FINAL REPORT

CARGO TANK ROLLOVER FORCE VERIFICATION

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Executive Summary

The broad goal addressed in this endeavor is the improvement of the crashworthiness of cargo tank motor vehicles that carry hazardous materials. The purpose of the current research is to aid the understanding of the effects of a rollover crash on the "rollover protection devices" on the tops of these vehicles. The overall objective was to quantify the pre-impact dynamics of a rollover through full-scale experiments, that is, rollover crashes of loaded cargo tank motor vehicles. More specifically, the research was intended to verify the results of dynamic simulations conducted in a previous study. The Federal Motor Carrier Safety Administration (FMCSA) funded this effort as part of its response to a recommendation from the National Transportation Safety Board (NTSB) to "improve… the performance of the rollover protection devices on bulk liquid cargo tanks by modeling and analyzing the forces that can act upon rollover protection devices during a rollover accident."

This project began with a preliminary analysis of rollover crashes previously conducted by other organizations. That task was completed in 2002 and was reported to the FMCSA at that time. The broad summary of that task was that the measured quantities fell within the range of the corresponding simulated quantities.

This report presents the major activity of this project, which was to measure the motions of cargo tank trucks as they rolled over. A small single-unit cargo tank vehicle was fitted with a roll cage so that it could withstand a crash, and it was rolled over four times. A cargo tank semitrailer was rolled over once. The five maneuvers leading to the rollovers were selected to approximate maneuvers that had been simulated in the earlier study. This provided a diverse set of rollover conditions and allowed comparison of the experimental to the simulated results. The first rollover was a relatively gentle one in which the truck barely turned onto its side. The final rollover, of the combination unit vehicle, was intended to be quite aggressive.

Vehicle motion was recorded by an onboard inertial navigation system combined with a global positioning system (GPS) receiver. The crashes were recorded by video cameras from several angles on the ground and, in most cases, by one or more cameras on the vehicle. The semitrailer was instrumented with strain gages and string potentiometers to measure the deflections of the tank and the rollover protection devices during impact. The velocity measurements in this study will provide quantitative guidance concerning the performance requirements of rollover protection devices, which must bring the vehicle to a safe stop following the dynamic conditions measured in the moments prior to impact. The measurements of the semitrailer deformation will serve as a case study of how the particular design of rollover protective devices performed during a crash of known conditions.

The vehicles obtained for the crashes were similar, but not identical, to some of those in the simulation study. Likewise, the maneuvers closely approximated but did not exactly duplicate those in the simulation study. Nevertheless, the experimentally measured values were compared with the results of the dynamic simulations. The simulations' order of magnitude was certainly corroborated. The experimentally

measured roll rates at the moment of impact were very much within the range of those calculated during the simulations. The data are presented in numerical and graphical form in the main text and the appendixes; CDs accompanying this report have videos of each crash and the raw motion and deformation data.

Acknowledgements

Regional Enterprises of Hopewell, Virginia, donated the semitrailer to the University of Michigan.

Dana Corporation of Kalamazoo, Michigan, allowed use of their tractor to pull the semitrailer through the crash.

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1.0 Introduction and Background

Cargo tank motor vehicles are required by federal regulations to have “rollover damage protection devices,” which are designed to protect the valves and other fixtures in the event of a rollover [1]. The National Transportation Safety Board (NTSB) issued a Special Investigation Report in 1992 on rollover crashes of commercial cargo tank vehicles and the spills of hazardous materials that could result [2]. In the report, the board formally recommended (H-92-10 and H-92-11) that forces acting on rollover protection devices be modeled and analyzed, and that new performance standards be promulgated based on this analysis. In response to the recommendation, the Federal Highway Administration (FHWA) funded a study at the University of Michigan Transportation Research Institute (UMTRI) [3]. The first portion of the study involved a number of computer simulations of trucks in rollover situations similar to the cases studied by the NTSB. In 1999, the Research and Special Programs Administration issued an Advance Notice of Proposed Rulemaking [4] soliciting public comments on the possibility of new rollover damage protection regulations.

The Federal Motor Carrier Safety Administration (FMCSA) funded the present study to experimentally verify the dynamic simulation results. The expected outcome of the present study was a set of measurements of the vehicle’s energy in various rollover scenarios that approximate the scenarios in the simulation study [3]. The FMCSA expects that any new regulations will be written in terms of the energy that rollover protection devices must absorb, rather than forces, because crash energy can be more generally applied to varied vehicle designs. Crash energy can be calculated from velocity by considering the inertia of the vehicle.

In a small preliminary task of the present study, videotapes of previously conducted rollover tests were quantitatively examined to estimate the roll rate and fall rate at impact. The results were presented to FMCSA [5] and published [6]. The quantities estimated from the videotapes agreed with the values in the simulation study, especially considering the diverse circumstances under which the previous rollovers had been conducted. The majority of the work in the current project was to conduct several rollover crashes under controlled circumstances, with each rollover approximating one of the events in the simulation study.

2.0 Approach

A single-unit truck was fitted with a roll cage so that it could be crashed several times in various maneuvers. A tractor semitrailer combination was crashed once. The vehicles proceeded without a driver, under closed-loop speed and path control, down a runway toward the rollover point. At that point, the vehicle executed a maneuver intended to produce a rollover. Instruments onboard the vehicle determined and recorded the motions of the sprung mass, and video cameras on and outside the vehicle documented its maneuver. The roll cage on the single-unit truck was designed so its pre-impact motion would be realistic; however, the post-impact motion was not representative of an actual crash. The semitrailer was crashed in the configuration that it was built, so its crash was representative through the moment when it came to rest. Strain gages and string potentiometers measured the deflection of the tank and rollover protection devices on the semitrailer.

Extra data, beyond the original plan for the project, was collected to take advantage of the rare opportunity to participate in full-scale heavy vehicle rollover crash tests. The single-unit truck, for three of its four crashes, carried a rollover sensor for an automatic collision notification system. The tractor pulling the semitrailer had two Hybrid III dummies, one uninstrumented and unrestrained in the driver's seat, and one instrumented and belted in the passenger seat.

2.1 Test Vehicles

The single-unit truck was a 1977 U-model Mack-2500 equipped with a tank designed for residential and farm delivery of gasoline, diesel, and heating fuels. It had a steer axle, a drive axle, and an unpowered tag axle. Figure 1 shows the truck as it looked when it was retired from service. A steel roll cage was built around the engine and around the tank to protect the truck so it could be crashed several times. The roll cage is visible in Figure 2, which shows the truck on the tilt table at UMTRI. The fill ports on top of the truck are also visible in the photograph, as are the two rails running the length of the tank, which are typical overturn protection devices for a gasoline cargo tank.

Figure 3 shows the weight distribution on the truck in its test configuration and the location of the "reference point," which is the point where the inertial navigation package was located and the point from which motion was referenced. In the process of armoring the truck some mass was removed, and much steel was added. The aft tank and the forward half of the front tank were left empty, while the other tanks were filled with water. The modifications were planned so that the total mass of the vehicle and the mass distribution of the vehicle in the test configuration were nearly identical what they were when the vehicle was in service. The tanks with water were filled, and the other tanks were empty, so sloshing was not a factor during the test. Thus, the dynamics of the vehicle during the test rolls were almost exactly as the rolls would have been had it rolled over in service, up to the moment of impact. The static rollover threshold of the truck in its test configuration was 0.48 g.

Figure 1. Single-unit truck

Figure 2. Single-unit truck on the tilt table

The roll cage, the fill ports for the tanks and the rails serving as "rollover protection devices" are visible in the photo.

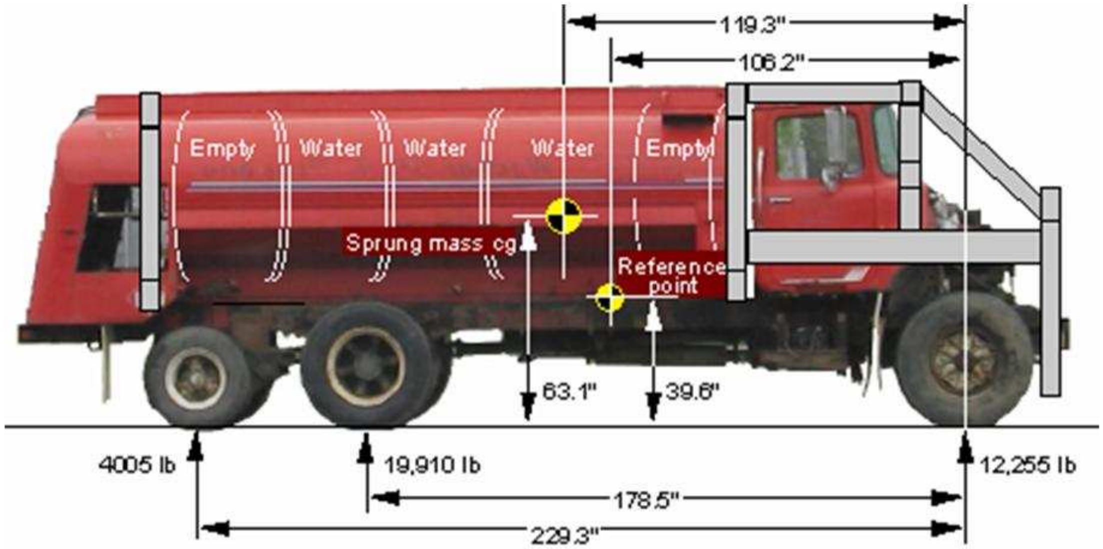


Figure 3. Single-unit truck mass distribution

The roll cage and tank filling were planned so that the mass and mass distribution in the test configuration closely matched those of the truck while it was in service

The semitrailer (Figure 4) had a tank of circular cross section. It carried muriatic acid during its service years. It was an MC 312 with a steel tank, built by Fruehauf in 1981. The trailer is nearly identical to the one in the Albuquerque crash in the NTSB report. It was filled with water for the test roll, so its test weight was 72,000 lb. The tractor was a Peterbilt 379, model year 2000, with a sleeper cab. Its tandem drive axles had a gross weight rating of 40,000 lb. The combination unit truck was tested on the tilt table, as in Figure 5. Its rollover threshold was 0.40 g. Figure 6 shows the dimensions of the trailer and the location of its center of gravity. As with the single-unit truck, the "reference point" is where the instruments were located and where the position was originally reckoned.

Figure 4. Tractor semitrailer combination

Figure 5. Tractor semitrailer on the tilt table

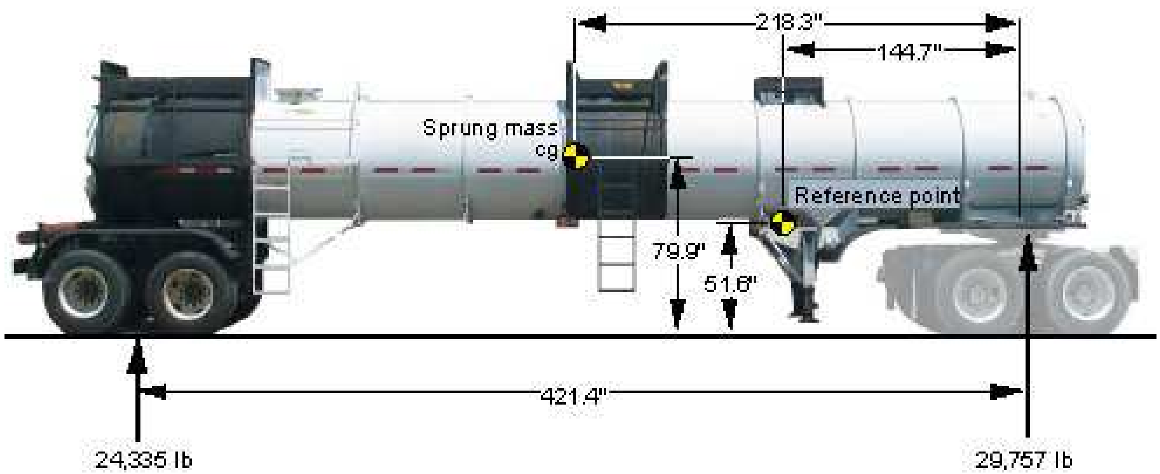


Figure 6. The dimensions and mass of the semitrailer in its test configuration

2.2 Test Instrumentation

The primary element of the instrumentation system was an RT3000 GPS-aided inertial navigation system by Oxford Technical Solutions. The system employs differential GPS in combination with tri-axial accelerometers and angular velocity sensors. The data sources are merged in a Kalman filter, and the unit outputs linear position, velocity, and acceleration and angular position and velocity, each in three dimensions. The position and velocity outputs from this system were used as feedback for closed-loop steering control of the vehicle as it came down the runway toward and through the crash maneuver. All the outputs were recorded and used to describe the vehicle's motions as it rolled over.

For the tractor-semitrailer combination, the sensor system had to be on the semitrailer because its motions were most important to record. Since the steering tires were on the tractor, the closed-loop steering system incorporated extra sensors to measure the articulation angle and tractor yaw rate.

The instrumentation was carried in a protected location. On the single-unit truck, it was nestled between the frame rails as shown in Figure 7. On the semitrailer, it was under the tank at the landing gear. The motion sensors needed to be affixed to the vehicle essentially rigidly up to the moment of impact, so they would faithfully record the rollover. However, if the instrument had been bolted directly to the frame, it would have suffered excessive shock forces during impact. Accordingly, UMTRI supported the instrument with fragile, but rather rigid, pieces of foam (the pink-colored foam in Figure 8), which would hold the instrument in place during ordinary maneuvers but would break at the moment of the rollover impact. The soft, white foam in the photograph would then cushion the instruments at impact. The broken pink pieces had to be replaced after every roll. This approach worked as planned.

Figure 7. Inertial guidance unit on the single-unit truck

It was mounted between the frame rails for protection.

Figure 8. Support for the inertial navigation system

The thin (pink) pieces of foam were rigid but broke away at impact.
The thicker (white) pieces of foam cushioned the unit from impact.

The instruments for the strain gages and string potentiometers were in a steel box welded beneath the tank near immediately forward of the trailer's axles. The steel box protected the instruments from possible crushing, and foam within the box cushioned the impact. The photographs in Figure 9 show these instruments. The locations of the strain gages and plots of their data are in Appendix B. The single-unit truck had no strain gages, so these instruments were not mounted on that truck.

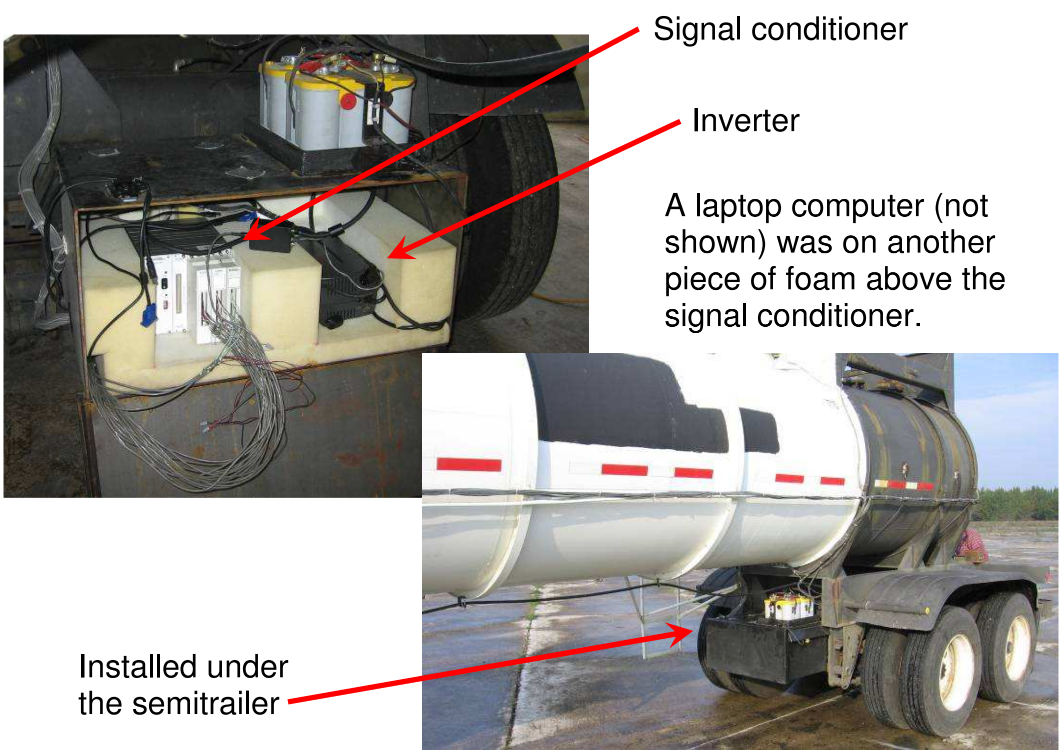


Figure 9. Strain gage conditioners

2.3 Experimental Procedure

During the rollover experiments, the test vehicles were driven by an on-board control system developed by UMTRI for this project. Steering was accomplished by a path-following control system embodied in the Data Acquisition System (DAS) computer. Speed was controlled using conventional cruise control modified to accept commands from the DAS computer.

The closed-loop steering system was design to follow paths that were predefined in coordinates of latitude and longitude. For the single-unit truck, the GPS-aided inertial navigation system provided the real-time data needed for feedback signals of position, heading, speed, and yaw rate. Since the inertial unit was mounted on the trailer of the combination vehicle, signals from additional transducers for yaw articulation angle and tractor yaw rate were also used in the feedback calculations. The steering actuator was a DC servo motor mounted to the input shaft of the conventional power-steering gear box (shown in Figure 10 on the tractor). The closed-loop steering system provided precise control of the truck's path through the entire run. The figures in Appendix A show that the truck was within 1 m of the planned path. Even the maneuver that induced the crash was commanded through the closed-loop control, though, of course, the truck was not able to follow the final portion of the path. To allow the truck to be maneuvered and positioned prior to the crash runs, the DAS had an operating mode where the vehicle could be steered through a potentiometer on the steering wheel.

Both trucks had manual transmissions, and a system to shift gears automatically as the truck accelerated would have been more difficult than justified for these tests. Instead, the test trucks were pushed up to speed. Before each test, the clutch was disengaged by a pneumatic actuator controlled by the DAS computer (see figure 10), and the transmission was placed in a gear appropriate for the planned test speed. (For the single-unit truck, fourth gear was used for the 27 mph crash and fifth, the top gear, for all higher speeds. For the semitrailer's Peterbilt tractor, sixth gear was used.) To initiate the run, a "pusher" truck was used to bring the crash truck up to an acceptable speed for the selected gear. (Figure 11 shows the white cabover prepared to push the combination vehicle.) At this point, the DAS computer commanded the clutch to engage and the cruise control to be activated, whereupon the crash truck's own engine continued to accelerate the truck and then maintain the test speed.

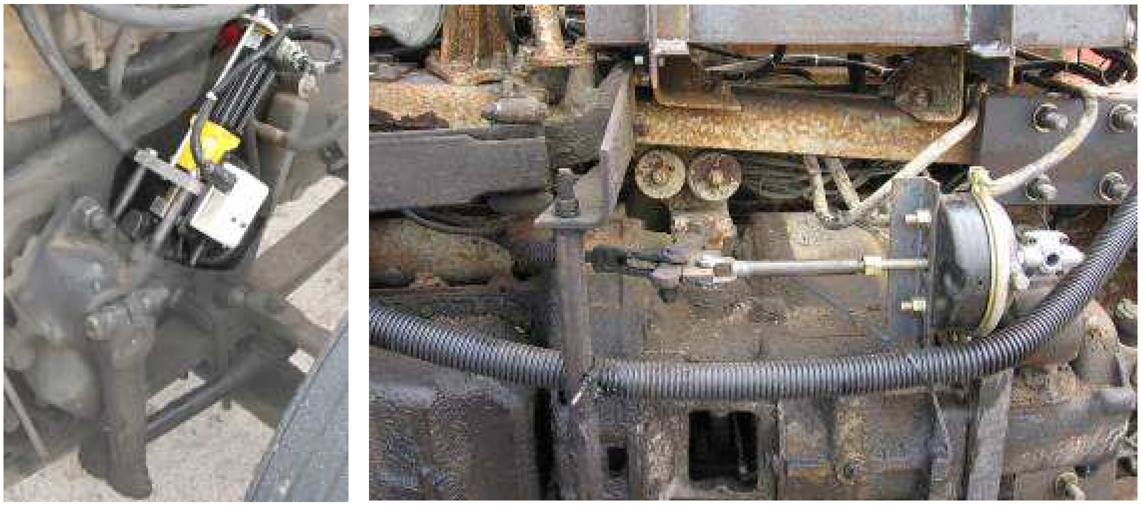


Figure10. Servomotor for steering (left) and clutch actuator (right) controlled by the DAS computer

Figure 11. Cabover tractor used to push experimental vehicles

2.4 Test Site

The tests were conducted at the Smithers Winter Test Center near Raco, Michigan. The facility is a former air base with three runways, each a mile long and 300 ft wide, as shown in Figure 12. All test runs began in the northwest corner of the site and proceeded by to the southeast with the rollovers taking place at the southern end of the field. The intersection of two runways provided a large area for the trucks to continue sliding after they rolled over.

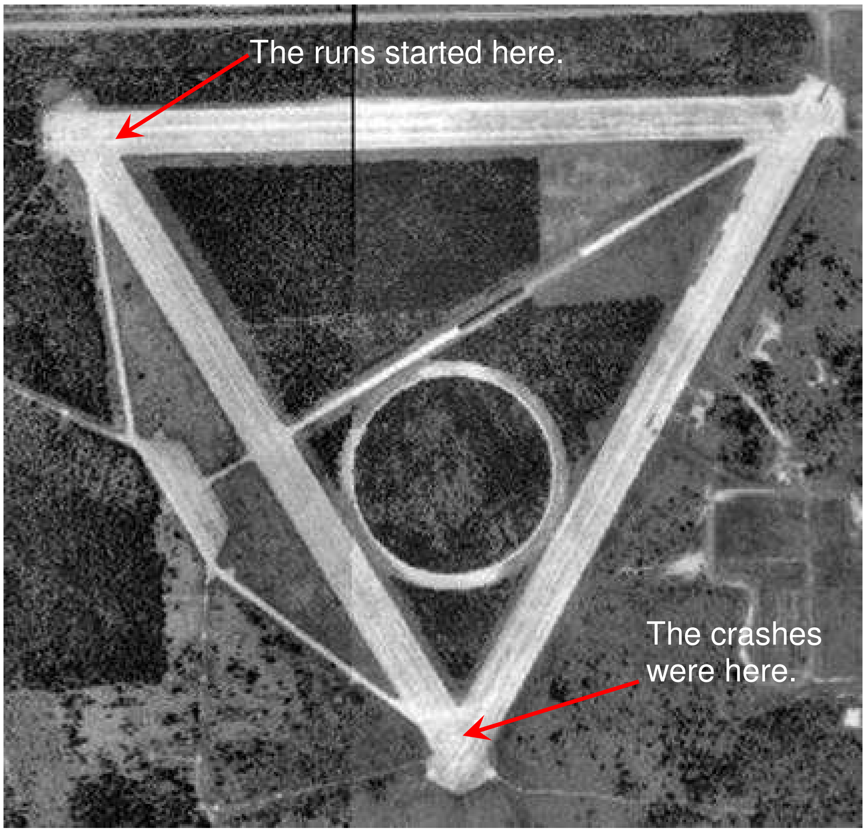


Figure 12. Smithers Winter Test Center, Raco, Michigan

3.0 Crash Maneuvers

Table 1 lists the maneuvers of the attempted rollovers. The Roll number is used to identify the events on the CDs with the videos. The Run ID is used to identify the raw data in the database on the data CD. (The Run ID is not consecutive because all practice runs were assigned a Run ID.) Complete plots of the motion data recorded on the vehicles is in Appendix A and on the data CD.

Table 1. Rollover maneuvers

Roll No.	Run ID	Maneuver Description	Vehicle type
--	105	27 mph, 100-ft-radius curve	Single-unit truck
1	106	31 mph, 100-ft-radius curve	Single-unit truck
2	110	40 mph, 100-ft-radius curve	Single-unit truck
3	115	45 mph, Closed-loop step steer	Single-unit truck
4	126	50 mph, Closed-loop swerve	Single-unit truck
semi	151	46 mph, 100-ft-radius curve	Tractor semitrailer

The first attempt to roll the single-unit truck was a 100-ft-radius turn at 27 mph, which was intended to provide a lateral acceleration exactly at the rollover threshold. The lateral acceleration experienced by the truck was momentarily above the static roll threshold, but the lateral force did not persist long enough to pull the truck over. Two effects kept the truck from actually rolling over. First, as one side of the drive axle lifted, the differential prevented the remaining side from providing any further thrust to the vehicle, so it began to slow. Second, as the tires reached their saturation in providing lateral force, the truck drifted slightly outside of the planned path, effectively increasing the radius. Together, these indicate that the rollover process is self-limiting to a certain extent. While this maneuver failed to crash the truck, it confirmed that the measurements and the dynamic model's predictions were consistent. The event was intended to be very close to the roll threshold, and the lifting of the inside tires showed that the event was indeed close to the threshold.

The next attempt to roll the truck was at 31 mph, 4 mph faster than the first, and the truck did roll over. Figure 13 was taken from one of the video cameras looking nearly down the truck's roll axis as it went over. The cone under the truck marked the predicted rollover point. The model predicted that the center of gravity would be above that point at the moment when the truck's roll angle was 45 degrees, and the truck was actually in the process of going over as it struck the cone.

This first crash was intended to be the gentlest possible roll, and the skid marks in Figure 14 show that the truck barely flopped over—the circular marks of the rear tires as they struck the pavement are touching the linear skid marks the tires made just before the roll. Contrast these skid marks with those in Figure 15, from the third rollover, the step steer. In a more typical, more severe roll, the truck "flies" through the air for a short distance, so the striking skid mark is a matter of feet from the pre-crash skid line.

Figure 13. Single-unit truck in the first rollover

Figure 14. Skid marks from the first rollover

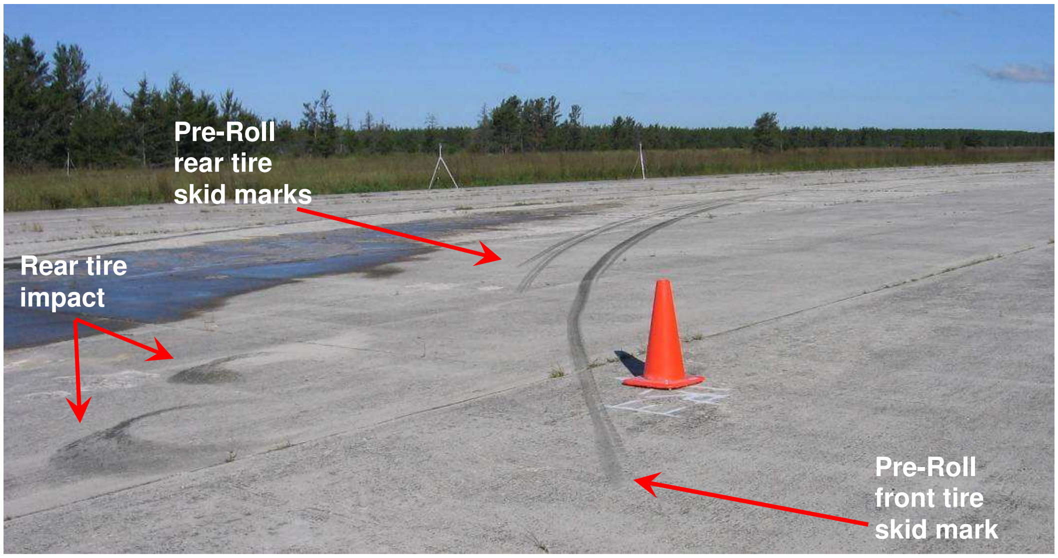


Figure 15. Skid marks from the third rollover

During the third rollover, the truck was momentarily airborne, so the linear skid marks end at the point where the tires left the ground. The marks left by the tires at impact are not complete circles because the truck had a roll angle of more than 90 degrees when it struck. The truck continued along its line of travel as it flew, and without the tires holding it in its curve, it also moved outward from the pre-flight curvature. Thus, the tires' impact marks are downrange and outward from the point where they left the pavement. The cone in Figure 15 marks the expected rollover point. The truck was at a steep roll angle when it passed the cone, so the cone was left standing.

The second rollover was two quarter rolls; that is, the truck came to rest upside down. The remaining three rollovers of the single-unit truck were one quarter roll; in each the truck came to rest on its right side. (As the roll cage is far more rigid than the actual truck, the post-impact motion of the single-unit truck is of little practical significance.) The semitrailer rolled slightly more than 90 degrees, its roll being arrested by the rollover protection devices.

4.0 Results and Comparison with Simulations

This section reviews key points of the NTSB report [2] and the simulation report [3]. It then presents a tabular summary of experimental data and, where appropriate, compares the data with the dynamic simulation results.

4.1 Accidents in the NTSB Report

The NTSB Special Investigation Report reviewed seven cargo tank rollover accidents that released hazardous material [2]. The NTSB chose these seven cases because (a) it was informed of the crash, (b) initial information was that the cargo was released through top fittings damaged by impact, and (c) relevant evidence was not destroyed by fire. These accidents are listed in Table 2.

