National Transportation Safety Board
Office of Research and Engineering
Washington, DC 20594

HWY23FH014

VIDEO/VEHICLE PERFORMANCE STUDY

Specialist's Study

April 18, 2023

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A. CRASH

Location: Philadelphia, Pennsylvania
Date: June 11, 2023
Time: 6:17 AM Eastern Daylight Time (EDT)
Truck-Tractor: 2017 International tractor in combination with a 2004 Heil tanker-trailer carrying gasoline

B. VIDEO/VEHICLE PERFORMANCE STUDY SPECIALIST

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NTSB
Washington, DC

C. SUMMARY

Please refer to the *Crash Summary Report* which is available in the docket for this crash.

D. DETAILS OF THE STUDY

1.0 Overview

In this crash, a 2017 International 3-axle tractor in combination with a 2004 Heil tanker-trailer hauling gasoline exited northbound I-95 at exit 30. After exiting the interstate, the truck traveled down the off-ramp and overturned as it entered a 300-foot-radius left-hand curve with a posted warning speed of 25-mph. For the purposes of this report the combination vehicle will be referred to as the tractor-trailer or truck. After crashing, the truck and gasoline in the trailer caught fire causing severe damage to the overpass. The goals of this study were: 1) to estimate the speed of the tractor-trailer as it traveled down the off-ramp and into the curve and 2) to evaluate the effectiveness of an Electronic Stability Control (ESC) system in preventing the rollover. The video analysis is based on video footage obtained from a Hanwha QNO-8010R security camera that was located at a warehouse near the crash site. This camera was part of a security system, and the resolution and speed of the camera changed if movement was detected by one of the cameras. Data used in this study was provided to the NTSB in the form of 1504 video frames in the MKV format. The video footage contained two different resolutions, 2592 x1944 and 640 x 480. The frame rate of the video varied between 5.95 and 62.95 fps.

Interstate 95 northbound (see Figure 1) approaching exit 30 consists of 4 northbound travel lanes and 2 exit lanes. As seen in the security camera footage (see

Figure 2), the truck exited I95 at exit 30, traveled down the off-ramp and overturned as it entered a left-hand curve with a posted warning speed of 25 mph. Based on the physical evidence, the truck was traveling in the right-hand lane when it overturned.

The portion of the video evaluated in the study begins approximately 5 seconds prior to the tanker entering the curve. As indicated by Figure 2, it was daylight when the crash occurred. The location of the camera is shown in Figure 3.

Figure 1. A Google Earth image showing the geometry of the accident scene.

