NATIONAL TRANSPORTATION RESEARCH CENTER, INCORPORATED
University Transportation Center

U15: Tripped Rollover (Phase A)

This project was funded by the NTRCI University Transportation Center under a grant from the U.S. Department of Transportation Research and Innovative Technology Administration (#DTRT06G-0043)

Douglas B. Pape, Jason T. Holdridge, J. Caleb Chitwood, and Alex W. Stilwell, Battelle

August 2009

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle **U15: Tripped Rollover (Phase A)**		5. Report Date **August 2009**
		6. Performing Organization Code
7. Author(s) **Douglas B. Pape, Jason T. Holdridge, J. Caleb Chitwood, and Alex W. Stilwell - Battelle**		8. Performing Organization Report No.
9. Performing Organization Name and Address **National Transportation Research Center, Inc.** **University Transportation Center** **2360 Cherahala Blvd.** **Knoxville, TN 37932**		10. Work Unit No. (TRAIS)
		11. Contract or Grant No. **DTRT06G-0043**
12. Sponsoring Agency Name and Address **U.S. Department of Transportation** **Research and Innovative Technology Administration** **1200 New Jersey Avenue, SE** **Washington, DC 20590**		13. Type of Report and Period Covered **Final Report March 2009 – August 2009**
		14. Sponsoring Agency Code **RITA**
15. Supplementary Notes		

16. Abstract

The Federal Highway Administration (FHWA) has expressed interest in learning more about pavement drop-offs at the edge of roadways and their relationship with the roll stability of heavy vehicles. Statistics kept by the National Highway Traffic Safety Administration (NHTSA) and other entities have shown that more than half of all heavy vehicle rollovers are associated with a run-off-road crash. Furthermore, the majority are “tripped;” that is, the truck rolled over because it ran over a drop-off or encountered a curb or other obstacle. Previous rollover research by the Heavy Truck Rollover Consortium [Knee et al., 2005; NTRCI, 2009a; NTRCI, 2009b], like nearly all previous full-scale rollover experiments, has focused on the “untripped” rollover; i.e., those in which the truck executes a maneuver (such as rounding a corner too quickly) and rolls on essentially level pavement. This report is the first publication to describe quantitative experiments in heavy vehicle behavior in roadway departure recoveries.

The long-term objectives of the recommended “tripped” rollover research are to:

- Develop and validate a model that explains how and when tripped rollovers occur and the influence of key components
- Develop recommendations and guidelines for reducing the likelihood of tripped rollovers, including recommendations for:
  - Highway and pavement design
  - Vehicle suspension and dynamics design
  - Stability control algorithms
  - Driver recovery procedures.

The objective for the experiments described in this report was to:

- Provide typical results from which further experiments can be designed
- Establish a dynamic vehicle model that can be enhanced in future years
- Attract participation from additional interested parties.

17. Key Word	18. Distribution Statement
Tripped rollover, heavy vehicles, roll stability, pavement drop-offs	**No restrictions**

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	**Unclassified**	**71**	

Table of Contents

List of Figures

List of Tables

List of Equations

Executive Summary

Experiments were conducted on a tractor and a cargo tank semitrailer to evaluate stability during a potential “tripped” rollover situation. A gravel shoulder was constructed next to existing pavement to form a 4-inch vertical edge. A test driver took the truck’s right-side tires onto the shoulder and then, at speeds ranging up to 35 mph, steered back onto the pavement, as if recovering from a roadway departure. Figure 1 shows the test truck executing the maneuver. Engineering data and video of the maneuvers documented the vehicle’s behavior.

Figure 1. Photograph. The truck drove with its right-side tires on a prepared gravel shoulder (left) and then steered to climb up over a four-inch vertical edge (right).

This was the first year of a planned multiyear effort. While the first year’s testing was a modest effort using readily available equipment and facilities, it did achieve its objective of providing useful results:

- Highway design and construction engineers can use the information that a four-inch vertical edge is not in itself dangerous at the conditions tested (tractor with a fully loaded cargo tank semitrailer, an alert and skilled driver, speed no greater than 35 mph). Softness of the shoulder, which was quantified after the experiments, figured into the response.
- Driver training will benefit from the descriptions of successful recoveries from roadway departure. In-cab videos of the driver’s steering action will be especially useful. (See Figure 2.)
- Designers of vehicles and their automated safety systems can use the measurements of acceleration, yaw rate, and other motion parameters that were recorded through the repetitions of the experiments.

Figure 2. Photograph. Videos of the forward view and of the test driver's handwheel motion will be invaluable in communicating safe recovery techniques to drivers.

The ultimate goal of the research is to determine the combinations of speed, steering input, edge height, and edge slope that are safe for heavy combination vehicles. Most prior experimental research on rollover of heavy commercial vehicles has focused on the stability of the vehicle in high-speed cornering. Experiments on mounting a pavement edge drop-off following a roadway departure have been conducted, but most were 25 or more years ago, and none have been conducted with heavy vehicles. The behavior of heavy vehicles on uneven pavement at high speeds is more difficult to predict than in better defined high-speed cornering maneuvers on level pavement. Such "tripped" rollovers are important to study because they are actually more common on the highway than are the "untripped" rollovers resulting from taking a corner too fast. The Federal Highway Administration has identified the need to conduct full-scale experiments with heavy vehicles attempting to mount pavement edge drop-offs. This project is the first to report quantitative experimental data for a heavy vehicle climbing a vertical pavement edge drop-off. While this first effort has yielded useful results, further research is needed at higher speeds, with the beveled "safety edge," and with more challenging shoulder conditions.

Chapter 1 – General Overview

The Federal Highway Administration (FHWA) has expressed interest in learning more about pavement drop-offs at the edge of roadways and their relationship with the roll stability of heavy vehicles. Statistics kept by the National Highway Traffic Safety Administration (NHTSA) and other entities have shown that more than half of all heavy vehicle rollovers are associated with a run-off-road crash. Furthermore, the majority are "tripped;" that is, the truck rolled over because it ran over a drop-off or encountered a curb or other obstacle. Previous rollover research by the Heavy Truck Rollover Consortium [Knee et al., 2005; NTRCI, 2009a; NTRCI, 2009b], like nearly all previous full-scale rollover experiments, has focused on the "untripped" rollover; i.e., those in which the truck executes a maneuver (such as rounding a corner too quickly) and rolls on essentially level pavement. This report is the first publication to describe quantitative experiments in heavy vehicle behavior in roadway departure recoveries.

Background

Motor vehicle rollovers fall in two broad categories—tripped and untripped. A rollover is said to be tripped if the tires suddenly encounter a fixed object, upsetting the vehicle. This can happen by striking a curb or guardrail or by tumbling down an embankment. A rollover would also be termed tripped if a lateral force on a tire is suddenly released, as when a tire is scrubbing a vertical pavement edge but quickly climbs the edge. Untripped rollovers, on the other hand, occur on essentially level pavement with the overturning moment being simply the cornering force on the tires, opposed by the centrifugal force at the center of gravity. Untripped rollovers are simpler to describe—they come from taking a curve too fast—but they are not the most common kind of heavy vehicle rollover. A recent report on cargo tank rollovers for the FMCSA [Pape et al., 2007] indicated that only 14% of cargo tank rollovers are untripped. Figure 3 shows the types of crashes in which rollovers occur.

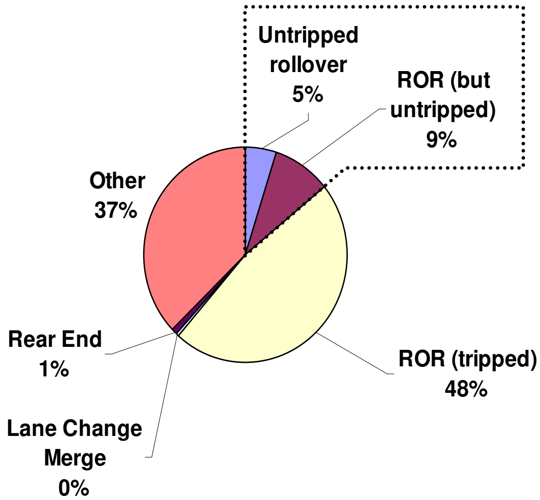

Figure 3.Pie Graph. More than half of all cargo tank rollovers are associated with a run-off-road (ROR) crash. Untripped rollovers account for 14 percent of the rollovers. Adapted from Table 2-8 of Pape et al. [2007], based on data in the General Estimates System.

Most experimental heavy vehicle rollover research involves untripped rollovers. There are many good reasons for that. The outcomes are simpler to predict. This means they are safer to conduct and models are easier to verify. Since untripped rollovers depend on fewer outside forces, they are a better measure of the vehicle's basic stability, and an improvement in the vehicle's stability will benefit both tripped and untripped rollovers.

Tripped rollovers can occur during a recovery maneuver after a vehicle has driven off the road. A severe drop-off, such as that shown in Figure 4 may lead directly to the rollover. Research with light vehicles has documented several ways this can happen. If a heavy vehicle suddenly mounts the drop-off and is on the pavement with a high crab angle (where the vehicle is pointed across the pavement but it still traveling more or less along the pavement), it can roll over. Also, overcoming the edge drop-off in a recovery maneuver can add to the centrifugal force causing rollover if the driver attempts to maintain lane integrity.

Figure 4. Photograph. A vertical pavement edge with an unusually high drop-off.

Research Objectives

The long-term objectives of the recommended “tripped” rollover research are to:

- Develop and validate a model that explains how and when tripped rollovers occur and the influence of key components

- Develop recommendations and guidelines for reducing the likelihood of tripped rollovers, including recommendations for:
  - Highway and pavement design
  - Vehicle suspension and dynamics design
  - Stability control algorithms
  - Driver recovery procedures.

The objective for the experiments described in this report was to

- Provide typical results from which further experiments can be designed
- Establish a dynamic vehicle model that can be enhanced in future years
- Attract participation from additional interested parties.

Summary of Previous NTRCI Rollover Work

In Phases 1 and 2 of their work for National Transportation Research Center, Inc., University Transportation Center (NTRCI), the Heavy Truck Rollover Consortium conducted a number of experiments on the roll behavior of a tractor with a van semitrailer [Knee et al., 2005]. In the third project of that series, named Phase A, the Consortium conducted a similar set of experiments with a flatbed semitrailer [NTRCI 2009a]. The Consortium is now completing Phase B [NTRCI 2009b] experiments with a cargo tank semitrailer, which was the same vehicle used in the Tripped Rollover experiments. To date, all of the reported experiments have been conducted on level pavement under conditions for potential “untripped” rollover.

A special task laid the groundwork for conducting experiments of tripped rollover following a pavement edge drop-off [Chapter 5 of NTRCI 2009a]. The report stated the problem and its significance, reviewed prior research in the field, outlined a set of experiments, and identified test tracks willing to undertake this unusual research. To fulfill the request of the FHWA, NTRCI has funded this Tripped Rollover project to actually conduct pavement edge drop-off rollover experiments.

Project Team

The project team was lead by Battelle Memorial Institute. Battelle is a multinational non-profit corporation dedicated to innovation in the areas of transportation, energy, health and life sciences, and national security and defense. Battelle staff members planned the “tripped” rollover experiments. Battelle outfitted the vehicle with additional instrumentation, a high-speed camera focused on the tractor steer tire, and strain gages on the tie rod to measure the force on the steering tire that encountered the pavement edge. Battelle was responsible for site preparation, test plan execution, data analysis, and reporting.

Link-Radlinski, Inc., of East Liberty, Ohio, provides comprehensive testing services for a variety of vehicle components. Link-Radlinski, Inc., was responsible for maintaining the tractor and semitrailer. This included installing instrumentation on the test vehicle, designing and mounting fixtures for the instrumentation, data collection and providing the test driver and test engineering support. The Link-Radlinski team had insight into vehicle stability during testing and driver capabilities.

Viewnyx Corporation of Ottawa, Ontario, is a leading provider of camera-based lane departure warning systems and video-based risk management software. Viewnyx provided a four-camera system and personnel for acquiring onboard video.

LBT, Inc., of Omaha, Nebraska, donated the tank semitrailer, which was custom built with outriggers for the NTRCI tests.

Michelin provided tires for the test, engineering advice, and custom software that aided in data reduction.

The tractor was leased from Volvo.

Project Description

The purpose of the project was to conduct full-scale experiments on the recovery of a heavy truck from a run-off-road condition. The test vehicle was a Class 8 tractor and cargo tank semitrailer. The tractor-trailer was controlled through the maneuver by a human driver. The maneuver consisted of the operator driving off the pavement onto a prepared shoulder of compacted gravel. At the appropriate location along the shoulder, the driver performed a recovery maneuver, turning back over a vertical edge onto the pavement while trying to maintain lane integrity. The truck was driven slowly for the early maneuvers. Tests were repeated at incrementally higher speeds up to 35 mph, the fastest that the facility could accommodate.

The heavy truck was outfitted with many sensors and video cameras. Engineering data was plotted and analyzed, and videos were studied. This data and information yields insight into the stability of heavy trucks as they return to the pavement over a vertical drop-off.

Chapter 2 – Experimental Procedure

A human driver maneuvered a tractor semitrailer combination truck off the pavement onto a prepared shoulder of compacted gravel and then steered back to the pavement over a four-inch vertical edge. Three recovery variants–oblique incidence, grazing incidence, and intentional overcorrection–were tested. Oblique and grazing runs were executed at speeds ranging from 5 to 35 mph. The overcorrection maneuver was attempted on a single run at 20 mph.

A written Test Plan was developed before the experiments so that all parties could agree on the test matrix and protocol. The safety precautions were identified in the Test Plan. The Test Plan is reproduced as Appendix A to this report. The actual experiments departed from the plan in several minor details; the plan has not been updated after the experiments. This chapter presents the experimental procedure as it was actually carried out.

Vehicle

A photograph of the test vehicle with its outriggers deployed is in Figure 5. The tractor was a 2007 model year Volvo VT830. Its overall wheelbase was 282 inches, and its tandem spacing was 53 inches. It had a leaf spring suspension in the front and air bags on the drive axles. Its weight was approximately 16,500 lb. It has been used extensively by Volvo for corporate testing, and it is the same tractor used in Phases A and B of NTRCI's Heavy Truck Rollover Characterization program. [NTRCI, 2009a and NTRCI, 2009b].

Figure 5. Photograph. The test truck on the runway at the airport.

The semitrailer was built specially for NTRCI's projects by LBT, Inc. Its length was 395 inches from the kingpin to the first axle, and the spacing between the axles was 49 inches It had a Hendrickson Intraax / Quaantum FX air bag suspension. The tank was the elliptical shape typical for carrying gasoline. It was built to be a test vehicle; it did not have the plumbing and electronics of a specification cargo tank. The outriggers were built into the trailer. They could be folded backward so the vehicle could be driven on public highways. The tank was specially manufactured so that compartments could be filled nearly full with water with the total weight distribution approximating a loaded gasoline tanker in revenue service. Three of the trailer's six 64-1/2-inch-high compartments were filled to within 12 inches of the top with water. The driver reported sensing a slight amount of sloshing in severe maneuvers. The axle weights in the as-tested condition are listed in Table 1. The manufacturer estimated that the center of gravity of the trailer loaded in this manner was 76 inches above the ground.

Table 1. Distribution of weight in the truck as it was tested.

Axle Set	Load, lb
Steer	11,880
Drive	34,220
Trailer	33,780
TOTAL	79,880

This is the same tractor and semitrailer combination that was used in the two related NTRCI projects: Heavy Truck Rollover (Phase B), and Co-simulation of Heavy Truck Tire Dynamics and ESC (Phase A). Testing for these two projects was at the Transportation Research Center, Inc., in East Liberty, Ohio, during the week before the Tripped Rollover experiments. The vehicle configurations for the three projects were identical, with two exceptions. The other projects alternated between dual and single tires, and all rims were aluminum; the truck had duals on the drive and trailer axles, and steel rims on all five axles for the Tripped Rollover experiments. The other two projects used two loading conditions, "high" and "low," ballasting the trailer with a combination of water and sand. For the Tripped Rollover experiments, three of the trailer's compartments were filled to a depth of 54.5 inches with water; there was no sand. Instrumentation was identical, too, except that the tie rod force (Appendix C) was recorded only during the Tripped Rollover experiments. Tractor and trailer were both equipped with electronic stability control (ESC), which was tested in one of the other NTRCI projects. The feature was enabled during the Tripped Rollover experiments to provide maximum safety, but neither the tractor nor the semitrailer's system activated during the experiments, so ESC was not a factor in the results.

Facility

Testing was conducted at the Darby Dan Airport west of Columbus, Ohio. The runway's orientation is east-west (numbers 9 and 27). It is about 5,900 ft long and 75 ft wide. A special gravel shoulder for this experiment was built on the north side of the runway. The truck drove east to west for all maneuvers, so the simulated roadway departures were to the right. The truck had over 2,500 ft to get up to test speed and 2,400 ft to stop after a completed test run. Wide sections at both ends of the runway allowed the truck to turn around.

The gravel shoulder constructed for these experiments was 1000 ft long and five ft wide. The initial 175 ft of its length was flush with the pavement so the truck could safely and gradually move to the shoulder, and then the four-inch drop-off was developed over a 50-ft-long ramp in the shoulder. Figure 6 is a photograph of the beginning of the shoulder. The tires often dug ruts in the shoulder, so it was re-compacted as necessary during the tests. Details of the shoulder design, construction, and testing are in Appendix B.

To allow adequate acceleration distance and stopping distance, a rule established before the tests permitted a maximum speed of 40 mph. The limiting factor during the tests was the condition of the shoulder. The highest test speed was 35 mph, though the fastest that was repeated was only 30 mph.

Figure 6. Photograph. The beginning of the gravel shoulder was flush with the runway, as is visible at the left. A ramp leads to the four-inch vertical edge.

