
Test and Evaluation of Recreational Off-Highway Vehicles (ROVs)

Dynamic Occupant Protection Performance Tests

For:
The Consumer Product Safety Commission

CONTRACT: CPSC-D-11-0003
Task Order 0001 – Task 2

September 2012



Scientific Expert Analysis™

**Biomechanics & Vehicle Dynamics
7349 Worthington-Galena Road
Columbus, Ohio 43085**

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“These comments are those of S-E-A, Ltd. staff and they have not been reviewed or approved by, and may not necessarily reflect the views of, the Commission.”

Report prepared by:
Douglas R. Morr, P.E.



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1. OVERVIEW

This report describes and reports the results of a series of tests conducted by S-E-A, Ltd. (S-E-A), for the Consumer Product Safety Commission under contract number CPSC-D-11-0003 Task Order 0001 – Task 2. This report presents the results from the Dynamic Occupant Protection Performance Tests, as performed on the S-E-A Roll Simulator.

The current work provides data relative to the occupant kinematics during a 90-degree rollover event of a range of 2009-2011 model year Recreational Off-Highway Vehicles (ROVs). Both minimum energy (threshold) and higher energy (tripped) roll events were studied. The kinematics of a belted Hybrid III 50th percentile male anthropomorphic test device (ATD) were recorded and the measured ATD head motion is presented within the Appendix. This current study specifically analyzed only belted occupant motion from 0 to 90 degrees of roll angle on a roll simulator.

The roll simulator can be used to simulate 90-degree rollover events of ROVs. The device has been validated through vehicle dynamics testing of vehicles within this vehicle class. The roll simulator has been shown to reproduce lateral accelerations, roll rates, and roll angles experienced by ROVs during field testing. For the subject testing protocol the roll simulator incorporated one Hybrid III 50th percentile male ATD for evaluation of occupant protection devices. Please refer to the following publications for additional information and validation details of the S-E-A Roll Simulator:

- “Modeling and Validation of a Roll Simulator for Recreational Off-Highway Vehicles,” Zagorski, et al., American Society of Mechanical Engineers, Paper Number: IMECE2011-62603, 2011.
- “Control Strategies for a Roll Simulator for Recreational Off-Highway Vehicles,” Zagorski, et al., American Society of Mechanical Engineers, Paper Number: IMECE2011-62601, 2011.
- “Validation of a Roll Simulator for Recreational Off-Highway Vehicles,” Zagorski, et al., Society of Automotive Engineers, Paper Number: SAE 2012-01-0241, 2012.

This work was completed as a follow-up to the work completed by S-E-A under CPSC Contract Number CPSC-S-10-0014, Vehicle Characteristics Measurements of Recreational Off-Highway Vehicles, April 2011. It should be noted that the vehicle code notation specified in those reports remains the same for the current report.

The Appendix to this report contains the requested test results for each vehicle tested.

2. ROLL SIMULATOR TESTING

2.1 Input Parameters

Input parameters for the roll simulator testing were determined through vehicle dynamics testing of representative vehicles within the subject vehicle class, as well as review of published literature. Tip-up tests with outriggers and 90-degree rollover tests were reviewed. The outrigger tests are referenced in the reports for contract CPSC-S-10-0014. The full, 90-degree rollover tests were completed on vehicles A, B, and C, as part of CPSC-D-11-0003 Task Order 0001 – Task 1 for both threshold and tripped rollover events. In these tests, each vehicle was instrumented with steering and brake/throttle robots for autonomous control. The threshold rollover tests were 30 mph dropped-throttle, step steer maneuvers. The tripped rollover tests were conducted with initial speeds in the range of 25 to 28 mph. A low friction surface was prepared by spreading a thin layer of sand on top of an asphalt test surface. For a tripped rollover test, the vehicle approached the low friction surface at the initial test speed and a step steer input was applied to initiate turning. Once the vehicle reached the low friction surface, the rear wheels of the vehicle were braked until they locked up, causing the vehicle to yaw sideways into the trip feature. The trip feature used was 4 to 6-inch high wooden beams, secured to the ground using wooden stakes. Sand tubes were placed in front of the beams to prevent damage to the suspension and to prevent tires from debonding.

The mean value of peak body-fixed lateral acceleration at the point of two-wheel lift (indicating tip up) for the 10 vehicles tested with outriggers is 0.83 g. For the autonomous, 90-degree threshold rollover tests, the body-fixed lateral acceleration levels remained in the range of 0.7 to 0.9 g during the rollover events; and maximum roll rates were found to be close to 180 deg/sec. Figure 1 shows the nominal response profiles from these threshold rollover events. These values compare well with the available published literature. Lateral acceleration, roll angle, and roll rate were numerically analyzed for the set of autonomous test data, and target input parameters for the roll simulation were developed based on the mean response profiles. These target profiles establish vehicle independent simulation parameters that represent a threshold rollover event, as shown in Figure 2.

For the tripped rollover events, the body-fixed lateral accelerations ranged from 2 to 3 g during the rollovers, with the mean of the peak values for all of the tests being approximately 2.5 g. While the range of roll rates for the autonomous tripped tests was larger than for the threshold tests, the mean of the peak roll rates for the tripped tests was also close to 180 deg/sec. Figure 3 shows the nominal response profiles from these tripped rollover events. These profiles were developed to establish vehicle independent simulation parameters representative of a tripped rollover event, as shown in Figure 4. For the tripped event, the lateral acceleration profile has a brief period of deceleration in the range of 0.6 g prior to tripping, followed by a higher lateral acceleration pulse of 2.5 g magnitude and 0.25 second duration. The deceleration prior to tripping simulates the build up of lateral acceleration before a tripped rollover event. The duration of the lateral acceleration pulse in the tripped rollover is much shorter than the lateral acceleration

profile used during the threshold event. The peak roll rates are 180 deg/sec for both simulated events; however, the roll acceleration (slope of roll rate from 0 to 180 deg/sec) for the tripped event is much greater than the threshold event.

Note that the standard SAE vehicle dynamics (SAE J670) and crash testing (SAE J1733) coordinate systems are used for Figures 1 through 4.

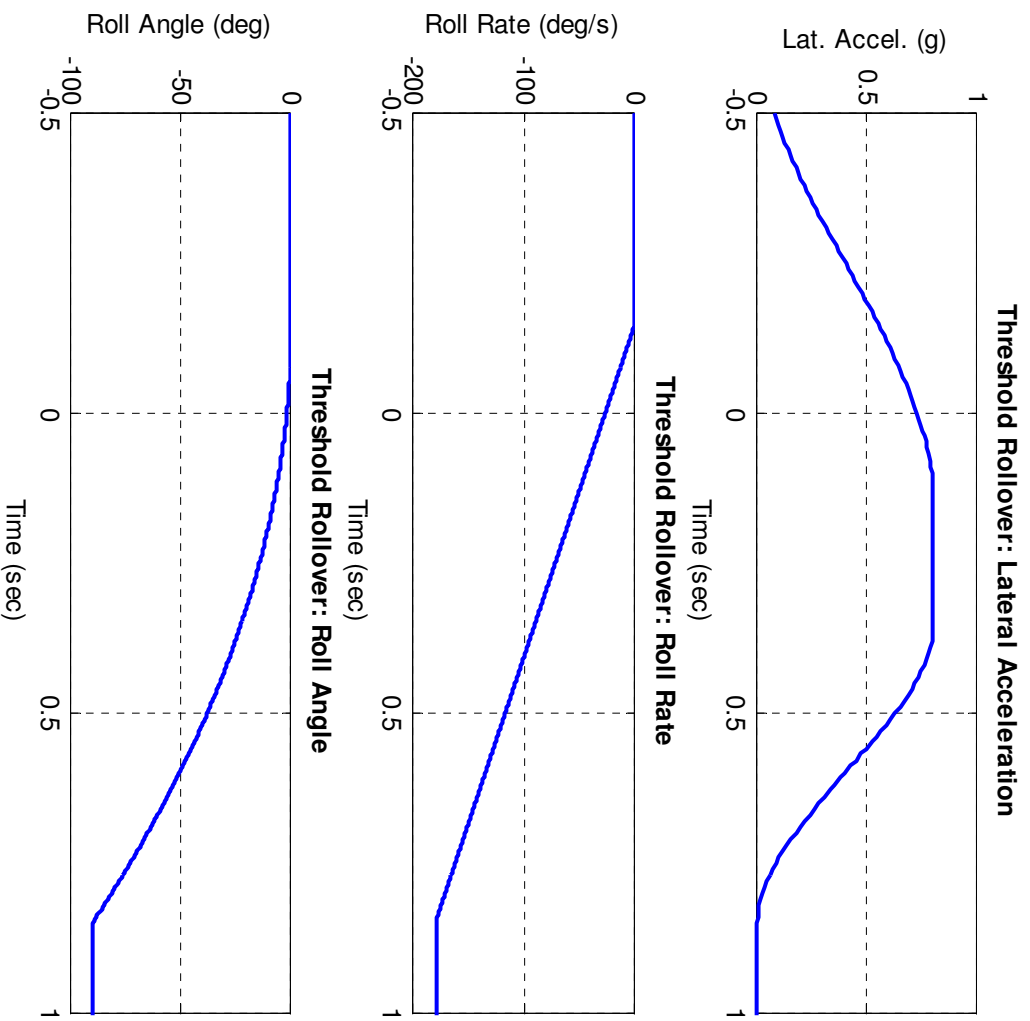
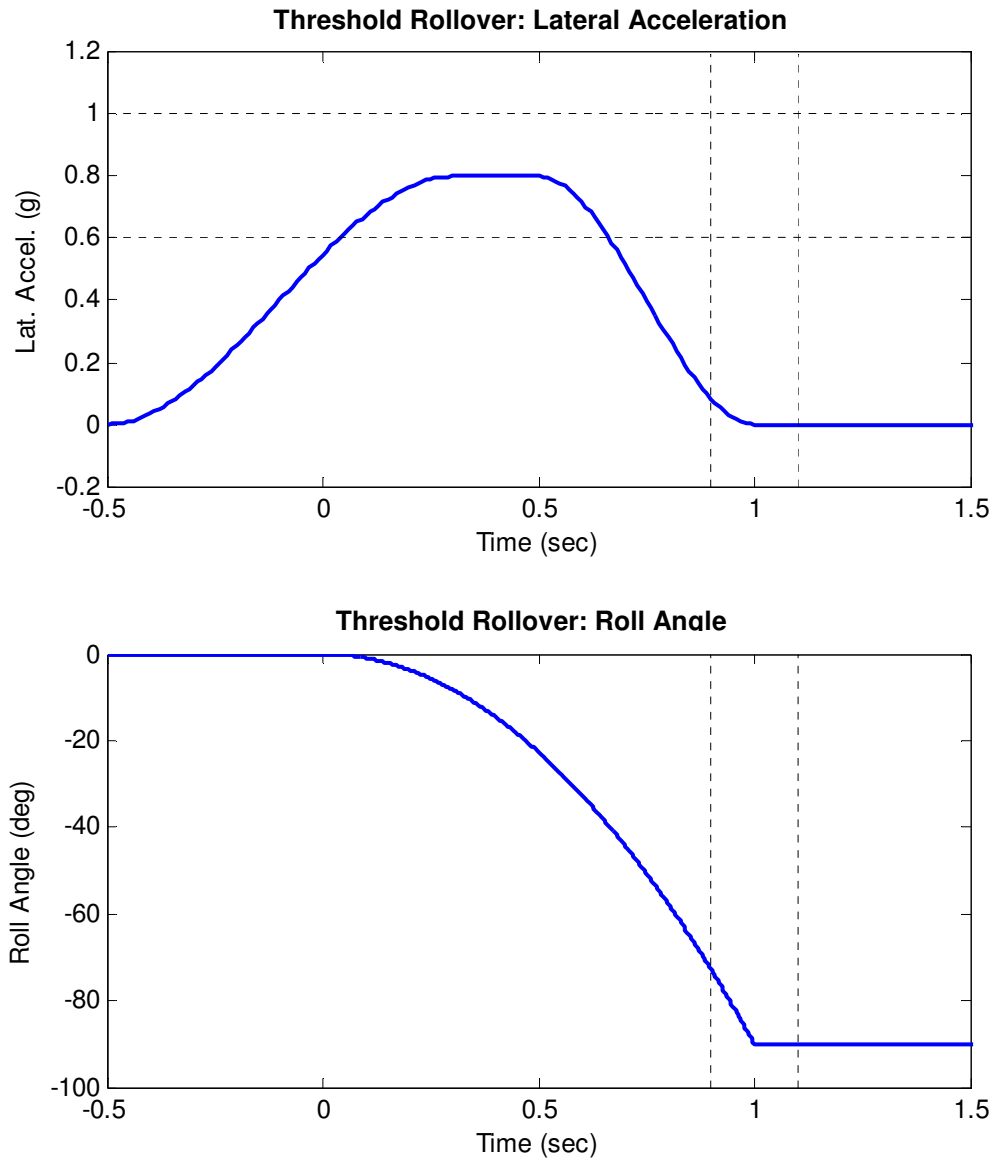


Figure 1 – Nominal response profiles from threshold events



Variable	Name	Units	Range
AY	Acceleration Peak	g	0.6 – 1.0
T ₉₀	Time to 90 Deg Roll (and End Accel.)	sec	0.9 – 1.1

Figure 2– Roll simulator test parameters for threshold event

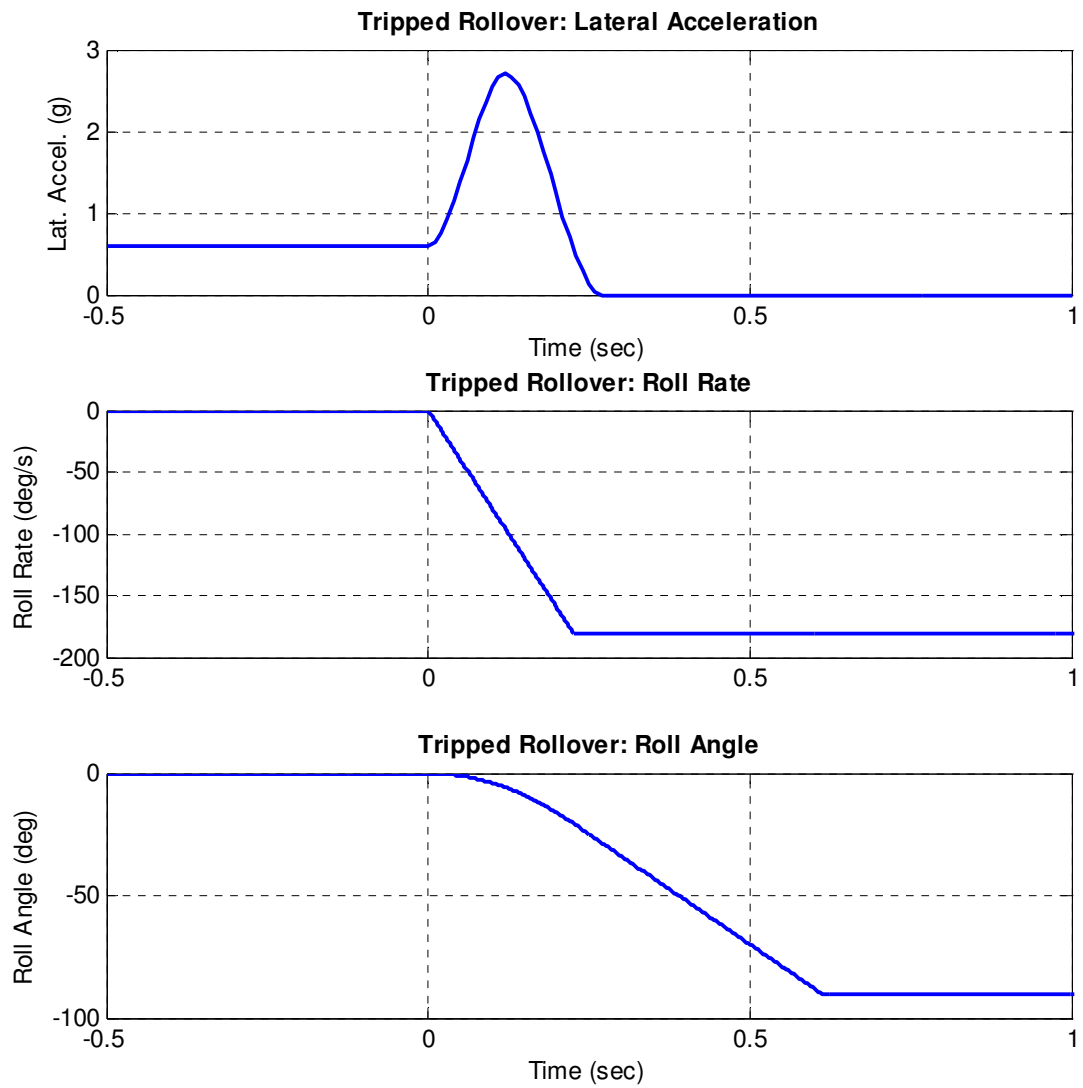
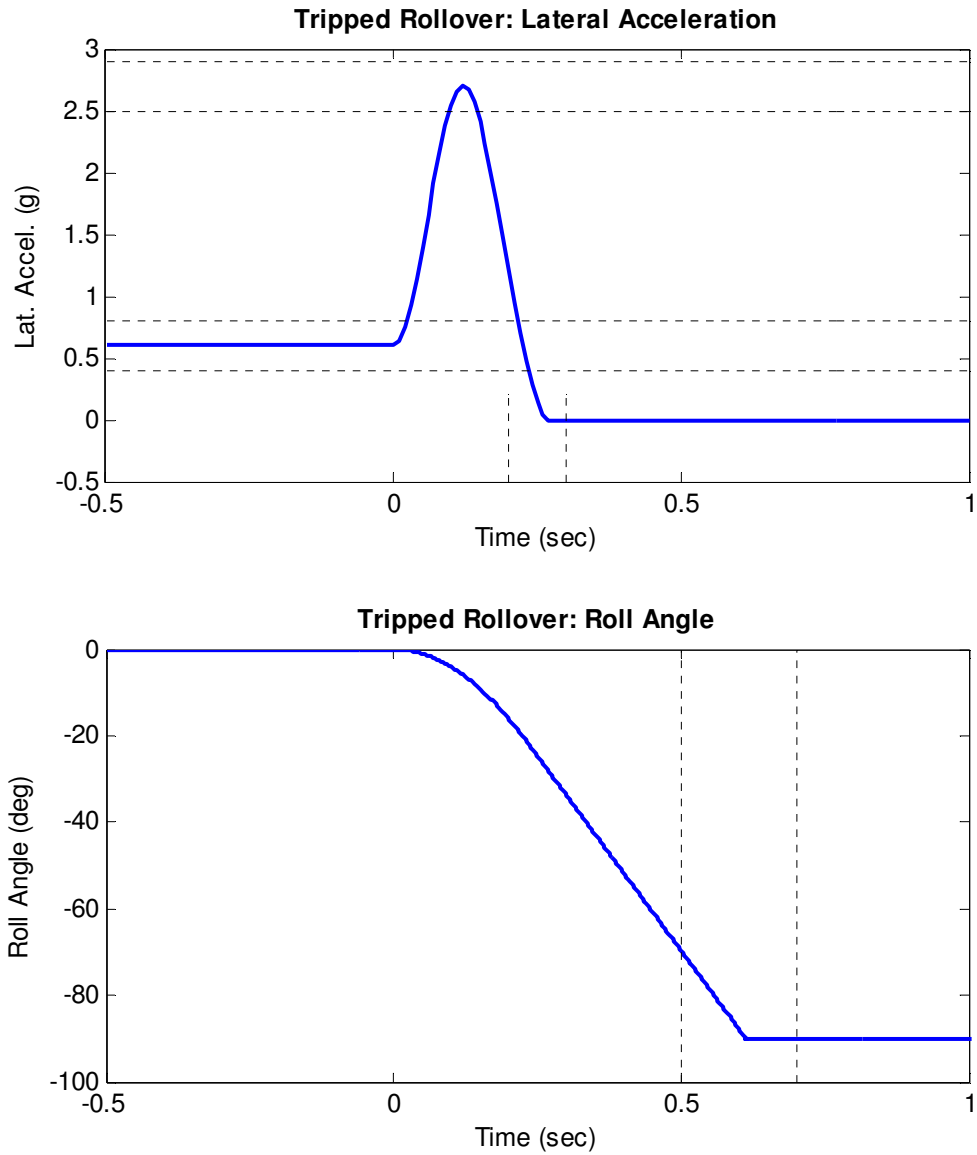


