

Vehicle Chassis, Body, and Seat Belt Buckle Acceleration Responses in the Vehicle Crash Environment

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ABSTRACT

For over 30 years, field research and laboratory testing has consistently demonstrated that proper utilization of a seat belt dramatically reduces the risk of occupant death or serious injury in motor vehicle crashes. The injury prevention benefits of seat belts require that they remain fastened during collisions. Federal Motor Vehicle Safety Standards and SAE Recommended Practices set forth seat belt requirements to ensure proper buckle performance in accident conditions. Numerous analytical and laboratory studies have investigated buckle inertial release properties. Studies have repeatedly demonstrated that current buckle designs have inertial release thresholds well above those believed to occur in real-world crashes. Nevertheless, inertial release theories persist. Various conceptual amplification theories, coupled with high magnitude accelerations measured on vehicle frame components are used as support for these release theories.

This study investigates vehicle frame, vehicle floor pan and seat belt buckle acceleration responses in various laboratory environments on a mid-size body-on-frame sport utility vehicle. This is accomplished through the analysis of acceleration data from a frontal barrier crash test, a vehicle drop test and direct floor pan impulse response tests. These tests demonstrate that the magnitudes and durations of the accelerations experienced by the buckle are well below those necessary for inertial release. Analysis of buckle acceleration magnitudes in conjunction with the coincident seat belt webbing tensions re-affirms that

inertial release of a seat belt buckle in the vehicle crash environment is unlikely. Lastly, data analysis of the performed tests demonstrates that the acceleration pulse transmitted from the vehicle chassis through the floor pan to the buckle was attenuated.

INTRODUCTION

Resolving issues and questions related to buckle performance in real world collision and rollover scenarios in general requires full vehicle crash testing and, in particular, a focus on the severity of the crash conditions. Numerous analytical and laboratory studies have investigated buckle inertial properties and have shown that current buckle designs have inertial release thresholds well above conditions believed to occur in real-world crashes. To attain a seat belt buckle release during a collision event, four independent elements must be satisfied simultaneously. They are: acceleration magnitude, acceleration duration, acceleration direction and insufficient webbing tension.

For inertial release to occur, a collision impulse is required that would move the buckle release button relative to the buckle housing a sufficient distance to actuate the buckle assembly. In order to achieve this relative motion of the release button, an impulse must have sufficient magnitude and duration along the axis of button motion.

The acceleration threshold required for inertial release of a given buckle is a function of the duration of the acceleration pulse. The threshold for release will

increase as the duration of the pulse decreases. This also assumes that there is no load imposed on the buckle assembly by the seat belt webbing at the time of the application of the acceleration pulse. When seat belt tension is introduced, the buckle release threshold is significantly increased. Inertial unlatching of end release buckles would require an axially oriented impulse. An axial buckle impulse can be generated by vertical impulses to the vehicle experienced during wheel-to-ground impacts in rollover and rebound crash scenarios.

A high magnitude acceleration, in and of itself, is not sufficient to cause an inertial release of a buckle assembly. Vehicle structures can experience high frequency (short duration) vibrations. The resulting displacement of these high magnitude short duration accelerations is not sufficient to cause inertial release.

Similar to acceleration, the change in velocity of an impulse is a necessary condition, but it alone is not a sufficient condition for inertial unlatching to occur. The change in velocity of a given impulse is a function of the acceleration magnitude and duration. An increase in the change in velocity for a given impact scenario, results in a greater chance for the conditions necessary for inertial release to occur. Most component testing has shown that a minimum change in velocity of approximately 8 mph along the release button motion axis is required to generate high enough magnitude acceleration for inertial release. The durations of these impulses are very brief and are on the order of 2 - 5 milliseconds. If the impulse durations are longer than this, impacts with even larger magnitude changes in velocity are needed to cause inertial release.

In addition, the onset of significant webbing tension or direct occupant contact with the buckle can cause high magnitude buckle accelerations. When these accelerations are caused by the onset of occupant load to the restraint system, the magnitude of belt tension at the time that the peak acceleration occurs must be considered since it increases the buckle resistance or threshold to release.

The purpose of this study is to obtain a better understanding of the end release seat belt buckle acceleration response at various seating positions. This was accomplished by performing two full vehicle tests of a 1998 Ford Explorer: a frontal fixed barrier collision and a vertical drop test. During these tests, the acceleration of various components of the vehicle and the front and rear seat belt buckle assemblies were monitored. The relative magnitudes and frequency content of the signal at various locations are compared and the transmission (amplification/attenuation) of acceleration to the buckle is assessed.

