Evaluation of Occupant Excursion and Restraint in Rollover

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Abstract - Providing effective occupant protection in rollover crashes requires supplying the occupant with a restraint system proven effective in the dynamic rollover accident mode. Preventing ejection and providing restraint sufficient to prevent potentially injurious contacts with both interior and exterior vehicle components is paramount for effective rollover occupant protection. Research has shown that the injury potential can be decreased by closely coupling the occupant to the seat.

This paper focuses on the effect of restraint system slack and its relationship to occupant excursion and ejection potential during rollover. Various restraint system configurations are evaluated in rollover-type test environments. A review of prior research is presented prior to presenting new quasi-static vehicle inversion studies conducted with live surrogate occupants. Additionally, dynamic rollover testing utilizing anthropometric test devices (ATDs) is presented. The influence of belt looseness and effects of various restraint designs on the belted occupants' injury potential are discussed.

INTRODUCTION

The rollover crash mode has been the focus of a significant amount of research for decades, yet a review of recent crash statistics confirms that the rollover crash mode continues to be overrepresented in terms of resulting serious injuries and fatalities [1]. This simple reality has and continues to motivate researchers to focus on restraint technologies capable of managing the multiplanar, multiple impact environments unique to the rollover mode. Managing the occupant's kinematics and providing protective occupant restraint by controlling or limiting an occupant's excursion via closely coupling the occupant to the seat has been shown to reduce injury and ejection potential.

During a real world rollover, however, many sources of slack in an occupant's restraint system can develop. Belt anchor deformation, deformation of the vehicle structure itself to which a restraint system's anchors are mounted, deployment of frontal designed load limiting features (such as torsion bars and/or webbing stitched loops), webbing elongation, retractor webbing payout or film spool can all add slack to the occupant's restraint system resulting in increased excursion and ejection risk.

In the presented studies, various amounts of belt looseness was added to production or OEM (original equipment manufacture) restraint systems with the effects on occupant restraint then being evaluated in rollover inversion (spit) tests. The relationship between given amounts of slack and the resulting occupant excursion was analyzed, along with the effects of various slack mitigation techniques.

PREVIOUS RESEARCH

The ability of the automotive seat belt to provide effective restraint, prevent full and/or partial ejection, and control potentially injurious interior impacts dates back as early as 1959 when Shoemaker [2], using a rollover simulator, studied the kinematics of restrained and unrestrained dummies. Shoemaker reported that lap belts are of great value but that in some tests the dummy's head struck the car's roof. Stone [3], in 1974, noted that belted dummies experienced significant lateral head and upper torso movement when reporting dummy kinematics in rollover crash tests. In 1984, Johnson et al. [4] noted similar partial ejection rates for both belted and unbelted occupants from their study of rollover crash films. Obergerfell et al. [5] simulated rollovers and observed early on that the occupant fell to the side and slipped the shoulder belt, which allowed the upper body to move around while the lap belt restrained the occupant.

In 1990, Bahling et al. [6] positioned three approximately 50th percentile males in a 1983 Chevrolet Malibu with 3-point restraints, which included a tension reliever and cinching latch plate, to observe their excursion in an inverted (180 degree roll) environment. The authors reported an average excursion of 3.9 in. (9.9 cm). This noted excursion was then used to adjust the restraint system on Hybrid III dummies to be used in subsequent rollover testing. During dolly rollover testing, the dummies' general kinematics were noted as moving upward and outward under centrifugal force until the lap belt restrained the pelvis. The lap belt was noted to restrict dummy movement with an average load of 342 lb (1520 N) reported. The authors further noted that their testing demonstrated the benefit of seat belt usage such that ejection was eliminated and there was a reduction in the number of potentially injurious impacts.

Arndt et al. [7] analyzed two-point lap belt restraint by varying its anchorage (belt angles) and slack/tension. The different scenarios were tested statically (-1 G) with inverted human occupants and both statically and dynamically (14 ft/s (4.25 m/s), -5 Gs) with 95th percentile Hybrid III Anthropometric Test Devices (ATDs), or dummies, subjected to inverted drops. These tests demonstrated that more vertical lap belt angles allowed less head excursion and that pretensioning the lap belt webbing could also reduce head excursion. In a later study, Arndt et al. [8] conclude that seat belt characteristics such as webbing spool out, anchor position and routing geometry play a significant role in the occupant's vertical motion and that by removing webbing, or effectively pretensioning the system, a reduction in vertical excursion can be achieved.

Herbst et al. [9] reported excursion for surrogate occupants of various sizes that were inverted, statically and dynamically (~100 deg/s), in a simulated vehicle compartment. The occupant excursion allowed by three different OEM restraint systems was compared to a manually adjusted lap belt only (two-point) restraint system with improved geometry (more vertical lap belt angles) for rollovers. The OEM three-point restraint systems demonstrated an average of 4.5 to 9.2 in. (11.4-23.3 cm) of static excursion and 3.7 to 10.2 in. (9.3-25.8 cm) of dynamic excursion. The dynamic rotational rate of 100 deg/s was reported to only increase the static excursion by 0.75 in. (1.9 cm) while the improved lap belt geometry of the two-point belt was reported to reduce excursion by 45 percent on average. The authors also noted that the lap belt controlled vertical excursion while the shoulder belt reduced upper torso motion.

Utilizing the same basic apparatus, Friedman et al. [10] and Meyer et al. [11, 12] expanded on this testing. Friedman et al. combined pretensioning (5.2 lb, 23 N) along with optimized seat belt anchor geometry which limited occupant excursion to 0.8 to 1.2 in. (2-3 cm). Meyer et al. [11] reported that by simply adding pretensioning to a typical OEM belt system, vertical occupant excursion was reduced by 30 to 40 percent in a static inverted environment. Further, in 2000 [12], OEM restraint systems' anchors were modified to simulate all-belts-to-seat (ABTS) anchorage geometry along with a buckle pretensioner, which removed approximately 3.9 in. (10 cm) of webbing. Occupant excursions of 3.4 to 7.4 in. (8.7-18.8 cm) were noted in the OEM restraint systems and the modified restraint systems reduced excursion to 0.8 to 1.8 in. (2.1-4.6 cm), resulting in 73 to 82 percent reductions.