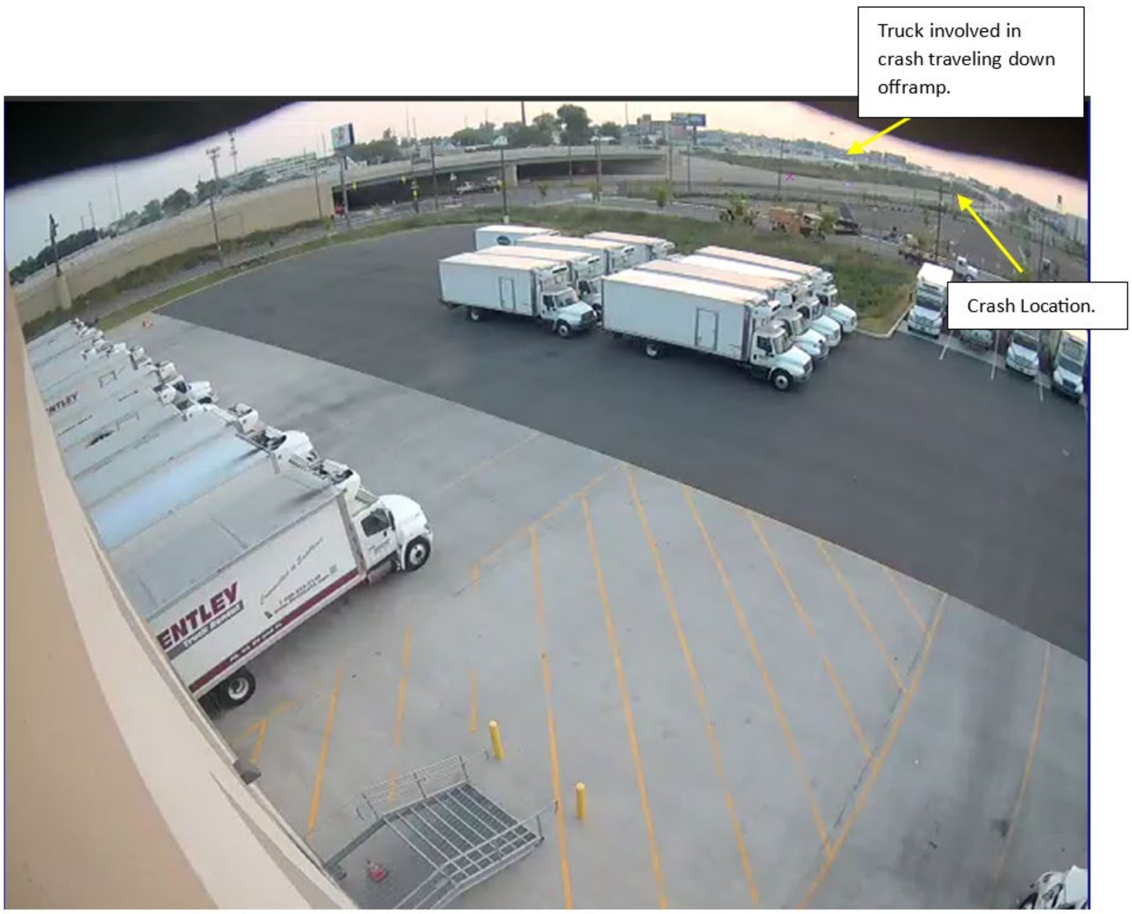

Figure 2. View from security camera.

Figure 3. A Google Earth image showing the location of the camera.

2.0 Video Measurements

The video tracking software Syntheyes (SynthEyes - Boris FX, Inc. (ssontech.com)) was used to measure the speed of the truck as it traveled down the off-ramp prior to the crash. Syntheyes is a commercially available camera tracking/match moving software that can be used to examine an image sequence and determine: 1) the location of the camera, 2) what the camera's angle of view was and 3) the speed and location of objects visible in the video relative to landmarks in the real world. The software contains a library of mathematical camera models which can be calibrated using survey data, and/or multiple view geometry. The software determines the camera position and properties by using non-linear least squares optimization and adjusting the camera properties, location, and orientation simultaneously over all frames to minimize the error between the survey measurements, the image data, and the mathematical lens model. Accuracy is determined by comparing survey points with the estimated locations based on the camera model (solved points). The software also provides a measure of the precision of the camera model in Horizontal Pixels (HPIX). The HPIX error measures how closely the camera solve approximates the locations of the 2-D image data.

The mathematical lens model used in this study was the Brown-Conrady model. The camera model was calibrated using survey data from Google Earth. Once the camera properties, locations and orientations were solved for, the motion of the truck was tracked across several frames and the image points reprojected onto a plane in the center of the right-hand lane of the off-ramp to estimate the position and speed of the truck. The resulting position data was fitted to a third order polynomial with two standard error of ±5.2 feet.

The results of the truck speed measurements shown in Figure 4 indicate the average speed of the truck just prior to the curve was 49 ±5.0 mph. The precision of the lens model used in the study was about 0.6 pixels (Root Mean Square (RMS)) which was within the recommended HPIX error. The RMS accuracy of the survey points used in the calibration was ±0.2 feet.