Several components are involved in the transmission of the impact pulse to an end release buckle assembly. In addition to the vehicle chassis and body, each buckle is mounted to the vehicle body through different restraint

anchorage designs. The front seat buckles of the 1998 Ford Explorer are attached to a mounting bracket that moves fore-aft with the front seat by webbing encased in a polymer sheath. The buckle bracket is anchored to the vehicle body by a polymer encased metal rail along which the bracket traverses. The left rear and center rear buckle assemblies are mounted on a metal strap affixed to a mounting bracket with a rivet joint. The mounting bracket is bolted directly to the vehicle body.

To better understand the origin of some crash induced buckle accelerations, a simple frequency dependent transmission model has been generated based on the impulse response of the floor pan and buckle. The free response of the vehicle floor pan and buckle assemblies to direct strikes to the under side of the vehicle floor pan were used to create a frequency based transmission function.

BACKGROUND

The use of safety belts significantly reduces an occupant's risk of fatal or severe injury during collisions. [1, 2, 3] In rollover crashes the unpredictable motion of the vehicle can be particularly injurious to unbelted vehicle occupants because they are more likely to contact the interior vehicle surfaces or be ejected from the vehicle. In passenger cars and light trucks, front seat occupants that use 3-point lap/shoulder belts are 74 to 80 percent less likely to be fatally injured in a rollover crash. [4]

A safety belt must remain buckled during a collision to effectively reduce injury and fatality potential. For almost 40 years, Federal standards and SAE recommended practices have addressed the issue of restraint system performance. However, they have not specifically addressed the issue of inertial seat belt buckle release (inertial release), other than to state in general terms that buckle design must have "minimal possibility of accidental release". [5]

Specific investigations into energy thresholds and mechanisms required for the inertial release of side-release belt buckles have been studied for more than four decades. Since the mid-1990's, the trend in production vehicles has been toward the end release buckle design. Most research has focused on testing individual vehicle components as part of seating and restraint systems outside of the total vehicle environment, with a lesser focus on full vehicle evaluation. [6, 7, 8, 9]

Frontal barrier crash tests with vertical accelerations exceeding 100g in both crush and non-crush zone locations have been used to suggest that the accelerations necessary for inertial release are present during collisions. High magnitude accelerations are possible on vehicle structures, however, these accelerations have not been shown to be transmitted to buckle assemblies or to cause inertial release in the

crash environment. Frontal barrier tests, by nature, do not provide the vertical change in velocity necessary for vertical acceleration impulses of sufficient magnitude and duration to cause inertial unlatching.

Klima et al. performed vertical drop testing of vehicles with impact speeds ranging from approximately 10 to 11 mph and recorded peak axial buckle accelerations between 17g and 33g for these severe vertical impulses in the vehicle environment. [10] The highest publicly reported dolly rollover crash pulse identified was a peak resultant floor pan acceleration of 28.5g by Moffatt et al. [11] This reported peak acceleration occurred after the left rear axle was broken off in the preceding roll. In all of the above testing the results were presented in accordance with SAE J211 and data filtered at Channel Filter Class (CFC) 600.

A recent publication by Haldenwanger et al. [12] describes 150g magnitude axial accelerations measured on buckle assemblies during various modes of crash testing. There were 17 reported axial buckle acceleration peaks over 150g in the direction necessary for inertial release out of a total of 44 buckles tested without pretensioner deployment. At the time of peak axial acceleration, significant transverse accelerations were also present. The average duration of the axial accelerations was 0.433 milliseconds with a maximum duration of 1.43 milliseconds. The average lap belt tension was approximately 2500 Newtons at the time of peak axial acceleration. A buckle release was not reported to have occurred during any of the crash tests. All of the elements required to produce a buckle inertial release were not present. Further, the belt tension, which is known to increase the threshold of the buckle inertial release may itself be contributing to the magnitude of the peak axial accelerations on the buckle.

Additionally, there has been a study that suggests that acceleration amplification occurs between the area of impact and the buckle due to buckle stalk designs. [13] Subsequent investigation of the amplification theory has been conducted by other researchers. [14, 15, 16] Davee et al. has shown that for a GEN III buckle and its associated cable stalk, a maximum amplification factor of 1.3 times is possible if the input pulse is near the natural frequency of the system. [14] Cooper et al. used a slide hammer on the underside of the vehicle body of several different vehicle models to evaluate the buckle and attachment hardware impulse response. [15] This testing demonstrated significant attenuation of acceleration peaks through various buckle attachment designs.

