NATIONAL TRANSPORTATION SAFETY BOARD
Vehicle Performance Division
Washington, D.C. 20594

May 1, 2018

# Vehicle Dynamics Study

## By Shane K. Lack

**1.0 Event Summary**

Location: 300 block of Talley Road, Chattanooga, Hamilton County, Tennessee

Operator: Durham School Services LP of Warrenville, IL

Vehicle: 2008 Thomas Built School Bus

Date: November 21, 2016

Time: Approximately 03:20 p.m. Eastern Standard Time (EST)

NTSB Number: HWY17MH009

**2.0 Crash Summary**

For a description of the accident, please see the Crash Summary report in the NTSB docket for this investigation.

**3.0 Abstract/Summary of Results**

This crash occurred in Chattanooga, Tennessee and involved a school bus occupied by a driver and 37 passengers that traveled partially onto the right shoulder after negotiating a curve. After the right-side tires of the bus traveled onto the right shoulder, the bus crossed the roadway, departed the left side of the road, struck a utility pole and overturned onto its right side before striking a tree. Figure 1 shows the geometry of the roadway and physical evidence gathered during the investigation. Included in the diagram are several feet of tire marks indicating the path of the accident bus. The path of the accident bus through the curve based on the simulations and physical evidence is shown in Figure 2.

Results of a video study conducted by the Safety Board [1] found that the bus was traveling approximately 52 mph as it was negotiating the curve. The speed limit in the area of the accident was 30 mph. The primary focus of this study was the loss of vehicle control and attempted recovery, and an evaluation of

how an Electronic Stability Control (ESC) system might have influenced the outcome.

The examination of basic ESC systems in the study suggests there are potential benefits for assisting drivers in these types of accident circumstances. The benefits associated with a stability control system in the study include: a reduction in the speed of the bus as it traveled through the curve (a reduction of about 10 mph) and an increased potential to safely redirect the bus along the roadway following the initial overcorrection in the curve.

The results of the simulations indicate the foremost contributing factor to the accident was the excessive speed of the bus in the curve.