Table 2. Summary of Accidents Investigated in the NTSB Report

City and Date	Cargo Tank Specification and Material	Vehicle	Cargo	Synopsis
Albuquerque, NM 01/18/91	MC 312 Steel	Semitrailer	4,900 gal. Hydrochloric acid	Accelerated on an exit ramp to avoid collision
Hamilton, OH 01/15/91	MC 306 Steel	Single-unit truck	2,100 gal. No. 2 fuel oil	Failure to control vehicle
Lantana, FL 01/21/91	MC 306 Aluminum	Semitrailer	8,800 gal. Gasoline	Left the right side of the roadway
Ethelsville, AL 04/20/91	MC 306 Aluminum	Semitrailer	7,400 gal. Diesel fuel	Collision with pickup truck
Bronx, NY 04/22/91	MC 306 Steel	Single-unit truck	4,000 gal. Gasoline	Lost control on wet pavement
Edenton, NC 04/22/91	MC 306 Aluminum	Single-unit truck	7,400 gal. Diesel fuel	Went off left side of freeway after driver fell asleep
Columbus, GA 05/02/91	MC 306 Aluminum	Single-unit truck	8,804 gal. Gasoline	Deceleration on a ramp

4.2 Summary of the UMTRI Simulation Study

The UMTRI simulation study [3] comprised two parts. The first was dynamic simulations of heavy truck rollovers in many scenarios; the second part was an analysis of forces on cargo tank deformation. The purpose of the present report is to compare the predictions of the dynamic simulations with experimentally conducted rollovers.

The simulation study included three kinds of vehicles—two- and three-axle Single-unit trucks and five-axle tractor-semitrailer combinations. Each vehicle was simulated in several maneuvers, and some were simulated as carrying different liquid cargoes. The five-axle semitrailers are representative of the cargo tank trailers that were reviewed by the NTSB. Also, the three-axle truck of the simulation study is illustrative of the vehicle of the Bronx, NY, accident and the two-axle truck is illustrative of the vehicle of the Hamilton, OH, accident.

Table 3 summarizes the maneuvers of the simulation study. The four experimental crashes with the Single-unit truck were intended to duplicate the low and moderate speed Intersection Turns, the step turn, and the high-speed avoidance maneuver. The experimental crash with the combination unit vehicle was intended to duplicate the Intersection Turn at high speed.

Table 3. Summary of simulated maneuvers

	Maneuver Type	Curve Radius (ft)	Speeds (MPH)	Impact Angles (Degrees)
Intersection Turn (I-turn)	Closed-loop	100	20, 23, 25, 27, 40, 55	
Highway/Exit-ramp Turn (H-turn)	Closed-loop	500	50, 55, 60, 70	
Curb-strike/Rail-strike (Trip and Rail)	Closed-loop	500	35, 40, 45, 50, 55	5, 10, 20, 30
Curb-strike (Trip-fall)	Closed-loop	500	45	20, 30
Spiral Turn (Spiral)	Open-loop		40	
High-speed Avoidance Maneuver (Swerve)	Open-loop		50	
Step-turn (Step)	Open-loop	(80°, 100° and 120° step changes)	(45, 60, 70), (35, 50, 65), (30, 45, 60)	

Table 4 lists the masses of the simulated vehicles that correspond most closely to the experimental vehicles, and it lists the properties of the experimental vehicles for comparison. The simulated vehicles are identified by the city of the crash in the NTSB report whose vehicle they approximate. The information on the simulated vehicles was taken from Appendix A of the simulation study [3]. The appearance of the Single-unit truck is more like the truck in the Bronx accident because both have three axles, but the tag axle on the experimental truck was not powered. The weight of the experimental truck is much more like that of the truck in the Hamilton accident, so it will be compared with simulations for that one.

Table 4. Summary of vehicle sizes and weights

Property	Single-unit Trucks			Combination Unit Trucks	
	Simulated Bronx (three axles)	Simulated Hamilton (two axles)	Experimental (Two axles plus tag axle)	Simulated Albuquerque	Experimental
Total Laden Weight, lb	50,798	33,760	36,170	76,782	72,000
Laden center of gravity height, in.	50	47	55	56*	76*
Wheelbase, in.	214	189	179†	388*	421*

* of the trailer

† between the steer and drive axles

4.3 Motions Recorded During the Rollover Crashes

Tables 5 and 6 summarize estimates of key dynamic values at the moment of impact. The time histories were filtered somewhat to determine the value at impact. The moment of impact was identified in part by the signals from accelerometers that were rigidly mounted to the vehicle. Appendix A contains plots of recorded data of primary interest. Each plot is presented twice—once for the duration of the entire maneuver and again for the few seconds surrounding the rollover. As noted in Appendix C, the data CD has a database with the raw data.

The angular rotation rates in the table are of the sprung mass center of gravity about the vehicle coordinates. (Coordinate systems are explained in Appendix A.) The column labeled ω_{Xv} is essentially the roll rate at impact.

ω_{Xv}, ω_{Yv}, and ω_{Zv} are the components of the rotational velocity of the vehicle about the respective vehicle axes, X_V, Y_V, and Z_V (See Appendix A).

Shaded cells are values from the simulation study. They represent the simulation cases that roughly correspond to the experimental case above the set of shaded rows.

The Run ID for the experimental runs (unshaded rows) corresponds to the Run ID in Table 1. The Run IDs for the simulated runs (shaded rows) are the run numbers from Appendix B of the simulation report [3]. An S has been added to the simulated run numbers to further distinguish them from the experimental Run ID. The vehicle for the simulated runs identifies the set of properties in the model. “Ham” indicates that the model properties were intended to represent the truck in the Hamilton crash in the NTSB report, and “Alb” indicates the properties represented the Albuquerque crash. The numbers following the city letters indicate that differences in how the roll inertia of the load was handled in the model.

Some signs have been changed from Appendix B because the simulation study used the ISO coordinate system and the experimental study used the SAE coordinate system. In both systems, positive X is forward, but the signs of Y and Z are opposite between the systems. The table is in the SAE system, where positive Y is to the right and positive Z is down.

Table 5. Vehicle orientation and angular and linear velocity components at time of first ground strike for four truck rollovers

	Vehicle	Run ID	Nominal speed mph	Vehicle orientation degrees Roll	Pitch	Yaw	Angular velocity components degrees/second ω_{XV}	ω_{YV}	ω_{ZV}	Linear velocity components at the center of gravity feet/second X	Y	Z
100-ft-radius turn	Unit	105	27		(no rollover)							
	Unit	106	31	90.0	-0.4	-93.0	138.4	-22.8	9.9	31.8	15.1	8.5
	Unit	110	40	92.7	2.2	-45.9	136.5	-34.9	-7.6	46.9	24.9	8.5
	Ham25	S61	25		(no rollover)							
	Ham50	S77	25		(no rollover)							
	Ham25	S62	40	108.8	-1.6	47.7	142.4	41.5	-7.9	49.0	-27.6	-11.9
	Ham50	S78	40	108.0	-1.6	47.9	141.1	41.3	-7.0	48.9	-27.6	-11.9
	Ham25	S63	55	120.4	-2.5	42.8	167.7	45.6	-14.3	66.8	-40.2	-10.8
	Ham50	S79	55	119.1	-2.6	43.0	161.6	45.5	-12.7	66.7	-40.2	-10.9
step	Unit	115	45	91.0	1.2	-47.2	118.7	-21.5	-1.1	56.8	25.9	9.8
Swerve	Unit	126	50	87.8	1.2	-35.3	121.8	-15.9	-1.7	62.3	24.6	8.5
	Ham50	S121	50	103.8	-1.7	21.5	125.3	27.7	-0.2	66.3	-27.6	-12.2
	Ham25	S122	50	104.8	-1.7	21.4	127.7	28.0	-0.9	66.3	-27.6	-12.1

Table 6. Vehicle orientation and angular and linear velocity components at time of first ground strike for tractor semitrailer rollover

	Vehicle	Run ID	Nominal speed mph	Vehicle orientation degrees Roll	Pitch	Yaw	Angular velocity components degrees/second ω_{XV}	ω_{YV}	ω_{ZV}	Linear velocity components at the center of gravity feet/second X	Y	Z
100-ft-radius turn	Semi	151	46	107.8	-0.3	-28.8	141.2	-27.7	30.2	57.4	24.9	8.9
	Alb10	S62	40	110.3	-0.2	36.7	137.7	34.7	-12.9	53.4	-21.0	-17.1
	Alb50	S78	40	109.8	-0.2	37.1	131.1	34.8	-12.3	53.2	-21.1	-17.1
	Alb10	S63	55	118.8	0.1	31.8	162.8	34.8	-19.6	73.5	-29.5	-16.2
	Alb50	S79	55	117.6	-0.1	32.2	154.6	35.2	-18.4	73.3	-29.8	-16.3

The vehicles and maneuvers of the experiments were intended to approximate the simulated conditions as closely as possible, but they could not be exact duplicates of any of the simulated cases. The maneuvers leading to the crashes were selected to approximate the maneuvers that had been simulated in the prior study. Some of the experimental maneuvers were reasonably good matches, but various constraints prevented exact duplicates in all cases. Most notably, the length of the runway, combined with the moderate engine power of the test vehicles, limited the maximum speed for some maneuvers. Also the “step” steer was not an instantaneous step, as was the simulation. The shaded rows in Tables 5 and 6 list the values from some roughly corresponding simulations.

The experimental values certainly confirm the orders of magnitude of the simulations’ results, and most of the end-of-run linear and angular velocities are close to or even within the range calculated by the simulations. Therefore the various values from the simulations, like those from the experiments, are definitely plausible for the range of crashes that can be expected to occur on highways.

5.0 Conclusions

The experiments proceeded almost completely according to the plans. The single-unit truck was rolled over four times, once in a gentle flop and three times in crashes of greater severity. The combination unit truck was rolled once in a deliberately aggressive crash. Motion data for the crash vehicle was recorded in all cases, and videotape was recorded from several vantage points on and off the vehicle. Deformation of the tank and the rollover protection devices was recorded during the semitrailer crash.

The project team was fortunate in that it was able to obtain two vehicles that were similar, though not identical, to two in the simulation study [3]. Some of the crash maneuvers were quite close to maneuvers in the simulation study. Various practical constraints, including the length of the runway, prevented other maneuvers from matching the simulations as closely. All maneuvers do represent plausible highway driving conditions. The experimentally measured values compared well with the results of the dynamic simulations. The simulations’ order of magnitude was certainly corroborated. The experimentally measured roll rates at the moment of impact were very much within the range of those calculated during the simulations for the corresponding maneuvers and vehicles. The vertical velocity of the center of gravity at the moment of impact was consistently measured to be a lower value than had been calculated in the simulation.

The goal of this research was to quantify the conditions under which rollover protection devices must function. There is no one kind of rollover crash, so a variety of rollovers were conducted to provide a diverse range of measurements. As with the simulation study, the distribution of values was not intended to be representative of the distribution in actual crashes. They do, however, provide quantitative guidance as to the needs imposed on rollover protection devices in actual crashes.

6.0 References

[1] Accident damage protection. 49 CFR 178.345-8(c).

[2] "Cargo Tank Rollover Protection," National Transportation Safety Board, Special Investigation Report, February 4, 1992. SIR-92/01. NTIS Report Number PB92-917002.

[3] "The Dynamics of Tank-Vehicle Rollover and the Implications for Rollover-Protection Devices," University of Michigan Transportation Research Institute. Contract No. DTFH61-96-C-00038, Task Order #1. November 1998. NTIS Report Number PB2001-102262. UMTRI Report Number 98-53. Available online as http://www.fmcsa.dot.gov/pdfs/umtrireport.pdf.

[4] "Hazardous Materials: Cargo Tank Rollover Protection Requirements." Federal Register 64(220):62161-62162. November 16, 1999. The notice and the public comments are online at http://dms.dot.gov/search/ with docket number 5921.

[5] Doug Pape and Jason Holdridge, "The Dynamics of previously conducted full-scale heavy vehicle rollover crashes." Task Report for Contract Number DTMC75-01-D-00003/REQ NO. M3310-042/TON 01. July 23, 2002.

[6] Douglas B. Pape and Jason Holdridge, "The Dynamics of previously conducted full-scale heavy vehicle rollover crashes." SAE Technical Paper 2003-01-3384, November 2003.

Appendix A Time histories of truck motion

The figures in this appendix show the motion of the vehicles as they proceeded toward their rollover maneuver. Figures on an expanded time scale show the rollover itself. An Access database containing the raw data recordings is on one of the CDs attached to this report. The table appearing before the plots identifies the fields in the database.

The vehicles' motions were determined by the inertial navigation system, which was located at the "reference" points shown in Figures 3 and 6 above. This system outputs a variety of motion variables, some in an axis system oriented to the compass (e.g., latitude, longitude, altitude, heading, north velocity, east velocity, etc.) and some in a coordinate system fixed in the unit, and therefore in the vehicle (e.g., three rotational velocities and three linear accelerations). Additionally, many motion variables were transformed (either in real time on the vehicle or in post processing) into a "local" earth-fixed coordinate system whose origin was at the starting position of the test run and whose X_E axis was oriented along the direction of the test runway, or into the so-called intermediate axis system that moves horizontally with the vehicle but otherwise retains a vertical orientation. In some cases motions determined by the unit at the reference point were used to calculate motions at other points in the vehicle. All the plots here are for motions at the reference point.

The following text and figures explain the relationships between the vehicle, intermediate and earth axis systems, and also defines the vehicle's Euler angles—yaw, pitch, and roll. These axis systems and angles are all in accordance with their definitions according to SAE J670, *Vehicle Dynamics Terminology.*

The vehicle axis system (X_V, Y_V, Z_V) is fixed in, and moves with, the vehicle. Relative to the normal, rest position of the vehicle, the X_V direction is forward, the Y_V direction is to the right and the Z_V direction is downward. The GPS/inertial measurement system is fixed in the vehicle and is therefore fixed in the vehicle axis system. The reference point or measurement point is the origin of the measurement system.

The intermediate axis system (X, Y, Z) has its X and Y axis in the horizontal plane (approximately the ground plane) and its Z axis is vertical. The X-Y axes rotate with the vehicle such that the X axis is the vertical projection of the X_V axis in the horizontal plane.

The earth axis system (X_E, Y_E, Z_E) is a stationary axis system with X_E and Y_E axes in the horizontal plane and Z_E axis vertical. The X_E direction is fixed and is the initial direction of travel of the vehicle at the beginning of the test run. That is, in these data, X_E is along the direction of the runway and Y_E is crosswise to the runway.

The vehicle's Euler angles, yaw, pitch, and roll, identify the vehicle's angular orientation in the earth axis system:

Table A-1. Orders of Rotation

Order of rotation	Angle produced by rotation	Nature of rotation
First Rotation	Yaw (ψ)	X_E axis to the X axis about the Z_E axis
Second Rotation	Pitch (θ)	X axis to the X_V axis about the Y axis
Third Rotation	Roll (ϕ)	Y axis to the Y_V axis about the X_V axis

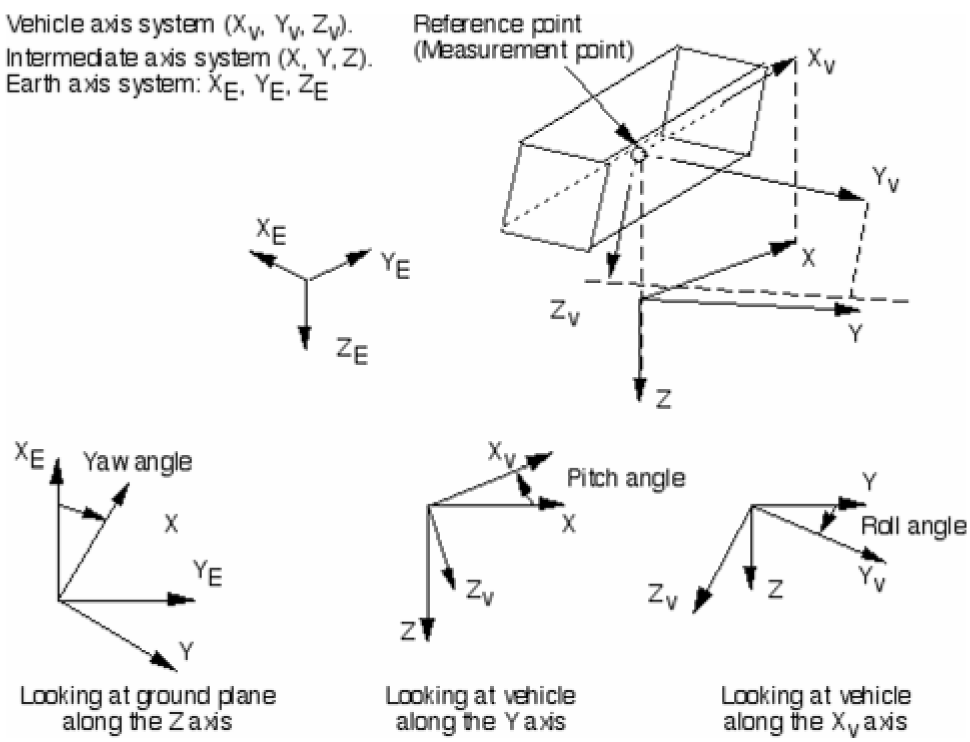


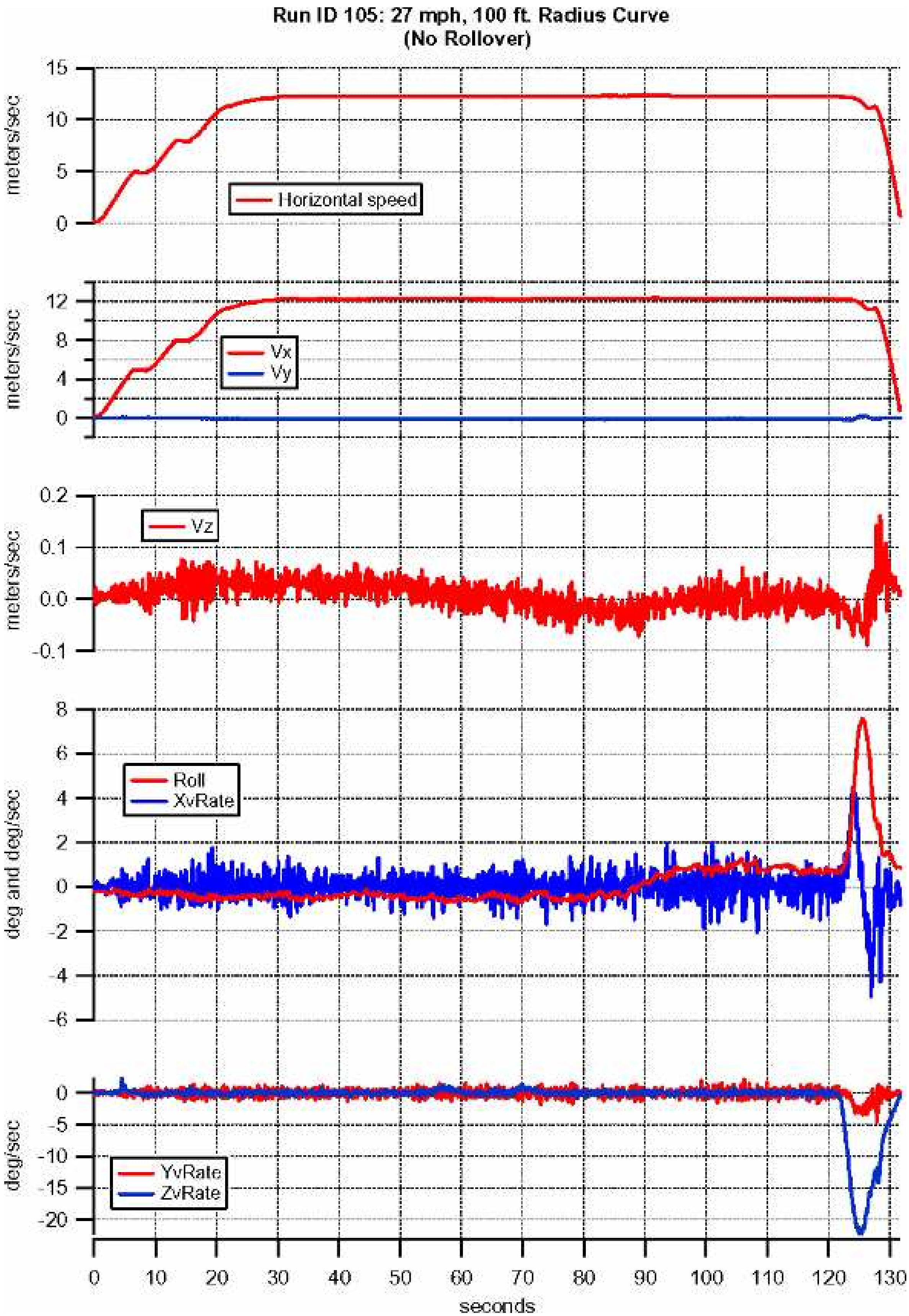
Figure A-1. Earth, intermediate, and vehicle axis systems and yaw, pitch, and roll angles

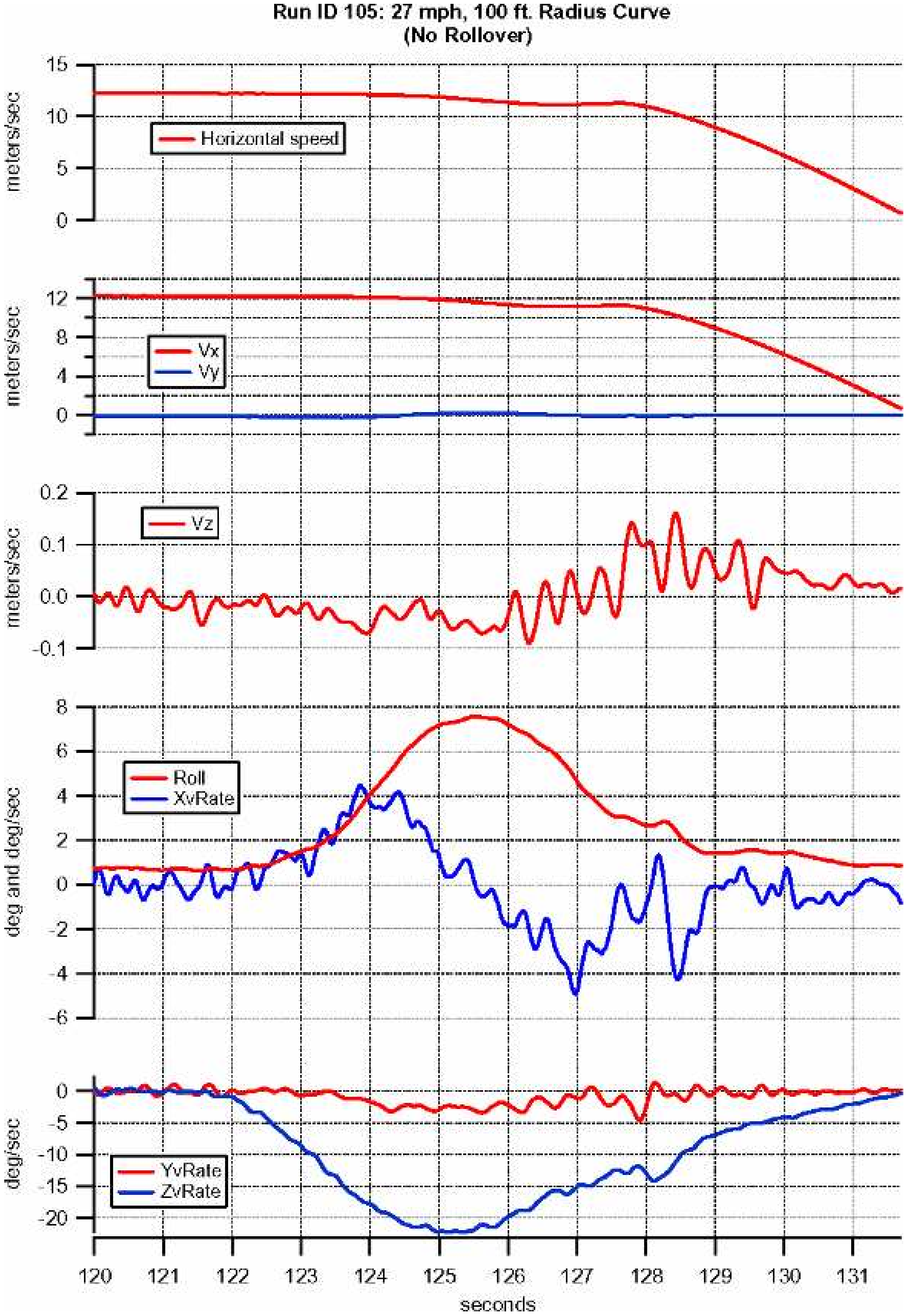
The table on the following page defines the fields in the database with the raw data. The database itself is on one of the CDs attached to this report, as described in Appendix C. The following figures are the time histories representing the truck's motion as recorded by the inertial navigation system.