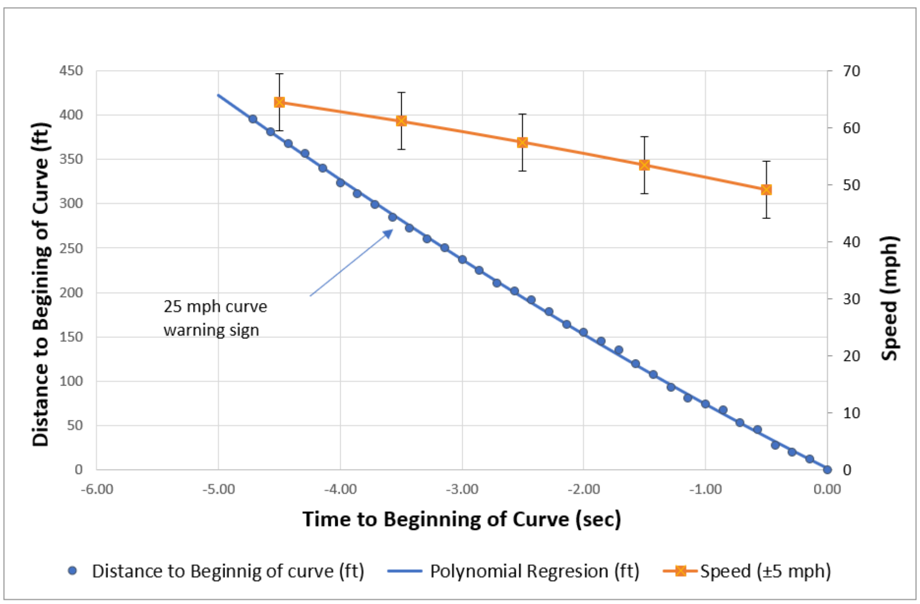

Figure 4. Distance to the beginning of the curve and speed of the truck.

3.0 Simulations

In the second half of the study a series of simulations were conducted using the TruckSim software (TruckSim Overview (carsim.com)). The purpose of the simulations was to evaluate the effectiveness of an ESC system in preventing the crash. TruckSim is a vehicle dynamics software which is used by a wide range of vehicle manufacturers and government agencies to model vehicle dynamics. The TruckSim model is three-dimensional and is fully capable of modeling tractor-trailer dynamics in cornering situations such as this crash. The software contains a library of different vehicle properties which are based on measured data. The software also allows the user to enter roadway data to match existing road geometry.

3.1 Description of the Vehicle

The tractor-trailer involved in the crash consisted of a three-axle International tractor in combination with a two axle 43-foot Heil tanker-trailer containing about 53,085 lbs of gasoline. According to data received from the trucking company, the wheelbase of the tractor was 222.9 inches, and the wheelbase of the trailer was 402 inches. The overall weight of the combination vehicle was 78,585 lbs and the weight of the tractor was about 15000 lbs. Estimates of the weight distribution received from the trucking company were as follows:

- Front axle tractor = 12285 lbs
- Second and third tractor axles = 17000 lbs (each)
- Trailer axles = 16000 lbs (each)

The center-of-gravity (cg) height of the trailer used in the simulations, 77.3 inches, is based on data for a similar tanker-trailer in reference [1].

At the time of the crash the truck was loaded with regular and premium gasoline. Percent fill of each of the compartments on the trailer was as follows:

- Compartment 1 – capacity of 2600 gallons, contained 2499 gallons - 96% of capacity.
- Compartment 2 – capacity of 2200 gallons, contained 1700 gallons - 77% of capacity.
- Compartment 3 – capacity of 1500 gallons, contained 1500 gallons - 100% of capacity.
- Compartment 4 – capacity of 2900 gallons, contained 2800 gallons - 96.5% of capacity.

3.1.1 Modeling the Vehicle in the Simulations

The tractor-trailer was modeled using the software's built-in 3-axle tractor and 2-axle trailer. The dimensions, weights and cg heights of the simulated tractor-trailer were modified to match the vehicle dimensions and weights described above. The crash-involved trailer was equipped with an air ride suspension which was modeled using a 10-ton air ride suspension. Braking was modeled using an air brake system with 2 channel ABS on both the tractor and trailer axles.

At the time of the crash the tank-trailer was at about 92 percent of its total capacity. Since the tanker was nearly full the liquid petroleum products in the tanker-trailer were modeled as a rigid payload. This is consistent with data in references [2] and [3] which indicate liquid payloads that nearly fill the volume of the tank have stability effects similar to rigid payloads. (Data in reference [2] for step steer transient maneuvers support that as long of the sloshing load of the tank is never more than 20 percent of the total load volume, the rollover threshold will not be less than the fully loaded vehicle.)

3.1.2 Background: Stability Control on Tractor-Trailers

Since the tractor involved in the crash was manufactured in May 2016 it was not required to have an ESC system and was not equipped with one. ESC systems have been required on all three-axle tractors like the crash-involved tractor since 2017. The Federal Motor Vehicle Safety Standard (FMVSS) which addresses stability control on heavy trucks is FMVSS 136. This portion of the study contains a short description of stability control systems on heavy trucks and is largely taken verbatim from the description contained in the final rule for FMVSS 136. For a more complete description, please see the final rule for FMVSS 136.