Figure 3 – Nominal response profiles from tripped events



Variable	Name	Units	Range
AY_{peak}	Acceleration Pulse Amplitude	g	2.5 – 3.0
AY_{init}	Initial Acceleration	g	0.4 – 0.8
T_{pulse}	Acceleration Pulse Width	sec	0.20 – 0.30
T_{90}	Time to 90 Deg Roll	sec	0.50 – 0.70

Figure 4– Roll simulator test parameters for tripped event

2.2 Test Protocols

For each vehicle, three threshold tests and three tripped tests were conducted, each with a belted and instrumented Hybrid III 50th percentile male ATD in the driver's seat. All roll events were driver's side leading; thus, the ATD was a belted nearside occupant. Following those tests, another threshold test was conducted for qualitative purposes, at the request of the CPSC, with an unbelted and uninstrumented Hybrid II 50th percentile male ATD as the nearside occupant (again in the driver position). The yaw angle used for testing on the roll simulator was determined through analysis of the resulting lateral and longitudinal vehicle accelerations at the time of roll in previously published tests. Vehicle C was the first vehicle tested in this series, and testing was completed at a yaw angle of eight degrees, based upon an initial analysis of the available real-world data and previous test results. However, upon completion of data reduction of tests completed per CPSC-D-11-0003 Task Order 0001 – Task 1, it was determined that while a yaw angle of eight degrees is well within the range of dynamic response for this class of vehicles, a yaw angle of 15 degrees was approximately the average across the range of vehicles tested. Therefore, a yaw angle of 15 degrees was used on all other vehicles. Additionally, during unbelted occupant testing, a series of tests was completed on Vehicle B at yaw angles of zero and eight degrees to allow for additional comparisons by the CPSC staff.

Currently, there is no published test method for use of ATDs in ROV tests. The ATD positioning and documentation protocol used here was based upon existing protocols. The ATD joints were set at 1 g, and prior to each test, the ATD was positioned within the occupant compartment. Measurements of its position relative to the occupant compartment and the on-board camera were recorded (based on applicable portions of SAE J128, 49CFRPart 572, FMVSS 208). These pretest measurements were used to determine the position of the outboard ROPS plane (x-z plane) and the ATD initial y-position relative to this plane for each test (Table 1). The ROPS plane is shown in the results in the Appendix as a solid constant y-value.

Table 1 – Initial ATD y-position relative to ROPS plane (in inches)

	Belted		Unbelted	
	Mean	StDev	Mean	StDev
Vehicle B_1	8.8	+/-0.00	8.7	+/-0.00
Vehicle B_2	N/A		8.3	+/-0.15
Vehicle C	8.6	+/-0.08	9.0	+/-0.00
Vehicle D	11.0	+/-0.08	11.0	+/-0.00
Vehicle F	7.0	+/-0.38	7.5	+/-0.00
Vehicle G	10.5	+/-0.08	11.0	+/-0.00
Vehicle H	8.0	+/-0.54	6.2	+/-0.00
Vehicle K	9.4	+/-0.20	9.0	+/-0.00

Pretest and post-test photographs were taken to document each test. In addition to the previously specified documents, the following were reviewed for determining the ATD positioning and pretest measurement protocols:

- “Improved ATD Positioning Procedures,” Reed, et al., Society of Automotive Engineers, Paper Number: SAE 2001-01-0117, 2001.
- NATO Document No. RTO-TR-HFM-090, Chapter 4 “Test Methods and Procedures,” and Annex I “Test Protocol for Occupant Safety Measurements and Injury Assessment,” Final Report of the HFM-90 Task Group 25, April 2007.
- U.S. Department of Transportation, National Highway Traffic Safety Administration Laboratory Test Procedure for FMVSS 208, FMVSS 212, FMVSS 219, and FMVSS 301F, TP208-13, July 27, 2005.

Linear accelerometers (Crossbow, CXL04GP3-R-AL, 4G triaxial, 100 Hz) and an angular rate sensor (Spectrum Sensors and Controls, 11206AC, 300 deg/sec uniaxial, 100 Hz) were rigidly attached to the vehicle. These vehicle measurements were recorded and transcribed to the vehicle center of gravity. Occupant motion was recorded with an on-board, high-speed video camera (250 fps). In addition to the on-board camera, three off-board high-speed video cameras (300 fps) were used to document each test. These cameras captured the vehicle and occupant motion from above, in front, and isometrically from the side of the vehicle during the actual roll phase. Synchronization of all video data with the vehicle and ATD data was accomplished through a synchronized electrical signal and on-board flash. ATD head and chest accelerations were also recorded for each test that used a Hybrid III ATD; however, further analysis of these data is beyond the scope of the current study. All ATD data were collected per SAE J211.

2.3 Results

The Appendix contains the requested test results for each belted occupant test. A sample of each plot presented and a brief explanation are provided in this section. The metrics presented in the Appendix are vehicle lateral acceleration, vehicle roll angle, and nearside occupant head displacement. Also included are still-frame photographs of occupant position at 0 degrees and 45 degrees of roll angle.

Occupant head kinematics are calculated through analysis of the high-speed video data. Markers were placed on the ATD head and torso, as well as on the vehicle and were digitized from 0 to 90 degrees of vehicle roll angle. A detailed procedure for this tracking analysis can be found in the paper below:

- “Establishing Occupant Response Metrics on a Roll Simulator,” Yoder, et al., Society of Automotive Engineers, Paper Number: SAE 2012-01-0099, 2012.

As has been described in the previously referenced papers, the initial phase of motion of the roll simulator involves accelerating the vehicle to a specified speed and then maintaining this speed prior to initiating any roll motion. During this initial phase, the ATD’s inertia causes the ATD to lean inboard and then, during the constant speed phase,

the ATD reaches a quasi-static position near its original position prior to roll initiation. Qualitative analysis of the on-board camera videos throughout the entire motion of the ATD was completed to ensure that a quasi-static position was achieved. Quantitative analysis of ATD head kinematics was only completed during the roll event. In the displacement data presented in the Appendix, zero displacement represents the initial position of the ATD head; positive displacement represents inboard motion; and negative displacement represents outboard motion. Since only the first 90 degrees of motion were being assessed in this test series, data that were collected after 90 degrees of roll are depicted in the results in grey.

As an example, Figures 5 and 6 show vehicle roll angle, vehicle lateral acceleration, and Y-axis (lateral) and Z-axis (vertical) ATD head motion for threshold tripped tests, respectively, of Vehicle C. The ATD head lateral and vertical motions are plotted against time and against roll angle, with the ROPS plane shown as a solid constant y-value on these plots for demonstrative purposes. Figure 7 is a sample of on-board video clips from the same threshold test as shown in Figure 5. In Figure 8, video clips from an unbelted ATD threshold test are shown for comparison purposes. These plots and photographs are provided in the Appendix for all tested vehicles. Table 2 presents the mean and maximum relative head displacements (in inches) for each test. In this table, the AVG values are the means of the peak value measured for all tests of that particular vehicle and event. Similarly, MAX values are the highest peak values measured from any test in the particular series.

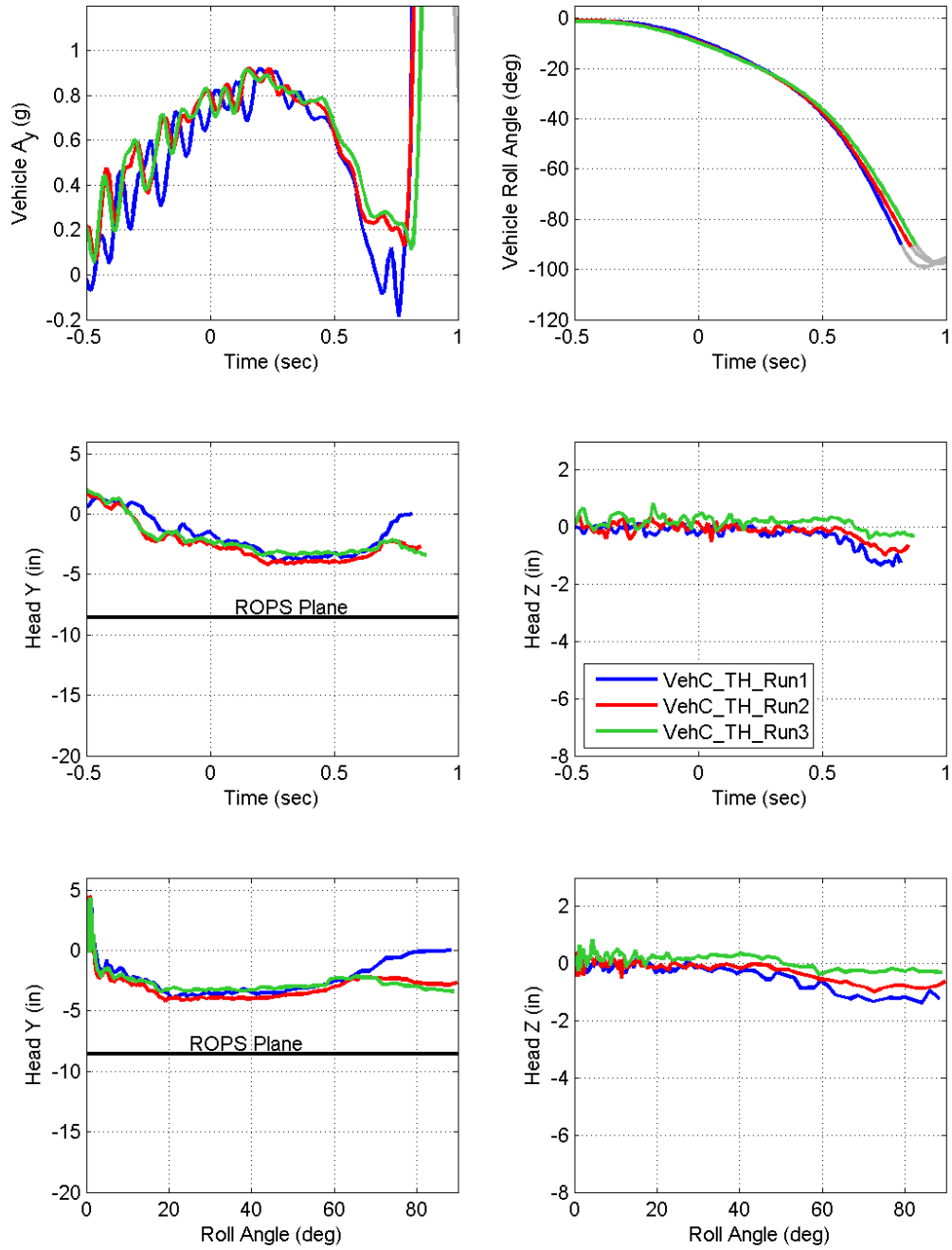


Figure 5 – Vehicle lateral acceleration, roll angle, and ATD head motion for threshold roll.

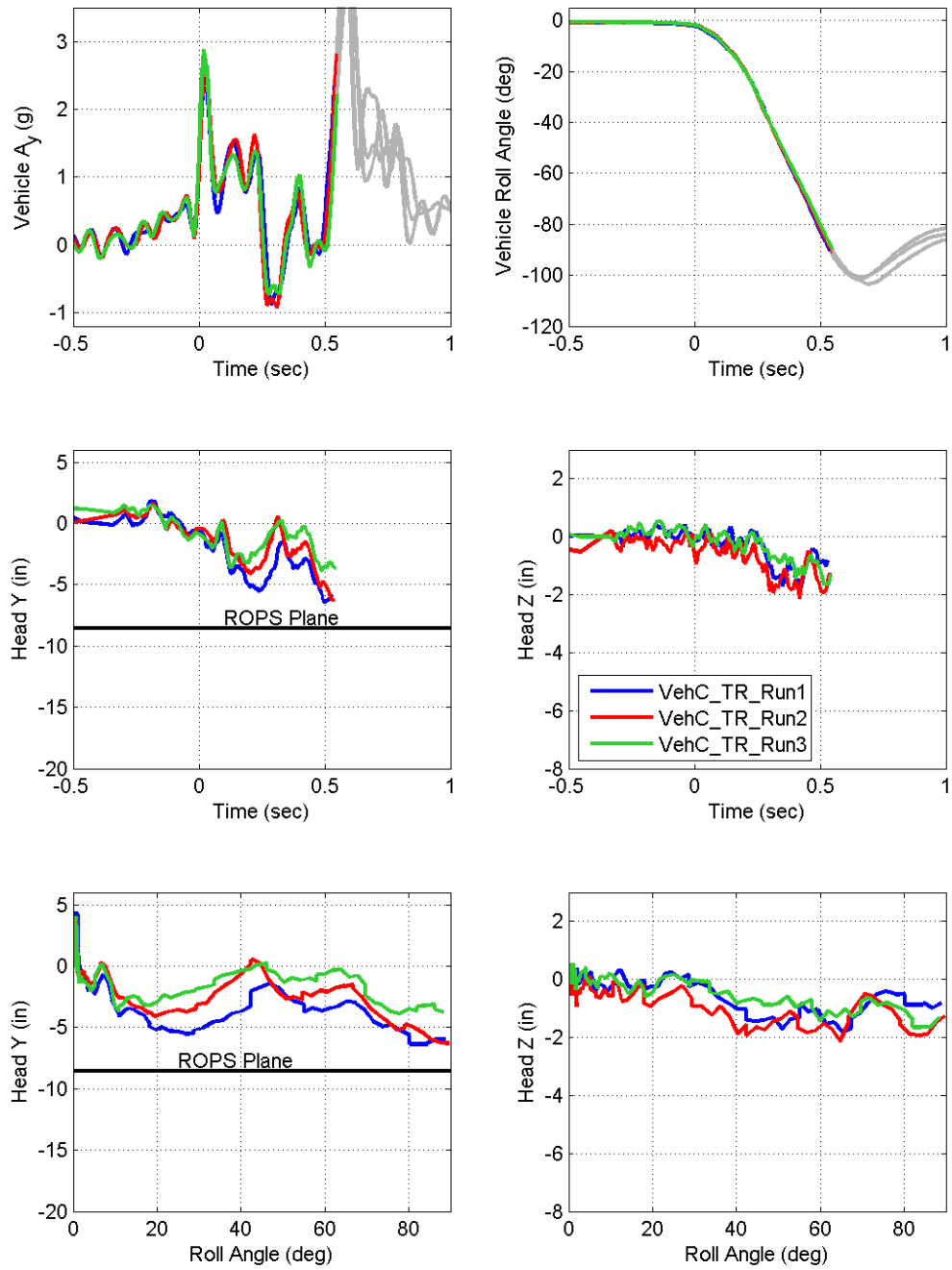


Figure 6 – Vehicle lateral acceleration, roll angle, and ATD head motion for tripped roll.