Maneuvers

The maneuver was to accelerate the truck on level pavement, drive the right side tires onto a gravel shoulder in a controlled manner, return to the pavement, and then steer to keep within 12 ft (a normal lane's width) of the pavement edge. The process is illustrated schematically in Figure 7, and Figures 8 to 10 are photographs of the experiments. Three snapshots in time are shown in the figures. The maneuver began with the truck running up to speed in a straight line. Figure 8 shows the truck approaching the shoulder. When the truck was abreast of the shoulder, the driver steered it so the right tires were on the gravel and the left tires remained on the pavement. The right tires descended a shallow ramp in the shoulder, which is visible in Figure 6. Snapshot number 1 in Figure 7 shows the truck fully on the pavement in the top view; the side view is a moment later, when the tire is descending the ramp. This established a stable, straight path with the left tires on the pavement and the right tires at a slightly lower level on the shoulder. The dropped off condition is snapshot 2 in Figure 7, and it is the two photographs in Figure 9. Cones on the shoulder (visible in the lower photograph in Figure 9) indicated to the driver where to return to the pavement. Immediately before reaching the cones, the driver steered toward the pavement edge. The front right steer tire climbed the pavement edge (snapshot 3 in Figure 7 and the photographs in Figure 10), with the rest of the vehicle following. The driver steered the truck back parallel with the pavement and brought it to a stop.

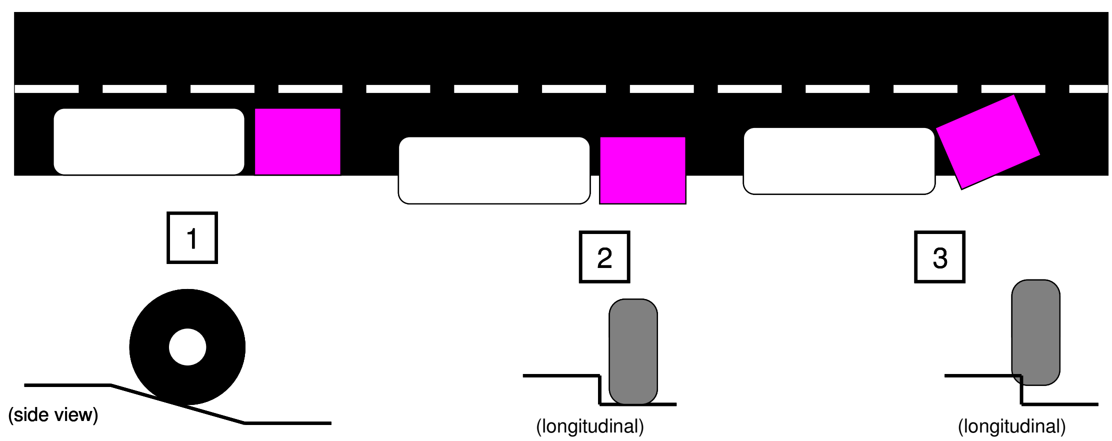

Figure 7. Illustration. Three snapshots in time during a drop-off recovery experiment. At snapshot 1, the truck, at speed, descends a gravel ramp with the right tires while the left tires remain on the pavement. At snapshot 2, the truck is in a stable condition with right tires off the pavement. At snapshot 3, the truck steers back onto the pavement, over the vertical edge.

Figure 8. Two photographs. The truck approaches the shoulder at the test speed.

Figure 9. Two photographs. The truck is in a stable straight path with its left tires on the pavement and its right tires in the gravel shoulder.

Figure 10. Two photographs. The tractor has climbed the vertical edge, and the trailer will soon follow.

Most trainers tell their drivers to recover from a pavement drop-off by first getting control of the vehicle in a straight path and then to gently “jerk” the handwheel. This will cause the steer tire to approach the edge at an oblique incidence, as illustrated in the sketch on the left in Figure 11. Trainers caution against steering back too gradually, because it can cause the steer tire to “lock up” against the pavement edge as in the right half of Figure 11. This grazing incidence can cause the tire to suddenly climb the edge and threaten the stability of the vehicle. In the first several maneuvers, the driver was instructed to return to the pavement by the preferred method, with oblique incidence. After experience was gained, maneuvers with grazing incidence were run. In these cases, the driver slowly turned the handwheel until the steer tire was against the pavement edge, and then slowly increased the force to the handwheel until the tire climbed the edge. In one instance, the driver was instructed to purposely overcorrect. The driver jerked the handwheel farther than in a normal maneuver and then held it longer than was necessary before countersteering.

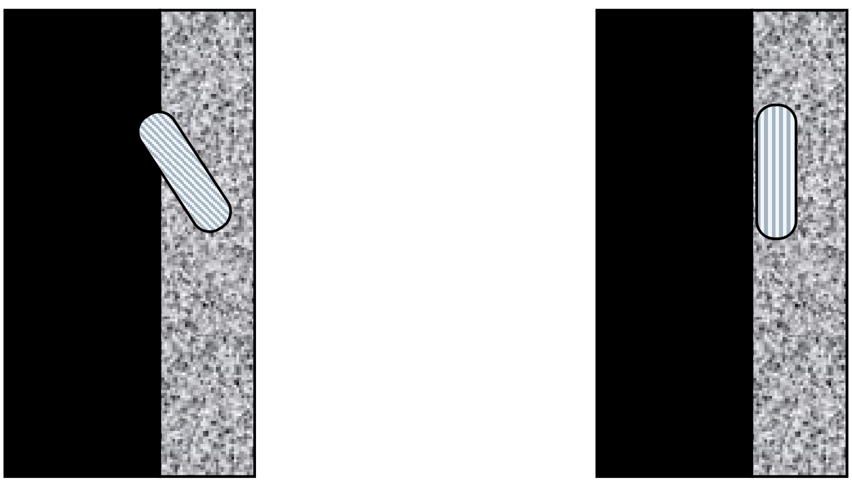

Figure 11. Illustration. Illustrated on the left is a recovery maneuver approaching the pavement edge at an oblique angle. Adjacent is an illustration of a tire grazing the edge of the pavement. Both of these maneuvers were executed during the experiment.

Table 2 is the list of test maneuvers. The first two columns are simply for identifying a set of data; each “run” was one trip down the runway. The speed is the nominal speed of the maneuver; the actual speed was recorded by the instruments. The path indicates whether the run was a preliminary maneuver conducted entirely on the pavement or an actual test maneuver to the shoulder with recovery. The handwheel action identifies the instructions given to the driver as in the discussion accompanying Figure 11. Three lines in the table are highlighted with yellow and indicated with an arrow; data from those runs is plotted in the next section.

Table 2. Summary of all test maneuvers.

Group	Run	Speed	Path		Handwheel Action		
		mph	Pavement	Gravel	Oblique	Grazing	Overcorrection
AA	1	10	X		X		
AB	1	20	X		X		
AC	1	30	X		X		
AC	2	(no data)					
AC	3	40	X		X		
AD	1	5		X	X		
AD	2	10		X	X		
AD	3	15		X	X		
AE	1	20		X	X		
AE	2	25		X	X		
AE	3	30		X	X		
AF	1	10		X		X	
AF	2	15		X		X	
AF	3	20		X		X	
AF	4	25		X		X	
AF	5	30		X		X	
AG	1	35		X	X		
AH	1	20		X	X		
AI	1	20		X	X		
AI	2	20		X	X		
AI	3	20		X	X		
AI	4	20		X	X		
AI	5	20		X	X		
AI	6	20		X	X		X
AJ	1	20		X		X	
AJ	2	20		X		X	

Instruments

Sensors and data recorders on the vehicle quantified its motions. There were five video cameras on the vehicle and four stationary video cameras.

The onboard instruments were identical to those for the two other NTRCI projects that used this vehicle. Inertial measurement units measured all six accelerations of both the tractor and the semitrailer. Speed was recorded both through the vehicle and the independent instruments.

Brake pressures were monitored. The driver's handwheel position was measured, as was the steer angle of the left front steer tire. A number of parameters were recorded from the truck's CAN bus.

One sensor not used in the other projects was added for Tripped Rollover. A pattern of four strain gages was mounted on the tie rod to measure the axial loading. Design and calibration of this sensor is documented in Appendix C.

Viewnyx provided four onboard cameras that recorded at a low frame rate—10 frames per second. Two were in the cab, one directed at the driver's hands and one forward showing the view that the driver saw. Two were mounted on the right-side mirror, one looking at the right steer tire and one looking backward. The fifth onboard camera recorded at a high frame rate—210 frames per second. It was mounted in the right steer tire's wheel well, looking rearward at the tire. It showed the tire deforming as it climbed the edge. The four Viewnyx cameras were synchronized with one another. An LED visible to one of the Viewnyx cameras and a separate LED visible to the high-speed camera illuminated when engineering data recording began so that all onboard recorders, data and video, could be synchronized.

Chapter 3 – Results

The extensive instrumentation on the test tractor allowed for a detailed study of the dynamics of the recovery maneuver. Of particular interest are the handwheel angle, the trailer roll angle, and the tie rod force. The handwheel angle serves as a good summary of the maneuver, capturing the driver's input. The vehicle roll angles provide an indicator of the severity of the maneuver and whether rollover was approached. The tie rod force provides information about the tire-to-soil interface as well as the effect of the roadway edge during recovery. This chapter presents these three data traces for three representative maneuvers.

These traces record the full steering event. Data recording began when the truck was at the test speed, before the driver steered onto the shoulder. Recording ended when the truck was stabilized and beginning to slow.

Characteristics of a Successful Recovery: Oblique Incidence

The first maneuver to be examined is an oblique incidence. This is the steering pattern drivers are trained to follow. The nominal speed was 30 mph, and the actual speed of this particular run was 29.8 mph. The experimental event was more aggressive than a driver would experience in a normal day's work, but the test driver was in full control at all times and the truck was not in danger of rolling over.

Figure 12 shows the handwheel angle. The sharp positive peak shortly after 15 seconds represents the driver's initial correction to return to the road. The following negative peak represents the correction to hold the lane. Figure 13 are stills from the video of the driver making this same maneuver. The two figures have the same information; the quantitative trace is more useful to engineers, and the pictorial video is more meaningful to drivers.

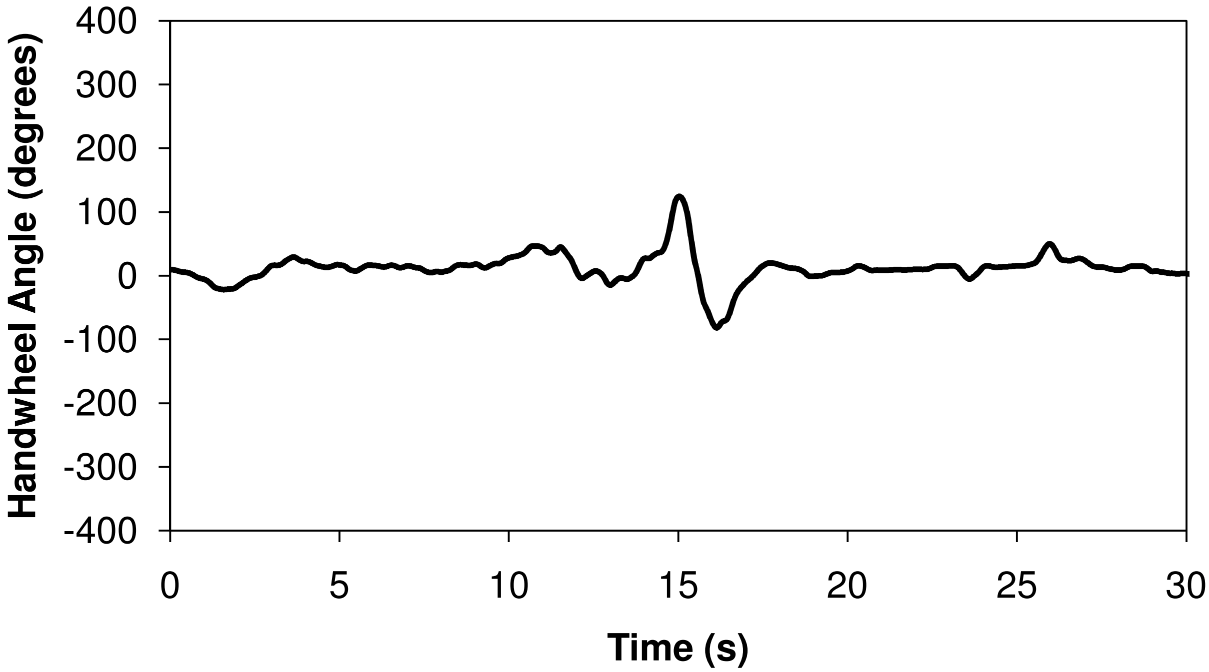

Figure 12. Graph. Handwheel Angle During a 30-mph oblique recovery.

Figure 13. Two photographs. Driver making a recovery maneuver onto the pavement (left) and then countersteering to remain in the original lane (right).

Figure 14 shows the roll angles of the tractor and trailer during the same 30-mph oblique incidence recovery. At roughly 5 seconds, both roll angles go to a range of 5 or 6 degrees. This is due to the right side tires rolling on a surface 4 inches below the left side.

The roll angles increase to 6 or 7 degrees as the truck continues. The rise to the peak roll angle of 7 degrees on the tractor and trailer that occurs 15 seconds into the run corresponds to the recovery maneuver.

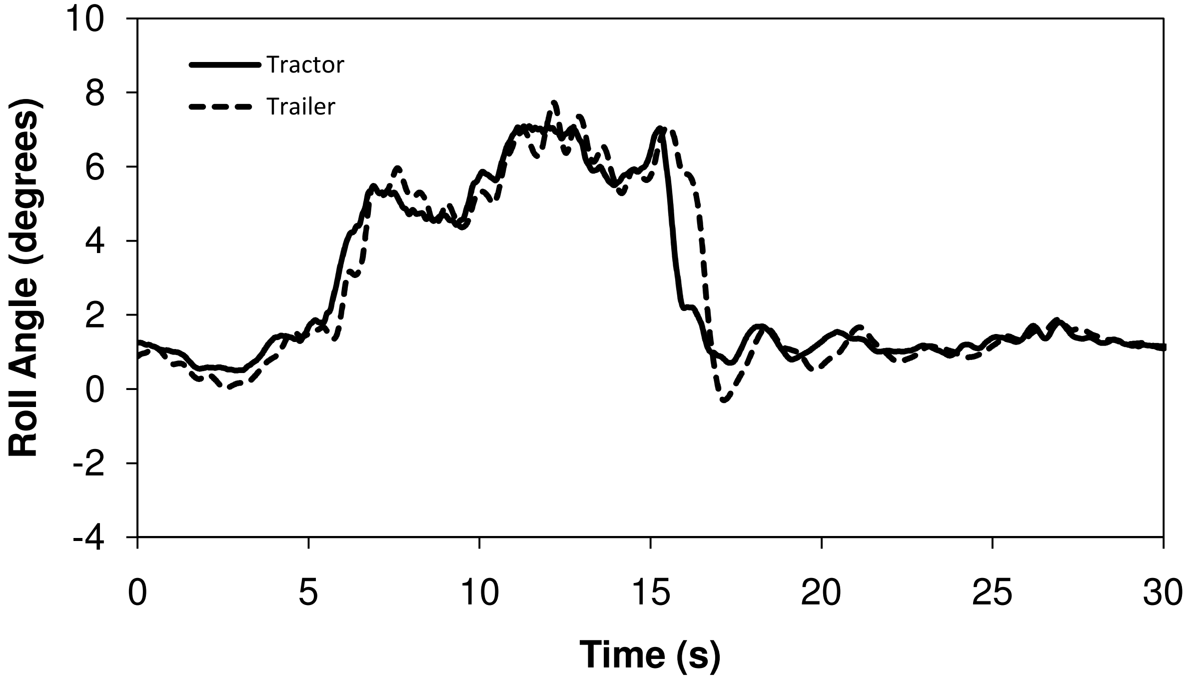

Figure 14. Graph. Tractor and Trailer roll angles during a 30-mph oblique recovery.

Figure 15 shows the force acting on the tie rod. Again, the peak that occurs 15 seconds into the run is due to the truck returning to the paved surface.

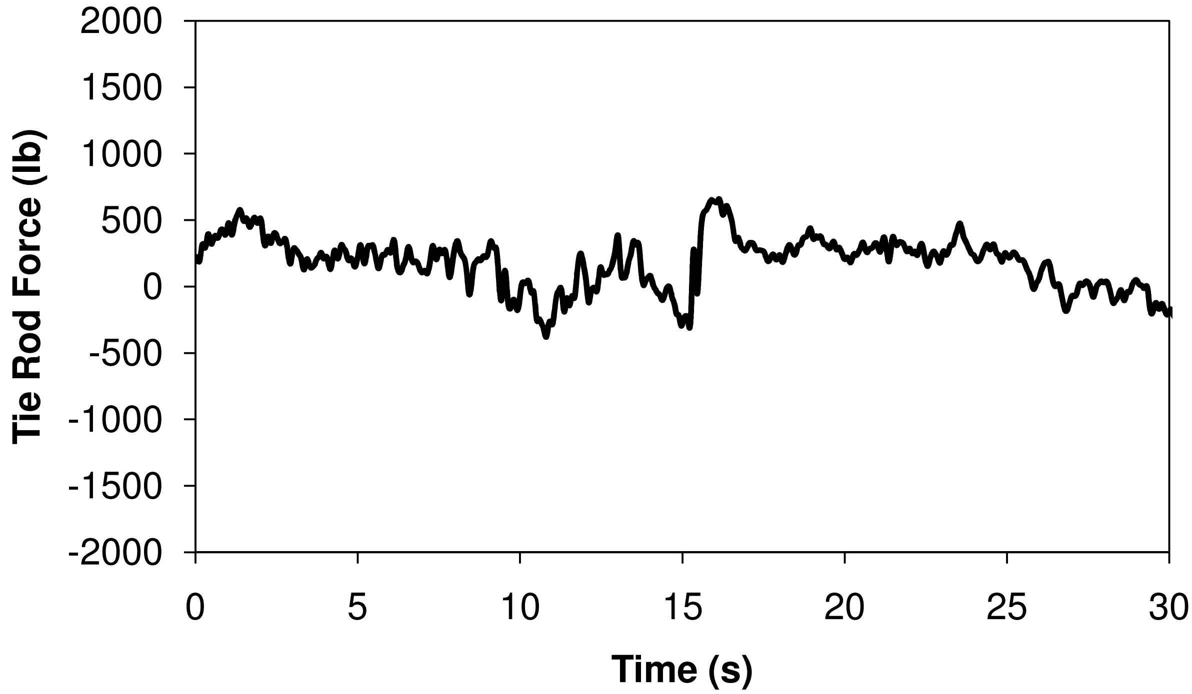

Figure 15. Graph. Force on the tie rod during a 30-mph oblique recovery (tension is positive).