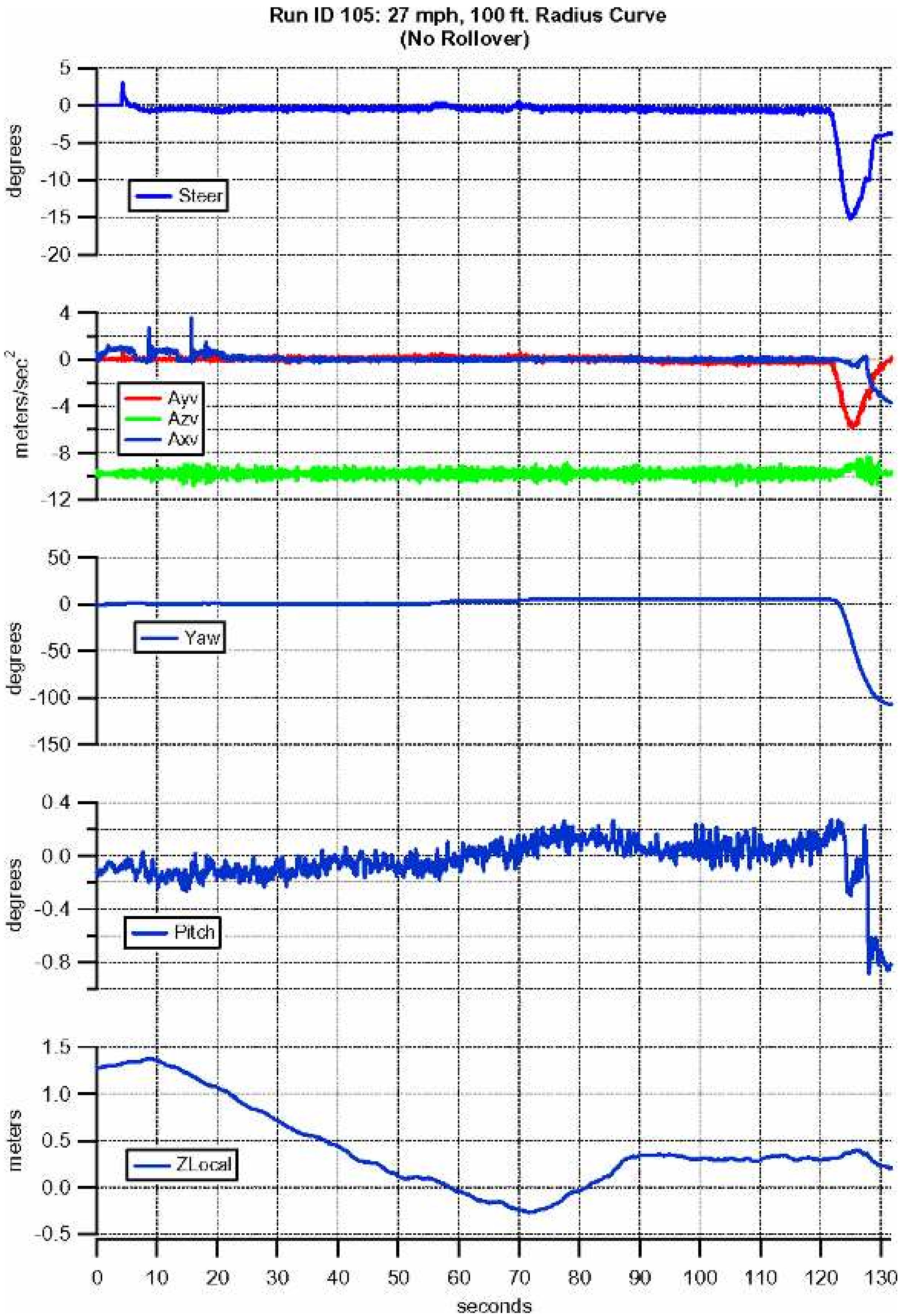
Channel Definitions

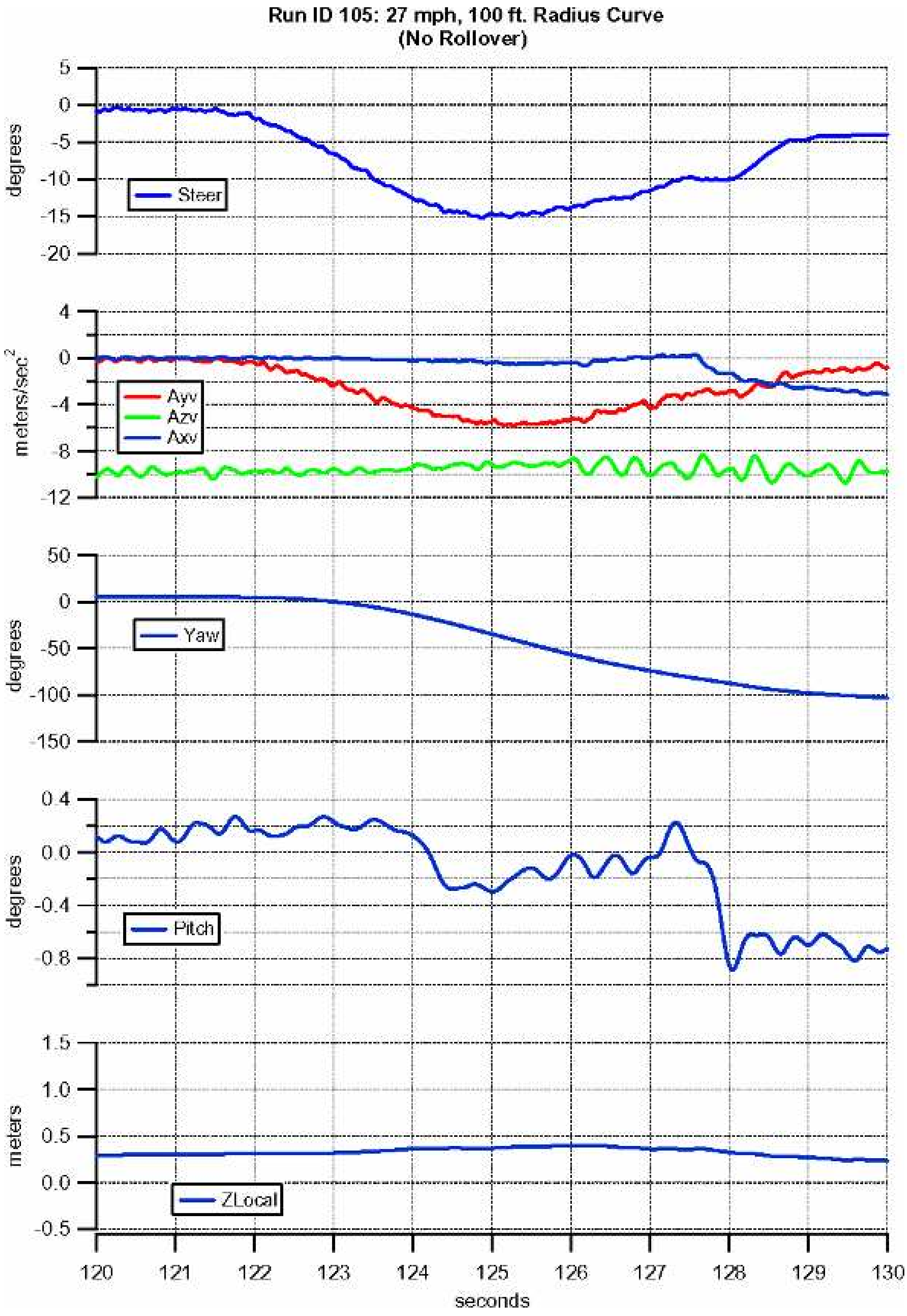
Name	Table	Type	Units	Desc
PathId	TestDef and PathF	Long Integer	none	Unique identification number
Path_X	PathPts	Single Float	m	X coordinate of the target path (earth axis system)
Path_Y	PathPts	Single Float	m	Y coordinate of the target path (earth axis system)
PathName	TestDef	Text		Description of path
VehicleType	TestDef	Text		Description of the vehicle
RunId	INS_Data, Tractor	Long Integer	none	Unique identification number
TestTime	INS_Data and Tra	Long Integer	msec	Time in milliseconds since DAS started
Latitude	INS_Data	Double Float	deg	Latitude from GPS
Longitude	INS_Data	Double Float	deg	Longitude from GPS
Axv	INS_Data	Single Float	m/sec2	Xv acceleration from INS (vehicle axis system)
Ayv	INS_Data	Single Float	m/sec2	Yv acceleration from INS (vehicle axis system)
Azv	INS_Data	Single Float	m/sec2	Zv acceleration from INS (vehicle axis system)
XvRate	INS_Data	Single Float	deg/sec	Xv angular rate from INS (vehicle axis system)
YvRate	INS_Data	Single Float	deg/sec	Yv angular rate from INS (vehicle axis system)
ZvRate	INS_Data	Single Float	deg/sec	Zv angular rate from INS (vehicle axis system)
XLocal	INS_Data	Single Float	m	Local coordinates XE value (earth axis system)
YLocal	INS_Data	Single Float	m	Local coordinates YE value (earth axis system)
ZLocal	INS_Data	Single Float	m	Local coordinates ZE value (earth axis system)
XVelocity	INS_Data	Single Float	m/sec	Xv Velocity (vehicle axis system)
YVelocity	INS_Data	Single Float	m/sec	Yv Velocity (vehicle axis system)
EastVelocity	INS_Data	Single Float	m/sec	North Velocity from INS
NorthVelocity	INS_Data	Single Float	m/sec	East Velocity from INS
DownVelocity	INS_Data	Single Float	m/sec	Down Velocity from INS (earth axis system)
Heading	INS_Data	Single Float	deg	Heading from GPS
Pitch	INS_Data	Single Float	deg	Pitch angle from INS, SAE definition
Roll	INS_Data	Single Float	deg	Roll angle from INS, SAE definition
Yaw	INS_Data	Single Float	deg	Vehicle Yaw angle, SAE definition
Steer	INS_Data	Single Float	deg	Front wheel steer angle
AxTank	INS_Data	Single Float	g's	Xv accelerometer on tank (vehicle axis system)
AyTank	INS_Data	Single Float	g's	Yv accelerometer on tank (vehicle axis system)
AzTank	INS_Data	Single Float	g's	Zv accelerometer on tank (vehicle axis system)
Vh	INS_Data	Single Float	m/sec	Horizontal speed (intermediate axis system)
TractorX	Tractor_Data	Single Float	m	Tractor CG local coordinates X value (earth axis system)
TractorY	Tractor_Data	Single Float	m	Tractor CG local coordinates Y value (earth axis system)
TractorXVelocity	Tractor_Data	Single Float	m/sec	Tractor CG Xv Velocity (vehicle axis system)
TractorYVelocity	Tractor_Data	Single Float	m/sec	Tractor CG Yv Velocity (vehicle axis system)
TractorYaw	Tractor_Data	Single Float	deg	Tractor Yaw angle, SAE definition
TractorYawRate	Tractor_Data	Single Float	deg/sec	Tractor Yaw rate (vehicle axis system)
Articulation angle	Tractor_Data	Single Float	deg	Articulation angle

Note: Access Database contains data from the INS unit (Inertial Navigation System) and not the strike point(s) or sprung mass CG

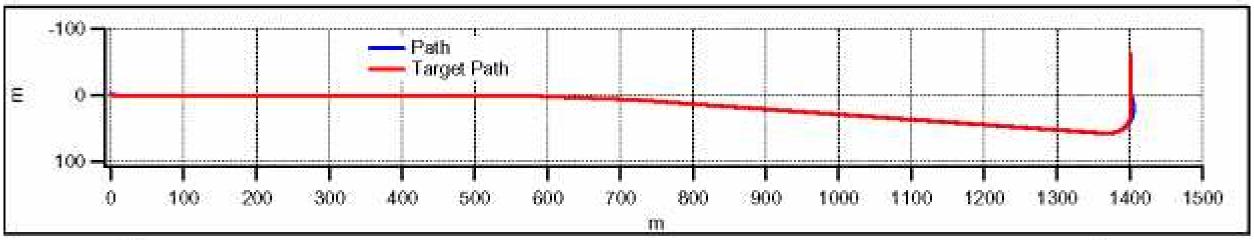

Run ID 105: 27 mph, 100 ft. Radius Curve
(No Rollover)
meters/sec
Horizontal speed
Vx
Vy
Vz
deg and deg/sec
Roll
XvRate
deg/sec
YvRate
ZvRate
seconds

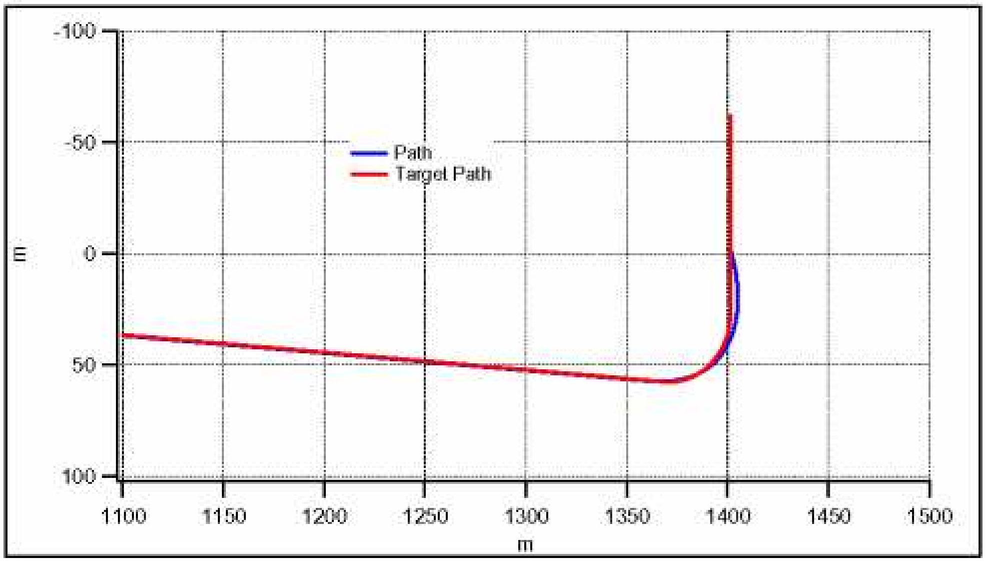

Run ID 105: 27 mph, 100 ft. Radius Curve
(No Rollover)
meters/sec
Horizontal speed
meters/sec
Vx
Vy
meters/sec
Vz
deg and deg/sec
Roll
XvRate
deg/sec
YvRate
ZvRate
seconds

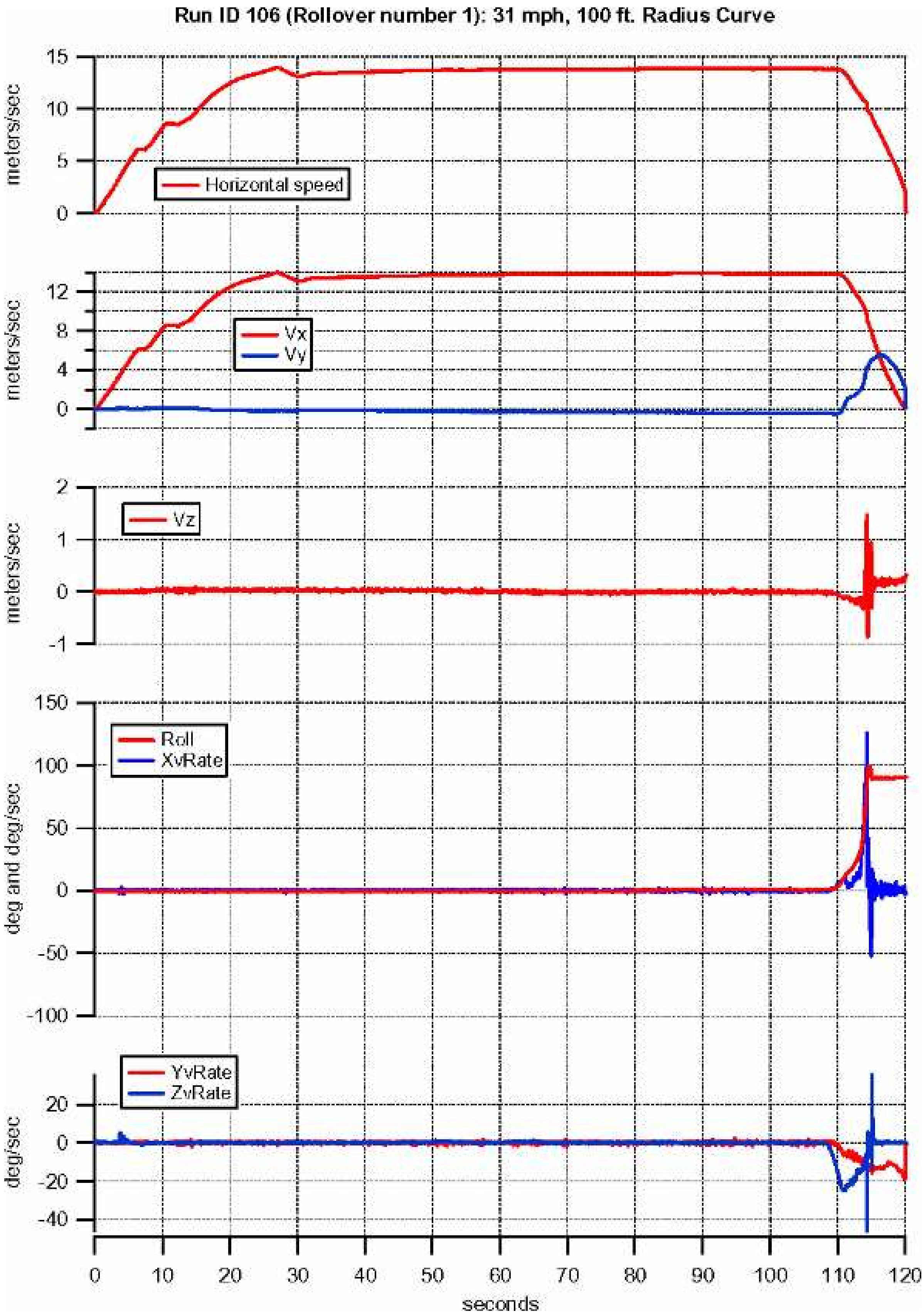

Run ID 105: 27 mph, 100 ft. Radius Curve
(No Rollover)
Steer
degrees
Ayv
Azv
Axv
meters/sec²
Yaw
degrees
Pitch
degrees
ZLocal
meters
seconds


Run ID 105: 27 mph, 100 ft. Radius Curve
(No Rollover)
degrees
Steer
meters/sec²
Ayv
Azv
Axv
degrees
Yaw
degrees
Pitch
meters
ZLocal
seconds

Run ID 105: 27 mph, 100 ft. Radius Curve
(No Rollover)

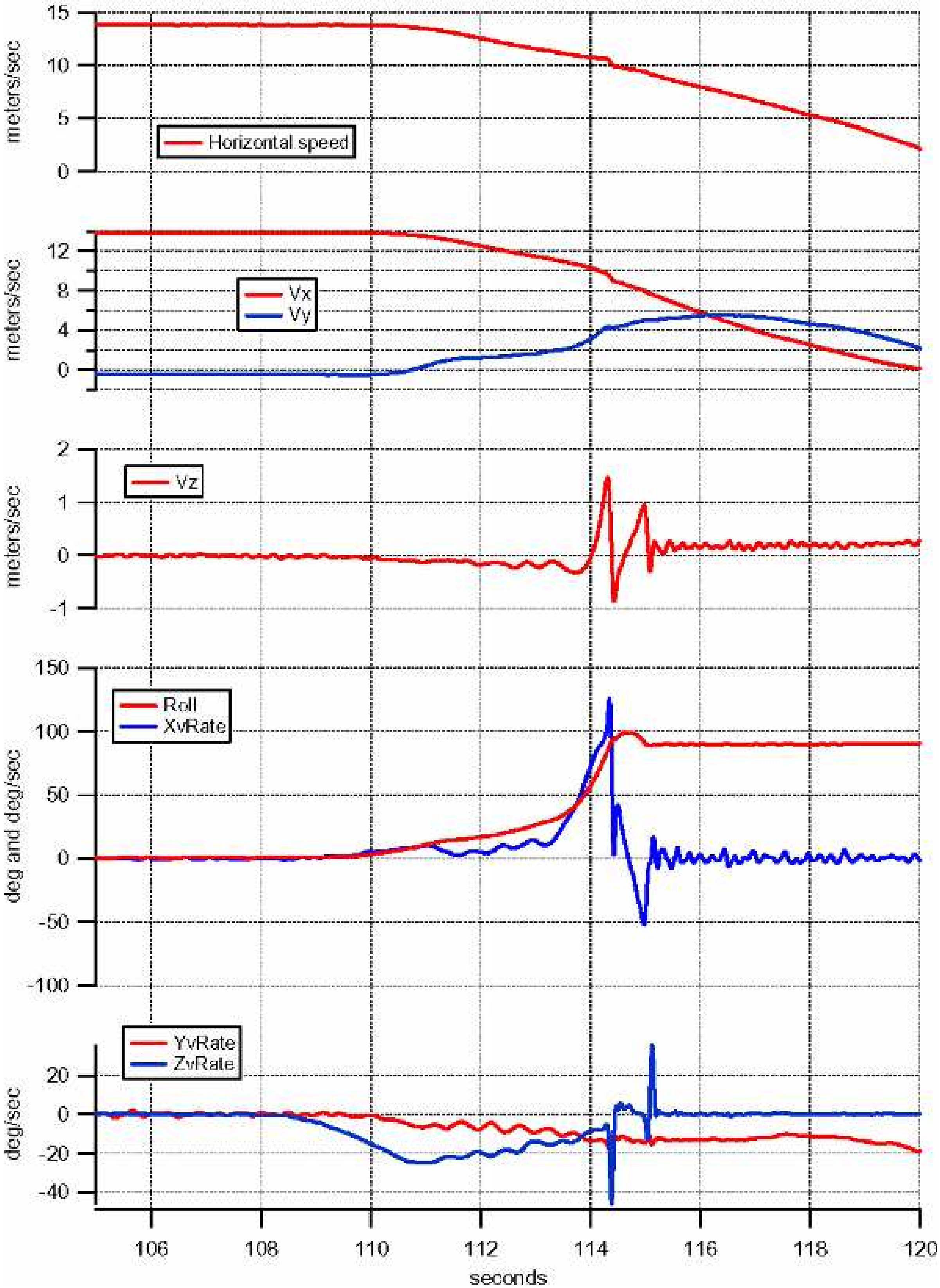


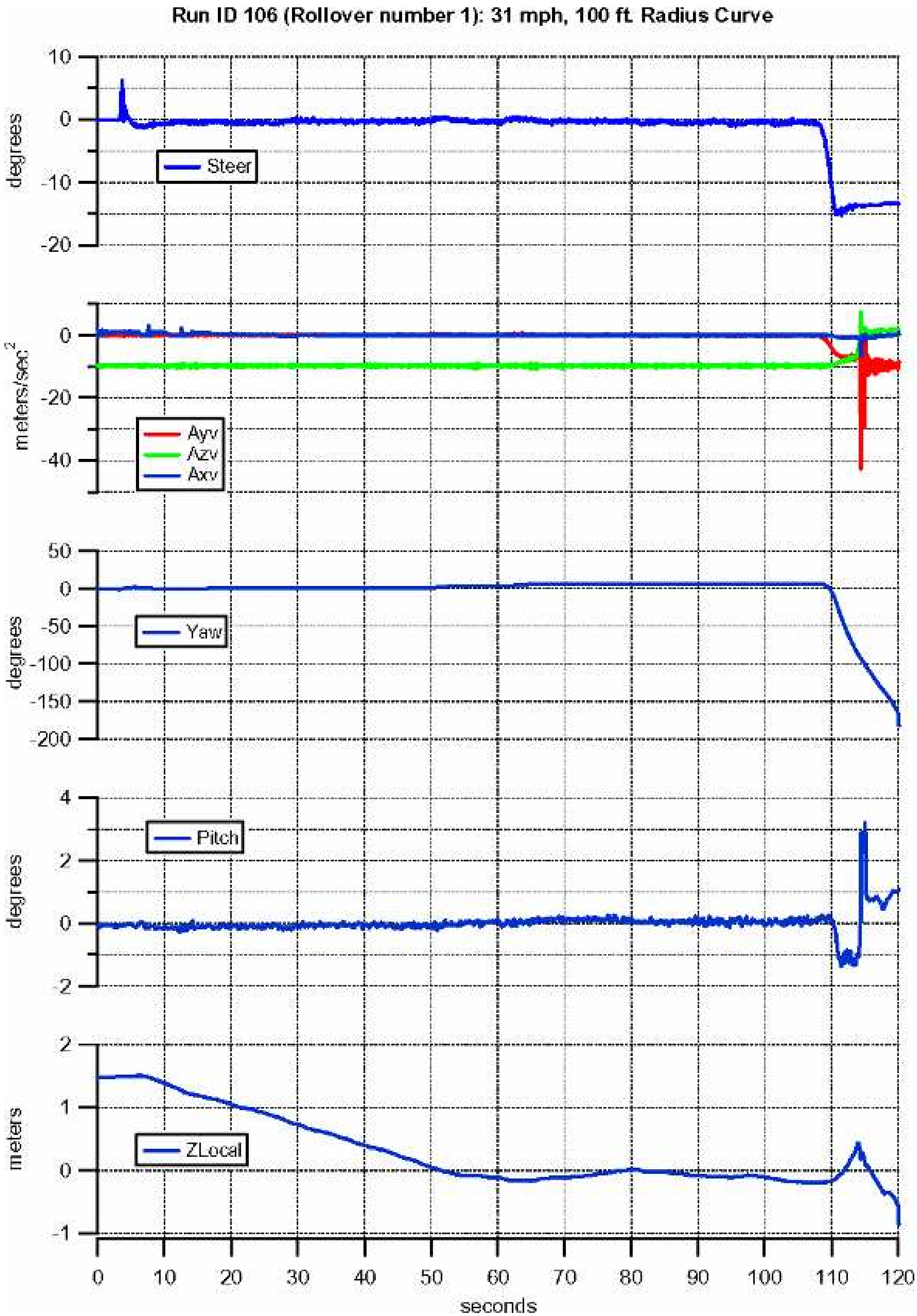




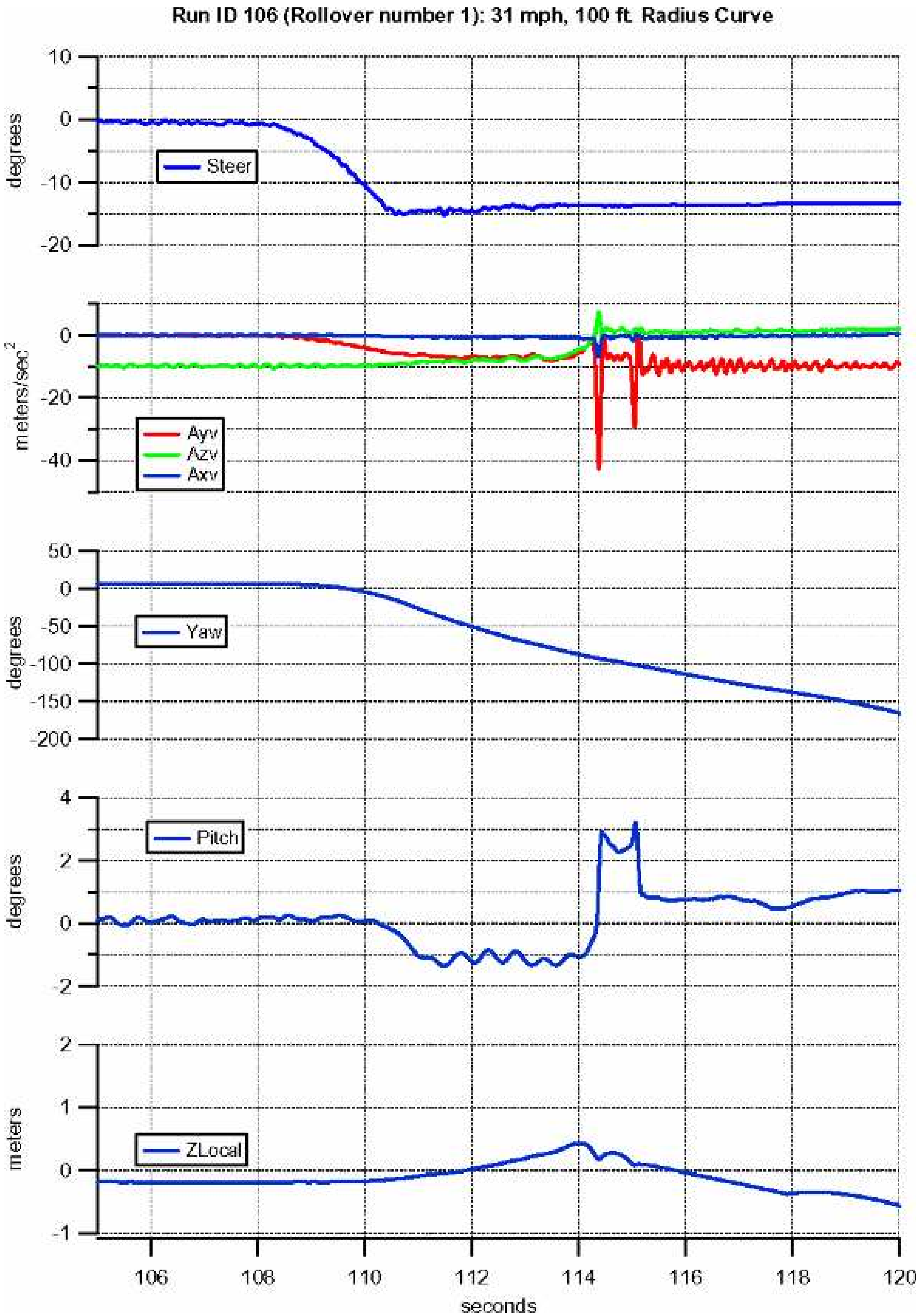
Run ID 106 (Rollover number 1): 31 mph, 100 ft. Radius Curve
meters/sec
Horizontal speed
Vx
Vy
Vz
Roll
XvRate
deg and deg/sec
YvRate
ZvRate
deg/sec
seconds

Run ID 106 (Rollover number 1): 31 mph, 100 ft. Radius Curve

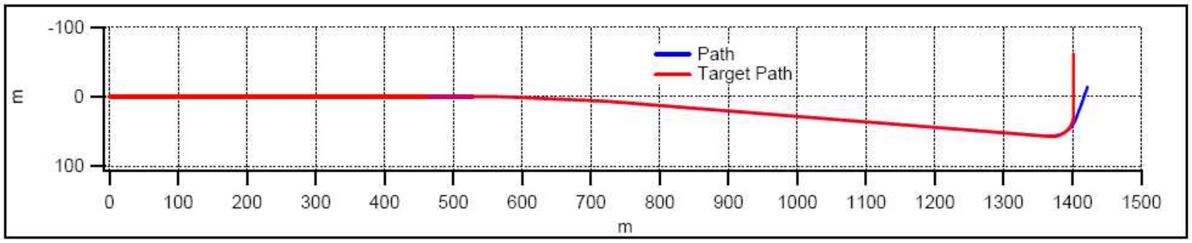


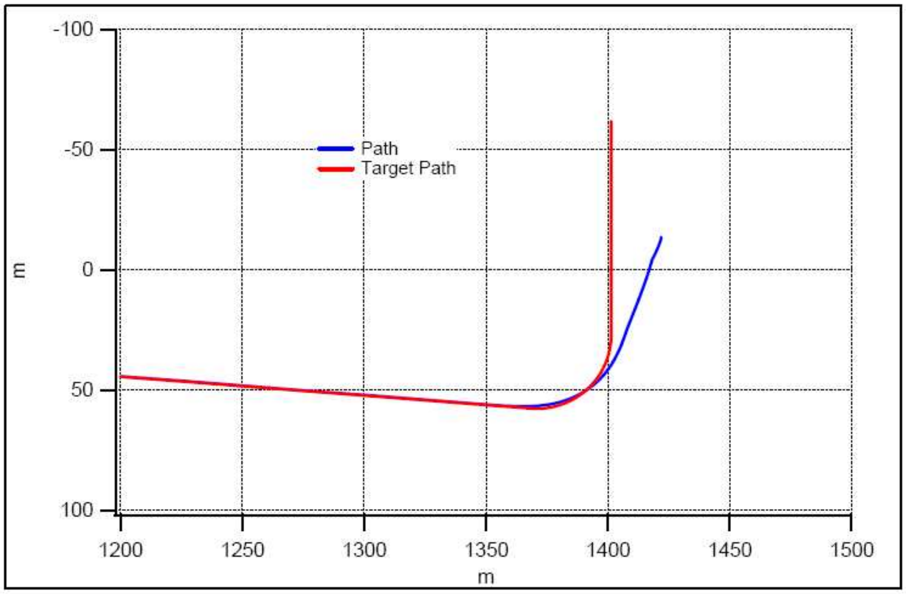


Run ID 106 (Rollover number 1): 31 mph, 100 ft. Radius Curve
degrees
Steer
10
0
-10
-20
meters/sec^2
Ayv
Azv
Axv
0
-20
-40
degrees
Yaw
50
0
-50
-100
-150
-200
degrees
Pitch
4
2
0
-2
meters
ZLocal
2
1
0
-1
0
10
20
30
40
50
60
70
80
90
100
110
120
seconds

