Assessing the Effects of Load Limiting Retractors on Occupant Motion

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Abstract Load limiting restraint devices used in conjunction with frontal airbags have been shown to provide a means to reduce belt induced occupant loads and the risk of belt induced injury. These load limiting devices have become increasingly common since the mid to late 90's and are currently commonplace in contemporary production vehicles. These devices are intended to feed out additional belt webbing during the collision when the belt loads exceed a predetermined threshold. Load limiters have been shown to reduce chest injury measures, both deflections and accelerations, in full frontal barrier impacts. During the full frontal barrier tests, however, the occupant benefits not only from the seatbelt (typically including a pretensioner), but also from full engagement of the frontal airbag. As the belt spools out webbing, it also allows additional occupant excursion. The challenge of balancing the dangers associated with this additional excursion against the potential for belt induced injury reduction has long been recognized. Unlike the full frontal test environment, real world crashes often direct the occupant off of 12 o'clock, result in additional structural intrusion, and produce longer duration crash pulses and/or include multiple impacts. This study reviews a series of selected cases in which occupant forward excursion allowed by a force limiting seatbelt resulted in injurious contact with vehicle interior structures. Often other contributing factors were involved (e.g., airbag or seatbelt malfunction, oblique collision, offset collision) that caused differences compared to what would typically be observed in the United States' New Car Assessment Program (NCAP) barrier tests. Force limiter spoolout observed in each reviewed case is compared and contrasted to that observed in frontal NCAP tests for equivalent vehicles.

Keywords Torsion Bar, Load Limiting, Belt Spoolout, Belt Payout, Offset Frontal Impact

I. INTRODUCTION

Seatbelts are often referred to as the most important and valuable safety device ever developed in the field of automotive safety. The United States National Highway Transportation Safety Association (NHTSA) consistently attributes the seatbelt to saving more lives than any other single crash protection device [1]. The seatbelt also, however, has long been acknowledged as a device against which the occupant is loaded and which has the potential itself to cause injury. Seatbelt load limiting devices have been recognized as a means to reduce and/or control the loading between the occupant and the belt itself. Common early designs included looped sections of seatbelt webbing that had been stitched together in such a way that the stitches would tear at a given load resulting in additional webbing being imparted while the seatbelt load was being "limited". The additional webbing was also seen to result in additional occupant excursion which, in some cases, was found to result in ineffective occupant restraint. As such, these devices were not widely used prior to the development and incorporation of the supplemental airbag restraint.

The first NCAP was created in 1979 by NHTSA in order "to improve occupant safety by developing and implementing meaningful and timely comparative safety information that encourages manufacturers to voluntarily improve the safety of their vehicles" [2]. Since that time, NHTSA has added a star rating system to the NCAP program to provide vehicle performance data to consumers in a more user-friendly format. By placing a simple star rating system on the vehicle's window sales sticker, the consumer is provided a simple comparative shopping tool. The star ratings for the NCAP's 56 kph (35 mph) frontal impact evaluate injury assessment of the anthropometric test devices (ATDs) in standardized crash testing (full frontal barrier at 56 kph (35 mph)). Head injury criterion (HIC), neck injury criterion (Nij), femur loads, and chest injury criteria are all

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considered in determining a frontal safety rating from one to five stars [3].

Load limiting seatbelts when used together with frontal airbags and pretensioners, have been shown to reduce chest injury criteria measured by the ATDs in these full frontal barrier impacts [4]. A contemporary load limiting device now typically incorporates a "torsion bar" within the retractor mechanism as compared to the earlier "rip-stitch" type stitched belt loops seen previously. The result is similar in that the torsion bar design limits the belt load by allowing webbing to spool off the retractor when the belt load reaches a predesigned threshold. Although this belt spoolout limits chest loading, it still correspondingly results in increased occupant excursions. In the full frontal test mode this additional excursion is managed by the frontal airbag.

In 2007, however, Brumbelow et al. [5] reported that in evaluating the 123 passenger car frontal offset tests that had been conducted by IIHS as of June 2006, "evidence from test film and dummy instrumentation plots suggests that driver dummy head impacts into the airbag resulted in steering wheel contact in 52% of vehicles with load limiters and in 20% of vehicles without". It was also noted that although many of these head contacts would be unlikely to cause serious injury, the contacts in about two-thirds (2/3) of the cases produced the maximum resultant head accelerations recorded during the tests. In other words, the load limiters were allowing sufficient forward excursion that the dummies' heads were seen to bottom out the airbag and impact the steering wheel such that the steering wheel impact itself caused the highest head accelerations recorded during the test.

Brumbelow et al. further utilized data from the 1996 through 2003 Fatality Analysis Reporting System (FARS) and examined the effects of load limiters on driver fatality risk in real world crashes. They noted that because these devices were usually integrated into vehicle designs at the same time as other crashworthiness changes, it was difficult to isolate the effects of their performance, but also noted that there was "unlikely a better opportunity [i.e., in 2007] to conduct such an evaluation." Their analysis concluded that, "Changes in driver fatality rates associated with the installation of load limiting belts in passenger cars suggests this restraint technology has not reduced and may have increased the risk of driver fatality in some crashes." [5]

More recently, in 2013, Kahane [6] published a report, "Effectiveness of Pretensioners and Load Limiters for Enhancing Fatality Reduction by Seat Belts", wherein he reported an estimate 12.8% lower fatality risk in passenger cars, CUVs and minivans for belted drivers or right front passengers where the belt was equipped with a pretensioner and a load limiter than if not equipped with either. Kahane's analysis looked at FARS data for 1986 to 2011 and considered the efficacy of load limiters and pretensioners, but also noted that the published effectiveness may have, "to some extent reflected the affects of other belt or belt-related improvements introduced in some makes and models at or about the same time as pretensioners and load limiters, such as adjustable anchors; integrated belt systems; or tuning the airbag, vehicle structure, or seats especially to improve protection for a belted occupant."