Characteristics of a Successful Recovery: Grazing Incidence

In a "grazing" recovery maneuver, the driver returned to the paved surface gradually, causing the tire to scrub against the pavement edge. The actual speed of the run shown in the next set of figures was 26.7 mph.

Figure 16 illustrates that the driver slowly increased the handwheel angle to create the grazing incidence. The handwheel angle briefly stopped climbing around 75 degrees of input as the steer tire contacted the edge and the scrubbing against the edge momentarily prevented further turning of the wheel. The driver continued applying force to the handwheel until the tire broke free and climbed the edge.

Figure 17 shows the tractor and trailer roll angles during the grazing recovery maneuver.

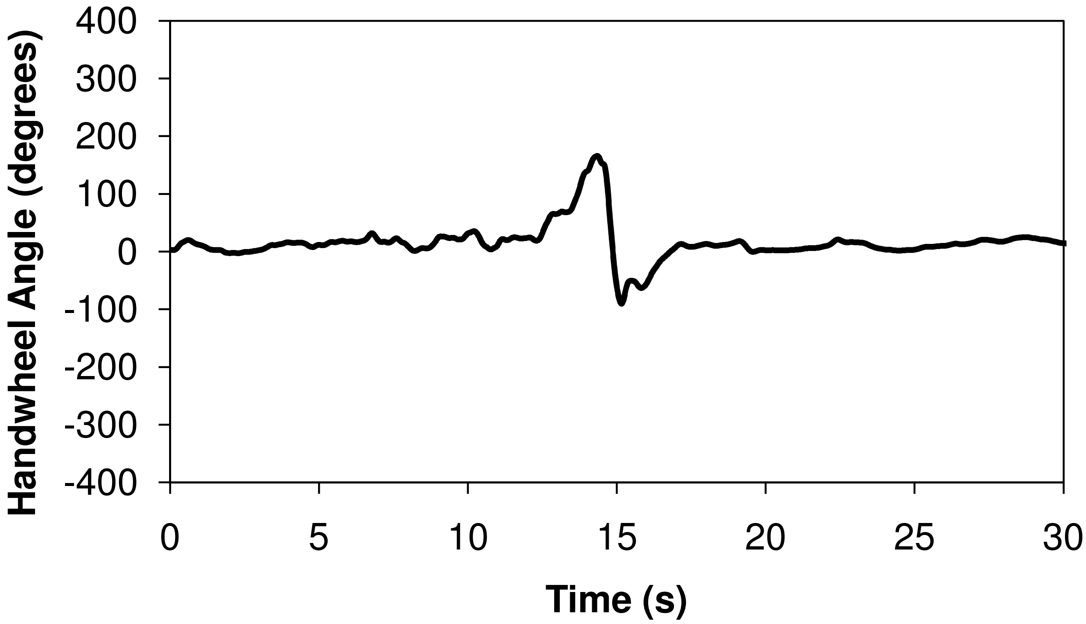

Figure 16. Graph. Handwheel angle during a 30 mph grazing recovery.

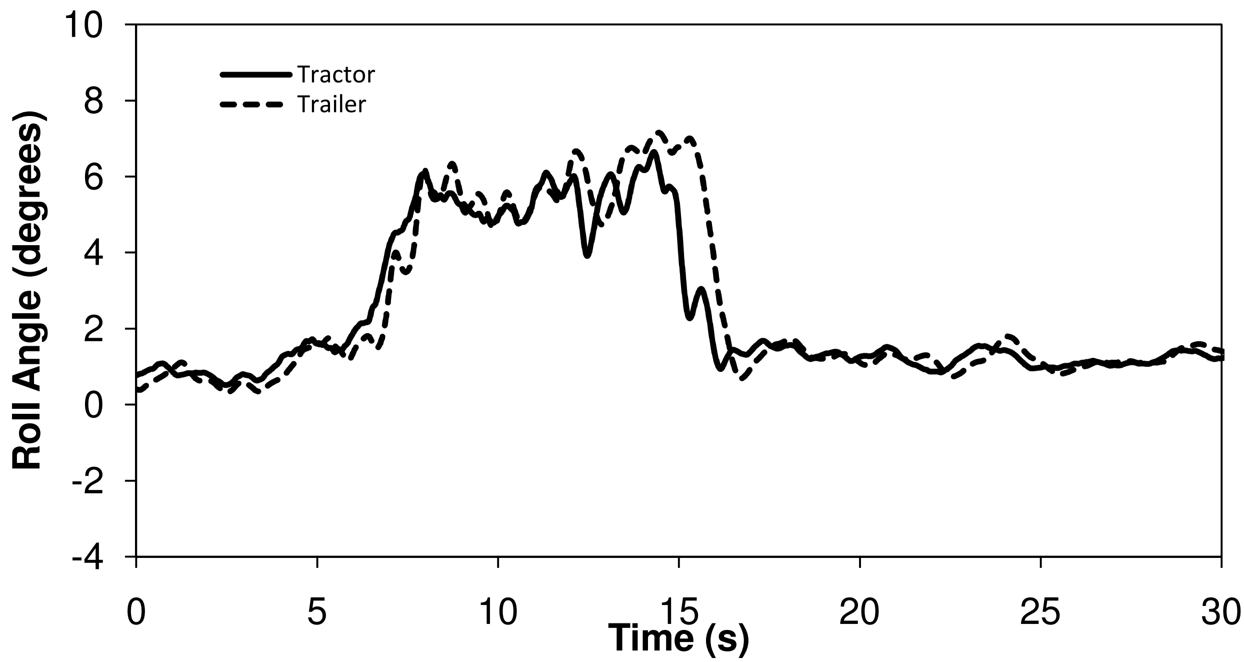

Figure 17. Graph. Roll angles during 30-mph grazing recovery.

Figure 18 shows that the peak tie rod force of this maneuver is significantly higher than during the oblique recovery maneuver. This is expected because the tire has more contact area with the paved edge during a grazing recovery than an oblique recovery. The force required to mount the edge is much greater. The compressive (negative) force increases as the scrubbing portion of the maneuver begins at around 13 seconds. The forces continue to rise for one second as the tire scrub continues and the driver applies increasing input in an attempt to regain the paved surface. Just prior to 15 seconds, the tie rod force goes to near zero as the tire mounts the edge and the compressive force associated with tire scrubbing is removed.

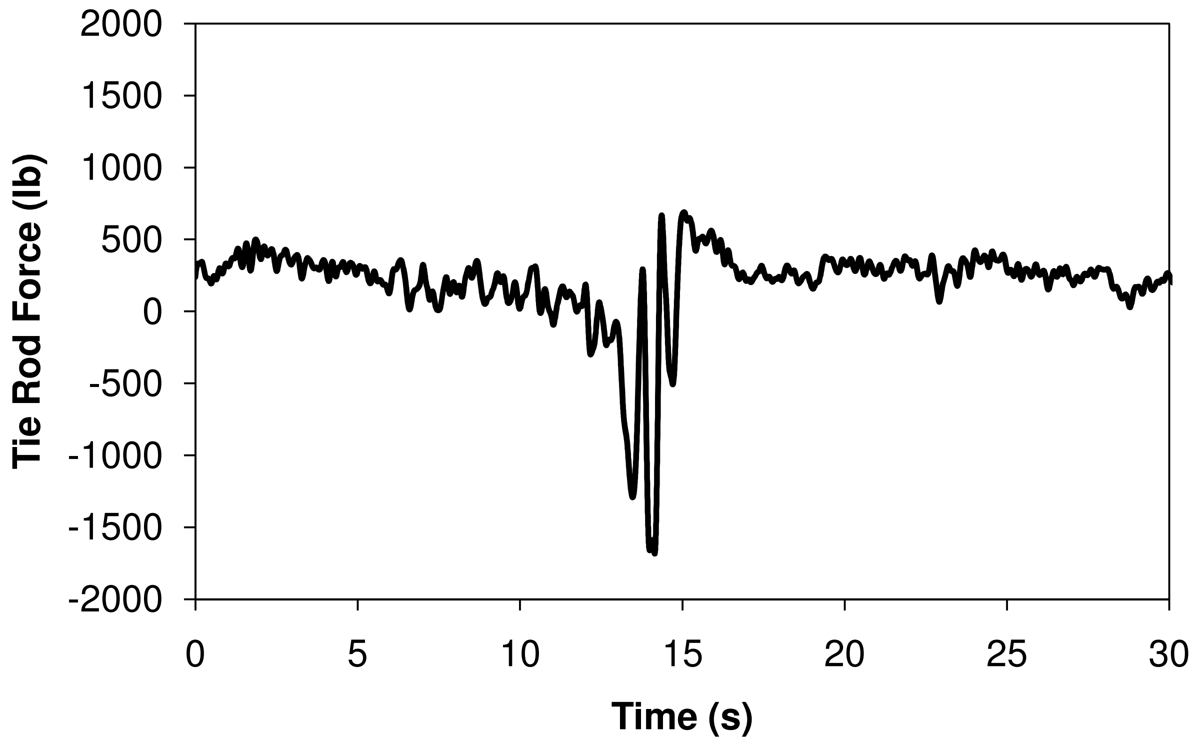

Figure 18. Graph. Force on the tie rod during a 30-mph grazing recovery. The high negative value indicates large compression in the tie rod as the left steer tire (controlled directly by the power steering) pushes on the right tire (through the tie rod) to make it turn into the pavement edge.

Figure 19 shows an expanded view of this grazing incidence maneuver around the moment where the right steer tire returned to the pavement. Shortly before the 13-second point, the handwheel angle begins holding a constant value of approximately 75 degrees. This represents the beginning of scrubbing. As the tire contacts the edge, the edge briefly prevents further rotation of the handwheel. The driver reported applying increased force to the handwheel until the tire climbed the edge. That is apparent in the figure, as the tie rod force builds while the handwheel is stationary. (As the compressive load is increasing, the signal becomes more negative.) At 13.5 seconds, the handwheel angle begins to increase as the turning force on the tire is enough to climb the edge. Figure 20 is a still picture taken from the high-speed video of this run. In the image, the inside half of the tire has mounted the pavement but the outside half of the tire remains at the level of the shoulder. High-speed video revealed that this behavior was typical of a grazing incidence recovery maneuver. During this particular maneuver, the video shows the tire briefly rotating back towards the shoulder as one half of the tire is on the pavement while the other half is off. This rotation corresponds to the brief drop in tie rod force at approximately 13.75 seconds. As the tire turns back away from the shoulder and continues to steer the truck onto the pavement, the edge of the pavement severely deforms the tire and causes the large peak load. Shortly afterwards, the outside half of the tire climbs onto the paved surface. As the tire returns to the roadway, tie rod force returns to near zero and the driver begins to decrease the handwheel input angle to finish the recovery maneuver.

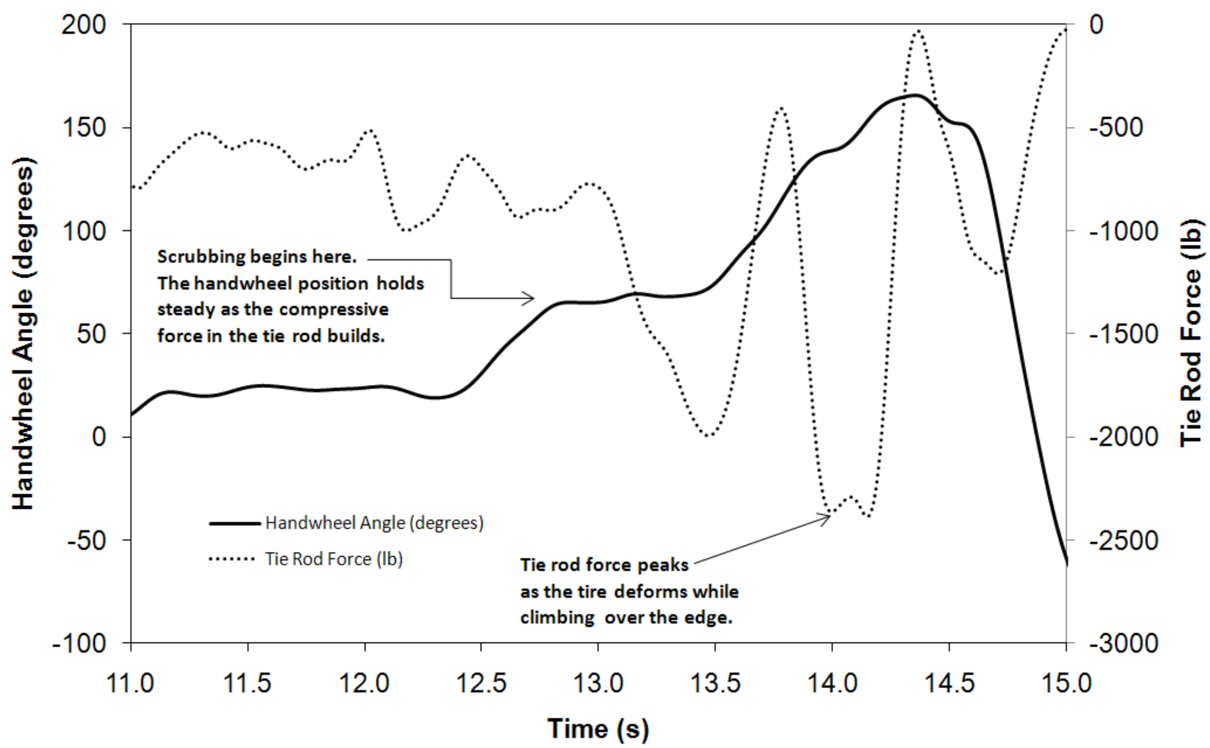

Figure 19. Graph. The tie rod force and handwheel angle during a grazing incidence recovery.

Figure 20. Photograph. A still from the high-speed video of the right steer tire, at the instant it climbs the pavement edge in the grazing-incidence maneuver.

Though the maneuver was harsher than the oblique incidence, the driver was able to control the truck and return it to its lane. In one grazing incidence recovery, the last one, the truck did touch a few cones marking 12 ft from the pavement's edge.

Characteristics of an Intentional Over-recovery

The test driver was instructed to perform an oblique recovery maneuver with an "over-corrected" handwheel input. This was intended to simulate a surprised or less well trained driver attempting to recover from a run-off-road event. The actual speed during the over-correction was 19.9 mph.

The handwheel input data is in Figure 21. The sharp positive peak at approximately 35 seconds represents the beginning of the recovery maneuver. As the truck re-enters the roadway, the driver reacts to the initial over-correction with a large input in the opposite direction, represented by the negative peak at approximately 37 seconds. An additional positive input is required to complete the recovery maneuver.

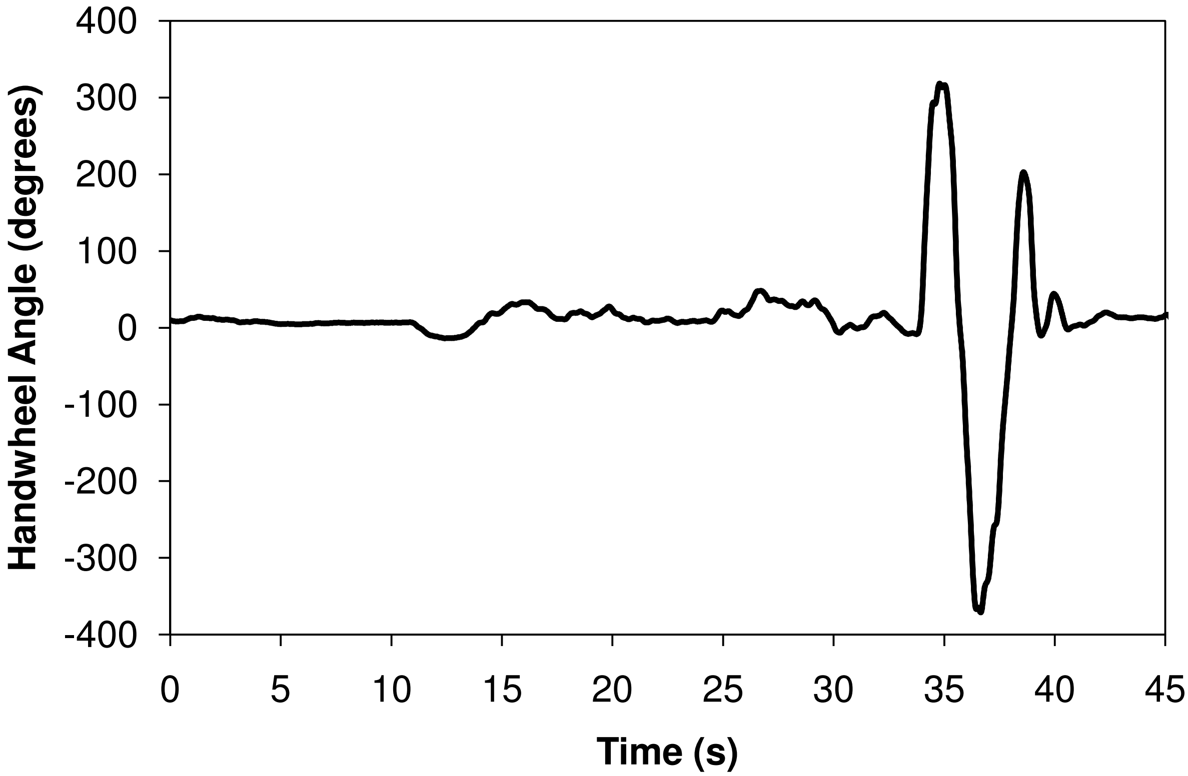

Figure 21. Graph. Handwheel angle during a 30 mph over-corrected recovery.

