WEBBING SENSITIVITY AS A MEANS FOR LIMITING OCCUPANT EXCURSION IN ROLLOVERS

Steven E. Meyer
Davis A. Hock
Arin A. Oliver
Stephen M. Forrest
Safety Analysis & Forensic Engineering (S.A.F.E.)
USA
Brian R. Herbst
SAFE Laboratories
USA
Paper Number 09-0501

ABSTRACT

Seatbelt performance in rollovers has come under increased scrutiny in recent years. This is due, in part, to growing popularity of sport utility vehicles which have a demonstrated inferior rollover resistance when compared to passenger cars [1]. In the United States (U.S.) the National Highway Traffic Safety Administration (NHTSA) has stated an intent to mandate an increase in the roof strength safety standard. Such an improvement in roof strength will undoubtedly bring an increased focus on the performance of seatbelts in rollovers. Many contemporary seatbelt retractors are equipped with both a vehicle crash sensor as well as a secondary, or backup, webbing sensor. The webbing sensor is intended as a backup locking device in the event of a failure of the primary inertially sensitive vehicle sensor. The crash modes presenting the most potential for the inertial sensor's failure include non-planar crashes, multiple impacts, and rollovers [2]. It follows, therefore, that to ensure reliable seatbelt retractor lockup in these modes, the redundant webbing sensor must be tuned with a lockup threshold consistent with expected occupant motions and webbing extraction rates seen during these events.

Rollover tests conducted by NHTSA wherein the belt systems were instrumented for both load and webbing payout were analyzed. This analysis provides insight for determining a baseline lockup threshold for the webbing sensor required to ensure activation in the rollover crash mode. Additionally, multiple retractors designed for both European and U.S. markets have been tested on a bench-top sled. These tests were conducted to include out-of-plane accelerations similar to those observed in rollover crashes.

The retractor sled test results, along with the analysis of the NHTSA rollover tests, are then discussed and used to develop a suggested webbing sensor lockup threshold necessary to ensure the effectiveness of the redundant and backup webbing crash sensor in real-world events.

INTRODUCTION

Occupant protection has undergone significant evolution and improvement since the inception of the automobile. This is particularly true for the seat belt restraint system, which has gone from a novel lap strap to prevent ejection in early motorized buggies to a sophisticated lap and shoulder belt system which provides the foundation of occupant protection in a variety of accident modes. Vehicle occupants now receive the benefit of improved restraint through the testing and application of technological advancements in the area of occupant protection, particularly in planar crashes.

Government standards, such as the U.S. Federal Motor Vehicle Safety Standards (FMVSS), now require manufacturers of automobiles to meet a number of component level tests and various dynamic tests in order to produce and sell their vehicles. These tests would include the frontal and side impact crashworthiness provisions required under FMVSS 208, as well as the component level testing required under FMVSS 209 and 210. As these government regulations do not specifically require it, current seat belt restraint systems are not typically evaluated for performance in rollovers. Unfortunately, the increased popularity of light trucks and sport utility vehicles have led to an increased incidence of rollover. Field accident data indicates this crash mode produces a disproportionably high number of serious injuries and fatalities suggesting a critical need for improvements in occupant protection and occupant restraint [1, 3].

Previous work by the authors, including research and investigation of real-world accidents, have shown an alarming trend in the number of rollovers which involved poor occupant restraint. This crash mode, as compared to planar crashes, has been found to result in more frequent instances of unintended seat belt spoolout [2-6]. Laboratory testing has shown that seat belt retractors equipped with vehicle/inertially sensitive lockup devices, when subjected to vertical and/or rotation accelerations such as those seen in rollovers, can fail to keep the retractor locked through the entire multiple impact, three-dimensional crash event [2, 7]. The inclusion of a secondary or redundant webbing sensitive locking sensor, if calibrated appropriately, can be an effective countermeasure to limit spoolout in the event of unintended failures of the inertial vehicle sensor that may result in belt spoolout and reduced occupant restraint.