II. METHODS

This study focuses on real world crashes involving belted front outboard occupants in various crash modes. The study presents and describes a cases series wherein forward excursion allowed by seatbelt force limiters was, for various reasons, seen to allow sufficient forward excursion to result in injurious occupant contacts with various interior surfaces. Force limiter seatbelt spoolout recorded in frontal NCAP barrier tests for each corresponding case series vehicle is reported and compared/contrasted to that observed in the individual case study. In many of the cases reviewed contributing factors included circumstances such as airbag or seatbelt malfunctions, oblique collisions or offset collisions that caused differences compared to crash circumstances and kinematics typically observed in NCAP barrier tests.

NCAP Tests: Load Limiter Belt Spoolout

A review of various NHTSA NCAP tests reveals the amount of webbing added to the restraint system via deployment of the load limiter in this 56 kph (35 mph) full frontal impact into a rigid barrier. Many of these publically available tests record belt extension data along with belt force data for the driver and right front passenger ATDs. Photographic analysis of the test films and approximation of the webbing spoolout is also possible if restraint data is not recorded/reported.

A summary of various NCAP test data, including measured or photogrammetrically determined belt spoolout relative to the field cases presented below is summarized in Appendix A. In some cases, a review of head acceleration data indicates, consistent with Brumbelow, et al.'s 2007 analysis of IIHS tests [5], that load limiting equipped seatbelts may allow sufficient forward excursion of the ATD such that the head can bottom out the airbag and strike the hub and/or instrument panel. Consistent with that reported by Brumbelow, the head acceleration data shows a spike in the head acceleration when such contact occurs. Also consistent with Brumbelow's findings, the complete system in this test circumstance does prevent such contact from reaching injurious levels. Fig. 1 depicts this circumstance in the 2007 Toyota Yaris NHTSA NCAP Test #5677 wherein the recorded ATD Driver's Head Peak G's corresponds to video analysis of the driver's forward most movement and airbag penetration.

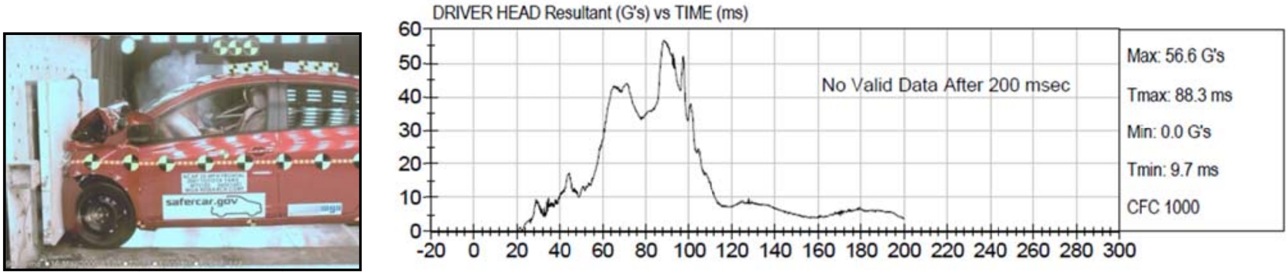

Fig. 1. NHTSA #5677 2007 Toyota Yaris NCAP, Head Peak G's Correspond to Noted Maximum Forward Excursion

Additionally, a review of NHTSA NCAP Test #6946 [7] wherein "the vehicle's supplemental restraint system was disabled", demonstrates the effective occupant excursion allowed by the load limiter without the benefit of the airbag. This tests shows that, despite being belted, the 50th percentile male driver ATD continues to move forward as the vehicle decelerates until the ATD's face impacts the vehicle's steering wheel hub approximately 75 milliseconds into the collision (See Fig. 2). A video analysis indicates the head is still moving forward at a speed of approximately 43 kph (27 mph) while the vehicle has decelerated to approximately 9 kph (5.5 mph), indicating the dummy's head impacted the steering wheel hub with a relative speed of approximately 34.5 kph (21.5 mph). Similarly, the belted 5th percentile female passenger ATD was also noted to impact the dash (See Fig. 3). With the load limiting seatbelt systems and without the benefit of frontal airbags, there was little limit to the forward movement of the ATDs (Note: neither ATDs were instrumented in this test).

Fig. 2. 50th Percentile Male ATD Contacting Steering Wheel

Fig. 3. 5th Percentile Female ATD Contacting Dash

Impact Orientation

A study of frontal crash statistics by Sullivan [8] shows that for 35% of frontal collisions the primary direction of force (PDOF) is not from straight ahead (12 o'clock) but rather at an angle. Similarly, more than 50% of frontal collisions are offset as opposed to occurring across the full width of the vehicle. Such numbers indicate that a significant percentage of "frontal" accidents are in fact offset and/or angled while the vehicle safety systems (seatbelt and frontal airbag) are typically optimized to yield favorable injury measures in full frontal crash tests with a 12 o'clock PDOF.

Offset and/or angled impacts will direct vehicle occupants inboard or outboard of the airbag centerline and may result in partial or non-engagement with the frontal airbag and increased seatbelt load limiter spoolout and associated forward excursion.

The significance of offset impacts is reflected in the test configuration established by the Insurance Institute for Highway Safety (IIHS) in the mid 1990s of a 40% overlap 64 kph (40 mph) frontal into a deformable barrier. The 40% overlap orientation is also used by European New Car Assessment Program (EuroNCAP), Japan New Car Assessment Program (JNCAP), Australian New Car Assessment Program (ANCAP). More recently, IIHS has added a "small overlap" (25% overlap) offset frontal test to its test matrix.

A review of accident and injury data by Digges [9] indicates that 24% of vehicles involved in tow away collisions endure more than one collision during the crash sequence. Consequently, 42% of MAIS 3+ injuries were found to be associated with occupants in vehicles that encountered a multiple collision crash. Digges also reported that approximately half of the multiple collision vehicles suffered a frontal impact first. Whether the frontal impact occurs initially or subsequent to other impacts, the timing and/or ability of the airbag to provide effective occupant restraint can be hindered. A collision which deploys an airbag as well as a seatbelt load limiting feature in the first impact can leave an occupant without a fully inflated airbag and with a loose seatbelt at the time of secondary, or subsequent, collisions. Similarly, non-deployment level impacts leading up to a significant frontal impact can put an occupant out of position and preclude deployment of a frontal airbag, depriving the occupant of the supplemental restraint relied upon by, and intended to work in conjunction with, the load limiter equipped seatbelt.