James et al. [13] conducted static rollover tests with a 5th percentile female and a 80th percentile male occupant in the driver's seat during a near sided roll in various OEM vehicles, model years 1983-1988, and their associated restraint systems. At 135 degrees of rotation, the occupants were noted to penetrate through an artificial ground plane, or out the driver's window, by 0.5 to 2.6 in. (1.2-6.5 cm). When inverted, the 80th percentile male's head was reported to be in contact with the roof and the 5th percentile female's head was reported to be either in contact or within an inch of the roof, representing approximately 5 in. (12.7 cm) of excursion for each. The authors state that neither occupant size nor type of restraint had any significant effect on the measured static excursion. Further, they noted that although seat belt systems can be modified to reduce vertical excursion, the head will still be exposed to lateral contact with the ground.

Pywell et al. [14] documented lateral and vertical excursion for a 50th percentile dummy positioned in a pivoting laboratory test fixture intended to simulate vehicle rotation. They found that a belt restraint system that would draw an occupant down and back into the seat quickly could reduce occupant contact with interior and exterior surfaces. The authors concluded that belt geometry, hardware configuration and tensioning had the greatest affect on dummy kinematics. Pretensioning was found to reduce vertical excursion by 41 to 63 percent, as well as reducing lateral head excursion by 15 to 38 percent, in all restraint types tested.

In 1997, Moffatt et al. [15] reported on head excursions of seat belted cadaver, volunteers and Hybrid III ATDs in static and dynamic rollover tests. These authors concluded that in rollover conditions the Hybrid III ATD was stiffer than the human volunteers in the static test and the cadaver subjects in both static and dynamic tests. They noted that statically, the Hybrid III averaged about 2.6 in. (6.5 cm) less vertical excursion than the volunteers and cadaver. When combining dynamic and post-dynamic results, the Hybrid III averaged about 2.75 in. (7 cm) less vertical excursion than the cadaver. These studies also reported vertical lap belt angles to be more effective at reducing excursion while the torso belt primarily restricted forward rotation of the torso. Lastly, by applying pretensioning loads of between 50 to 150 lb (222-667 N), these authors concluded that early application of pretension loads can significantly reduce head excursion.

Rains et al. [16] compared OEM restraints to inflatable restraints using the National Highway Transportation Safety Administration's (NHTSA) rollover restraints tester. 50th percentile male Hybrid III ATDs were positioned in the fixture and subjected to a rollover of approximately a 260 deg/s with a subsequent impact to simulate a roof strike at 180 degrees of inversion. The experimental inflatable restraints were shown to reduce ATD vertical excursion by 60 to 75 percent over the baseline restraints by effectively providing pretensioning.

Ward et al. [17] studied inverted excursion for various sized occupants and 50th percentile dummies positioned in the driver seat after a far side static roll. The effects of a pass-through latch plate versus a cinching latch plate were analyzed with the cinching latch plate demonstrating an average reduction in human head excursion of 53 percent. The authors conclude that "occupants who slip out of their shoulder belts and are restrained with a pass-through latch plate are at a greater risk for injury in a rollover" and that "a tight lap belt is needed to prevent neck injury" when headroom is reasonably maintained.

Meyer et al. [18] subjected water ballast dummies to dynamic inverted drop testing resulting in 4 to 11 Gs decelerations. The dynamic excursion of the dummies was found to be only 0.9 to 2.2 in. (2.3-5.5 cm) greater than that of the static 1 G inverted excursions recorded.

In 2003, Moffatt et al. [19] measured the vertical excursion of approximately 5th percentile female and 50th percentile male ATDs and human subjects in a production 2001 Nissan Pathfinder with its window and roof structure removed allowing for unrestricted excursion. In total, 35 tests of both near and far side roll static inversion or dynamic rollovers with roll rates up to 360 deg/s were conducted. With a typical three-point restraint system with pass-through, or sliding, latch plate, an average static roll excursion of approximately 4.9 in. (12.5 cm) was reported. The authors concluded that static excursion tended to overestimate near-side dynamic excursion and underestimate far-side dynamic excursion. They noted that occupants positioned on the far side of the rollover tend to have greater head excursion than occupants located on the near side of the rollover likely due to the far side occupant slipping out from under the shoulder belt during inboard rollover motion. During the dynamic testing, belt webbing of up to 3.2 in. (8.3 cm) was noted to move from the shoulder into the lap belt. These authors also concluded that the Hybrid III dummy was a reasonable surrogate for restrained human volunteers when measuring vertical head excursion.

In 2005, Lai et al. [20] reviewed Moffatt's 2003 [19] excursion data in an attempt to model the same testing in MADYMO with both a human facet model and a Hybrid III model. The authors concluded that the Hybrid III ATD model produced the most comparable results to the human subject tests. Newberry et al. [21] then expanded on the previous study by developing a MADYMO computational model of a rolling airborne vehicle that was validated from Moffatt's 2003 [19] data set. Occupant kinematics for steady state rollovers were then examined at up to 720 deg/s. Although the model developed appears to consistently overestimate occupant excursion relative to the data collected by Moffatt [19], the authors found that the average static ATD inversion data of 4.9 in. (12.5 cm), as reported by Moffatt, is not exceeded dynamically until roll rates of above 450 degrees per second. Newberry et al. further concluded that additional vertical head excursion, on the order of 3 in. (7.6 cm), can occur in the absence of significant torso restraint or when the occupant escapes from the shoulder belt.