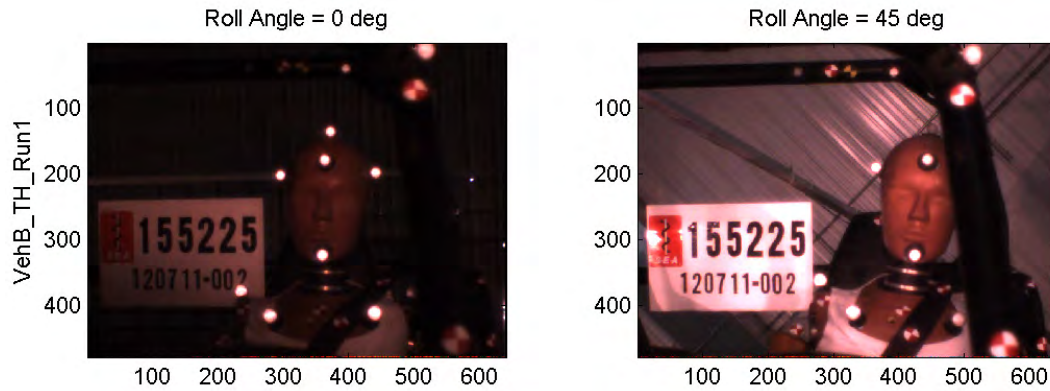


Figure 7 – Sample video clips from on-board camera at 0 and 45 degrees for threshold roll with belted ATD.

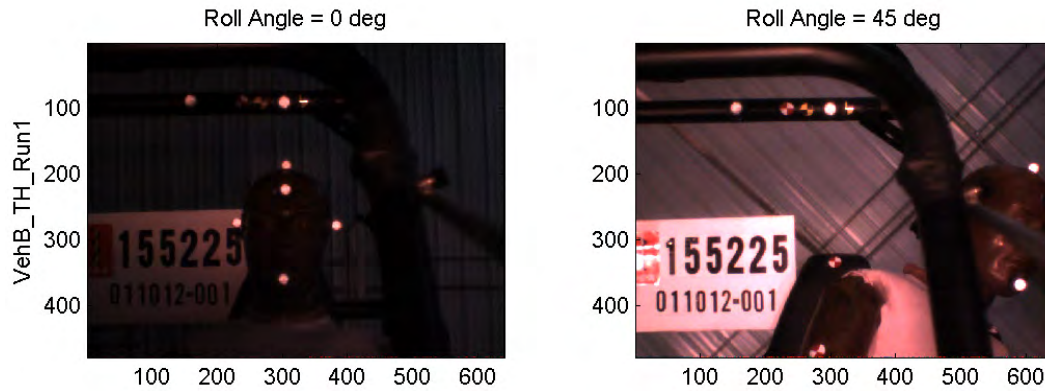


Figure 8 – Sample video clips from on-board camera at 0 and 45 degrees for threshold roll with unbelted ATD.

Table 2 – Head Displacement

BELTED TEST RESULTS						
Vehicle	Event Type	Yaw Angle (degrees)	Head Excursion (inches)			
			Y-Avg	Y-Max	Z-Avg	Z-Max
B	Threshold	15	-3.8	-4.0	-1.8	-3.0
B	Trip	15	-5.6	-5.7	-2.1	-2.3
C	Threshold	8	-3.9	-4.2	-0.9	-1.4
C	Trip	8	-5.5	-6.4	-1.8	-2.1
D	Threshold	15	-9.3	-9.5	-2.8	-1.7
D	Trip	15	-13.0	-16.1	-5.1	-7.8
F	Threshold	15	-8.7	-12.0	-6.0	-6.1
F	Trip	15	-13.1	-14.3	-6.9	-7.3
G	Threshold	15	-16.0	-16.8	-3.1	-3.9
G	Trip	15	-14.0	-14.1	-3.1	-3.2
H	Threshold	15	-16.8	-18.9	-3.2	-4.0
H	Trip	15	-14.3	-14.4	-2.5	-3.0
K	Threshold	15	-15.6	-16.2	-0.6	-1.0
K	Trip	15	-14.0	-14.7	-2.2	-2.3

3. SUMMARY

The current work provides objective occupant kinematic data on a range of 2009-2011 model year Recreational Off-Highway Vehicles during 90-degree threshold and tripped rollover events. The test inputs utilized here, and developed under CPSC-D-11-0003 Task Order 0001 – Task 2, are shown to be repeatable and produce meaningful results relative to passive occupant kinematic assessment. In general, the range of 0 to 90 degrees on the roll simulator provides good representation of lateral acceleration and roll motion as observed in the literature and measured during actual 90-degree rollover events.

This current study specifically analyzed only belted occupant motion from 0 to 90 degrees of roll angle. The metric utilized to quantify ATD kinematics for these tests was head displacement toward the outboard ROPS plane relative to the initial head position. The methodology applied for these measures has been discussed in the referenced literature. In the subject test series test-to-test differences were observed, primarily in overall magnitude of head motion and in timing of maximum displacement. These differences were not significant for the majority of vehicles, however some vehicles did have larger differences. ATD pre-test placement variations and head excursion evaluation technique accuracy are two known sources of test-to-test response differences. These sources do not account for the range on some vehicles, suggesting additional repeat runs are necessary for full characterization.

Initial unbelted tests have been completed, clearly showing that passive occupant response is dramatically different in the unbelted scenario. However, occupant interaction with both occupant compartment and outboard containment structures varies considerably based upon lateral acceleration and yaw angle. Further parametric-type testing is needed to refine test procedures for assessment of unbelted occupant response.

APPENDIX

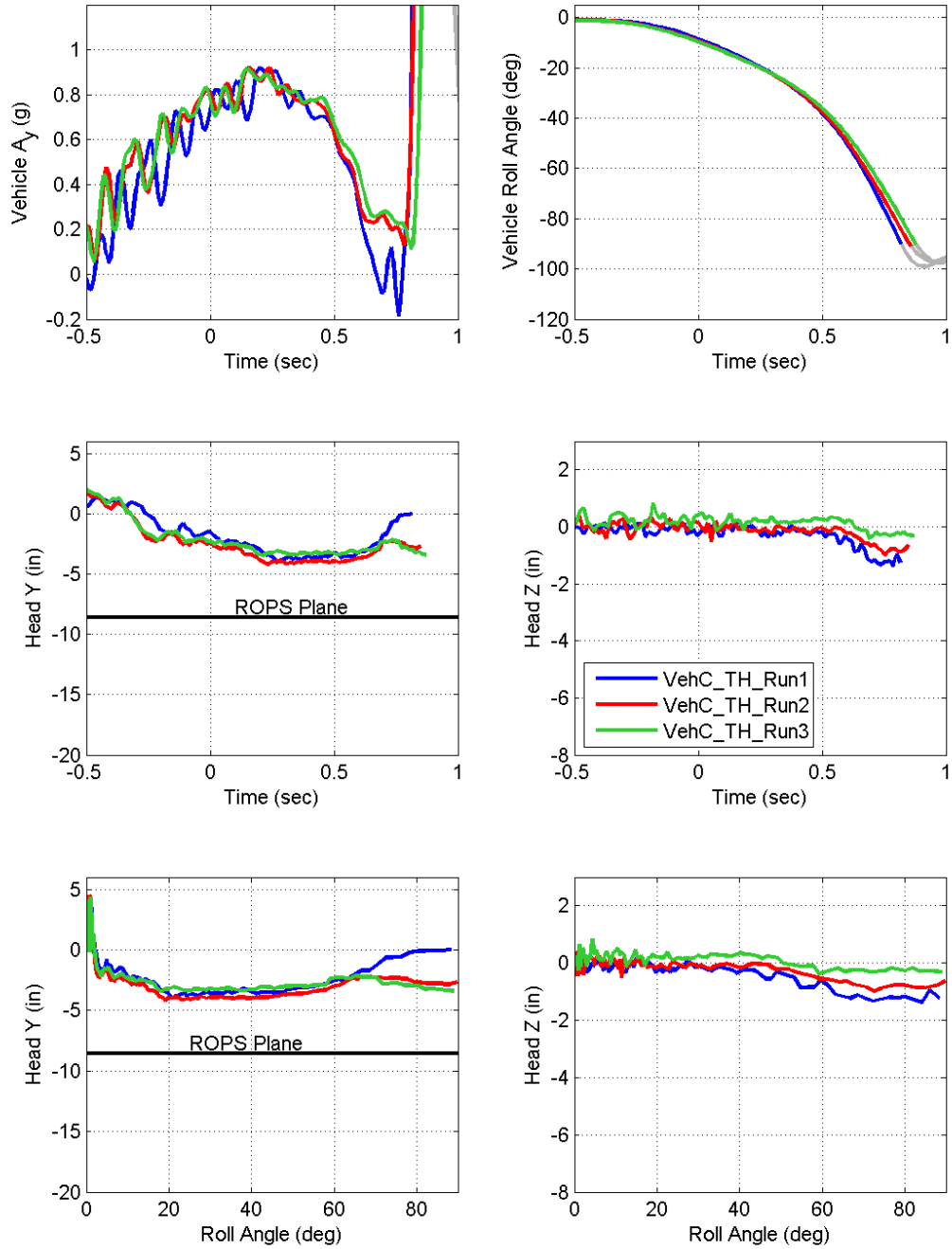
Maximum Head Displacement (in)

		Threshold		Tripped	
Vehicle		Head Y	Head Z	Head Y	Head Z
C	Run 1	-4.0	-1.4	-6.4	-1.8
	Run 2	-4.2	-1.0	-6.3	-2.1
	Run 3	-3.5	-0.4	-3.9	-1.6
	Mean	-3.9	-0.9	-5.5	-1.8
B	Run 1	-3.3	-3.0	-5.4	-1.8
	Run 2	-4.0	-1.2	-5.7	-2.1
	Run 3	-4.0	-1.1	-5.7	-2.3
	Mean	-3.8	-1.8	-5.6	-2.1
K	Run 1	-16.2	-1.0	-13.1	-2.1
	Run 2	-16.0	-0.2	-14.7	-2.2
	Run 3	-14.7	-0.6	-14.2	-2.3
	Mean	-15.6	-0.6	-14.0	-2.2
D	Run 1	-9.5	-4.3	-16.1	-7.8
	Run 2	-9.3	-2.5	-11.7	-3.8
	Run 3	-9.1	-1.7	-11.3	-3.7
	Mean	-9.3	-2.8	-13.0	-5.1

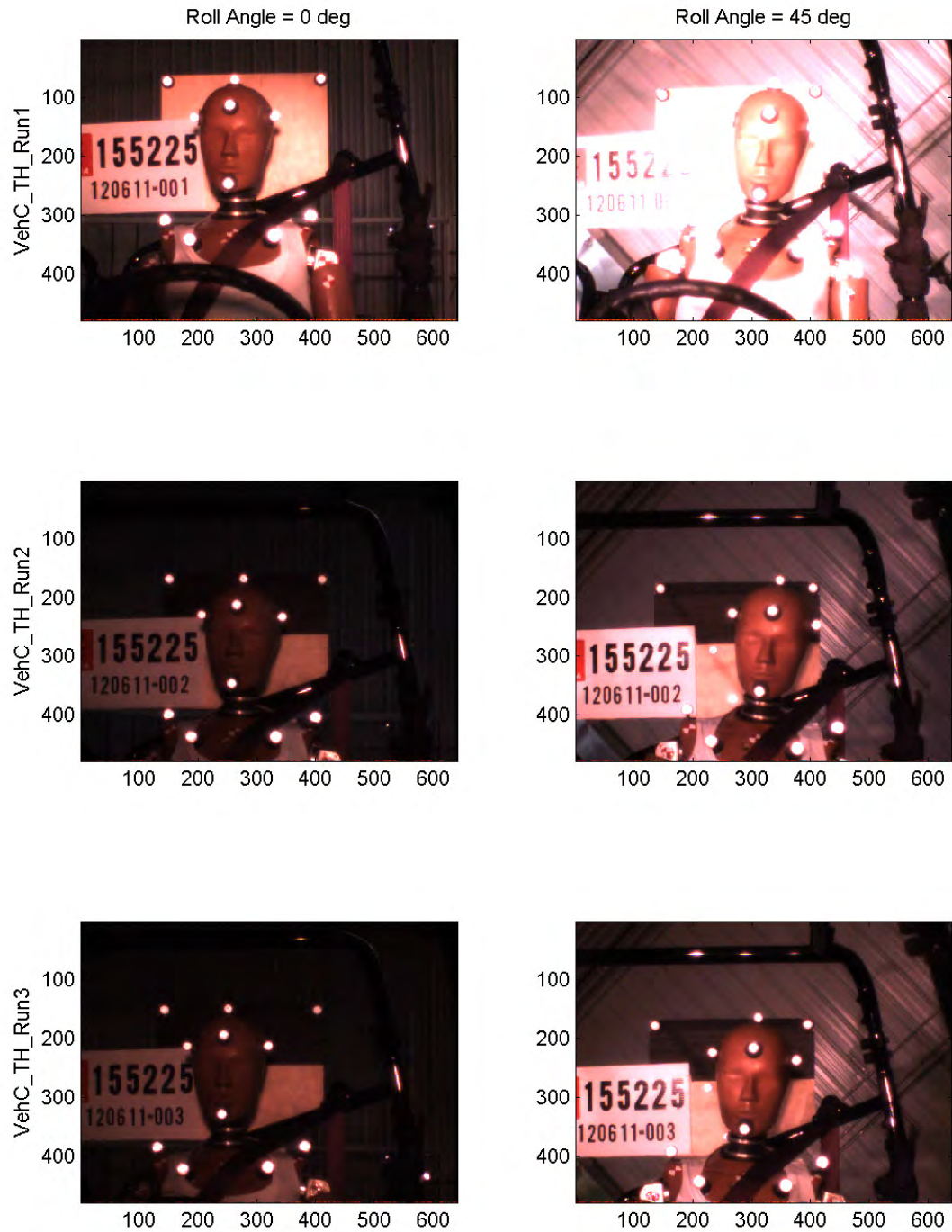
		Threshold		Tripped	
Vehicle		Head Y	Head Z	Head Y	Head Z
F	Run 1	-5.8	-6.0	-13.2	-7.2
	Run 2	-12.0	-6.1	-14.3	-7.3
	Run 3	-8.8	-6.0	-11.8	-6.3
	Mean	-8.7	-6.0	-13.1	-6.9
G	Run 1	-16.4	-2.9	-13.7	-3.2
	Run 2	-16.8	-2.6	-14.0	-3.1
	Run 3	-14.7	-3.9	-14.1	-2.9
	Mean	-16.0	-3.1	-14.0	-3.1
H	Run 1	-18.9	-4.0	-14.2	-2.1
	Run 2	-16.3	-2.4	-14.4	-3.0
	Run 3	-15.1	-3.2		
	Mean	-16.8	-3.2	-14.3	-2.5
		Threshold Belted		Threshold Unbelted	
B	Run 1	-15.3	-4.3	<i>-14.9</i>	<i>-4.3</i>
	Run 2	-12.6	-2.6	<i>-16.2</i>	<i>-2.6</i>
	Run 3	-12.9	-2.1		
	Mean	-13.6	-3.0	<i>-15.6</i>	<i>-0.4</i>

The results shown in *red* indicate that the maximum excursion was not obtained because it exceeded the field of view of the camera. The ATD was not contained in the vehicle. Please refer to the videos.

