

Vehicle and Occupant Responses in a Friction Trip Rollover Test

David C. Viano and Chantal S. Parenteau
ProBiomechanics LLC

Madan M. Gopal
Delphi Corporation

Michael B. James
Collision Safety Engineering LC

Copyright © 2009 SAE International

ABSTRACT

Objective: A friction rollover test was conducted as part of a rollover sensing project. This study evaluates vehicle and occupant responses in the test.

Methods: A flat dolly carried a Saab 9-3 sedan laterally, passenger-side leading to a release point at 42 km/h (26 mph) onto a high-friction surface. The vehicle was equipped with roll, pitch and yaw gyros near the center of gravity. Accelerometers were placed at the vehicle center tunnel, A-pillar near the roof, B-pillar near the sill, suspension sub-frame and wheels. Five off-board and two on-board cameras recorded kinematics. Hybrid III dummies were instrumented for head and chest acceleration and upper neck force and moment. Belt loads were measured.

Results: The vehicle release caused the tires and then wheel rims to skid on the high-friction surface. The trip involved roll angular velocities >300 deg/s at 0.5 s and a far-side impact on the driver's side roof at 0.94 s. The driver was inverted in the far-side, ground impact. Head impact and torso deceleration resulted in 8.75 kN neck compression load with about 1/2" of roof deformation, <1/4" vehicle cg displacement and >5 g vehicle deceleration. The vehicle came to rest on its roof after 1 1/2 rolls.

Conclusion: The friction rollover involved centrifugal accelerations moving the driver's head to the roof at ground impact. The driver was inverted and the torso dove toward the ground causing high neck compression

loads. This test confirms the conclusions of Malibu II and CRIS testing that belted occupants can experience neck loads before much roof deformation. This test involved a modern vehicle with a strong roof. Increasing roof strength would not reduce neck loads; reclining the head-neck-torso angle before the far-side roof impact seems a more reasonable approach to improving safety.

INTRODUCTION

During 1999-2000, 24 full scale rollover tests were conducted in two phases. Phase 1 involved 8 rollover tests and phase 2, 16 rollover tests at Millbrook Proving Ground (MBK), UK (Viano, Parenteau 2004a,b, Parenteau et al. 2001, 2003). The purpose of the tests was to determine rollover sensing requirements to activate occupant protection systems. Such safety systems may include belt pretensioners, inflatable side curtains and airbags, and pop-up rollbars for convertibles. The tests were sponsored by Saab, Delphi and GM.

Each vehicle was equipped with sensors to measure translational and rotational acceleration and suspension deformation. Instrumented dummies were lap-shoulder belted in the driver and passenger seats to study the timing requirements for activation of safety systems. While the objective of the tests was not to study occupant injury mechanisms, the tests are unique and involved belt restrained dummies in Saab 9-3s. This vehicle has a relatively strong roof structure.

This study analyzes vehicle and occupant dynamics in the high friction, trip rollover test run June 5, 2000 (MBK #B2086, Saab #K2511) and presents occupant kinematic and biomechanical results not previously reported. The friction rollover resulted in significant neck compression force in the driver dummy.

METHODOLOGY

Figure 1 shows the vehicle mounted on a flat dolly, which was towed and then stopped suddenly by crushable tubes. The vehicle slid off and dropped to a high friction surface on the ground. The dolly speed at release was 26 mph (42 km/h). A high friction surface was provided by coating 760 mm (2.5 feet) wide strips of 12 mm (0.5") thick plywood with high-friction paint. The high-friction paint was Rocol Safestep 200 (Rocol Site Safety Systems, Rocol House, Swillington, Leeds, LS26 8BS). The strips were bolted to the laboratory floor and extended 12 m (39 feet) beyond the vehicle release point.



Figure 1: Test setup with the vehicle on a dolly that allows the vehicle to drop onto a high friction surface (MBK #B2086, Saab #K2511, June 5, 2000).

The dolly was arrested by a reaction surface fixed to the laboratory floor. A crush tube of 0.7 m (27.6") length was used (steel tubes St35-NBK, German specification DIN 2391/A) to stop the 970 kg dolly at speeds up to 30.5 mph (49 km/h). The vehicle was placed on the platform with the outer face of the tire 0.72 m (28.3") from the edge of the cantilever. The dolly had 140 mm (5.5") ground clearance to move above the guide rail.