Tractor and trailer roll angles are in Figure 22. The over-corrected maneuver shared many of the characteristics of the standard oblique recovery. The roll angles approached a level of 4 or 5 degrees initially due to the surface height difference between the shoulder and pavement. The shoulder was softer near the outside edge. As the right side tires moved out onto the soft portions of the shoulder, roll angles further increased to 6 or 7 degrees due to subsidence. The roll angles peak at almost 8 degrees as the recovery maneuver begins. The over-corrected maneuver also displays a significant roll in the other direction as the driver countersteers. This was the only maneuver of the project where the truck was significantly beyond the 12-ft lane markers.

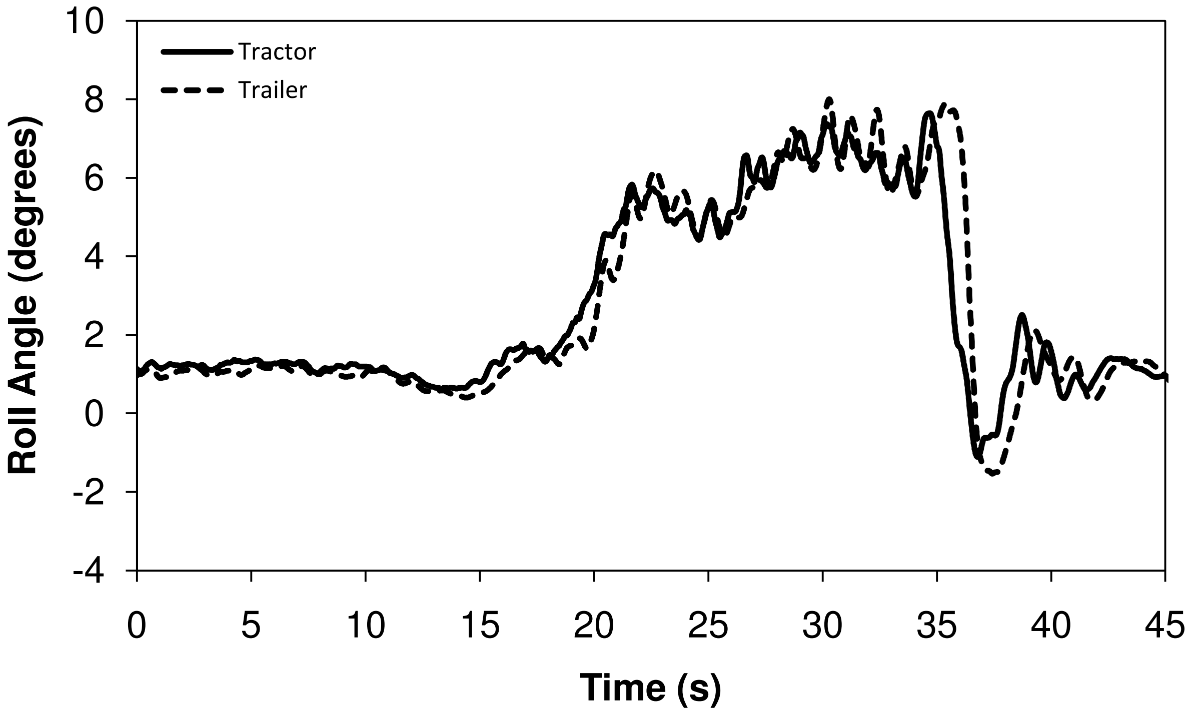

Figure 22. Graph. Roll angles during an over-corrected recovery maneuver.

Figure 23 shows the tie rod force during the over corrected recovery maneuver. Much like the roll angles, this plot begins similarly to the standard oblique recovery maneuver. However, the magnitudes are exaggerated, with forces reaching almost 1000 lb in the over corrected case. The typical oblique recovery generated only 500 lb at the same nominal 20 mph.

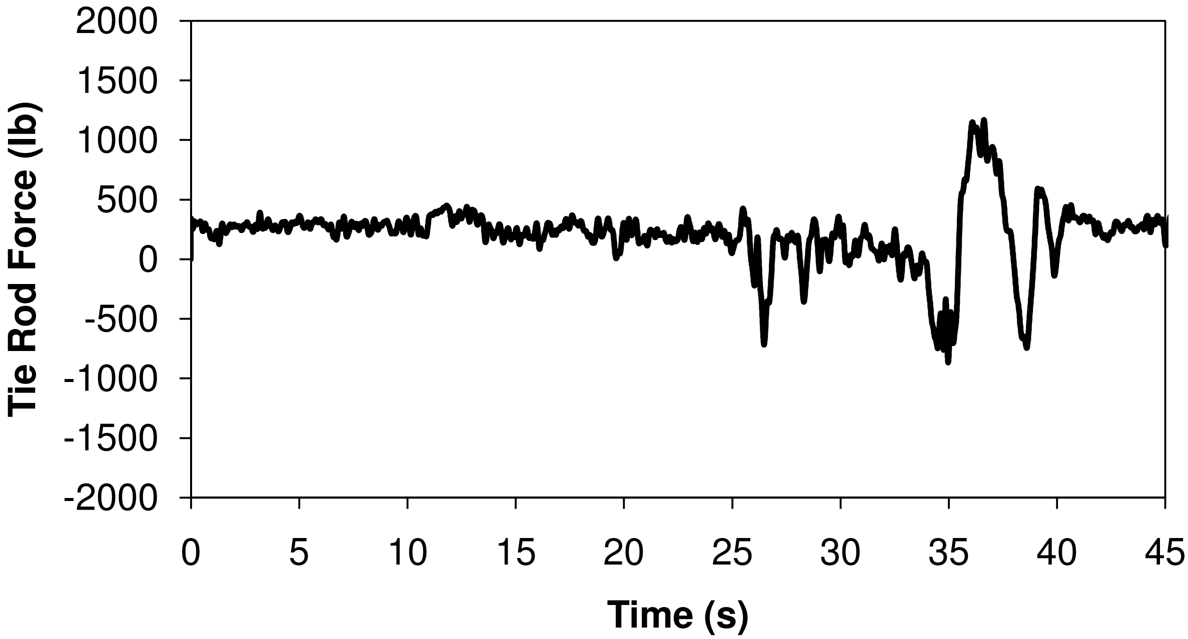

Figure 23. Graph. Tie rod force during a 20-mph over corrected recovery maneuver (tension is positive).

Chapter 4 – Implications

Though these experiments had only a single edge condition (vertical), a single combination vehicle (tractor and cargo tank semitrailer), and the maximum repeatable speed was limited to 30 mph, the results do provide implications for three broad categories of users. The fact that a truck can safely climb a 4-inch edge at 30 mph tells highway designers that a beveled edge may not be necessary for low-speed roads, and it tells drivers that slowing to 30 mph is adequate for climbing such an edge, if other conditions are favorable. The hazards of a soft shoulder were known before the experiments, and they were certainly confirmed.

Highway Construction

At speeds up to 30 mph, recovering from a run-off-road incident with a 4-inch-high asphalt edge is not inherently difficult. This experiment's conditions of speed and edge height do not produce enough vehicle instability to produce a "tripped" rollover. However, any difficulty in this recovery maneuver resided in overcoming the conditions of the shoulder. At 30 mph, the test driver indicated that steering had become difficult because the shoulder was soft. The driver had to over-steer to return the vehicle to its lane. At speeds higher than this, a recovery maneuver may not be possible given the shoulder conditions. The maneuver may produce a "tripped" rollover or the vehicle may be forced further off the road due to subsidence. Therefore, a shoulder this soft increased the likelihood of an incident during the recovery maneuver. A soft shoulder may lead to rutting, a dangerous condition for vehicles.

The Ohio Department of Transportation (ODOT) performed a Falling Weight Deflectometer (FWD) test on the shoulder. Analysis of this data revealed the moduli along the shoulder to be between 2,000 and 22,000 psi. These are normal values for a typical shoulder with a compacted sub-base and stabilized crushed aggregate. Therefore, soft sections of typical highway shoulders could possibly increase the severity of a recovery maneuver. Highway shoulder construction can benefit from the knowledge of the effect that shoulder stiffness has on a run-off-road recovery maneuver.

A recent comprehensive study of pavement edge drop-offs [Hallmark et al., 2006] surveyed states and provinces for their construction and maintenance practices concerning drop-offs. As construction designs typically call for flush shoulders, most do not have a standard for a drop-off in new construction. The majority of jurisdictions do have a practice of inspecting for edge drop-offs that have developed due, for example, to erosion. Maintenance is scheduled if the height exceeds a limit (ranging from 1-1/2 to 3 inches among jurisdictions). Ideally, then, a vertical edge would never exceed 4 inches, except possibly for a brief time in a construction zone, where it would be marked.

The test driver's comments and the video of the truck traversing the softer sections of the shoulder at higher speeds show that this combination is near the limit of a driver's ability to control the vehicle. Further experiments at higher speeds, soft shoulders, and various edge designs are needed to completely quantify the requirements for safe recovery.

Driver Training

The project team consulted with a number of carriers' safety officers in planning the experiments. They were asked for their suggestions of good shoulder recovery practice, so the practice could be documented in the experiments. All safety officers said that part of the training for their drivers is to slow down before considering a return to the pavement. When pressed, though, only a few provided a particular safe speed, and those ranged by more than 20 mph. Repeated successful recoveries at speeds of 20 to 30 mph (in one case 35 mph) proved that a vertical edge can be climbed at that speed if other conditions are favorable. (One vice president's advice to drivers will never be negated—"If you are at all in doubt that you can safely get back to the road, stop and call for a tow.") Videos and descriptions of the successful recovery maneuvers will be useful training materials for drivers.

Several of the experts soberly cautioned of the dangers of a soft shoulder: attempting to steer the tractor up to the pavement while the trailer is falling to a ditch is almost certain to lead to a rollover. The test driver reported that the shoulder was "fighting" the steering actions during some of the faster test runs. The tests did not progress beyond speeds where the driver began experiencing difficulty with the softness of the shoulder.

With nearly all of the experimental runs resulting in a successful recovery maneuver, the question naturally arises as to what factors may lead to a rollover or severe lane crossing. Certainly the test driver was awake, alert, and prepared for the event. A driver who is suddenly faced with a roadway departure may not respond as appropriately. In a natural roadway departure, the vehicle would hit the shoulder following a drop-off, not a ramp, and it would reach the shoulder at a highway speed, not a slow recovery speed. These effects would make a recovery more difficult than the tests, even for a skilled driver. They deserve further attention.

Vehicle Design

Prior to performing the recovery maneuver experiments, two related NTRCI projects put the test truck through a series of maneuvers to assess its roll stability [NTRCI, 2009b; Limroth et al., 2009]. These tests were conducted on the large Vehicle Dynamics Area at the Transportation Research Center, Inc. The maneuvers were a high-speed ramp steer, a step steer, and a pulse steer that was similar to a lane change. The tests were conducted with the same vehicle in two loading conditions that were not used in the Tripped Rollover project. The high-speed ramp steer was carried out in those two loading conditions, plus the loading condition of the Tripped Rollover project, so direct comparisons can be made.

Trailer lateral acceleration versus trailer roll angle, from the ramp steer maneuver at 30 mph, are plotted in Figure 24.

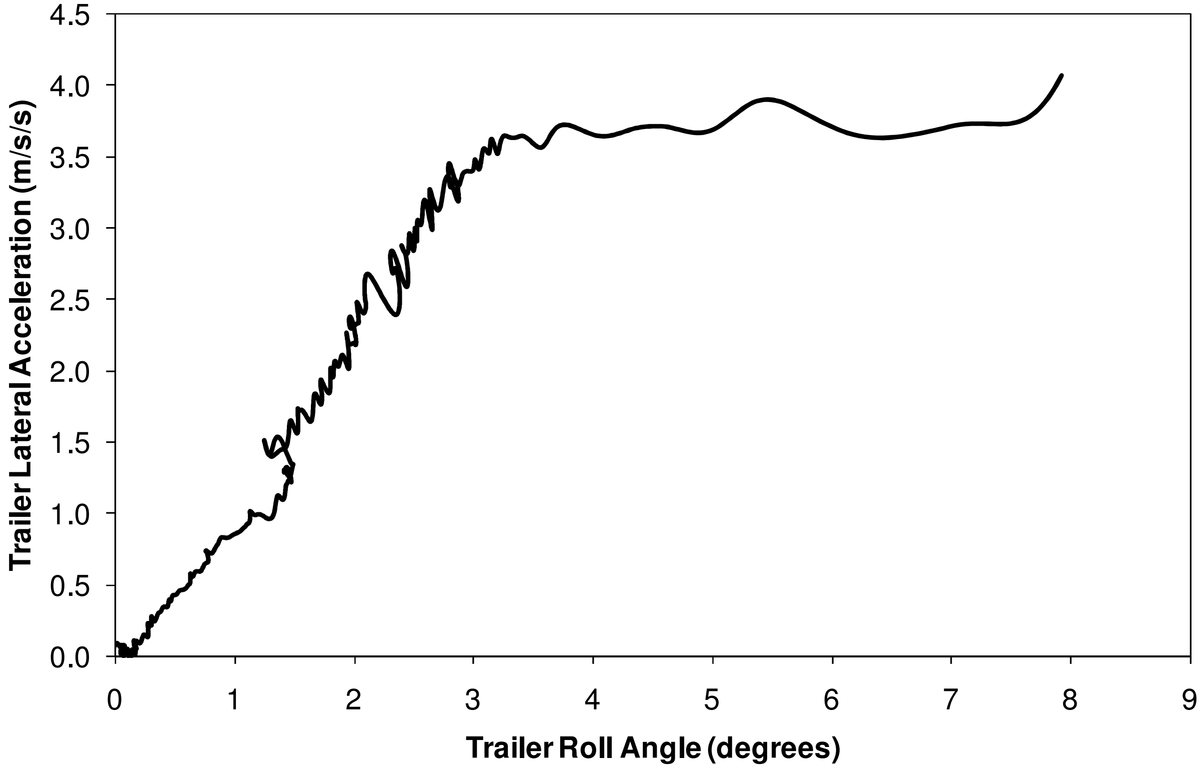

Figure 24. Graph. "Tilt Table" analog for 30 mph ramp steer.

This data is analogous to data from a "tilt table" experiment commonly used when studying vehicle roll stability. The plot shows that a sustained lateral acceleration above 3.5 m/s^2 will lead to rollover. The recovery experiments conducted during the Tripped Rollover project achieved peak lateral accelerations of only 2.4 m/s^2. This quantitatively verifies what was qualitatively observed during the experiments—the vehicle was not in danger of rolling over due to cornering forces.

Future experiments will build on the results of this experiment as well as the results of future modeling efforts. Data from all three NTRCI projects will be valuable for developing a model of this heavy vehicle's stability. The predictions made using TruckSim prior to this study suggest that modeling is a valid tool for studying these types of maneuvers. With further refinement, a dynamic simulation could be used to target maneuvers of interest for live testing. This increases experimental efficiency and safety.

While conducting this experiment, one factor that was noted as being significant was the condition and stability of the roadway shoulder. At higher speeds, the gravel shoulder would subside and impact the behavior of the truck. Future modeling efforts that include the effects of the tire and soil interaction would be particularly useful in studying tripped rollovers.

Chapter 5 – References

Hallmark, Shauna L., David Veneziano, Tom McDonald, Jerry Graham, Karin M. Bauer, Rushi Patel, and Forrest M. Council. (September 2006) "Safety impacts of pavement edge drop-offs." AAA Foundation for Traffic Safety and Federal Highway Administration. Available online at http://www.aaafoundation.org/pdf/PEDO_report.pdf.

National Transportation Research Center, Inc. (2009a) "U02: Heavy truck rollover characterization (Phase A) Final Report." Available online at http://www.ntrci.org/library/U02-_Heavy_Truck_Rollover_Characterization_Phase_A_1239201531.pdf

National Transportation Research Center, Inc. (2009b) "U19: Heavy truck rollover characterization (Phase B) Final Report." (in press)

Knee, H. E., Gary Capps, Oscar Franzese, Paul Pollock Daniel Coleman, Ibrahim Janajreh, Steven Haas, Norman Frey, E. Harry Law, Eric Johnson, Joe Petrolino, and David Rice, (November 2005) "Heavy truck rollover characterization: new-generation single tires vs. standard duals." Truck and Bus Safety and Security Symposium. Alexandria, Virginia.