Case Series Review

The authors routinely investigate real world crashes including conducting reconstructions of the collision sequence, analysis of the restraint system and the resulting occupant kinematics and injuries. From these field investigations this study has specifically intended to identify and present individual cases that illustrate force limiter allowed forward excursions that have resulted in undesirable occupant kinematics and resulting injury. Potential contributing factors are also presented and may include airbag or seatbelt malfunction, oblique or offset impact orientation and/or multiple impact collisions. The effected occupant's anthropometry is reported along with the general crash circumstance and resulting kinematics and occupant injuries. Resulting seatbelt load limiter spoolout is documented and reported and compared/contrasted with seatbelt load limiter spoolout observed in NCAP tests of the corresponding case series vehicle.

The included case series was chosen based upon the authors' field investigations which demonstrated a quantifiable amount of load limiter spoolout (based upon observable forensics including traditional belt webbing load marks and/or inspection of the load limiters torsion bar itself [10]) which allowed for occupant excursion sufficient to result in injurious occupant contact with interior vehicle structures or components. All included case series vehicles were equipped with both pretensioners as well as load limiters and frontal airbags. Inclusion of the case series was not limited by occupant anthropometry and as such includes occupants of various heights and weights. The case series was limited to injury levels above AIS 3.

III. Results

A review of specific real world collision cases (case series review) personally investigated and studied by the authors, including accident vehicle inspections, review of and/or performance of reconstruction, review of occupant data including physical attributes and resulting injuries, is presented with the intention to include specific cases in which forward excursion allowed by the shoulder belt load limiter contributed to occupant contact and AIS 3+ injury. The individual cases selected included offset and angled impacts wherein the occupant did not fully engage the airbag, cases wherein the airbag did not deploy, cases of multiple impact wherein the airbag deployed during an initial impact and was subsequently then not fully inflated at the time of the second impact, and/or cases wherein intrusion compromised the occupant compartment. These cases were chosen to illustrate when force limiter allowed forward excursion can be problematic and, therefore, include contributing real world crash characteristics dissimilar to NCAP barrier tests. As shown below, load limiter torsion bar spoolout can often be evidenced by transfer of material or abrasion to load bearing surfaces during frictional contact (polymer D-ring transferring to belt webbing under load) or via disassembly of the retractor itself and evaluation of torsion bar twist/metal striations [10,11]. The selected case series included cases wherein quantified load limiter spoolout exceeded that recorded or observed in the NCAP barrier test for the corresponding vehicle.

Field Case 1 (2007 Toyota Yaris, Driver Load Limiter spooled out ~12" with Intrusion)

Fig. 4. Offset Frontal Impact

Fig. 5. Driver's Door Opened During Collision

Fig. 6. 304 mm (12") of Load Limiter Belt Spoolout

In Field Case 1, oncoming traffic crossed the roadway centerline resulting in an offset frontal collision to the vehicle of study (See Fig. 4). The collision reconstruction indicated a deltaV approximately 67 kph (~42 mph) with a PDOF of approximately 10-15 degrees to the left, or counter-clockwise. During this offset frontal collision, the driver's door unlatched such that the driver was allowed to travel to the left unimpeded by the side door structure. Additionally, the benefit of the load transfer through the side door structure was lost and the driver's side A-pillar intruded into the occupant compartment (See Fig 5).

Inspection of the driver's belt system revealed approximately 304 mm (12 in) of load limiter belt spoolout (See Fig. 6). This belt spoolout, the left directed PDOF, and the structural damage associated with the offset frontal impact, caused the driver to move to the left of the airbag and aggressively impact the A-pillar structure with his head. The driver sustained an open, depressed, comminuted skull fracture to the left temporoparietal region of his head with associated soft tissue and permanent brain injuries. These head injuries were all associated with the contact between his head and the left A-pillar. The male driver was 178 cm (70 in) tall and weighed approximately 77-82 kg (170-180 lbs).

Similar occupant kinematics were observed in an IIHS car-to-car crash test. The car-to-car test was a 50% offset frontal test of a 2009 Toyota Camry into a 2009 Toyota Yaris (equivalent platform to the 2007 model year) at approximately 65 kph (40 mph) (See Fig. 7) [12]. The driver's door in the Yaris was again seen to open (See Fig. 8 & Fig. 10), similar intrusion was observed, the PDOF was again forward and to the left, and the driver ATD was seen to move forward and glance off the left side of the frontal airbag and impact the vehicle structure to his left (See Fig. 9). Both the test and the field study demonstrate that in such a car-to-car offset circumstance the occupant did not receive the full benefit of the frontal airbag while also experienced a load limiter allowed forward excursion.

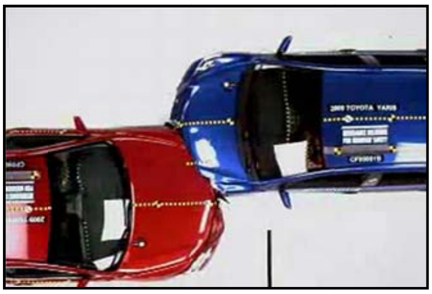

Fig. 7. IIHS 50% Offset 65 kph (40 mph) Frontal

Fig. 8. Blue Yaris Driver's Door Opens during Impact

Fig. 9. Driver Does Not Fully Engage Airbag

Fig. 10. Blue Yaris's Door Opens during Impact

IIHS had also conducted a 40% Overlap frontal barrier test on a 2007 Toyota Yaris at 65 kph (40 mph). This test resulted in a more frontal PDOF than the field case or IIHS car-to-car test and the door remained latched. Video analysis of the load limiter seatbelt spoolout showed approximately 406 mm (~16 in) of seatbelt spoolout which allowed the head to bottom out the airbag and impact the steering wheel (See Appendix B). Although with the door structure still in place, the driver ATD was seen to more fully engage the airbag and the head-to-steering wheel contact was not above injury assessment reference values (IARV).