Accelerometers, string pots and gyros were welded or bolted to the vehicle and dolly. The instrumentation included accelerometers at the dolly center of gravity (cg), vehicle center tunnel, A-pillar left and right hand at the roof rail, left and right B-Pillar at the sill, rollover sensors, left and right sub-frame close to the suspension and points on the suspension for all four wheels. Figure 2 shows the positions of the biaxial accelerometers on

the top of the A-pillar and base of the B-pillar. Roll, pitch and yaw gyros were placed close to the vehicle cg. String pots were mounted to the vehicle body to measure vertical suspension movement at the four wheels.

The vehicle was equipped with gyros capable of 500 deg/s roll rate (BE1 Gyrochip II, model QR514 - 0500 - 102 from Systron Donner Inertial Systems, UK). Accelerometers were placed at the vehicle cg and other locations. Since the rigid body motion of the vehicle can be within 5 g, dedicated low g accelerometers were also used to provide greater accuracy. A Kayser-Threde (K3600) data acquisition system was used with 8 Megawords memory and onboard battery. This allowed data acquisition for 108 transducers at 10 kHz for 7 seconds.

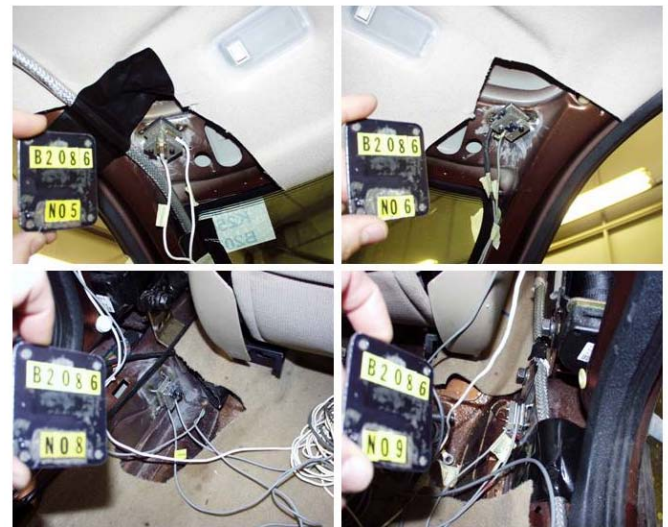


Figure 2: Position of accelerometers on the top of the A-pillar and base of the B-pillar.

Figure 3 shows the driver and passenger in design position. Hybrid III dummies were placed in the vehicle using the FMVSS 208 seating procedure. The H-point location was recorded. Dummy instrumentation included head tri-axial acceleration, upper neck tri-axial force and moment and chest tri-axial acceleration. Seat belt load cells were installed on the lap and shoulder belts.



Figure 3: Position of the driver and passenger Hybrid III dummies and interior instruments and targeting.

Tire pressure was checked and set to manufacturer recommended cold inflation pressure. Frontal airbags

and belt pretensioners were disarmed before the test. Vehicle oil, power steering, wash fluids and fuel were drained and replaced with ballast. Major underbody and external components of the vehicle were painted to improve contrast of the photographic coverage. Targets were placed on the vehicle interior, exterior and wheel trims. MBK and Saab test numbers were fixed to the vehicle in each camera view.

Onboard cameras viewed the upper body of the driver and passenger dummies. Targets were placed on the dummy head and torso for film analysis of occupant kinematics. Contact switches were fixed to the head. The on-board cameras also viewed the artificial horizon, high speed clock and reference plane. The artificial horizon was Model RCA26AK-4 (Adams Aviation). The reference targets were in the field of view of each on-board camera. On-board lighting (CTR 3 kW lights) was fit to the vehicle to illuminate occupant motion.

Five off-board cameras were used, four with overlapping side views of the vehicle roll, and one placed so that the vehicle rolls towards it. The initial side camera has the dolly and some of the laboratory floor in its view. The second side camera's view overlaps the first but usually just has the laboratory floor in its view. The third and fourth cameras have overlapping side views of the laboratory where the vehicle rolls. The total distance covered by the side views of the four cameras is about 35 m (115'). The camera viewing the vehicle roll towards it was placed 40 m (130') from the vehicle release point and at a height of 1.8 m (5'11").

