Results from Calculating the Acceleration at an ELR in a Steer Induced Rollover Crash Test

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Mark William Arndt
Transportation Safety Tech. Inc.

John Wiechel
The Ohio State Univ.

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Abstract

Assuming rigid body motion, recorded acceleration and recorded roll rates at the center of gravity, equations are used to calculate the local three-dimensional accelerations at hypothetical seating positions' Emergency Locking [seat belt] Retractors (ELR) during a steer induced rollover crash. For a threshold of 0.7 g, results demonstrated that intervals in the vehicle's response that may cause the ELR's inertial sensor to move into a neutral zone were limited to localized high magnitude negative vertical acceleration events during the rollover segment with a median duration of 4 ms, average duration of 4.8 ms and a maximum calculated duration of 31.7 ms. Changing the threshold to 0.35 g reduced the interval count by 70 percent and maximum duration by approximately 50 percent. Since a retractor in an interval when an inertial sensor may move into a neutral position will unlock only after belt retraction and at an acceleration ratio below its threshold, the duration that a retractor may be unlocked was probably less than the duration of an interval when a vehicle's response would allow an inertial sensor to move into a neutral zone. Results of the analysis were consistent with prior published research that noted limited and brief periods of instances in rollover crashes when the inertial sensor may be in a neutral zone. Calculating an interval that a vehicle's response may allow a retractor to move into a neutral zone does not mean that a specific retractor will move into a neutral zone. To asses if a specific retractor will move into a neutral zone its performance should be analyzed. It is beyond the scope of the paper, and not possible from the analyzed testing, to include a complete analysis of occupants' kinematics. As identified in prior research, occupant kinematics analysis was necessary in determining whether an inertial sensor in a neutral zone during a rollover event will result in belt spool out.

Introduction

In 2002 Thomas and co-authors issued a lengthy American Society of Mechanical Engineers (ASME) paper on the Emergency Locking [seat belt] Retractor (ELR) performance in rollover crashes. Thomas specifically addressed a theorized failure mode of vehicle sensitive ELRs in which seat belt webbing can "spool out" and concluded that the "circumstances necessary for retractor spool out to occur are not present in rollover accidents" [1]. Thomas described the seat belt retractor underlying operation; discussed prior published literature; including literature with opposing findings; identified conditions that must be present for spool out failure mode to occur; provided an analysis of each condition with extended discussion on occupant kinematics; and presented additional support of conclusions including description of personal experience from rollover crash testing. A resultant acceleration at the base of a SUV's B-pillar in a dolly rollover test was presented. While Thomas discussed the implications of angular velocity at an ELR mounted distant from the vehicle CG, and noted that, "There is no doubt that some ground contacts may cause the sensing mass to momentarily pass through a neutral position" [1], recorded or calculated 3-D accelerations at a retractor were neither referenced nor presented. Discussion and specific results were reported for only lateral motion or dolly rollover tests.

Beginning in 2000 and through 2008, Meyer and co-authors issued a series of papers which subjected ELRs to two different test methods and documented that, when a vertical component dominates the acceleration at a retractor, its sensor will move to a neutral zone [2, 3, 4, 5, 6, 7]. Meyer called the phenomena "an overpowering neutral-directed acceleration pulse". Meyer's later tests used a fixture rotating at 150 to 200 degrees per second about the roll axis and, secondly, a linear fixture that accelerated a rolled or pitched ELR along its vertical axis at 2 to over 3 g's [7]. Meyer's tests provided detailed information about the retractor motion including high speed video of retractor lock components, but in relating test results to rollover crashes, neither referenced nor presented any recorded or calculated accelerations at a retractor in a rollover and related the rotating retractor test motions to only lateral motion or dolly rollover tests. Meyer's also referenced Jones' 2000 paper [8] on reconstructed rollovers.

Thomas provided a listing of the Federal Motor Vehicle Safety Standards 209 (FMVSS209) requirements for an ELR and summarized them as requiring that all ELRs must lockup at or below 0.7 g, must possess a relatively low retraction force and must not lock at vehicle pitch or roll angles of 15 degrees or less [1]. Tests prescribed by the FMVSS209 evaluate compliance by subjecting ELR's to acceleration in the horizontal plane and by static pitch or rotation [9]. Under these requirements, pitch or rotation angle can be expressed with equivalency to a ratio of resultant horizontal acceleration to vertical acceleration. Conversely, constant acceleration in the horizontal plane can be expressed with an equivalency in static roll or pitch angle.

In the context of the testing described in FMVSS209, an implication of the relationship between the roll and/or pitch angle of a vehicle (and hence the ELR) and horizontal accelerations is that under static conditions an ELR-neutral position is dictated by the ratio of resultant horizontal accelerations to vertical acceleration (acceleration ratio or ratio). This concept was repeatedly demonstrated by Meyer's previously introduced reports, most recently and comprehensively published in 2008 [7].

A core concept outlined in the 2002 Thomas paper was the identification of conditions (Thomas Conditions) that must be met to permit belt spool out. The conditions were: (1) the acceleration sensor must move to a neutral position; (2) while in the neutral position, occupant motion must occur that effectively relieves all belt tension, allowing some belt retraction, so that a locking mechanism can disengage and (3) while the acceleration sensor remains in the neutral position occupant motion must occur that spools out webbing. [1]

The subject paper presents an analytical method by mathematically shifting accelerations and rotations recorded at a vehicles center of gravity to accelerations at an ELR sensor location to determine if an ELR sensor may move into a neutral position. The paper uses data recorded during a steer induced rollover of a SUV and adds insight into ELR responses and exposure in rollover crashes other than dolly rollover tests or under solely lateral conditions. The paper presents, in greater detail than described in Thomas' resultant acceleration data presentation, key vehicle parameters that dictate whether an ELR may move into a neutral zone. The paper also presents the dynamics of a real rollover crash when considering the findings of Meyer and co-authors [7].

Method

The analysis presented in this paper uses the recorded results of the vehicle response from rollover three (R3) from the steer-induced rollover testing presented by Stevens and co-authors in 2011 [10]. The recorded results are analyzed using rigid body dynamics to calculate the local three-dimensional acceleration at four outboard seat belt retractors. Calculations translate the measured three dimensional accelerations at the vehicle CG to each retractor position by considering the effect of angular and centripetal acceleration. The measured acceleration and angular motion was assumed to be located at the vehicle's center of gravity. While no localized deformation was noted at the ELR locations, deformations and transitory ground contacts at the periphery of the vehicle were not modeled.

Stevens' rollover three (R3) was a steer-induced left-side-leading rollover of a 1997 four-wheel drive Ford Explorer Sport. The tripping and roll phases occurred on soil. The rollover response and documentation from the original paper are contained in Appendix A. In 2012, Funk and co-authors further analyzed Stevens' R3 and reported its agreement with their sliding and rolling model [11] (see statistics at the end of Appendix B).

This paper calculates the vehicle's response at the ELR and is not intended to calculate the ELR's response. Throughout the paper the terminology "may" is meant to convey that a localized acceleration of the vehicle is conducive to movement of the ELR into the neutral zone and does not mean that an analysis of the ELR has been conducted to determine if in fact a neutral condition was attainable. Calculations use recorded data filtered to the SAE class 60 standard of SAE J211 to evaluate a vehicle response that may allow an ELR to move into a neutral zone. The class 60 filter is nominally a 100 HZ filter that removes high frequency components of recorded crash data. SAE J211 recommends a class 600 filter (1000 Hz) for component evaluations.

A standard SAE reference system incorporating a right-hand rule with positive x forward, positive y rightward (toward the passenger side) and positive z downward is positioned with (0, 0, 0) at the vehicle CG. Angular orientations are denoted by φ for roll, θ for pitch and ψ for yaw. The center of gravity was assumed to lie at the middle of the vehicle's lateral dimension. The variables p, q and r refer to roll rate, pitch rate and yaw rate, respectively, and α is angular acceleration. For the illustrative purpose of this paper, a set of exploratory but unspecific "dummy" coordinates were made up for each of four retractor positions. The dummy coordinates are listed in Table 1.

Table 1. "Dummy" coordinates. Retractor coordinates used for exploratory purposes only.

	LF	RF	LR	RR
X (m, ft)	0, 0	0, 0	-.61, -2	-.61, -2
Y (m, ft)	-.61, -2	.61, 2	-.61, -2	.61, 2
Z (m, ft)	.06, .2	.06, .2	0, 0	0, 0

Equations used to calculate the local retractor acceleration are (using the LF position for illustration):

$$a_{RLFx} = a_{CGx} + r^2 \times d_{LFx} + q^2 \times d_{LFx} + \alpha_\psi \times d_{LFy} + \alpha_\theta \times d_{LFz}$$

$$a_{RLFy} = a_{CGy} + p^2 \times d_{LFy} + r^2 \times d_{LFy} + \alpha_\psi \times d_{LFx} + \alpha_\varphi \times d_{LFz}$$

$$a_{RLFz} = a_{CGz} + p^2 \times d_{LFz} + q^2 \times d_{LFz} + \alpha_\theta \times d_{LFx} + \alpha_\varphi \times d_{LFy} \tag{1}$$

In Equation 1 the centripetal acceleration was directed at the center of rotation, assumed to be the vehicle's center of gravity. Equation 1 was meant to convey that the effect of acceleration from angular rotation rates was added to calculate point acceleration at an ELR; in other words, for a retractor located on the positive or negative side of the CG the acceleration due to angular rotation is subtracted or added, respectively. The acceleration ratio was calculated with the equation:

$$ratio = (a_{RLFX}^2 + a_{RLFY}^2)^{1/2} \div a_{RLFZ} \quad (2)$$

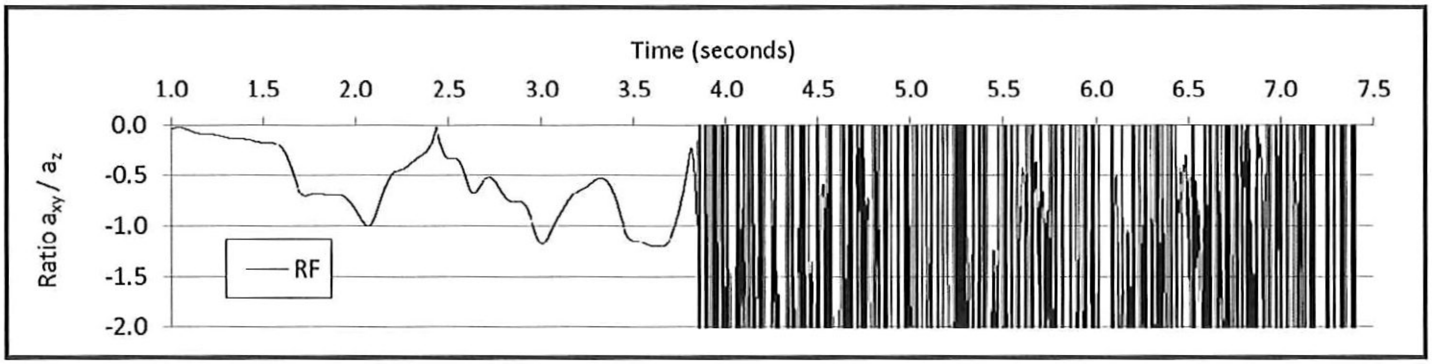


Figure 1. Acceleration ratio as a function of time at the right front ELR.