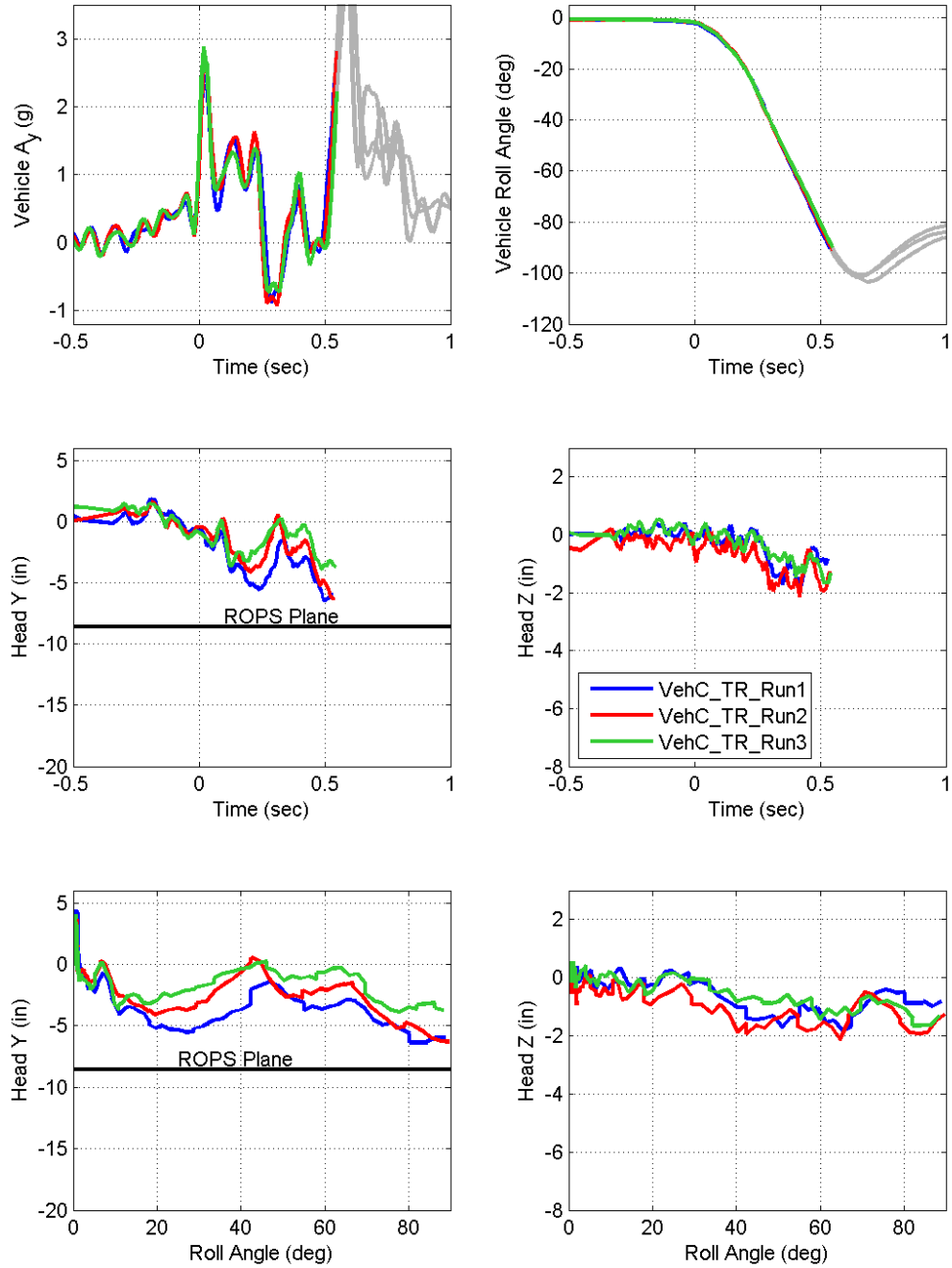
Vehicle C Threshold Rollover



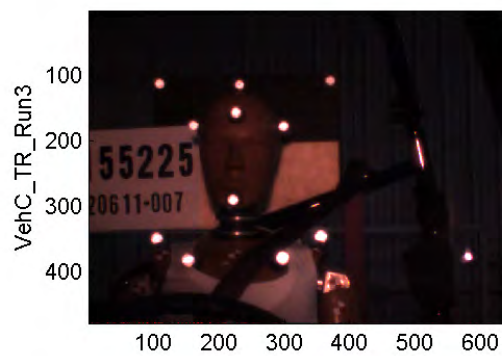
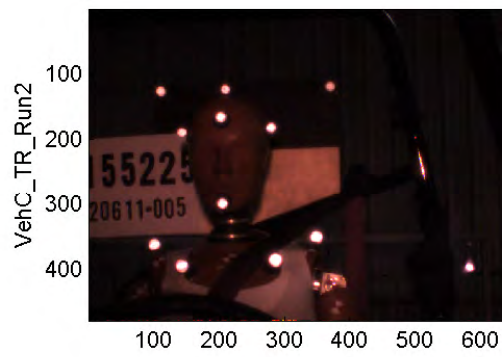
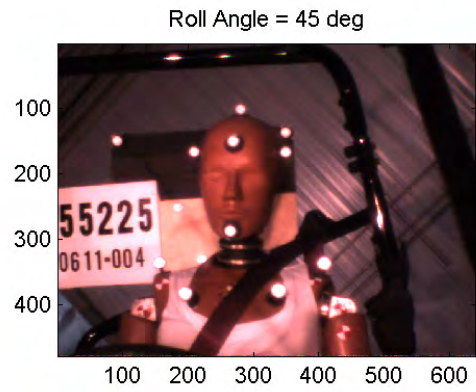
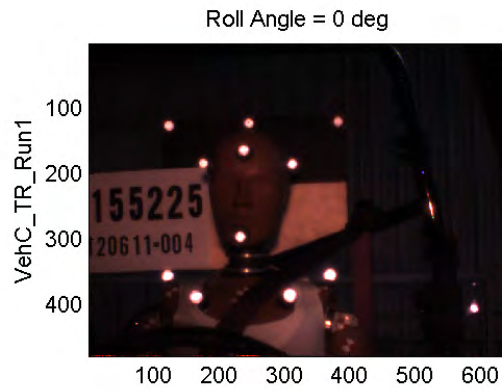
Vehicle C Threshold Rollover



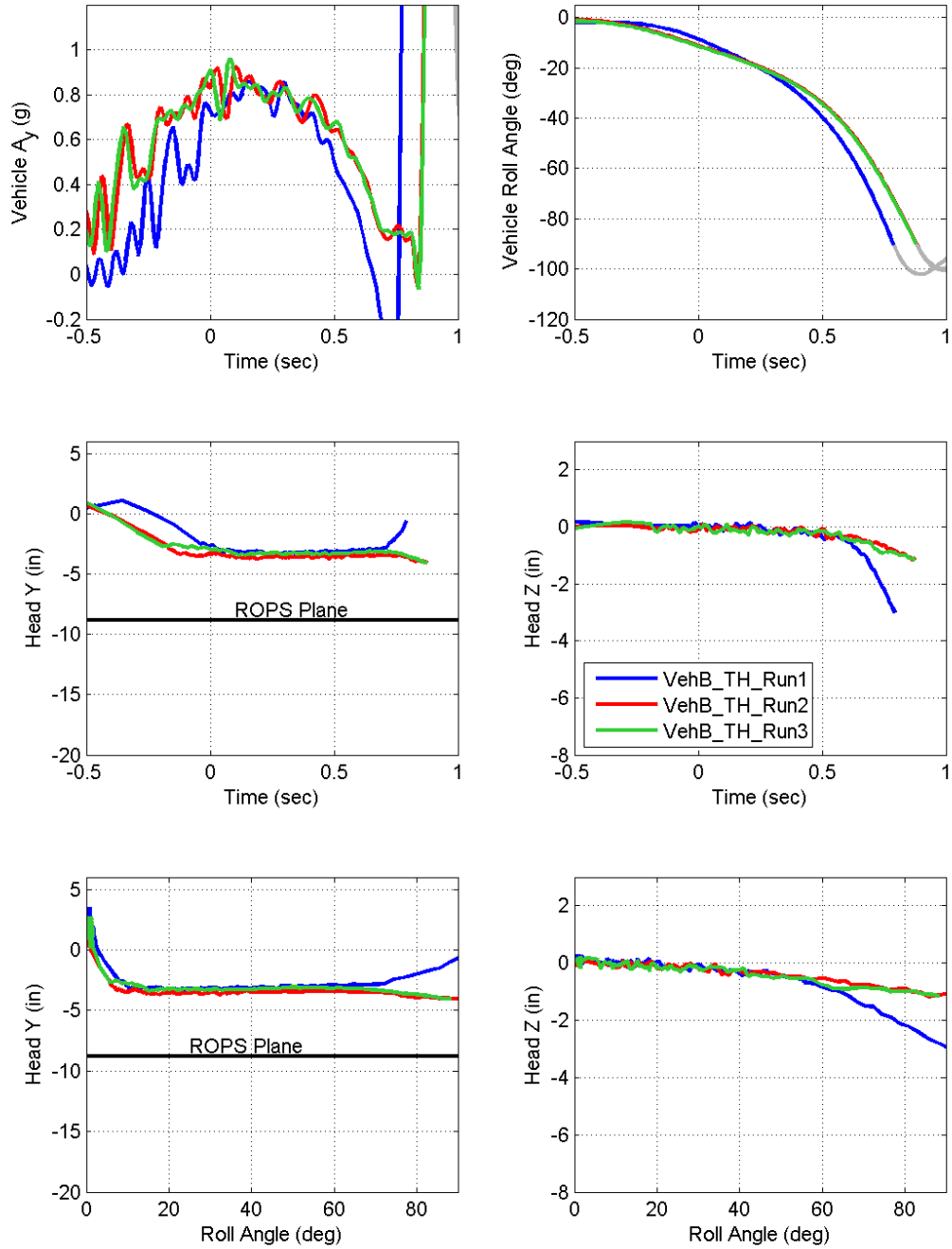
Vehicle C Tripped Rollover



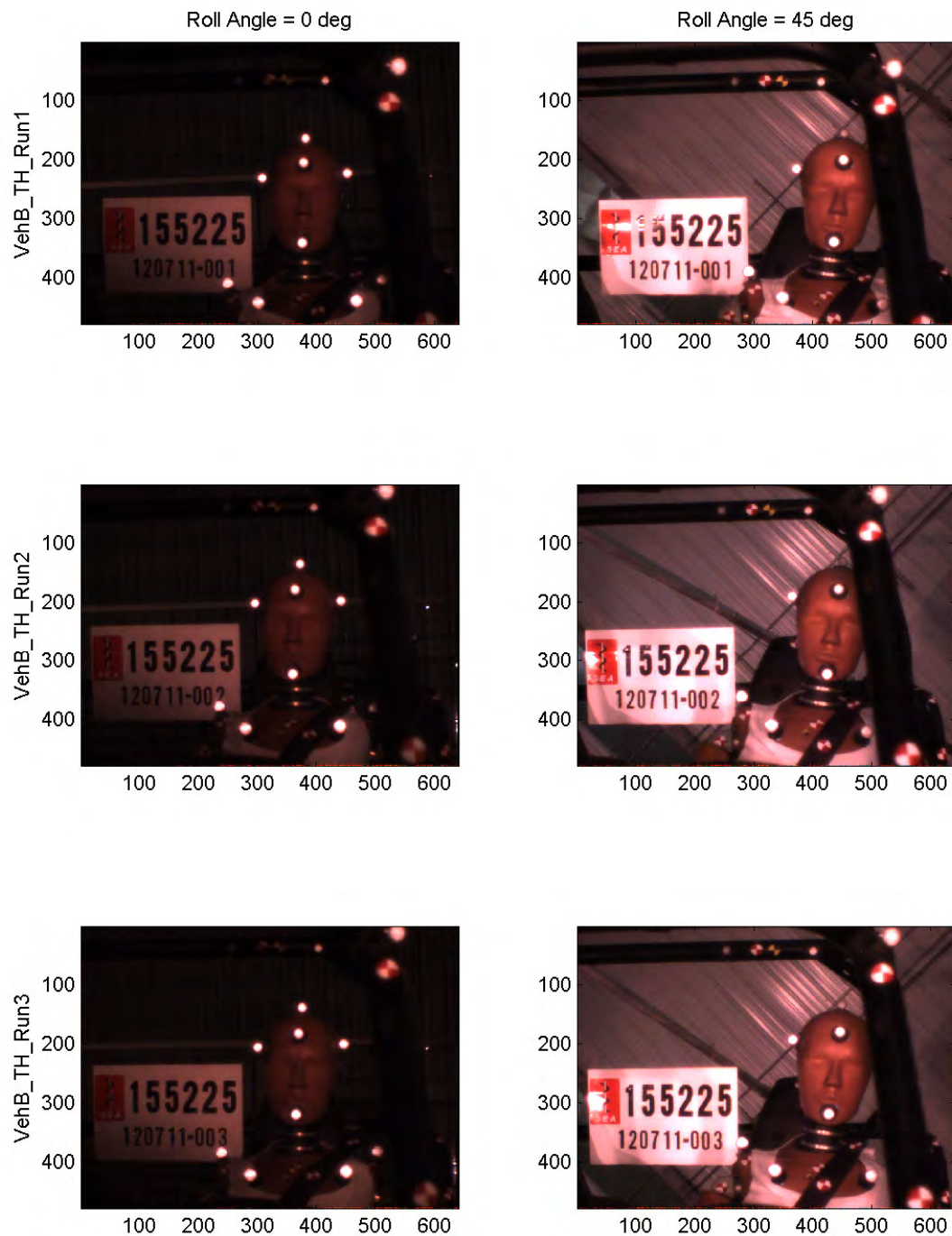
Vehicle C Tripped Rollover



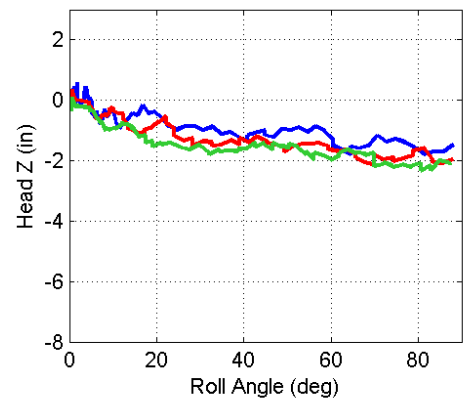
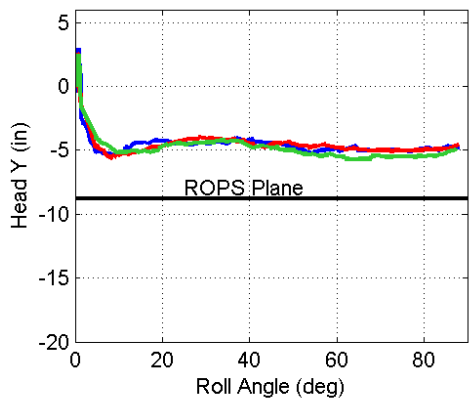
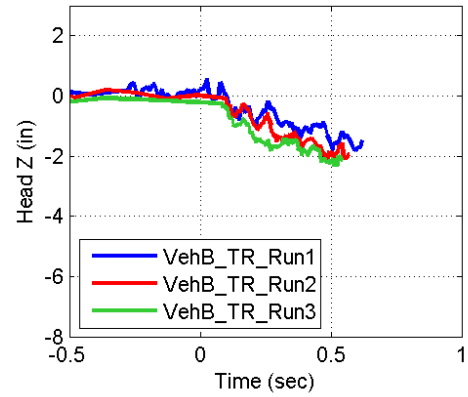
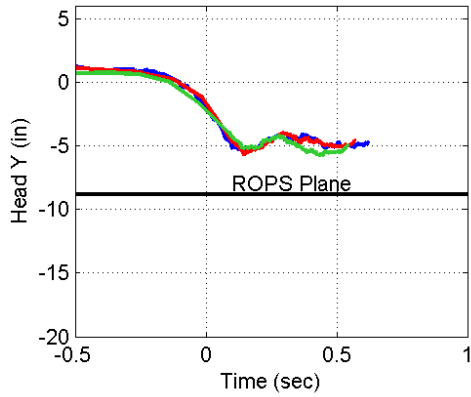
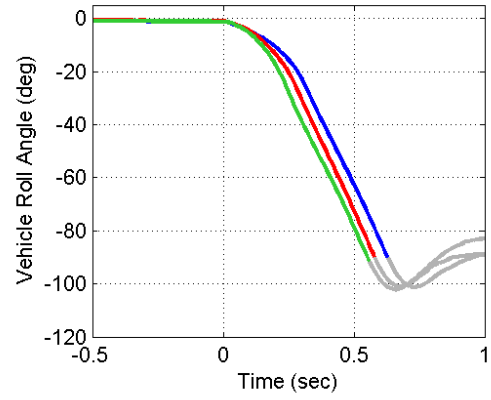
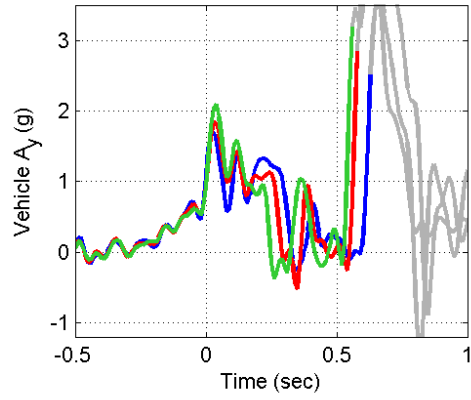
Vehicle B Threshold Rollover