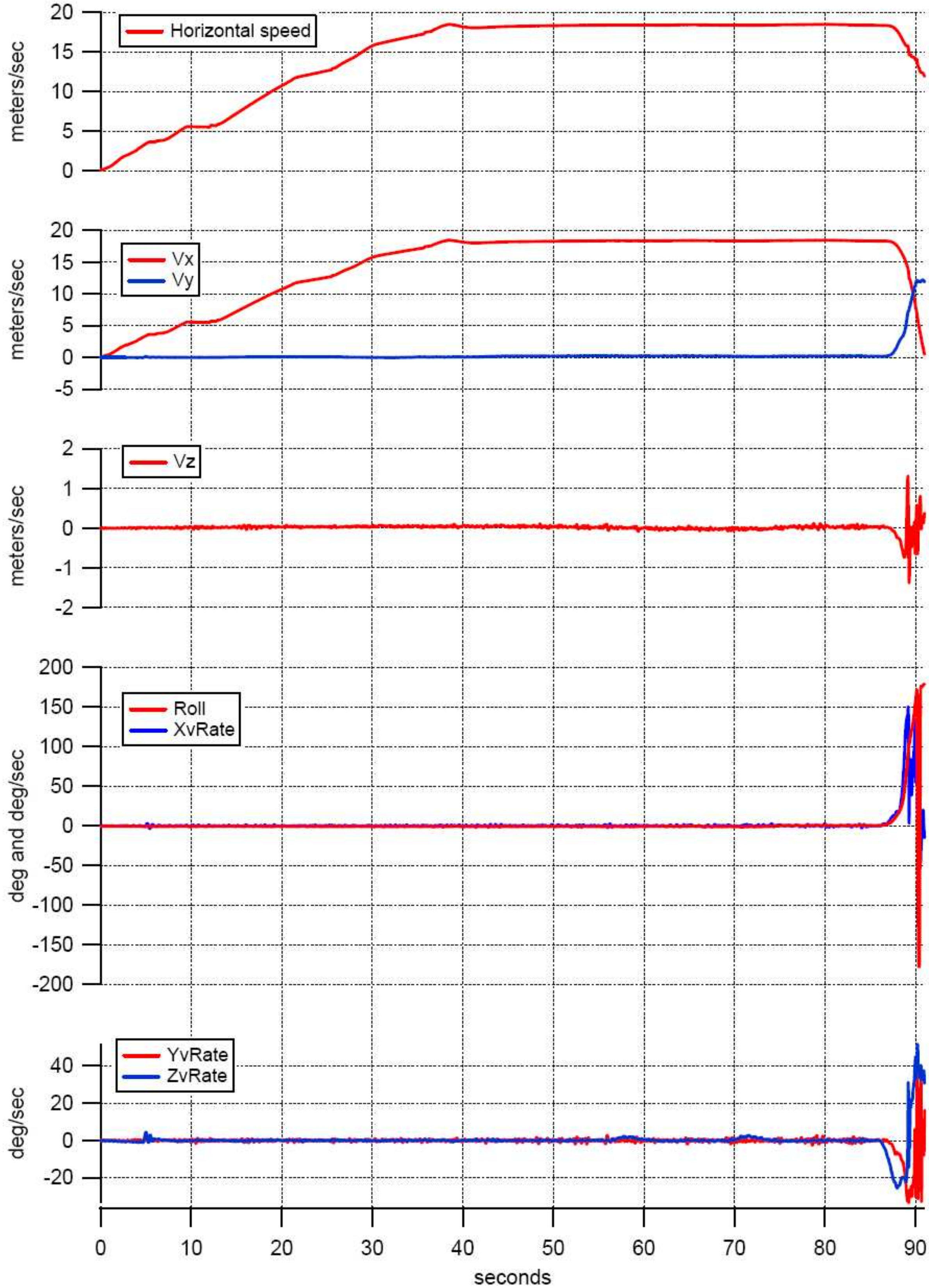

Run ID 106 (Rollover number 1): 31 mph, 100 ft. Radius Curve
degrees
Steer
meters/sec²
Ayv
Azv
Axv
degrees
Yaw
degrees
Pitch
meters
ZLocal
seconds

Run ID 106 (Rollover number 1): 31 mph, 100 ft. Radius Curve

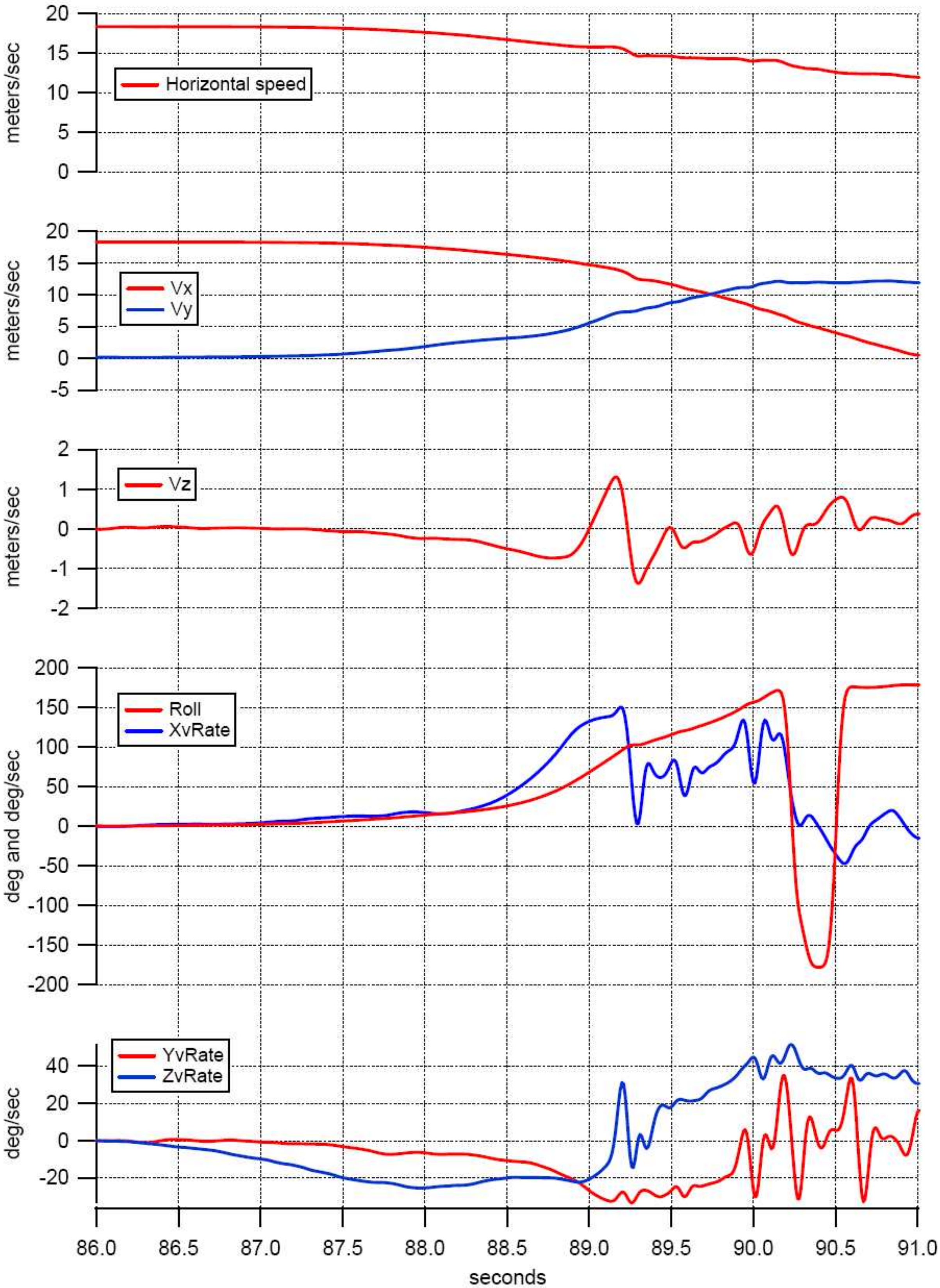




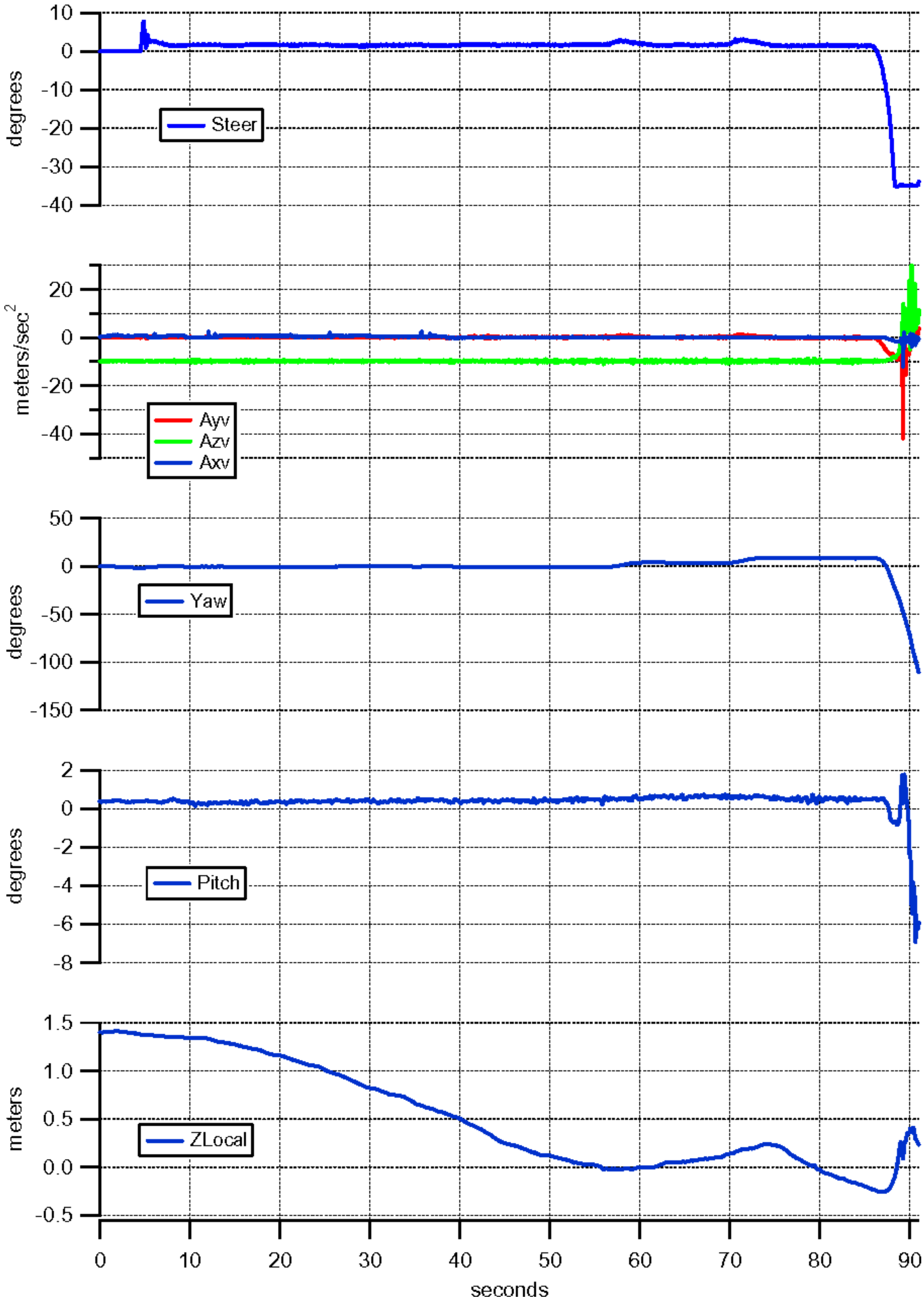
Run ID 110 (Rollover number 2): 40 mph, 100 ft. Radius Curve



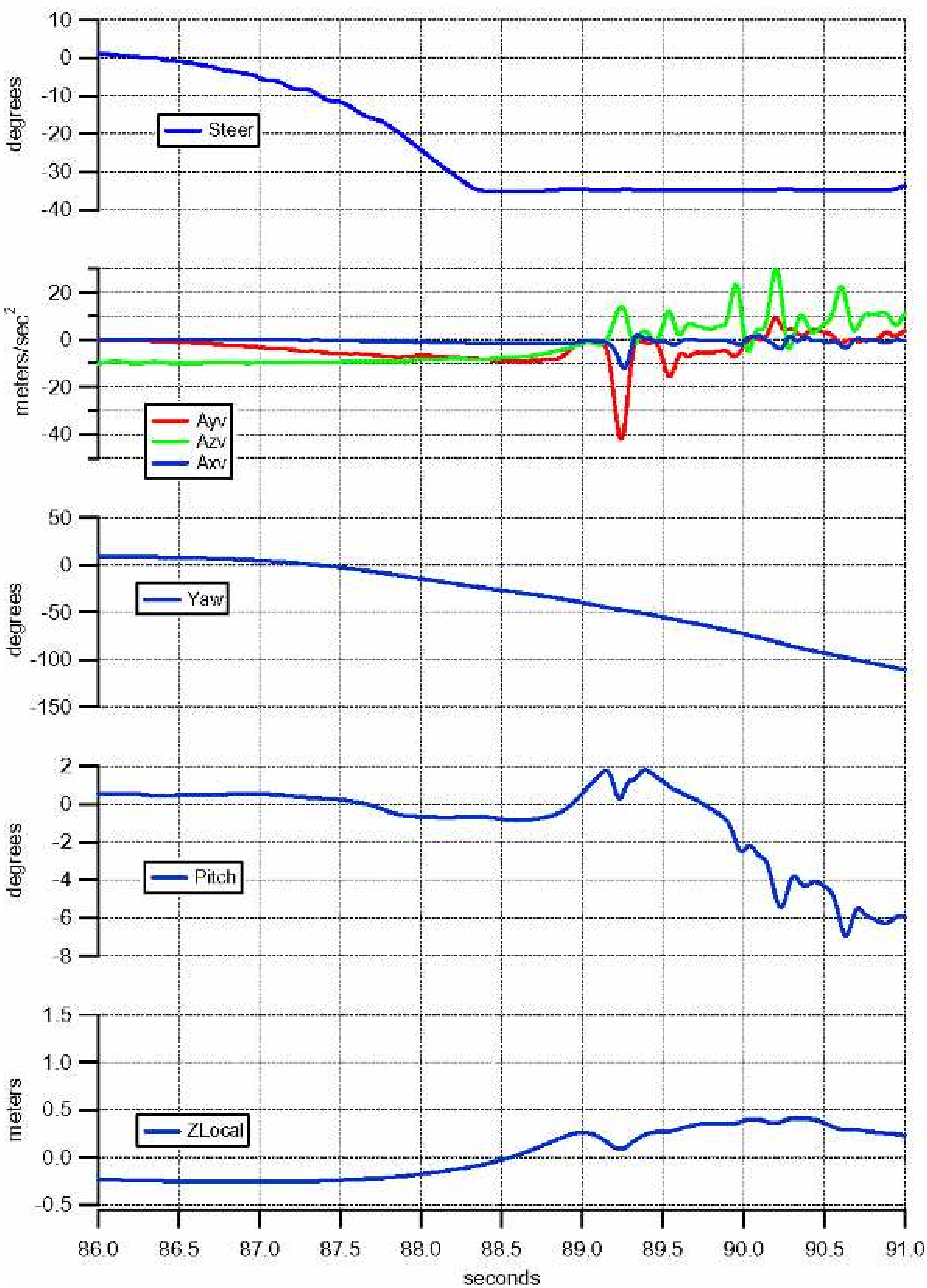
Run ID 110 (Rollover number 2): 40 mph, 100 ft. Radius Curve



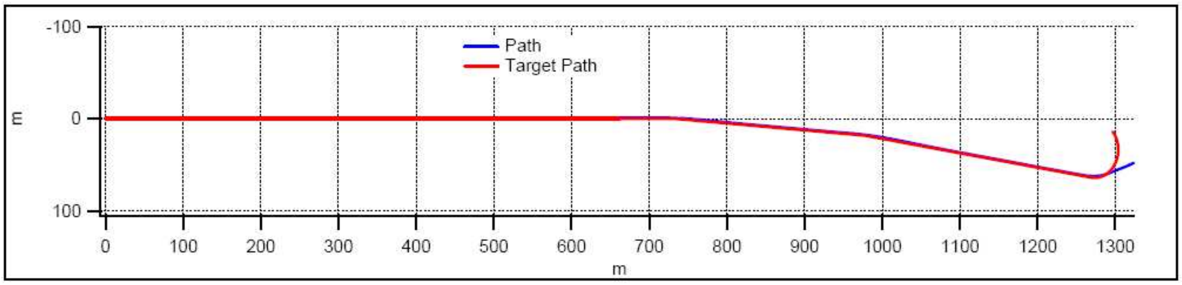
Run ID 110 (Rollover number 2): 40 mph, 100 ft. Radius Curve

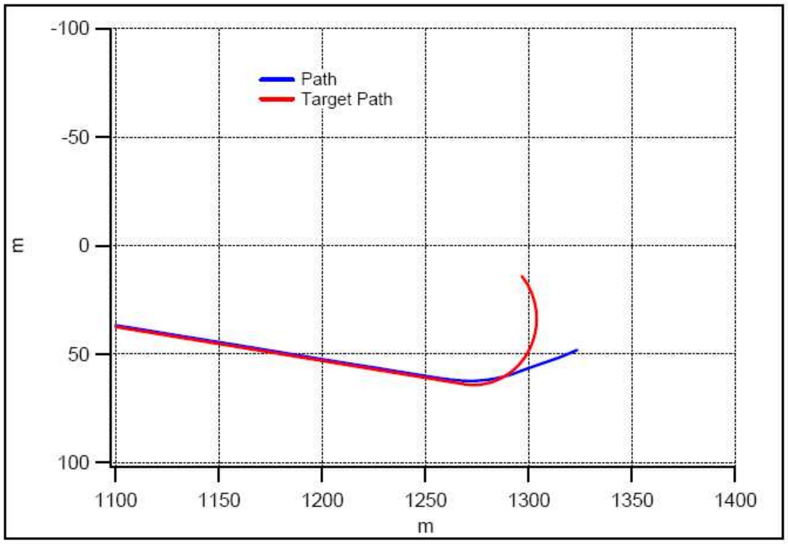


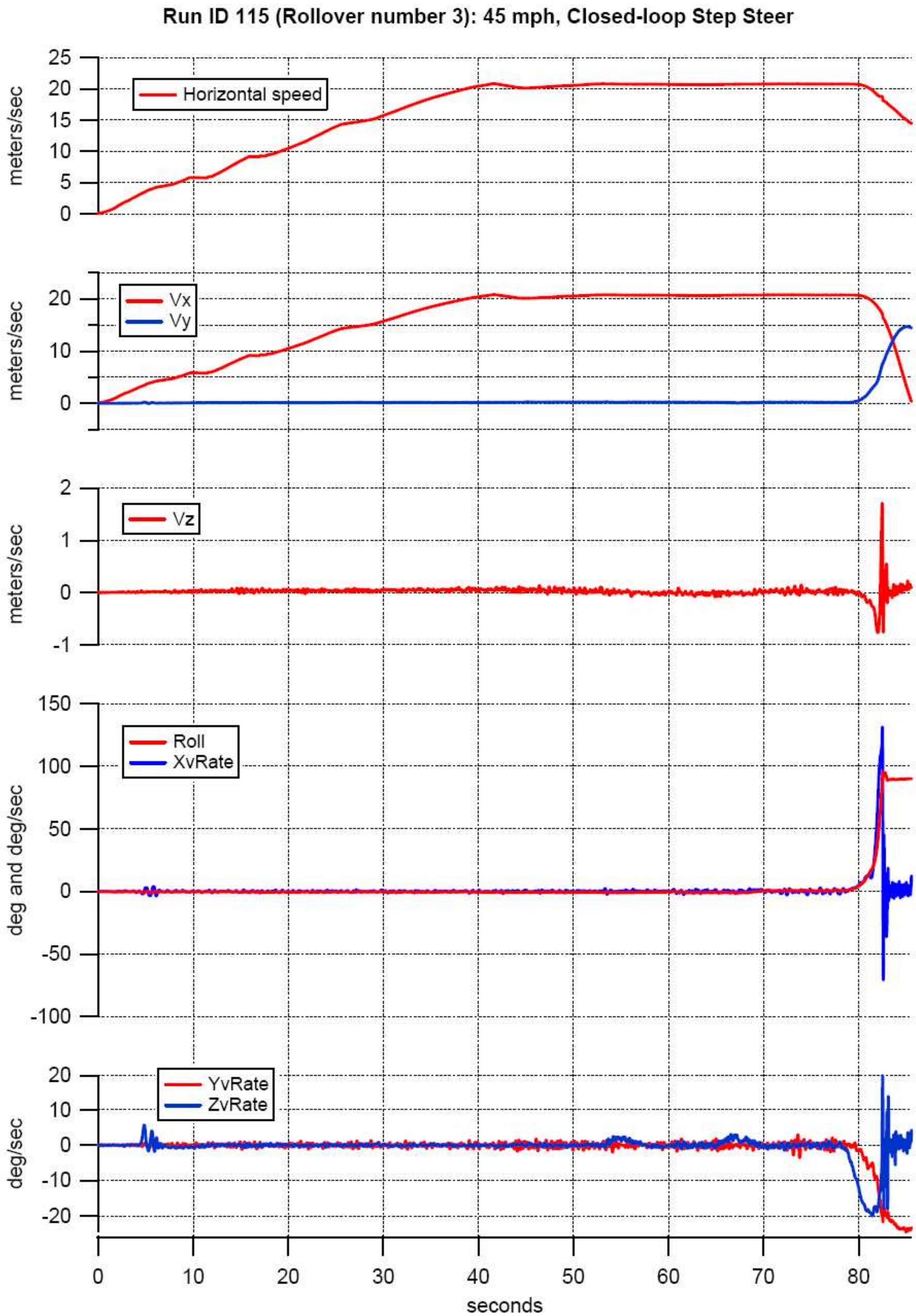
Run ID 110 (Rollover number 2): 40 mph, 100 ft. Radius Curve



Run ID 110 (Rollover number 2): 40 mph, 100 ft. Radius Curve

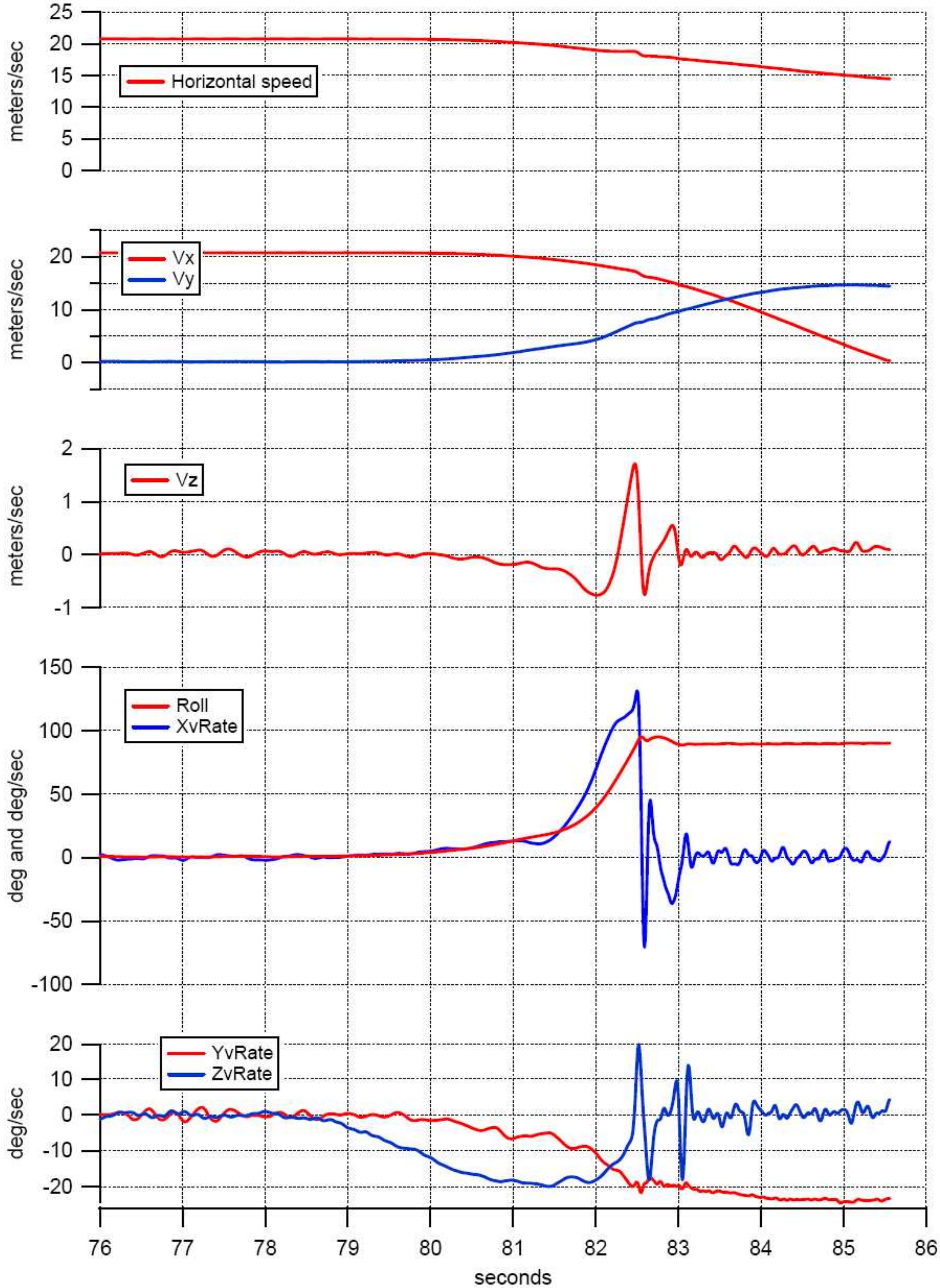




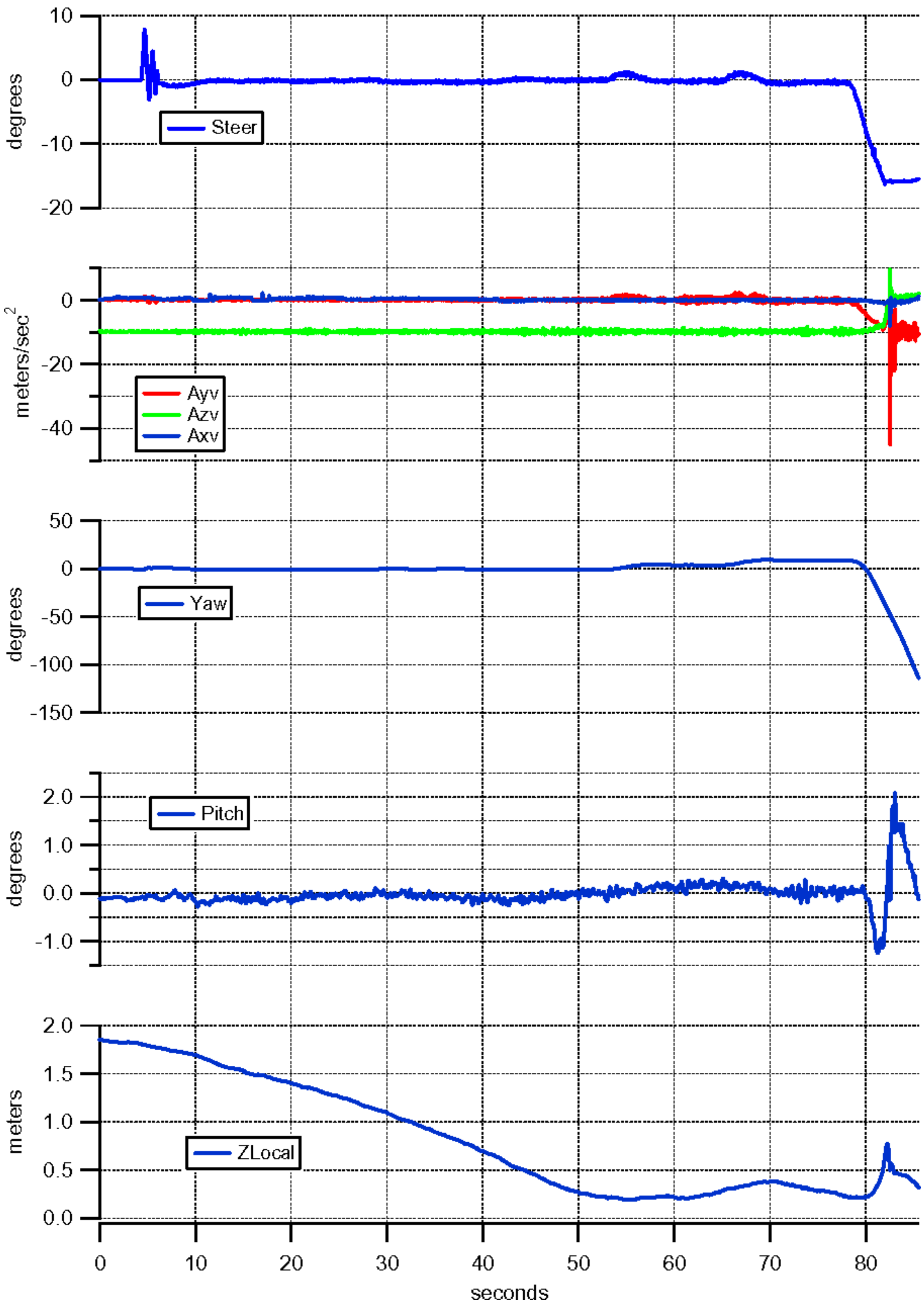


Run ID 115 (Rollover number 3): 45 mph, Closed-loop Step Steer
Horizontal speed
meters/sec
Vx
Vy
meters/sec
Vz
meters/sec
Roll
XvRate
deg and deg/sec
YvRate
ZvRate
deg/sec
seconds