Sances et al. [22] conducted a series of dynamic rollover spit tests using a 1999 Lincoln Navigator at roll rates up to 180 deg/s. A 50th percentile male Hybrid III ATD, with its weight ballasted up to 248 lb (112 kg), was placed in the driver's seating position and subjected to a far side rollover for each test. The authors analyzed the effect of different torso belt routing with the OEM restraint system's pass-through latch plate in comparison with a restraint system incorporating a cinching latch plate with a normal lap belt length and the torso belt fully extended. The authors noted that a securely fastened lap belt (via a cinching latch plate) held the ATD to only 3.5 to 4 in. (8.9-10.2 cm) of dynamic movement. They further note that occupant motion is less affected by various upper torso belt routings with a tight lap belt.

In 2005, Moffatt et al. [23] identified numerous human and vehicle factors that lead to human excursion and head-to-roof contact in rollovers. The authors use graphical illustrations to explain how various factors contribute to total occupant excursion: static excursion, rotational excursion, impact excursion and seat belt anchor (due to roof crush) excursion.

Benda et al. [24] analyzed ATD excursion for two restraint system designs during inverted drop testing. The first system replicated Bahling's 1990 study with its approximately 4 in. (10 cm) of pre-drop, static inverted excursion. In this system, under the drop testing of approximately -8 Gs, head strike occurred in each test with the test fixture roof plate. The second restraint system tested utilized seat integrated restraints (SIR) with the webbing tightened to simulate 13 to 15 lb (58-67 N) of pretension which prevented any head strikes during the drop testing. The authors noted that in all head strikes a head and/or neck injury criterion was violated, and as such, they conclude that a goal of restraint design must be to minimize head excursion to reduce the likelihood of head strike with a vehicle's roof.

Meyer et al. [25] noted that deforming vehicle structure during drop testing and rollovers introduced slack into the torso belt via upper anchor movement down and in towards the occupant compartment. That slack was then seen to migrate through the OEM restraint systems' pass-through latch plates, resulting in increased occupant excursion. Occupant excursion studies were presented in which cinching latch plates and pretensioning counteracted the effects of slack on occupant excursion. An ABTS restraint system was found to effectively reduce occupant excursion and isolate the restraint system from the noted deforming vehicle structure.

Herbst et al. [26, 27] examined the effects of roof crush and occupant excursion in a parametric analysis with a deformable occupant test device and Hybrid III ATDs. This deformable test device, referred to as DOCIT, was designed to replicate roof crush seen in real world rollovers, yet it can then be reset to an undeformed state for a repeatable environment without destruction of a full-sized vehicle. Four inverted impact test series were presented in which lower ATD injury measures were recorded when either roof crush or occupant excursion was reduced. Roof contacts were eliminated in several tests by the reduction of both roof crush and occupant excursion.

Curzon et al. [28] utilized MADYMO software to examine belt length and restraint system geometry in simulations of the first roof-to-ground strike in near and far side rollovers as well for a frontal impact. The authors studied whether occupant protection could be improved in rollover without sacrificing frontal impact protection and concluded that decreasing the lap belt length will likely increase protection in both accident modes.

TEST METHOD

A series of rotational inversion tests, both static with surrogate occupants and dynamic with Hybrid III dummies, have been performed within various automotive vehicle compartments. These tests included the introduction of varying amounts of belt slack to evaluate the effect of such slack on occupant excursion. As pointed out above, there are numerous foreseeable sources of belt slack which may develop during the course of a real world multiple impact rollover sequence. The effect of the belt slack on excursion is recorded and compared to the OEM excursion allowed by a properly locking, or tight, belt configuration. Various restraint systems are considered.

In each of the static tests series described below, the vehicle or vehicle compartment (buck) was positioned in a rotational test fixture which allowed rotation about the vehicle's longitudinal axis at its approximate center of mass (Figure 1). The vehicle compartments were first positioned upright such that a baseline head position was recorded. The test vehicles were then rotated about their longitudinal axes, either driver side or passenger side leading, to an inverted position (180 degrees roll) wherein the inverted head position was then recorded. Various occupant sizes and restraint configurations were included.

Figure 1. Static Roll Spit Test Fixtures

In the dynamic test series, a vehicle buck was used and mounted into a high speed rotational fixture that allowed for dynamic roll rates of up to 500 degrees/s. The vehicle rotation was again centered about a longitudinal axis located at the approximate center of mass of the vehicle buck (See Figure 2). Hybrid III ATDs only were used in the dynamic environment with the effect of various belt configurations and induced slack circumstances on occupant excursions being recorded.

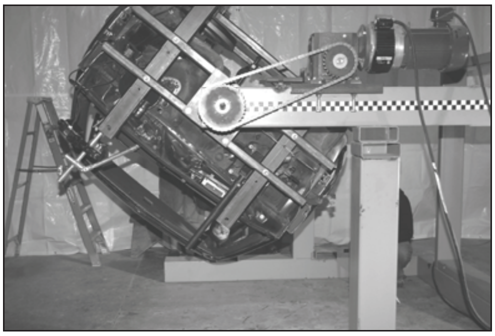


Figure 2. Dynamic Roll Spit Test Fixture

STATIC TESTING

Series 1

A female surrogate standing approximately 66 in. (167.6 cm) tall, seated height 33.75 in. (85.7 cm), weighing 230 lb (104 kg), was positioned in the right front passenger seat of a 1995 model year

Chevrolet Corsica sedan. The full vehicle was mounted into the rotating fixture as described above. An opening was cut in the roof panel to allow the full extent of occupant excursion to be recorded. The vehicle's OEM restraint system incorporated a stitched latch plate and door mounted D-ring. The right front seat was positioned at approximately its mid fore/aft position with the seat back at 33 degrees of recline (as measured at the lower portion). Inverted occupant excursions were measured utilizing the OEM seat belt with the retractor locking during rotation. Additionally, the effects of belt pretensioning were recorded with 10 to 20 pounds (44-89 N) of belt tension being added to both the lap and torso belt prior to inversion. Lastly, the OEM three point seat belt was equipped with a stitched belt loop (EA loop) at the lap belt. This stitched loop was designed to rip upon impact and was, therefore, cut prior to inversion to evaluate the resulting effect on occupant excursion. This stitched loop of webbing added an additional 5.25 in. (13.3 cm) of slack into the OEM lap belt.