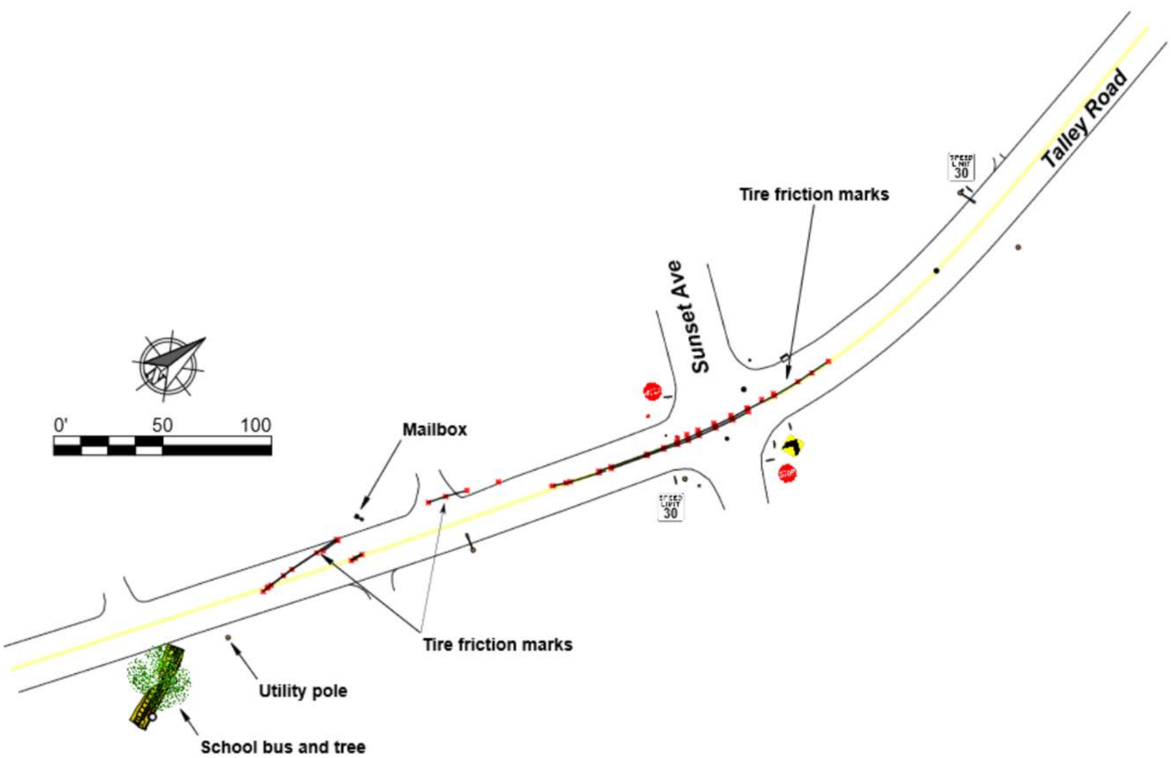


**Figure 1** – Roadway geometry and physical evidence.

## 4.0 Description of Simulated Conditions

### *4. 1 Software and Overview*

The software used in the study was PC-Crash [2]. PC-Crash is a commercially available vehicle dynamics simulation software capable of modeling three-dimensional motions of trucks and buses to the level needed for this study. For more information on the simulation software, please refer to reference [2].

### *4.2 School Bus*

According to the Vehicle Factors Group Chairman's report the accident bus was a 2008 Thomas Built School bus. A description of the baseline school bus model used in the simulations and data sources are shown in Table 1.

**Table 1**

| | Simulated Bus Model (Baseline) | Vehicle Factor's Group Chairman's Report [3] | Other Sources |
|---|---|---|---|
| **Overall length** | 481.5" | 481.5" | |
| **Front overhang** | 81.3" | 81.3" | |
| **Wheelbase** | 231" | 231" | |
| **Cg location rear of front axle** | 133.9" (58%) | (54% - 62%) | |
| **Cg height** | 42.9" | | 40-48" [4] |
| **Unladen weight** | 19482 lbs | 19482 lbs | |
| **Number of passengers** | | 37 students 1 driver | |
| **Estimated weight of passengers and cargo** | 37 * 100 lbs + 1* 180 lbs = 3880 lbs | | |
| **Total weight Laden** | 23,362 lbs | | |

### *4.3 Simulated Driver Behavior*

Driver steering control is represented within the PC-Crash software by a closed-loop mathematical driver model that mimics basic preview path-following behavior. The driver model "looks ahead" at the upcoming path and calculates steering inputs to cause the vehicle to follow the path. The driver model reacts to any external disturbances (crosswinds, road slope, etc.) by steering the vehicle in a corrective manner, within its limits.

Throttle control is represented within the PC-Crash software by a prescribed open-loop time model history, or table look up procedure. In the simulations a throttle setting sufficient to maintain a constant speed was specified and maintained unless the stability control system intervened.

### *4.4 Modeling the ESC*

Electronic Stability Control or ESC on heavy vehicles is generally divided into two types. Roll Stability Control (RSC) which slows the vehicle to reduce lateral accelerations and prevent rollover, and yaw control which uses differential braking in an attempt to make the vehicle response more familiar to the driver as the vehicle is at or near the limits of its cornering capability.

To model RSC, the throttle was released, and braking was applied to decelerate the vehicle at 0.25 g when the lateral acceleration reached a threshold of 0.3 g. These thresholds are based on a review of data on stability control systems in reference [5]. In this study the yaw control was modeled using the ESC model available within the PC-Crash software.

*4.5 Description of the Accident Curve*

According to survey information, the radius of the accident curve was 352 feet and the posted speed limit was 30 mph. At 30 mph the lateral acceleration of the bus needed to negotiate the curve in the righthand lane would have been approximately 0.2 g.

*4.6 Tire/Road Friction*

The tire/road friction used in the simulations, 0.61, is based on friction measurements taken at the accident scene by the Chattanooga Police Dept. The results of the simulations indicate that this level of friction is consistent with the speed of the bus estimated in the video analysis (52 mph) and the dynamics of the accident. (At 52 mph the simulations indicated that the lateral acceleration of the accident bus in the curve, given the path it traveled, would have been about 0.61g.) Ranges of friction evaluated in this study were from 80 percent to 110 percent of the measured friction. Variations within this range which matched the physical evidence did not affect the conclusions presented in this report.