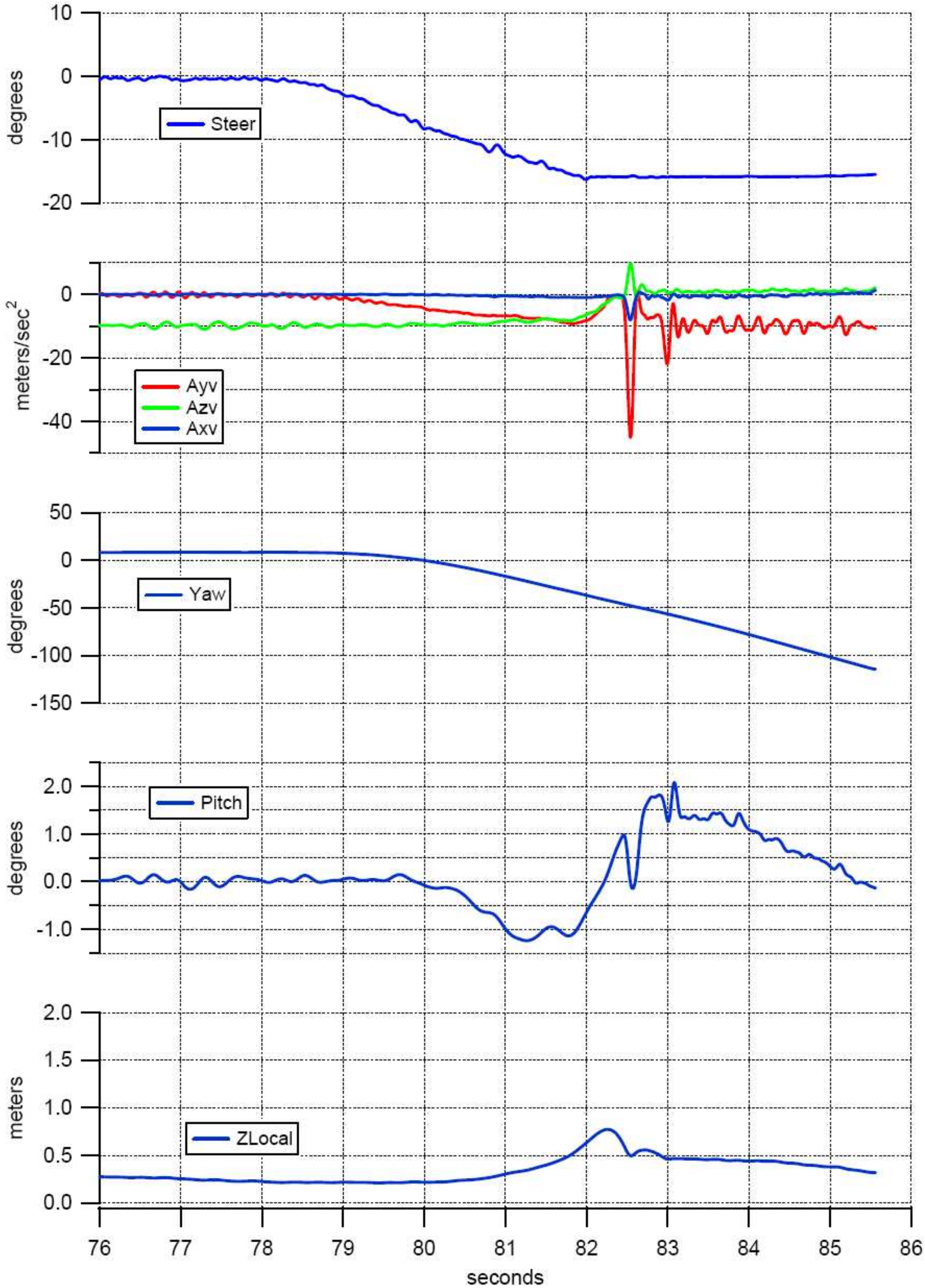
Run ID 115 (Rollover number 3): 45 mph, Closed-loop Step Steer



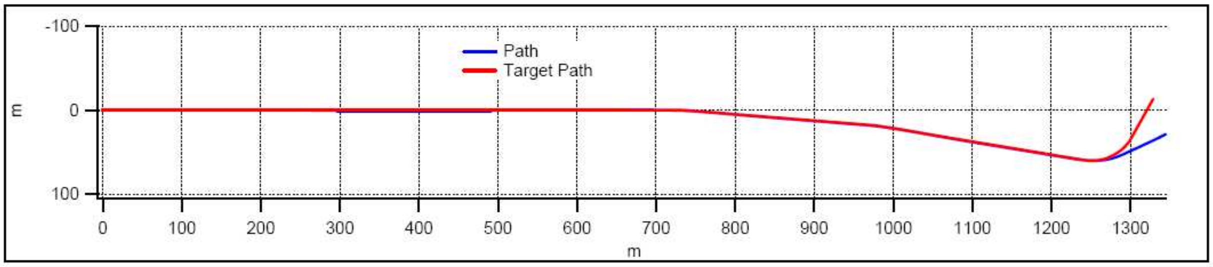
Run ID 115 (Rollover number 3): 45 mph, Closed-loop Step Steer

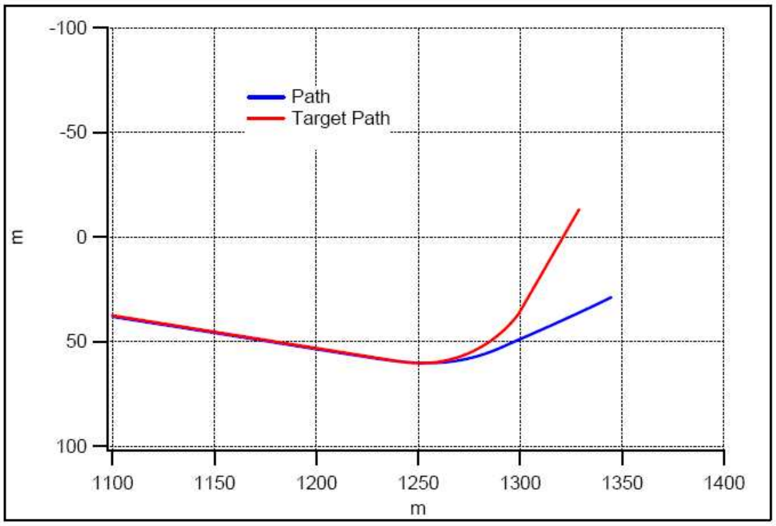


Run ID 115 (Rollover number 3): 45 mph, Closed-loop Step Steer

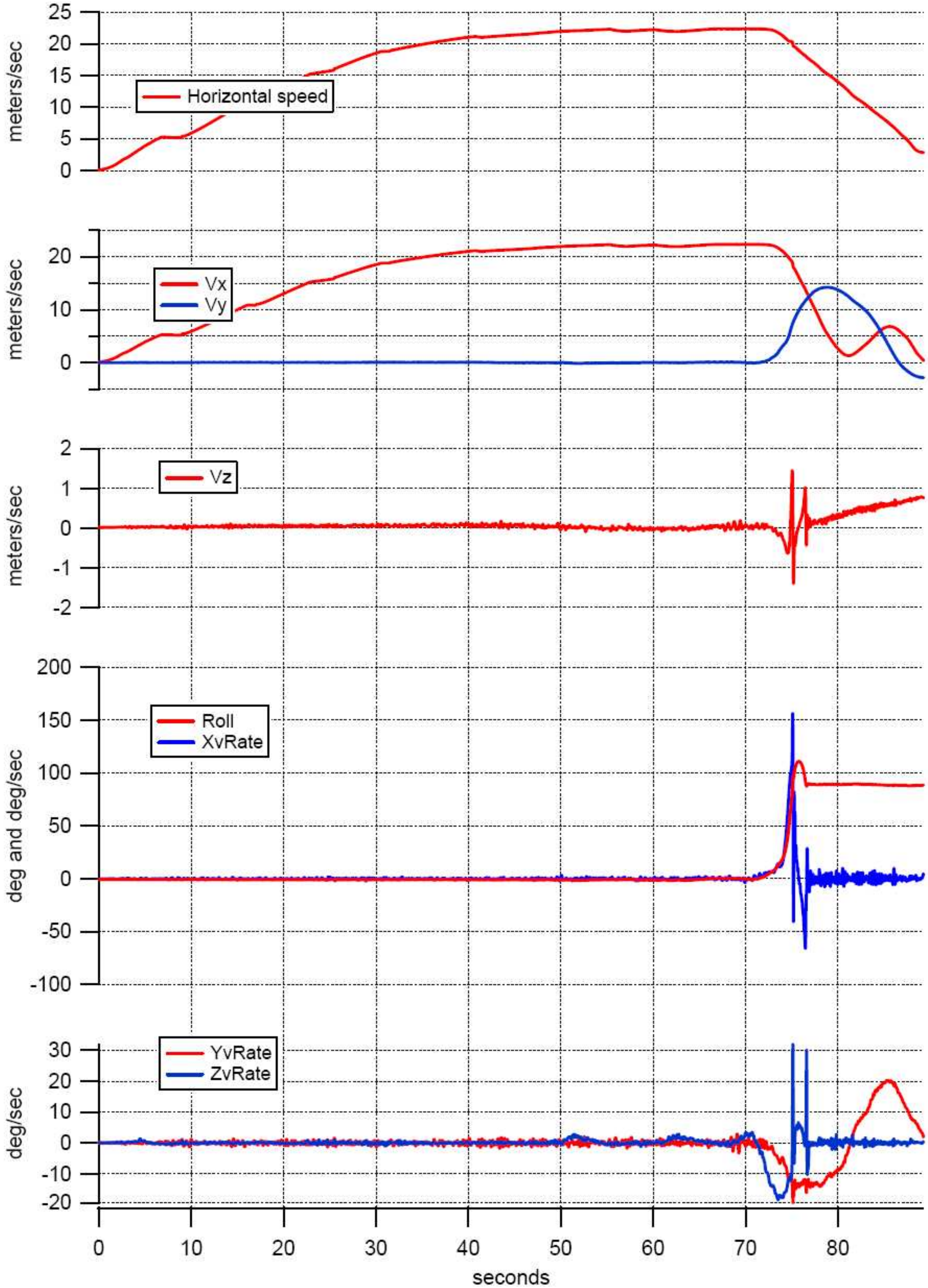


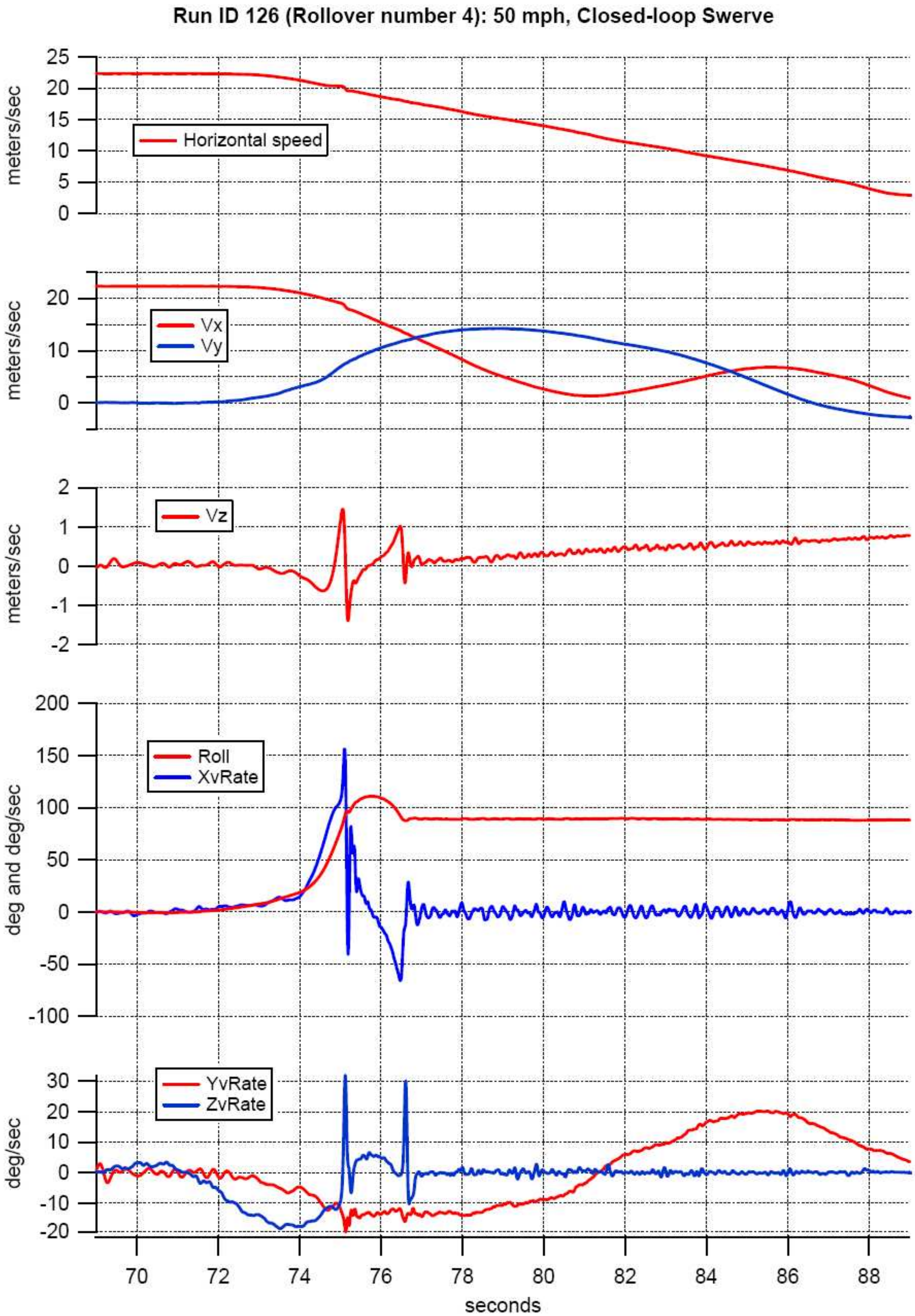
Run ID 115 (Rollover number 3): 45 mph, Closed-loop Step Steer





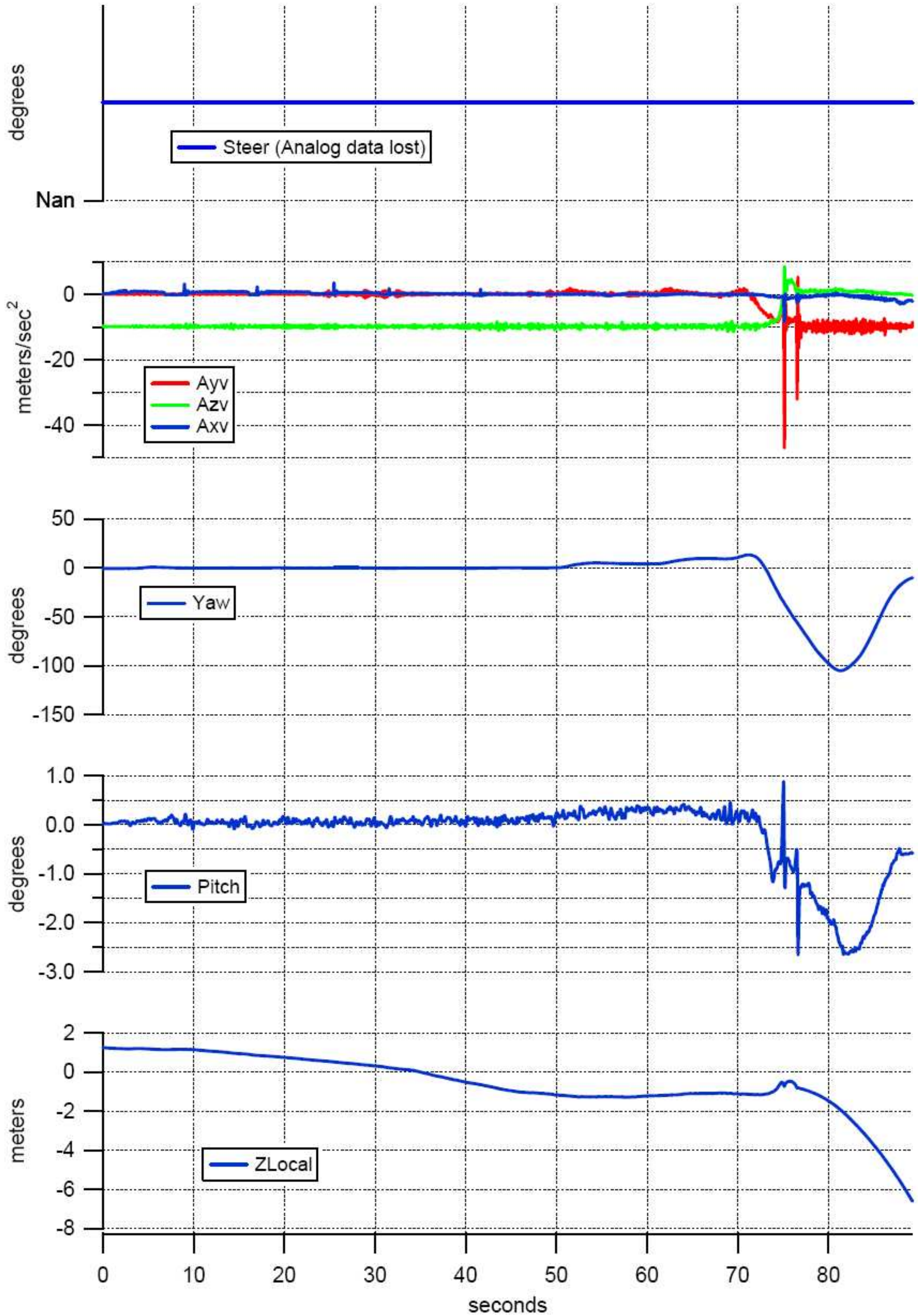
Run ID 126 (Rollover number 4): 50 mph, Closed-loop Swerve

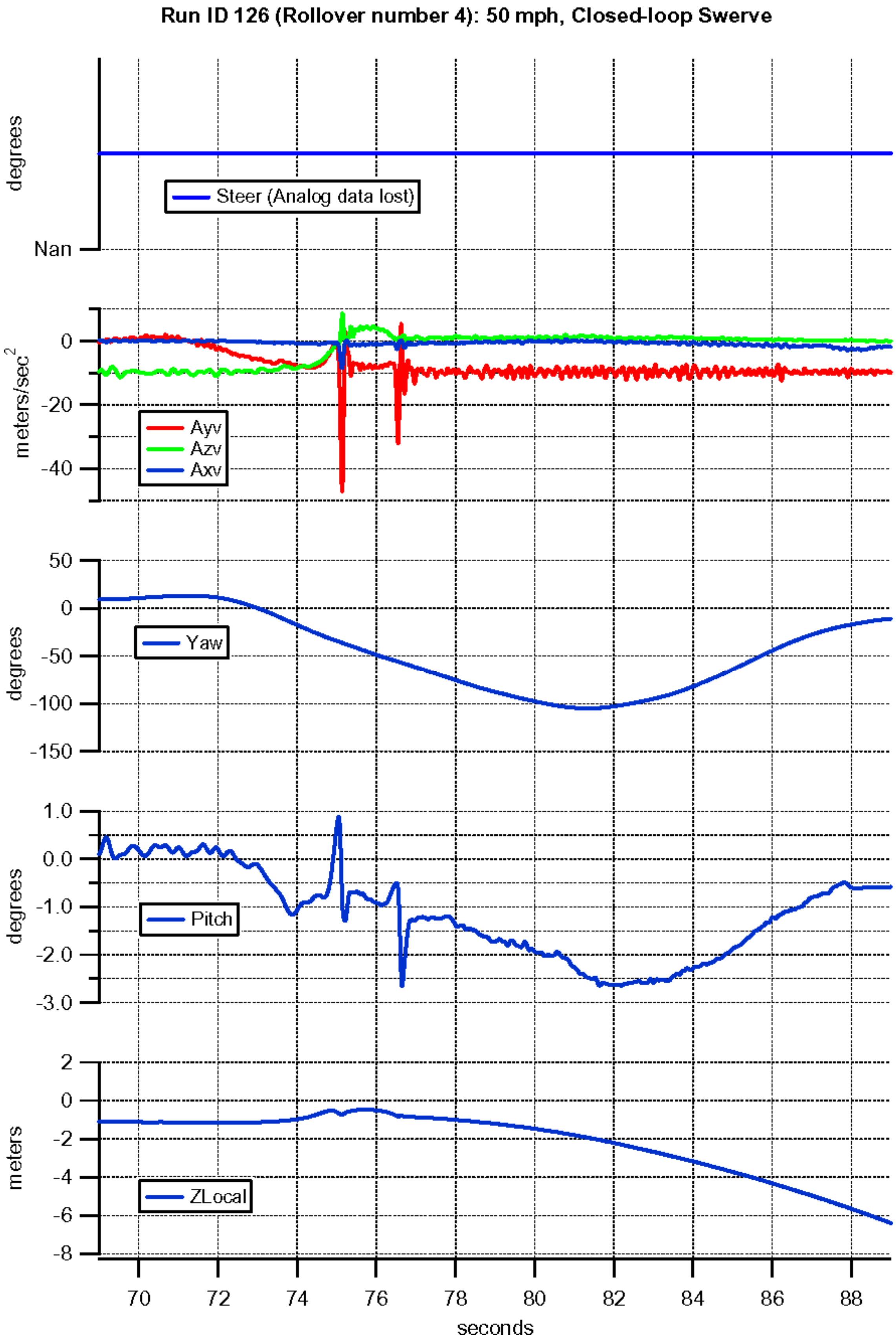




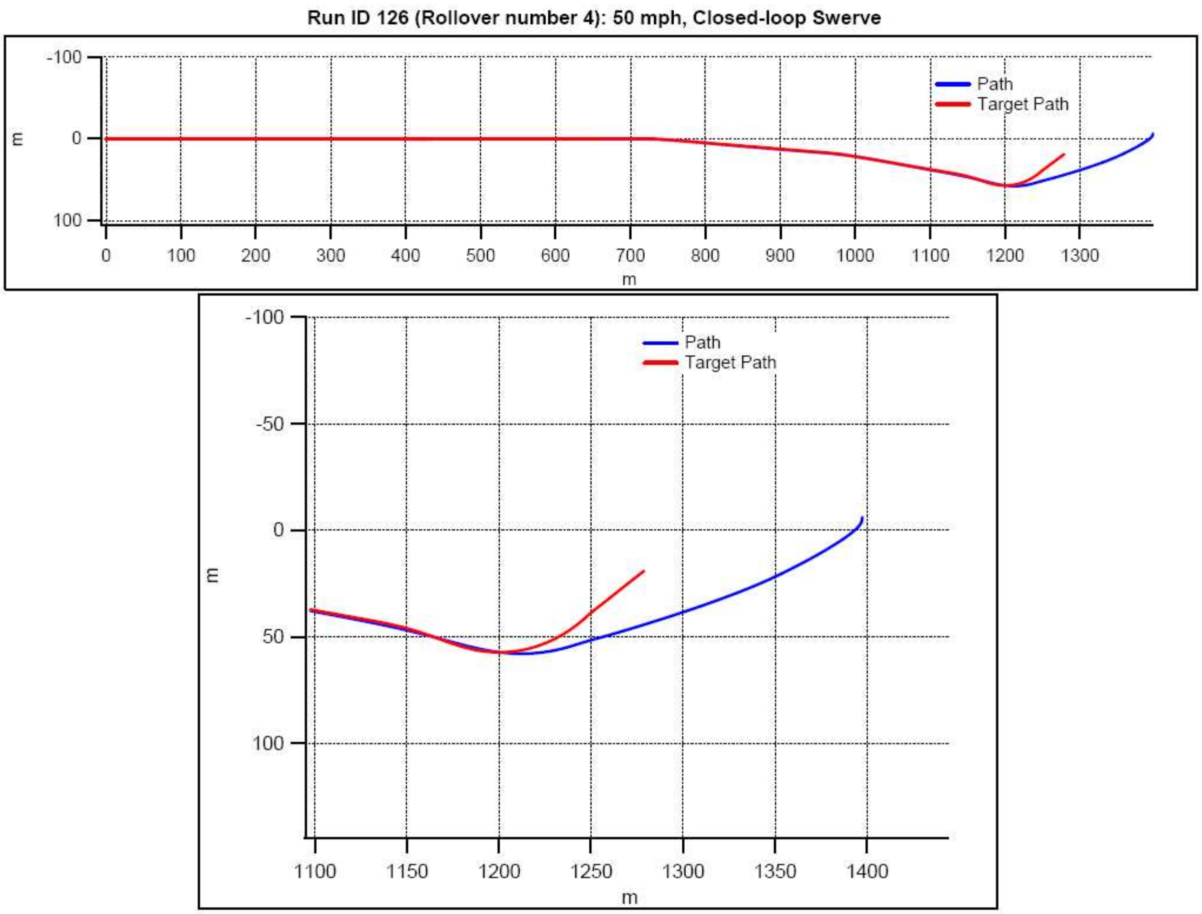
Run ID 126 (Rollover number 4): 50 mph, Closed-loop Swerve
Horizontal speed
meters/sec
Vx
Vy
meters/sec
Vz
meters/sec
Roll
XvRate
deg and deg/sec
YvRate
ZvRate
deg/sec
seconds

Run ID 126 (Rollover number 4): 50 mph, Closed-loop Swerve

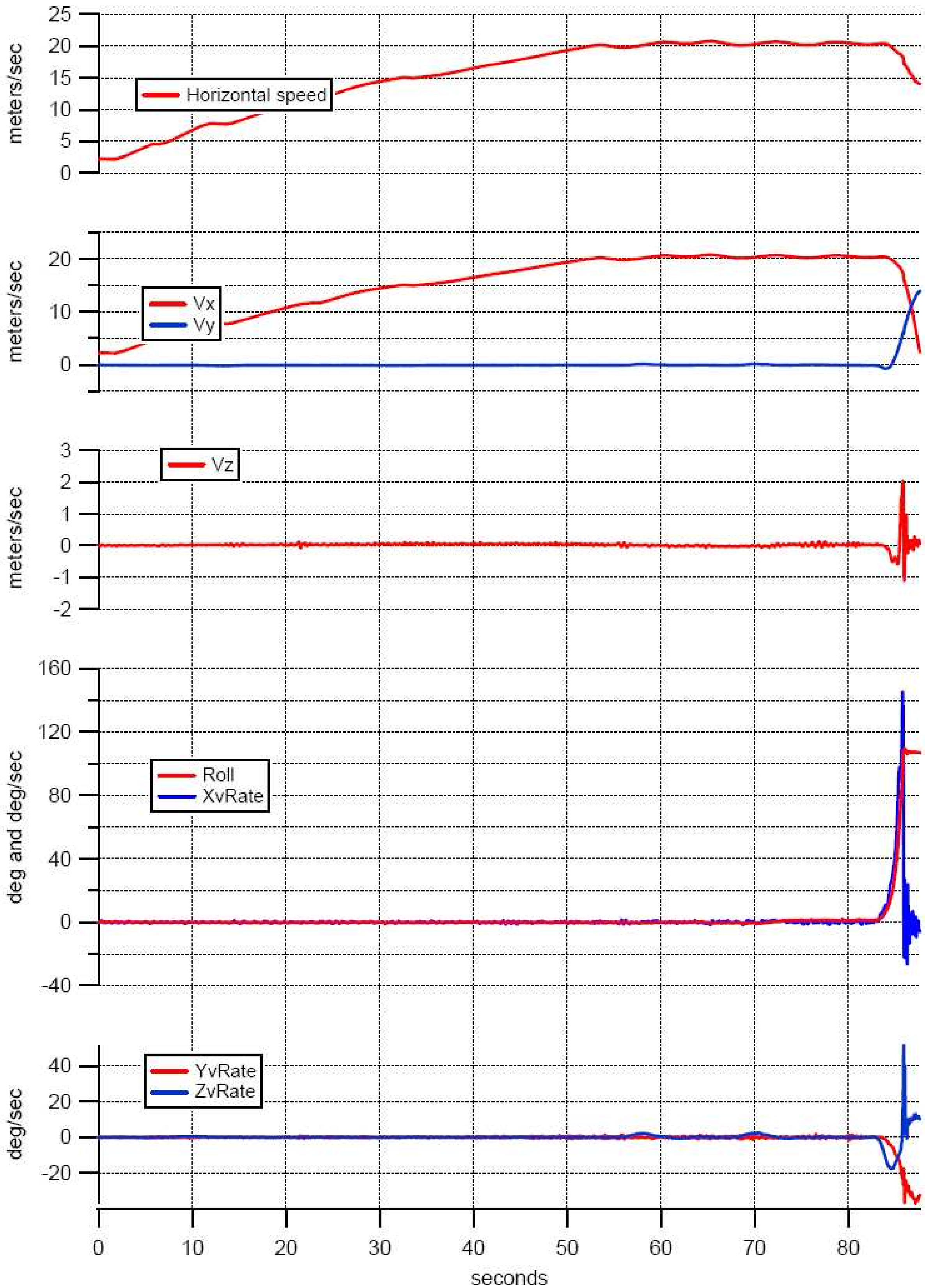


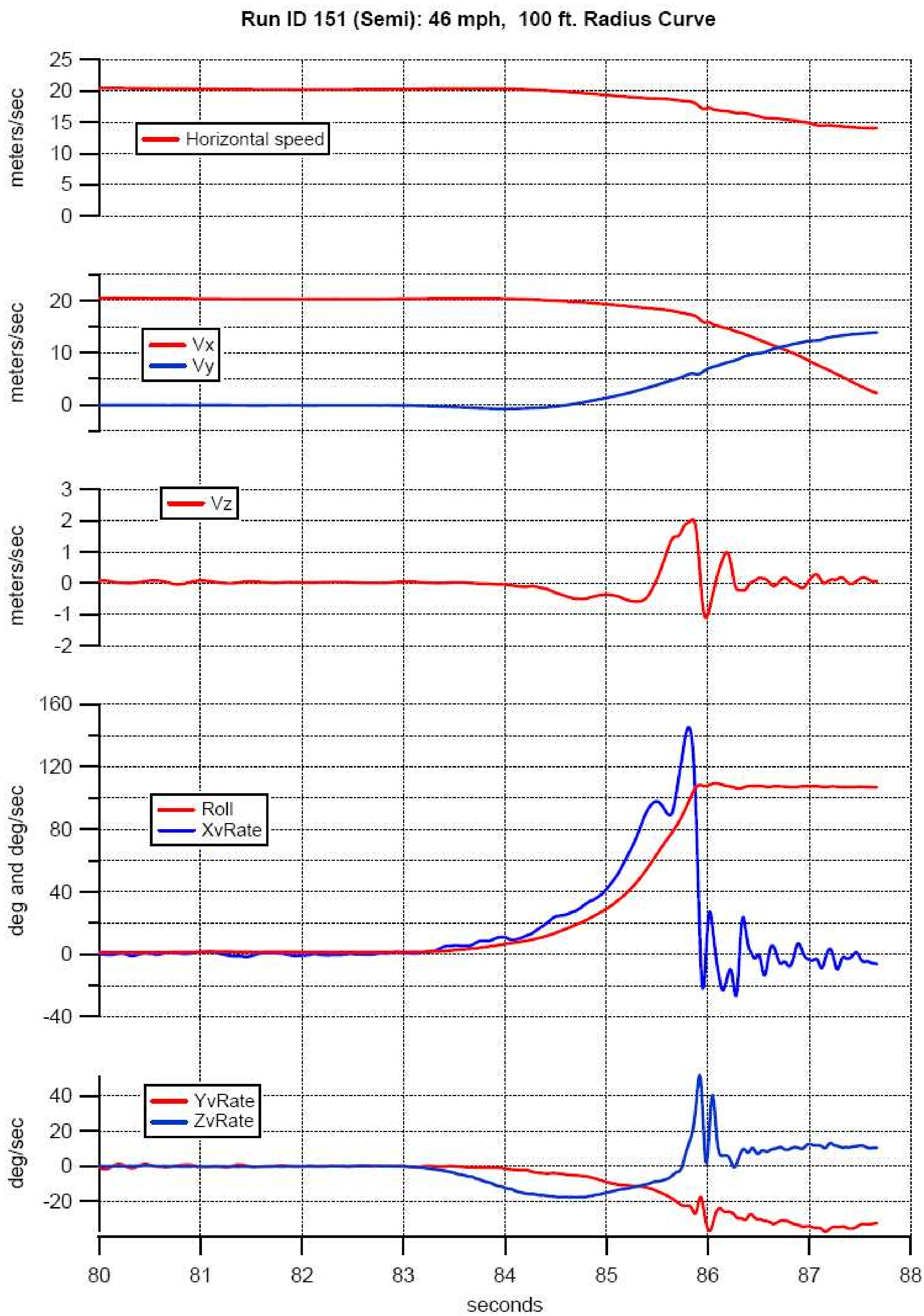


Run ID 126 (Rollover number 4): 50 mph, Closed-loop Swerve
degrees
Steer (Analog data lost)
Nan
meters/sec2
0
-20
-40
Ayv
Azv
Axv
50
0
-50
-100
-150
degrees
Yaw
1.0
0.0
-1.0
-2.0
-3.0
degrees
Pitch
2
0
-2
-4
-6
-8
meters
ZLocal
70
72
74
76
78
80
82
84
86
88
seconds