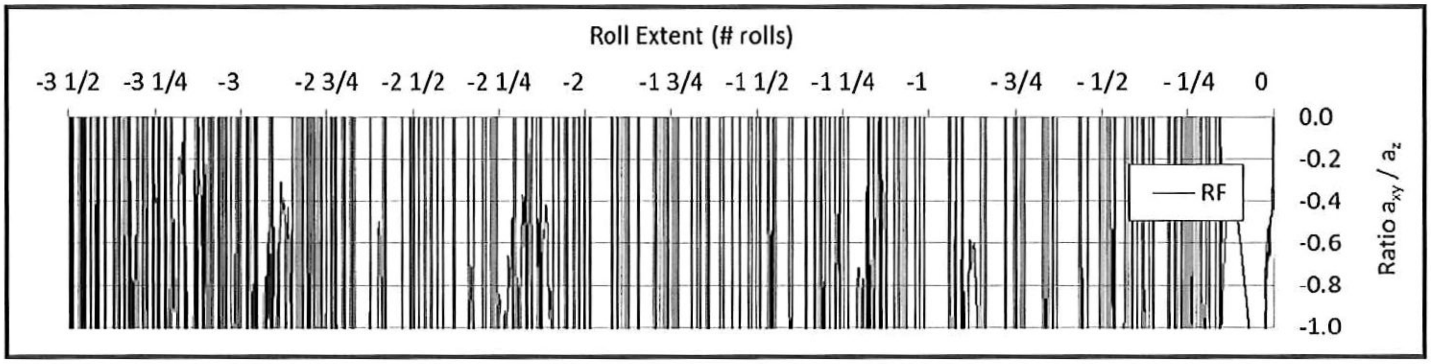


Figure 2. Acceleration ratio as a function of roll for the right front ELR.

An assessment as to whether the vehicle response may move a sensor into a neutral position was made from the above expression based upon direct calculation. Periods of ELR acceleration during any phase of the rollover with the acceleration ratio magnitude below 0.7, but only for conditions when the z acceleration is negative, or upward ($-0.7 <$ acceleration ratio < 0) are identified. Minus 0.7 g was selected because of the FMVSS209 requirement, but should not be construed to indicate when a specific retractor will lockup or attain a neutral condition.

Though not the main point of the paper and not a substitute for the occupant kinematic analysis required by the Thomas Conditions, a second calculation was made to gain insight into vehicle positions and motions that may exclude or promote the occupant kinematics required to allow the ELR locking mechanism to unlock. According to the Thomas Conditions, after attaining a neutral position, the next condition that must occur is that the net motion of an occupant must allow the webbing to unlock by a slight belt retraction. Such a condition was explored by using the same set of equations (1) used for calculating local retractor acceleration. An exploration of such a condition might assume an occupant with a starting center of gravity outward, above and in front of the seat. The second calculation focused on the direction of acceleration in the XY plane during periods when z acceleration was already demonstrated to cause relative occupant motion downward. This quantity was calculated by the equation:

$$a_{XYANGLE} = \arctan(a_{OLFX} \div a_{OLFY}) \quad (3)$$

During periods when the sensor may be in a neutral position, a direction of acceleration in the XY plane that was, or transitioned through, sufficiently forward (relative occupant motion rearward) may indicate an occupant motion downward and rearward. Downward and rearward occupant motion may allow a slight belt retraction and release of the locking mechanism.

Results

Figure 1 and figure 2 display results of the acceleration ratio analysis as a function of time and roll angle, respectively, at the right front (RF) ELR. Figure 1 displays the minimum to maximum acceleration ratio on the Y axis as −2 g to 0 g with respect to time; results of all four modeled retractor locations are shown in Appendix A. Figure 2 displays the minimum to maximum of the Y axis as −1 g to 0 g with respect to roll; the LF and LR retractor responses are shown in Appendix B. Rollover three (R3) was a left-side-leading roll meaning the roll direction was negative.

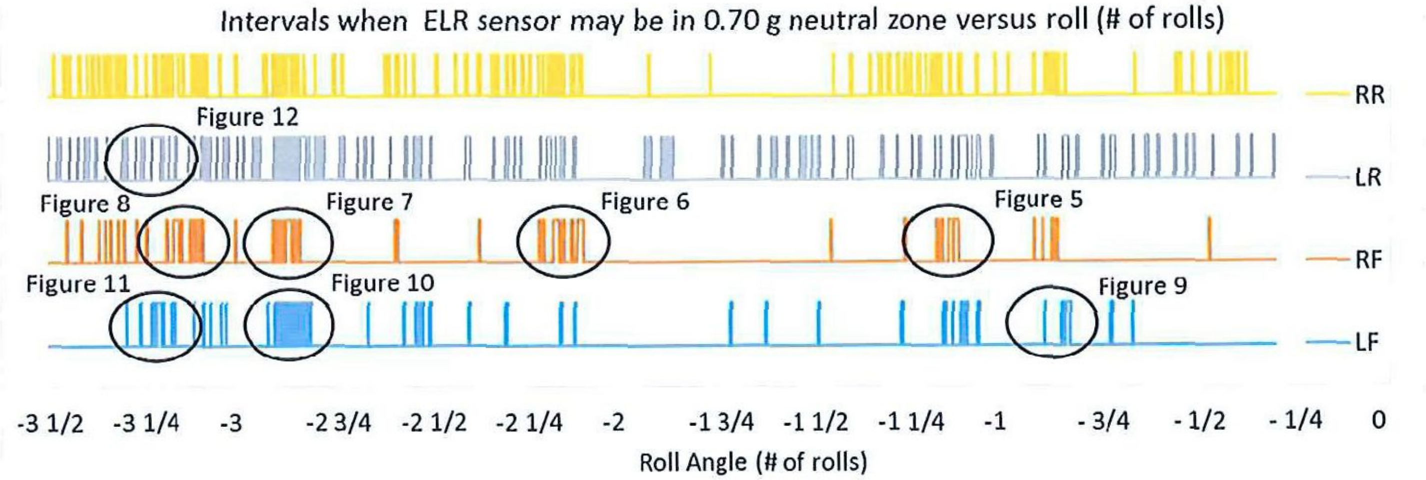


Figure 3. Calculated neutral zone condition (−0.7 < ratio < 0) shown as high magnitude as a function of roll angle.

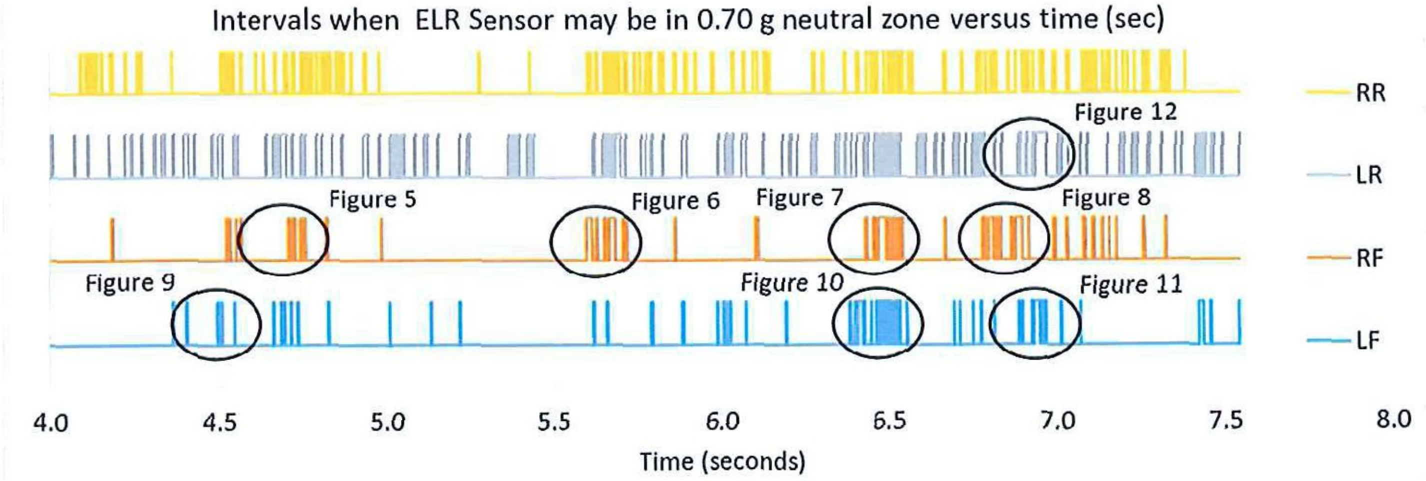


Figure 4. Calculated neutral zone condition (−0.7 < ratio < 0) shown as high magnitude as a function of time.

By displaying a state of high or low, Figures 3 and 4 indicate instances (circled with reference to detailed Figure 5, Figure 6, Figure 7, Figure 8, Figure 9, Figure 10, Figure 11, Figure 12) in the rollover phase when vehicle response may have moved the ELR for each retractor to a neutral zone position. The results in Figures 3 and 4 are for a threshold of 0.7 g. In Figure 3 and Figure 4 vehicle response that may have moved the ELR to a neutral zone is a high indication. Figure 3 and Figure 4 display *results in the time and roll domains, respectively.* There were no calculated periods greater than 5 ms during the first airborne segment, when the ELR may have been in a neutral zone.

Figures 5, 6, 7, 8, 9, 10, 11, 12 are select intervals with instances when the LF, RF, or LR retractor location responded with a calculated acceleration ratio between −0.7 and 0.0. The figures plot the acceleration ratio, vertical acceleration, roll rate, and direction of XY acceleration at a specific position. These figures do not show all instances where the acceleration ratio was within range, but rather represent the longer periods and noted periods. *Figure 7 and Figure 10 are the same interval* but for the RF and LF retractors, respectively. Similarly, Figure 11 and Figure 12 are the same interval but for the LF and LR retractors, respectively. The interval in Figure 6 was a cluster of instances that predominantly occurred at the RF retractor in the 9/4 roll. Figure 7 shows the longest duration for the front positions and Figure 12 shows the longest duration overall. The illustration of vehicle position above each figure demonstrates the roll angle at the beginning and end of groupings of instances. The illustration at the top of the graphs was looking forward, so the roll direction is to the left, while the charts read to the right as a function of increasing time.