A substantial number of production retractors are currently designed to include both the vehicle (inertial) sensor, as well as the webbing sensitive crash sensor. The vehicle sensor is typically calibrated, by government regulation, to lock pursuant to vehicle accelerations of above 0.7 Gs [8]. The webbing sensitive lockup device responds to the rate of webbing withdrawal and is found to typically be calibrated to lock the retractor at webbing accelerations from between 2 to 10 Gs. These calibrated lockup thresholds result in the vehicle sensor being the primary locking sensor and the webbing sensor then being secondary or redundant. Although the webbing sensor is included and intended to lock the retractor in the event of a vehicle sensor failure, the webbing sensor will only be effective if it is calibrated to lock at levels consistent with occupant motions in any given crash mode [9]. The rollover crash mode typically results in a longer duration multiple impact crash pulse(s) with lower peak accelerations and lower webbing withdrawal rates than those seen in a typical single impact planar collision. To ensure the effectiveness of the redundant lock feature in rollovers, it is therefore important to quantify webbing withdrawal rates expected in this mode.

ROLLOVER TESTS WITH BELT INSTRUMENTATION

In the United States there has been no government regulation requiring auto makers to conduct rollover testing on their production vehicles. Although recent years have seen a marked increase in rollover testing by various manufacturers, this testing is typically done only to develop roll sensors required to bring to market rollover protection systems such as side curtain airbags. Even still, the number of publicly available rollover tests is relatively small when compared to other required test modes, such as frontal and side impacts. Rarer still are rollover tests which were instrumented to provide meaningful data with respect to the performance of the seat belt, namely the ability of a seat belt to timely lock and remain locked throughout the course of the rollover.

If restraint data is recorded in a rollover test it oftentimes includes load cells placed on the belt webbing to record how the dummy loads the belt itself. However, a review of available rollover test data indicates that only a few include a provision for measuring and recording webbing extraction and retraction (spoolin and spoolout) from the seat belt retractor itself. To that end, of the numerous rollover tests reviewed by the authors, only the tests run by NHTSA are presented and discussed.

The NHTSA crash test library was searched for rollover tests which could be analyzed and eighteen (18) tests with instrumented belt payout recorded were identified. The data files for these 18 tests were obtained from the NHTSA Crash Test Database and then analyzed with respect to the shoulder belt payout performance and behavior. Incidences of belt payout were noted and are summarized below in Table 1. Review of the shoulder belt plots associated with these 18 tests revealed a number of recorded payout events in excess of 25 millimeters.

Table 1.
NHTSA Rollover Crash Test Summary

Test	Year	Make/Model	Speed (kph)	Occupant	Max. Spool Out (mm)
1266	1988	Dodge Caravan	48.3	Right Front	38
1274	1988	Nissan Pickup	48.3	Driver	48
1289	1989	Nissan Pickup	48.3	Driver	i.m.
1391	1989	Dodge Caravan	48.3	Right Front	25
1392	1989	Ford Bronco II	48.3	Driver	28
1393	1989	Nissan Pickup	48.3	Driver	25
1394	1989	Nissan Pickup	48.3	Driver	23
1395	1989	Pontiac Grand Am	48.3	Driver	i.m.
1516	1988	Dodge Caravan	48.3	Driver	38
1520	1988	Ford Ranger	48.3	Driver	53
1521	1988	Dodge Ram 50	48.3	Driver	20
1522	1988	Nissan Pickup	48.3	Driver	53
1530	1988	Dodge Caravan	81.3	Driver	48
1531	1988	Nissan Pickup	94.0	Driver	32
1925	1990	Nissan Pickup	48.3	Driver	76
1929	1990	Nissan Pickup	48.3	Driver	58
2141	1990	Nissan Pickup	48.3	Driver	196
2270	1989	Nissan Pickup	48.3	Driver	18

i.m. = instrument malfunction (no reliable data)

The instrumented and recorded data for each of these tests included a belt displacement versus time plot ($X_{belt}(t)$). Although the instrumented data did not include direct recording of webbing withdrawal acceleration, double differentiation of the displacement curve will yield the webbing acceleration versus time data ($a_{belt}(t)$) (See Equation 1). In order to validate this double differentiation methodology, a set of laboratory sled tests were conducted on a typical passenger car production seat belt retractor.