In the normally locking OEM belt, the average head excursion was recorded at 8.17 in. (20.8 cm) when inverted 180 degrees. This excursion was reduced by 33 percent to an average of 5.5 in. (14 cm) with the addition of the pretensioning. With the EA loop deployed, and an increased lap belt length of 5.25 in. (13.3 cm), the average head excursion recorded was 10.38 in. (26.4 cm), or approximately 2.6 in. (6.6 cm) beyond the OEM. Static test data and photographs can be found in Table 1 and Figure 4 below.

Series 2

A male surrogate, 67 in. (170 cm), 35 in. (89 cm) seated height, 173 lb (78 kg), was positioned in the driver's seat of a 1995 Nissan Pathfinder. The vehicle was again mounted in the rotational test fixture with an opening cut in the roof panel to allow unrestricted occupant excursion. The vehicle was rotated with the passenger side leading. The driver's seat was positioned at its full rear fore/aft position, the seat back was set to 25 degrees of recline, and the D-ring was non-adjustable. The belt configurations included the (1) OEM system, which provided a pass-through latch plate, with the retractor locking due to roll angle, (2) the addition of 6 in. (15.2 cm) of slack added into the belt system (3 in. (7.6 cm) into the lap and 3 in. (7.6 cm) into the shoulder belt), and (3) the system was modified to include a cinching latch plate with, again, 6 in. (15.2 cm) of looseness being added into the shoulder belt portion of the webbing.

With the tight OEM restraints, the inverted head excursion averaged 3.5 in. (8.9 cm). With the OEM pass-through latch plate and the addition of the 6 in. (15.2 cm) of slack (3 in. (7.6 cm) in each belt segment) the head excursion was found to increase to 6.2 in. (15.7 cm) on average. The inclusion of the cinching latch plate was found to isolate the lap belt such that the 6 in. (15.2 cm) of slack remained in the shoulder belt portion and the resulting vertical head excursion was recorded at 3.5 in. (8.9 cm), consistent with the tight OEM belts (See Table 1 and Figure 4).

Series 3

A female surrogate 64 in. (163 cm) tall, 34.5 in. (87 cm) seated height, weighing 204 lb (93 kg), was positioned in the right front seat of a 2003 model year Ford Explorer. The OEM restraint included a vehicle mounted adjustable D-ring (mid position) and a pass-through latch plate. The seat was set to a comfortable position for the occupant with the seat in its approximate mid fore/aft position. The vehicle was rotated driver's side leading with occupant excursion recorded at both 180 degrees as well as 220 degrees of roll angle. The normally tight OEM restraint configuration was evaluated along with the OEM configuration with 3 in. (7.6 cm) of belt slack evenly distributed between the lap and shoulder segments. Lastly, the effects of belt pretensioning were studied by pretensioning the lap belt with 25 lb (111 N) of initial belt tension which effectively reduced the lap belt length by 5 in. (12.7 cm).

The normally tight OEM restraints allowed an average of 4.5 in. (11.4 cm) of vertical head excursion at 180 degrees of vehicle rotation. The 3 in. (7.6 cm) of additional belt slack evenly distributed between the lap and torso belt segments increased the OEM excursion to 5.9 in. (15 cm), or by an additional 1.4 in. (3.6 cm), when inverted. The addition of lap belt pretension was found to reduce the excursion to approximately 2.6 in. (6.6 cm) (See Table 1 and Figure 4).

Series 4

A 62.6 in. (159 cm) tall, 120 lb (54 kg), female surrogate was seated in the driver's position of a 2003 model year Ford Explorer. The OEM restraints included a three point belt with a pass-through latch plate and vertically adjusted D-ring (positioned full up). The seat was set to a comfortable driving position for the occupant. The vehicle was then rotated passenger's side leading. Occupant excursion was evaluated with a normally tight OEM belt, with the addition of 7 in. (17.8 cm) of slack introduced into the belt system and evenly distributed between the shoulder and lap belt segments, and lastly with a normally tight OEM belt tightened with 30 lb (133 N) of belt pretensioning at the lap belt, which effectively removed 5 in. (12.7 cm) of lap belt webbing.

With the normally tight OEM restraints, inverted occupant head excursion of approximately 3.1 in. (7.9 cm) was recorded at 180 degrees of rotation. With the addition of the evenly distributed approximately 7 in. (17.8 cm) of slack, the resulting excursion was measured at approximately 6.9 in. (17.5 cm), or approximately 3.8 in. (9.7 cm) greater than the OEM condition. The pretensioning was found to reduce the vertical excursion dramatically to an average of only 1.3 in. (3.3 cm) (See Table 1 and Figure 4 below).

Series 5

Two female surrogates, each approximately 60 in. (152 cm) tall and weighing 115 to 120 lb (52-54 kg), were positioned in the right front seat of a 2003 Ford Expedition. The vehicle's OEM restraint included a pass-through latch plate and an adjustable vehicle mounted D-ring (adjusted full down). The right front seat was positioned approximately 3 in. (7.6 cm) forward of full rear and the seat back was reclined to approximately 23 degrees. The vehicle was positioned in the rotational fixture and rotated driver side leading to 180 degrees. Occupant excursion was evaluated with the OEM latch plate as well as the OEM restraint modified to include a cinching/locking latch plate. Excursions were measured with the tight OEM system as well as a normally tight OEM with locking latch plate plus the addition of a fully spooled out or loose torso belt combined with the normally tight lap belt isolated by the locking latch plate.