Adequate lighting was provided over the area of the car trajectory in the rollover. For an area 6.1 m (20') wide by 35 m (115') long, 220 kW of light was evenly distributed along the length of the track. In addition, to cover the first 15 m (49') from the release point of the vehicle, 30 kW of light were used for cameras running at 250 or 500 frames/sec. The vehicle's center of gravity (cg) and moments of inertia were determined before the test with the vehicle at curb weight.

The response plots in this paper were generated using every tenth or hundredth time step, so that there was a manageable number of points. The full 6.2 s of data had 62,000 rows at 0.01 ms interval. The tabulated peak values are from the full database and may be higher than what is shown in the plots because of the selection of points for plotting.

Analysis of Impact Biomechanics: The Hybrid III dummy instrumentation included triaxial head and chest accelerations and upper neck force. The z-direction components were analyzed to qualitatively describe the head impact on the roof liner leading to a high neck compression force. The head (a_{Hz}) and chest (a_{Cz}) z-direction accelerations were integrated using 0.95 s as time zero. This time involved minimal acceleration and no neck z-direction load. Integration gave the head (V_{Hz}) and chest (V_{Cz}) velocity in the z-direction during the head impact. The difference is the relative velocity between

the head and chest (V_{Rz}), or the neck compression velocity in the z-direction. A second integration of the head and chest accelerations gave their displacement. The difference in displacement is neck compression (d_{Nz}) in the z-direction.

Impact force (F_z) on the head in the z-direction was determined by adding the head inertia force and neck compression force in the z-direction: $F_z = m_H a_{Hz} + F_{Nz}$, where a_{Hz} is the z-acceleration of the head, F_{Nz} is the neck compression force in the z-direction and m_H is the mass of the head, which is $m_H = 4.54$ kg (Mertz et al. 1989). The neck load cell measures the contribution from the torso mass in the impact; it adds to the impact force. The effective mass of the torso can be calculated using the z-direction acceleration of the chest (a_{Cz}): $m_{Cz} = F_{Nz} / a_{Cz}$. The impact force and other biomechanical responses, including head and chest acceleration and change in velocity of the head and chest describe the impact biomechanics in the rollover.

Simulation of vehicle and occupant kinematics

Vehicle Motion Model: The friction trip rollover was simulated using PC-Crash accident reconstruction tool. The environment is simulated using very low friction surface while the vehicle is on the moving dolly as the vehicle and dolly slide toward the friction strips on the ground. Since the vehicle tires drop onto the friction strips in the test, the ground surface is modeled as a high friction coefficient patch.

PC-Crash vehicle model represents the test vehicle with measured inertial parameters as main inputs, weight of the vehicle in the model includes two 50th Hybrid IIIs and the only initial condition is the test speed of 42 km/h. PC-Crash automatically calculates the vehicle kinematics with the rollover option turned on. The output of the PC-Crash vehicle model was used as input to a Madymo Occupant Simulation model.

Occupant and Restraint Kinematics Model: A Madymo model of the test vehicle was built incorporating two 50th Hybrid III dummies in the front seats. Figure 4 shows the vehicle and occupant model. Both ATDs were belted and the occupants were seated matching the test setup. Some elements of the model are not displayed to show the belt geometry in relation to the seated dummy (e.g. D-ring). The grid on the seatback is 1" wide and is used as a reference to measure head kinematics. The Madymo model is a prescribed motion model using the linear and angular displacements as input from the correlated PC-Crash model output.

RESULTS

VEHICLE AND DUMMY RESPONSES

Figure 5 shows the roll angular velocity and roll angle in the 26 mph (42 km/h) friction rollover with data on the vehicle dynamics out to 3.5 s. The roll angular velocity exceeded 300 deg/s and then decreased as the vehicle slowed. The vehicle experienced a number of ground

impacts on the wheels and body resulting in accelerations exceeding 15 g laterally (y-axis) and vertically (z-axis).



Figure 4: Madymo vehicle and occupant model of the friction rollover.

The prolonged deceleration at about 0.95 s involved the driver's head near the roof while it was in contact with the ground. The torso moved towards the ground causing neck compression forces and chest deceleration.

