbag can be considered to consist of two zones. A smaller ‘side impact’ zone that is defined by the FMVSS 214 seating position that falls within a larger ‘rollover’ zone that can be considered related to ejection mitigation. To study the potential trade-offs between side impact and ejection mitigation, a series of component tests were conducted on a surrogate ‘rollover’ curtain airbag at various airbag pressures.

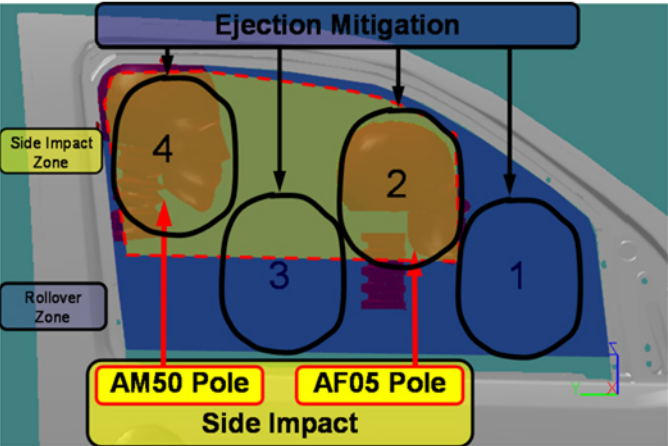


Figure 5. Side impact dummy seating compared with the ejection mitigation impact points for the front row.

For side impact, the requirements of FMVSS 214, Side NCAP, and the IIHS side impact test were considered. The FMVSS 214 pole test was chosen as representing the most severe side impact condition. This was determined by studying full scale crash tests for each of the test modes. As can be seen in Table 3, the FMVSS 214 Oblique pole test represents the highest energy absorbed by the curtain airbag for the AM50 and AF05 occupants, respectively.

<table 3 here>

A linear impact testing method was used to simulate the FMVSS 214 oblique pole test. A 254mm simulated rigid pole was positioned directly behind the Head C.G. impact location. The test setup is shown in Figure 7. A Hybrid III AM50 half head-form was mounted on a linear actuator with an effective mass of 5.5 kg. Testing was conducted for both the AM50 and AF05 seating positions per Figure 6. The impact speed was adjusted to achieve the desired impact energy for the AM50 or AF05 occupants depending on which position was tested. The head injury criterion (HIC) was predicted based on the peak force measured in the component test.