$$a_{belt}(t) = \frac{d^2 X_{belt}(t)}{dt^2} \qquad (1).$$

RETRACTOR SLED TESTING PERFORMED

A series of tests were performed on a driver's seat belt retractor provided in a typical U.S. passenger car. The retractor was fixed to the base of the linear slide (sled) with the webbing attached to the sled's slide carriage. The vehicle inertial sensor was disabled so that the performance of the webbing sensor could be observed. The sled was accelerated, thereby spooling belt webbing off of the retractor at the rate of the carriage acceleration. The slide and seat belt retractor were oriented as shown in Figure 1. The amount of webbing extended off the retractor at the start of the test was approximately 75% of the total webbing available. Webbing acceleration was recorded, as well as payout displacement, both as a function of time. (See Table 2.)

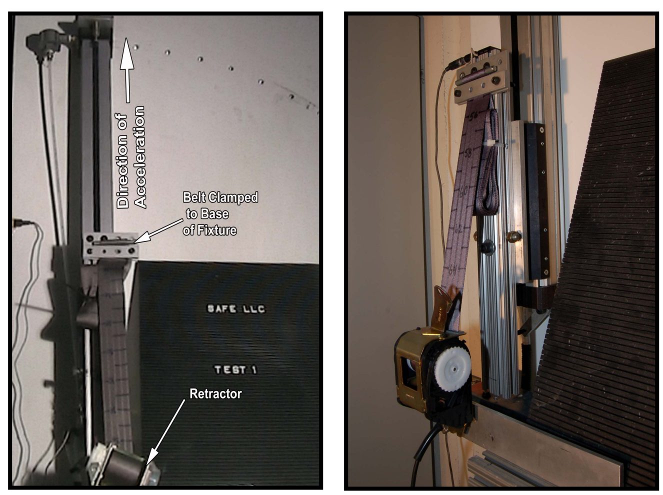

Figure 1. Webbing Sensor Test Setup

Table 2.
Web Sensing Tests

Test Number	Duration (msec)	Webbing Acceleration (Gs)	Belt Payout (mm)
1(a)	251	2.4	257
1(b)	249	2.4	257
1(c)	250	2.4	257
2(a)	56	2.9	20*
2(b)	246	2.6	257
2(c)	64	2.5	30*
3(a)	53	3.2	20*
3(b)	62	2.8	25*
3(c)	58	2.9	25*

*Web sensor locked during event

The seat belt spoolout was recorded via a string potentiometer in a similar way to the displacement data recorded in the NHTSA rollover tests of Table 1 above. Unlike the rollover tests, however, the webbing extraction acceleration was also recorded. Double differentiation of the recorded displacement versus time data (See Figure 2) results in an acceleration versus time curve. This calculated acceleration was then compared to the directly recorded acceleration plot. Although the double differentiation methodology of Equation 1 results in some additional noise, when plotted as a function of time, a comparison between the calculated accelerations versus the directly recorded data shows reasonable correlation. (See Figure 3.)