Limroth John C., Thomas R. Kurfess, and E. Harry Law, (2009) "U13: Co-Simulation of Heavy Truck Tire Dynamics and Electronic Stability Control Systems (Phase A)." (in press)

Pape, Douglas B., Kate Harback, Nancy McMillan, Art Greenberg, Heather Mayfield, J. Caleb Chitwood, Michelle Barnes, Christopher B. Winkler, Daniel Blower, Timothy Gordon, and John Brock. (April 30, 2007) "Cargo tank roll stability study." Final Report on Contract No. GS23-F-0011L. Available online at http://www.fmcsa.dot.gov/safety-security/hazmat/cargo-tank-roll-stability-finalreport-april2007.pdf

Appendix A

HEAVY VEHICLE RUN-OFF-ROAD RECOVERY
“TRIPPED ROLLOVER”
TEST PLAN

Battelle
Sponsor: National Transportation Research Center, Inc. (NTRCI)
15 May 2009

REFERENCED DOCUMENTS

1. Battelle, Technical Proposal OP48217R, “Tripped Rollover,” 13 March 2009
2. Pape, Douglas B., “A Preliminary plan for rollover experiments of a heavy vehicle following a pavement edge drop-off.” Report to NTRCI. Project DTRT-06-G-0043-U02-01-01, Task Order No. 002. 21 December 2007.
3. Battelle’s Project Plan for NTRCI Task Orders 007 and 008, 17 April 2009.
4. Heavy Truck Research Consortium (HTRC), “Phase B Test Plan” 20 February 2009.
5. “Safety Planning.” EAS/EDMS Quality Management System Operating Procedure SOP 45. Issue 1.1. March 12, 2008.

INTRODUCTION

This document is the test plan for the first year of a multi-year program to study the stability of a heavy truck in a recovery from a run-off-road incident. The experiments are intended to be a modest effort using available equipment and executing maneuvers that can be relatively simply planned. The fundamental question addressed by this research is illustrated in Figure A- 1.

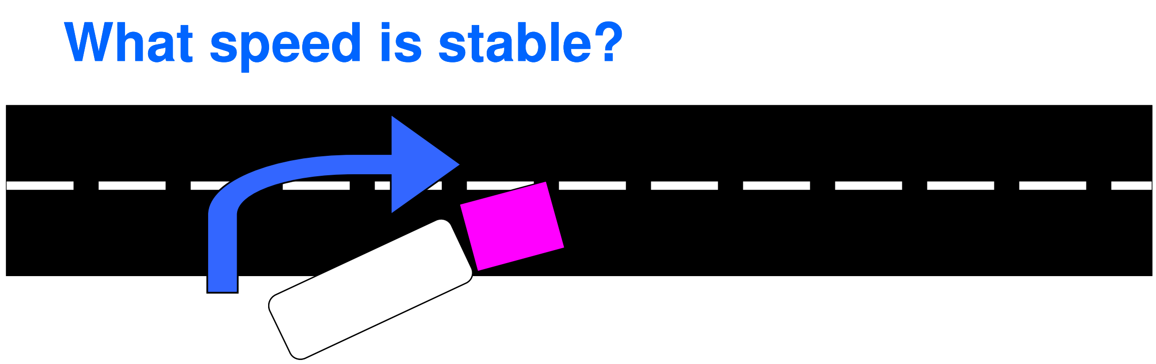

Figure A- 1. Illustration. The purpose of the research program is to quantitatively identify the limits of safe and unsafe handling for a heavy vehicle to return to the pavement over a pavement edge drop-off.

<u>Background</u>

The Federal Highway Administration has expressed interest in learning more about pavement drop-offs at the edge of roadways and their relationship with the roll stability of heavy vehicles. Statistics kept by the National Highway Traffic Safety Administration (NHTSA) and other entities have shown that more than half of all heavy vehicle rollovers are associated with a run-off-road crash. Furthermore, the majority are "tripped;" that is, the truck rolled over because it ran over a drop-off or encountered a curb or other obstacle. Previous rollover research by the Heavy Truck Rollover Consortium, like nearly all previous full-scale rollover experiments, has focused on "untripped" rollovers; i.e., those in which the truck executes a maneuver (such as rounding a corner too quickly) and rolls on essentially level pavement. This is because untripped rollovers are simpler to describe, and they are easier and safer to execute in full scale. The outlined testing will be the first published experiment in heavy vehicle rollovers resulting from roadway departure recoveries.

The research will lead ultimately to experimentally-backed recommendations for safe highway edge design. Manufacturers of vehicles and suspensions will benefit from improved models of vehicle roll stability, as will vendors of electronic stability control algorithms. Working together and separately, they will be able to design vehicles that are inherently more stable and resistant to tripped rollovers. Videos and practical lessons learned from the experiments can be incorporated in training for drivers on how to handle roadway departures. All these benefits together will lead to a reduction in the number of heavy vehicle rollovers and a safer transportation system.

The first year's work will draw on the results of the simultaneous Phase B work of the Heavy Truck Research Consortium. Subsequent years will include a series of progressively more challenging experiments alternating with improvements in modeling fidelity. The plan is structured so that each year's effort will have value in itself, in case further years are not funded.

Objective

The long-term objectives of the multi-year program are to:

- Develop and validate a model that explains how and when tripped rollovers occur and the influence of key components
- Develop guidelines for reducing the likelihood of tripped rollovers, including recommendations for:
    - Highway and pavement design
    - Vehicle suspension and dynamics design
    - Stability control algorithms
    - Driver recovery procedures.

The objective for the testing outlined in this document will be to execute an experiment that is limited but meaningful and representative. The work conducted during this first year's testing will

- Provide typical results from which further experiments can be designed
- Establish a dynamic vehicle model that can be enhanced in future years
- Demonstrate the envelope of safe recovery within a limited set of conditions.

Scope

This run-off-the-road testing will involve a class 8 tractor and cargo tank semitrailer. The tractor-trailer will be controlled through the maneuver by a human operator. The maneuver will consist of the operator driving off the pavement onto a prepared shoulder of compacted gravel. At the appropriate location along the shoulder, the driver will perform a recovery maneuver, turning back onto the pavement while trying to maintain lane integrity. The first maneuvers will be at 5 mph, and subsequent maneuvers will be at higher speeds. The approach angle will be varied.

Participation and Location

Testing will be led by Battelle in cooperation with NTRCI and Link-Radlinski, Inc. NTRCI is funding the testing and establishing the contractual obligations of Link-Radlinski. Battelle has developed this test plan, following its proposal to NTRCI. Battelle will coordinate and conduct the testing. Link-Radlinski, Inc., is responsible for ensuring the vehicle configuration and instrumentation. Galloway Airport Authority, LLC, is providing the testing facility at Darby Dan Airport in Galloway, Ohio. Messer Construction will be responsible for building the shoulder. The Battelle Advanced Media Solutions group will produce a short video to document the testing. Viewnyx Corporation will mount video cameras on the test vehicle.

TEST APPROACH

The basic maneuver will be to accelerate an instrumented vehicle to the test speed, purposely drive it to a prepared shoulder, and then return it to the pavement over a vertical pavement edge. Instruments and videorecordings will quantify the vehicle's behavior. Those and the expert judgment of the test driver and observers will establish what combinations of speed, steering practice, and other conditions constitute a safe recovery.

Vehicle Under Test

The testing will be conducted using a class 8 tractor with a cargo tank semitrailer. Standard dual tires will be on the tractor and trailer. The trailer has been specially built so that, when certain compartments are filled with water, the CG height and load distribution will approximate those of a vehicle loaded with gasoline in revenue service. The CG height will be intermediate, between the high and low configurations used for the Phase B testing. The trailer will have outriggers, and anti-jackknife cables will be installed between the tractor and trailer. Both the tractor and trailer are equipped with the Bendix Electronic Stability Control (ESC), which will be enabled for a majority of the testing.

Site Layout

Testing will be conducted at the Darby Dan Airport located at 7535 W. Broad St., Galloway, Ohio, 43119. The runway is 5892 ft long and 75 ft wide with an additional 25 ft width at the east and west ends. Figure A- 2 shows the runway with labels of the approximate acceleration, maneuver, and stopping zones.

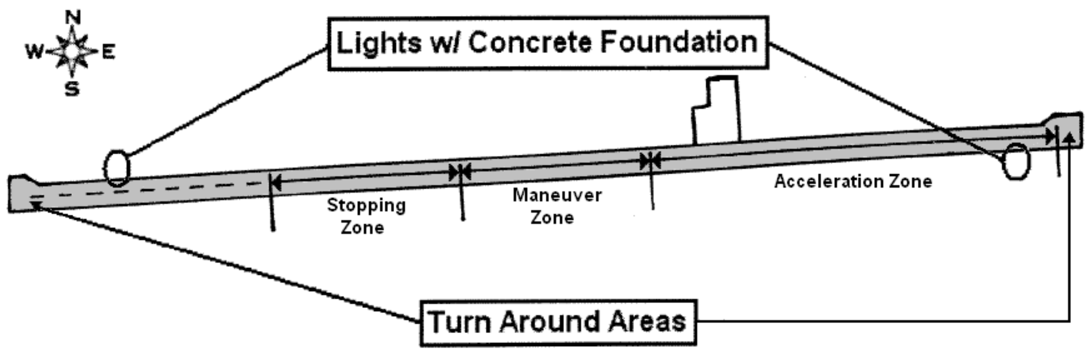

Figure A- 2. Diagram. Overhead view of Darby Dan Airport.

Figure A- 3 shows the areas for staging each test run and viewing the maneuvers. Test team members will be in the staging area. Team members viewing the maneuvers must remain south of the runway centerline and upstream (east) of the location where the truck will first attempt to re-mount the edge. One or two team members may be on the field north of the runway and of the service road, but also upstream of the re-mount location.

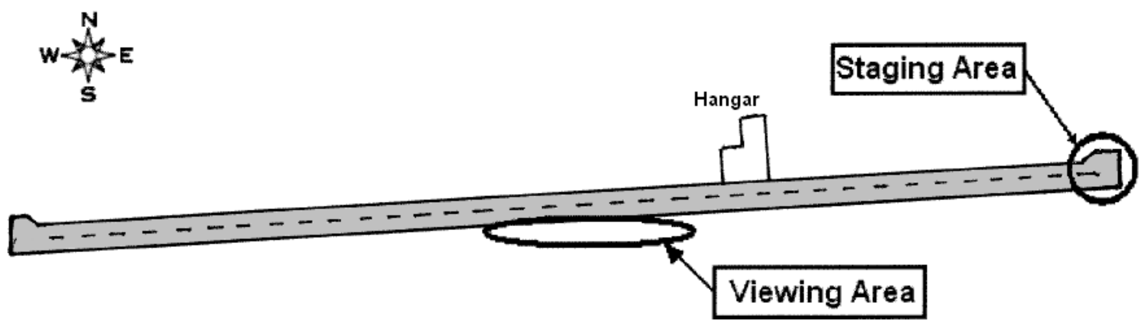

Figure A- 3. Diagram. Staging and viewing areas at Darby Dan Airport.

The airport hangar is the white roofed building on the north side of the runway. It is equipped with DSL internet service and a local wireless network. A Battelle computer at the test site will connect with the Battelle network to obtain a Matlab license. Matlab will be used to confirm sensor operation and proper data format and range.

The maneuver zone will be excavated and filled with compacted gravel by Messer Construction. Level gravel is critical for safe maneuvers. The pavement will be saw cut to produce a solid, vertical edge. Ramps will lead into and out of the shoulder. The construction drawing for the shoulder is Figure A- 8 at the end of this document, and Figure A- 4 is a close-up of the test section. The terrain slopes downward away from the prepared shoulder, the amount of slope varying along the test section.

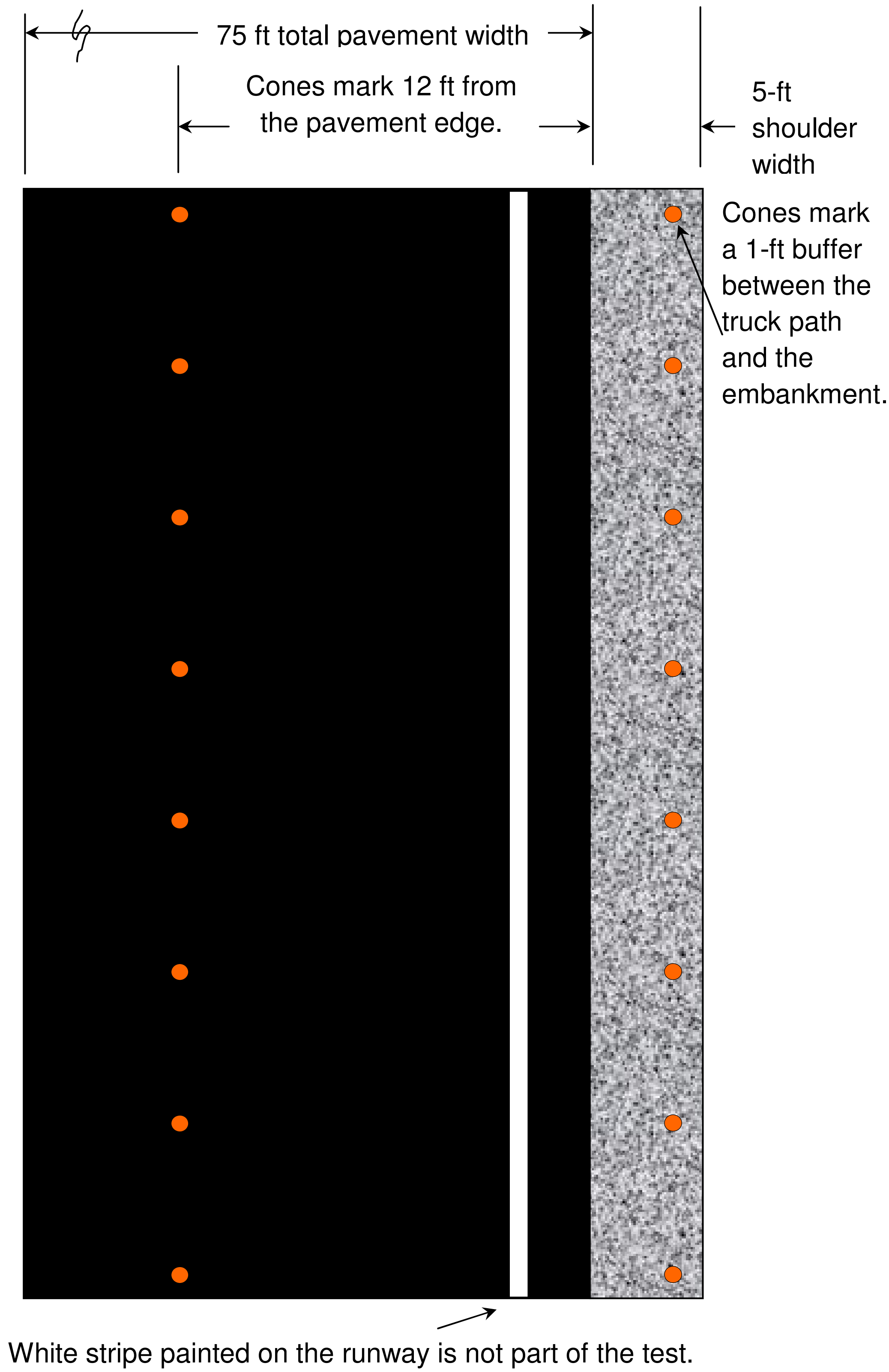

Figure A- 4. Illustration. Pavement, shoulder, and traffic cone layout.

Traffic cones as shown in Figure A- 4 will be used to mark certain testing areas. A row of cones along the outer edge of the gravel shoulder will provide a one-foot-wide buffer zone between the truck's tires and the beginning of a drainage embankment. Another row of cones will indicate the intended maneuver location. These cones will indicate where the driver should turn into the driving lane. Two more rows of cones will be used to identify the traffic lanes on the runway. One row will indicate the traffic lane centerline 12 ft from the shoulder edge. The second row will indicate the edge of the next lane of traffic and will be 12 ft from the first row. Finally, several cones will be used to mark the location of lights at the west end of the runway that have dangerous concrete foundations. A total of about 75 cones will be needed.

<u>Maneuvers</u>

The vehicle will perform a recovery maneuver from near the edge of the pavement back into the driving lane. In this way, the maneuver is like the lane change or evasive maneuver. The pavement will have a raised edge that must be overcome to return to the driving lane. The process is illustrated in Figure A- 5.

As shown in Figure A- 6, the maneuvers will include an oblique as well as a gentle approach angle to the pavement.

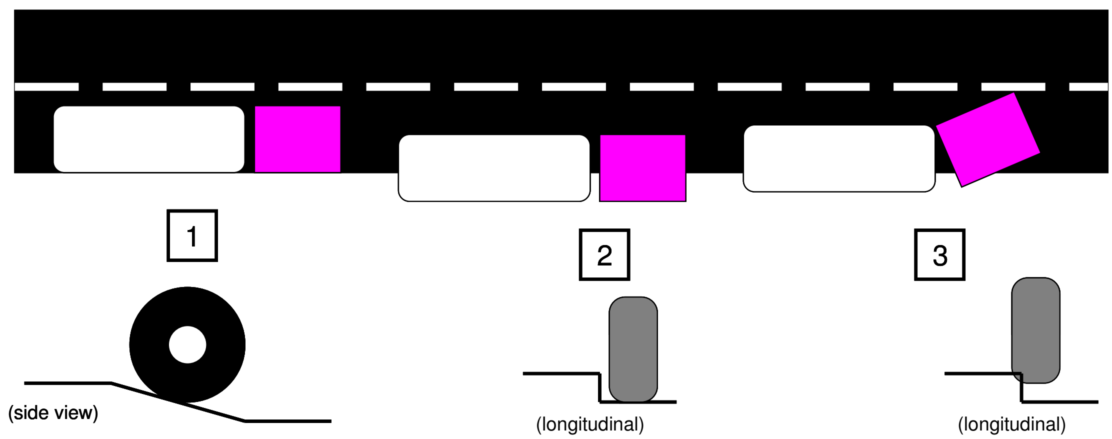

Figure A- 5. Illustration. Three snapshots in time during a drop-off recovery experiment. At snapshot 1, the truck, at speed, descends a gravel ramp with the right tires while the left tires remain on the pavement. At snapshot 2, the truck is in a stable condition with the right tires off the pavement. At snapshot 3, the truck steers back onto the pavement, over the vertical edge.