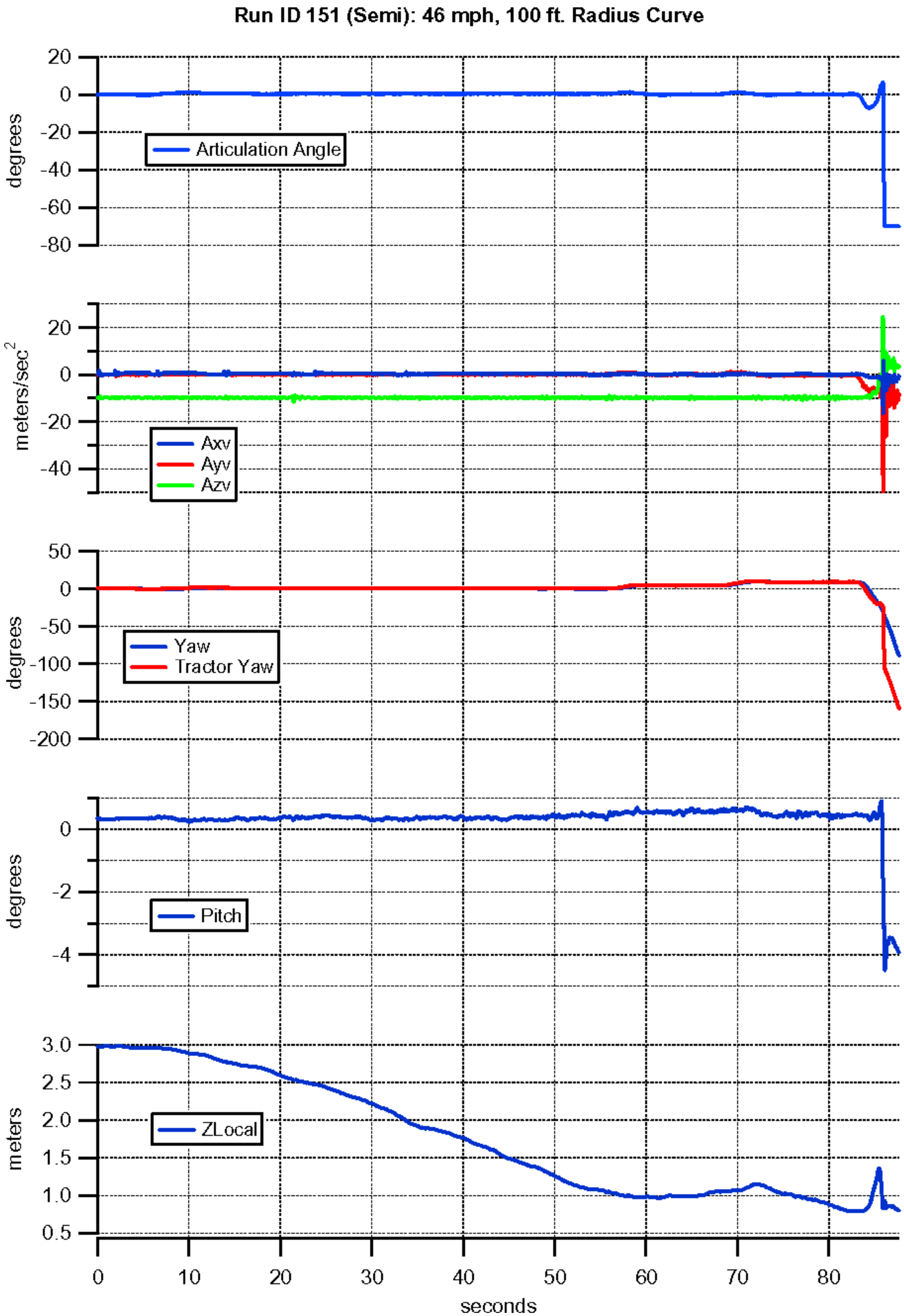

Run ID 126 (Rollover number 4): 50 mph, Closed-loop Swerve
Path
Target Path
m
-100
0
100
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
m
Path
Target Path
-100
-50
0
50
100
m
1100
1150
1200
1250
1300
1350
1400
m

Run ID 151 (Semi): 46 mph, 100 ft. Radius Curve



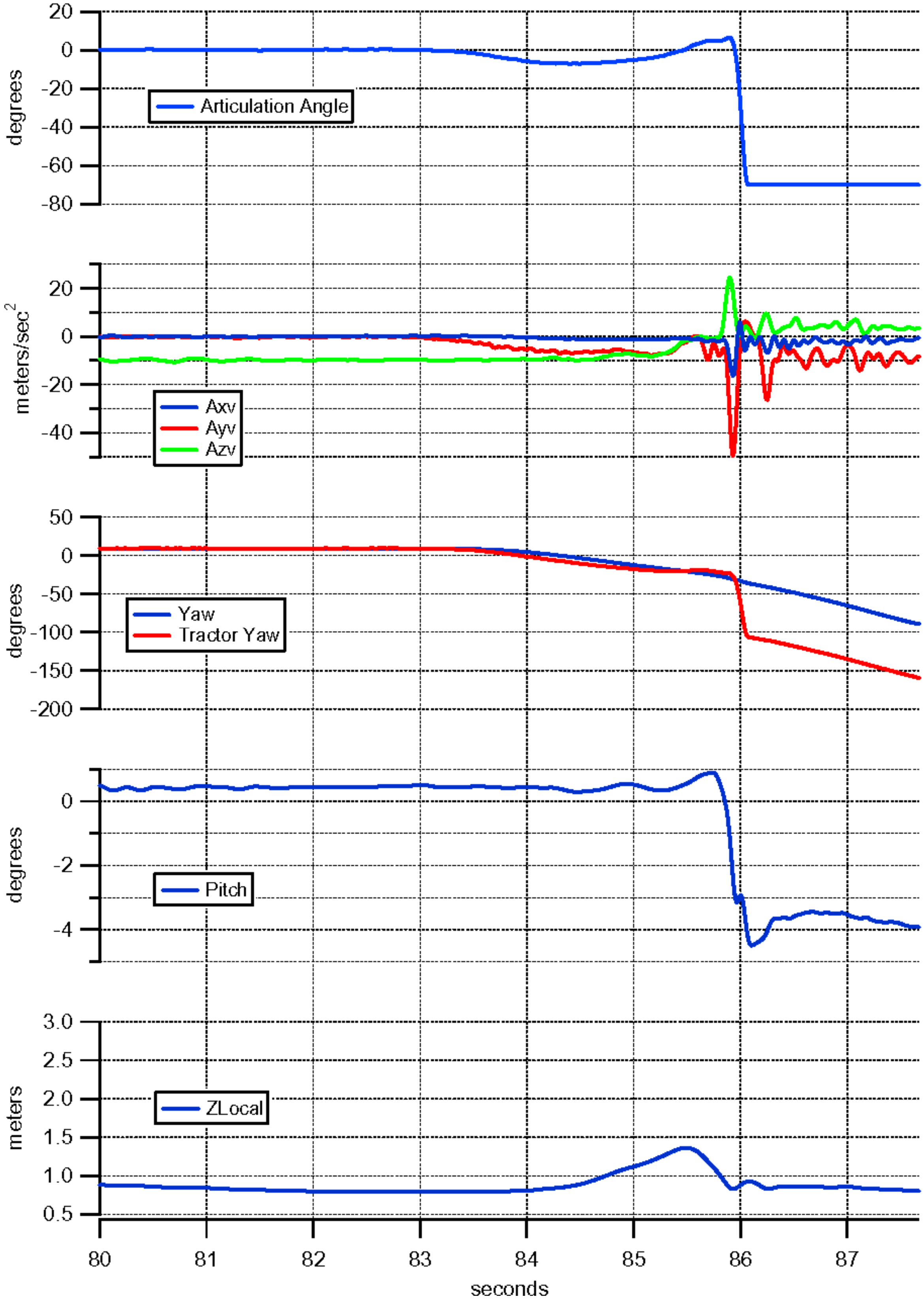


Run ID 151 (Semi): 46 mph, 100 ft. Radius Curve
meters/sec
Horizontal speed
Vx
Vy
Vz
deg and deg/sec
Roll
XvRate
deg/sec
YvRate
ZvRate
seconds

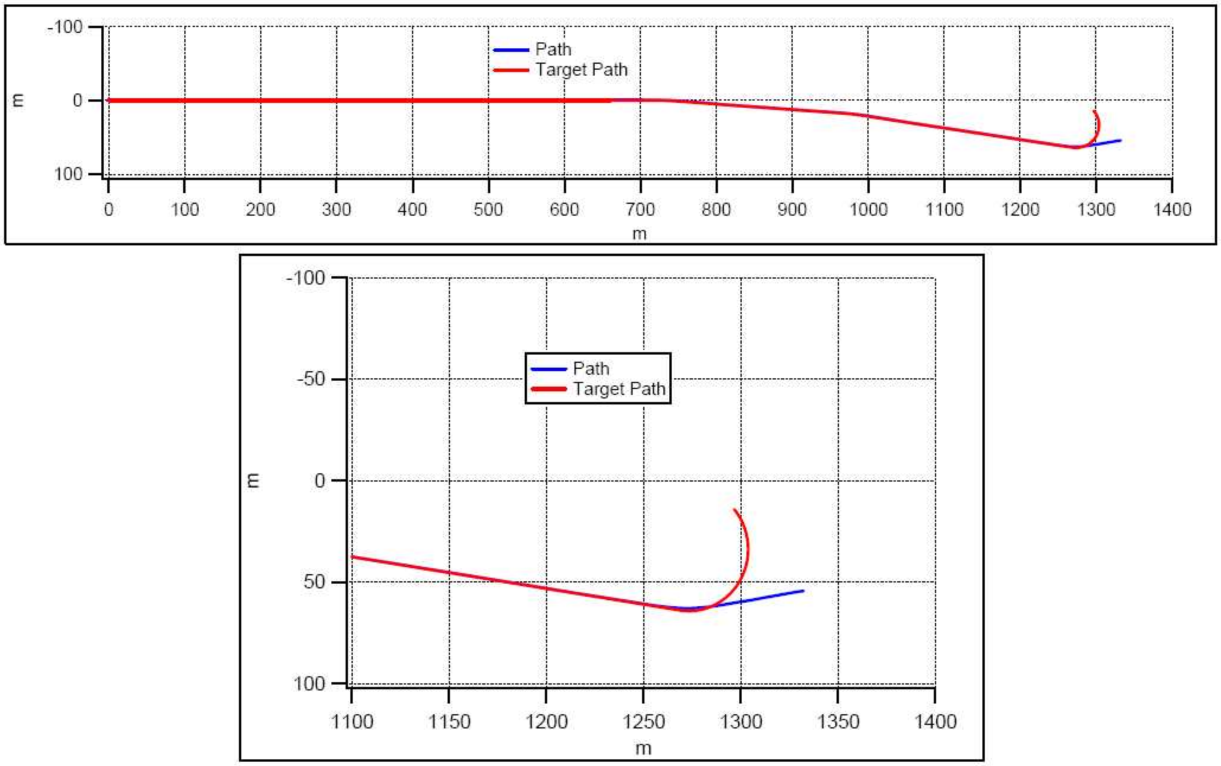


Run ID 151 (Semi): 46 mph, 100 ft. Radius Curve
Articulation Angle
Axv
Ayv
Azv
Yaw
Tractor Yaw
Pitch
ZLocal
degrees
meters/sec2
meters
seconds

Run ID 151 (Semi): 46 mph, 100 ft. Radius Curve



Run ID 151 (Semi): 46 mph, 100 ft. Radius Curve



Appendix B Time histories of semitrailer tank deflection

The figures on the following two pages mark the locations where the strain gages were mounted on the trailer. The locations were selected by staff from the Federal Highway Administration working on a finite-element model of cargo tank trailers.

In addition to the strain gages, there were three string potentiometers to measure the deflection across the rollover protection devices.

Plots of the time histories recorded at these instruments are on the following pages. The raw data is on one of the CDs attached to this report as described in Appendix C. The numbers in the data file have units of microstrain for the strain gages and inches for the string potentiometers. The data was recorded at 2000 Hz; each time step is 0.5 ms

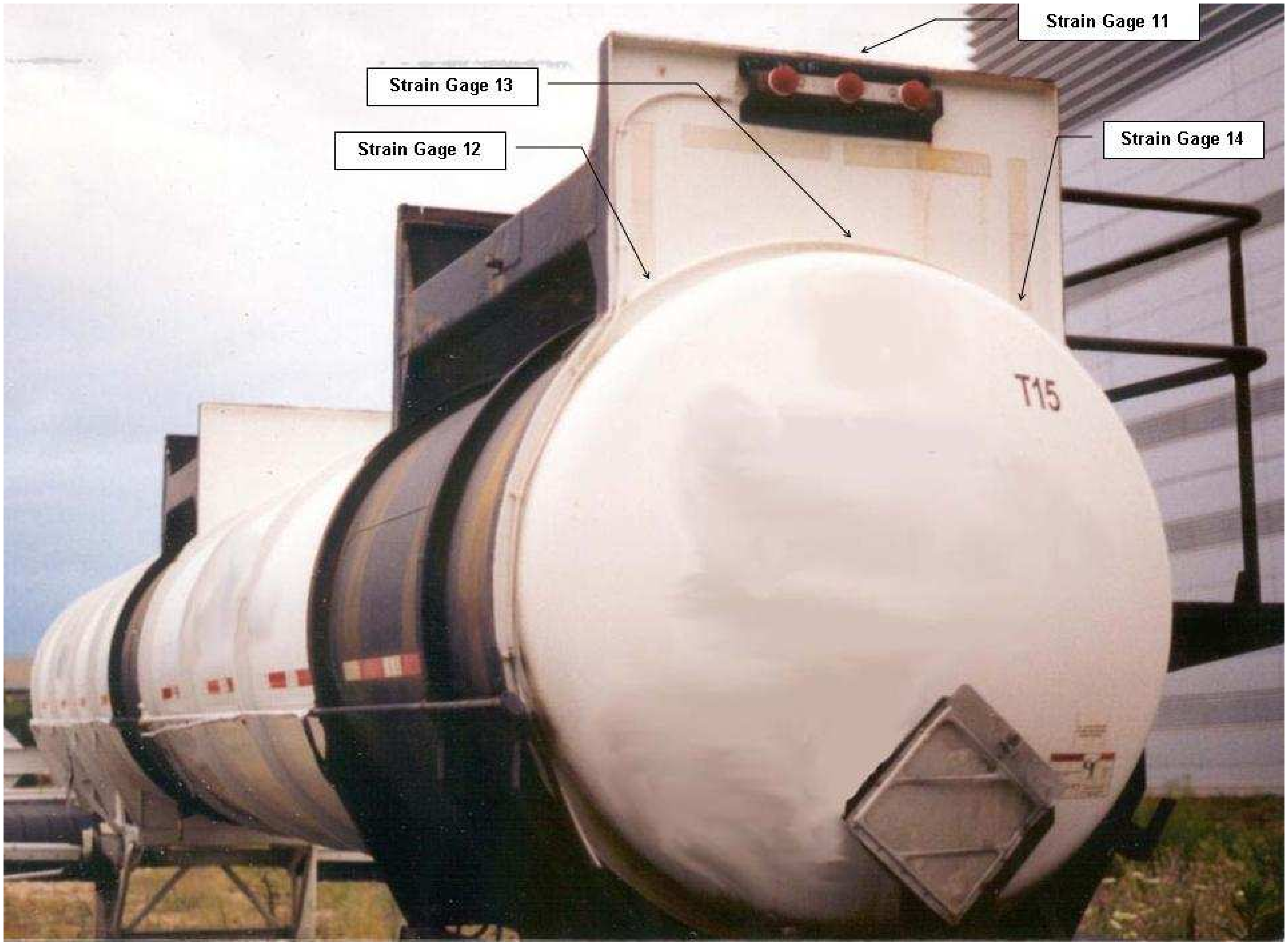


Figure B-1. Strain gage locations on the rear of the semitrailer

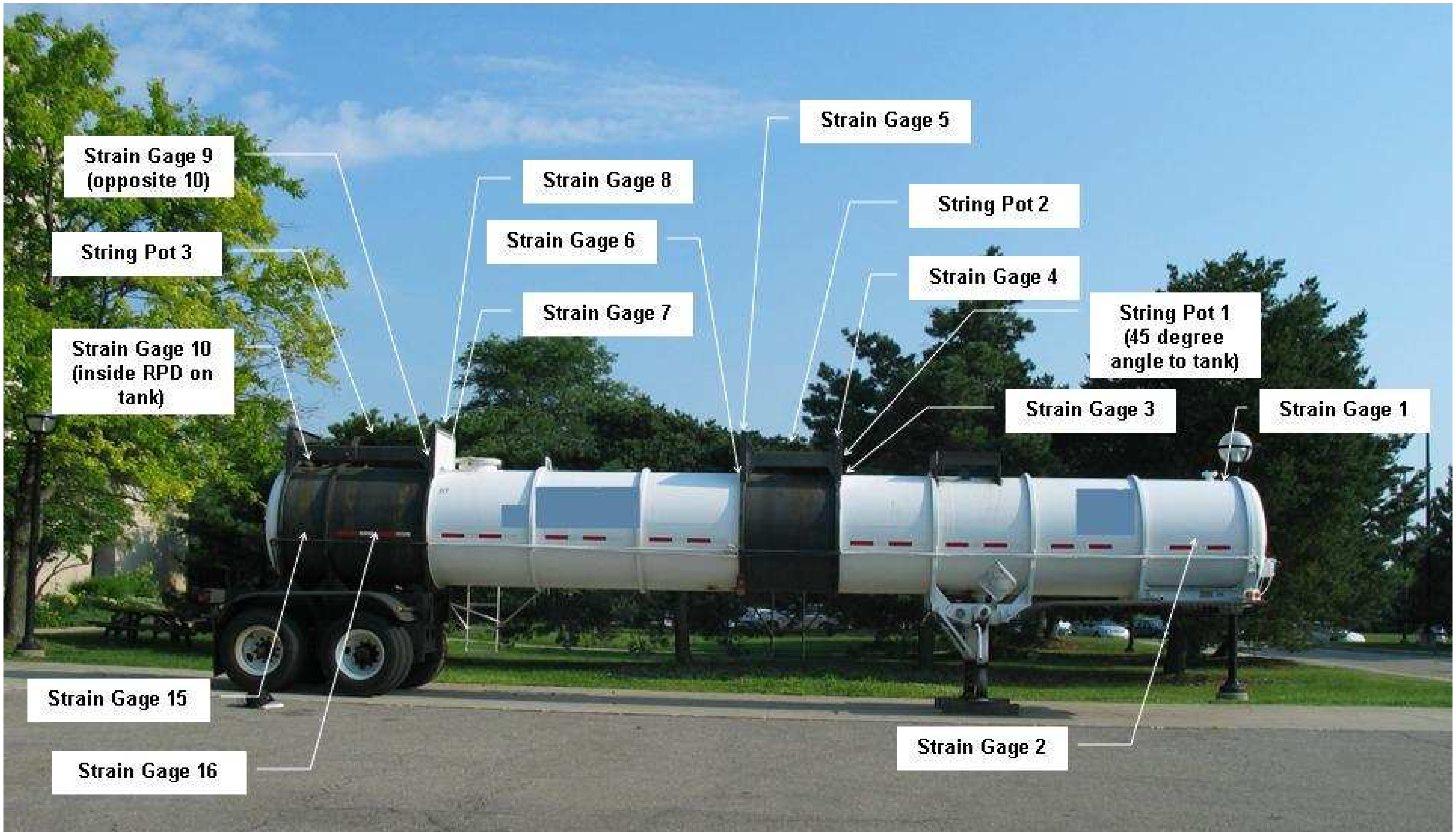


Figure B-2. Strain gage and string potentiometer locations

Table B-1. Sensor orientations

Sensor	Orientation
Strain Gage 1	Axial along trailer
Strain Gage 2	Hoop on trailer
Strain Gage 3	Axial along trailer
Strain Gage 4	Lateral on front rollover protective device
Strain Gage 5	Lateral on front rollover protective device
Strain Gage 6	Axial along trailer
Strain Gage 7	Axial along trailer
Strain Gage 8	Lateral on rear rollover protective device
Strain Gage 9	Axial along trailer
Strain Gage 10	Axial along trailer
Strain Gage 11	Lateral on rear rollover protective device
Strain Gage 12	Vertical on rear rollover protective device
Strain Gage 13	Axial along trailer
Strain Gage 14	Vertical on rear rollover protective device
Strain Gage 15	Hoop on trailer
Strain Gage 16	Hoop on trailer
String Pot 1	45 degree to tank on front rollover protective device
String Pot 2	Horizontal on front rollover protective device
String Pot 3	Horizontal on rear rollover protective device