A review of 2007 Toyota Yaris NCAP test (NHTSA #5677) shows driver and right front seated male 50th percentile ATDs in a 12 o'clock PDOF and approximately 64 kph (40 mph) deltaV impact. The test video recorded driver load limiter spoolout of approximately 330 mm (13 in), similar to the 304 mm (12 in) observed in the field case, however, the 12 o'clock PDOF and the lack of any significant intrusion into the occupant compartment allowed for full engagement of the driver ATD with the frontal airbag. All recorded ATD injury measures were below IARV values (See Appendix A).

Field Case 2 (2010 Kia Forte, Right Front Load Limiter spooled out ~11", Full Spoolout of All Remaining Available Webbing)

Fig. 11. Offset Frontal Impact

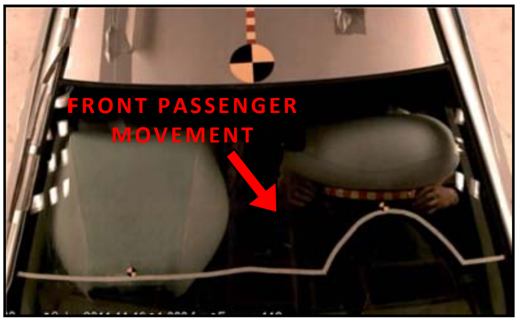

Fig. 12. Airbag Deployment in NCAP
(Depicting Gap Between Deployed Frontal Airbags)

Fig. 13. Vehicle Deformation*

*Showing RF Passenger allowed to travel towards Driver's Side of Vehicle

Field Case 2 experienced an offset frontal collision when opposing traffic crossed into its lane of travel (See Fig. 11). The police report narrative describes that post-accident the fatally injured right front passenger's head was very firmly lodged between the steering wheel of the vehicle and the driver's right leg. The right front occupant was a female, approximately 150-152 cm (59-60") tall and approximately 114 kg (251#). NCAP barrier tests demonstrating frontal airbag deployment reveals a gap between the driver's and passenger's airbags such that in the angled frontal with the PDOF and vehicle rotation taking the right front occupant forward and to the left, she moved between the two frontal airbags making fatal head contact with the front vehicle structure (See Fig. 12 & Fig. 13).

Inspection of the right front seatbelt demonstrated load limiter deployment to the full extent of the remaining available webbing, or approximately 280 mm (~11 in) (See Fig. 14). Abrasions noted on the upper restraint system anchor, or D-ring, are consistent with the transfers noted on the webbing and as having been made during load limiter spoolout (See Fig. 15).

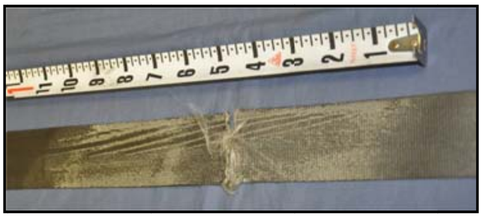

Fig. 14. RF Load Limiter Spooled Out All Available Webbing, ~280 mm (~11 in)

Fig. 15. D-ring Abraded during Webbing Spoolout

A review of the NCAP frontal barrier test for a 2010 model Kia Forte (NHTSA Test #6766) recorded approximately 241 mm (9.5 in) of driver load limiter spoolout and 240 mm (9.4 in) on the passenger side before exceeding the potentiometer's capability, as compared to the approximately 280 mm (11 in) observed in the field case study. The 50th percentile male ATDs in the 12 o'clock PDOF NCAP test were again seen to fully engage the frontal airbags such that no ATD IARVs were exceeded (See Appendix A).

Field Case 3 (2005 Toyota Corolla, Driver Load Limiter spooled out ~12")

Fig. 16. Offset Frontal Impact

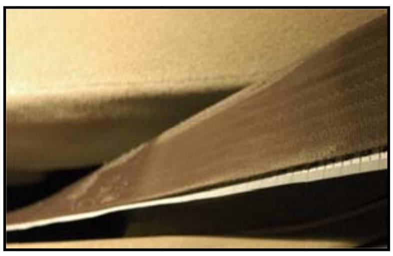

Fig. 17. 300 mm (~12") of Load Limiter Belt Spoolout

Field Case 3 involves a 2005 Toyota Corolla which lost control in a dangerous section of curved roadway, ultimately traveling into on-coming traffic and experiencing an offset frontal collision (See Fig. 16). The deltaV was approximately 35 mph with a PDOF forward and significantly to the right. The driver's seatbelt demonstrated evidence of approximately 300 mm (~12") of webbing spoolout before the belt became bound up and cut by the latch plate (See Fig. 17 & 18). The tearing the belt was determined to be associated with belt geometry changes associated with the PDOF and the significant belt spoolout.

Fig. 18. Driver's Belt Cut via Roping in the Latch Plate

Once the belt had been cut, the driver was then free to travel across the occupant compartment interacting with the center console, dash and right front door before ultimately being ejected out the right front window sustaining traumatic and permanent brain injuries (See Fig. 19). The driver was 175-178 cm (69-70 in) tall and approximately 75-82 kg (165-180 lbs).

Fig. 19. Deformed Interior and Right Front Door Structure

Review of the NCAP for the 2003 Toyota Corolla (NHTSA Test #4266) reveals that the driver side recorded load limiter payout was 194 mm (7.6 in) while the passenger side was 278 mm (10.9 in). Again, the 50th percentile front seated ATDs moved forward squarely into the frontal airbags with no significant intrusion into the occupant compartment and recorded non-injurious IARVs (See Appendix A).

Field Case 4 (2010 Toyota Prius, Driver Load Limiter spooled out ~23", Multiple Impact/Prior Airbag Deployment)

Fig. 20. Multiple Angled Frontal Impacts

Field Case 4 experienced an intersection collision when another vehicle, that had failed to yield right of way, turned left in front of the subject vehicle. This resulted in an initial vehicle-to-vehicle impact which redirected the subject vehicle across the intersection and into a concrete barrier (See Fig. 20). This collision therefore involved multiple frontal impacts. The frontal airbag deployed and physical evidence on the driver's webbing revealed load limiter spoolout of approximately 590 mm (23 in) (See Fig. 21). The initial impact, per the airbag module data, resulted in a deltaV of approximately 51 kph (32 mph), sufficient to deploy the airbag as well as several inches of load limiter spoolout. The second frontal impact was estimated to have produced a deltaV of approximately 48 kph (30 mph). The airbag control module indicated that the airbag had deployed at the first impact such that at the time of the second impact the airbag would have been partially deflated. The load limiter would also have spooled out during the initial impact such that at the time of the second impact it was able to spoolout further, however, at this point the airbag would have been less than optimally inflated. As such, the driver was allowed to move aggressively forward into the steering wheel (See Fig. 23). The steering column was found stroked and the occupant sustained fatal traumatic injuries associated with his forward excursion. The male driver was reported as being 183 cm (72 in), 109 kg (240 lbs) and sustained fatal head, chest and abdominal trauma.