Stability control technologies help a driver maintain directional control and help reduce roll instability. Two types of heavy truck technologies have been developed. One such technology is Roll Stability Control (RSC). RSC monitors the speed and lateral acceleration to detect if the vehicle is reaching the roll stability threshold. A tractor-based RSC system consists of an electronic control unit (ECU) that is mounted on a vehicle and continually monitors the vehicle’s speed and lateral acceleration based on an accelerometer, and estimates vehicle mass based on engine torque information. The ECU continuously estimates the roll stability threshold of the vehicle, which is the lateral acceleration above which a combination vehicle will rollover. If the RSC system detects that a vehicle is approaching its roll stability threshold the system intervenes by slowing the vehicle. Depending on how quickly the system is approaching the roll threshold, the RSC system intervenes by one or more of the following actions: Decreasing engine power, using engine braking, applying the tractor’s drive axle brakes, or applying the trailer brakes. According to FMVSS 136 when RSC systems apply the trailer brakes, they use a pulse modulated system because tractor stability control systems at the time of the rulemaking could not detect whether the trailer was equipped with ABS.

An ESC system incorporates all of the inputs of an RSC system. However, it also has additional sensors (a steering wheel angle sensor and yaw rate sensor) which it uses to monitor a vehicle for loss of directional control, which may result in understeer (“plowing out”) or oversteer (jackknifing and/or “spinning out”). The systems inputs are monitored by the system’s ECU which estimates when the vehicle’s directional response begins to deviate from the driver’s steering command and oversteer or understeer. The ESC system then intervenes to restore directional control using one or more of the following actions: decreasing engine power, selectively applying brakes on the truck-tractor to create a counter-yaw moment to turn the vehicle to its steered direction or applying the brakes on the trailer. An ESC system enhances the RSC functions because it has the added information from the steering wheel angle and yaw sensors.

Currently FMVSS 136, the regulation which covers stability control systems, only requires an ESC system on the truck-tractor not the trailer. The regulation contains a 150-foot-radius J-turn maneuver test which is designed to test the ESC's ability to mitigate roll instability but does not contain a test of the system's ability to mitigate yaw instability which results in understeer or oversteer.

While the regulation requires that the tractor be equipped with an ESC system capable of pulsing the trailer brakes there is no performance test for the trailer brakes and the 150-foot-radius J-turn maneuver used to test roll stability is performed with an unbraked control trailer.

3.1.3 Modeling the ESC System

As noted in the previous section, the tractor involved in the crash was not equipped with a stability control system. The ESC system used in the simulations was the default tractor ESC available in the software. This system monitors the yaw rate, lateral acceleration, and steer angle to determine if the vehicle risks lateral or directional instability.

To prevent rollover the ESC will apply brakes on the lead unit to reduce speed if limits are reached in rollover angle or lateral acceleration. The roll stability lateral threshold used in the simulations was 0.3g. This value is consistent with performance requirements for the FMVSS 136 J-turn test described later in this report. The maximum brake pressure allowed for the ESC in the simulations was 100 psi.

To maintain directional stability the ESC uses a simple vehicle model to predict the intended yaw rate using the steering wheel angle, speed, and a few other parameters. The predicted yaw rate is compared to the actual yaw rate to determine if the vehicle is oversteering ("spinning out" or jackknifing (too great of yaw rate)) or understeering ("plowing out" (too small of yaw rate)). If the difference is large enough the controller applies braking to individual wheels to try and make the vehicle steer the way the driver intends as indicated by the steering wheel. When the ESC applies brakes, it may also set engine throttle to zero. (The predicted yaw rate used in the ESC controller in the simulations was determined by performing a series of Slowly-Increasing-Steer (SIS) maneuvers and matching the predicted controller yaw rate to the SIS yaw rate by adjusting the understeer gradient.)