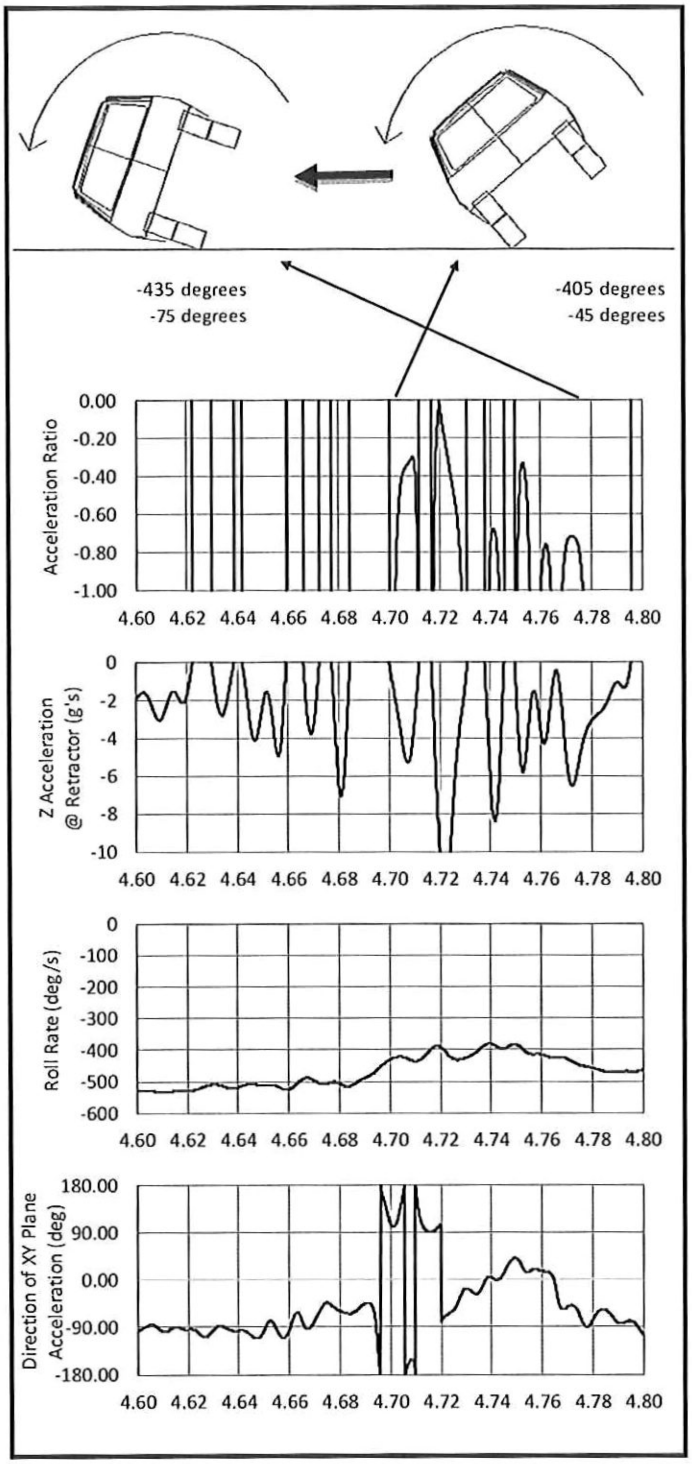


Figure 5. Response at RF retractor for the interval 4.60 seconds to 4.80 seconds.

Discussion

Transformation of acceleration from the center of gravity relied on the assumptions that the vehicle can be treated as a rigid body and that the measured acceleration and angular motion was located at the vehicle's center of gravity. Results of an acceleration transformation should be considered within the context of rigid body assumptions, which lead to two important simplifications in the vehicle's response. First, a rigid body implies that the ELR locations were experiencing the same acceleration at the same time as the accelerometers mounted near the vehicle's center of gravity. The second implication is that the theoretical ELR locations near the perimeter of the vehicle were not deformed. Carter [2002] placed accelerometers near the perimeter of a rolling vehicle in the roof area and reported that localized deformation resulted in acceleration values much higher than would be predicted from acceleration measurements taken at the center of gravity [12].

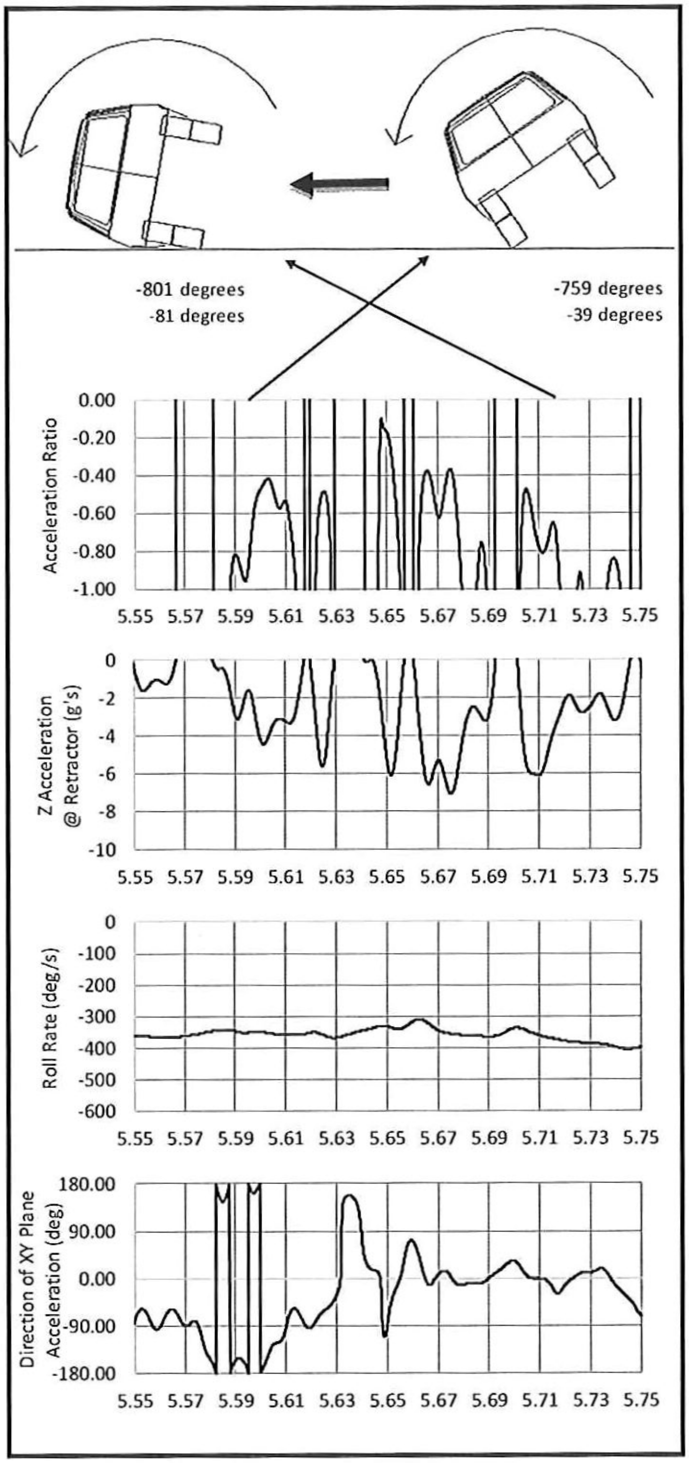


Figure 6. Responses at RF retractor for the interval 5.55 seconds to 5.75 seconds.

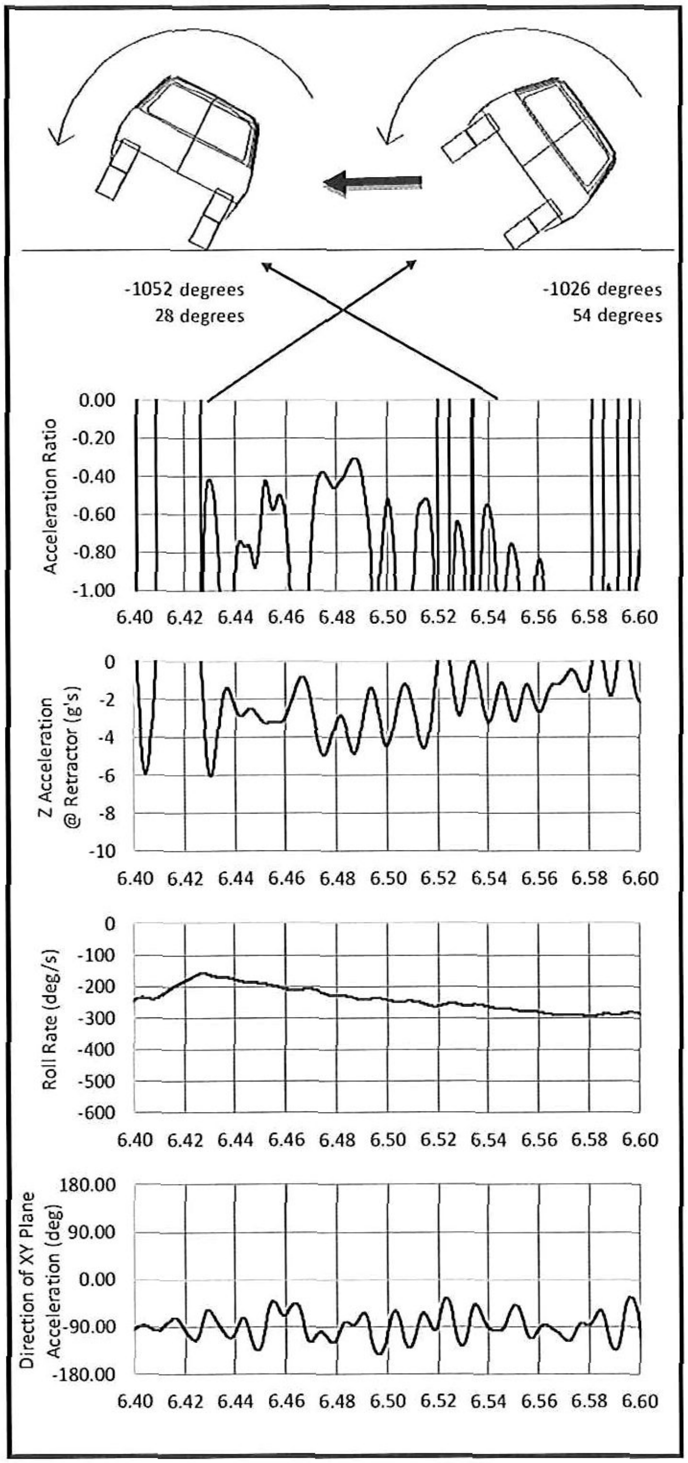


Figure 7. Responses at RF retractor for the interval 6.40 seconds to 6.60 seconds. For the front positions the longest duration is shown beginning at 6.47 seconds, 22.6 ms.

In this paper, the theoretical ELR locations were located near the rocker panel area. For a localized deformation at the rocker panel to cause a vehicle response that may allow an ELR to move into a neutral zone, dominate vertically-oriented narrow impacts between the front and rear tires must occur. These circumstances did not occur in the test that was the subject of this paper.