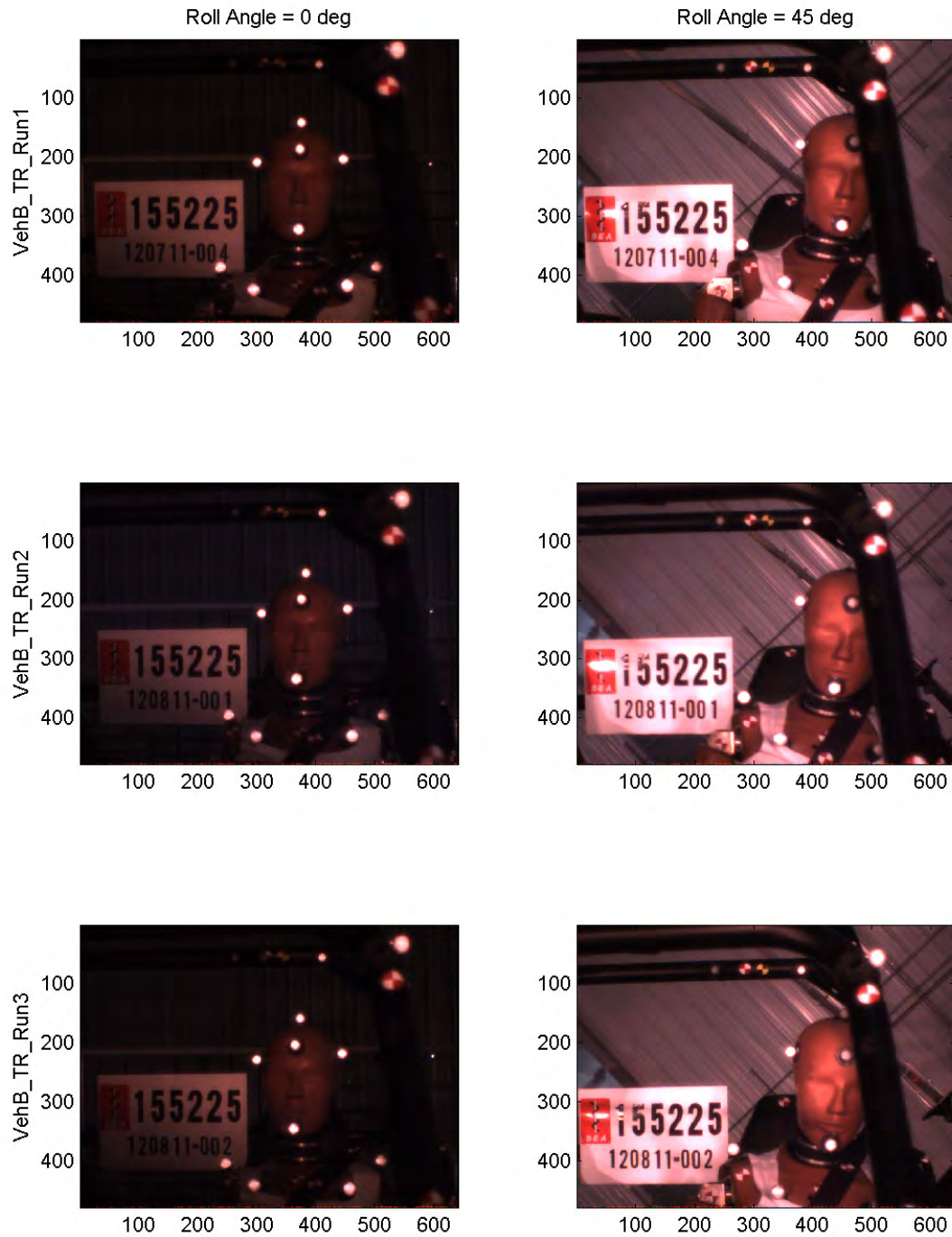
Vehicle B Threshold Rollover



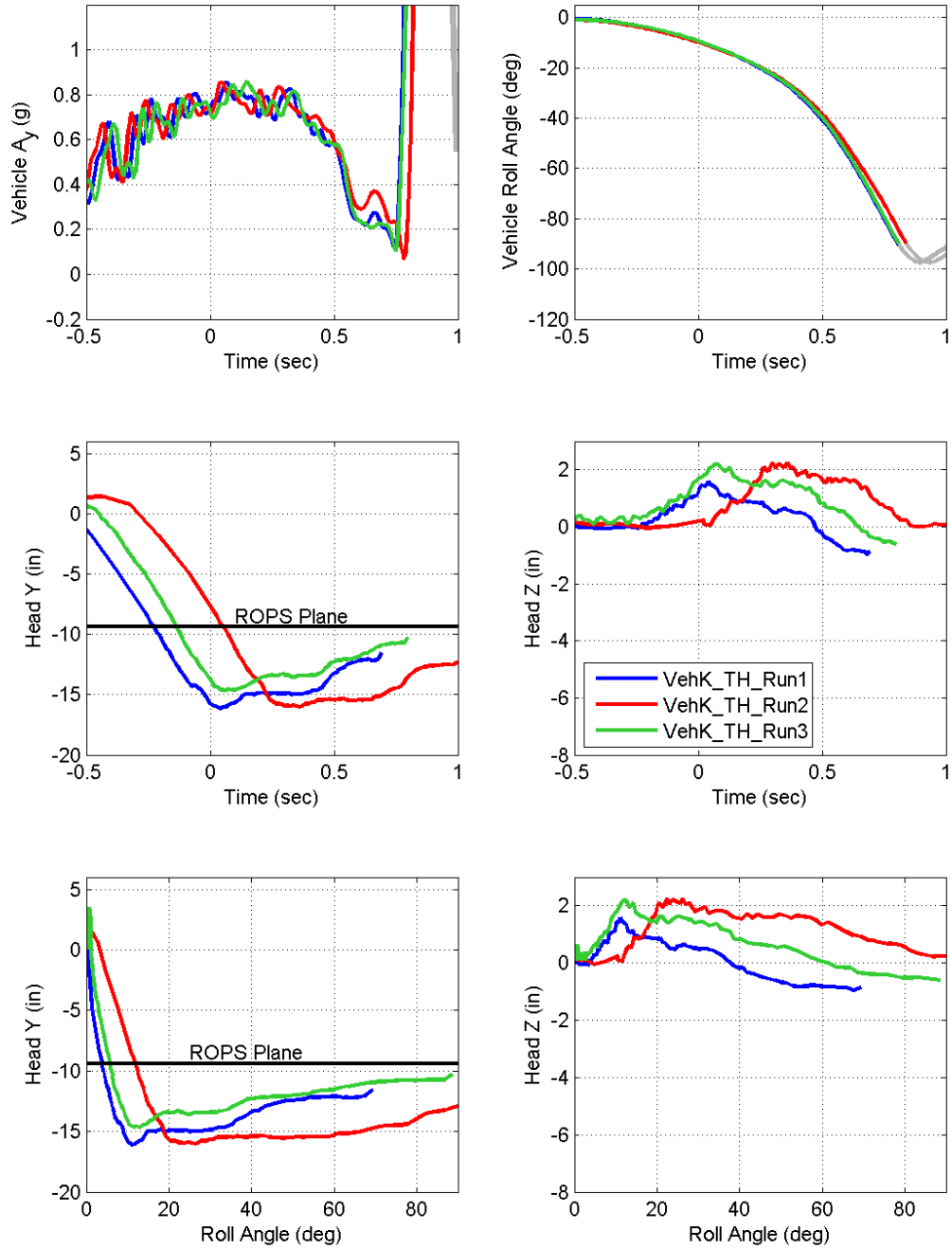
Vehicle B Tripped Rollover



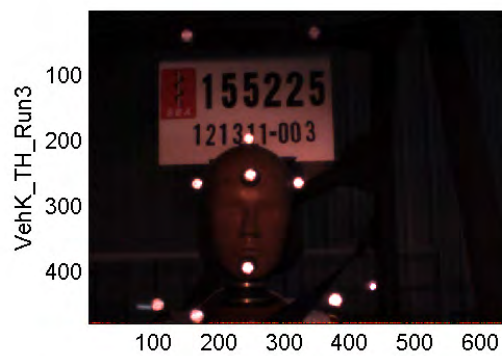
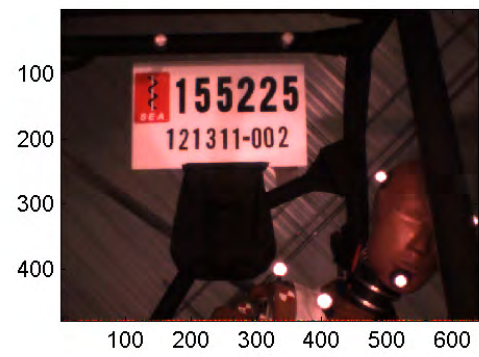
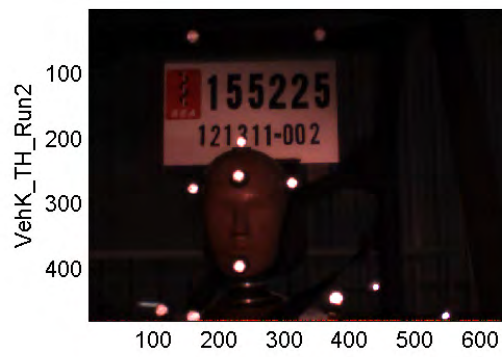
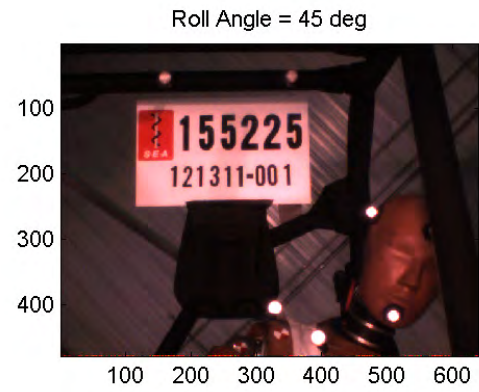
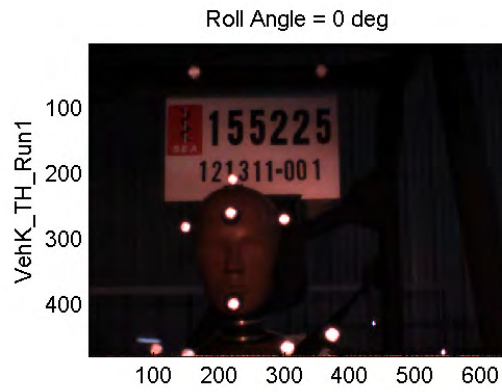
Vehicle B Tripped Rollover



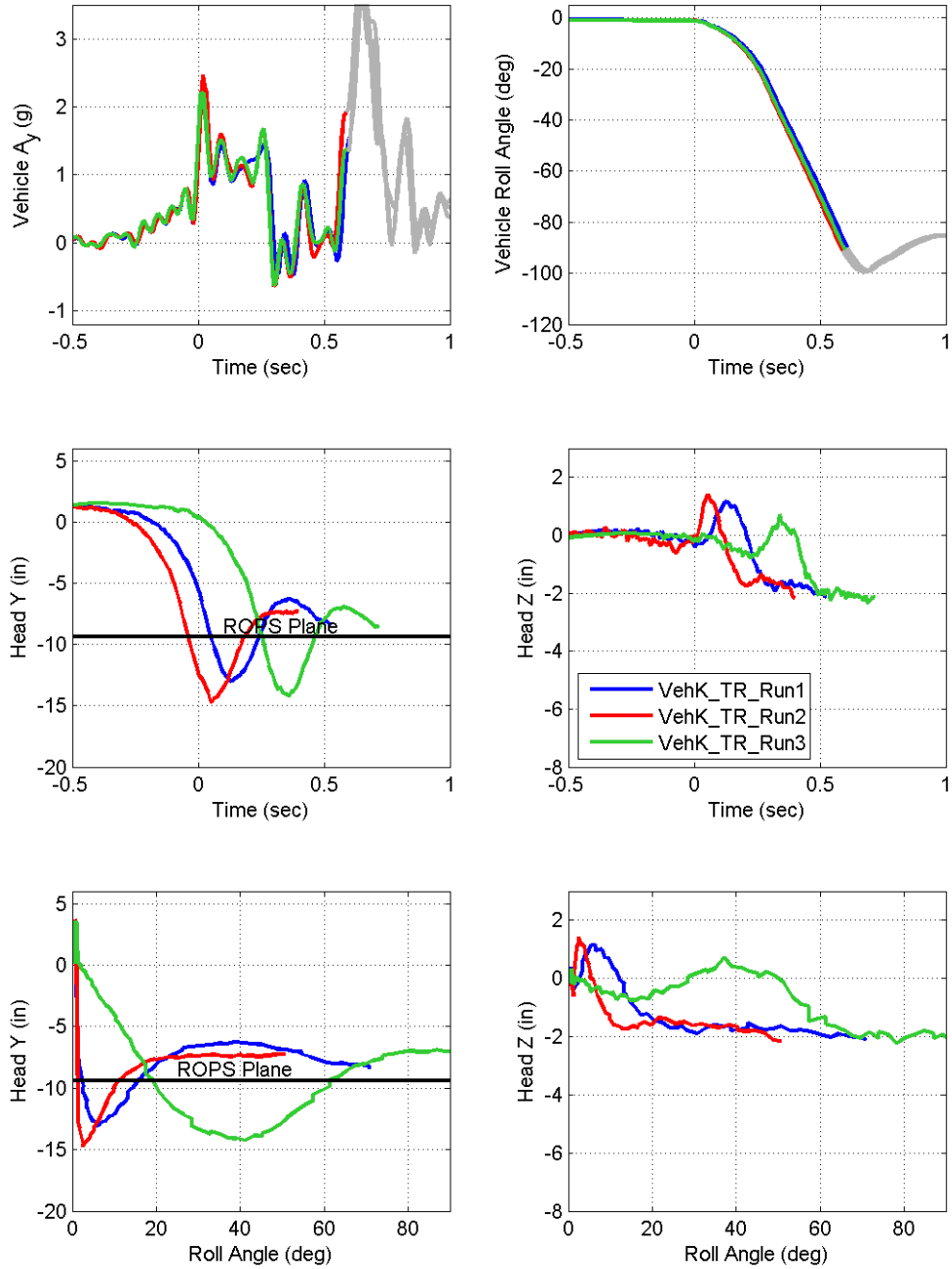
Vehicle K Threshold Rollover



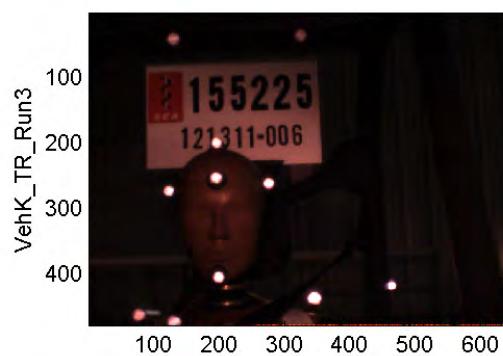
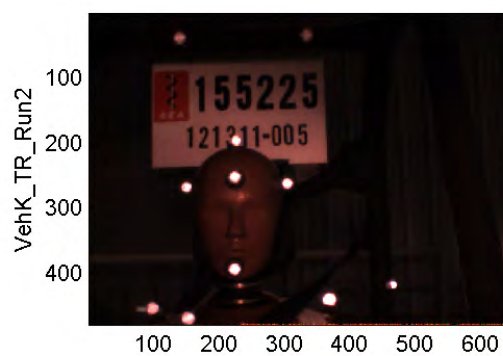
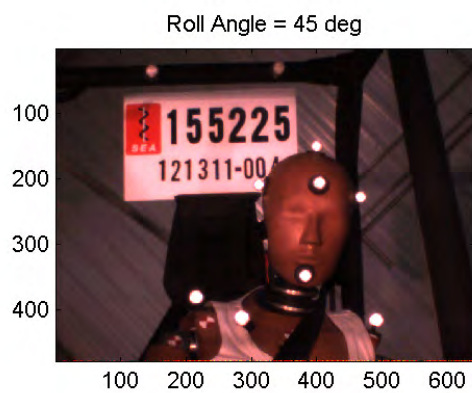
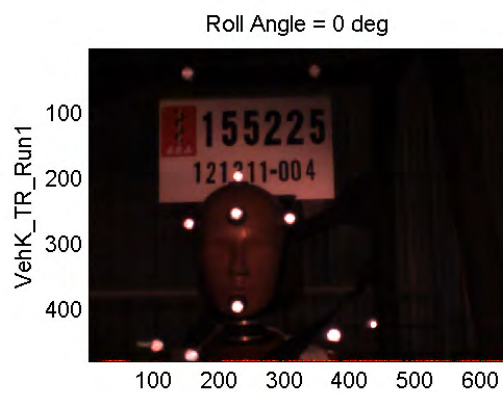
Vehicle K Threshold Rollover



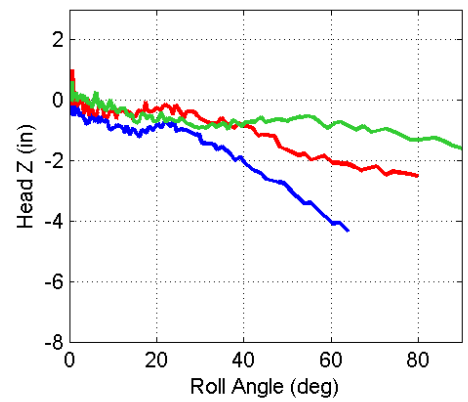
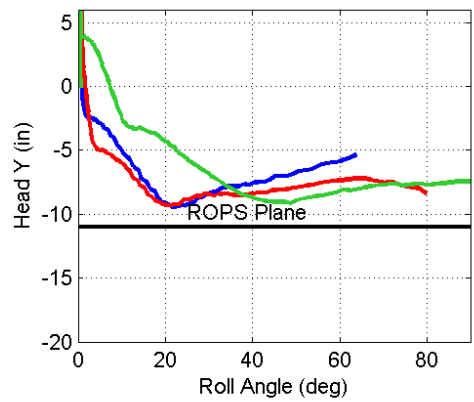
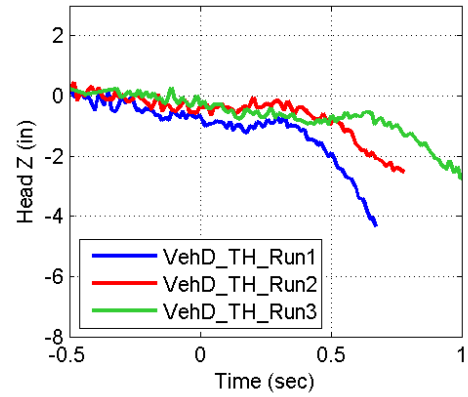
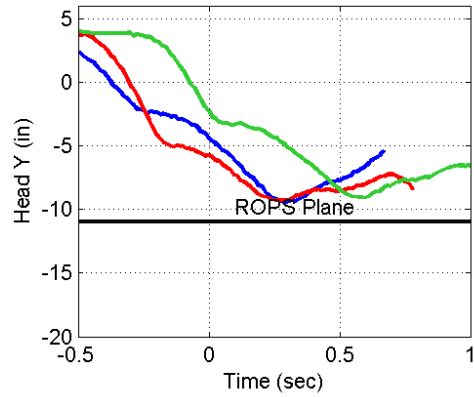
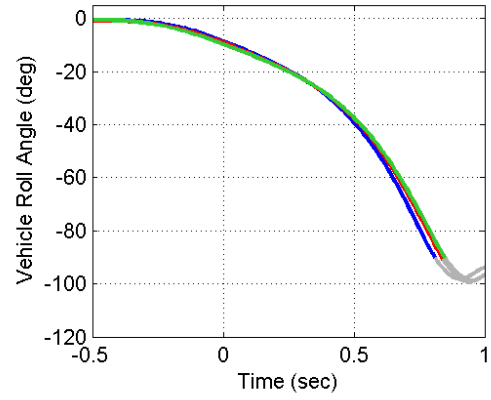
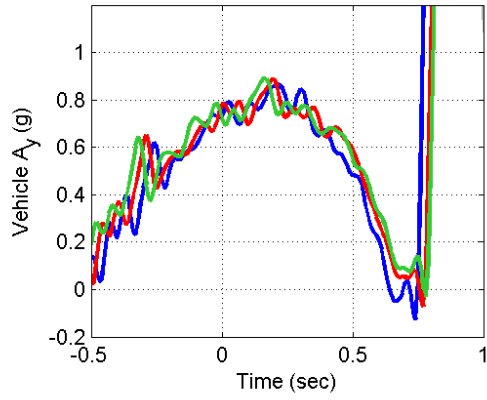
Vehicle K Tripped Rollover