Fig. 21. 590 mm (~23") of Load Limiter Belt Spoolout

Fig. 22. Abraded Driver's D-ring

Fig. 23. Stroked Steering Column

A review of the NCAP data for the 2005 Toyota Prius (NHTSA Test #5587) reports 325 mm (12.8 in) of load limiter spoolout for the driver ATD's seatbelt and that the data channel for the right front passenger ATD seatbelt failed after 44 mm (1.7 in) of spoolout. Both 50th percentile male ATDs were seen to fully engage the frontal airbags and recorded no injury measures above IARVs.

Field Case 5 (2010 Mini Cooper Clubman, Driver Load Limiter spooled out ~17", No Airbag & Intrusion)

Fig. 24. Offset Frontal Impact

Fig. 25. Driver's Airbag Did Not Deploy, Door Failed to Remain Closed

Field Case 5 experienced an offset frontal collision when a vehicle traveling in the opposite direction hydroplaned, lost control, and crossed into its lane of travel. During the collision, the vehicle's airbags failed to deploy and the driver's side door unlatched, resulting in the loss of supporting side structure and intrusion of the A-pillar (See Fig. 24 & Fig. 25). The PDOF was to the left of forward and the deltaV was in the mid 50's kph (mid 30's mph).

Evidence found on the seatbelt webbing indicates the load limiter allowed approximately 432 mm (17 in) of belt to be spooled out of the retractor (See Fig. 26). The driver moved forward and to the left sustaining multiple skull fractures as a result of contact with the A-pillar and was killed. The male driver's stature was approximately 183 cm (72 in) and 111 kg (244 lbs).

Fig. 26. 432 mm (~17") of Load Limiter Belt Spoolout

A review of the NCAP for the 2008 Mini Cooper (NHTSA Test #6291) revealed approximately 330 mm (13 in) of load limiter payout for the driver 50th percentile male ATD. The airbag deployed and no injurious IARVs were recorded.

Field Case 6 (2008 Kia Spectra, Right Front Load Limiter spooled out ~22", Multiple Impact Prior Airbag Deployment)

Fig. 27. Multiple Frontal Impacts

Fig. 28. Occupant Compartment

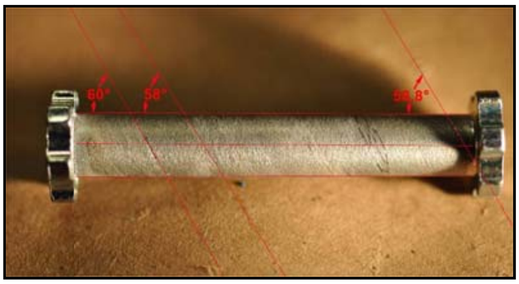

Fig. 29. Occupant Compartment

Field Case 6 experienced a loss of control with the car exiting the roadway into the adjacent shoulder where it ultimately impacted an embankment (See Fig. 27). The vehicle's frontal airbags were determined to have deployed during a curb impact as the vehicle exited the roadway such that at the time of the more significant frontal embankment collision, the occupants did not have the benefit of interacting with a fully inflated frontal airbags as they had deployed previously at the curb. At the time of the collision the vehicle was carrying two belted front seat occupants as well as an unbelted occupant in the rear seating area. No significant intrusion into the occupant compartment was observed. The right front occupant's belt spooled out approximately 560 mm (22 in) such that his head was able to make forcible contact with the front header structure causing neck fractures resulting in permanent quadriplegia (See Fig. 28, 30 & 31). The male right front occupant was 175-178 cm (69-70 in) tall and weighed approximately 75-77 kg (165-170 lbs).

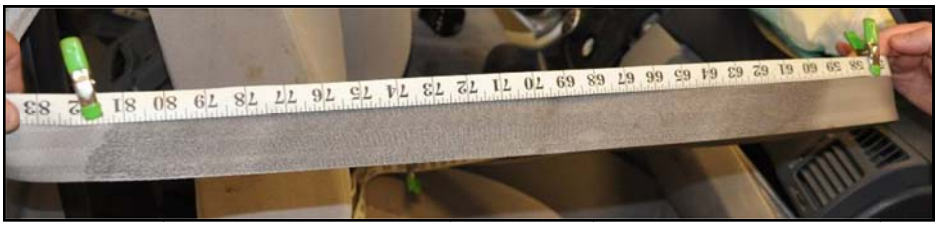

Fig. 30. 560 mm (~22") of Load Limiter Belt Spoolout

Fig. 31. Abraded D-ring

The disassembled retractor revealed the torsion bar component of the load limiter to have experienced up to 60 degrees of twist indicating it allowed the webbing spool to rotate 3 ½ times during torsion bar deformation (See Fig. 29). Given the amount of webbing that would be present on the spool with this sized occupant, 3 ½ rotations is consistent with the approximately 560 mm (22 in) of transfer marks noted on the webbing.

A review of the NCAP for a 2007 model year Kia Spectra (NHTSA Test# 5906) demonstrates approximately 292 mm (11.5 in) of load limiter spoolout for the right front 50th percentile male ATD. The ATD is again seen to fully engage the frontal airbag and the injury measures recorded by the ATD are below IARVs.

Field Case 7 (2005 Mazda 3, Driver Load Limiter spooled out ≥ 22", No Airbag Deployment)

Fig. 32. Narrow Object Frontal Impact

Fig. 33. Driver's Airbag did Not Deploy

In Field Case 7, the vehicle exited the roadway after swerving to avoid an animal and ultimately collided with a large tree (See Fig. 32). The vehicle's frontal airbags failed to deploy and the seatbelt demonstrated clear evidence of load limiter spoolout (See Fig. 33). D-ring load marks on the webbing indicate shoulder belt spoolout of greater than 560 mm (22 in) (See Fig. 34). In this case, the driver's injuries were fatal and included multiple facial fractures. The male driver was 185 cm (73 in) tall and weighed 82 kg (180 lbs).