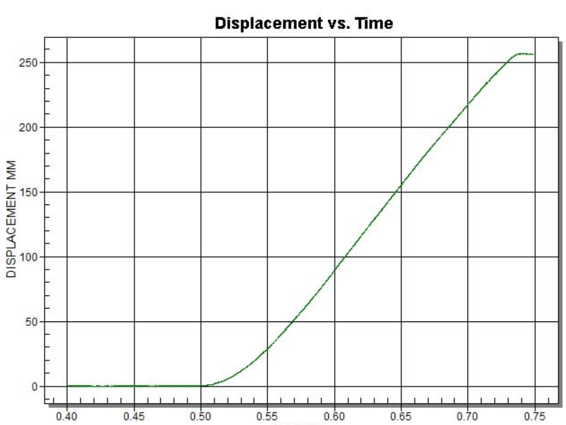

Figure 2. Displacement vs Time

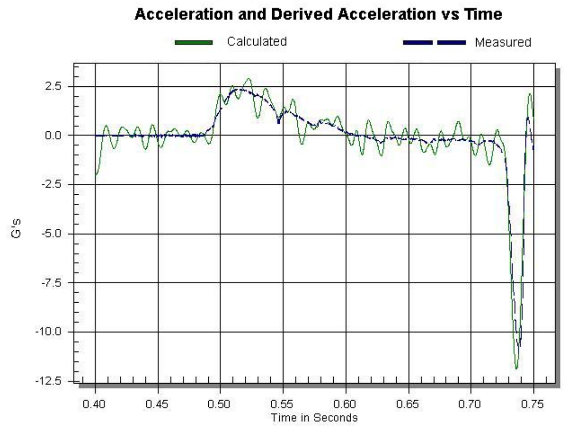

Figure 3. Calculated and Measured Acceleration vs Time Curves

ROLLOVER TESTS ANALYSIS

The 18 NHTSA rollover crash tests reported in Table 1 were provided with belt displacement versus time curves. Using this same methodology, webbing extraction accelerations were calculated for each NHTSA rollover test recording belt payout events during the rollover in excess of 25 millimeters. These calculated belt payout accelerations were found to generally range from 2 to 6 Gs. (See Table 3.)

Based upon the authors' experience involving analysis of numerous field accidents and various production retractor designs found in both U.S. and European model vehicles, it has generally been observed that the calibrated lockup threshold for the webbing crash sensors are found to be lower (more sensitive) in the European retractors than in their U.S. counterparts. This is likely due to the European safety regulations [10] requiring the webbing sensor to lock the retractor at webbing withdrawal rates of 2 Gs or above. In the U.S., FMVSS 209 [8] includes no webbing sensor lock requirement if the retractor is also equipped with a vehicle inertial sensor. In order to confirm this observed trend, an additional series of retractor sled testing has been conducted.

Table 3.
NHTSA Spoolout Table

Test	Year	Make/Model	Speed (kph)	Occupant	Max. Spool Out (mm)	Webbing Acceleration (Gs)
1266	1988	Dodge Caravan	48.3	Right Front	38	5.4
1274	1988	Nissan Pickup	48.3	Driver	48	2.6
1289	1989	Nissan Pickup	48.3	Driver	i.m.	i.m.
1391	1989	Dodge Caravan	48.3	Right Front	25	2.9
1392	1989	Ford Bronco II	48.3	Driver	28	4.8
1393	1989	Nissan Pickup	48.3	Driver	25	4.4
1394	1989	Nissan Pickup	48.3	Driver	23	2.1
1395	1989	Pontiac Grand Am	48.3	Driver	i.m.	i.m.
1516	1988	Dodge Caravan	48.3	Driver	38	10.9
1520	1988	Ford Ranger	48.3	Driver	53	2.9
1521	1988	Dodge Ram 50	48.3	Driver	20	2.3
1522	1988	Nissan Pickup	48.3	Driver	53	3.9
1530	1988	Dodge Caravan	81.3	Driver	48	4.0
1531	1988	Nissan Pickup	94.0	Driver	32	1.6
1925	1990	Nissan Pickup	48.3	Driver	76	3.4
1929	1990	Nissan Pickup	48.3	Driver	58	2.8
2141	1990	Nissan Pickup	48.3	Driver	196	14.3
2270	1989	Nissan Pickup	48.3	Driver	18	3.2

i.m. = instrument malfunction (no reliable data)

ADDITIONAL RETRACTOR SLED TESTING

Four sets of retractors, each set consisting of design variance produced by one manufacturer, were tested under similar conditions on a linear accelerator (sled) fixture. The tested retractors are listed in Table 4. The retractors in each test were mounted to the sled itself while the sled is mounted to a fixed base. The sled allows up to 546 millimeters of travel. In each test, the belt webbing was attached to the base of the test fixture such that approximately 381 millimeters of webbing remained on the spool of the retractor. For each set of retractors the slide was oriented at an angle off vertical beyond the point at which the least sensitive retractor in the group was observed to statically lockup via its inertial sensor. This orientation ensured that the retractors were all in a pre-locked condition by virtue of the vehicle inertial sensor. At the start of the test there was no pre-load in the retractor webbing. An accelerometer was mounted on the sled itself to record acceleration of the sled while webbing spoolout was measured via a string potentiometer. A high-speed video camera was mounted to the fixture to document the retractors' inertial sensors dynamic performance. A displacement transducer was also used to measure the amount of webbing that spooled off the retractor. Figure 4 demonstrates the test setup.