Vertical head excursions were found to be consistent between the tight OEM restraint as well as with the fully slack shoulder belt configured with the locking latch plate. In other words, the locking latch plate was found to effectively maintain a tight lap belt and control the vertical excursion equally as well as the normally tight OEM lap and shoulder belt. The loose shoulder belt segment had no significant effect on the vertical excursion as long as the lap belt was kept tight. The cinching latch plate with the normally tight torso belt was found to slightly reduce vertical excursion when compared to the OEM three point belts by virtue of controlling or limiting upper torso rotation (See Table 1 for complete data and Figure 4 for photographs).

Series 6

A female surrogate, approximately 63.25 in. (161 cm) tall and 127 lb (58 kg), was positioned in the right front seat of a 2001 Ford Explorer Sport 2-door buck mounted in the rotating test fixture. The occupant was positioned in the right front seat while the vehicle was rotated with the driver's side leading. The OEM restraint included a vehicle mounted three-point seat belt with a pass-through latch plate. The right front seat was positioned such that its leading edge is approximately 12.5 in. (31.8 cm) aft of the trailing edge of the vehicle A-post, the seat back at approximately 19 degrees of recline, and the adjustable D-ring was in the full up position. Occupant excursion was documented at both 180 degrees and 220 degrees of vehicle rotation. Restraint configurations tested included (1) tight OEM belt (no slack), (2) the OEM with the addition of 17 in. (43.2 cm) of slack induced into the torso belt and allowed to move through the non-cinching latch plate and self distribute into the lap belt, (3) the

OEM restraint reconfigured with a locking latch plate and 17 in. (43.2 cm) of slack induced to the torso belt segment only, and (4) the vehicle buck was reconfigured to include an ABTS, or SIR System, from a 2002 Ford F-150 with excursion measurements being taken with the ABTS provided restraint worn in the normally tight configuration.

At 180 degrees of rotation (fully inverted) the OEM belt allowed 5 in. (12.7 cm) of vertical excursion. The introduction of the OEM belt with 17 in. (43.2 cm) of slack added to the torso belt, allowed the occupant's head to move well beyond the roof and fully outside the vehicle at 220 degrees of rotation. At 180 degrees the head was firmly on the roof while at 220 degrees the occupant's head was 5.5 in. (14 cm) beyond the roof rail. By adding the cinching latch plate the occupant's vertical excursion at 180 degrees of rotation was recorded at approximately 4.75 in. (12.1 cm), or slightly less than the OEM configuration, even with the 17 in. (43.2 cm) of looseness or slack added to the shoulder belt (See Figure 4 below). The geometry improvements afforded by the SIRS further reduced the vertical excursion at 180 degrees as compared to the OEM, but most notably, resulted in a dramatic reduction in lateral head excursion when compared to the vehicle mounted system. The SIRS was found to reduce the vertical excursion to approximately 2.75 in. (7 cm), a 45 percent reduction from that of the OEM configuration (See Table 1).

Series 7

A 2006 Volkswagen Beetle vehicle compartment was mounted to the roll spit fixture such that the vehicle, once inverted, could then be pivoted, or pitched, such that not only a vertical force component but also a rearward force component would act upon the restrained occupants. The test fixture first rotated the vehicle compartment about its longitudinal axis with the passenger side leading until fully invert inverted (180 degrees of rotation). Once inverted, a cable winch attached to the rear bumper area of the vehicle structure was activated to lower the rear of the buck, thereby including a rearward force component to the restrained occupants (Figure 3).

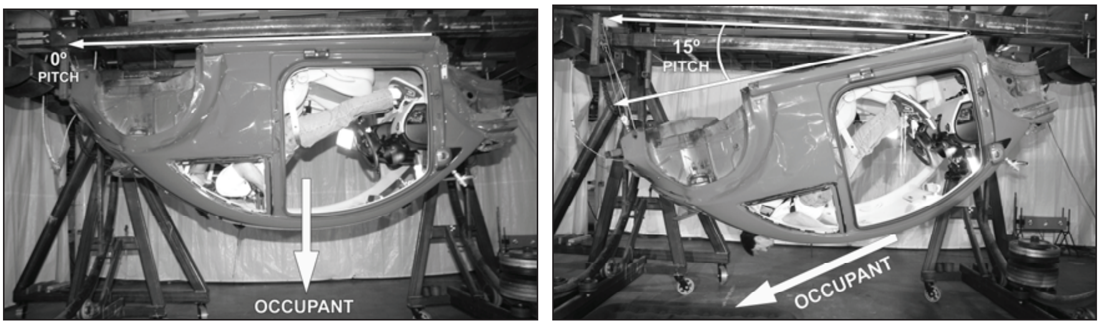


Figure 3. Inverted Vehicle Buck without and with Pitch

In order to simulate crash induced seat deflection, the driver's seat was position in both a normal upright position (approximately 71 degrees from horizontal), as well as at a reclined position (approximately 38 degrees from horizontal). A surrogate male occupant approximately 71 in. (180 cm) tall (36 in./91 cm seated height) and weighing approximately 185 lb (84 kg) was positioned into the driver's seat. The provided OEM restraint system was a three-point lap/torso belt which included a load limiting retractor (torsion bar), a vehicle mounted adjustable D-ring, a pass-through latch plate and, at the outboard lap belt anchor, a deformable slide bar belt anchor. The driver's seat was positioned such that its leading edge is approximately 13 in. (33 cm) aft of the trailing edge of the vehicle A-post with its vertical adjustment set to the full down position. The D-ring was also in its full down position.