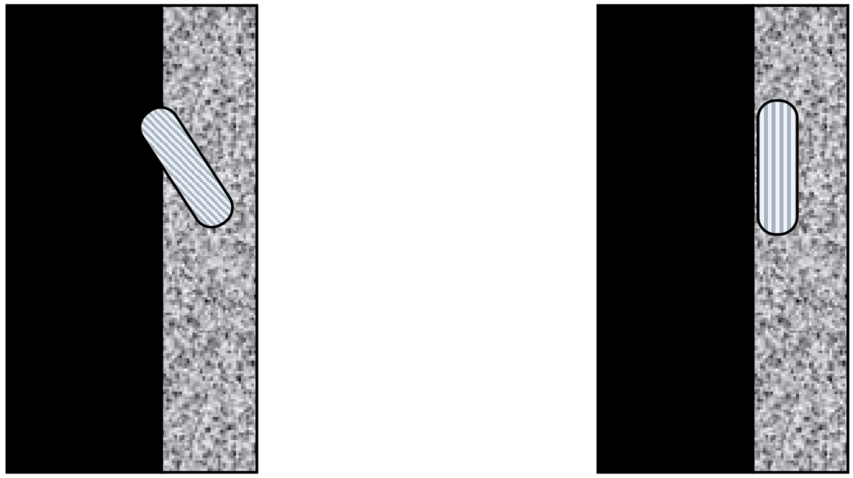

Figure A- 6. Illustration. Recovery is expected to be safer when the steer tire approaches the pavement edge at an oblique angle, as in the illustration at the left. The driver can have difficulty steering when the tire is grazing the edge of the pavement, as on the right. When the tire is grazing, the driver must steer hard, which can result in a sudden movement of the truck or, in a severe case, de-bead the tire.

<u>Testing Summary</u>

The first maneuvers will be at only 5 mph. After the procedure is established, the speed will be gradually increased. The maximum speed of the maneuvers is anticipated to be between 30 and 40 mph. Initially, the speed will be increased in 5 mph increments switching where necessary to 2 mph increments at the higher speeds. The first set of maneuvers will call for the driver to begin 4 ft away from the edge and to turn sharply toward the pavement. This is the most stable recovery procedure recommended by corporate safety professionals. Beginning again at low speeds, the second maneuver variation will be a gentle approach angle where the steer tire rides close along the edge of the pavement before returning to the driving lane.

If time allows, a decelerating recovery maneuver will be preformed. The driver will get up to speed and enter the maneuver zone. Then at the appropriate location, the driver will remove pressure from the accelerator to slow down before turning back toward the traffic lane. If time and safety allow, this slow down maneuver may be performed by gently applying the truck brakes.

Each of these maneuvers will be repeated at least once. Conditions that are just short of the limits of safe maneuvering will be repeated several times to establish the limits of safety and refine the recovery procedure. The goal of the experiments is not to roll the truck nor even to exercise the outriggers. The instruments, the eyes of stationary observers, and the professional test driver's experience will determine the threshold of safe, reasonable recovery maneuvers. Continuous monitoring of the maneuver conditions will provide real time insight into the limits of this testing. These factors may dictate that more variations of tests at slower speeds be conducted. Final decisions regarding the conditions of test runs and quantity of test runs will be made during the test.

Most testing will be performed with ESC on. One condition that might benefit from ESC will be identified, and it will be repeated with ESC disabled. ESC will be enabled for all but the slowest cases where brakes are applied with one side's tires on the gravel.

Table A- 1. Testing Variations Summary.

Speed	5, 10, 15, 20, 25, 30, 32, 34, 36, 38, 40 mph
Maneuver	Oblique entry, grazing incidence entry, reduce speed then recover
Repeats	1 for slower maneuvers, 2 (minimum) for faster maneuvers (30 mph and above)
ESC	On for both tractor and trailer for most maneuvers, Disabled for selected maneuvers, as testing time allows.

Each run will take 25 minutes or less to perform. This can be broken down as follows. For the slowest maneuver, the drive down the runway and performing the maneuver will take 12 minutes. It will take 5 minutes to unhook the jackknifing cables and then 3 minutes to drive back up the runway. The jackknifing cables can be reattached at the same time as the data is being transferred from the Somat eDAQ system, which will take 5 minutes. If the tape in the video camera requires changing, that can be done in this time as well. At higher speeds, the total turn-around time will be approximately 15 minutes.

Allowing for a half hour at the start and end of the day for setup, steering sensor alignment and then wrap up, approximately 20 runs can be completed in a 7-hour day. The minimum number of runs from Table A- 1 is 56 (excludes any runs with ESC off and any braking maneuvers) which can be completed in 2.7 days. This allows the remaining test days for additional repeats of tests, additional approach angle tests, tests where the ESC systems are disabled, and variations of braking tests. More of these tests will also be accommodated if the maximum maneuver speed of 40 mph is not attained.

<u>Test Procedure</u>

1. Every day begins with a pre-trip inspection.
2. The steering sensor will be zeroed by driving straight down the runway centerline. A simple double lane change maneuver will exercise the sensors. The jackknife cables will be disengaged during this time to allow for turning around.
3. The jackknife cables will be reattached, and the operation of the eDAQ system will be confirmed.
4. A Safety Briefing will be conducted before each group of tests
5. Driver and team will be updated on the test conditions for the current test
6. Driver will start from the east end of the runway and begin accelerating to the speed of the current maneuver
7. Driver will manually trigger the data acquisition when passing the east wall of the airport hangar
8. Driver will enter the shoulder from the east side, where the gravel shoulder is flush with the level of the pavement.
9. Driver will perform the maneuver at the appropriate location indicated by traffic cones
10. Back on the pavement, the driver will attempt to maintain lane integrity indicated by traffic cones spaced 12 ft from the shoulder edge on the runway. If lane integrity cannot

be maintained, the driver can try to maintain the vehicle in the next lane which will also be indicated with cones

11. When the maneuver is complete, the driver will stop the vehicle at the west end of the runway, disconnect the jackknife cables and return to the staging area at the east end of the runway
12. The driver and stationary spotters on the ground will discuss whether the maneuver approached the limits of safety. If the margin of safety and confidence is high, then the maneuver can be repeated or the next maneuver can be begun, according to the test plan. If an outrigger touched down, the driver sensed difficulty in controlling the truck, or another concern is raised, then the maneuver may be repeated at a lower speed or less demanding path, or the tests with the maneuver may be terminated. This decision process is detailed in Figure A- 9 at the end of this document.
13. The eDAQ data will be transferred, jackknife cables reinstalled and camera tape changed if necessary
14. The next run will be conducted.

Schedule

The Run-off-road tests will take place the week starting May 26, 2009. Table A- 2 indicates the schedule of testing milestones:

Table A- 2. Schedule.

Task	Date
Visit to Link-Radlinski	4/13/09
Visit to Darby Dan Airport	4/15/09
Shoulder Drawing Complete	4/20/09
Shoulder Quote Received	4/30/09
Strain Gages Installed on Tractor Tie Rod	5/13/09
CG Height Implemented and Trailer Weighed	5/22/09
Shoulder Preparation	5/11/09 – 5/15/09
Trial Runs of Data Acquisition during the Conventional-Maneuver Phase B Testing	5/18/09 – 5/22/09
Run-off-road Tests	5/26/09 – 5/29/09
Contingency Day at the Airport	5/30/09

The testing is planned to cover four days as outlined in Table A- 3. A more detailed sequence of runs is in a separate notebook. The sequence is certain to be adjusted according to weather, findings at the test site, and the schedule and results of Phase B. Constant radius circles, identical to those of Phase B, will be conducted at TRC on the vehicle configured for the run-off-road recovery tests. If time permits, a pulse steer maneuver with the steering robot, as with Phase B, will also be conducted at TRC. Four-foot lane changes with a human driver will be conducted at TRC or the airport. All subsequent tests will be at the airport.

Table A- 3. Sequence of Tests.

Time	Group of Tests
Preparatory day (at TRC)	Convert to the CG height for the run-off-road tests, change from aluminum to steel rims. Measure axle weights, execute constant radius circles. If possible, dry pulse steer 4-ft lane change.
Day 1 morning	4-ft lane change on the pavement. 5 to 40 mph.
Day 1 afternoon	Complete 4-ft lane change on the pavement, begin oblique steering recover maneuvers, beginning at 5 mph
Day 2 morning	Complete oblique steering recovery maneuver
Day 2 afternoon	Begin grazing pavement incidence recovery maneuvers beginning at 5 mph
Day 3 morning	Complete grazing incidence recovery maneuver
Day 3 afternoon	Video shoot. Select maneuvers from early testing. Repeat good practices. Demonstrate bad practices. Drive-bys and interviews.
Day 4 morning	Any uncompleted maneuvers, braking recovery
Day 4 afternoon	Complete deceleration and brake recovery maneuvers, tests with and without ESC, repeats of any maneuvers

List of Sensors, Measurement Devices, and Other Hardware

All of the sensors used for other Phase B testing will be on the vehicle. Table A- 4 lists the additional instruments specific to the run-off-road tests. A high-speed video camera will be mounted in the wheel well for the right steer tire to observe its behavior as it climbs the pavement edge. Quantitative data on suspension deflection and steering force will benefit tire modeling in future work. The Somat eDAQ system will be used for a string potentiometer on the suspension.

Table A- 4. Measurement Instruments.

Manufacturer	**Model**	**Description**	**Target**
Casio	**EXILIM EX-FH20**	High-Speed Video Camera	Front view of curb side front axle tire
Viewnyx		video camera	several locations, outside the vehicle and inside the cab.
Vishay	CEA-06-250UT-3	Strain Gages	Force measurement on steering tie rod
(Link-Radlinski's)		String Potentiometer	Measure suspension deflection on the right steer axle

Analysis

Limits of stable maneuvering will be listed and described qualitatively and quantitatively. The apparent roll stability of the test vehicle in the steady state and transient maneuvers of Phase B will be compared to the roll stability in the run-off-road recoveries. Plots will show the envelope of conditions (speed, approach angle) that lead to stable and safe response.

Behavior of the test truck will be compared with predictions of the dynamic truck model. Discrepancies will be noted in the form of recommendations for enhancements to the model.

SAFETY PLAN

The Safety Planning procedure (SOP 45) of the EAS/EDMS Quality Management System was used to develop the following safety plan. The hazards associated with this testing have been analyzed based on the likelihood and consequence of each risk. The test plan has been organized to minimize the hazards by executing the more benign maneuvers first, so that experience is gained before the more hazardous maneuvers are reached. Hazard avoidance procedures have been developed to protect personnel from the remaining hazards.

Discussion and Assessment of Hazards

The Safety Planning Procedure includes the guidance in Figure A- 7 for categorizing hazards. Risk ratings from very low (VL) to extreme (E) are assigned to risks according to their maximum consequence and likelihood of occurrence.

	Maximum Consequence with higher than negligible probability				
Likelihood of Occurrence	**Minor** (first aid)	**Moderate** (medical treatment)	**Serious** (lost time)	**Major** (fatality)	**Catastrophic** (multiple fatalities)
Almost Certain	H	H	VH	E	E
Likely	M	H	H	VH	E
Possible	L	M	H	H	VH
Unlikely	L	L	M	H	H
Rare	VL	L	L	M	H

Figure A- 7. Chart. Risk Assessment Guidance from the Safety Planning Procedure.

The test plan has been developed so that the most severe consequence of the maneuvers will be

1. the vehicle driving through the line of cones that indicate a lane,
2. an outrigger gently touching the pavement, or
3. a set of tires momentarily lifting from the pavement.

None of these outcomes will injure the driver or personnel standing on the runway. When testing reaches the point where one of these three events occurs, it will be declared the limit of reasonably safe recovery according to the test rules. The maneuver may be repeated at the same condition or slightly lower speed, but certainly not in a more risky condition.

Other foreseeable outcomes of more significant consequence are

4. A violent maneuver arrested by the outriggers might cause a minor injury such as a contusion, so it is a “Minor” consequence. Since it is “Possible” that this will occur, it carries a “Low” risk rating. This risk is mitigated by limiting the maneuver speed based on driver and test team input. Also, this risk is mitigated by allowing the driver to abort the maneuver at any time a condition is considered unsafe.

5. A rollover at a low speed can cause a lost time injury, so it is a “Serious” consequence. This is “Unlikely” to occur, and it carries a “Low” risk rating. The outriggers reduce this risk. The driver and test team evaluation of each maneuver and speed will reduce this risk. Cases have been reported where a driver has survived a low-speed rollover without injury, but then was hurt by falling sideways across an overturned cab after releasing the seat belt. The driver will be instructed to remain in place until other test personnel arrive, should a rollover occur.

6. A rollover at a substantial speed can be fatal, so it is a “Major” consequence that must absolutely be avoided. The conditions of the maneuvers will be constantly monitored so that this situation will not occur. Vigilance will increase when the maneuver speeds are 30 mph or above.

7. A dangerous condition with high likelihood of a rollover can occur when a trailer's tires are down a slope and the tractor is climbing up on the pavement. The terrain to the right of the prepared shoulder slopes downward, and precautions will be implemented to prevent the trailer’s tires from reaching the slope. A row of cones along the outer edge of the gravel shoulder will provide a one-foot-wide buffer zone between the truck's tires and the beginning of the foreslope. The driver will be instructed that, should the trailer tires reach the slope to the right of the shoulder, the truck is to be steered straight and brought slowly to a stop with minimal braking. Driving down the slope at speed above about 10 mph would be a “Minor” to “Moderate” consequence with possible injury to the driver and likely damage to the vehicle. Rolling the truck by attempting to steer back to the pavement while the trailer continues to descend the slope would be a “Serious” consequence at low speed and a “Major” consequence at high speed.

8. Loss of the right steer tire could lead to loss of control and a rollover. The tire will be damaged by driving over the pavement edge. The condition of this tire is crucial to the safety of the experiment. The surface of the tire, its pressure, and its seating on the rim will be inspected before every run.

9. Running the truck into pedestrian observers would be a "Major" consequence. During each maneuver, observers and team members will be placed at the east end of the runway or on the south side of the maneuver zone upstream from the recovery point. These areas are shown in Figures A-1 and A-2. We will establish radio control procedures so personnel are in their positions when a run begins and so all eyes are aware when the truck has to drive back east to the starting point.

<u>Hazard Reduction Controls</u>

In addition to the organization of the test sequence and the safety equipment on the vehicle, the following procedures will constitute the hazard reduction controls.

Precautionary Procedures

- Darby Dan Airport staff are responsible for traffic on the runway. They will close the runway to air traffic and advise the team if the runway must be opened. Team members and spectators will be made aware that even though it is private and shut down for the week, Darby Dan is an active airport and proper vigilance is prudent. Team members and spectators will be told that another activity may be scheduled at Darby Dan during the testing week where various aircraft will be flying overhead.
- A pre-trip inspection (including the brakes, tire pressures, and steering linkages) will be performed every day.
- The jackknife cables and outriggers must be inspected before each run. Because the jackknife cables will be disconnected to turn around the truck, their re-attachment will be on the written checklist before every run.
- The tires and truck on the right side will be inspected before every run. Noting the condition of the right steer tire will be especially important.
- Some team members will be at the east end of the runway in the staging area to confer with the driver between runs and transfer data. Other observers must remain on south side of the runway as indicated in Figure A- 3, or north of the service road. All observers will be upstream (east) of the point where the truck first attempts to re-mount the pavement.
- We will develop a written checklist to be followed before every run. The checklist will include safety items, such as inspecting the tires, and data items, such as ensuring the cameras are recording. Items on the checklist will be initialed by the individual who performed or verified each item.

Test Rules to Ensure the Safety of the Observers

- Individuals standing on the runway will wear high-visibility vests.
- Before the truck begins driving for a test run, we will verify that all personnel are accounted for and in safe locations. Similarly, before the truck drives from the west end

of the runway back to the starting point, it will obtain radio clearance to ensure observers are expecting its passage.

- An individual at the starting location and another near the test section will have fog horns. If they see a need to abort a run, they will sound the horn continuously until the truck stops. The horns will not be used for any other purpose while the truck is in motion.

Test Rules to Ensure the Safety of the Maneuvers

- Driver feedback between each run is critical for determining the safety of the next maneuver.
- If the driver senses an unsafe situation at any time during a maneuver, the driver should perform the appropriate steps (as determined by best driving practices) to end the maneuver.
- The driver and the in-cab observer will each wear a helmet.
- The maximum maneuver speed will be determined by the driver and test team.
- Any individual at the test site has the authority to stop the test before a run or during a run to discuss a safety concern.
- After every run, the driver and stationary spotters on the ground will discuss whether the maneuver approached the limits of safety. If the margin of safety and confidence is high, then the maneuver can be repeated at the same or a higher speed, according to the test plan. If an outrigger touched down, the driver sensed difficulty in controlling the truck, or another concern is raised, then the maneuver may be repeated at a lower speed or less demanding path, or the tests with the maneuver may be terminated. This decision process is detailed in Figure A- 9 at the end of this document.
- We will shoot footage of the test truck from a chase vehicle. Special procedures and speed limits will be developed to ensure the safety of the videographer.
- Any of the following individuals has the authority to suspend or terminate testing for a safety concern:
  - Battelle: Test Director and Safety Observer
  - Link-Radlinski: Manager of Commercial Vehicle Test Services and Test Driver
  - NTRCI: On-site representative

Emergency Procedures

- The Prairie Township Fire Department responds to medical emergencies at the airport. Their direct dial emergency phone number is 878-5366. If we call 911 from a staff cell phone, we may reach another agency, and we will ask for the Prairie Township Fire Department. If the cell phone is not operable, then we will call the Prairie Township Fire Department from a land line at the airport office.
- If a person at the test requires medical treatment but not emergency medical service, we will transport the person in a personal car. The destination hospital might be
  - Doctors Hospital, 5100 West Broad Street (east on Broad Street from the airport, past Hilliard-Rome Road) emergency phone 544-1046, or
  - The Ohio State University Medical Center, 1654 Upham Drive, (Medical Center exit from 315), emergency phone 293-8333.