Shock table testing has shown the threshold for inertial release for the buckle design employed in the 1998 Ford Explorer is approximately 200g over an 8 to 10 millisecond pulse with a nominal 3 pounds of belt tension. When the pulse is decreased to approximately 3 to 4 milliseconds, the threshold increases to approximately 230g. All of these threshold tests were

run with the buckle oriented so the acceleration was applied along the direction of release button travel. [17]

METHODOLOGY

FIXED FRONTAL BARRIER CRASH TEST

A 35 mph vehicle impact test was conducted to evaluate crash induced accelerations and vibrations in various chassis and body components. The purpose was to determine whether or not the acceleration magnitudes were of sufficient levels to cause inertial release of an end release seat belt buckle. The test vehicle was equipped with extensive acceleration measurement and data acquisition equipment. The vehicle utilized was a 1998 Ford Explorer, 4-door, 4x2 with a 4.0 liter engine.

The test vehicle was equipped with five Anthropomorphic Test Devices (ATDs) of differing configurations. The ATD configurations were a 50th percentile male at each front seating position; a 5th percentile female in the right rear position; a 3 yr-old in a child seat at the rear middle position; and a 6 yr old in a booster seat at the left rear position. The vehicle test weight was 4603 pounds. The vehicle speed at impact was approximately 35 mph.

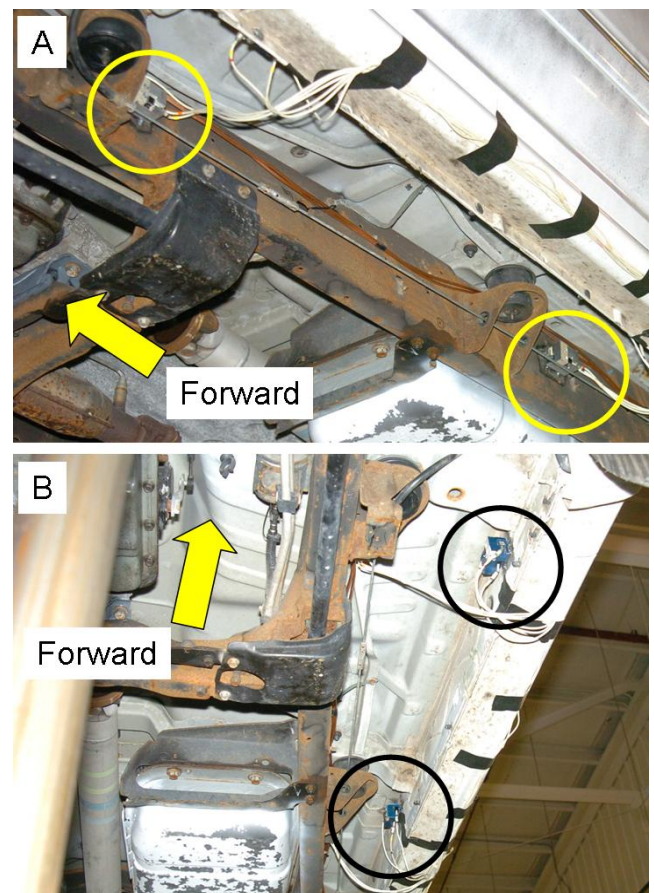


Figure 1 – Mounting locations for the (A) left frame and (B) rocker panel accelerometers in line with the A-pillar and B-pillar

Accelerometers were mounted to the test vehicle and acceleration data was recorded in the X, Y and Z vehicle directions per SAE conventions. All accelerometer blocks were welded into position on the frame and body. Figure 1 shows an example of the mounting of the left frame and rocker accelerometers in line with the A-pillar and B-pillar. The accelerometer blocks were positioned on the outside of the frame rail and also on the rocker sill approximately in-line with the mid-sections of the body A-pillar, B-pillar and C-pillar. These mountings were on both the driver and passenger sides of the vehicle.

Additional accelerometers were mounted on the floor pan under each designated seating position. An accelerometer on the floor pan tunnel was added to record data at the approximate fore-aft and lateral CG location of the vehicle. A total of eighteen (18) accelerometer blocks with fifty-four (54) individual X, Y and Z plane accelerometers were utilized for the test. Entran EGAX-T 1000g accelerometers were affixed to the end release buckles in the lateral and axial (along the release button axis) directions at each seating position. The buckle coordinate system and a photograph of an instrumented buckle are shown in Figure 2. In addition to the accelerometers, real-time and high-speed video were recorded, both of which were synchronized with the data acquisition.