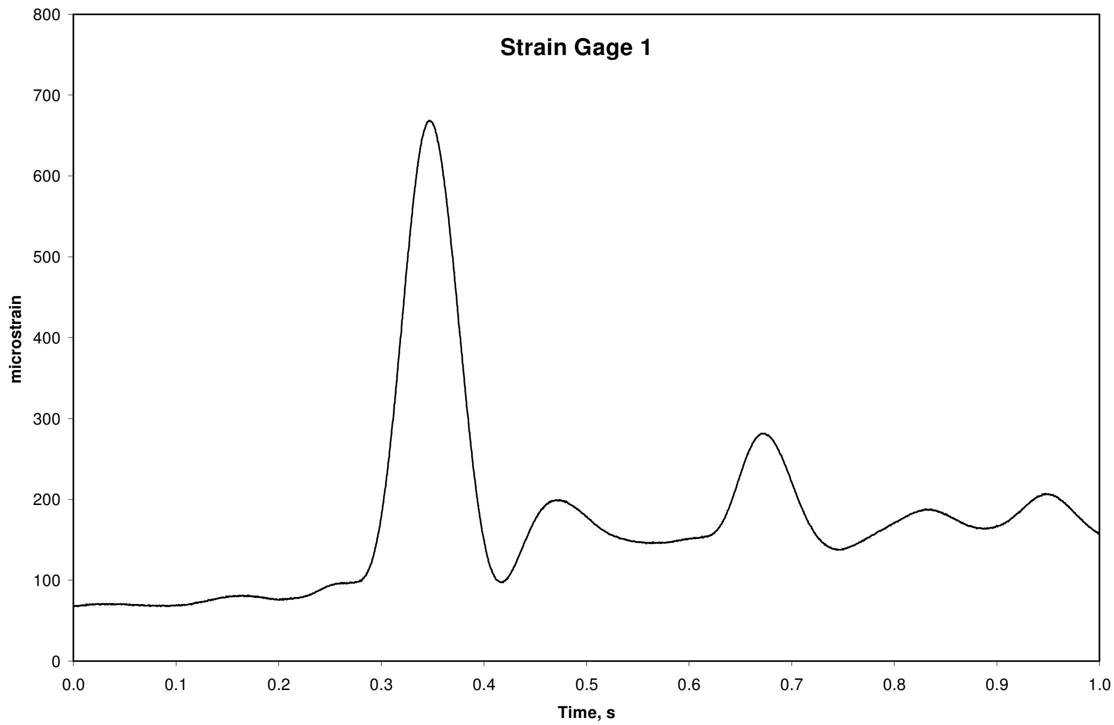


Figure B-3. Strain gage 1

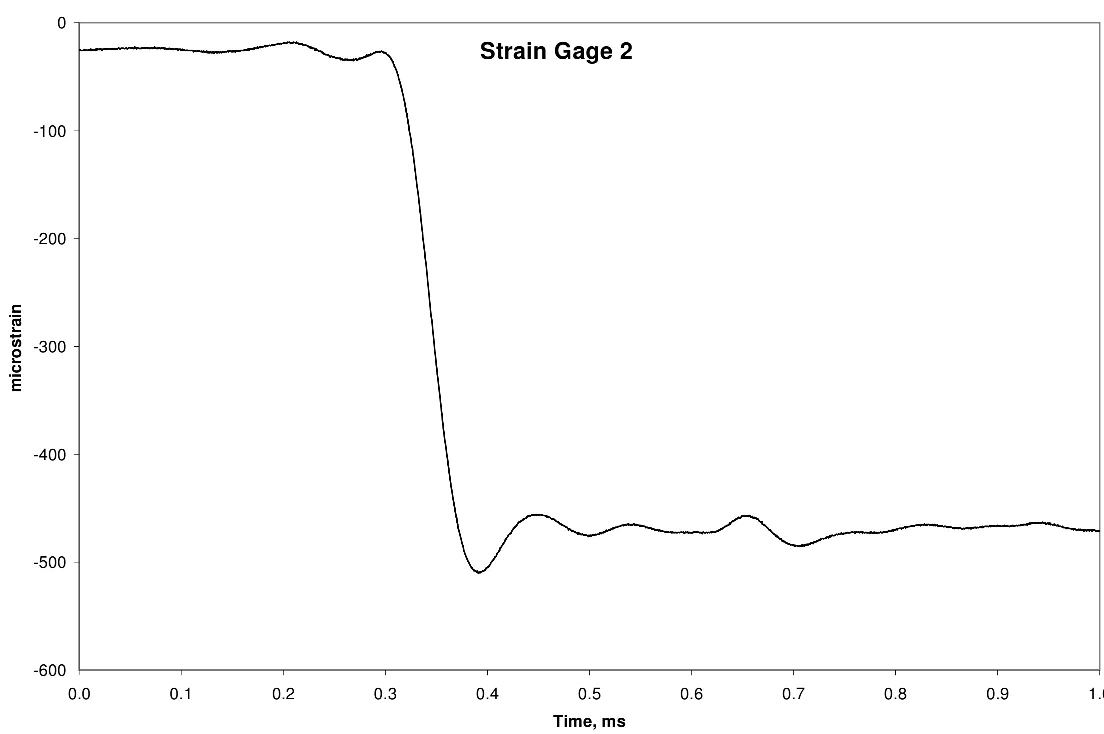


Figure B-4. Strain gage 2

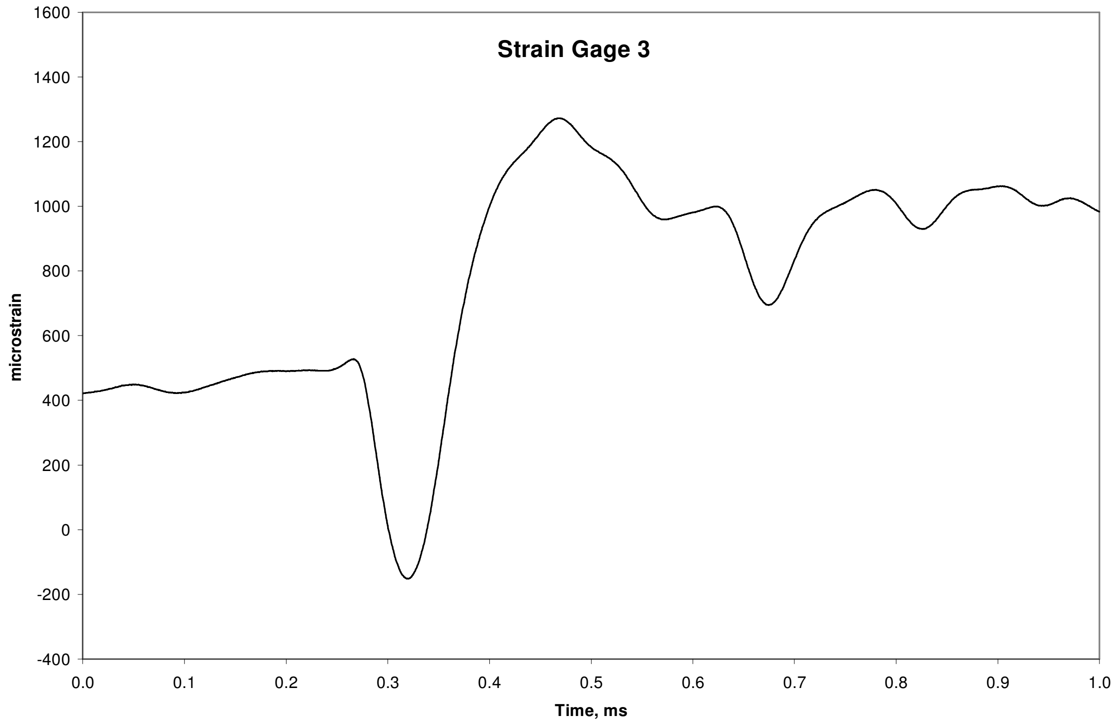


Figure B-5. Strain gage 3

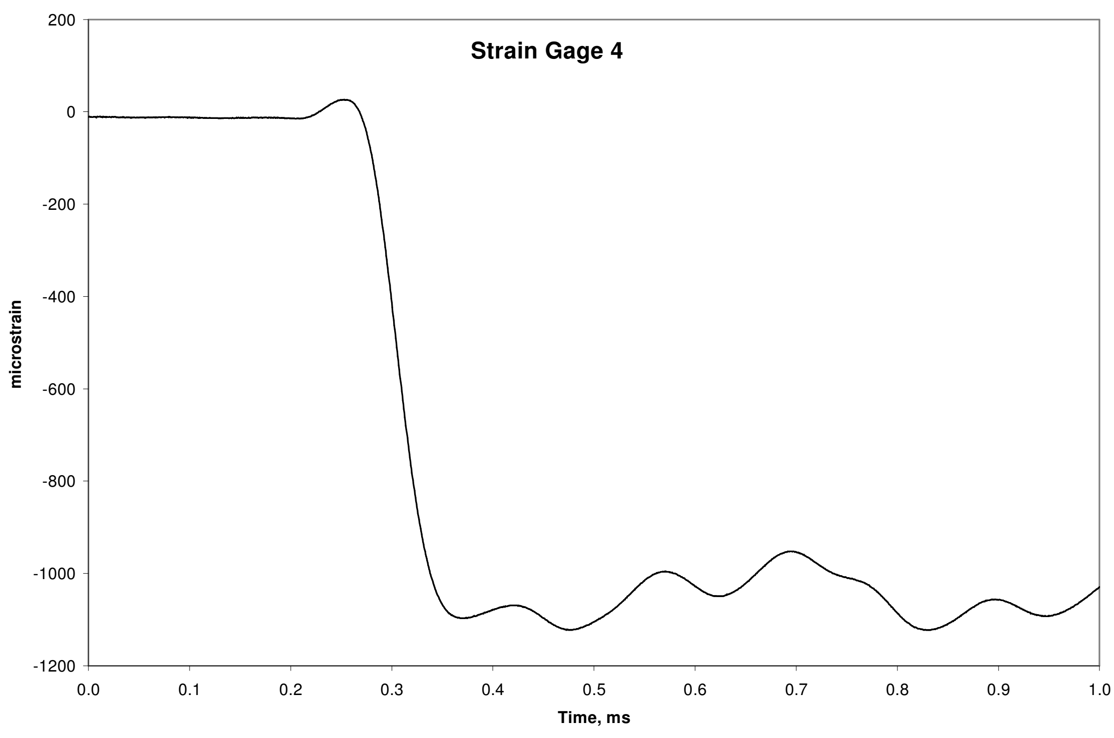


Figure B-6. Strain gage 4

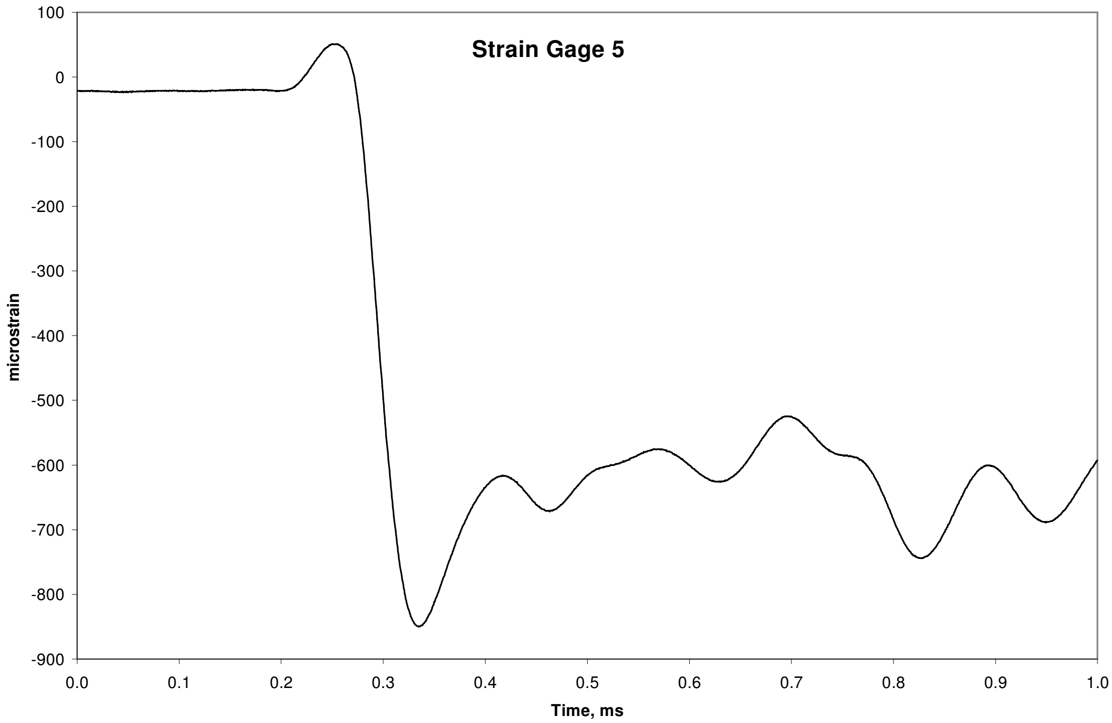


Figure B-7. Strain gage 5

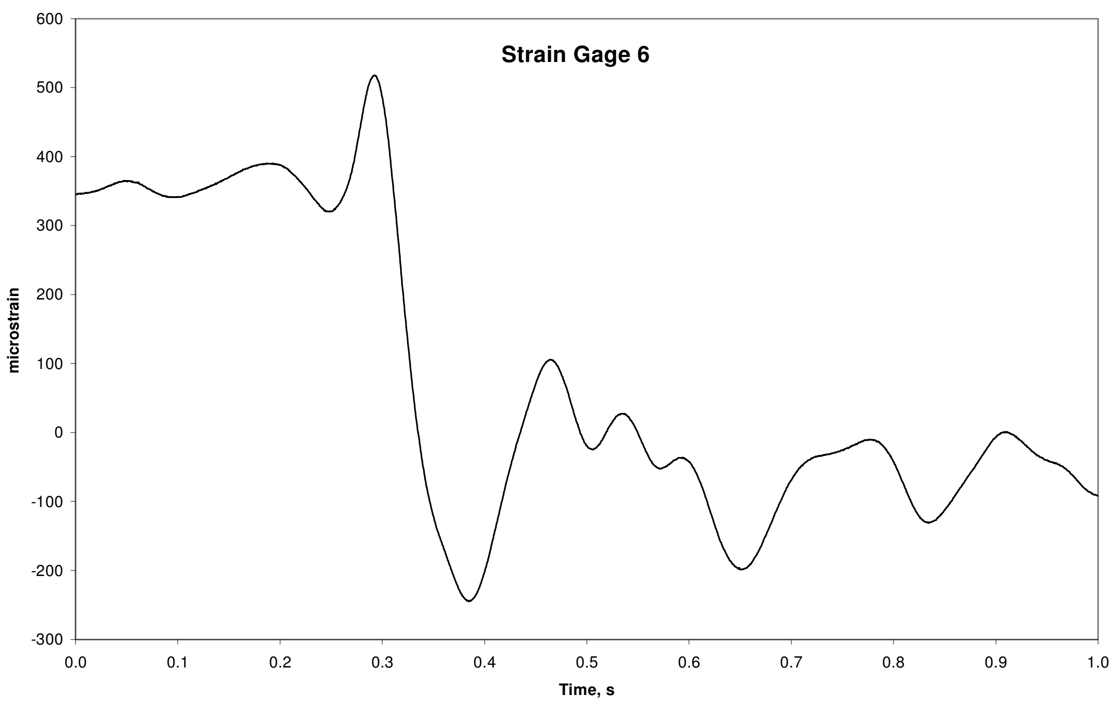


Figure B-8. Strain gage 6

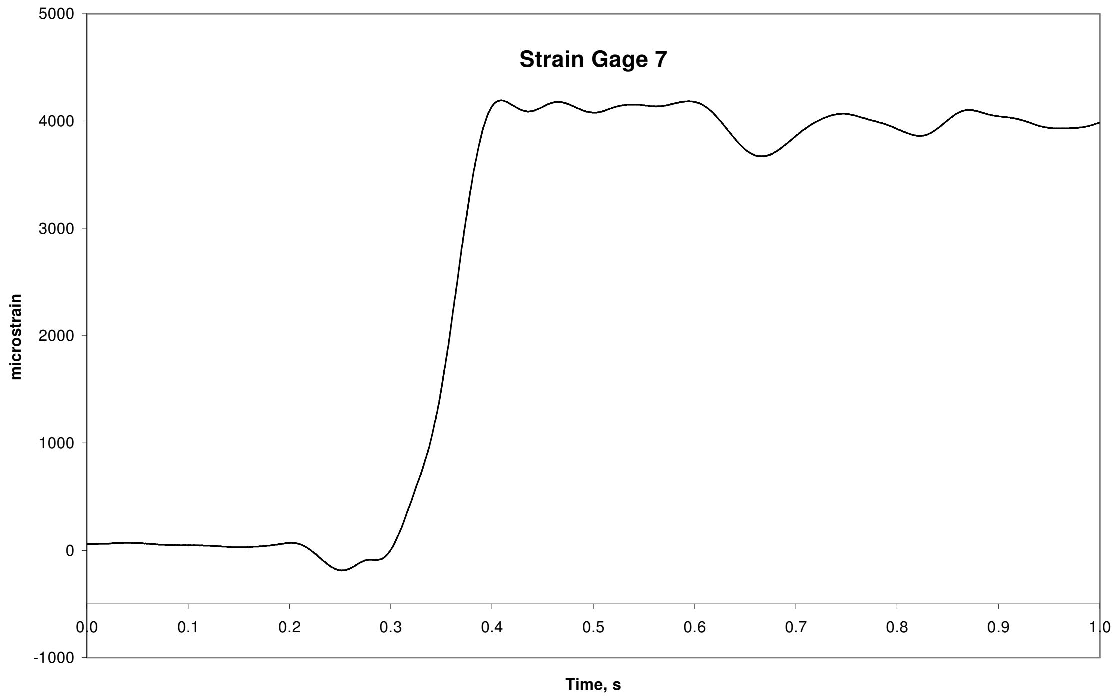


Figure B-9. Strain gage 7

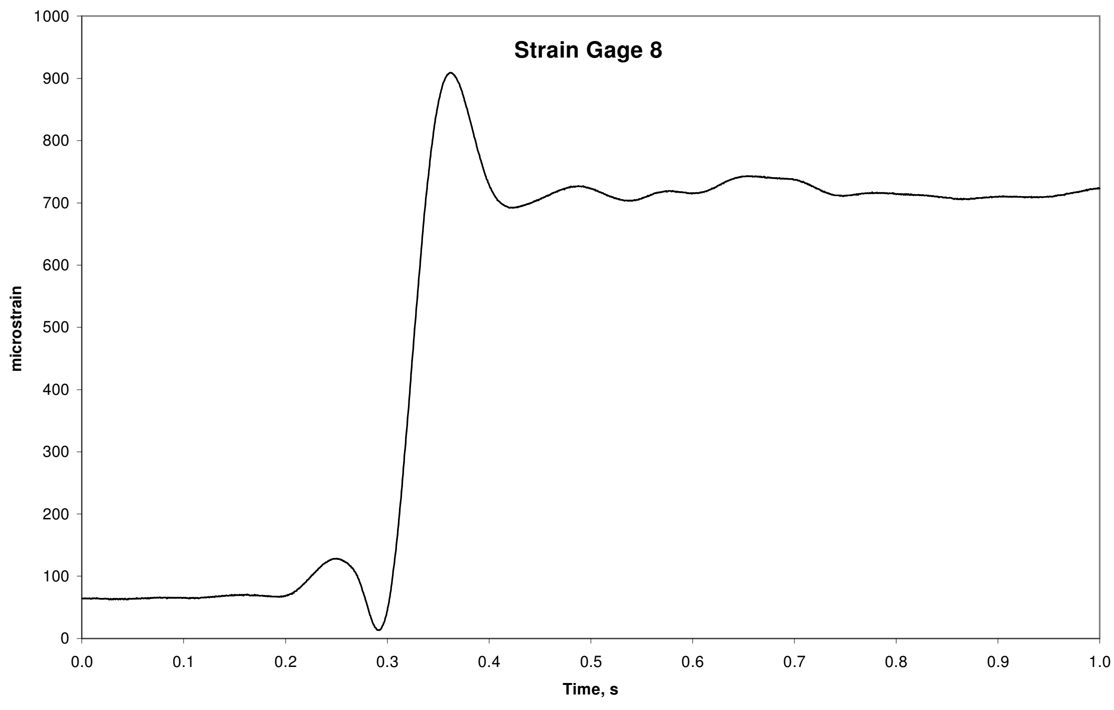


Figure B-10. Strain gage 8

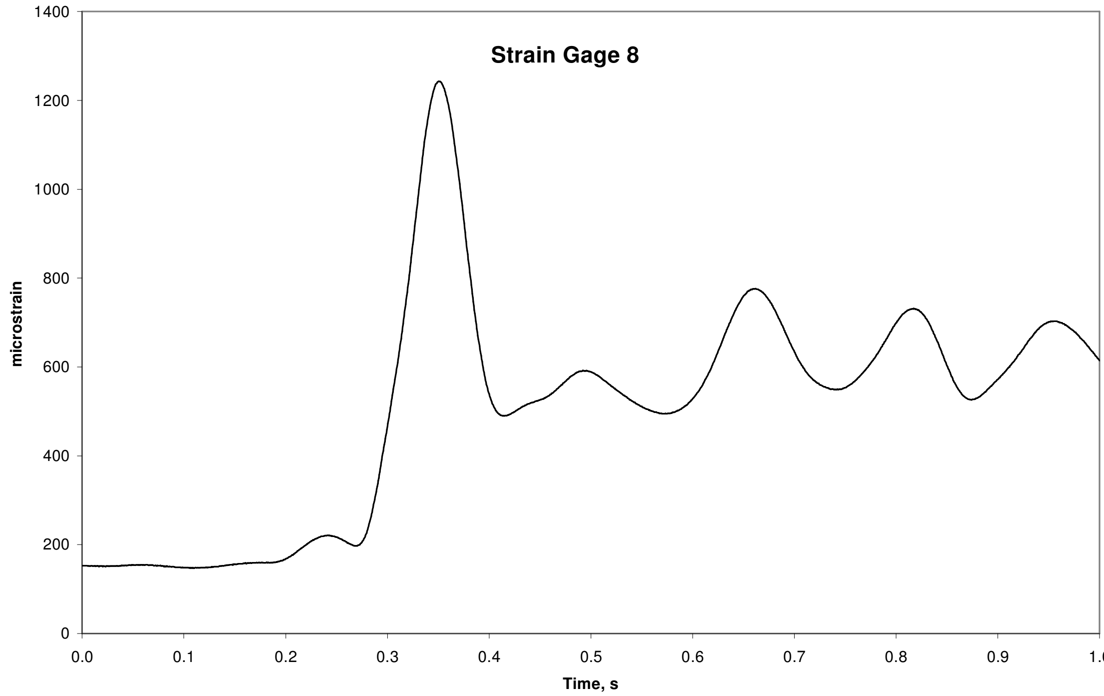


Figure B-11. Strain gage 9

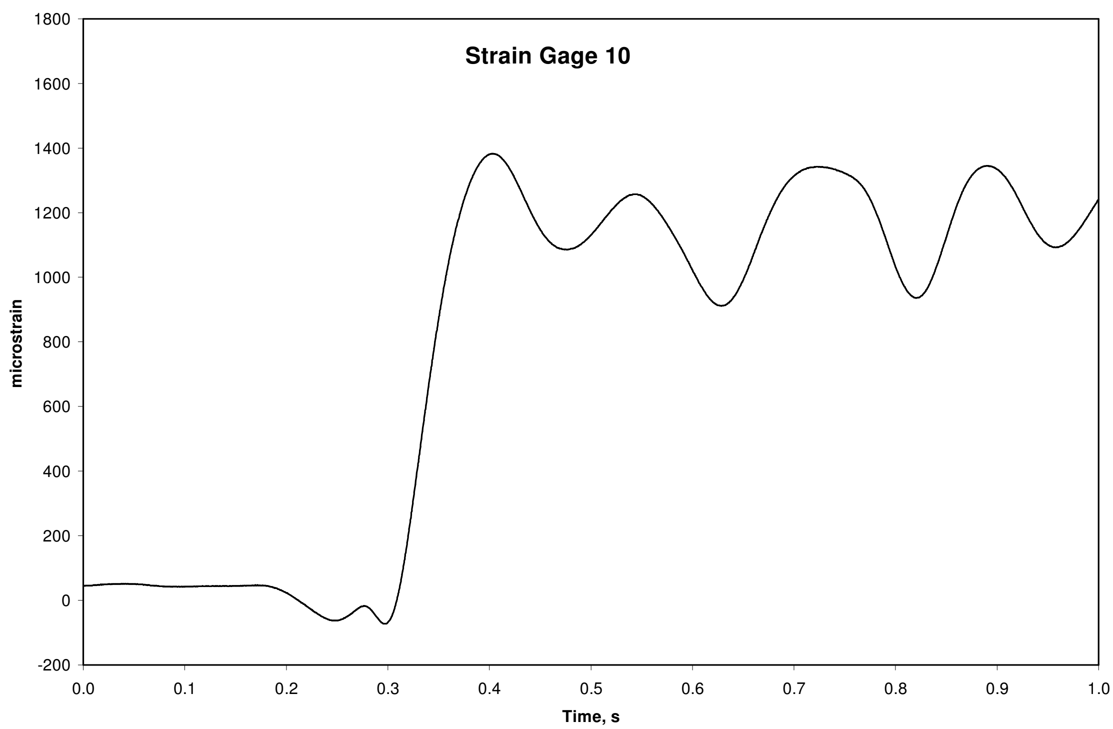


Figure B-12. Strain gage 10

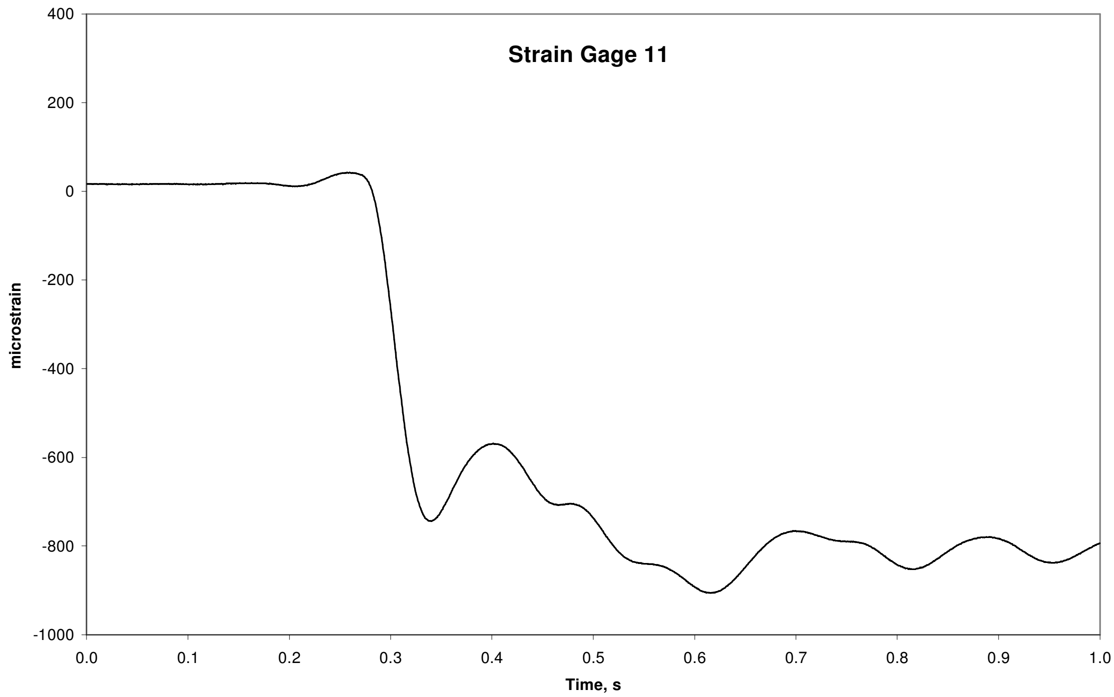


Figure B-13. Strain gage 11

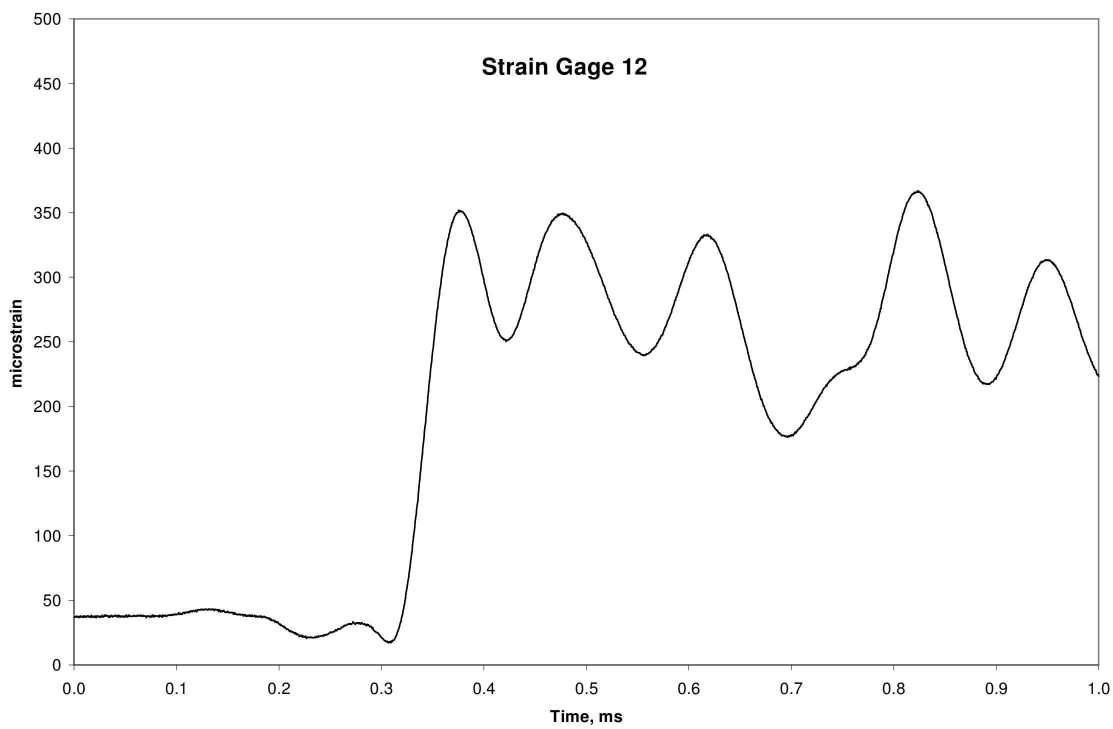


Figure B-14. Strain gage 12

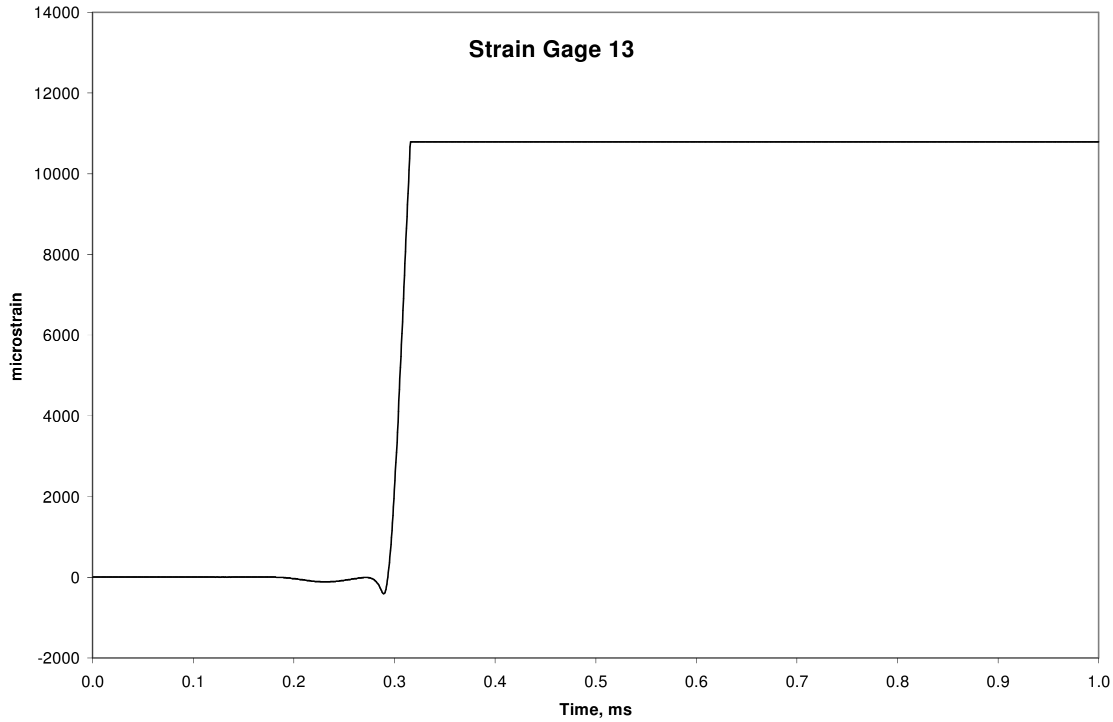


Figure B-15. Strain gage 13

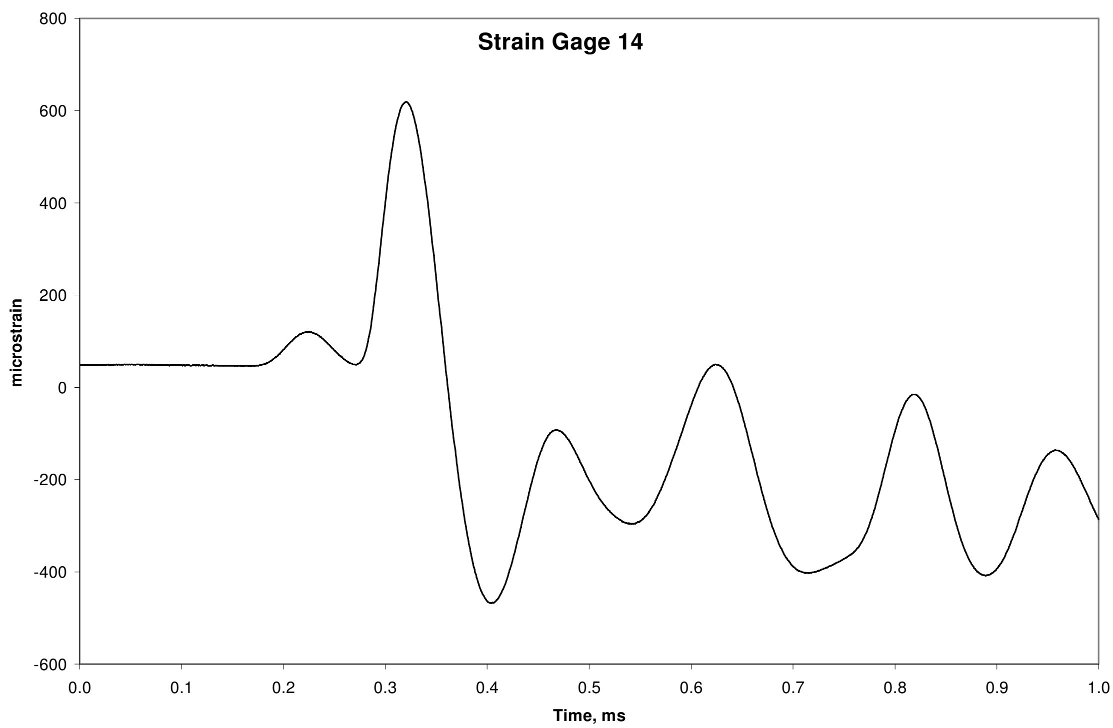


Figure B-16. Strain gage 14

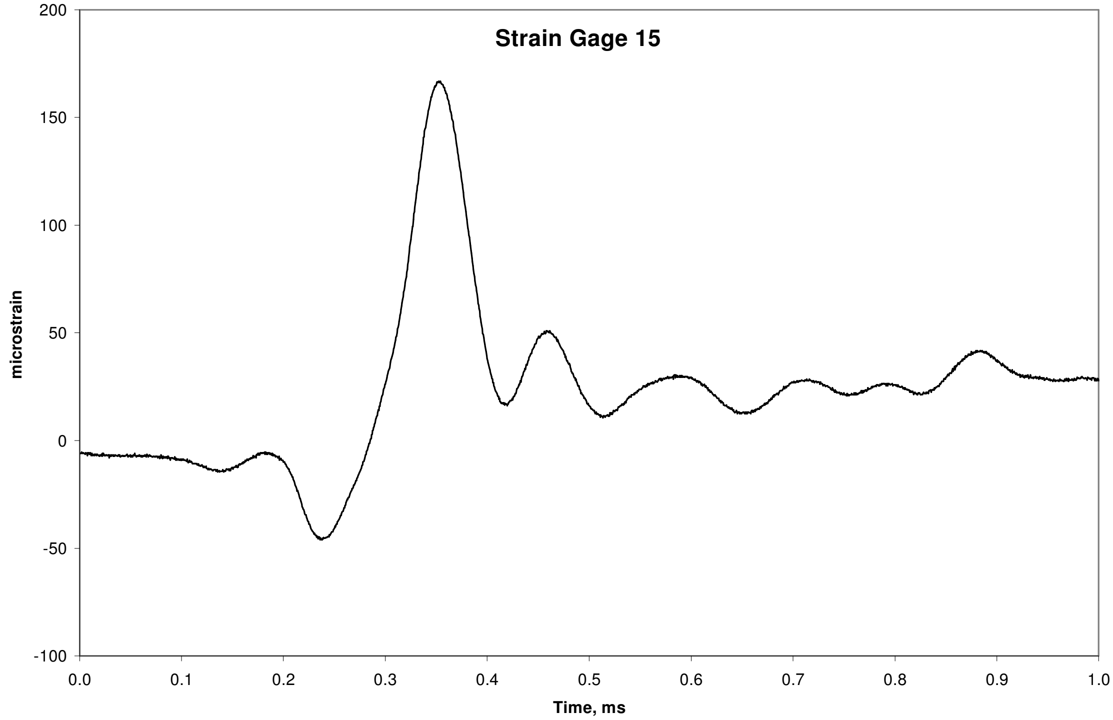


Figure B-17. Strain gage 15

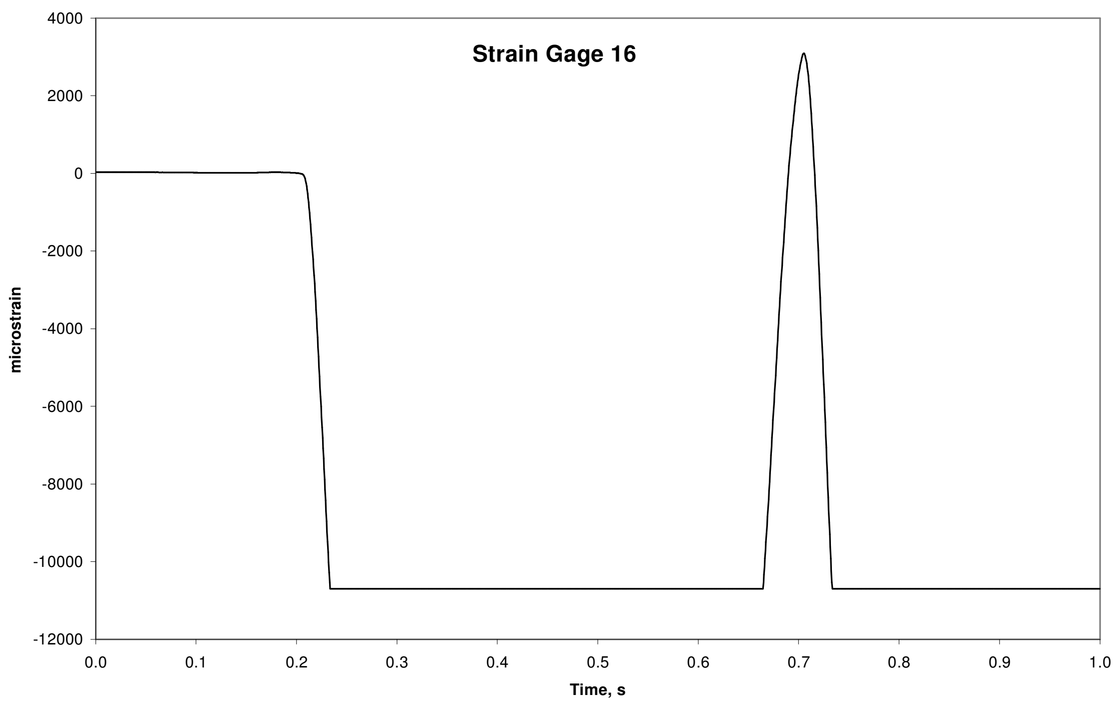


Figure B-18. Strain gage 16

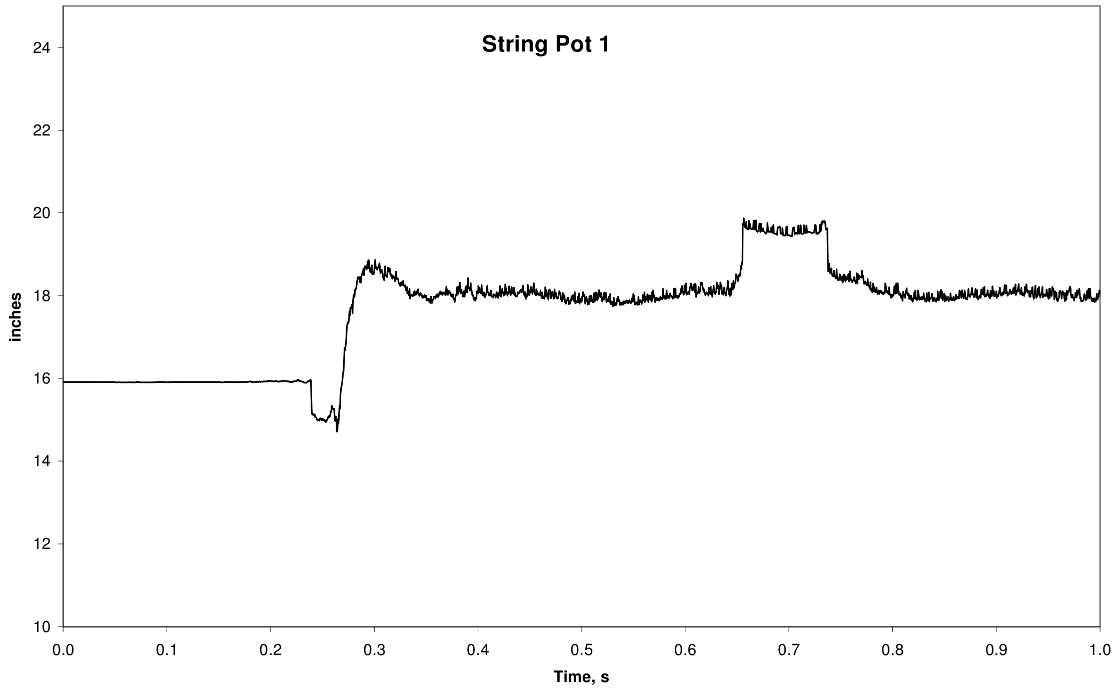


Figure B-19. String potentiometer 1

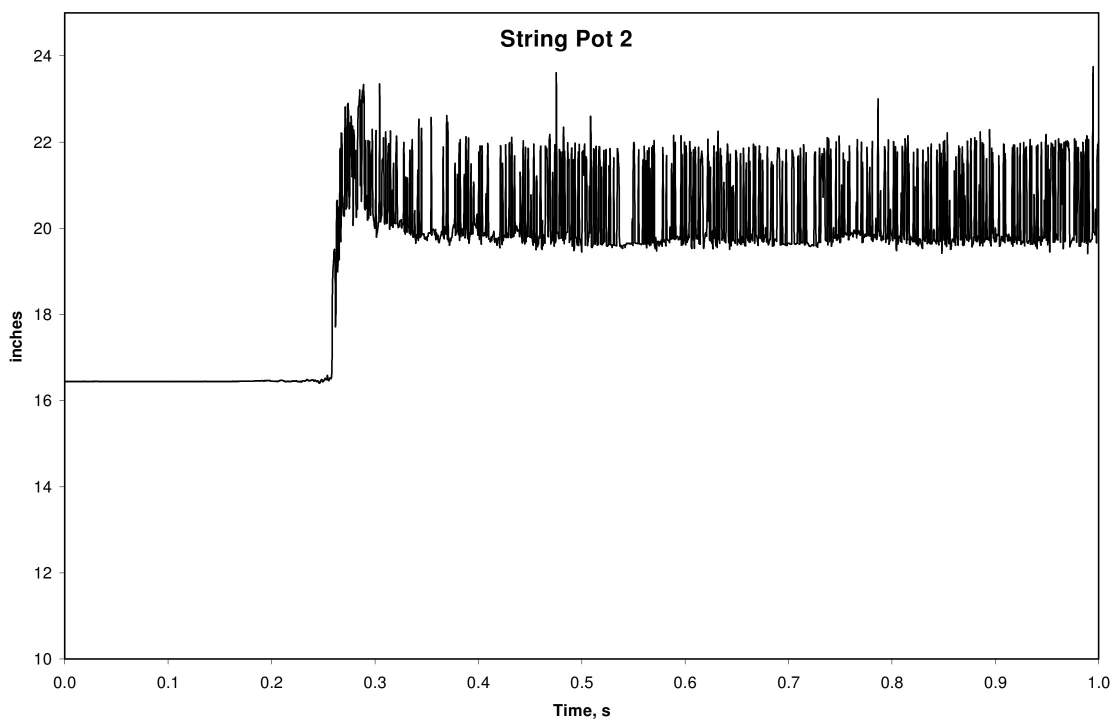


Figure B-20. String potentiometer 2

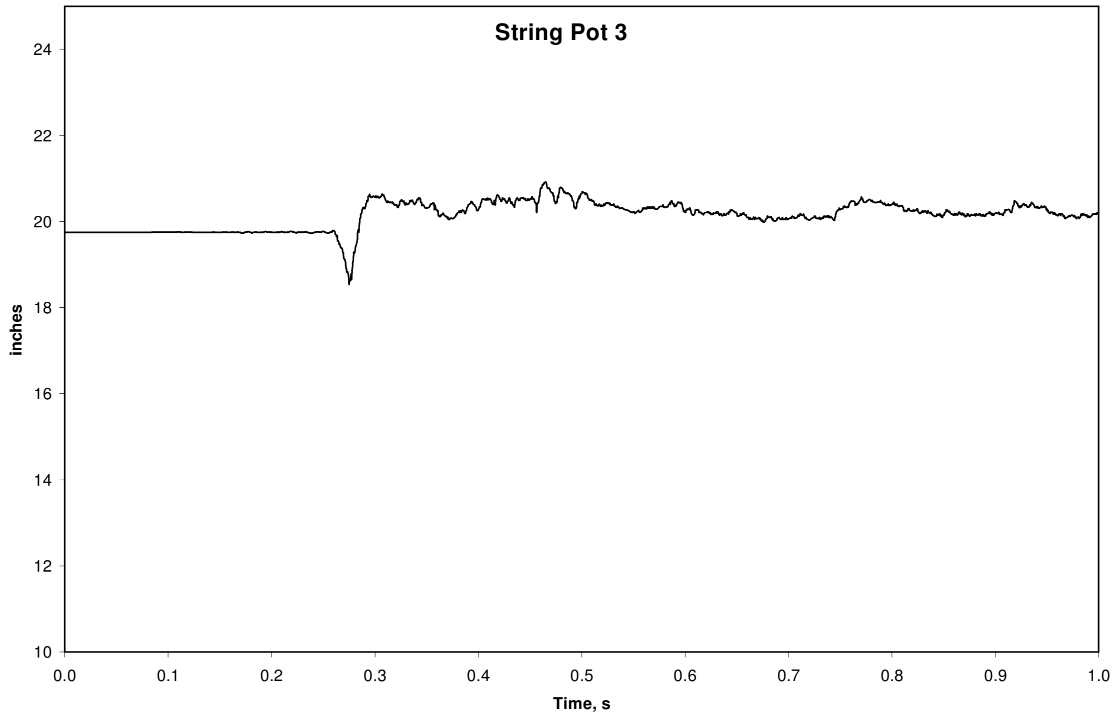


Figure B-21. String potentiometer 3

Figure B-22. Rollover protection devices after the crash

Appendix C List of CDs

There are four data CDs attached to this report. The first three have video of the rollovers, and the fourth has raw data files. The contents of the four CDs are

- Video of Rollover 1 and Rollover 2
- Video of Rollover 3 and Rollover 4
- Video of the tractor semitrailer rollover
- Data files. An Access database of the raw data from the inertial navigation system (See Appendix A), and a series of Excel files with the raw strain gage and string potentiometer data (See Appendix B).

The figures on the following pages indicate the locations of the cameras that were not on the vehicle. Cameras are identified by a two-digit code in the figures. The name of the file with the video indicates the rollover number and the camera number. For example, "1-7-80.wmv" is for Rollover #1, Camera 80, which was downstream of the expected rollover point. (The center digit can be ignored.) Cameras 81 and 88 were manned and panned the truck as it passed. Other external cameras were fixed on tripods.