*4.7 Speed of the Bus*

The initial speed of the bus in the simulations is based on data from the video study by the NTSB. At 52 mph the available tire/road friction needed to negotiate the curve in the righthand lane is about 0.52, which is below the measured friction of 0.61. As is shown in Figure 2 of this study, the fact that the bus was able to steer a smaller radius through the curve than the actual curve radius indicates that there was adequate friction available to negotiate the curve in the southbound travel lane.

*4.8 Northbound Vehicle in the Video Study*

The video study identified a white vehicle that was traveling in the northbound direction on Tally Road. There was no indication in the video that this vehicle intruded on the bus's lane or the speed the vehicle was traveling. The speed limit in the direction the white vehicle was traveling (northbound) was 30 mph. Information from the video study was used to determine the position of the white vehicle when it passed by the bus in the study.

On December 1, 2016, the city of Chattanooga conducted a 24-hour speed study in the 318 block of Talley Road southbound. The average recorded speed was 26 mph (for 1,588 vehicles), with at least half of the vehicles traveling in the 20-25 mph range or lower [6].

## 5.0 Simulations

### *5.1 Driver Steering*

The path of the accident vehicle and the steering history were estimated using the simulation results and physical evidence. The key position/time histories of the bus and the oncoming vehicle based on the simulations that most closely matched the physical evidence are shown in Figure 2. In the figure, the white vehicle is in shown in brown to make it easier to identify, and the school bus is shown in red. The 25 mph speed used for the white vehicle in the figure is based on the study described earlier. Notations on the figure indicate the steering wheel angle (SWA) and the rate at which the steering wheel angle is changing.