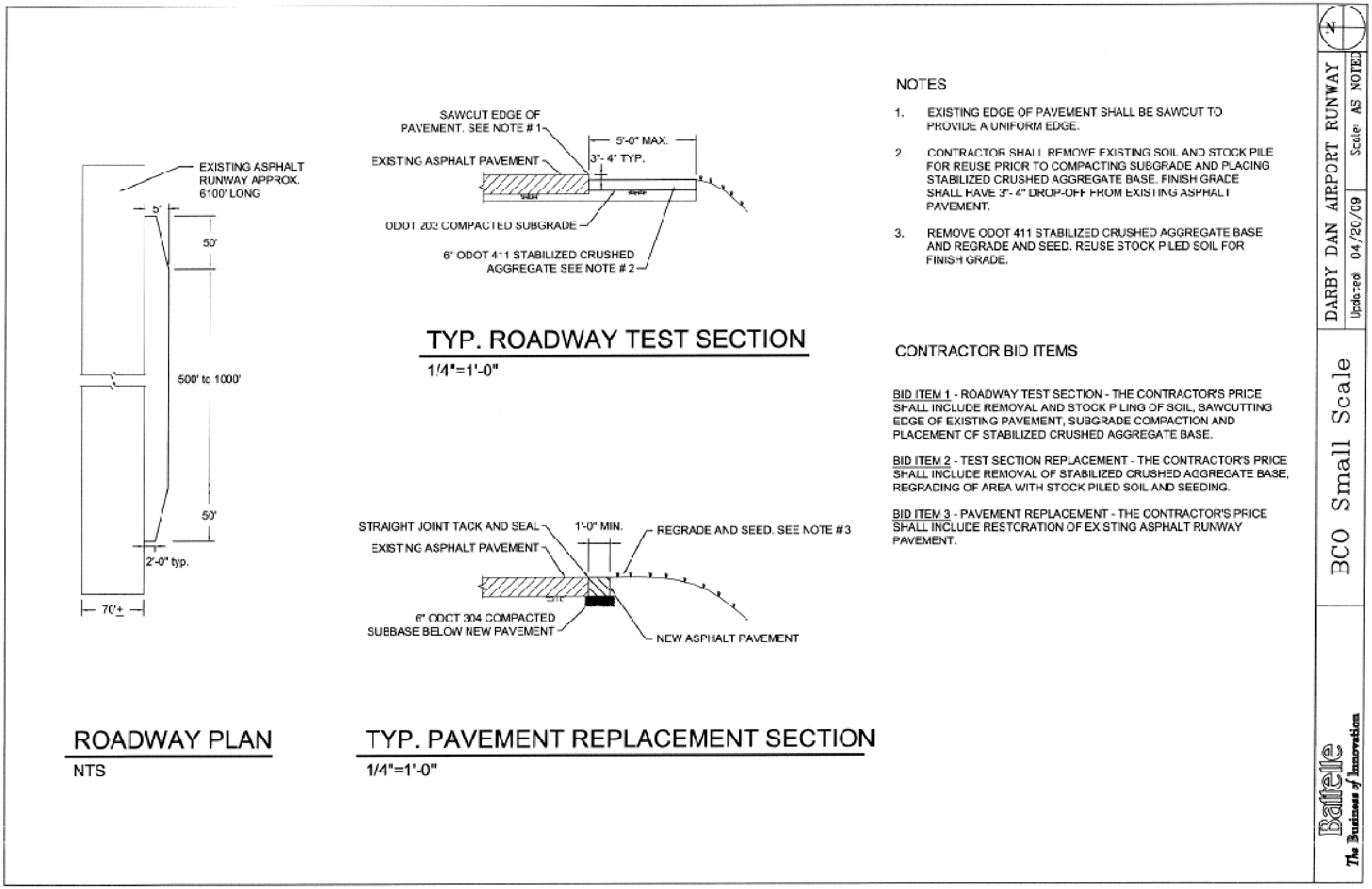

Figure A- 8. Diagram. Construction plans for the prepared shoulder.

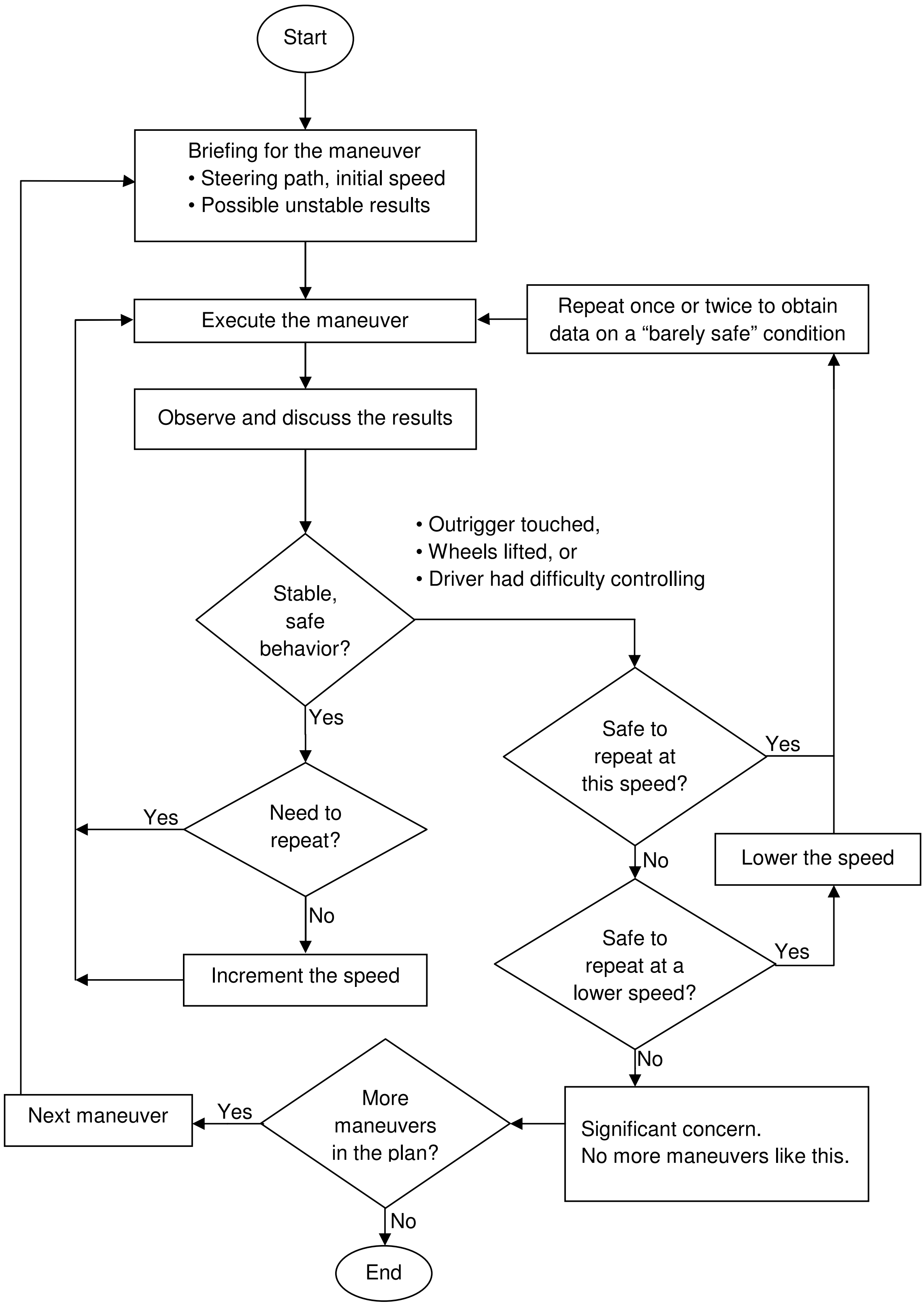

Figure A- 9. Diagram. Maneuver decision flowchart.

Appendix B

Shoulder As-Built Description

A gravel shoulder five ft wide and 1000 ft long was built next to the existing runway at the airport where the tests were to be conducted. The pavement was cut with a saw to form a vertical edge. This appendix describes the design and construction of the shoulder.

The shoulder was built to Ohio Department of Transportation specifications. The shoulder drawing given to the contractor to bid is in the test plan, which is Appendix A to this report; Figure B- 1 on the next page is a drawing of the shoulder as it was actually constructed.

The shoulder had an entry portion where the gravel was flush with the pavement for 175 ft. This length was based on the approximate time for a five-axle truck to make a lane change, planning for a maximum test speed of 40 mph. A ramp of 50 ft provided a grade gentler than 1% to develop the four-inch vertical edge. The flush section and ramp were reflected at the far end of the shoulder. This exit from the shoulder was never used for testing; it was precaution in case the driver for any reason could not climb the vertical edge. With an overall shoulder length of 1000 ft, this left 550 ft for the maneuver area. A photograph of the completed shoulder is in Figure B- 2.

The sub grade below the gravel aggregate was compacted in accordance with Ohio Department of Transportation (ODOT) Item 203, “Roadway Excavation and Embankment”. The gravel aggregate conformed to ODOT Item 411, “Stabilized Crushed Aggregate.” The stabilized crushed aggregate was compacted before and during testing with a vibratory compaction roller as shown in Figure B- 3.

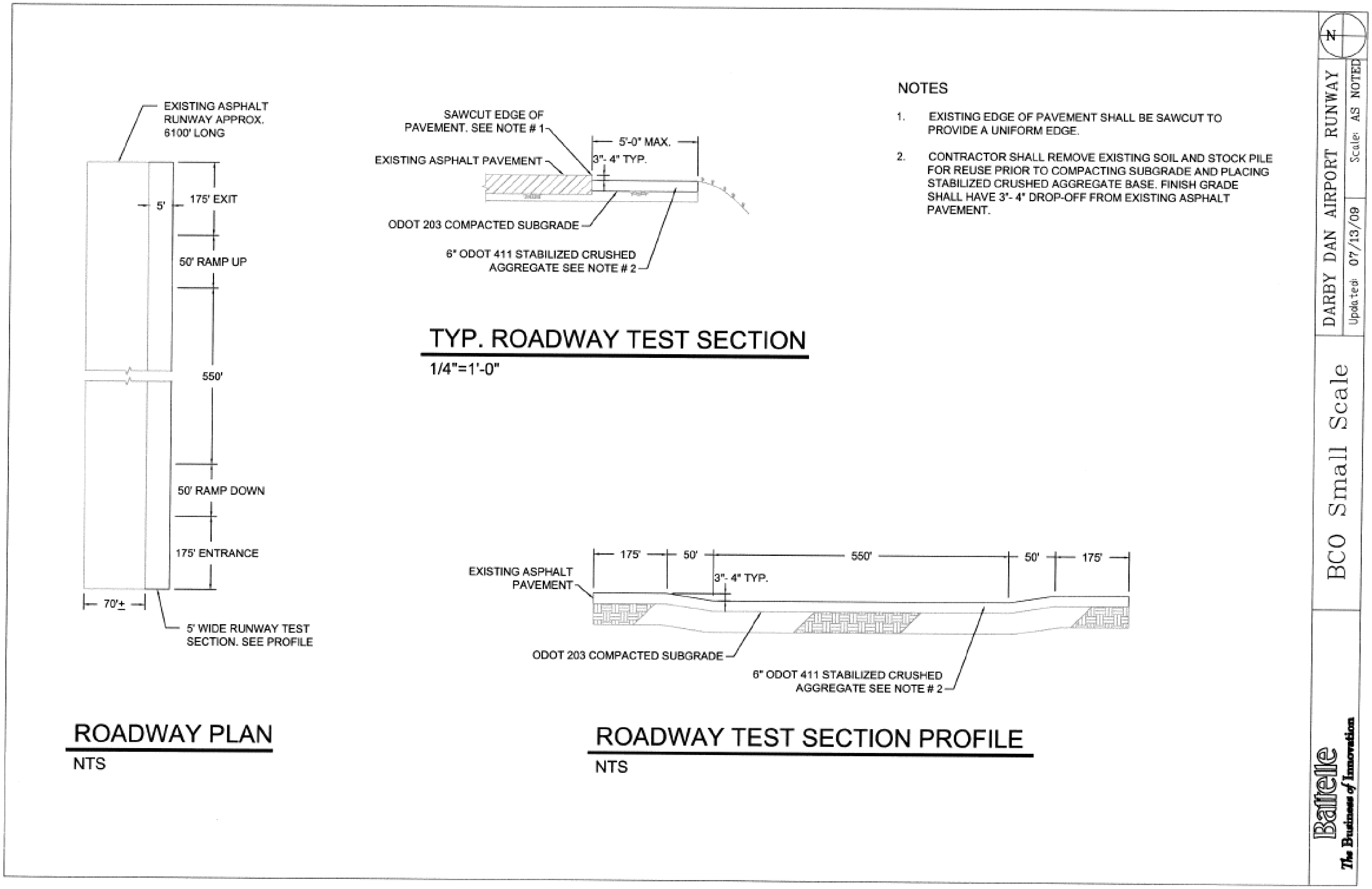

Figure B- 1. Drawing. As-constructed shoulder.

Figure B- 2. Photograph. Prepared shoulder.

Figure B- 3. Photograph. Shoulder compaction roller.

The modulus of elasticity of the shoulder was determined at 21 locations along the shoulder length. This was measured using the Falling Weight Deflectometer (FWD) method, as shown in Figure B- 4. The measurements and analysis below were provided courtesy of the Ohio Department of Transportation. To perform this testing, weight was dropped on a pressure plate that impacted the shoulder surface. Sensors measured the deflection due to this impact. Using the weight and deflection information, the modulus was calculated for each location. The shoulder modulus ranged from 2000 to 22000 psi as shown in Figure B- 5. This is the effective modulus and represents the combined modulus of the soil and stabilized crushed aggregate. The figure shows the variation in effective modulus over the length of the shoulder. The region from approximately 400 ft to 750 ft is where water collected after a heavy rain and was therefore softer than the surrounding shoulder. Even in this region, though, the values are typical for a shoulder prepared with these materials in this manner.

Figure B- 4. Photograph. The falling weight deflectometer.

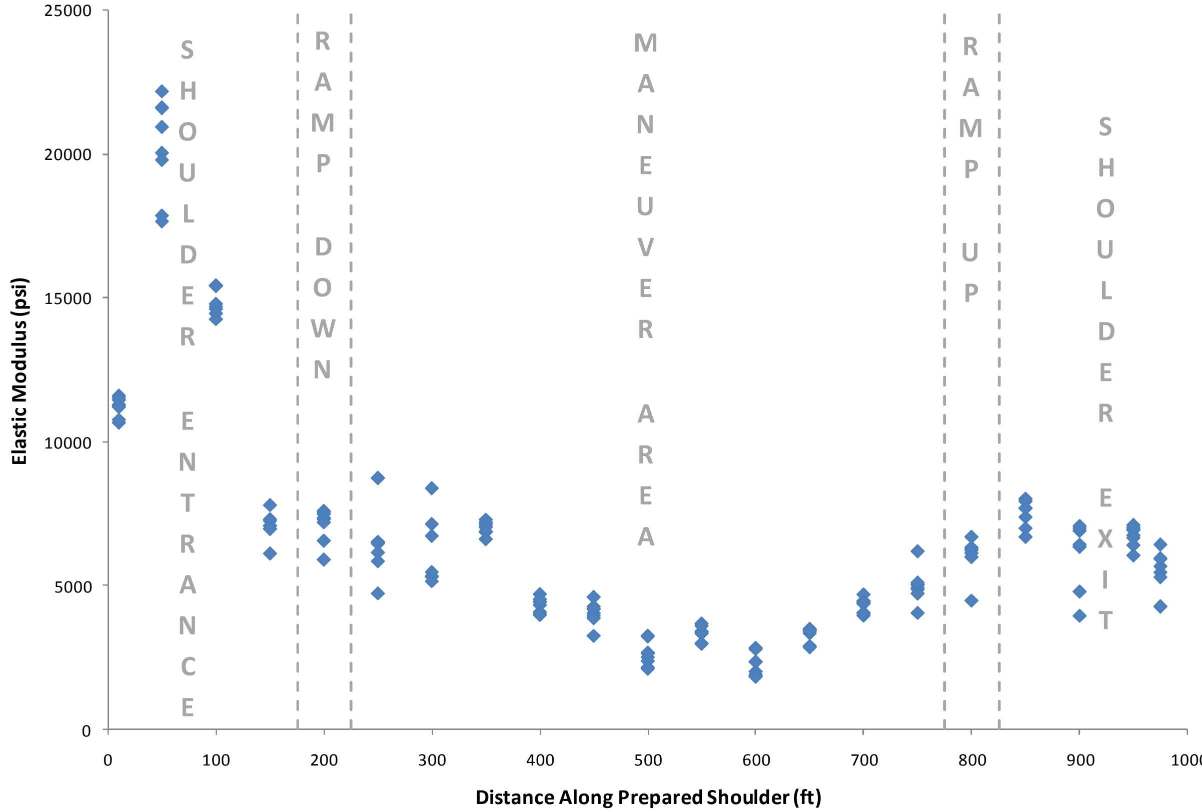

Figure B- 5. Graph. Effective elastic modulus of the prepared shoulder.