Fig. 34. ≥ 560 mm (~22") of Load Limiter Belt Spoolout

Fig. 35. Abraded D-ring

A review of 2004 Mazda 3 NCAP test (NHTSA #4864) shows a driver and right front seated male 50th percentile ATDs, 12 o'clock PDOF and deltaV of approximately 64 kph (40 mph). The reported driver load limiter spoolout was approximately 428 mm (16.9 in) and 568 mm (22.4 in) for the right front passenger. The frontal airbags deployed and recorded ATD injury measures were below IARV values (See Appendix A).

IV. DISCUSSION

Retractor based seatbelt load limiters used in conjunction with frontal airbags have become commonplace relative to frontal impact protection [6]. A review of the case series vehicle NCAP tests supports the efficacy of these systems' ability to produce non-injurious injury measures. The occupants in these tests are consistently provided the full benefit of timely deployed frontal airbags and 12 o'clock PDOFs. These barrier impacts are also producing fairly short duration crash pulses, no vehicle rotation, no notable intrusion, and effectively provide an optimum environment for the seatbelt/airbag system to work together. Seatbelt load limiters are typically designed with constant deployment thresholds and without practical limitations as to the extent of spoolout. In contrast, a review of field accident data indicates that 24% of vehicle involved tow away collisions and 42% of resulting MAIS 3+ injuries were attributable to occupants involved in multiple impact collisions [9]. Moreover, 35% of the most common frontal crash mode involve angular frontal impacts with PDOFs different than the 12 o'clock PDOF seen in the full barrier crash tests [8]. Additionally, more than 50% of frontal collisions are described at offset as opposed to full width [8]. These real world type crashes will include not only multiple type impacts, but longer duration crash pulses, vehicle rotations, and impact force directions that will move the occupant away from the centerline of the airbag. These real world crashes will also often result in varying degrees of intrusion, all of which greatly enhance the risk of excursion related injuries that may, or may not be, alleviated by the frontal airbag.

The case series reviewed included cases that were selected targeting these specific types of kinematic phenomenon that differentiate these real world collisions from the NCAP tests in terms of both collision characteristics as well as occupant size versus NCAP employed ATDs. While the NCAP events are full frontal with 50th percentile ATDs, limited to no intrusion and well performing airbags with predictable occupant kinematics, the included case series specifically targeted inclusion of case studies wherein various sized occupants were seen to experience significant forward excursion, while spooling out load limiter provided shoulder belt webbing, such that injurious contact with vehicle interior structures was allowed.

In Field Cases 1 & 2, the load limiter spoolout observed was similar to that observed in the NCAP test, however, vehicle intrusion and/or oblique angles of impact force contributed to injurious vehicle interior contacts. In Field Cases 4, 5 & 6, field load limiter spoolout was observed to be significantly more, in Cases 4 & 6 nearly twice, than that observed in the NCAP test environment. In Field Case 4, this was likely due to multiple impact circumstance providing two load limiter deploying events in addition to a second event having occurred with a previously deployed airbag. This case also included a 183 cm (72 in), 109 kg (240 lb) occupant as compared to the 175 cm (69 in), 78 kg (172 lbs) HIII ATD used in the NCAP tests. The larger occupant will of course provide a greater force demand on the load limiter.

Field Case 6, although having a similar sized occupant to the HIII ATD, nearly twice the amount of load limiter spoolout was observed than that reported in the NCAP test. This case again, however, involves a previously deployed airbag that would have been less than optimally inflated at the time of the load limiter deploying impact. Field Case 5 & 7 again highlight the importance of occupant-to-airbag interaction such that in these studies the airbag did not deploy at all and the load limiter spoolout was again seen to be significantly greater than that observed in the NCAP test. This is true with both the larger occupant in Field Case 5 (111 kg/244 lbs) as well as in the closer to the 50th percentile occupant in Field Case 7 (82 kg/180 lbs).

This case series review suggests that although current airbag/load limiter tuning may be effective in reducing injury measures in the NCAP test environment, the extent of belt spoolout allowed when other contributing factors described above are present may result in injurious occupant excursions and contacts. In these cases, the occupant was rarely seen to move forward into the center of a timely deployed frontal airbag and illustrate specific circumstances in which occupant forward excursion with load limited restraints allowing injurious contact with vehicle interior structures. These cases demonstrated characteristics that are not typically observed in full frontal tests such as those of NCAP. Any reduction in chest injury measures provided by the load limiter must be balanced against risk of excursion related injuries. In the case series, these injuries are significantly affected by the occupants' interaction with the airbag. Non-injurious load limiter spoolout in an NCAP environment is seen in the case series to become injurious with intrusion and/or oblique or angled kinematics. The case series also suggests that forward kinematics, typically seen to be non-injurious in the NCAP environment, can result in significantly increased load limiter spoolout in multiple impact circumstances or failure to deploy circumstances.

Limitations of Analysis

This study specifically intended to seek out and present cases that illustrate when forward excursion allowed by load limiters can be problematic. As such, the results are not intended to suggest that any additional forward excursion allowed by the inclusion of a load limiter in a particular broadly described crash mode (e.g. frontal impacts) would be undesirable, but rather highlights and describes kinematics that may be observed in specific circumstances.