The OEM load limiting retractor is designed to limit torso belt loads by spooling out torso belt webbing when the torso belt tensions reach approximately 900 lb (4000 N), while the outboard lap belt side bar anchor is designed to mechanically deform upward while under load. Vertical and rearward inverted occupant excursion data was, therefore, collected with (1) normally tight OEM belts (seat upright and no belt slack), (2) OEM belts with slack (including 4 to 5 in. (10.2-12.7 cm) of belt slack added to the shoulder belt and slight upward deformation of the lap belt outboard anchor slide bar, which raised the outboard anchor approximately one inch (2.5 cm) vertically off the floorboard from the OEM condition), (3) OEM belts with slack but with a locking/cinching latch plate and (4) the OEM seat replaced with a SIR seat from a 2002 Ford F-150.

The addition of 4 to 5 in. (10.2-12.7 cm) of belt slack, along with the upward deformed lap belt anchor, into the OEM restraint system with its pass-through latch plate was found to increase the vertical head excursion from 4.5 in. (11.4 cm) to 7.25 in. (18.4 cm), or by approximately 2.75 in. (7.0 cm). The introduction of a cinching latch plate into this slack belt system allowed approximately 6 in (15.2 cm) of vertical excursion, or only 1.5 in. (3.8 cm) more than the tight belt condition, fairly consistent with the approximate one inch (2.5 cm) vertical deformation of the outboard lap belt anchor. The addition of rear vehicle pitch and rearward seat back deflection resulted in a dramatic uncoupling of the occupant from the vehicle such that partial ejection, with possible full ejection if not for the secondary safety harness, out the rear glazing was observed (See Figure 4 below). The addition of ABTS reduced the OEM tight belt excursion from 4.5 in. (11.4 cm) to 3.25 in. (8.3 cm) or by approximately 28 percent. See photographs in Figure 4 and testing results in Table 2 below.

Series 8

A male surrogate approximately 70 in. (177 cm) tall, seated height 35.8 in (90.8 cm), weighing approximately 195 lb (88 kg) was seated in the right front seating position of a 2000 Mitsubishi Montero Sport occupant compartment buck. The occupant adjusted the restraint system, including seat, to a normal and comfortable position prior to the testing. The OEM provided restraints included an energy absorbing (EA) loop of stitched belt webbing at the lap belt outboard anchor, which when fully deployed induced 8.25 in. (21 cm) of belt slack into the lap belt. The OEM belt included a pass-through, non-cinching latch plate. Occupant vertical excursion was measured when inverted with the driver's side leading at 180 degrees of roll with tight OEM belts, OEM belts with 30-35 lb (133-156 N) of lap belt pretensioning, and OEM belts with the EA loop fully deployed, or with 8.25 in. (21 cm) of belt slack evenly distributed between lap and torso portions of the restraint.

With the tight OEM belt condition, vertical head excursion measured 4.625 in. (11.7 cm). The pretensioned lap belt reduced the vertical excursion to 2.25 in. (5.7 cm). The addition of the EA loop's 8.25 in. (21 cm) of belt slack into the lap belt with the pass-through latch plate increased the vertical excursion by 4.5 in. (11.4 cm) over the tight OEM condition to approximately 9.125 in. (23.2 cm) (See Table 1 and Figure 4).

STATIC TESTING RESULTS AND PHOTOGRAPHS

Table 1. Static Testing Summary Table

Series/ Vehicle	Surrogate Data				Roll[c] Direct.	Analyzed Scenarios in (cm)					
	M/ F[a]	Ht in (cm)	Wt lbs (kg)	Seat[b]		OEM	OEM with Slack	CLP	CLP with Slack	ABTS	Pre-tens.
Series 1: 1995 Chevy Corsica	F	66 (168)	230 (104)	RF	DSL	8.2 (20.8)	10.4 (26.4), [slack=5.3 (13.3)]	-	-	-	5.5 (14)
Series 2: 1995 Nissan Pathfinder	M	67 (170)	173 (78)	LF	PSL	3.5 (8.9)	6.2 (15.7), [slack=6.0 (15.2)]	-	3.5 (8.9)	-	-
Series 3: 2003 Ford Explorer	F	64 (163)	205 (93)	RF	DSL	4.5 (11.4)	5.9 (15.0), [slack=3.0 (7.6)]	-	-	-	2.6 (6.6)
Series 4: 2003 Ford Explorer	F	62.6 (159)	120 (54)	LF	PSL	3.1 (7.9)	6.9 (17.5), [slack=7.0 (17.8)]	-	-	-	1.3 (3.3)

Series/ Vehicle	Surrogate Data				Roll[c] Direct.	Analyzed Scenarios in (cm)					
	M/ F[a]	Ht in (cm)	Wt lbs (kg)	Seat[b]		OEM	OEM with Slack	CLP	CLP with Slack	ABTS	Pre-tens.
Series 5: 2003 Ford Expedition	F-A	61.4 (156)	117 (53)	RF	DSL	4.3 (10.8)	-	3.5 (8.9)	4.3 (10.8)	-	-
	F-B	59.8 (152)	115.5 (52)			2.0 (5.1)	-	1.5 (3.8)	2.0 (5.1)	-	-
Series 6: 2001 Ford Explorer Sport	F	63.3 (161)	127 (58)	RF	DSL	5.0 (12.7)	~13 (33) as measured at 220 deg of roll [slack=17.0 (43.2)]	-	4.8 (12.1)	2.8 (7.0)	-
Series 7: 2001 VW Beetle	M	71.3 (181)	184.5 (84)	LF	PSL	See Table 2 (below) for Data					
Series 8: 2000 Mitsubishi Montero Sport	M	69.8 (177)	195 (88)	RF	DSL	4.6 (11.7)	9.1 (23.2), [slack=8.3 (21.0)]	-	-	-	2.3 (5.7)