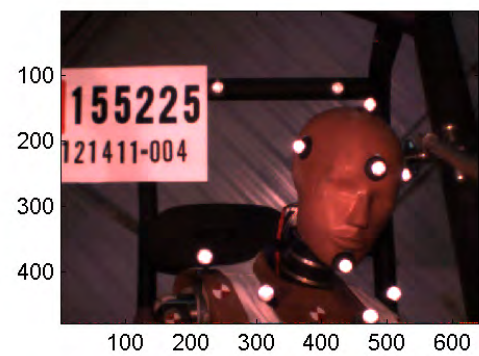
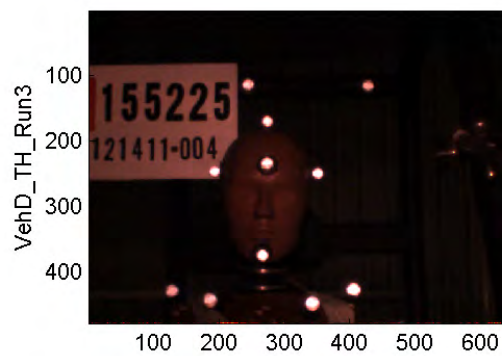
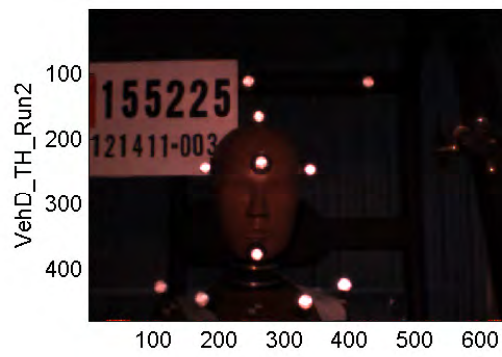
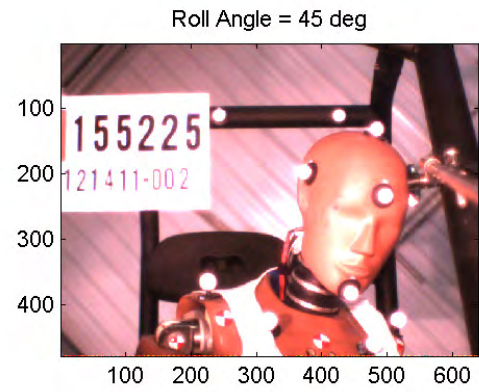
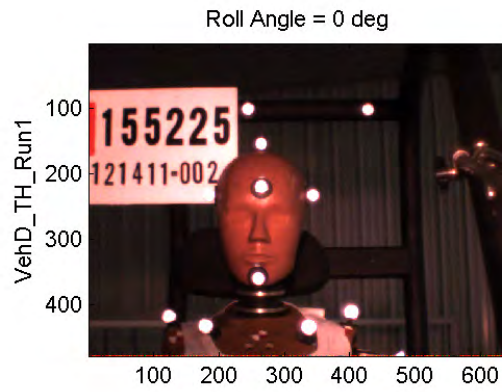
Vehicle K Tripped Rollover



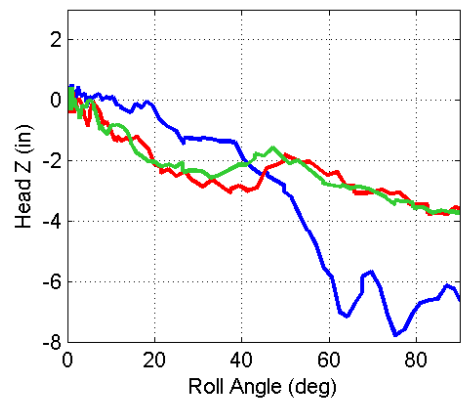
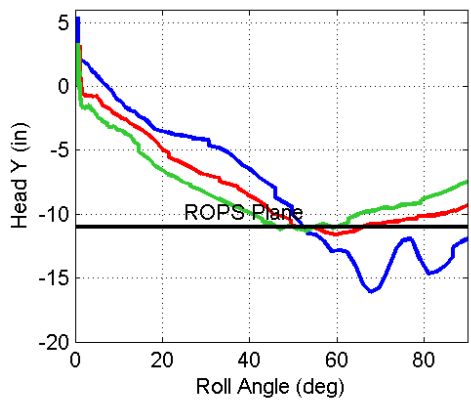
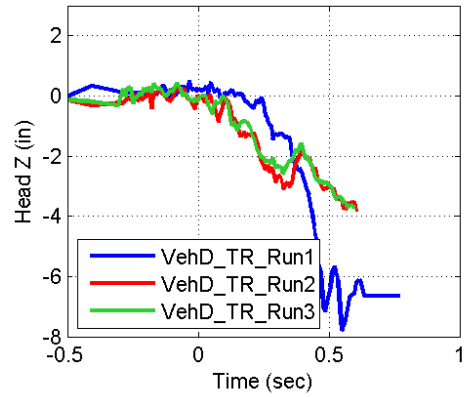
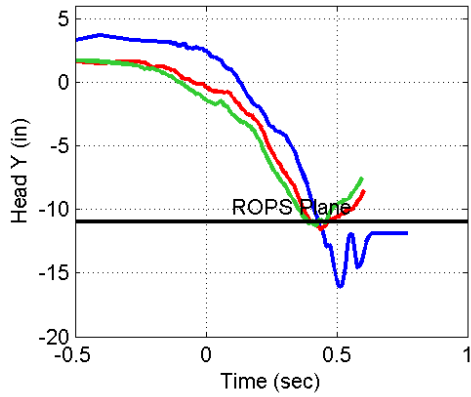
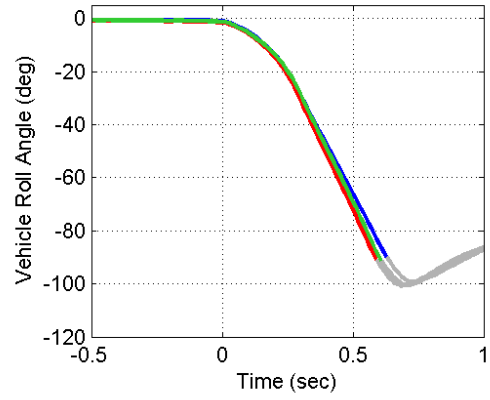
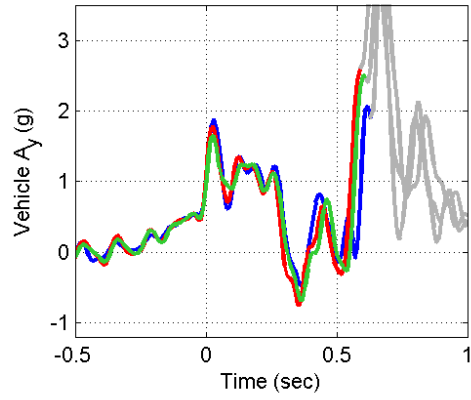
Vehicle D Threshold Rollover



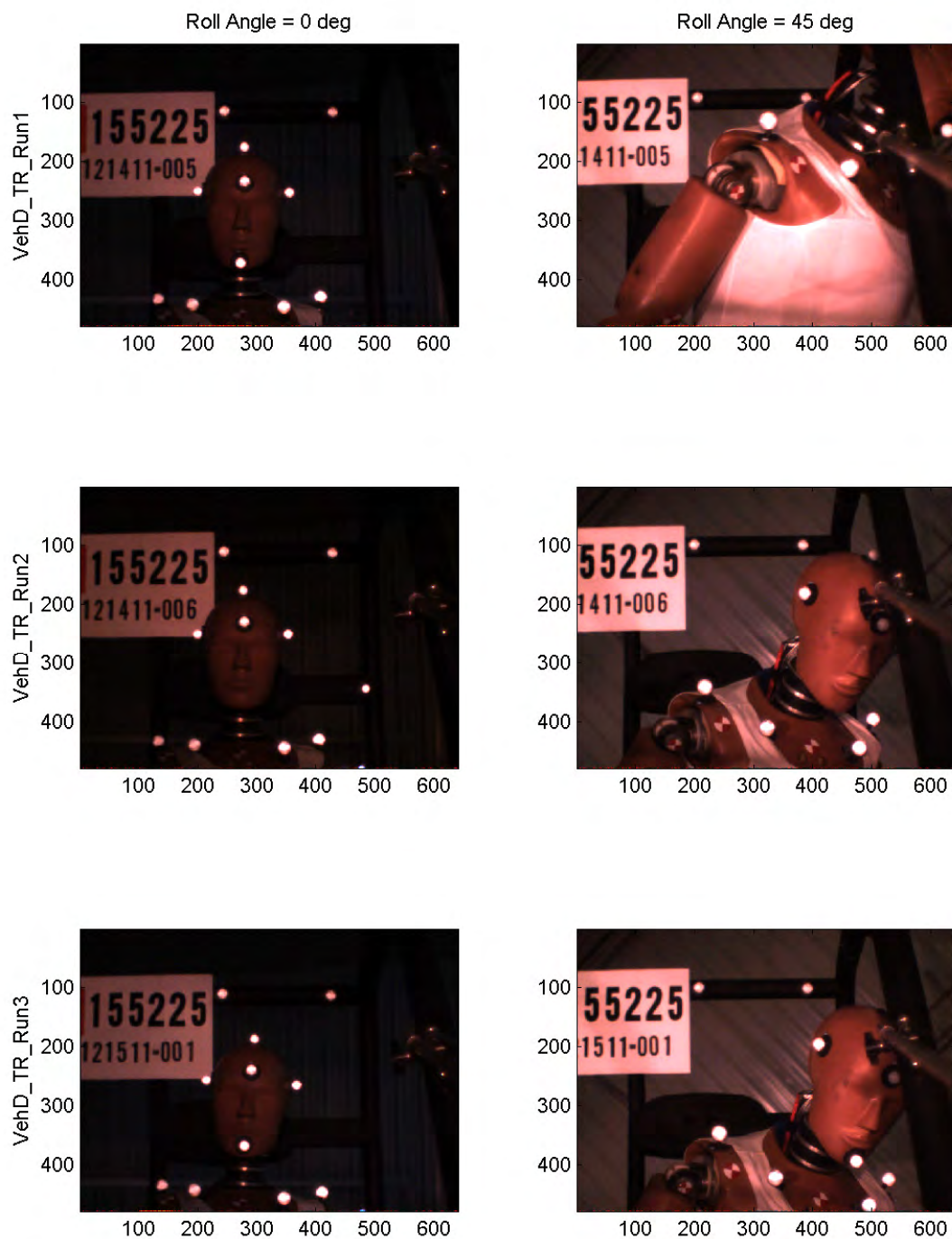
Vehicle D Threshold Rollover



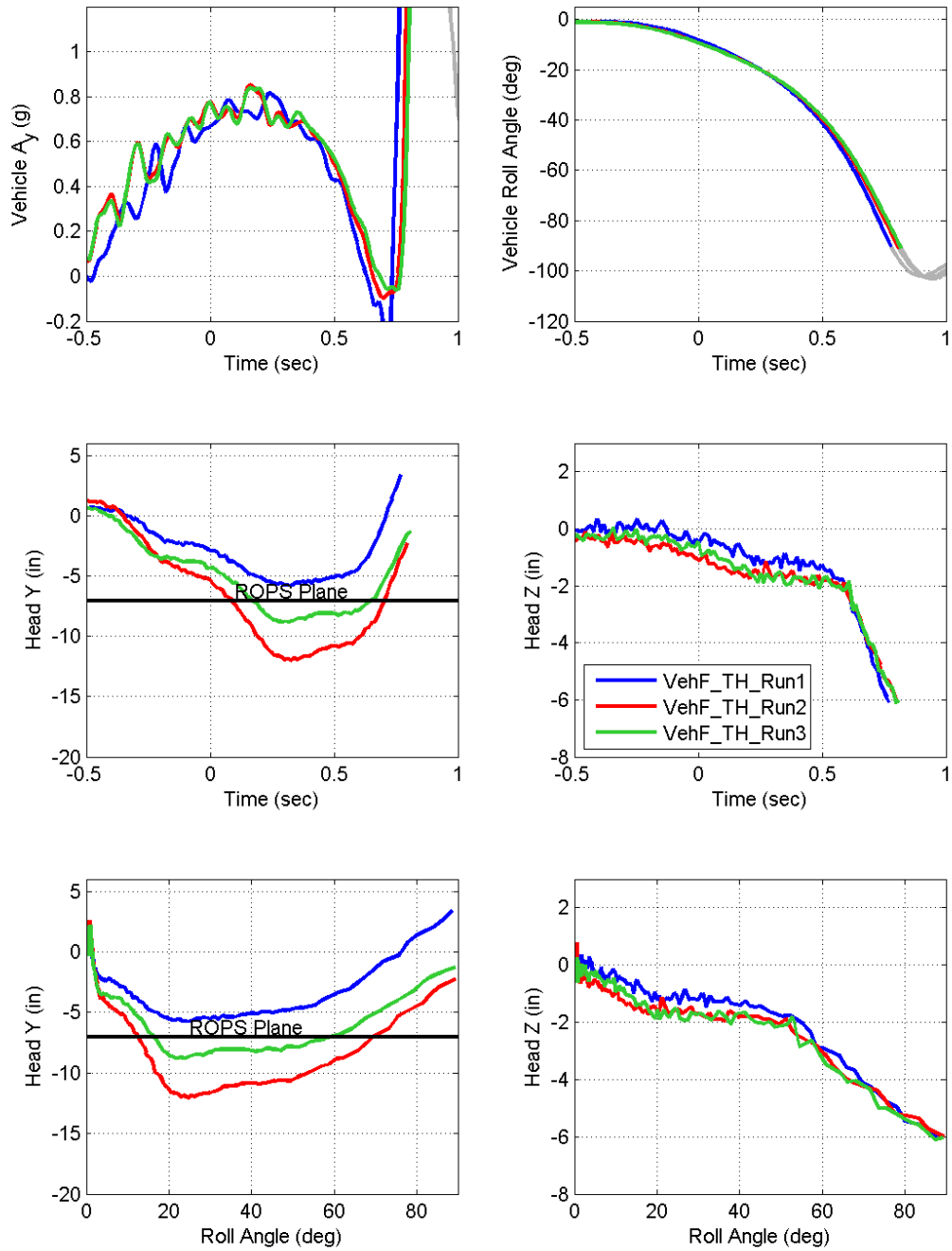
Vehicle D Tripped Rollover



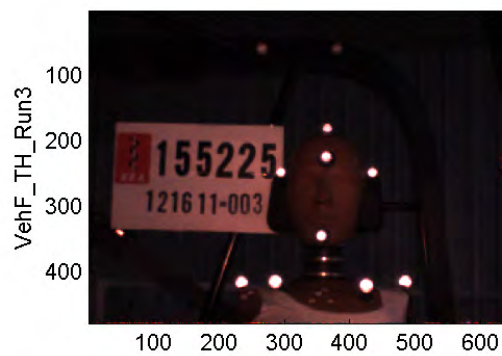
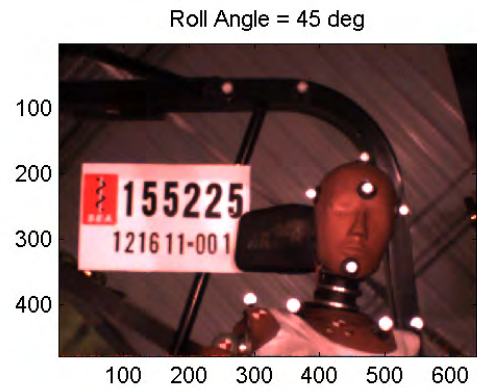
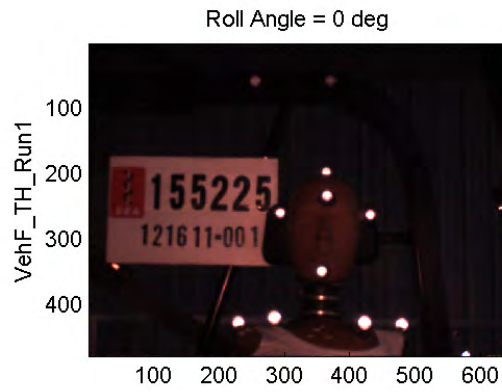
Vehicle D Tripped Rollover