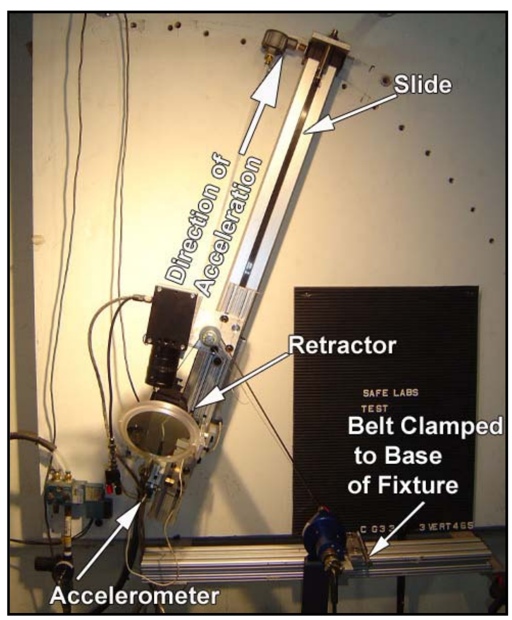

Figure 4. Linear Test Set Up

Table 4.
Tested Retractors

No.	Manufacturer	Specification	Belt Code
1	NSK	U.S.	NSB072EL19
2	NSK	European	NSB072TR019
3	TRW	U.S.	H-4103
4	TRW	European	XL2A78611B69
5	Autoliv	U.S.	Ef-93
6	Autoliv	European	C66LA ANG
7	Autoliv	U.S.	NSB085TR47-P
8	Autoliv	European	3083/12A

The sled was manually activated once for each test resulting in the retractor experiencing an acceleration directed along the sled axis, as well as the gravitational acceleration associated with the angular orientation of the sled. This configuration subjected the inertial sensor to multiple direction accelerations including those directing the inertial sensor towards a neutral or unlocked condition [7]. When these accelerations result in the vehicle sensor returning to neutral or becoming unlocked, the redundant webbing sensor is then relied upon to lock the retractor and prevent webbing spoolout.

In each of the tests the vehicle inertial sensor was found to unlock, allowing for various amounts of belt payout. Towards the end of the slide travel, the sled acceleration became more constant such that at belt payouts beyond approximately 280 millimeters, the inertial sensor was found to reengage. (See Table 5.)

Table 5.
Linear Accelerator Tests

Test Number	Webbing Extraction Acceleration (Gs)	Δ Time Unlocked (msec)	Webbing Sensor Activated	Webbing Payout (mm)
NSK U.S. SPECIFICATION				
1	2.1	196	No	305
2	2.2	186	No	292
3	2.2	184	No	292
NSK EUROPEAN SPECIFICATION				
1	2.1	44	Yes	28
2	1.9	44	Yes	28
3	1.9	50	Yes	28
TRW U.S. SPECIFICATION				
1	2.2	252	No	401 *
2	2.1	242	No	401 *
3	2.2	242	No	404 *
TRW EUROPEAN SPECIFICATION				
1	2.2	46	Yes	36
2	2.2	46	Yes	36
3	2.2	44	Yes	36
AUTOLIV U.S. SPECIFICATION				
1	2.5	182	No	284
2	2.7	196	No	323
3	2.5	210	No	361
AUTOLIV EUROPEAN SPECIFICATION				
1	2.7	36	Yes	20
2	2.7	36	Yes	23
3	2.7	36	Yes	23
AUTOLIV U.S. SPECIFICATION				
1	1.9	260	No	406
2	2.1	258	No	406
3	1.9	262	No	406
AUTOLIV EUROPEAN SPECIFICATION				
1	1.8	32	Yes	18
2	1.9	36	Yes	18
3	1.8	40	Yes	20