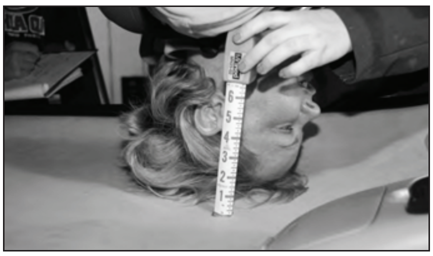
a. M = Male, F = Female; b. RF = Right Front, LF= Left Front; c. DSL = Driver's Side Leading, PSL = Passenger's Side Leading

Series 1: OEM with Slack from Deployed EA Loop

Series 1: OEM with 10-20 lb (44-89 N) of Tension

Series 2: OEM with 6 in. (15.2 cm) of Slack

Series 2: Cinching Latch Plate with Slack



Series 3: OEM with 3 in. (7.6 cm) of Slack

Series 3: OEM with 25 lb (111 N) of Tension

Series 4: OEM with 7 in. (17.8 cm) of Slack

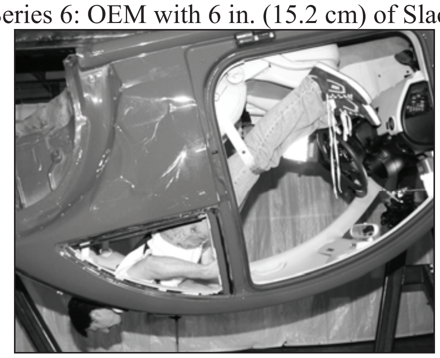
Series 4: OEM with 30 lb (133 N) of Tension

Series 5: Female A - Cinching Latch Plate with Fully Slack Belt

Series 5: Female B - Cinching Latch Plate with Fully Slack Belt

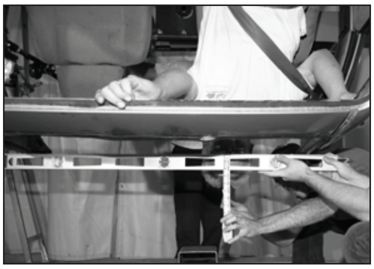
Series 6: OEM with 6 in. (15.2 cm) of Slack

Series 6: Cinching Latch Plate with Slack

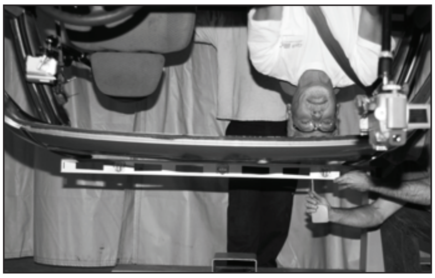


Series 7: OEM with 4 to 5 in. (10.2-12.7 cm) of Slack in Pitched Vehicle

Series 7: Cinching Latch Plate with Slack in Pitched Vehicle



Series 8: OEM with 8.25 in. (21 cm) of Slack from Deployed EA Loop



Series 8: OEM with 33 lb (147 N) of Tension

Figure 4. Various Excursion Photographs

Table 2. Static Series 7 Testing Summary Table

Test Condition	Pitch deg	Excursion Towards Rear Glazing in (cm)	Excursion or Clearance to Roof [d] in (cm)
OEM Seat Back Upright with Tight Belt	0	-	4.5 (11.4)
Upright Seat Back with Slack Belt	0	-	7.25 (18.4)
	15	-	7.25 (18.4)
Upright Seat Back & Slack Shoulder Belt with Cinching Latch Plate	0	-	6.0 (15.2)
Reclined Seat Back with Slack Belt	0	15.5 (39.3)	-
	10	25.5 (64.8)	-
	15	27.0 (68.6)	-
Reclined Seat Back & Slack Shoulder Belt with Cinching Latch Plate	0	4.0 (10.2)	9.25 (23.5)
	10	6.0 (15.2)	9.75 (24.8)
	15	6.75 (17.1)	8.75 (22.2)
ABTS Upright with Tight Belt	0	-	3.25 (8.3)
ABTS Reclined with Tight Belt	0	3.0 (7.6)	5.25 (13.3)
	15	4.25 (10.8)	8.5 (21.6)

d. Excursion data calculated by subtracting the inverted head to roof clearance from the upright head to roof clearance.

DYNAMIC TESTING

Series 9

Using the vehicle buck and loose belt configuration described in Static Test Series 8 above with the EA loop deployed, but substituting a Hybrid III 50th percentile male ATD occupant, the occupant excursion was evaluated dynamically at a peak roll rate of 260 deg/s. The occupant was again seated in the right front passenger seat and the vehicle compartment, with the seat in the same position as in Test Series 8, was rotated driver's side leading (See Figure 5). During ramp up, the ATD experienced 10.5 in. (26.7 cm) of excursion. Review of test video shows a movement of the ATD's body in the restraint system after which a maximum excursion of 13.5 in. (34.3 cm) was recorded (See Figure 6). Under these loose belt dynamic conditions, the ATD experienced approximately 1.375 in. (3.5 cm) to 4.375 in. (11.1 cm) more vertical excursion in this far side roll than the human occupant in Test Series 8.

Figure 5. Test Series 9 Set Up

Figure 6. Test Series 9 ATD Dynamic Excursion

Series 10

The driver's seat and restraint of a 2001 Ford Explorer Sport (2-door) were replaced with an OEM 1996-2000 left front Chrysler Sebring ABTS seat and restraint system. The Sebring seat was positioned in the Explorer Sport such that the seat-to-roof clearance measurements were confirmed to be consistent with the original Explorer OEM seat configuration. A 50th percentile male Hybrid III ATD, modified with a shorter lumbar spine which decreased the seated height by 2 in. (5.1 cm) and reduced the overall weight by 15 lb (6.8 kg), was seated normally in the ABTS restraint system with the belts normally tight (no added slack). The fixture was rotated about a fixed longitudinal axis such that ATD kinematics could be examined at roll rates of approximately 300 and 500 degrees per second (Figure 7).