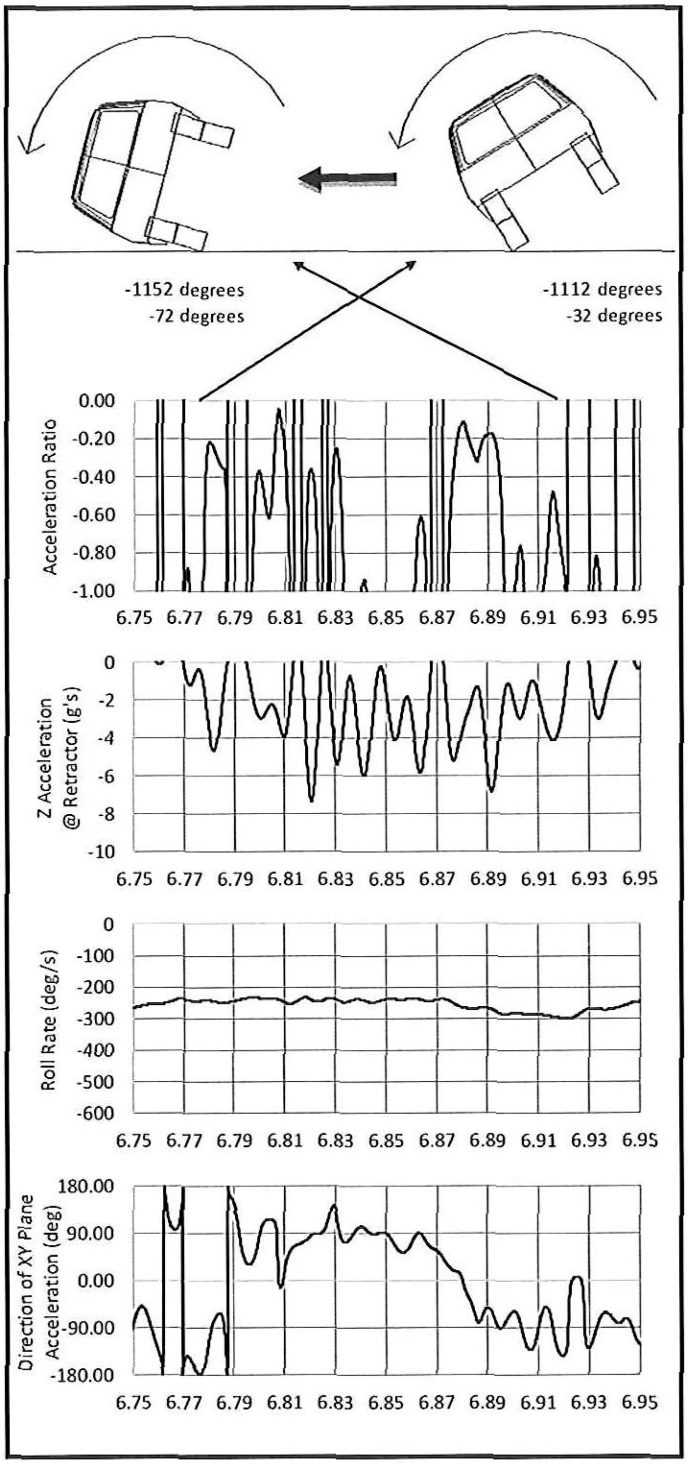


Figure 8. Responses at RF retractor for the interval 6.75 seconds to *6.95 seconds. The second longest duration for the front positions is* shown beginning near 6.87 seconds, 21.0 ms.

There are periods in the roll motion where the acceleration ratio at a specific retractor approaches zero from either a positive or negative direction. These periods and their respective approach direction were associated with specific vehicle orientations at ground contact; in other words, the roll angle at ground impact. The ratio's approach from the negative direction occurred when the vehicle was impacting with *dominate negative Z acceleration response* - generally with or near its bottom side. There are no instances shown in Figures 3 and 4 where roof contact caused the acceleration ratio at the

LF or RF to enter the range −0.7 to 0.0 and remain at that ratio longer than 5 ms. An approach from the positive direction in general was from a roof or near roof contact. In airborne phases ELR located laterally distant and vertically close to the vehicle's center of gravity cannot attain a neutral condition because of centripetal acceleration.

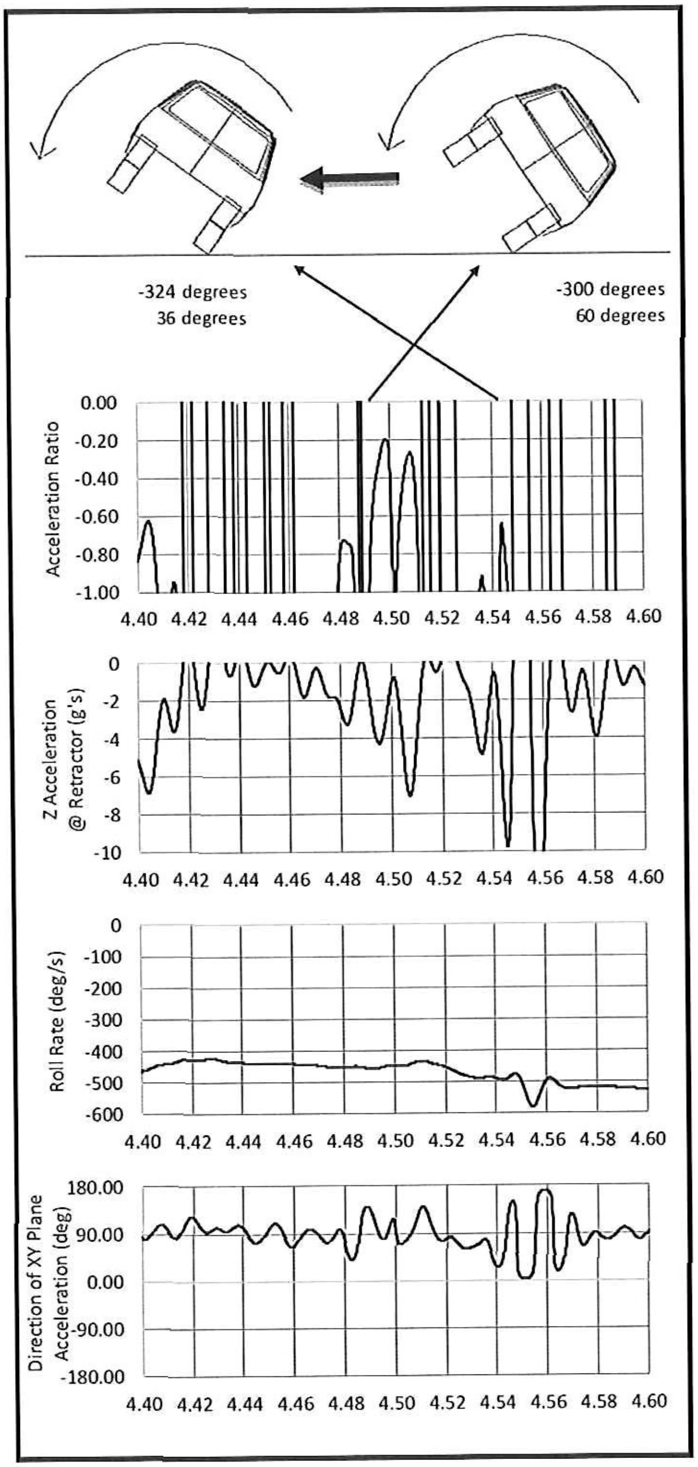


Figure 9. Response at LF retractor for the interval 4.40 seconds to 4.60 seconds. The double peak beginning at 4.49 seconds has a duration of 18.3 ms.

Both Figure 1 and Figure 2 show what appear to be vertical lines. The lines represent sign changing oscillations in the vehicle's response and display as vertical lines because of the clipped Y axis. Figure 1 and Figure 2 show instances in which calculated accelerations at a retractor produce a ratio that moves above −0.7 - the vehicle responds with an acceleration in which the ELR sensor may return to neutral.

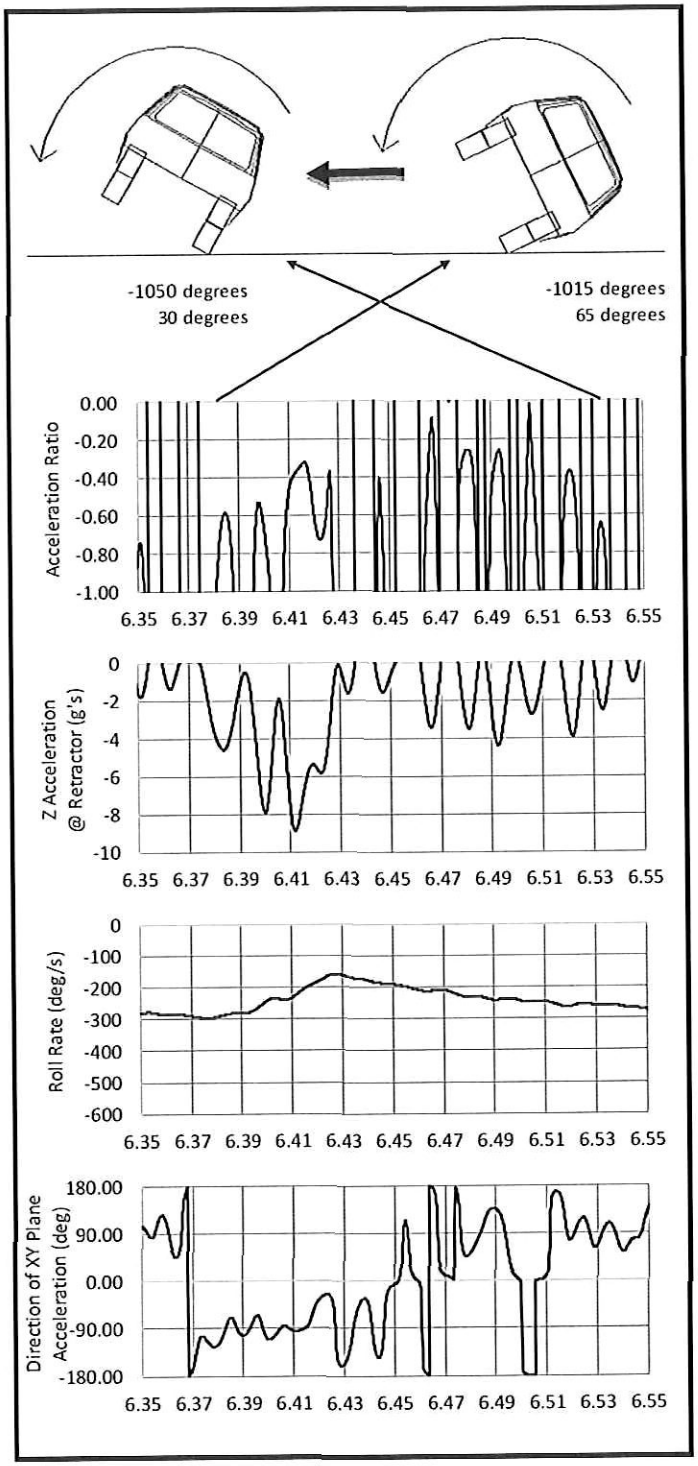


Figure 10. Response at LF retractor for the interval 6.35 seconds to 6.55 seconds.