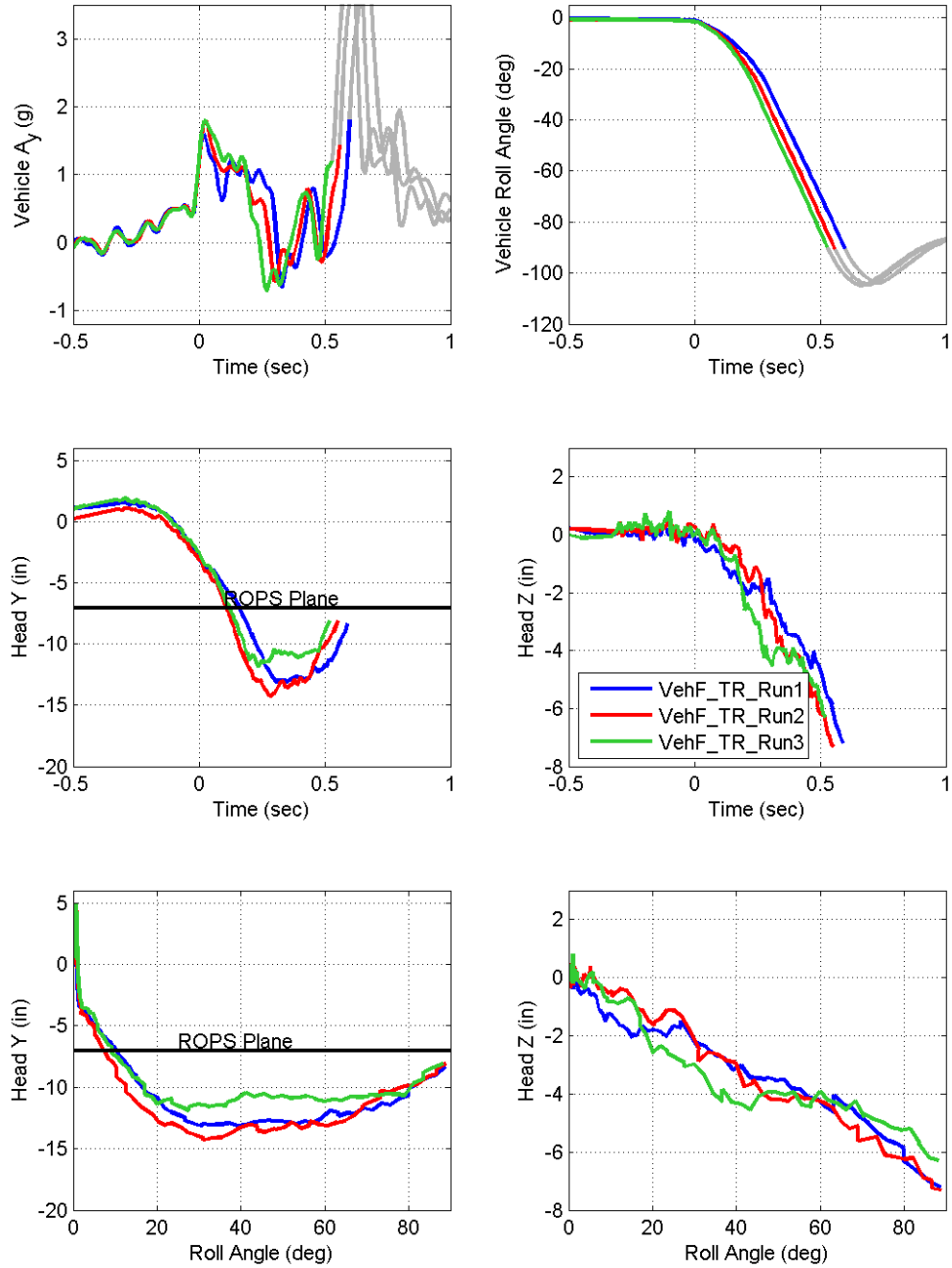
Vehicle F Threshold Rollover



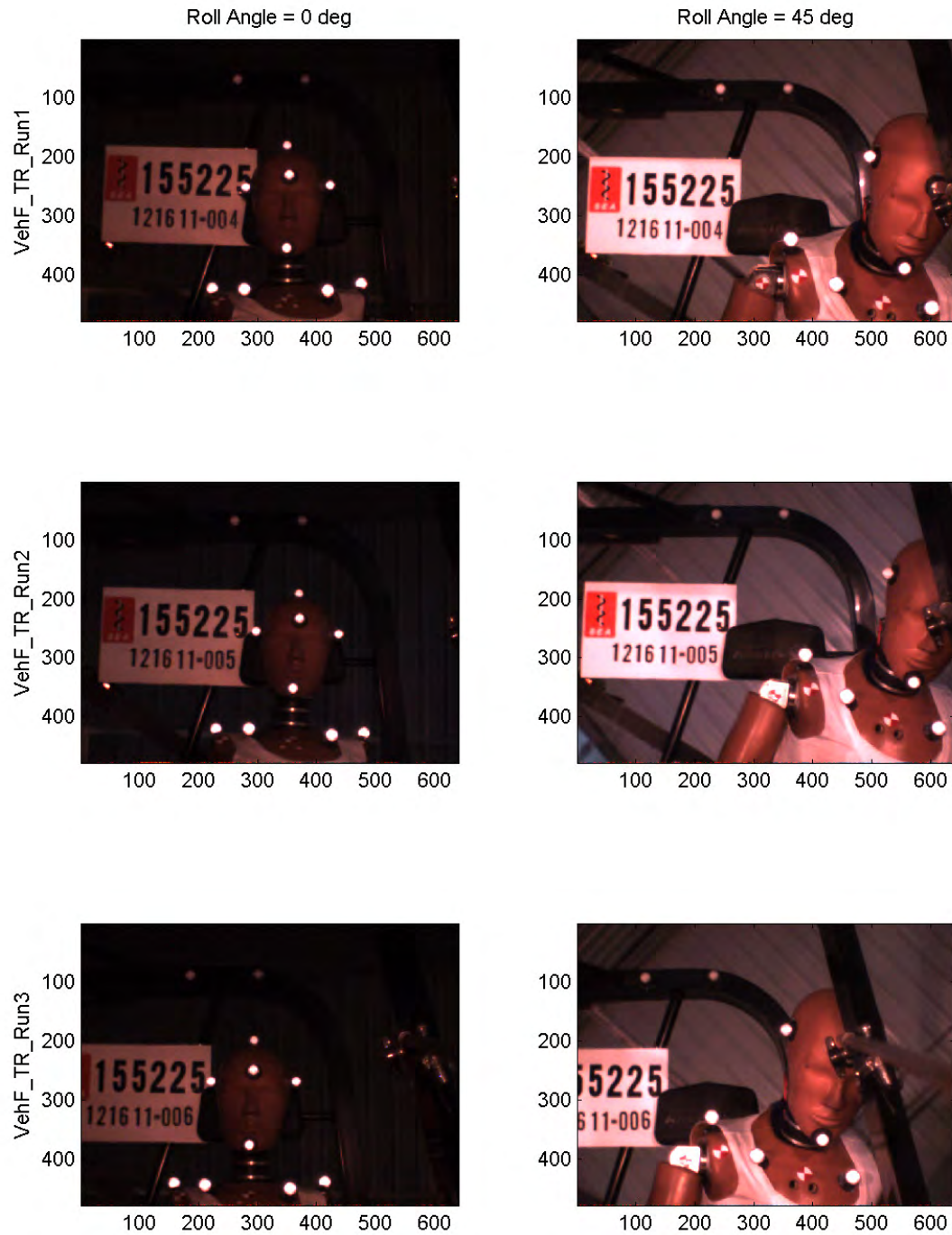
Vehicle F Threshold Rollover



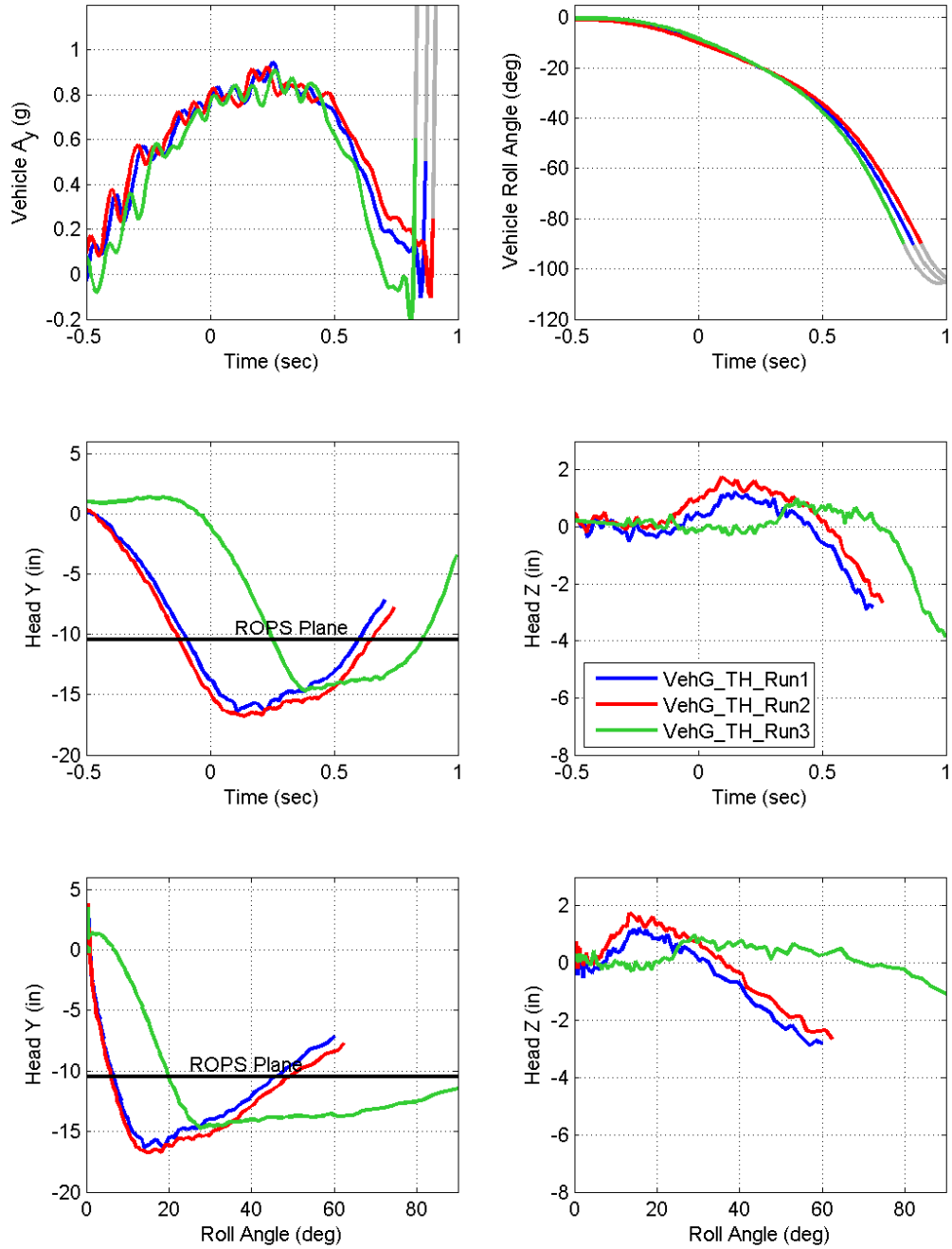
Vehicle F Tripped Rollover



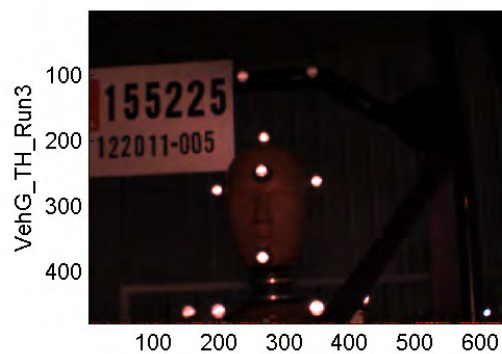
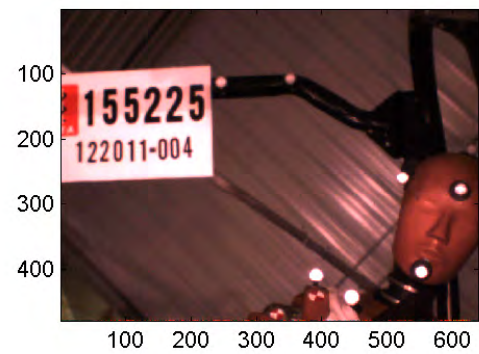
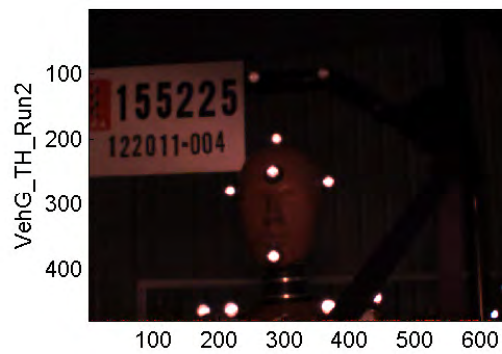
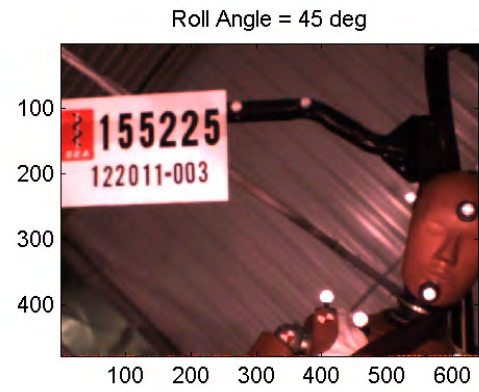
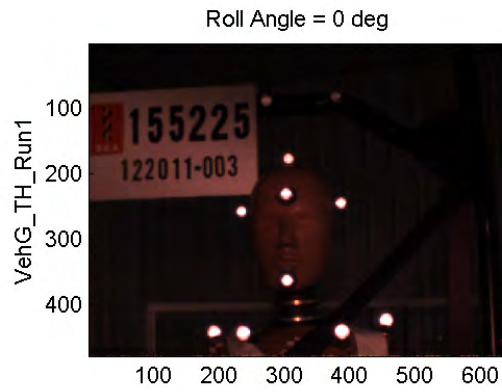
Vehicle F Tripped Rollover



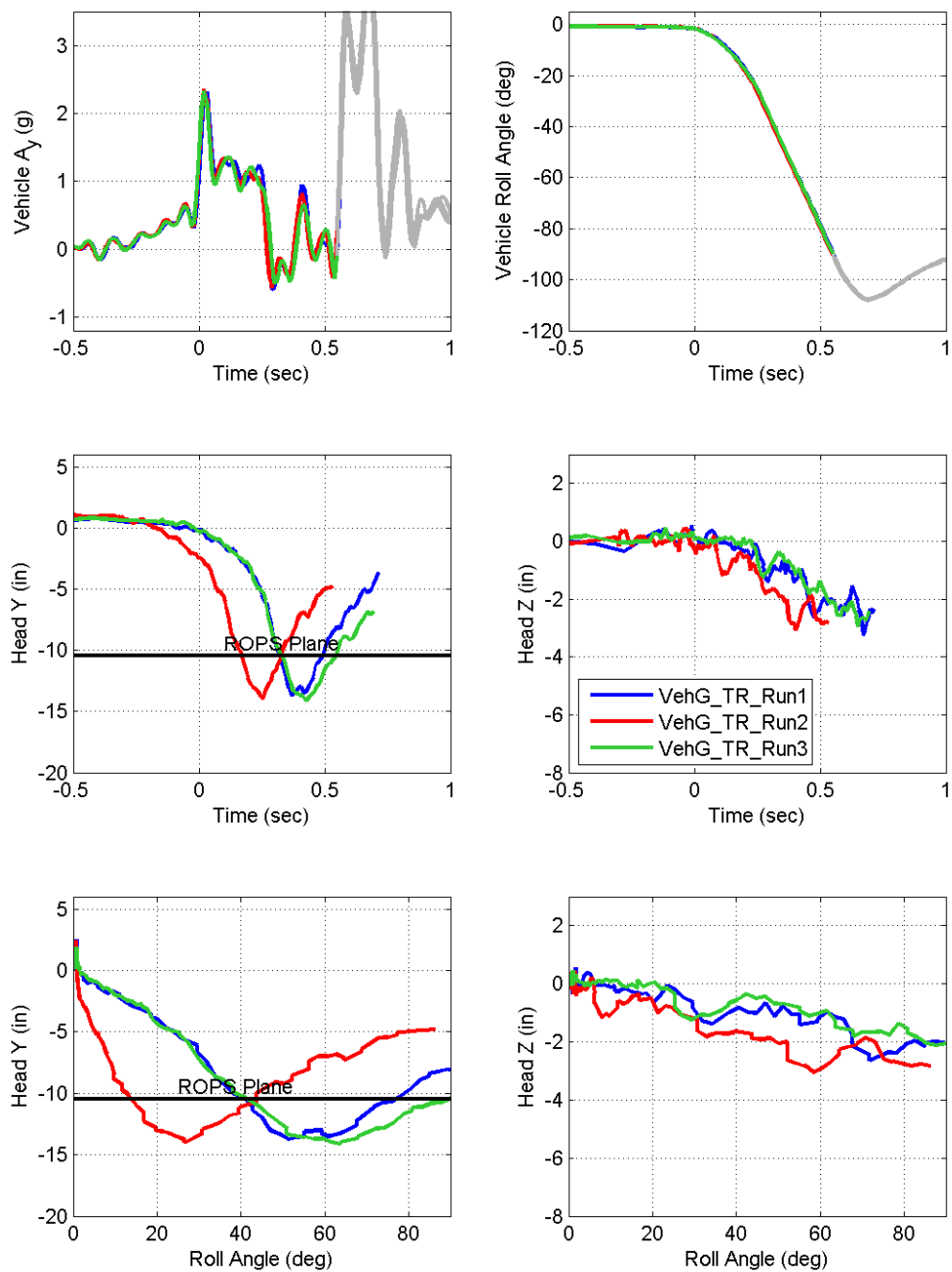
Vehicle G Threshold Rollover



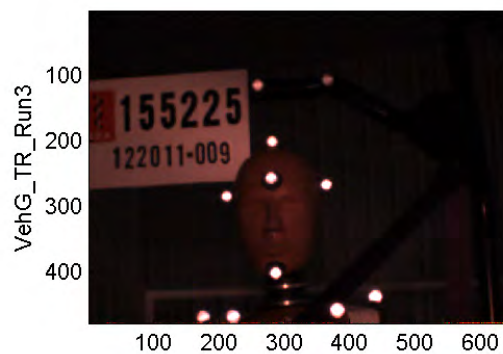
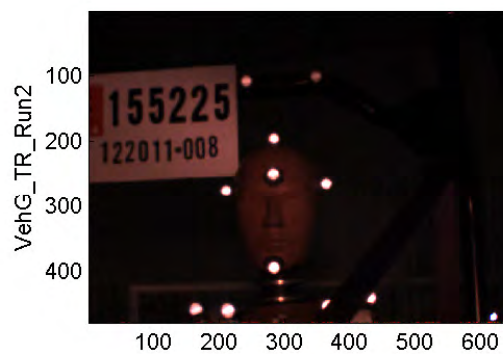
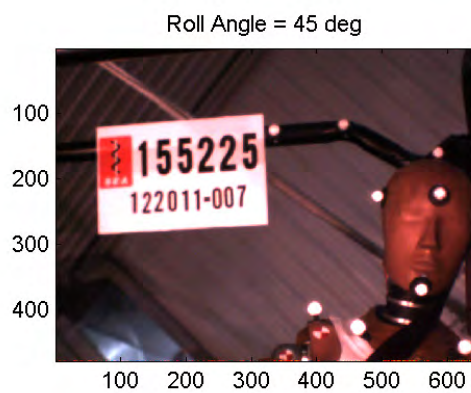
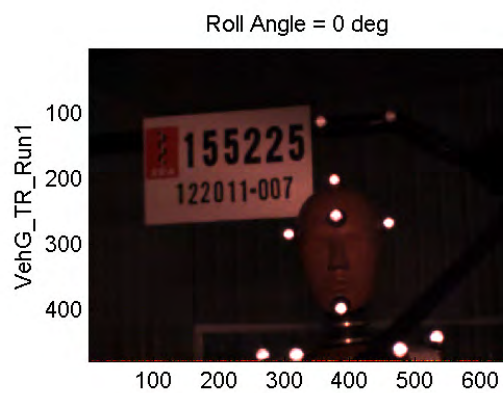
Vehicle G Threshold Rollover