As indicated earlier, while FMVSS 136 requires that the tractor ESC system be capable of pulsing the trailer brakes it does not specify how the brakes are to be pulsed. To prevent the trailer brakes from locking up in the simulations the tractor ESC pulsed the trailer brakes at lower pressures than the tractor brakes when a roll instability was detected. Simulations were also performed in which the trailer ABS system was used to prevent trailer wheel lockup. The utilization of the ABS on the trailer by the ESC would likely require more research before implementing since FMVSS 136 indicates that tractor RSC systems at the time of the rulemaking were not able to detect if the trailer was equipped with ABS.

3.1.4 FMVSS Roll Stability Control Performance Test: J-Test

The key requirement which addresses rollover in FMVSS 136 is the Roll Stability Control Performance J-test. To determine if the simulated ESC system could comply with the slowing requirements for the J-test a series of simulated 150-foot-radius J-turn maneuvers were performed. The test procedure and requirements are summarized as follows:

"To test the performance of ESC systems, NHTSA included a 150-foot radius J-turn test maneuver. The test course for the test maneuver is shown in Figure 1. This maneuver involves accelerating to a constant speed on a straight stretch of high-friction track before entering into a 150-foot radius curve. After entering the curve, the driver attempts to maintain the lane. At a speed that is up to 1.3 times the lowest entrance speed at which the ESC system activates, but no less than 48.3 km/h (30 mph), an ESC system must activate the vehicle's service brakes to slow the vehicle to 46.7 km/h (29 mph) within 3 seconds after entering the curve and 45.1 km/h (28 mph) within 4 seconds after entering the curve. The test vehicle must also remain within the lane." (Note: The regulation requires that the lowest entrance speed at which the ESC system activates (the reference speed) be at least 20 mph.)

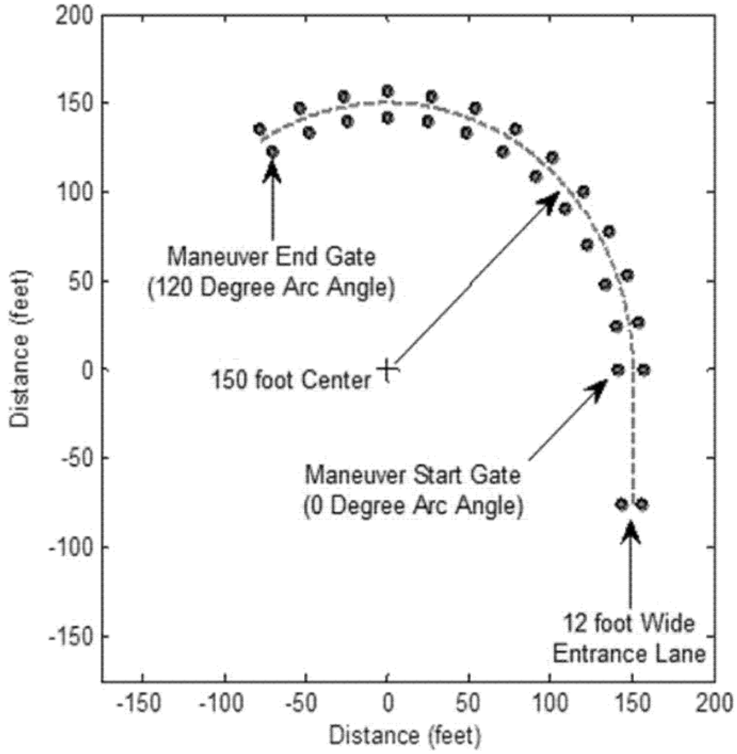

Figure 1. J-turn Test Maneuver Course (shown with the curved lane section in the counter-clockwise direction – the test is conducted in both the counter-clockwise and clockwise directions)

In the simulations of the J-turn, the software's built-in driver model was used to steer the truck through the curve. Simulations were performed with an (unbraked) control trailer which met the specifications (including loading conditions) for the test procedure. The results of the simulations confirmed that the ESC model could meet the slowing requirements for the roll stability control performance test.

3.2 Evaluating the Simulated ESC System Performance in the Curve

This crash occurred on a 300-foot radius left-hand curve which was banked at about 6 percent. The roadway prior to the curve was straight (tangent) for about 495 feet prior to the curve. Examination of the rollover in the simulations determined that the crash was the result of a roll instability that occurred as a result of the high speed at which the truck entered the curve.