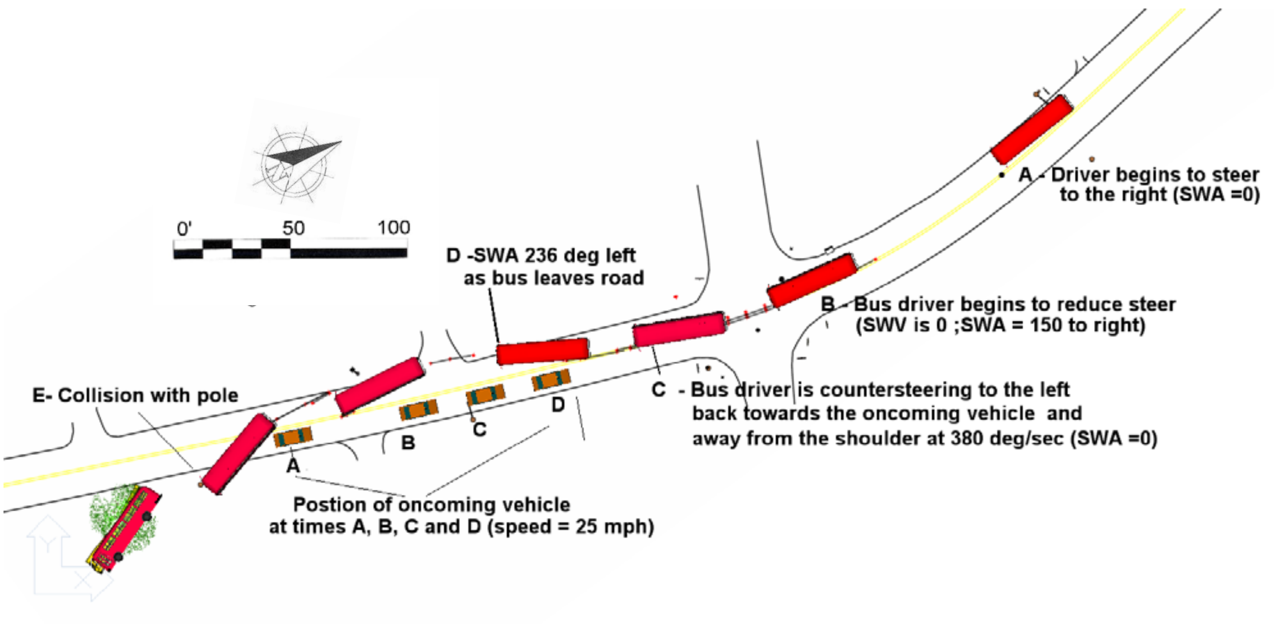


**Figure 2**

As shown by the diagram, the simulation results indicate that as the bus entered the curve it initially drifted toward the outside of the lane and a steering input to the right was needed to steer the bus back towards the right lane (the increase in steering occurs between A and B in the diagram). After reaching the maximum steer angle to the right (about 150 degrees in the simulation), the simulations indicate that a rapid countersteer to the left was needed as the bus exited the curve (approximately 380 degrees/sec), reaching a maximum steer angle of about 236 degrees to the left as the vehicle departed the roadway. In the simulations the beginning of this countersteer to the left coincided with the bus reaching its cornering limit in the simulations. After crossing onto the shoulder, the simulations indicate an almost constant steer angle to the left was maintained, which caused the vehicle to veer back across the road.

Other simulation results which matched the physical evidence displayed similar steering patterns involving a rapid countersteering to the left as the bus exited the curve and approached the right shoulder. These results indicate that to have developed sufficient sideslip to have matched the motion of the bus as it reentered the roadway, a rapid countersteer to the left was necessary as the bus approached the right shoulder of the road. These results indicate that the driver may have been attempting to avoid going off the shoulder of the road rather than attempting to drive onto the shoulder.

*5. 2 Vehicle Path through the Curve*

To determine if the bus could have safely negotiated the curve while remaining in the southbound lane, a series of simulations were conducted in which the bus was driven through the curve in the southbound lane at a constant speed of 52 mph. The results of these simulations support the conclusion that the bus could have safely negotiated the curve while remaining in the southbound lane.

While the simulations indicate that the bus could have safely negotiated the curve at 52 mph in the southbound lane, the lateral accelerations needed to negotiate the curve at 52 mph would have been about 0.5 g, which is close to the friction limits. Because a bus in this situation would be operating near the limits of its cornering capability, the risk of a lateral instability (sliding) due to incorrect steering input would be significant, and the driver would have had to minimize his steer input to prevent this. By allowing the bus to drift to the outside of the curve and then having to steer back to the right, the driver increased the risk that a lateral instability would occur. By contrast if the driver had attempted to negotiate the curve at the posted speed limit of 30 mph, the lateral accelerations would have been about 0.2 g and the risk of lateral instability and sliding due to incorrect steering would have been substantially less than at 52 mph.

*5.3 Speed Reduction by the Stability Control System*

To test how much an ESC system could have reduced the speed of the bus in the curve, the simulated bus was driven in the southbound lane of Talley road with the ESC system model enabled. The initial speed of the bus in the simulations was 52 mph. The results of the simulations indicate that the stability control system would reduce the speed of the bus in the curve by about 10 mph.

*5.4 Evaluation of the ESC and a Bus Speed of 30 mph*

A driver model loss-of-control similar to what occurred in the accident was modeled by specifying the driver model path along the roadway and varying the settings until the motion of the simulated bus closely matched the motion of the accident vehicle (running off the road). The simulation was then rerun at 52 mph with ESC enabled and at 30 mph with no ESC using the same driver model path and settings. In the simulations, the driver model is attempting to steer the bus through the curve along the roadway and toward the right side of the southbound lane as it exits the curve. The red bus shown in Figures 3 and 4 shows the results of the simulation of the accident bus with no ESC at 52 mph. As indicated, its motion is similar to the motion of the accident bus through the curve until the bus reenters the road. (No attempt was made to model the motion of the bus after it re-entered the road.) The blue bus shown in Figure 3 shows the results of the same simulation with ESC enabled (initial speed 52 mph). The green bus shown in Figure 4 shows the results of the simulation with the bus traveling at the posted speed limit of 30 mph with no ESC system. Plots of data from the simulations are shown in Figure 5.