Figure 6 shows an overview of the rollover sequence. The top 18 images show the inline view of the friction rollover as the vehicle proceeds in a lateral roll toward the camera. The image sequence is from top to bottom and from left to right. The fifth image on the left shows the far-side impact on the driver's side roof. The vehicle continues to roll to about 1¼ and then rocks back onto the roof. The last roll involves more of the vehicle front as the rear is in the air. The bottom 12 images are from 3 cameras at different positions along the length of the track. The sequence is from the left to right and then top to bottom following the motion of the vehicle down the track. During the roll sequence loads on the tires compress the suspension and the rims deform. As energy is returned from the deformed components, the vehicle lifts in the air as it rolls. This results in a ground impact with the top and side of the far-side (driver's side) roof and door.

Figure 7 shows responses for the driver and right-front passenger, including the resultant head and chest acceleration, resultant upper neck force and moment and the lap-shoulder belt loads during the rollover. Table 1 lists the peak driver responses in the friction rollover and the IARVs used to normalize the data to tolerances (Mertz et al. 2003). The largest response compared to IARVs was neck compression at 2.19 (8.75 kN), which occurred at 0.96 s during the first far-side roof impact on the ground. During the rollover, two of the neck N_{ij} values were above 1.00: compression-flexion and

compression-extension. The right lateral bending of the neck approached tolerance (0.98). Table 1 also includes the driver responses at peak neck compression at 0.96 s. Load was 0.52 kN in the lap and 0.19 kN in the shoulder belt. Peak head and chest accelerations are reported, not 3 ms clip values.

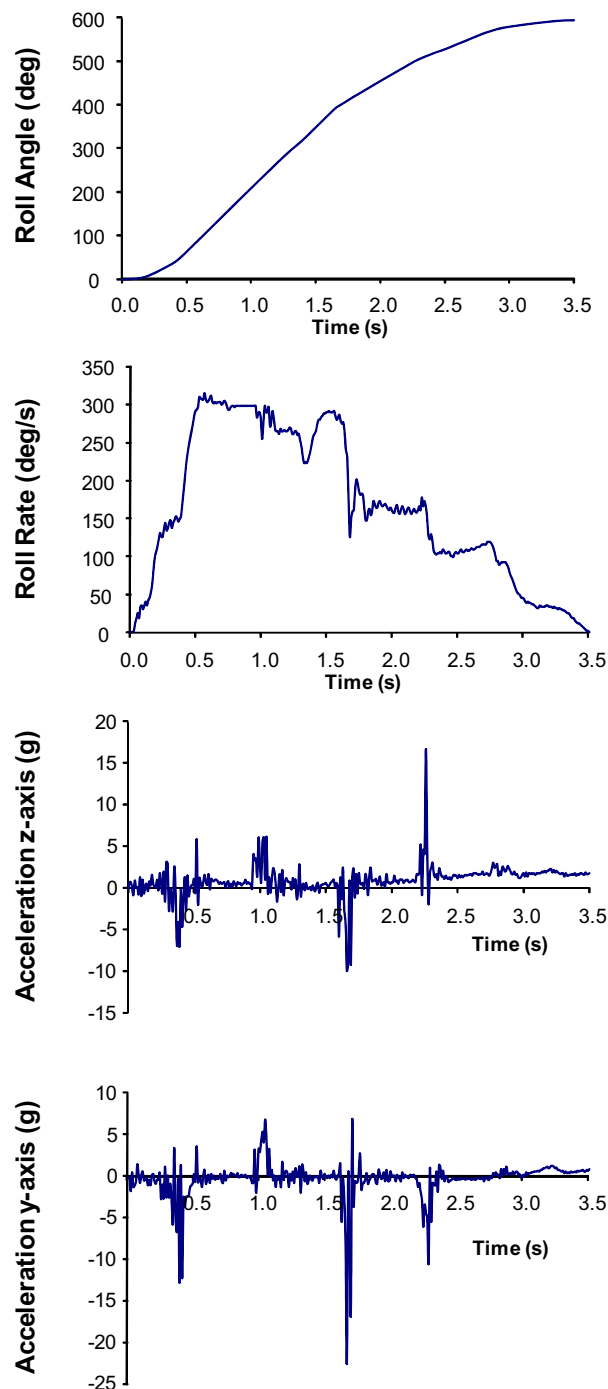


Figure 5: Roll angular velocity, roll angle and lateral and vertical vehicle acceleration at the vehicle cg in the friction rollover (plotted at $\Delta t=0.01$ s).