Some of the rollovers with the single-unit truck had a camera mounted in the cab. (The camera was upside-down, so the ground is at the top of the images.) There were four cameras on the combination vehicle: two in the cab of the tractor aimed at the dummies, and two on the trailer. One on the trailer looked rearward, and one looked upward at the front of the forward rollover protection device. All of the videos on the CDs will normally play in real time except the two of the dummies taken inside the cab; these will play in slow motion.

Roll No.	RunId	Maneuver Description	Vehicle Type
1	106	31 mph, 100-ft-radius curve	Single-unit Truck

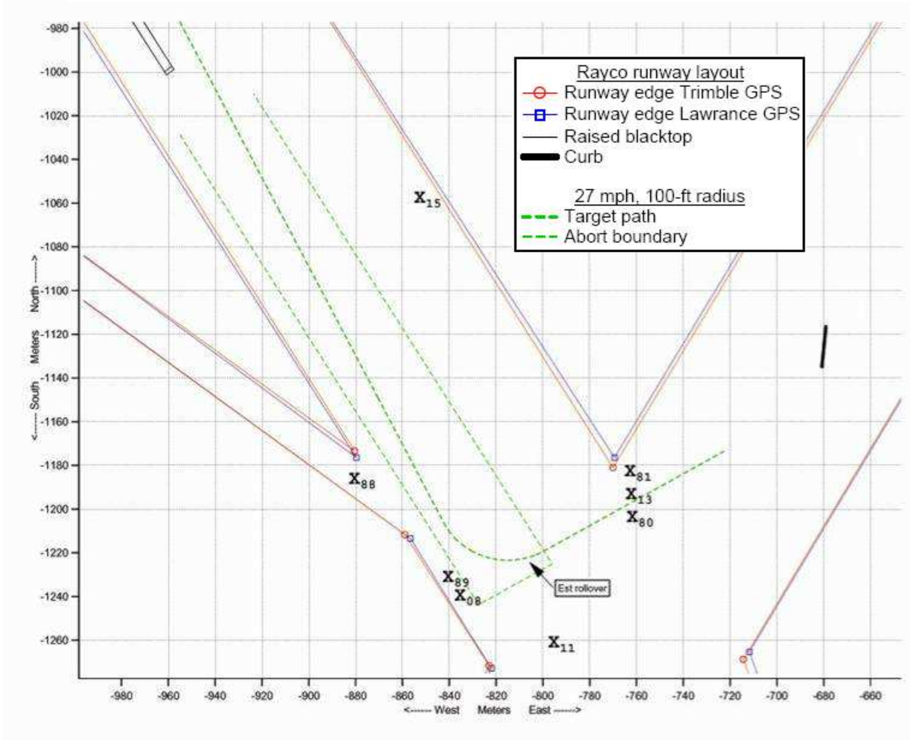


Figure C-1. Locations of the cameras for Roll No. 1

Camera 14 was held by hand by a passenger in the pusher truck.

Roll No.	RunId	Maneuver Description	Vehicle Type
2	110	40 mph, 100-ft-radius curve	Single-unit Truck

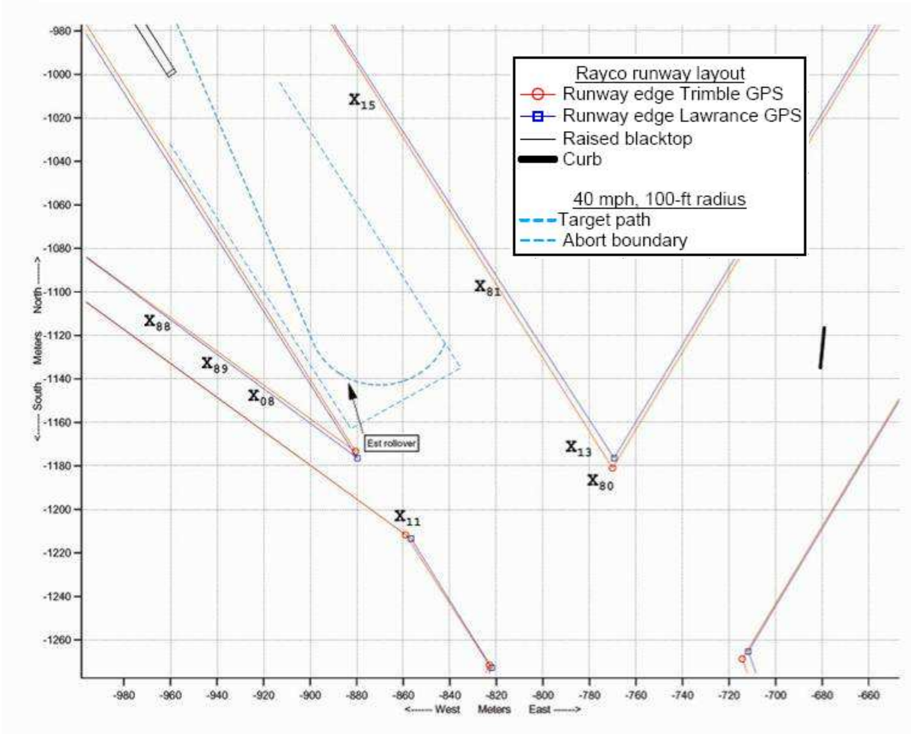


Figure C-2. Locations of the cameras for Roll No. 2

Camera 14 was held by hand by a passenger in the pusher truck.

Camera 7 was mounted to the truck, under the header.

Roll No.	RunId	Maneuver Description	Vehicle Type
3	115	45 mph, Closed-loop step steer	Single-unit Truck

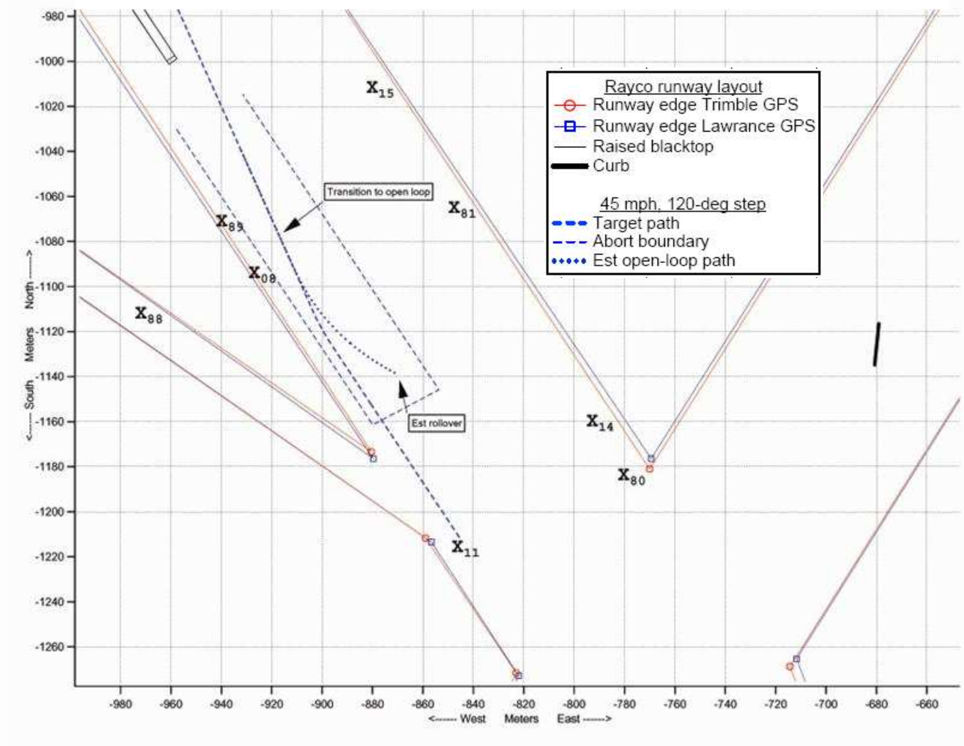


Figure C-3. Locations of the cameras for Roll No. 3

Camera 7 was mounted to the truck, under the header.

Roll No.	RunId	Maneuver Description	Vehicle Type
4	126	50 mph, Closed-loop swerve	Single-unit Truck

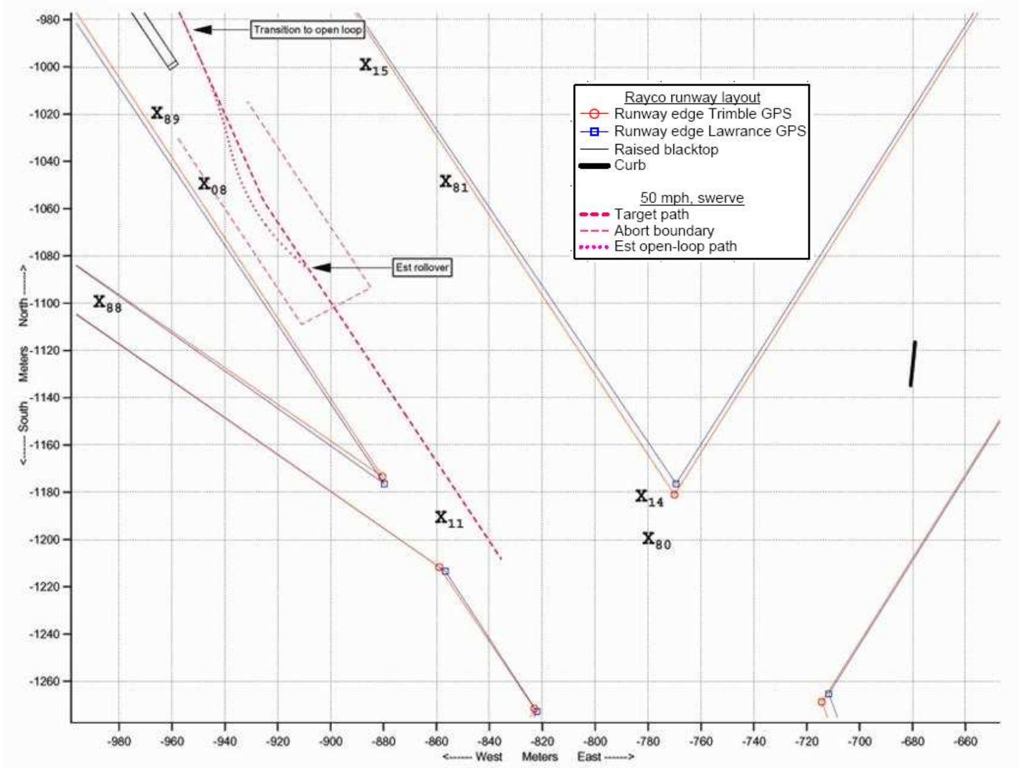


Figure C-4. Locations of the cameras for Roll No. 4

Roll No.	RunId	Maneuver Description	Vehicle Type
Semi	151	46 mph, 100-ft-radius curve	Tractor semitrailer

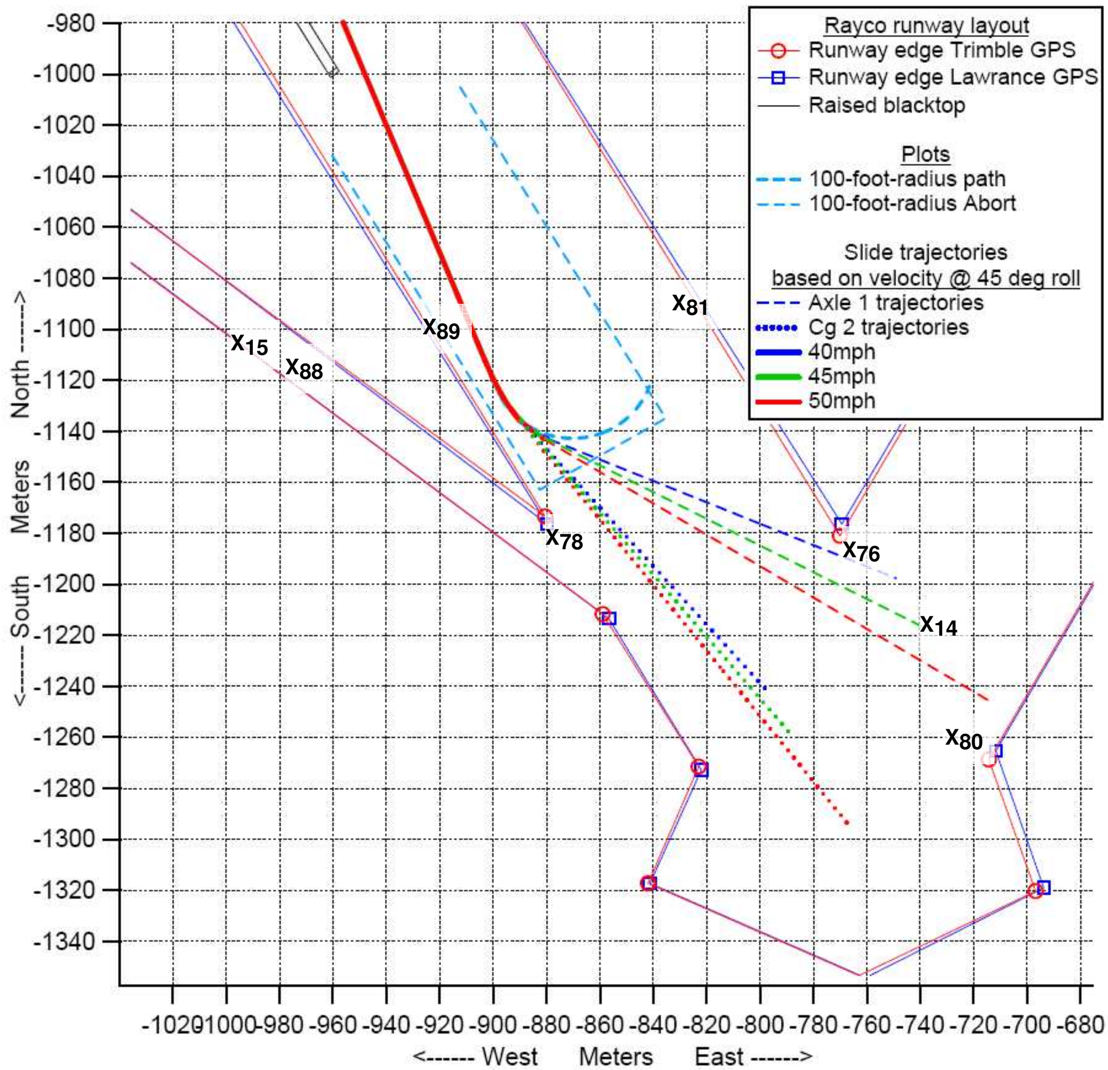


Figure C-5. Locations of ground-mounted cameras for the combination-unit rollover.

There were four cameras on the vehicle:

One on the trailer looking backward,

One on the trailer looking upward at the center rollover protection device, and

Two in the cab looking at the driver and passenger dummies.

See the photos on the next page for the mounting locations of the two trailer cameras.

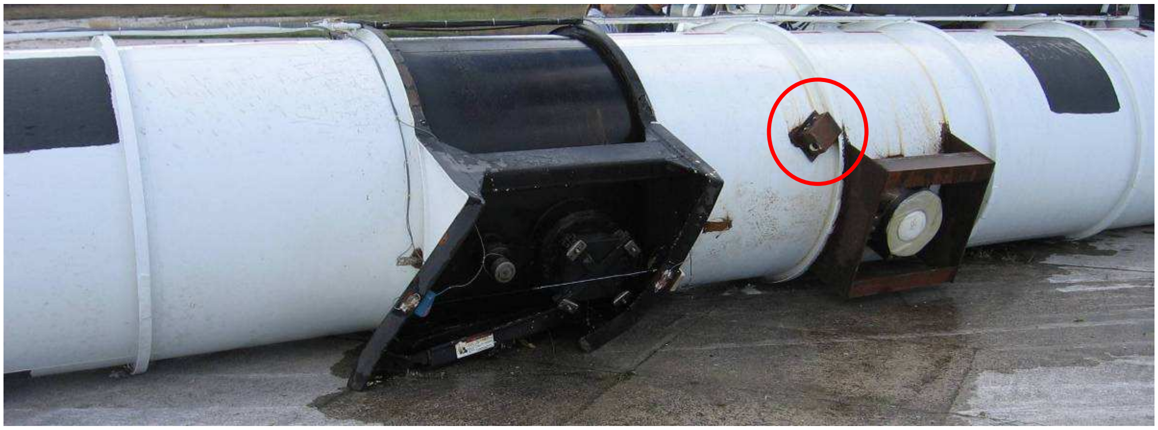


Figure C-6. The housing for the camera looking at the rollover protection device is in the circle. The GPS antenna is visible below and to the right of the camera.

Figure C-7. The rearward-looking camera on the trailer.