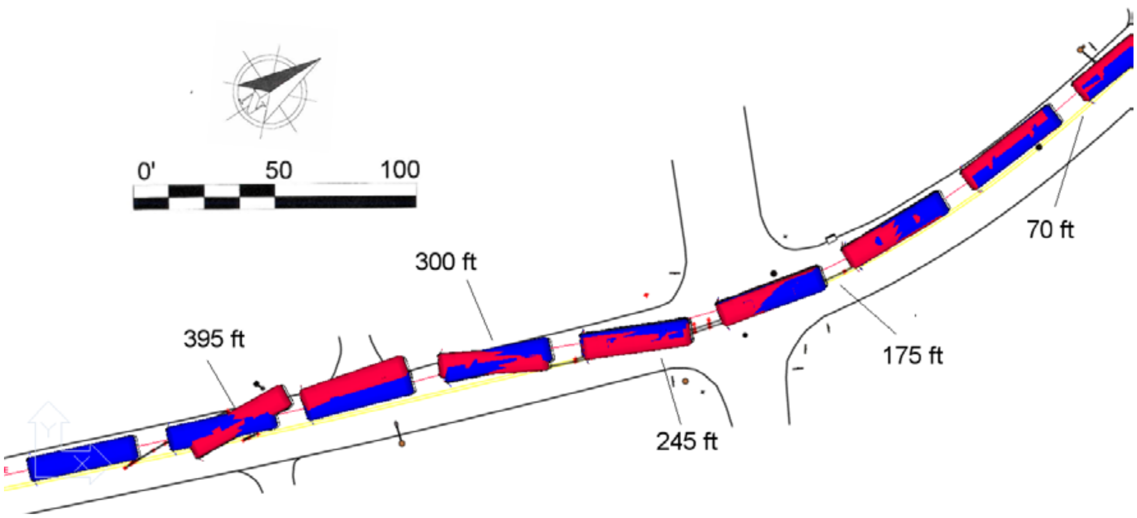


**Figure 3** – In this set of simulations, the driver model is attempting to steer the bus through the curve along the roadway and toward the right side of the southbound lane as it exits the curve. Both simulations use the same driver model path and settings. The red vehicle shows the results of the simulation with the vehicle traveling 52 mph with no ESC (the accident). The blue vehicle shows the result of the same simulation with the ESC enabled (initial speed 52 mph). Distances shown in the diagram correspond to distances used in the plots in Figure 5. (Because of the speed differences between the buses in the simulations, the buses would have reached the positions shown at different times in the simulations.)