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VI. Appendix A

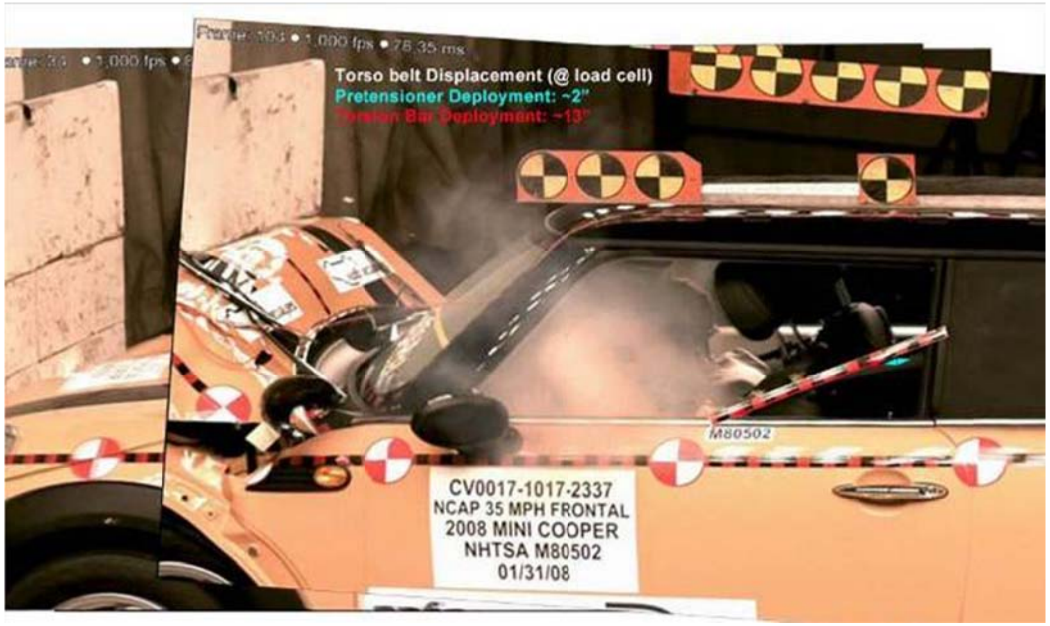
TABLE 1
NCAP & Field Case Data

<table>
<tr><th>Field Case / Test #</th><th>NCAP Vehicle (Equivalent Model Years), Field Vehicle</th><th>ATD Size & Max Belt Loads (Shoulder / Lap)</th><th>Injury Measurements</th><th>NCAP Belt Spoolout</th><th>Field Case Spool out</th><th>Occupant Location/ Gender/ Stature</th><th>Injury</th><th>Accident Data</th></tr>
<tr><td>Field Case #1 / NHTSA #5677</td><td>2007 Toyota Yaris, (2006-2009), 2007 Toyota Yaris</td><td>LF, 50th M ATD:
3743 N / 6935 N
RF, 50th M ATD:
4125 N / 9815 N</td><td><table><tr><th></th><th>LF</th><th>RF</th></tr><tr><td>HIC</td><td>427</td><td>485</td></tr><tr><td>Chest Accel</td><td>45 g</td><td>48 g</td></tr><tr><td>Chest Defl</td><td>22 mm</td><td>25 mm</td></tr></table></td><td>Not Reported
Video Analysis indicates:
LF: ~13” (~330 mm) spoolout</td><td>12”
(304 mm)</td><td>LF,
M,
5’10”,
170-180#</td><td>Skull fractures & permanent brain injuries</td><td>Left Offset, ~-10 to -15º PDOF, ~42 mph ΔV</td></tr>
<tr><td>Field Case #2 / NHTSA #6766</td><td>2010 Kia Forte 4-dr, (2009-2012), 2010 Kia Forte 2-dr</td><td>LF, 50th M ATD:
7298 N / 8686 N
RF, 50th M ATD:
6819 N / 9397 N</td><td><table><tr><th></th><th>LF</th><th>RF</th></tr><tr><td>HIC</td><td>332.8</td><td>461.9</td></tr><tr><td>Chest Accel</td><td>43.7 g</td><td>38.3 g</td></tr><tr><td>Chest Defl</td><td>27.6 mm</td><td>30.9 mm</td></tr></table></td><td><table><tr><th></th><th>LF</th><th>RF</th></tr><tr><td>Pretens</td><td>1.3”
(34 mm)</td><td>1.1”
(29 mm)</td></tr><tr><td>Spool out</td><td>9.5”
(34 + 207 mm)</td><td>9.4+”
(29 + 211 mm before exceeding Potentiometer)</td></tr></table></td><td>All available webbing: ~11”
(~280 mm)</td><td>RF,
F,
4’11”-5’,
251#</td><td>Fatal head injuries</td><td>Left Offset</td></tr>
<tr><td>Field Case #3 / NHTSA #4266</td><td>2003 Toyota Corolla 4-dr, (2003-2006), 2005 Toyota Corolla 4-dr</td><td>LF, 50th M ATD:
4887 N / 7610 N
RF, 50th M ATD:
4886 N / 8263 N</td><td><table><tr><th></th><th>LF</th><th>RF</th></tr><tr><td>HIC</td><td>435.5</td><td>391.9</td></tr><tr><td>Chest Accel</td><td>42.4 g</td><td>41.4 g</td></tr><tr><td>Chest Defl</td><td>28.7 mm</td><td>22.1 mm</td></tr></table></td><td><table><tr><th></th><th>LF</th><th>RF</th></tr><tr><td>Pretens</td><td>1.9”
(48 mm)</td><td>2.2”
(55 mm)</td></tr><tr><td>Spool out</td><td>7.6”
(48 + 146.3 mm)</td><td>10.9”
(55 + 222.5 mm)</td></tr></table></td><td>~12”
(300 mm)</td><td>LF,
M,
5’9-10”,
165-180#</td><td>Traumatic and permanent brain injuries</td><td>Right Offset, Forward & significantly to Right PDOF, ~35 mph ΔV</td></tr>
<tr><td>Field Case #4 / NHTSA #5587</td><td>2005 Toyota Prius, (Gen 2: ’03-09) (Gen 3: ’10-15), 2010 Toyota Prius</td><td>LF, 50th M ATD:
6500 N / 9311 N
RF, 50th M ATD:
5749 N / 9175 N</td><td><table><tr><th></th><th>LF</th><th>RF</th></tr><tr><td>HIC</td><td>511.2</td><td>430.9</td></tr><tr><td>Chest Accel</td><td>45.8 g</td><td>45.7 g</td></tr><tr><td>Chest Defl</td><td>24.7 mm</td><td>24.7 mm</td></tr></table></td><td><table><tr><th></th><th>LF</th><th>RF</th></tr><tr><td>Pretens</td><td>1.9”
(47 mm)</td><td>1.7”
(44 mm)</td></tr><tr><td>Spool out</td><td>12.8”
(47 + 278 mm)</td><td>Channel failed after ~1.7” (44 mm) of spoolout</td></tr></table></td><td>~23”
(590 mm)</td><td>LF,
M,
6’,
252#</td><td>Fatal head, chest & abdominal trauma</td><td>Multiple frontal impacts, both ~30mph ΔV, Prior Airbag Deployment</td></tr>
<tr><td>Field Case #5 / NHTSA #6291</td><td>2008 Mini Cooper 2-dr, (2007-2010), 2010 Mini Cooper Clubman</td><td>LF, 50th M ATD:
4935 N / 8868 N
RF, 50th M ATD:
4555 N / 8908 N</td><td><table><tr><th></th><th>LF</th><th>RF</th></tr><tr><td>HIC</td><td>379.4</td><td>622.2</td></tr><tr><td>Chest Accel</td><td>47.7 g</td><td>45.9 g</td></tr><tr><td>Chest Defl</td><td>27.1 mm</td><td>31.8 mm</td></tr></table></td><td>Not Reported
Video Analysis indicates:
LF: ~2” (~51 mm) pretens &
~13” (~330 mm) spoolout</td><td>~17”
(432 mm)</td><td>LF,
M,
6’,
244#</td><td>Fatal, Multiple skull fractures</td><td>Left Offset, Left PDOF, Mid 30’s mph ΔV, No Airbag Deployment</td></tr>
</table>