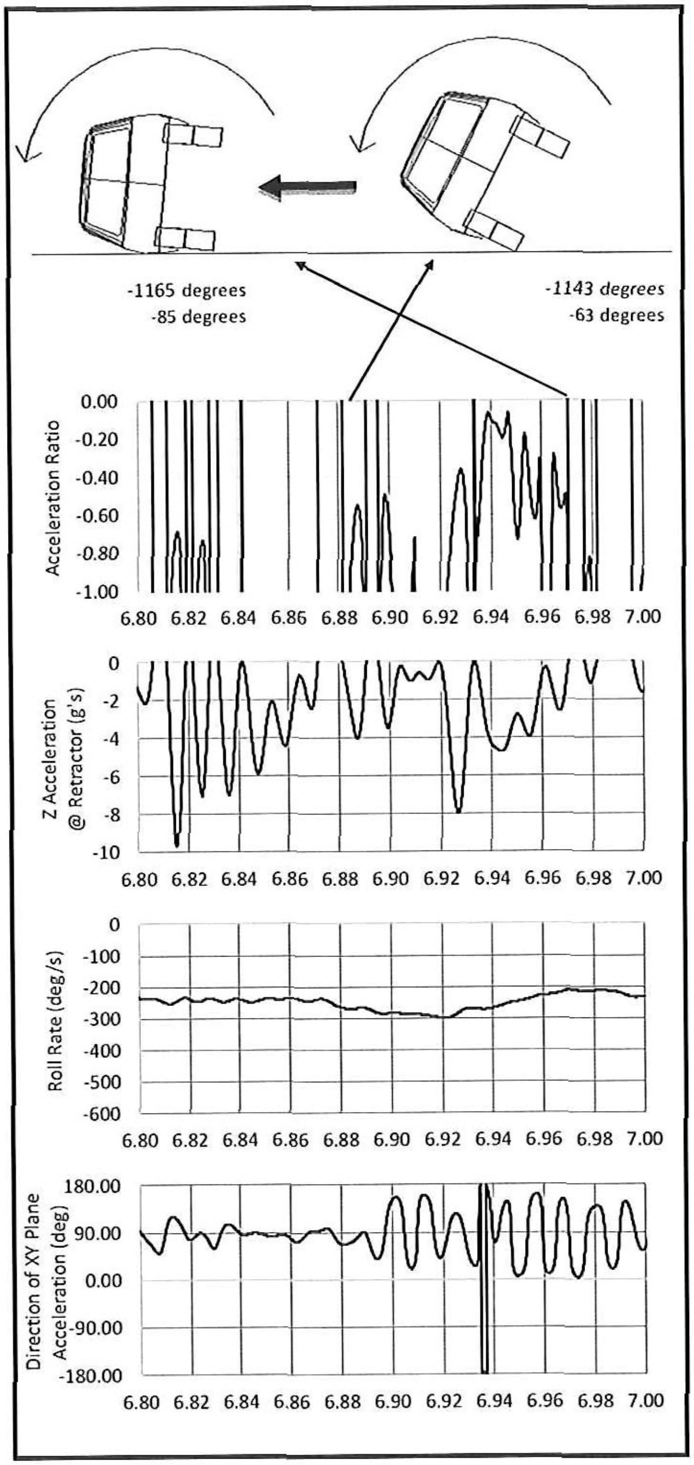


Figure 11. Response at LF retractor for the interval 6.80 seconds to 7.00 seconds. The 15.1 ms interval beginning at 6.935 seconds was the longest at the LF retractor and occurred in the 13/4 roll. Combining possible neutral zone responses at this time results in a greater than 35 ms duration.

Figure 3 and Figure 4 demonstrate that for the selected test the longest period when a vehicle response may allow a retractor to be in a neutral position was 31.7 ms for the LR at approximately 6.94 seconds (13/4 rolls), also shown in Figure 12. For front locations the longest duration was 22.6 ms for the RF at 6.470 seconds (11/4 rolls). For all instances calculated, the median result was 4 ms and the average result was 4.8 ms. Ninety-five percent of all instances were less than 12.6 ms in duration.

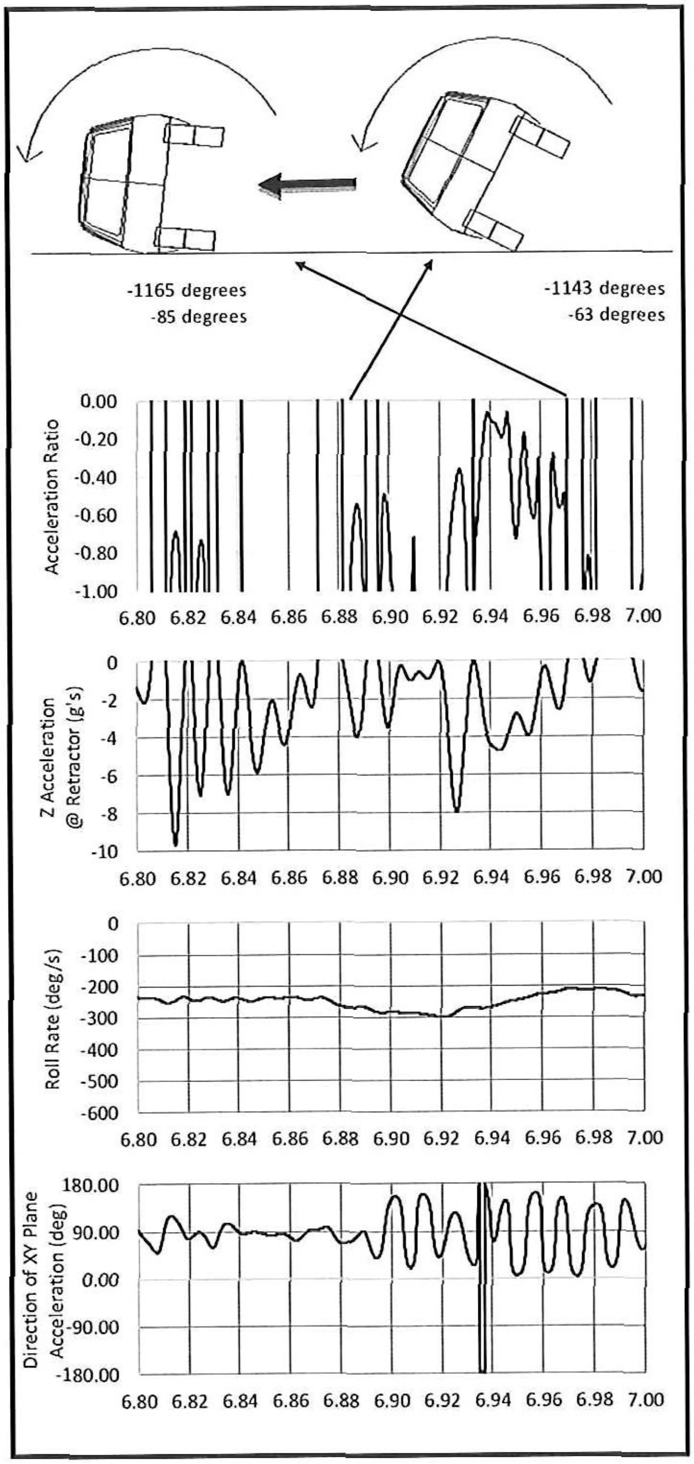


Figure 12. Response at LR retractor for the interval 6.80 seconds to 7.00 seconds. The 31.7 ms interval beginning at 6.938 seconds was the longest calculated overall and occurred in the 13/4 roll.

Using the threshold of 0.7 g, an analysis of all periods when the vehicle response may allow the LF and RF ELR to be in a neutral position resulted in the histogram in Figure 13 as summarized in Table 2. At the front positions for this single analyzed test two instances were calculated when a vehicle may have responded so that a retractor may have been in a neutral position for a duration of between 20 ms and 25 ms.

Table 2. Counts of durations calculated for intervals when the retractor may be in a 0.7 g neutral zone.

Bin (sec)	Frequency
0.005	65
0.010	21
0.015	5
0.020	3
0.025	2
0.030	0
0.035	0
0.040	0
total	96

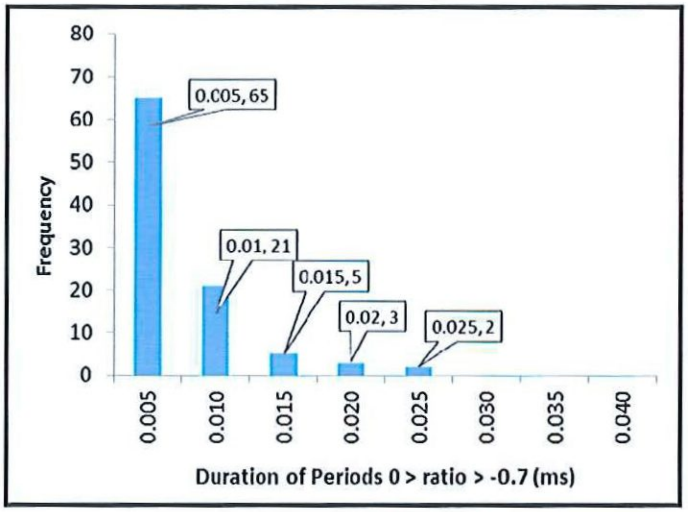


Figure 13. Histogram representing the distribution of durations calculated for intervals when the LF and RF retractors may be in a 0.7 g neutral zone.

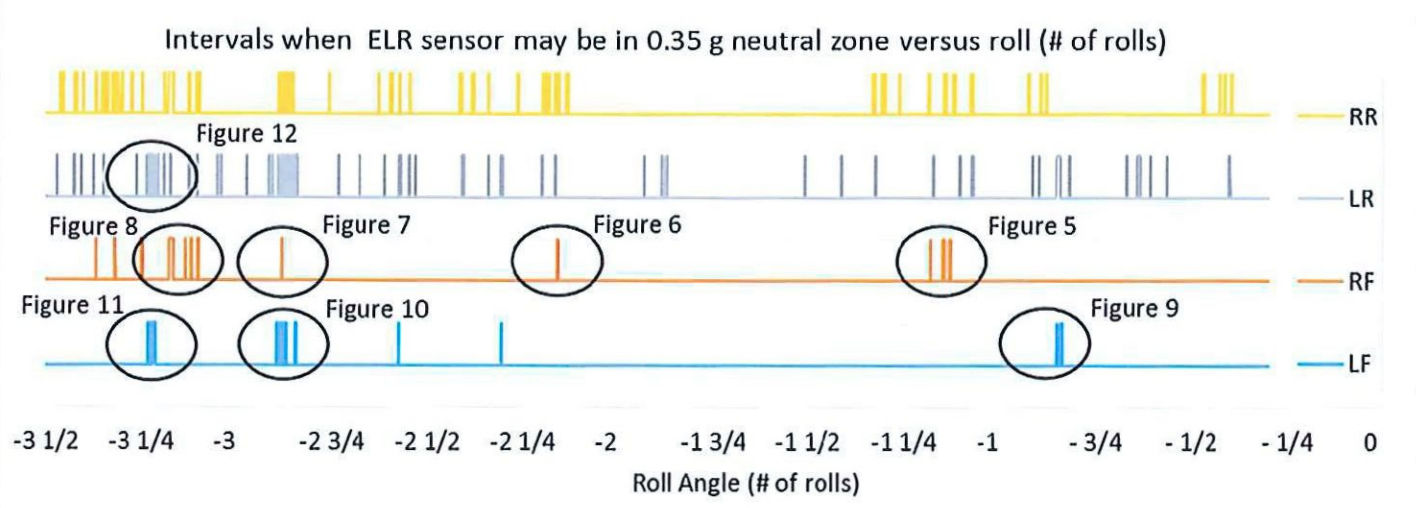


Figure 14. Calculated neutral zone condition (−0.35 < ratio < 0) shown as high magnitude as a function of rolls.