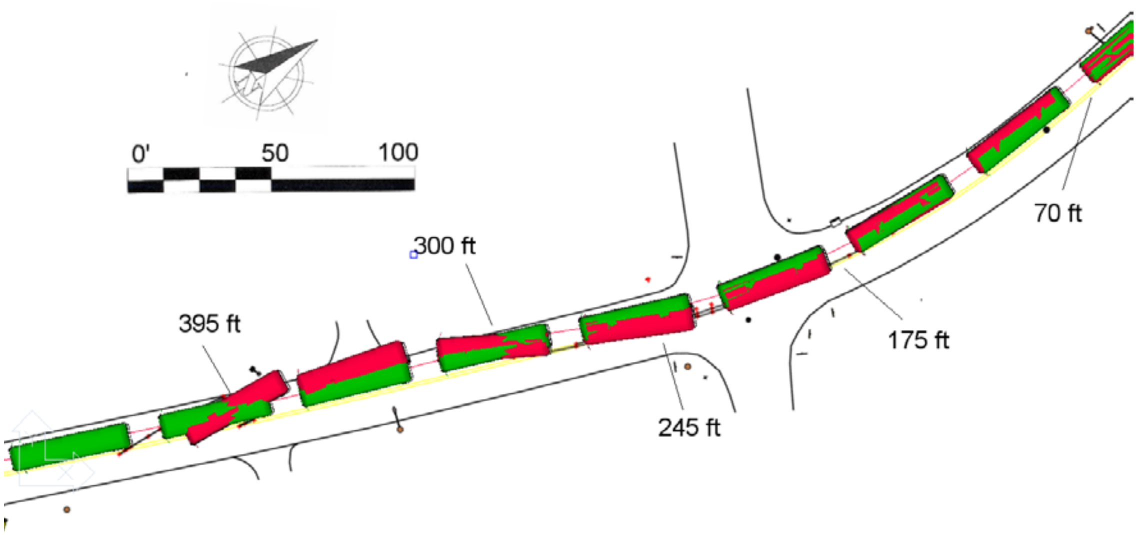


**Figure 4** – In this set of simulations, the driver model is attempting to steer the bus through the curve along the roadway and toward the right side of the southbound lane as it exits the curve. Both simulations use the same driver model path and settings as the results shown in Figure 3. The red vehicle shows the results of the simulation with the vehicle traveling 52 mph with no ESC (the accident, this is the same as the red vehicle shown in Figure 3). The green vehicle shows the result of the same simulation with the bus traveling at the posted speed limit 30 mph with no ESC. Distances shown in the diagram correspond to distances used in the plots in Figure 5. (Because of the speed differences between the buses in the simulations, the buses would have reached the positions shown at different times in the simulations.)