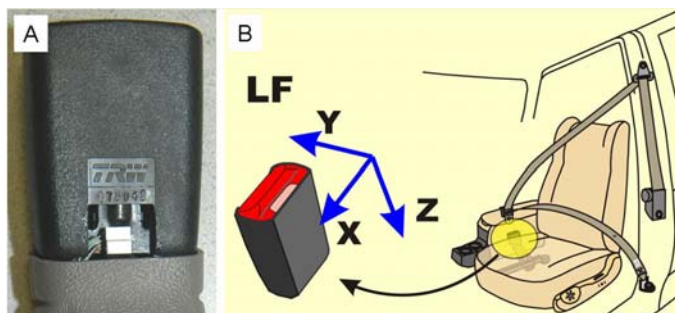


Figure 2 – (A) Instrumented driver buckle and (B) local coordinate system schematic

Webbing tension was measured and recorded for each lap belt and shoulder harness of the four outboard occupants and the lap belt for the center rear occupant. In total, 73 data channels were passed through anti-aliasing filters, sampled at 12.5 kHz and recorded by a data acquisition system. Data acquisition was triggered by contact between the Explorer front bumper and crash barrier. Data was post processed at SAE CFC 600 per SAE J211.

VEHICLE VERTICAL DROP TEST

To evaluate the vehicle floor pan and seat belt buckle response to a severe vertical impulse, a drop test of a mid-size body on frame sport utility vehicle was conducted. The vehicle utilized was a 1998 Ford Explorer, 4-door, 4x4 with a 4.0 liter engine.

For the vertical drop test, ATDs of differing configurations, with weights ranging from 52 pounds to 155 pounds, occupied four of the five possible seating positions. The left front ATD was a 5th percentile female ballasted to 155 pounds, the left rear ATD was a hybrid III 10 year old child dummy ballasted to 84 pounds, and the center rear ATD was a hybrid III 6 year old child dummy. The right front seat, needed for camera access, was replaced with a fixed mass equivalent to the seat itself plus a 280 pound occupant.

The vehicle was raised until the height of its center of gravity (CG) was elevated approximately three feet above its rest position and then released, falling on a concrete floor. (see Figure 3) This drop height was selected to represent a severe vertical impact based on available public domain rollover test data. The lateral and axial buckle accelerations were recorded for the driver, left rear and center rear occupant positions using the buckle-fixed coordinate system displayed in Figure 2A. Corresponding accelerations were recorded on or near the buckle mounting points, as well as on the floor pan at the approximate vehicle CG location. The purpose of the non-buckle mounted accelerometers was to assess the magnitude and duration of the pulse compared to public domain rollover data, and to assess the magnitude of any pulse amplifications or attenuation between the vehicle floor pan and buckle assemblies prior to any identifiable ATD interaction with the restraint. Endevco 25A piezoelectric accelerometers were utilized at each location. A vertically oriented laser displacement sensor on the ground was used to calculate impact speed.



Figure 3 – 1998 Ford Explorer prior to vertical drop

Special adapters that attached to each wheel were fabricated to allow the vehicle to be raised by an overhead crane in its rest position body roll and pitch angles. A manual trigger released the vehicle and a ground contact strip provided a common zero reference

for all data acquisition and high-speed and real-time videos. All data channels were passed through anti-aliasing filters, sampled at 10 kHz and recorded by a data acquisition system. Data was post processed at SAE CFC 600 per SAE J211.

BUCKLE IMPULSE RESPONSE TESTS

Multiple impulse response tests were performed on the left front and left rear floor pan of a 1998 Ford Explorer 4-door to measure and characterize the free response of the floor pan and respective buckle assemblies. Similar to the method introduced by Cooper et al. [13], a slide hammer with a UHMW head was used to generate an impulse directly on the floor pan. Entran EGAX-T 1000g accelerometers on the floor pan and buckle assemblies were used to measure the respective acceleration responses. Anti-aliasing filters were utilized and pre-sample filters limited acceleration response to 2000 Hz. The data was subsequently sampled at 20 kHz. The buckle and floor pan time domain responses to an impulse can be represented in the frequency domain using standard Fourier methods. This approach is useful for evaluating vibration transmission (attenuation or amplification) between floor pan and buckle as a function of frequency.