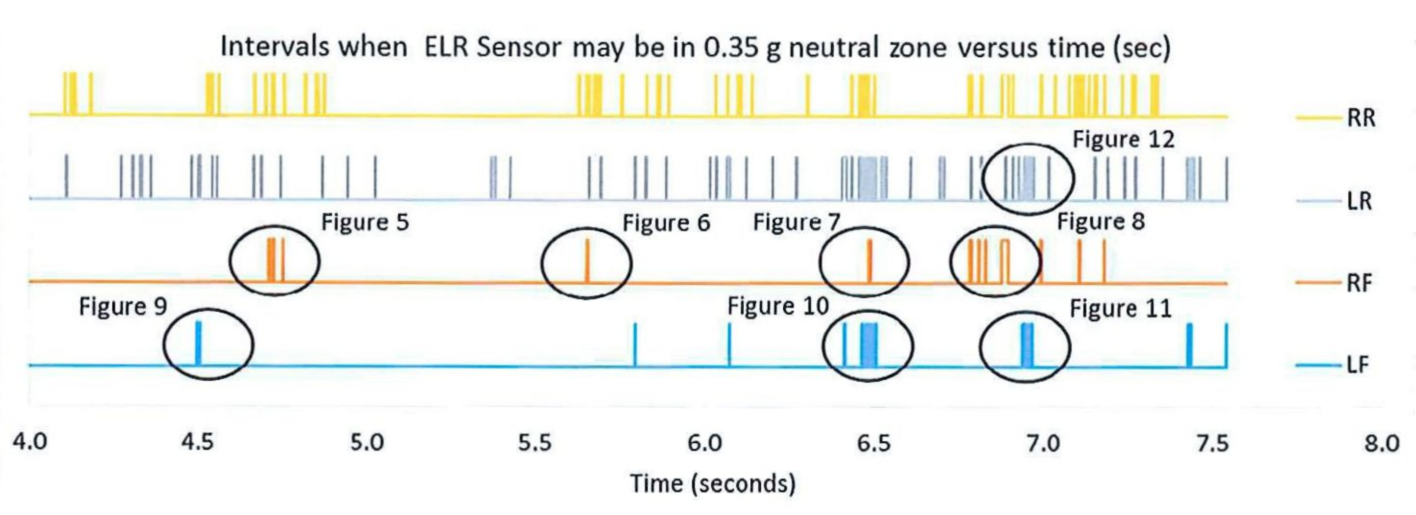


Figure 15. Calculated neutral zone condition (−0.35 < ratio < 0) shown as high magnitude as a function of time.

Table 3. Counts of durations calculated for intervals when the LF and RF retractors may be in a 0.35 g neutral zone

Bin(sec)	Frequency
0.005	23
0.010	3
0.015	1
0.020	1
0.025	0
0.030	0
0.035	0
0.040	0
total	28

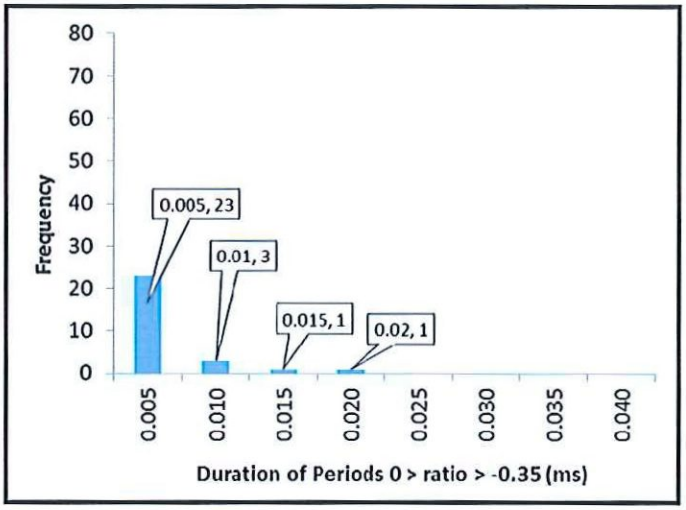


Figure 16. Histogram representing the distribution of durations calculated for intervals when the LF and RF retractors may be in a 0.35 g neutral zone

Three instances were calculated for a duration within the range of 15 ms to 20 ms and 91 other instances were calculated with periods less than 15 ms. Sixty-five calculated instances when the ELR may have been in the neutral zone had durations less than 5 ms. Only the results from the LF and RF retractor position are summarized and displayed in Figure 13 because the shape of the distributions are similar for the rear ELRs. Calculation at the rear locations are influenced by oscillations in the yaw and pitch accelerations which cause corresponding oscillation in the acceleration ratio. The oscillations complicate results at all locations, but produce significantly more instances at the rear locations where the duration is less than 5 ms.

Minus 0.7 was selected as the locking threshold of the ELR because of the FMVSS209 requirement. Individual retractors probably have lower threshold magnitudes (threshold > −0.7 g) and should be tested when studying specific crashes. For example, a threshold that was 0.35 g would result in decreased and shorter intervals when a vehicle's response may result in an ELR moving to a neutral zone as shown in results of Figure 14 and 15. In this example the reduced threshold decreased the maximum duration to 18.3 ms, median duration to 2.6 ms, average duration to 3.2 ms and the count of all intervals was reduced by 71 percent.

Using the threshold of 0.35 g, an analysis of all periods when the vehicle response may allow the LF and RF ELR to be in a neutral position resulted in the histogram in Figure 16 as summarized in Table 3. At the front positions for this single analyzed test one instance was calculated when a vehicle may have responded so that a retractor may have been in a neutral position with a duration between 15 ms and 20 ms, one instance was calculated with a duration in the range of 10 ms to 15 ms and 26 other instances were calculated with periods less than 10 ms. Twenty-three calculated instances when the ELR may have been in the neutral zone had durations less than 5 ms.

Many of the periods associated with instances when the vehicle response may move the ELR to a neutral zone occurred in clusters with relatively short times between each instance. For the longest periods (Figure 5, Figure 6, Figure 7, Figure 8, Figure 9, Figure 10, Figure 11, Figure 12) when the vehicle response may move the LF or RF ELR to a neutral zone, the roll angle associated with clustered events was between 65 degrees and −85 degrees (measured from a positive pointing upward vertical plane). For left side wheel contacts the range was −32 degrees to −85 degrees, and for RS wheel contacts the range was 65 degrees to 28 degrees

Though not the main point of the paper and not a substitute for the occupant kinematics analysis required by the Thomas Conditions, the second calculation was performed to gain insight into vehicle positions and motions that may exclude or promote the occupant kinematics required to allow the ELR locking mechanism to unlock. According to Thomas,

"Thus, in order to achieve webbing spool-out, forces must be applied to the rolling vehicle in such a manner as to cause the occupant to move in such a way to release tension from the belt webbing and allow the retractor to wind a small amount of webbing back onto the spool to disengage the lockup mechanism. This requires the occupant to move vertically downward and back toward the seat bottom cushion. The necessary forces to accomplish this downward motion do occasionally occur in rollover accidents. These forces are most likely present during a ground impact with a tire/wheel assembly" [1, pg. 16].

An approximation of the occupant acceleration can be made by investigating the acceleration of a point on the vehicle near the occupant as was done by Thomas [1].

There was minimal overlap between an acceleration field that may result in a neutral position and directionally positive XY plane acceleration. Directionally positive XY plane acceleration would be near an angle of zero (zero pointing forward in the XY plane) and would cause the "and back" occupant movement described above by Thomas. Positive 180 degrees and minus 180 degrees were identical and directionally backward. An example of overlap between an acceleration field that may result in a neutral position and a directionally positive XY plane acceleration is demonstrated for the RF position at several intervals in Figure 6 and in Figure 8 at approximately 6.88 seconds.

The final condition for spool-out in the Thomas Conditions [1] was that, while the retractor is unlocked, motion of the occupant against the webbing must occur in a manner that will cause spool out. Assessing the kinematics of an occupant in each period that the vehicle response may move the retractor to a neutral position was beyond the scope of this paper and not possible because of the setup of the Stevens' testing. The Stevens testing did not attempt to evaluate occupant kinematics and used belted water dummies filled with salt pellets in each designated seating position. Secondary straps were also used in securing the salt pellet filled water dummies to the seats. The testing did not record belt load, belt motion, or occupant motion. While the authors do not believe the water dummy responses in the Stevens' testing should be used to describe occupant kinematics, there was no noted or photographed belt spool out.

An analysis of belt spool out would need to take into consideration already discussed constraints on articulation and motion. If the ELR unlocks, an articulation of the occupant into the belt must occur due to the same acceleration and rotation response that is producing a neutral position of the ELR sensor. After discussing his final condition Thomas concluded, "*A set of forces, that causes the sensing mass to remain in the neutral position while the occupant moves to reengage the belt webbing do not coexist in dynamic rollover accidents*" [1, pg. 16].

Conclusion

The conditions outlined by Thomas [1] provide an objective basis for evaluating whether belt spool out from an ELR may occur. The analysis in this paper included calculations and detailed results of vehicle responses consistent with Thomas' first condition and discussed a limited method for considering his second condition.

The results presented are consistent with Thomas' statement that, "ground contacts may cause the sensing mass to momentarily pass through a neutral position" [1]. The results presented in this paper provide an objective description of vehicle orientations and interval durations conducive to attaining a neutral position. Further, the results identified a subset of intervals that may be consistent with Thomas' statement regarding his second condition that, "The necessary forces to accomplish this downward motion [vertically downward and back toward the seat cushion] do occasionally occur in rollover accidents" [1].

The calculations of acceleration at each retractor assume that the vehicle is a rigid body and that the measured acceleration and angular motion was located at the vehicle's center of gravity. Conducting steer-induced rollover tests with accelerometers and cameras mounted at each retractor would provide a direct measurement of an ELR's crash-sensing state.

An objective of this study was to investigate instances where the vehicle is in a state for an ELR to be in a neutral zone of $0.0<\text{Ratio}<-0.7$. An associated calculation presented conditions where the ELR has the potential to unlock. For spool out to occur during these intervals the belt must reach an unloaded condition so the retractor can unlock and then the occupant must experience the necessary acceleration to spool belt from the retractor. The ability of the occupant to change from not loading the belt to loading the belt during the intervals that the acceleration ratio is within the neutral zone is dependent on the occupant's kinematics and the forces applied to the occupant by contact with the vehicle. The occupant's kinematics need further study perhaps through testing or simulation.