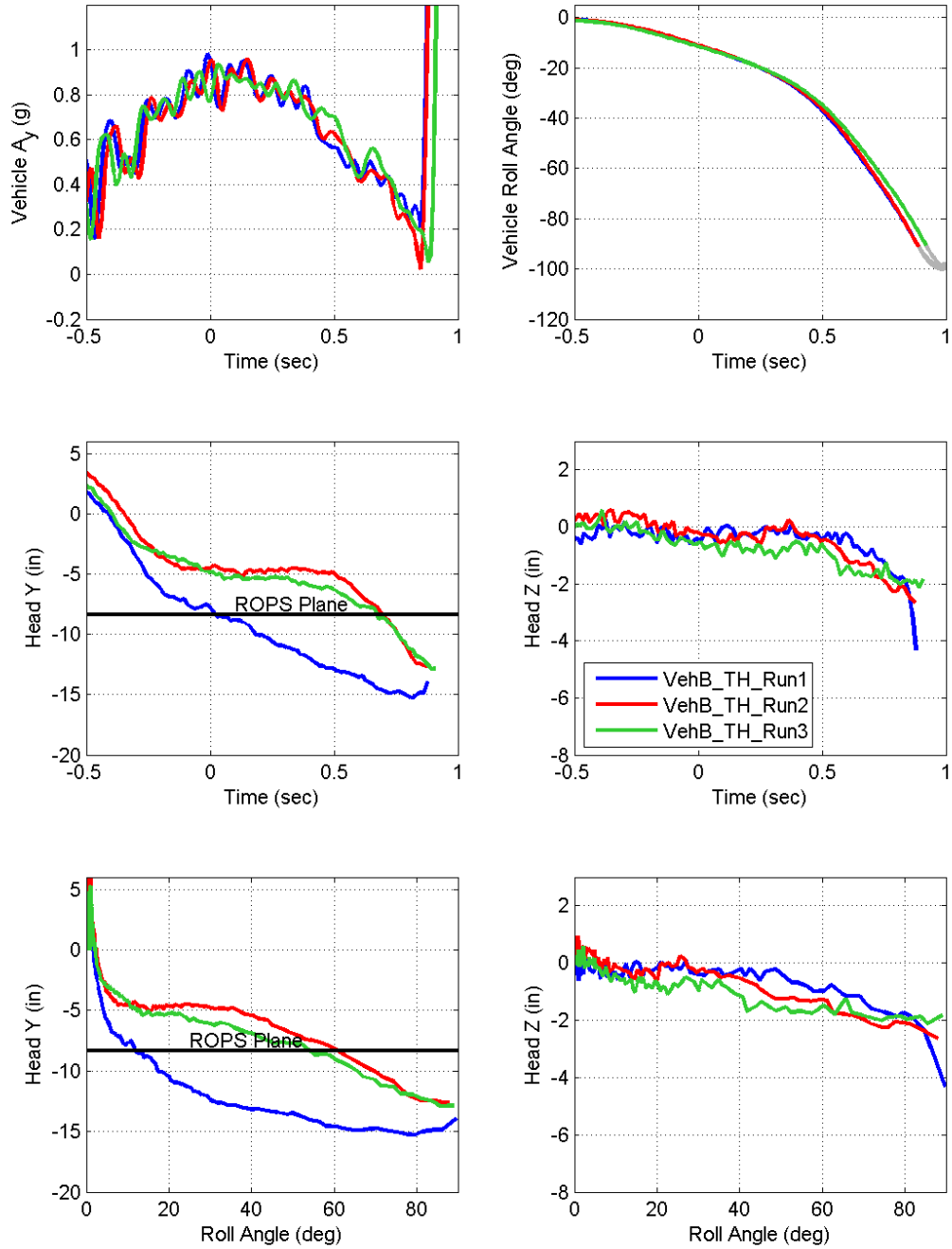
Vehicle G Tripped Rollover



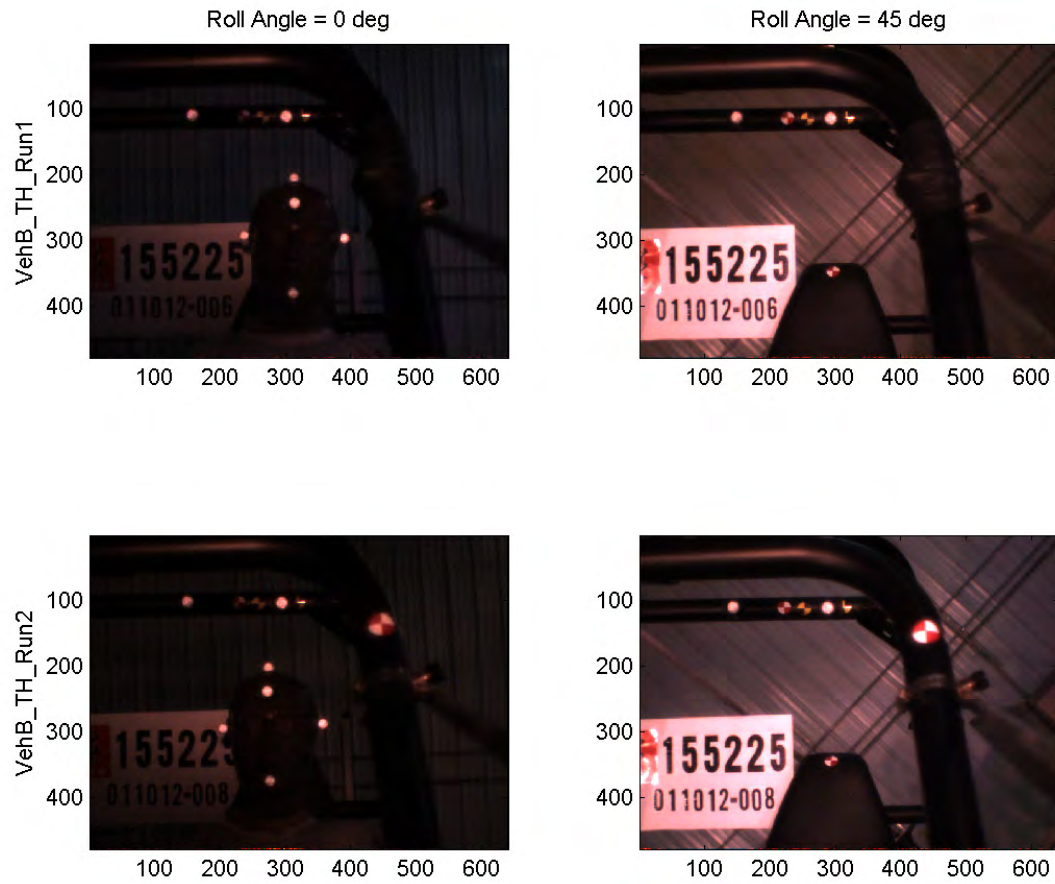
Vehicle G Tripped Rollover



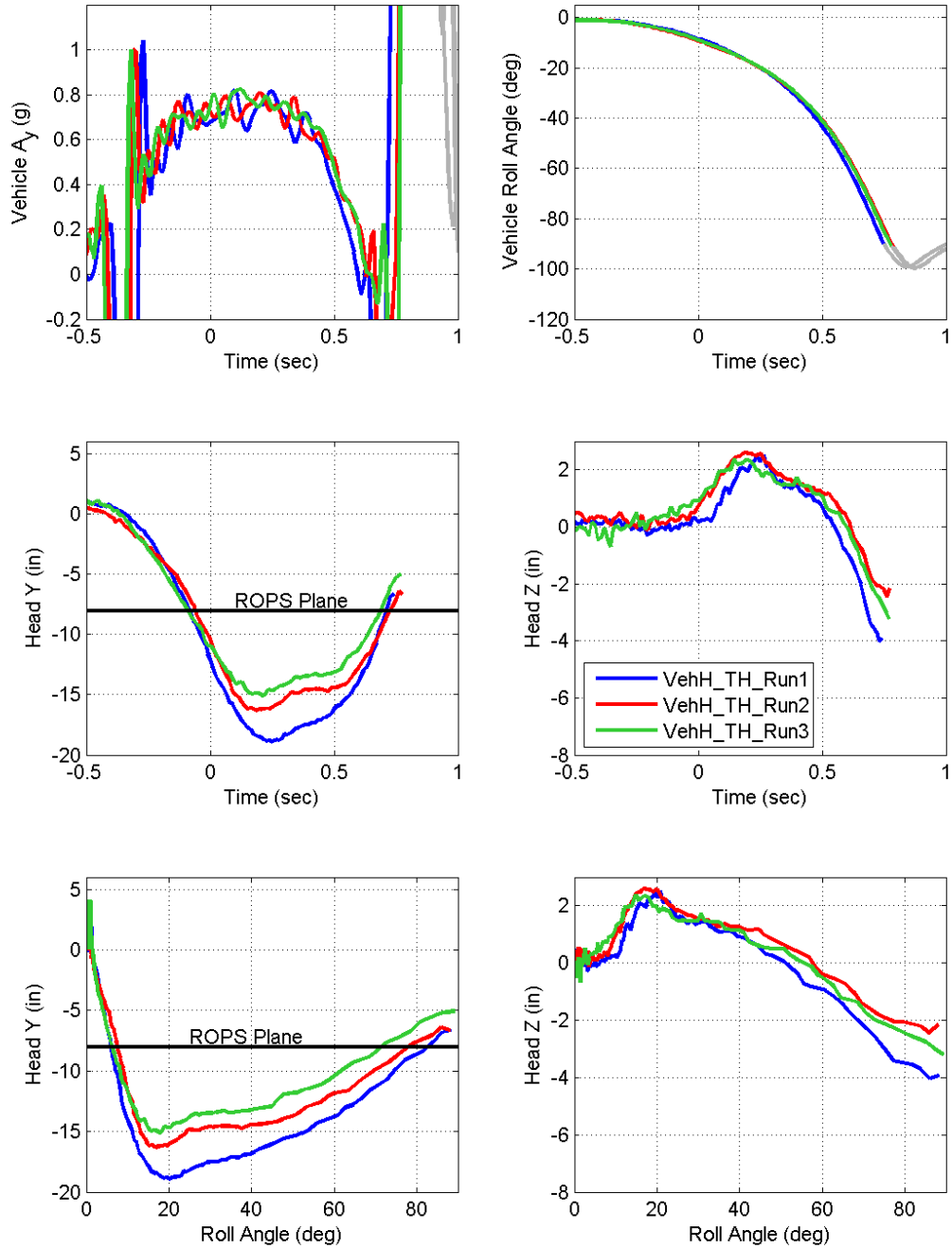
Vehicle B Threshold Unbelted Rollover



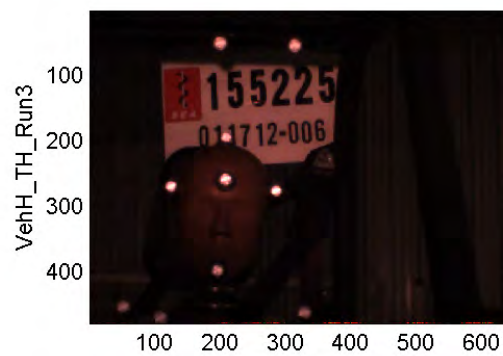
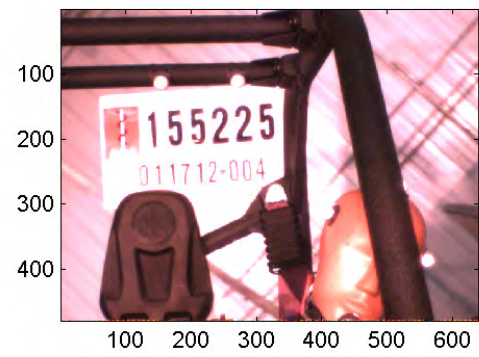
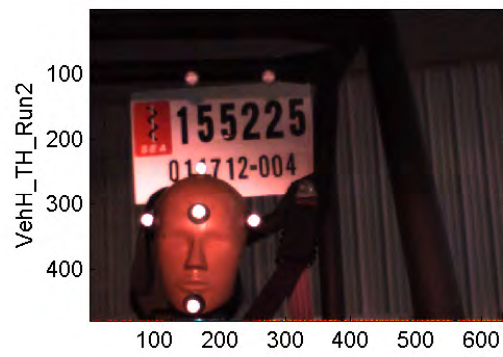
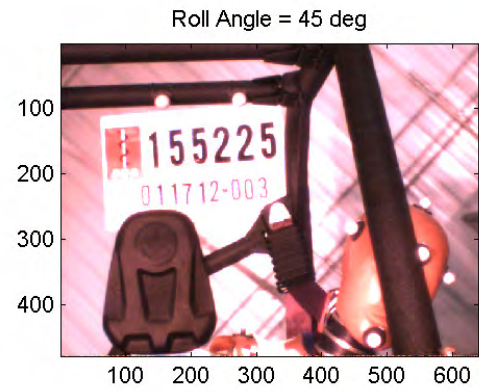
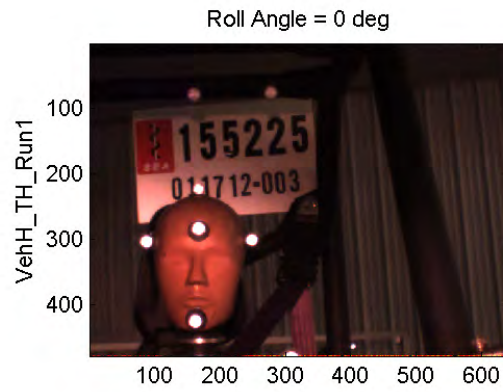
Vehicle B Unbelted Rollover



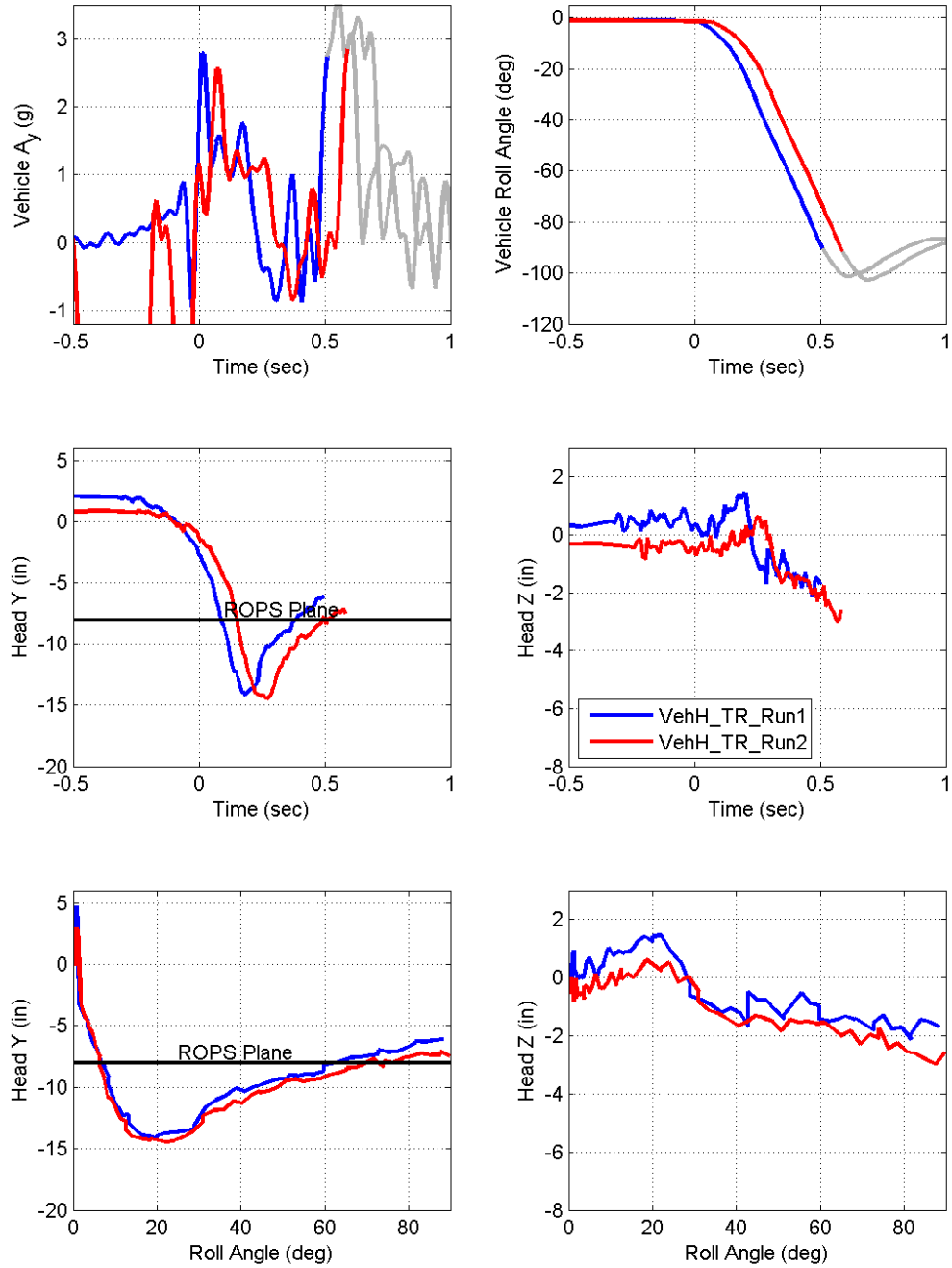
Vehicle H Threshold Rollover



Vehicle H Threshold Rollover



Vehicle H Tripped Rollover



Vehicle H Tripped Rollover