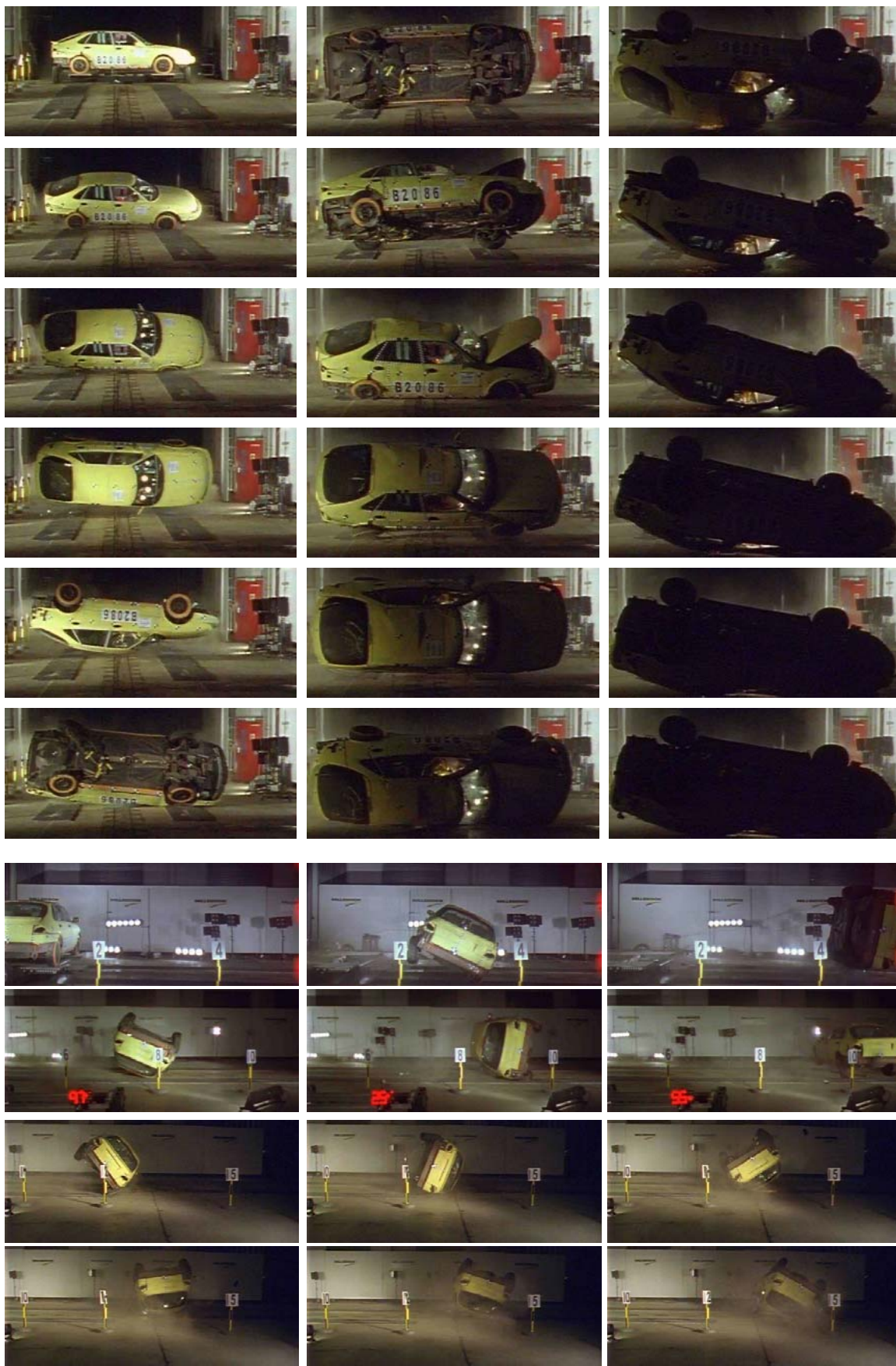


Figure 6: Sequence showing the vehicle kinematics in the friction trip rollover with passenger-side leading at 26 mph (42 km/h).