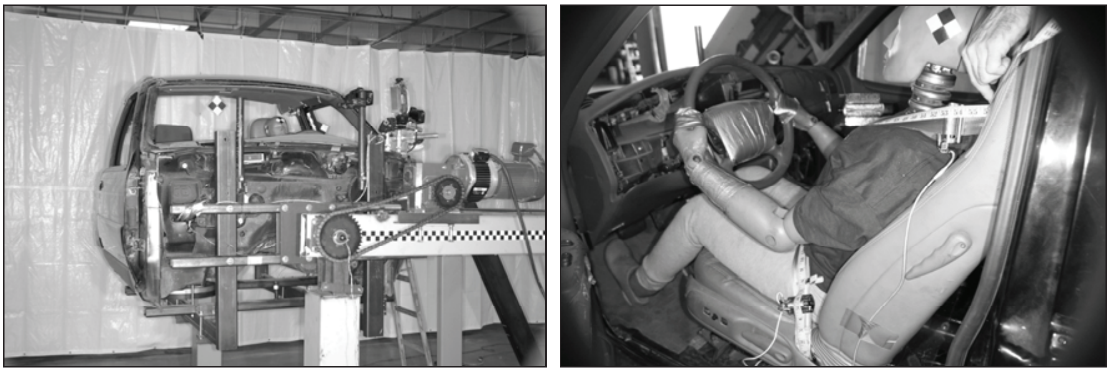


Figure 7. Test Set Up

The ATD's hands were attached to the steering wheel (at approximately 3 and 9 o'clock) in order to simulate an occupant's grip, as well as to secure the ATD's upper appendages from blocking the high speed camera documentation. The dummy was still able to move freely in the provided restraint system during the testing with its hands in this position. The lap and shoulder portions of the restraint system were instrumented with belt load cells in order to record the belt loads during testing.

The test buck was rotated with the passenger side leading at rotational rates of approximately 300 and 500 degrees per second, taking approximately 10 seconds to ramp up to the steady state speed. The ATD's maximum vertical and lateral head displacements are recorded in Table 3 and shown in Figure 8 below. At both roll rates, there was no excursion of the ATD's head or body sufficient to reach the roof or move beyond the plane of the driver's side window. Maximum vertical excursion was 2.7 in. (6.9 cm) and 2.5 in. (6.4 cm) at 300 deg/s and 500 deg/s, respectively.

Figure 8. ATD Initial and Maximum Excursion During 500 deg/s Testing

Table 3. ATD Dynamic Excursion in ABTS

Test Roll Rate	Max. Vertical Excursion in (cm)	Max. Lateral Excursion in (cm)	Max. Shoulder Belt Load lb (N)	Max. Lap Belt Load lb (N)
300 deg/s	2.7 (6.9)	7.7 (19.6)	66 (294)	114 (507)
500 deg/s	2.5 (6.4)	10.5 (26.7)	142 (632)	129 (574)

DISCUSSION

Presence of belt slack prevents effective coupling of the occupant to the vehicle and results in increased excursion. A number of currently available production technologies and components have been shown to minimize the effects of belt slack in rollovers. Effective positioning of belt anchorages can reduce routing slack and more closely hold a belted occupant to the vehicle. Effective outboard anchor and buckle placement can reduce routing slack in the lap belt and minimize vertical excursion, while effective D-ring positioning (such as at the top of the seat back as opposed to the B-pillar) can minimize lateral excursion by allowing the occupant to engage the belt before reaching the plane of glass. Pretensioners can similarly minimize occupant excursion by removing existing slack (routing and/or film spool) from the belt system. Cinching or locking latch plates can reduce occupant motion by preventing existing slack, as well as slack added in the torso belt, from entering the lap belt portion of the restraint.

Inversion testing, whether in a quasi-static or a dynamic condition, can provide valuable insight into the ability of a given restraint system to restrain a vehicle occupant against rollover related motion, namely, motion or excursion of the occupant upward and outboard relative to the seat. This motion exposes the occupant to a risk of serious or fatal injury via interior contact and/or ejection. The use of inversion testing compliments a systems design approach by allowing evaluation of various combinations of available design options in a variety of foreseeable circumstances. These circumstances can include various sized occupants, restraint configurations, the inclusion of belt slack, consideration of various rates of rollover and as well as the effects of vehicle pitch.

CONCLUSIONS

These studies indicate that additional belt looseness, or slack, added to both or either of the lap and torso belt segments was found to significantly increase occupant excursion. Slack in the torso belt allows for increased freedom in rotation of the upper torso while an increase in lap belt slack directly contributed to the lower torso's ability to move up and out of the seat.

Cinching latch plates are an effective means of preventing torso belt webbing slack from migrating into the lap belt. Simply the addition of a cinching latch plate to a restraint system prevents vertical excursions beyond that of the tight belt configuration even with slack in the torso belt.

If slack in the torso belt is allowed to pass into the lap belt portion of the restraint it has a detrimental effect on the ability of the belt to restrain the occupant against vertical excursion. Maintaining an effective lap belt length is critical to reducing excursion and decreasing occupant ejection and injury potential in a rollover.

Improved belt geometry, as seen in the ABTS configuration, can reduce vertical as well lateral excursion of the occupant.

Pretensioning was also found to dramatically reduce and limit occupant excursion. Lap belt pretension of 10 to 30 lb (44-133 N) was shown to reduce occupant excursion by 33 to 58 percent.

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