Appendix C
Tie Rod Instrumentation

This appendix explains how the tie rod in the tractor's steering linkage was instrumented to measure the steer loads during the Tripped Rollover experiments. Strain gages were applied to the tie rod to turn the tie rod into a load cell. This appendix presents theory, construction, and calibration of this device.

Figure C- 1 shows the four gages as they were mounted on opposite sides of the tie rod. Figure C- 2 is a close-up showing the two orthogonal gages in the tee rosette. The strain gages were manufactured by Vishay Micro-Measurements of Raleigh, North Carolina, model number CEA-06-250UT-350.

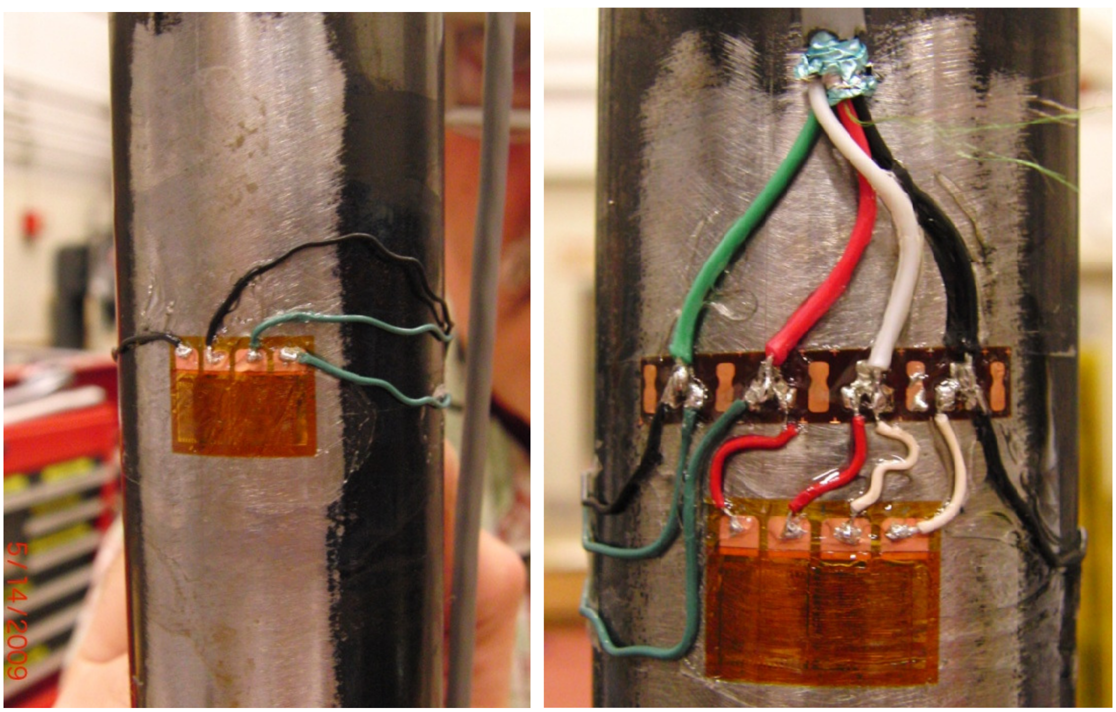

Figure C- 1. Photographs. The strain gages mounted and wired on the tie rod.

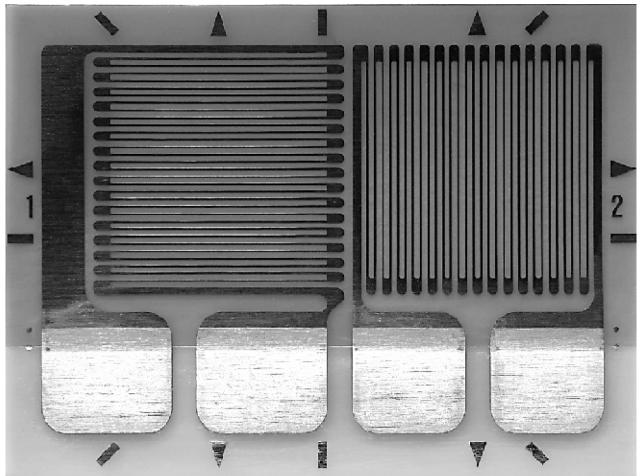

Figure C- 2. Photograph. Adjacent strain gage elements in a 90º 'tee' rosette arrangement.

The two gage pairs were applied at circumferentially opposite locations near the center of the tie rod. One of the elements in each rosette was in the tie rod's longitudinal direction, and the second element was in its circumferential direction. In this arrangement, two of the strain gages were sensitive to longitudinal strain and two were sensitive to circumferential strain. The circumferential strain exists because of Poisson's principle, which states that with the application of a compressive load, the tie rod will increase in circumference. The arrangement of the strain gages in a Wheatstone bridge was as shown in **Error! Reference source not found.**, so that the response of the two longitudinal patterns adds to the response of the two circumferential patterns. This has the effect of amplifying the sensitivity to strain by

$$\epsilon + \epsilon + \epsilon\nu + \epsilon\nu = \epsilon \cdot 2(1 + \nu) = \epsilon \cdot Quad$$

Equation C- 1.

where the amplification factor $2(1 + \nu)$ is given the term "Quad."

Because each longitudinal and circumferential element had a corresponding element on the opposite side of the tie rod, response of the load cell to twisting and bending was, theoretically, eliminated.

The load cell's sensitivity was predicted prior to gage installation. These calculations required the specifications for the tie rod and the strain gages, as well as knowledge of the amplification and excitation voltage to be used for the test. Volvo supplied the dimensions of the tie rod. The elastic properties were assumed as typical for steel. All of the relevant data for the tie rod load cell design are shown in Table C- 1.

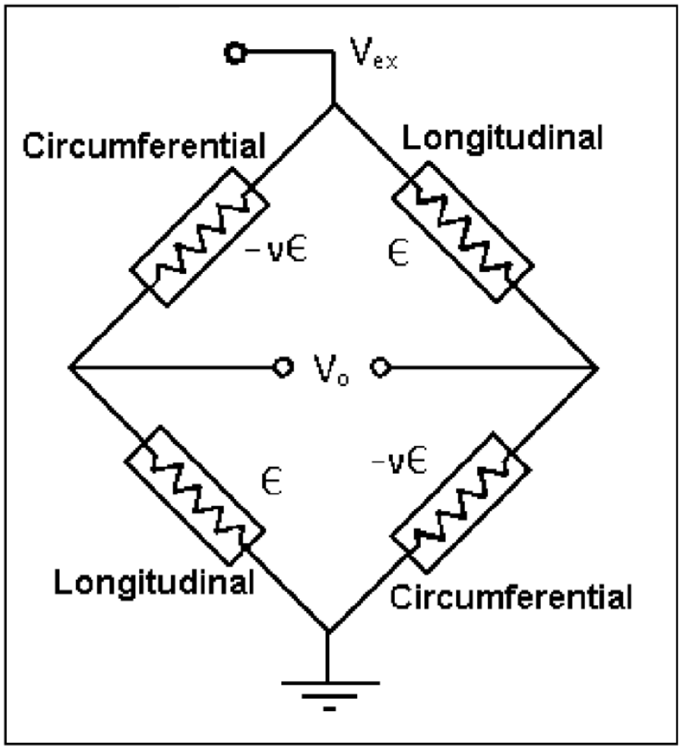

Figure C-3. Diagram. Wheatstone Bridge in Poisson Orientation for measuring axial loads.

Table C- 1. Tie rod, strain gage, and amplifier specifications.

Quantity	Value	Units	Source
Tie Rod Outside Diameter	1.75	inches	Volvo
Tie Rod Wall Thickness	0.25	inches	Volvo
Cross Section Area (A)	1.178	in^2	Calculated from above
Modulus (E)	29×10^6	psi	Assumed
Poisson's Ratio (ν)	0.27	--	Assumed
Gage Factor (GF)	2.10	--	Strain gage lot
Gage Resistance (R)	350	Ω	Strain gage lot
Excitation Voltage (Vex)	5.0	V	Amplifier spec
Amplifier Gain	1000	--	Amplifier spec

The signal conditioner was an Ektron M420 amplifier, which provided the 5-V excitation and a fixed gain of 1000.

The voltage output of the strain sensing circuit depends on the applied load by

$$V_o = Quad \cdot \left(\frac{1}{4} \cdot GF \cdot \frac{load}{A \cdot E} \cdot V_{ex} \right) \cdot gain$$

Equation C- 2.

Using values from Table C- 1 with an arbitrary load value of 1000 pounds yields the following:

$$V_o = 2.54 \cdot \left(\frac{1}{4} \cdot 2.10 \cdot \frac{1000}{1.178 \cdot 29E6} \cdot 5 \right) \cdot 1000 = 0.1952\ V$$

Equation C- 3.

The predicted sensitivity of the load cell, therefore, is

$$Sensitivity_{Predicted} = \frac{load}{volts} = \frac{1000\ lb}{0.1952\ V} = \mathbf{5124}\ \frac{\boldsymbol{lb}}{\boldsymbol{V}}$$

Equation C- 4.

Post test, the tie rod was mounted in a mechanical test machine for calibration, as shown in Figure C-4. Known loads of both compression and tension were applied at 500-lb intervals up to 5000 lb using the same Ektron amplifier used during the tests. Zero and gain of the amplifier during the calibration were unchanged from the settings used during the field tests, so an indicated zero during the calibration assures that indicated zero load during the tests is indeed actual zero load.

Figure C- 3. Photograph. Tie rod being calibrated in the mechanical test machine.

Each data point during the calibration run was recorded and graphed in Figure C- 4 along with the predicted values for each load. The dotted line is a regression for the calibration data points. Its slope, 5270 $\frac{lb}{V}$, is the actual sensitivity of the load cell. This is sufficiently close to the prediction to conclude that the load cell gage installation and wiring was done correctly.

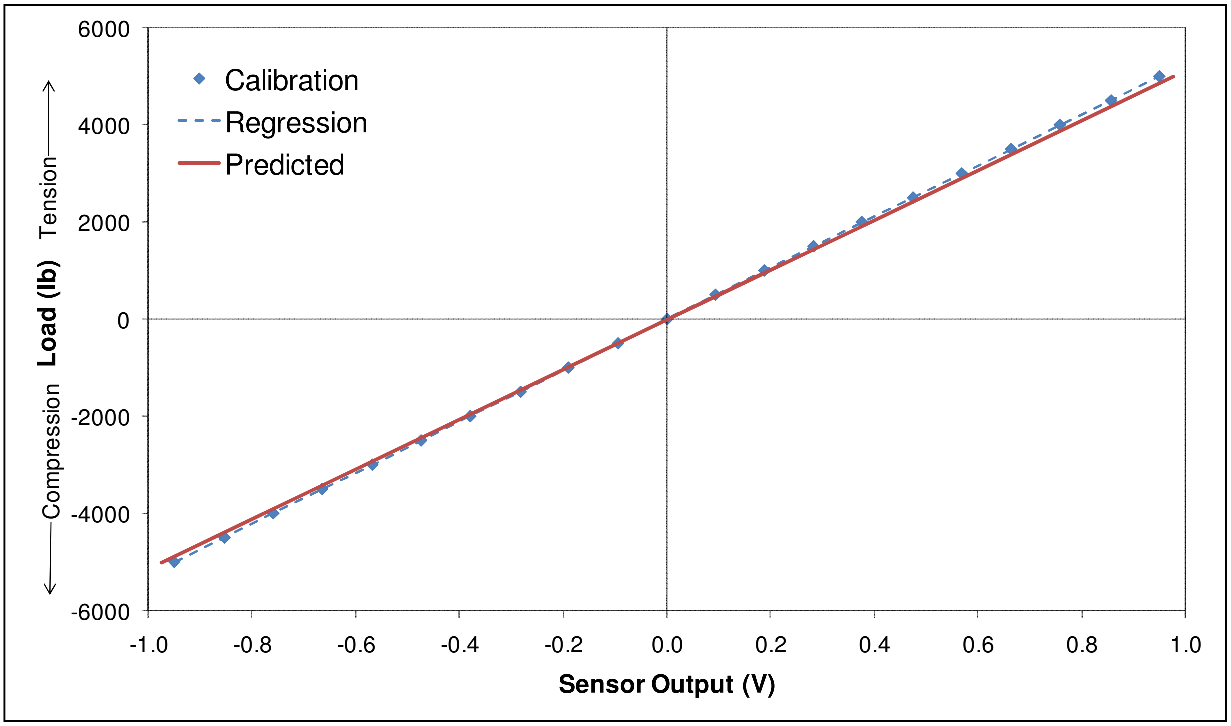

Figure C- 4. Graph. Voltage output predictions and calibration for tie rod.

A 3-MΩ (R_{cal}) shunt calibration resistor was selected for verifying the functionality of the electronics and the correct scaling factor for the output. When a shunt calibration resistor is added in parallel to one side of a Wheatstone bridge, it simulates a load being applied to the tie rod. The voltage change that would occur with the addition of the 3-MΩ resistor is

$$V_o = V_{ex} \cdot \frac{1}{4} \cdot \left(\frac{R}{R + R_{cal}}\right) \cdot Gain$$

Equation C- 5.

Using the measured sensitivity of the load cell, the 3-MΩ shunt simulates 747 pounds tension in the tie rod.

$$V_o = 5 \cdot \frac{1}{4} \cdot \left(\frac{350}{350 + 3{,}000{,}000}\right) \cdot 1000 = \mathbf{0.146\ V}$$

Equation C- 6.

$$load_{Predicted} = Sensitivity_{Predicted} \cdot volts = 5124 \frac{lb}{V} \cdot 0.146\, V = \mathbf{747\ lbs}$$

Equation C- 7.

After gaging, the tie rod was installed on the truck. During the week of testing, the 3-MΩ calibration resistor was periodically added to one leg of the Wheatstone bridge to verify the integrity of the load cell and the scaling factor. Figure C-6 shows the load recorded as the calibration resistor was applied and then removed one time during the week of testing.

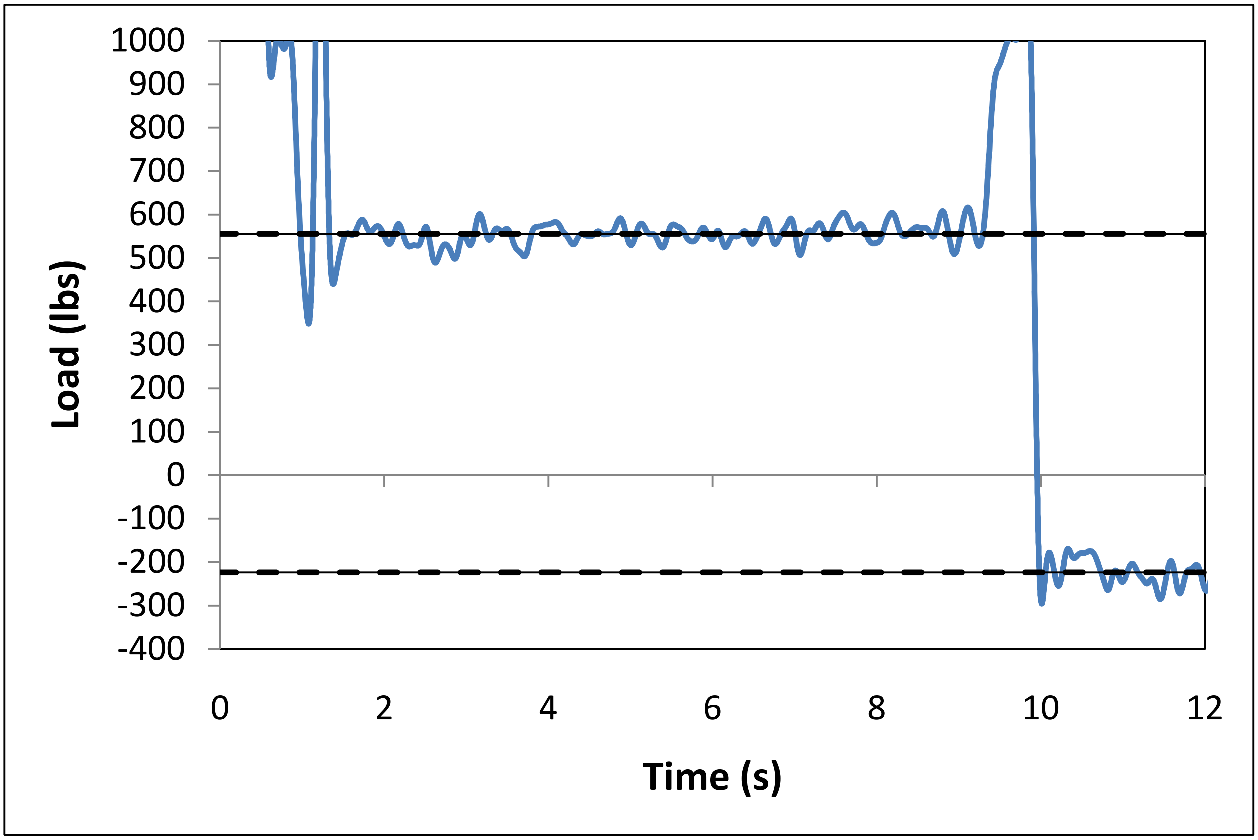

Figure C- 5. Graph. Recorded load with application of 3-MΩ calibration resistor.

With the shunt in place, the load cell indicates 555 pounds (between 2 and 9 seconds). Removing the shunt at 10 seconds, the load drops to 223 pounds, a difference of 778 pounds, which is within 4.2% of the theoretical shunt value of 747 pounds. Spikes in the plot shown in Figure C-6 are noise from connecting and disconnecting the shunt. The reading following the resistor's removal is not zero because both steer tires were on the ground, and the load in the tie rod was not zero. On a separate occasion, a true zero was recorded when the right front tire was jacked off the ground.