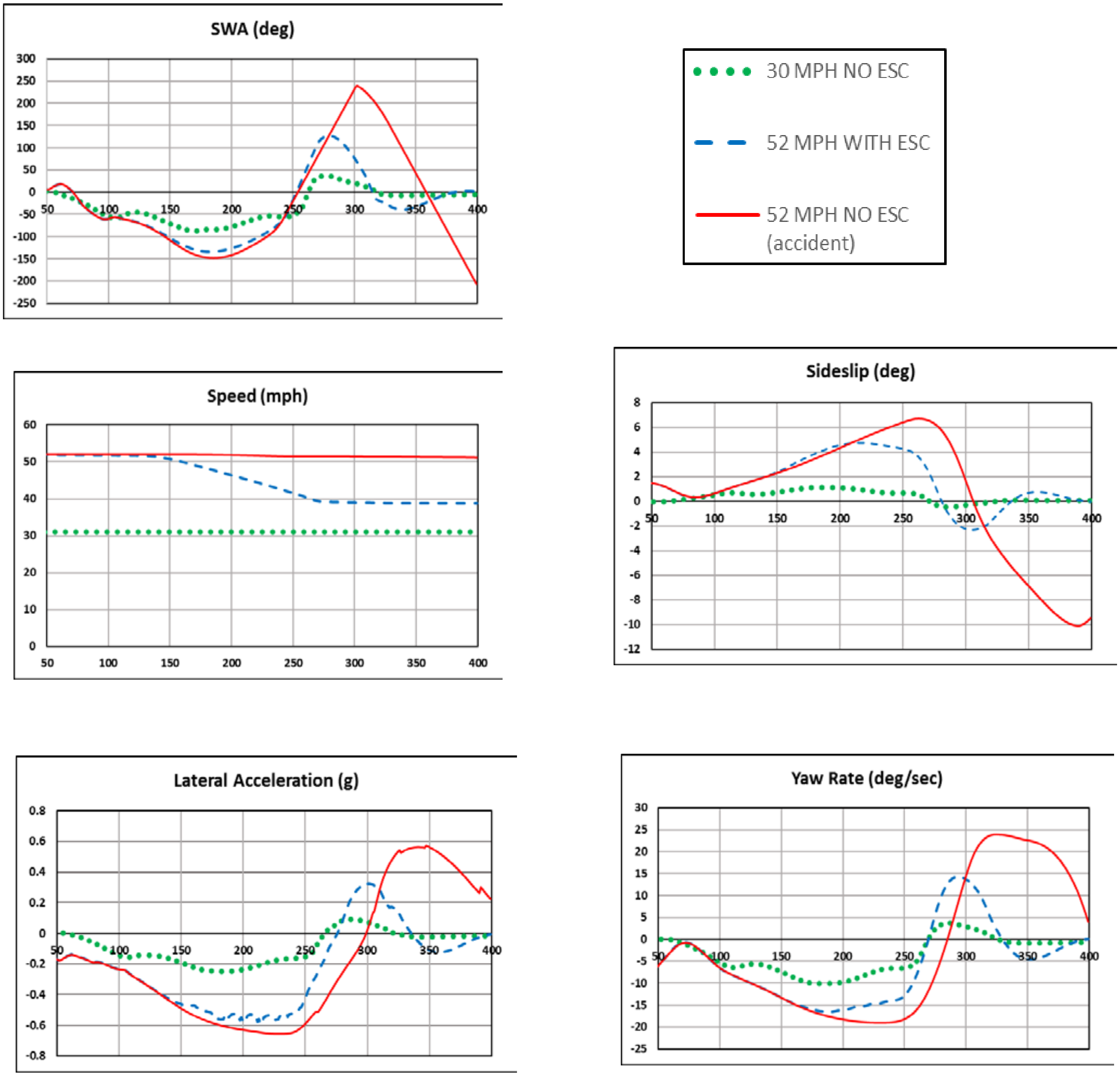


**Figure 5** – Plots of data from the simulations shown in Figure 3 and 4. The horizontal axis represent the distances in feet shown in Figures 3 and 4.

As indicated by Figures 3 and 5, slowing of the bus by the ESC better enabled the driver model to redirect the bus and stabilize it in the right lane. This improvement was in large part due to slowing of the bus by the roll portion of the ESC which made it "easier" for the driver model to redirect the bus back to the righthand lane and stabilize. Without the stability control system, the bus approached the limits of friction and developed larger slip angles, greater path deviations, and required larger steering inputs to stabilize the bus, which made it more difficult for the driver model to redirect the vehicle back into the right-hand lane.

### *5.6 Discussion of Speed as a Possible Contributing Factor*

The results of the simulations shown in Figures 3-5 indicate that the excessive speed of the bus as it entered the curve was the primary contributing factor to the initial loss of control. The high speed significantly increased the risk that the bus would reach the limits of its cornering capability, resulting in handling changes such as lateral sliding that could surprise a driver and potentially cause a loss of control. Higher speed would have also reduced the amount of decision-making time available to the driver. The simulations further indicate that the high speed would have required rapid countersteering (greater than 380 degrees/sec in the simulations) as the bus exited the curve to align the bus with the right lane and stabilize it. Reducing the speed of the bus to the posted speed limit of 30 mph in the simulations moved the bus away from the cornering limits and greatly reduced the handling changes and steering effort, which better enabled the driver model in the software program to safely direct the vehicle back into the right lane and align it with the roadway.

Two other possible contributing factors considered in this study were the initial drift of the bus to the left as it entered the curve and the oncoming traffic (the white vehicle shown in the video). In both cases the simulations indicate the risks associated with redirecting the bus back to the right in response to either of these hazards would have been significantly reduced had the bus been traveling 30 mph instead of 52 mph (see Figures 4 and 5).

## 6.0 Summary of Findings

The examination of basic ESC systems in the study suggests potential benefits for assisting drivers in these types of accident circumstances. The benefits associated with the stability control system in the study include: a reduction in the speed of the bus as traveled through the curve (about 10 mph) and an increased potential to redirect the bus into the right lane and stabilize after it exited the accident curve. In addition, it is possible that the braking intervention of the ESC system in the curve could have alerted the driver to the severity of the situation which may have better enabled him to react.

The results of the simulations indicate the foremost contributing factor to the accident was the excessive speed of the bus in the curve, which significantly increased the risk that vehicle would reach the limits of its cornering capability and become more difficult to control if the driver steered incorrectly while negotiating the curve. Reducing the speed of the bus from 52 mph to the posted speed limit 30 mph in the simulations moved the bus away from the cornering limits, which significantly reduced handling changes and steering effort, and better enabled the driver model in the software program to safely redirect the vehicle back into the right lane.

References:

1. “Video Study”, in the NTSB docket HWY17MH009.

2. http://www.pc-crash.com/

3. “Vehicle Factors Group Chairman’s Factual Report”, in the NTSB docket for HWY17MH009.

4. Zagorski, S.B., R.L. Hoover, and A.L. Dunn, “Class 8 Straight Truck and Class 7 School Bus, Brake Performance Improvement Study,” DOT HS 811 790, 2013.

5. Elsasser, D., F.S Barickman, H. Albrecht, J. Church, X. Guogang, and M. Heitz, “Test Track Lateral Stability Performance of Motorcoaches Equipped With Electronic Stability Control,” DOT HS 811 790, 2013.

6. “Highway Factors Group Chairman’s Factual Report”, in the NTSB docket HWY17MH009.