To determine if an ESC system could have prevented the crash the roadway geometry was entered into the software and a series of simulations were conducted. In the simulations the tractor-trailer was driven through the curve using the software's built-in driver model and the curve entrance speed was increased from 40 mph in 1 mph increments up to the maximum speed before the crash of 54 mph (based on the video analysis). The results of the simulations were evaluated to determine the speeds at which wheel lift and rollover occurred.

Simulations were conducted with three different vehicle configurations: The crash-involved vehicle with no ESC, the crash-involved vehicle with ESC, and the crash-involved vehicle with ESC and a modified trailer. In the simulations with the modified trailer, the trailer center of gravity height was reduced by 6 inches and the trailer trackwidth increased by 6 inches. These modifications are consistent with ranges proposed in reference [1]. They are also consistent with discussions with a trailer manufacturer (MinimizerTank.com) who indicated they had trailer designs capable of carrying gasoline which could reduce cg height by about 10 ½ inches.

Note that for the purposes of this report the speeds referenced are the speeds that the truck enters the curve.

3.3 Results:

The results of the simulations are summarized in Table 1.

Table 1 – Simulation Results. Maximum curve entry speed w/o wheel lift and maximum curve entry speed without rollover

Vehicle configuration	**Maximum Curve Entry Speed in Simulations without Wheel lift (mph) (Actual Crash Speed =49 ±5.0 mph (based on video))**	**Maximum Curve Entry Speed in Simulations without rollover (mph) (Actual Crash Speed =49 ±5.0 mph (based on video))**
No ESC	44	48
With ESC	50	>54
ESC + 6 Inch reduction in the trailer's cg height + 6-inch increase in the trailer's trackwidth.	> 54	>54

The results of the simulations in the table indicate that an ESC system could help prevent rollover in circumstances like this crash. As indicated by the table, when ESC was added to the simulated tractor-trailer the rollover was prevented over the entire range of speeds before the crash (44 to 54 mph). While adding the ESC system did not prevent wheel lift over the entire range of speeds it did increase the curve entrance speed at which wheel lift occurred from 45 to 51 mph. When ESC was combined with reductions in the trailer's cg height of 6 inches and increases in the trailer’s trackwidth of 6 inches the simulated tractor-trailer was able to steer through the curve at entrance speeds above 54 mph without wheel lift or rollover. These results support that combining ESC with reductions in the trailer cg height and increases in the trailer’s trackwidth would be more effective in preventing rollover crashes in the crash circumstances than just adding ESC to the existing tractor-trailer design.

E. CONCLUSIONS

The results of the video analysis contained in this report indicate that the tractor-trailer was traveling 49 ±5.0 mph when it entered the curve where the crash occurred. The warning speed just prior to the curve was 25 mph so the tractor-trailer was traveling almost twice the posted warning speed. Evaluation of the rollover indicates that the crash was the result of a roll instability that occurred as result of the high speed at which the truck entered the curve (rather than a directional instability resulting from driver steer input). The results of the simulations indicate that an ESC system could help prevent rollover in circumstances like this crash. Examination of basic ESC control mechanisms on the tractor suggests that ESC has potential to assist drivers in preventing rollover in circumstances like this crash. In the simulations the ESC rapidly slowed the truck as it entered the curve which reduced the lateral acceleration and helped prevent rollover and wheel lift. The results of the study support that combining ESC with reductions in the trailer cg height and increases in the trailer’s trackwidth would be more effective in preventing rollovers like this crash than just adding ESC to the existing tractor-trailer design.

It should be noted that these results are based on loading conditions in which the tanker-trailer is almost fully loaded and there is limited lateral movement of fluid. Load conditions in which there was significant lateral movement (sloshing) of the liquid cargo could significantly reduce the speeds at which stability control systems are effective in preventing rollover or loss of control. It is therefore important that be ESC be combined with measures to prevent lateral movement of liquid.

Submitted by:

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Vehicle Performance Engineer

References:

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2. Wrinkler, C.B.; Ervin, R. D.; “*Rollover of Heavy Commercial Vehicles*”; University of Michigan Transportation Research Institute; UMTRI-99-19; August 1999.
3. Barickman, F. S.; Elsasser, D. E.; Albrecht, H.; Church, J.; Guogong, X; “*Tractor Semi-Trailer Objective Performance Test Research – Roll Stability*”; U.S. Department of Transportation; Report No. DOT HS 811 467; May 2011.