Only one crash test and selected intervals were presented in the subject paper. The results of this paper should not be used to describe any individual crash in the distribution of possible rollovers. The presentation demonstrated that there are candidate intervals when the ELR may move to a neutral condition. Interval durations for the threshold of 0.7 g were presented as a distribution in Table 2 with a median duration of 4.0 ms, average duration of 4.8 ms and a maximum calculated duration of 31.7 ms. A sensitivity analysis was conducted and demonstrated that if the threshold is 0.35 g the interval count and durations are reduce by 71 percent and approximately 50 percent, respectively.

Since a retractor in an interval when an inertial sensor may move into a neutral position will unlock only after belt retraction and typically at an acceleration ratio below the upper threshold, the duration that a retractor may be unlocked was probably less than the duration of an interval when an inertial sensor may move into a neutral zone.

References

1. Thomas, T.M., Marine, M.C., Wirth, Jeffrey L., and Peters B. W.. "Emergency-Locking Retractor Performance in Rollover Accidents." *American Society of Mechanical Engineers* (2002): 1-25.
2. Meyer, Steven E., Forrest, Stephen M., Hayden, Joshua D., Herbst, Brian R., and Sances Anthony. "The Effect of Vertical Acceleration on Emergency Locking Seatbelt Retractors." *Conference Proceedings from the American Society of Mechanical Engineers Advances in Bioengineering, BED* 48 (2000).
3. Meyer, Steven E., Forrest, Stephen M., Hock, Davis A., Herbst, Brian R., and Sances AnthonyJr., "Test Methods for Evaluating Seatbelt Retractor Response in Multiplanar Acceleration Environments." *Conference Proceedings from the American Society of Mechanical Engineers Advances in Bioengineering, BED* 50 (2001).
4. Meyer, S., Hock, D., Herbst, B., and Forrest, S., "Dynamic Analysis of ELR Retractor Spoolout," SAE Technical Paper 2001-01-3312, 2001, doi:10.4271/2001-01-3312.
5. Meyer, Steven E., Hock, Davis A., Forrest, Stephen M., and Herbst Brian R.. "Motor Vehicle Seat Belt Restraint System Analysis During Rollover." *Conference Proceedings from the 40th Annual Rocky Mountain Bioengineering Symposium, Biomedical Sciences instrumentation* 39, ISA Volume 437 (2003, April): Biloxi, MS, USA.
6. Hock, Davis A., Meyer, Steven E., Herbst, Brian R., Forrest, Stephen M., Renfroe, David A., Hutchinson, Brandon,

Canalichio, Troy, Sances, Anthony, and Kumaresan Srirangam. "Evaluation of Motor Vehicle Seatbelt Retractor Locking Devices." *Conference Proceedings from the IMECE04 2004 ASME International Mechanical Engineering Congress and Exposition* IMECE2004-60201 (2004, November): Anaheim, CA, USA.

7. Meyer, Steven E., Oliver, Arin A., Hock, Davis A., Hayden, Joshua D., Forrest, Stephen M., Herbst, Brian R., and Clarke Chris C.. "The Effect of Vertical and Multiplanar Accelerations on Differing Production Seat Belt Sensor Designs." *Conference Proceedings from the International Mechanical Engineering Congress and Exposition* IMEC2008-6893 (2008, October): Boston, MA, USA.
8. Jones, I. and Wilson, L., "Techniques for the Reconstruction of Rollover Accidents Involving Sport Utility Vehicles, Light Trucks and Minivans," SAE Technical Paper 2000-01-0851, 2000, doi:10.4271/2000-01-0851.
9. Code of Federal Regulations, Title 49, Part 571.209 (2000).
10. Stevens, D., Arndt, S., Wayne, L., Arndt, M. et al., "Rollover Crash Test Results: Steer-Induced Rollovers," SAE Technical Paper 2011-01-1114, 2011, doi:10.4271/2011-01-1114.
11. Funk, J., Wirth, J., Bonugli, E., Watson, R. et al., "An Integrated Model of Rolling and Sliding in Rollover Crashes," SAE Technical Paper 2012-01-0605, 2012, doi:10.4271/2012-01-0605.
12. Carter, J., Habberstad, J., and Croteau, J., "A Comparison of the Controlled Rollover Impact System (CRIS) with the J2114 Rollover Dolly," SAE Technical Paper 2002-01-0694, 2002, doi:10.4271/2002-01-0694.

Definitions/Abbreviations

ASME - American Society of Mechanical Engineers

CG - Center of Gravity

ELR - Emergency Locking Retractor

FMVSS - Federal Motor Vehicle Safety Standard

LF - Left Front

LR - Left Rear

RF - Right Front

RR - Right Rear

Thomas Conditions - Conditions for belt spool out from an ELR as described in Reference 1

APPENDIX

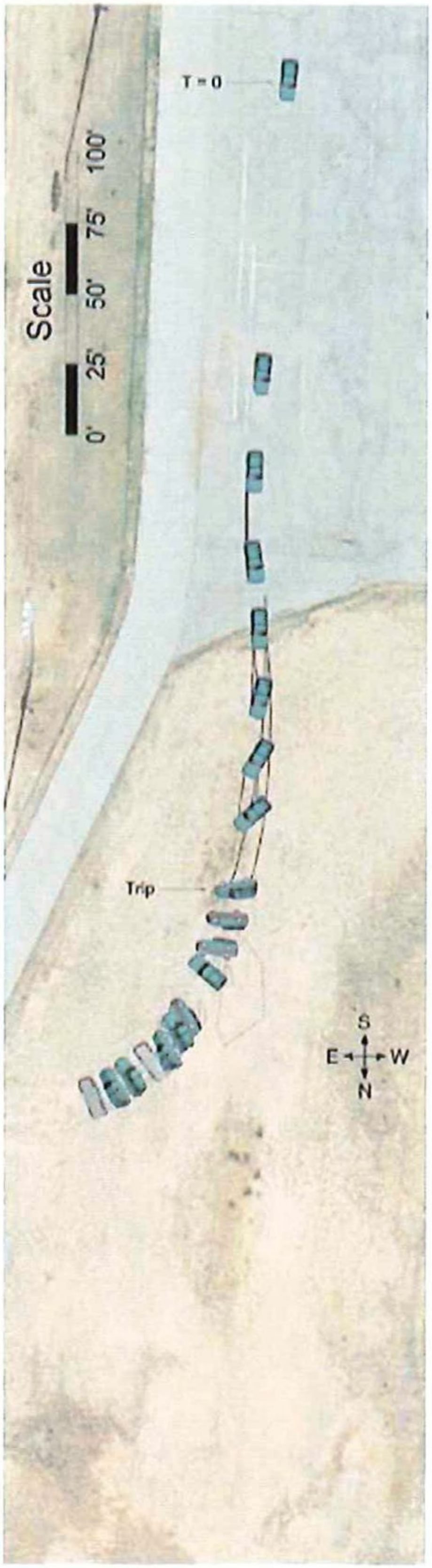
APPENDIX A









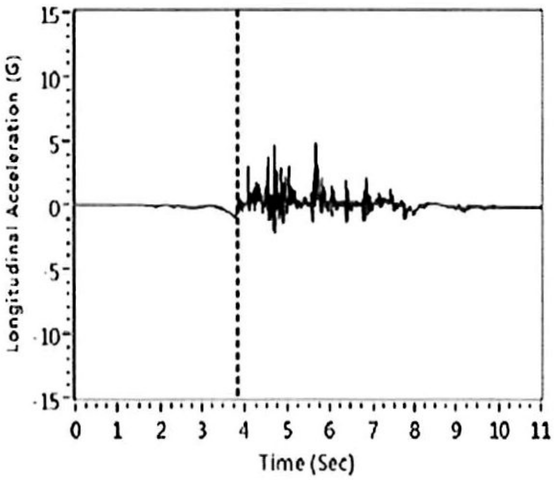
Test 3

Test #3 Notes

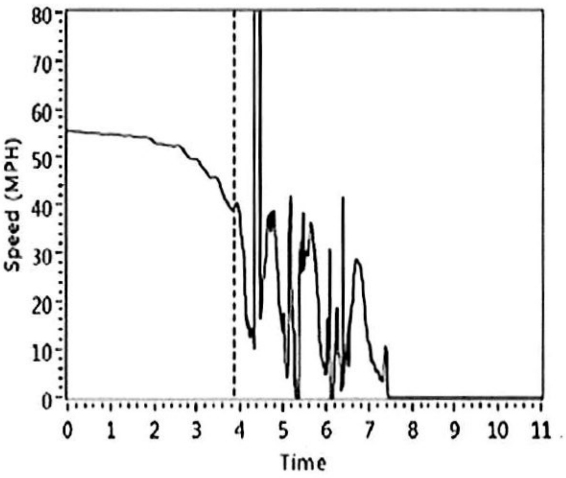
- 1997 Ford Explorer Sport 4x4
- Vehicle Test Weight: 5025 lbs
- Tires: Avon Radial SXT All Terrain 30x9.50R15LT
- Tire pressure:
  - Pre-test: All four tires 36 psi
  - Post-test: RF = 31 psi, RR = 24.5 psi, LF/LR = 0 psi
- Driver side leading rollover
- Trip surface: Desert soil
- Roll surface: Desert soil
- Ambient temperature 75 °F
- LF tire debeads approaching trip
- Dust cloud obstructs video footage for first 1.5 rolls