The time trace of the acceleration signals can be readily converted to the frequency domain using standard fast Fourier transform (FFT) algorithms. The vibrational energy of each component at a given frequency, f , can be represented in the form of the power spectral density (PSD), S_{aa} , given by Equation 1,

$$S_{aa}(f) = FFT(a_1(t)) * FFT^*(a_1(t)) \quad (1)$$

where $a_1(t)$ is the time-domain acceleration signal and $*$ denotes the complex conjugate of the FFT. Of primary importance to the concept of inertial buckle release is the magnitude of vibrational energy transferred to the buckle, and the corresponding amplification or attenuation at each frequency. A frequency-based power transfer function, $|H_{1-2}(f)|^2$, is defined as the ratio of the PSDs of any two components, given by Equation 2.

$$|H_{1-2}(f)|^2 = \frac{S_{aa2}(f)}{S_{aa1}(f)} \quad (2)$$

A power transfer function from the floor pan to the buckle was generated using the average PSD of multiple impulse response tests of the buckle/floor-pan system. A simple model for predicting buckle response from the floor pan acceleration has been generated using the following method. First, the time-trace of the floor-pan signal is converted to its frequency domain counterpart

using standard FFT algorithms. Once in the frequency domain, the content of the floor-pan signal is weighted based on the power transfer relationship from the buckle to floor pan determined from impulse tests. The frequency domain signal was then converted back to the time domain using an inverse FFT algorithm.

This type of model should be relatively successful in predicting buckle acceleration from the floor pan signal if the primary mode of excitation to the buckle is from the vertical acceleration of the floor pan. However, if other sources of excitation dominate the buckle acceleration, such as the onset of belt tension or buckle interaction with ATDs, this type of model is expected to perform poorly.

RESULTS

FIXED FRONTAL BARRIER CRASH TEST

All five buckles remained fastened throughout the frontal barrier crash test. A summary of the peak vertical frame and rocker accelerations in the negative direction are presented in Table 1. The acceleration magnitudes decrease substantially between the frame and adjacent body mounted accelerometers. Figure 4 compares frame and rocker accelerations at one location, near the left B-pillar. The other five locations measured can be found in Appendix A.

	Left Frame	Left Rocker	Right Frame	Right Rocker
A-Pillar	-170g	-57g	-153g	-49g
B-Pillar	-121g	-32g	-224g	-63g
C-Pillar	-152g	-40g	-137g	-39g

Table 1 – Frame and rocker vertical acceleration negative peaks in fixed frontal barrier crash test

A summary of the peak vertical floor pan accelerations in the negative direction under each seating position is presented in Table 2. Buckle peak axial accelerations along with concurrent lap and torso belt webbing tensions are summarized in Table 3. Figure 5 compares the floor pan vertical acceleration under the left front seat with the driver buckle axial acceleration. Qualitative visual inspection indicates that there is little or no correlation between the left front buckle and left front seat floor pan accelerations during this crash.

	Left	Center	Right
Front Seat	-64g	-84g (CG)	-86g
Rear Seat	-73g	-96g	-103g

Table 2 – Floor pan vertical acceleration negative peaks in fixed frontal barrier crash test

Left Front		
Buckle	Lap Belt	Torso Belt
-98g	380 lbs	200 lbs
Right Front		
Buckle	Lap Belt	Torso Belt
-85g	296 lbs	136 lbs
Left Rear		
Buckle	Lap Belt	Torso Belt
-111g	500 lbs	1246 lbs
Center Rear		
Buckle	Lap Belt	
-63g	778 lbs	
Right Rear		
Buckle	Lap Belt	Torso Belt
-45g	276 lbs	150 lbs

Table 3 – Buckle axial acceleration negative peaks and concomitant seat belt webbing tensions in fixed frontal barrier crash test