*Retractor did not lock, payout ceased when all available webbing was exhausted

DISCUSSION

The disproportionately high rate of serious injuries and fatalities resulting from an increasing number of rollover crashes requires an increased priority on rollover occupant protection. Effective occupant restraint has consistently been relied upon as a primary means of providing occupant protection in these relatively long duration, multi-impact events. Moreover, the acceleration and crash forces seen in rollover events have been shown to enhance the potential for the retractor's primary locking sensor, the vehicle inertial sensor, to fail [2]. Therefore, the need for a reliable redundant, or secondary, webbing crash sensor is paramount in this crash mode.

A review of the retractor sled test results shown in Table 5 indicate that in each of the four European/U.S. paired retractors, only the European versions were found to limit webbing payout by virtue of activation of the retractor's webbing sensor. This data confirms the authors' experience that the European retractors are often calibrated at lower lockup thresholds than those found in the U.S. The data reported in Table 5 further indicates that of the four retractors found to lock and limit webbing payout by virtue of the webbing sensor, they locked at webbing extraction accelerations of between 1.8 and 2.7 Gs. Their U.S. counterparts, however, did not lock at these levels and required webbing accelerations somewhere above 2.7 Gs to engage the webbing sensor. U.S. manufactures' specifications have been seen to require webbing sensor calibrations in the U.S. ranging anywhere from 2.5 Gs to as high as 10 Gs on some models. As noted, European safety regulations require having sensor lockups at above 2.0 Gs.

A review of the NHTSA rollover test data shown in Table 3 indicates typical webbing extraction accelerations generally ranged from 2 to 6 Gs. In only one of the examined tests was a webbing extraction rate recorded at below 1.5 Gs, and in only two tests were extraction rates recorded above 10 Gs. This data suggests that a webbing sensitive calibration threshold of 1.5 Gs would be effective at preventing belt payout in rollover crashes even with a failure of the vehicle based inertial sensor. Such a threshold is only slightly more sensitive than the European retractors tested here and is within compliance of the European regulations. Although, based upon the above analysis, 1.5 Gs appears to be a low enough threshold to ensure reliability of the webbing sensor as a redundant feature in rollover crashes, additional rollover testing with webbing withdrawal accelerations directly instrumented is recommended.

REFERENCES

[1] Department of Transportation, 2001, Federal Register / Vol. 66, No. 204 Notice of Proposed Rulemaking, Docket 1999-5572, NHTSA

[2] Meyer, S., et al, 2001, "Dynamic Analysis of ELR Retractor Spoolout," SAE 01ATT-370

[3] Meyer, S., et al, 2003, "Motor Vehicle Seat Belt Restraint System Analysis During Rollover," Biomedical Sciences Instrumentation, Vol 39

[4] Shaibani, S., 1991, "Characteristics of Safety Systems Activated by Inertial Sensors," 19th International Workshop on Human Subjects for Biomechanical Research, San Diego, CA

[5] Shaibani, S., 1992, "Performance of Inertial Sensors During Multiplanar Travel," 20th International Workshop on Human Subjects for Biomechanical Research, Seattle, WA

[6] Renfroe, D.A., 1996, "Rollover Ejection While Wearing Lap and Shoulder Harness: The Role of The Retractor," SAE 960096

[7] Meyer, S., et al, 2001, "Test Methods For Evaluating Seat Belt Retractor Response In Multiplanar Acceleration Environments," BED-Vol. 50, 2001 Bioengineering Conference ASME

[8] Department of Transportation, National Highway Traffic Safety Administration, "Federal Motor Vehicle Standards; 571.209 Standard No. 209; Seat Belt Assemblies," 49 CFR 571.209

[9] Hock, D., et al, 2004, "Evaluation of Motor Vehicle Seat Belt Retractor Locking Devices," ASME International Mechanical Congress, ASME IMECE2004-60201

[10] United Nations Economic Commission for Europe (UNECE), "Vehicle Regulations; Regulation No. 16."