1997 Ford Explorer Sport 3.5 Rolls Test #3

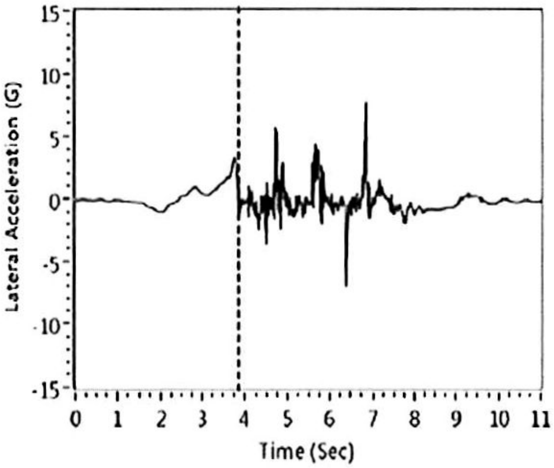
Uncorrected Longitudinal Acceleration



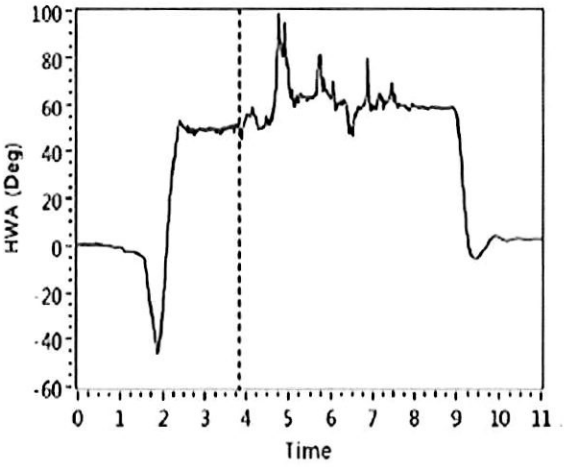
Velocity



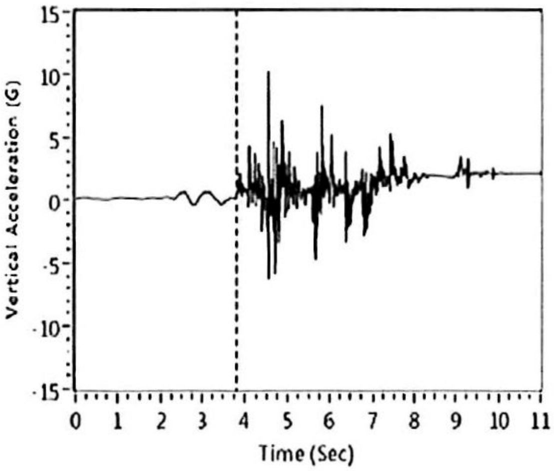
Uncorrected Lateral Acceleration



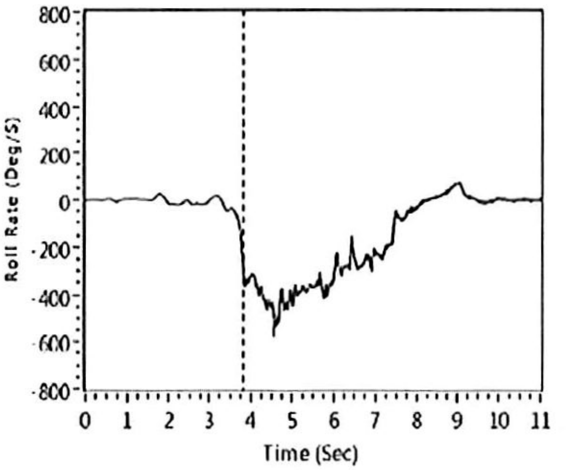
Steering



Uncorrected Vertical Acceleration



Roll Rate



All data filtered 6Hz phaseless filter prior to trip point, class 60 phaseless filter after trip point; Speed and HWA unfiltered

f_s	h_1 (ft)	h_2 (ft)	h_1/r	h_2/r	R_2 (trans)	R_2 (rot)
0.63	1.6	1.35	0.44	0.37	1.00	0.97

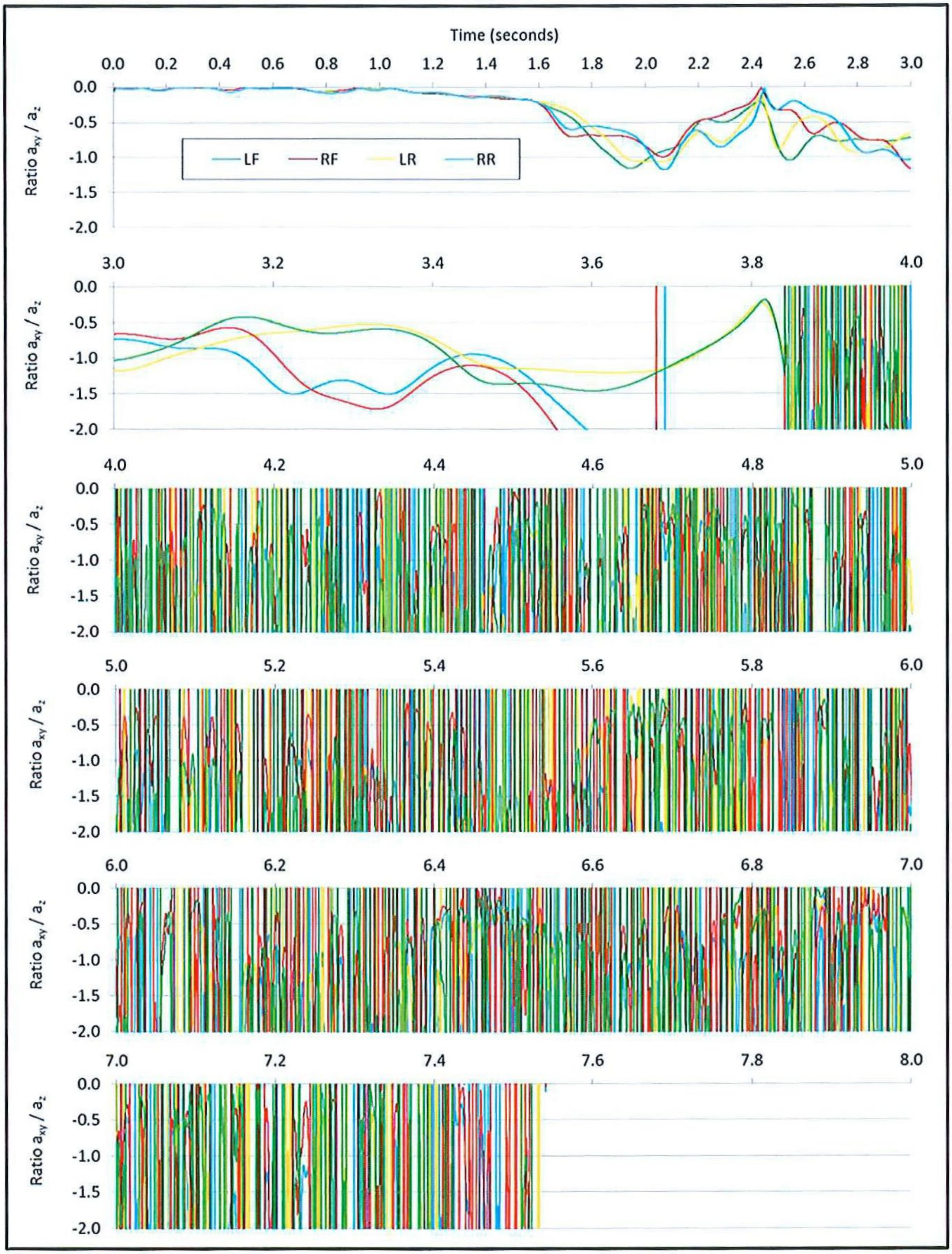
a_1 (g)	a_2 (g)	$a_{overall}$ (g)	α_1 (deg/s2)	α_2 (deg/s2)	t_1 (s)	t_2 (s)	t_f (s)
-0.63	-0.27	-0.33	249	-134	0.25	0.89	4.54

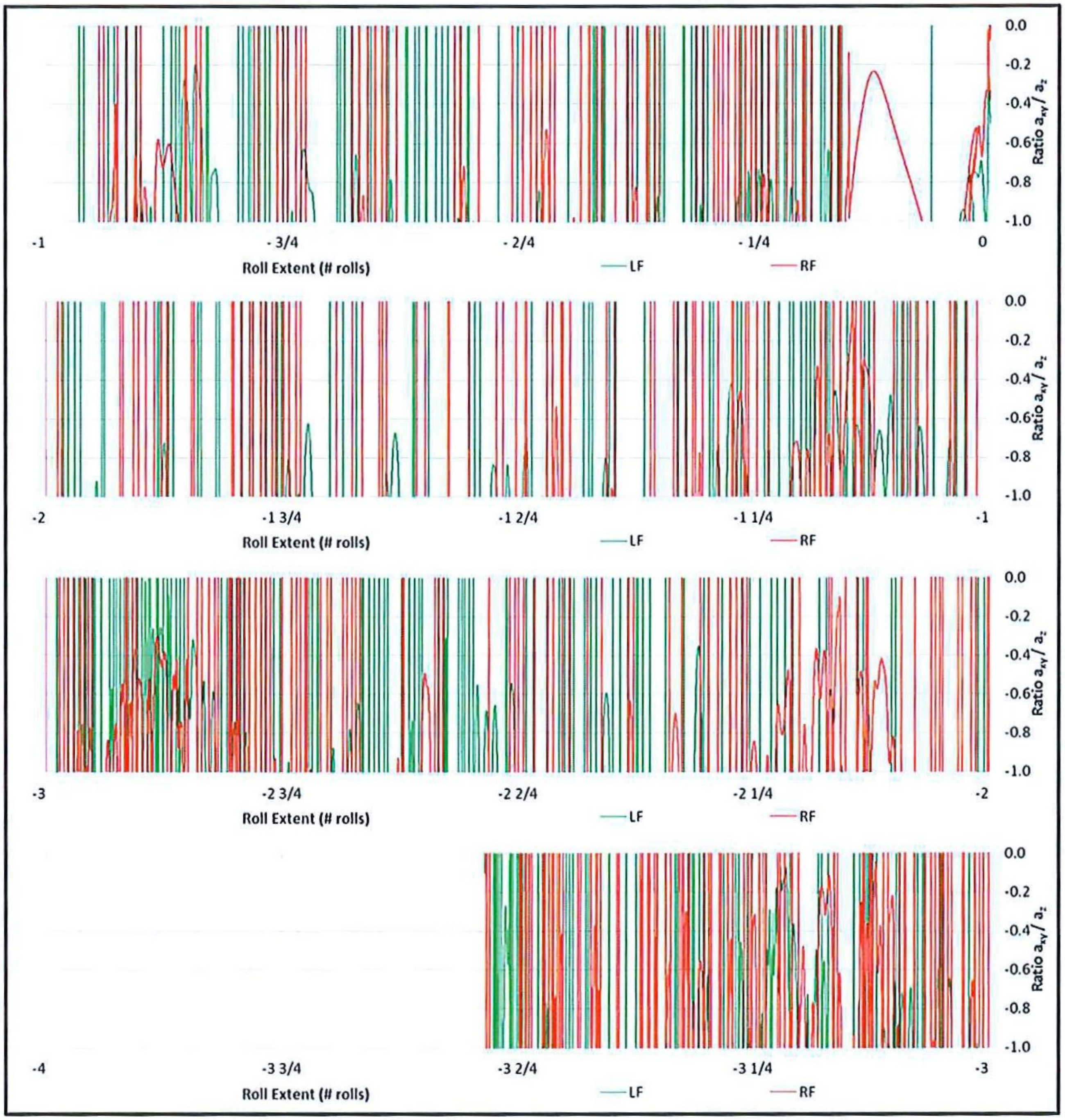
ω_1 (deg/s)	ω_1 (deg/s)	θ_0 (rolls)	θ_1 (rolls)	θ_2 (rolls)	θ_f (rolls)	V_0 (mph)	V_2 (mph)
332	491	0.15	0.38	1.11	3.6	30	21

d_1 (ft)	d_2 (ft)	d_f (ft)	t_2/t_f	θ_2/θ_f	d_2/d_f
11	35	93	0.2	0.31	0.38

Statistics from Funk [11] for the Stevens R3 test response.

APPENDIX B


Time (seconds)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
3.0
3.2
3.4
3.6
3.8
4.0
4.2
4.4
4.6
4.8
5.0
5.2
5.4
5.6
5.8
6.0
6.2
6.4
6.6
6.8
7.0
7.2
7.4
7.6
7.8
8.0
Ratio a_{xy} / a_z
0.0
-0.5
-1.0
-1.5
-2.0
LF
RF
LR
RR



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