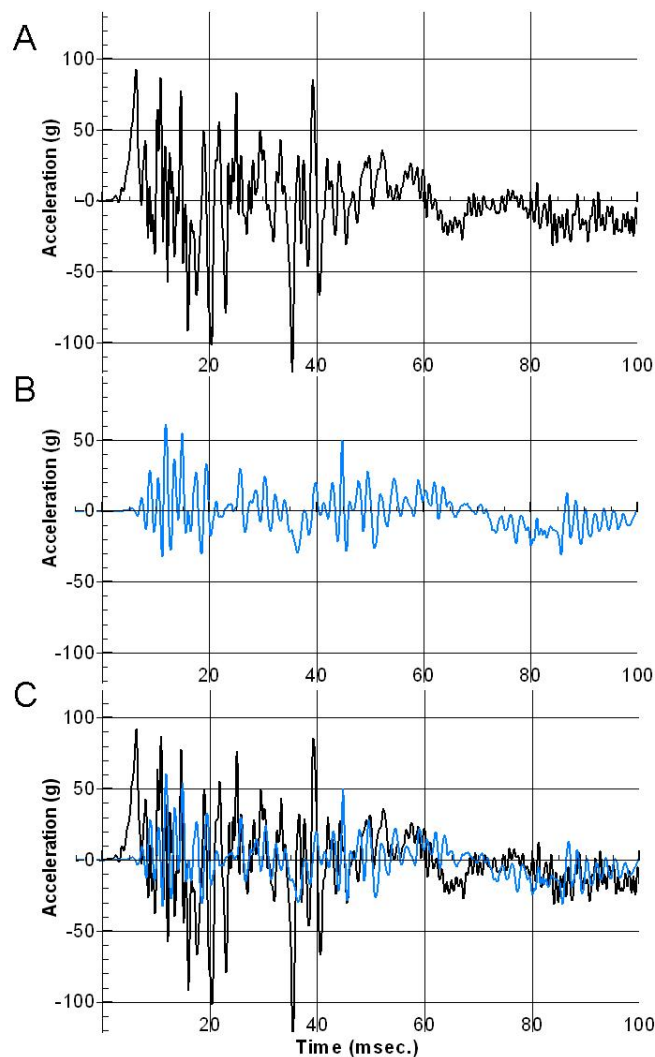


Figure 4 – Frontal barrier test (A) left frame vertical acceleration at the B-pillar, (B) left rocker vertical acceleration at the B-pillar, and (C) a composite overlay

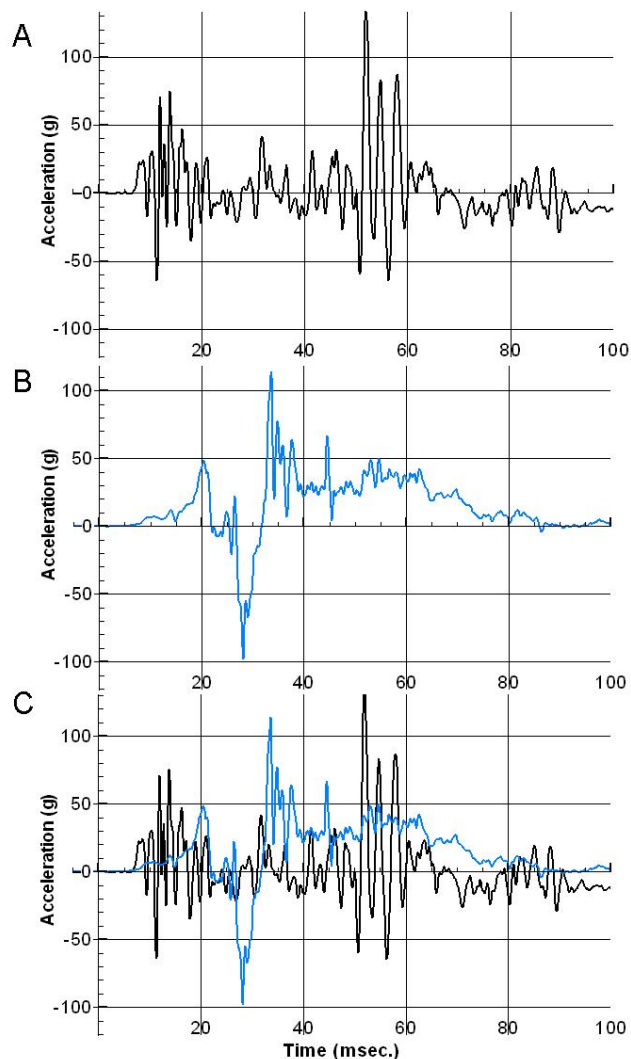


Figure 5 - Frontal barrier test (A) floor pan vertical acceleration under the left front seat, (B) left front buckle axial acceleration, and (C) a composite overlay

Figure 6 compares the vertical floor pan and axial buckle accelerations for the left rear seating position. The vertical floor pan and buckle accelerations for the other three seating positions, along with seat belt tensions, can be found in Appendix B. As with the left front seat position, there does not appear to be a correlation between the left rear floor pan and the buckle accelerations.