Field Case / Test #	NCAP Vehicle (Equivalent Model Years), Field Vehicle	ATD Size & Max Belt Loads (Shoulder / Lap)	Injury Measurements	NCAP Belt Spoolout	Field Case Spool out	Occupant Location/ Gender/ Stature	Injury	Accident Data
Field Case #6 / NHTSA #5906	2007 Kia Spectra 4-dr, (2004-2008), 2008 Kia Spectra 4-dr	**LF, 50th M ATD:** 5088 N / 7144 N **RF, 50th M ATD:** 2531 N / 6172 N	LF / RF HIC: 500.5 / 344.2 Chest Accel: 43.3 g / 38.6 g Chest Defl: 25.7 mm / 25.4 mm	**Not Reported** Video Analysis indicates: **RF:** ~2.5" (~64 mm) pretens & **~11.5"** (~292 mm) spoolout	**~22"** (560 mm)	RF, M, 5' 9-10", 165-170#	Neck fractures, quadriplegia	Multiple frontal impacts, Prior Airbag Deployment
Field Case #7 / NHTSA #4864	2004 Mazda 3 4-dr, (2003-2008), 2005 Mazda 3 4-dr	**LF, 50th M ATD:** 3587 N / 8580 N **RF, 50th M ATD:** 3779 N / 9396 N	LF / RF HIC: 498.7 / 296.3 Chest Accel: 45.1 g / 48.3 g Chest Defl: 21.2 mm / 24.4 mm	LF / RF Pretens: 0.0" (0 mm) / 0.0" (0 mm) Spool out: **16.9"** (428 mm) / **22.4"** (568 mm)	**≥ 22"** (~560 mm)	LF, M, 6'1", 180#	Fatal injuries, Including multiple facial fractures	Narrow object frontal impact, No Airbag Deployment

Video Analysis

Field Case #1 / NHTSA #5677 2007 Toyota Yaris NCAP, ~ 330 mm (~13") Belt Spoolout

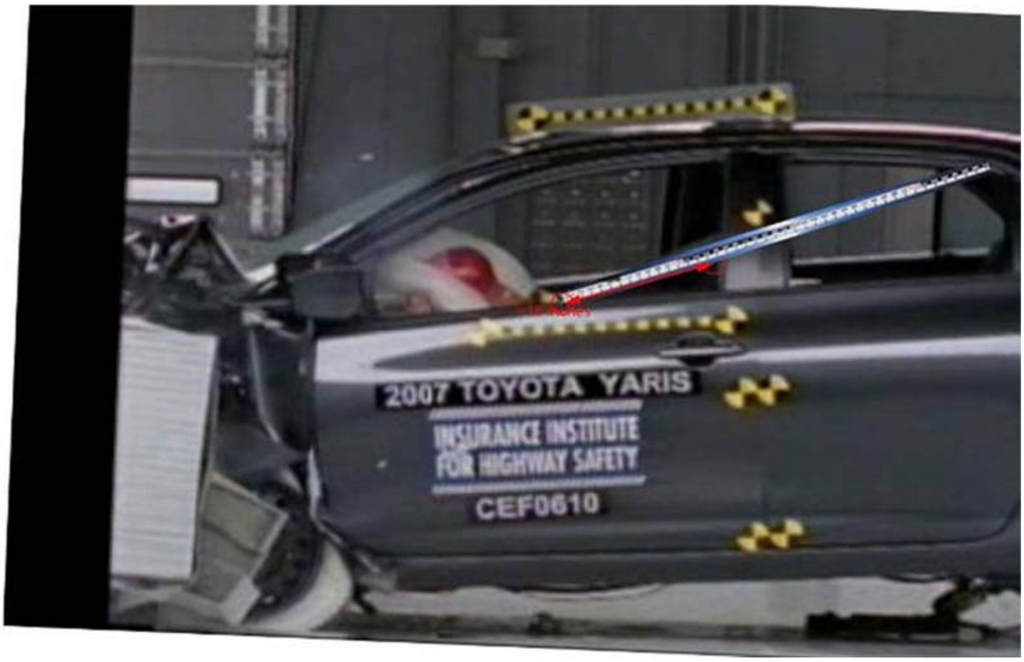


Field Case #5 / NHTSA #6291 2008 Mini Cooper NCAP, ~ 330 mm (~13") Belt Spoolout

Field Case #6 / NHTSA #5906 2007 Kia Spectra 4-dr Sedan,
~ 64 mm (~2.5") Belt Pretension

Field Case #6 / NHTSA #5906 2007 Kia Spectra 4-dr Sedan,
~ 292 mm (~11.5") Belt Spoolout

VII. APPENDIX B



IIHS 2007 Toyota Yaris Moderate Overlap Frontal, ~ 406 mm (~16") Belt Spoolout