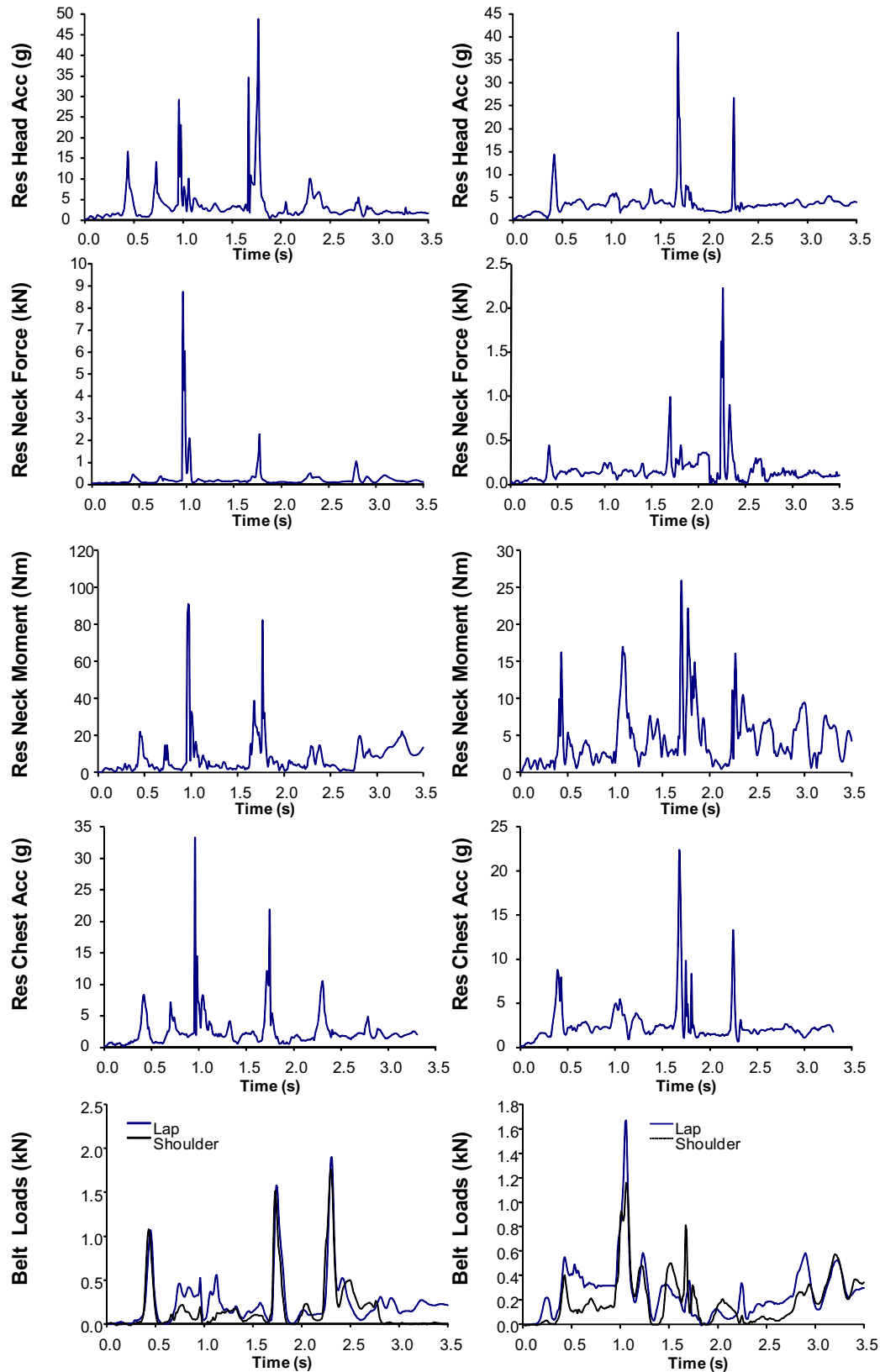


Figure 7: Driver (left) and passenger (right) responses, including resultant head and chest acceleration, resultant neck force and moment and lap-shoulder belt loads (plotted at $\Delta t=0.01$ s).