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U21: Co-Simulation of Heavy Truck Tire Dynamics and Electronic Stability Control (Phase B)

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16. Abstract

In the past decade, electronic stability controls (ESC) have become increasingly common on vehicles operating in the United States. The acceptance of this technology has progressed to the point where all new passenger vehicles sold in the US are required to have an ESC system. With this successful adoption of ESC technology by the passenger car market, there is increasing interest by both the industry and government in having ESC systems developed for and implemented in the heavy truck market.

As the typical commercial vehicle is much heavier and has a higher center of gravity compared to a passenger car, the migration of ESC from passenger cars to heavy trucks will require a re-assessment of the demands placed on the ESC system and the corresponding reactions of the ESC system. The research presented here has been conducted to help identify and document the needed performance capabilities of an ESC system for a class 8 tractor and semi-trailer.

The procedure used for assessing the performance of a tractor and semi-trailer with a yaw control ESC system was to adapt a typical passenger car yaw stability system to a class 8 commercial tractor and trailer vehicle. Several configurations of the ESC system were assessed using two different maneuvers. It is intended that the research presented here be used as the starting point for the development of a comprehensive yaw and roll ESC system for a class 8 tractor and semi-trailer.

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Executive Summary

In the past decade, electronic stability controls (ESC) have become increasingly common on vehicles operating in the United States. The acceptance of this technology has progressed to the point where all new passenger vehicles sold in the US are required to have an ESC system. With this successful adoption of ESC technology by the passenger car market, there is increasing interest by both the industry and government in having ESC systems developed for and implemented in the heavy truck market.

As the typical commercial vehicle is much heavier and has a higher center of gravity compared to a passenger car, the migration of ESC from passenger cars to heavy trucks has required a re-assessment of the demands placed on the ESC system and the corresponding reactions of the ESC system. The research presented here has been conducted to help identify and document the stability needs of a typical class 8 tractor and semi-trailer. Additionally, this research has documented the performance of existing yaw stability ESC systems on a class 8 tractor and semi-trailer in an effort to answer the questions on stability needs for commercial vehicles. It is intended that the research presented here be used as the starting point for the development of a comprehensive ESC system for a class 8 tractor and semi-trailer.

The work presented here documents the migration of a yaw control ESC system developed in phase A of this research from a passenger sedan to a class 8 tractor and semi-trailer. The results obtained indicate that the basic control strategy can be migrated to commercial vehicles but the system, as it is currently configured, is insufficient and will require additional development before it will meet all of the needs of a commercial vehicle. The two key short comings of the current stability system are the lack of a method to monitor and respond to roll instability and the lack of an ability to directly monitor the trailer’s dynamic behavior.

In situations where the vehicle was subjected to yaw instability only, the controller was generally effective and did improve the stability of the tractor. However, if the vehicle was also subjected to a roll instability the ESC system’s effectiveness was reduced. Further, as the trailer’s behavior was not monitored, the system was not able to improve trailer stability in some cases.

This research has been successful in documenting the performance of a commercial tractor and semi-trailer with the existing ESC controller. Using this information, the project is now in a good position to develop a complete yaw and roll control ESC system for a class 8 tractor and trailer vehicle.

Chapter 1 – General Overview

Background

This Phase B report covers the application of yaw stability control strategies to class 8 commercial vehicles. The Phase A work was documented in the National Transportation Research Center Inc. (NTRCI) funded report "U13: Co-Simulation of Heavy Truck Tire Dynamics and Electronic Stability Control Systems (Phase A)" (Limroth, Kurfess & Law 2009). In the Phase A work, John Limroth developed yaw control strategies for a passenger car using LabVIEW and CarSim®. These strategies were subsequently adapted and expanded to evaluate the potential for yaw stability of class 8 tractor trailer vehicles in this Phase B.

During the course of the initial model development work, John Limroth graduated from CU-ICAR with his doctorate degree. As a result, there was a significant delay in time between his departure and the arrival of the current doctoral student / researcher. As with any change in research lead, the change here has resulted in a re-focusing of the work. At the same time, the Co-Simulation project and the NTRCI sponsored Heavy Truck Rollover Characterization (HTRC) project have become increasingly closer in terms of research calibration and goals. All of these changes have resulted in a redirection of the research toward the development of an integrated ESC system to be implemented on a redesigned tractor and trailer vehicle.

Based on these changes, the focus of the research for this phase shifted somewhat from the development of a standalone ESC system to preparatory work for a planned conceptual re-design of a class 8 tractor and trailer. This paper redesign of a class 8 vehicle is planned for the first phase (Phase A) of the integrated CoSim and HTRC projects to be called the Heavy-duty Commercial Vehicle Stability project. The integration of these projects should be transparent to the research activities as the lead researcher on this project has also been a lead researcher on the HTRC work (Phases A, B, and C).

Project Team

As with the CoSim Phase A research, the project team for the CoSim Phase B work consisted of both academic and industry partners:

- Michelin Americas Research Company (MARC)
- Clemson University (CU)
- National Instruments Corp.(NI)

Each of these members brought special skills and resources to the ESC development task.

MARC Roles and Responsibilities:

Michelin's main contribution for this phase was in characterizing a class 8 tractor and trailer used to make a TruckSim® (Mechanical Simulation Corporation 2009b) model for ESC evaluation. This vehicle characterization was made as part of the HTRC Phase B project and the data was then shared with the inter-related CoSim Phase B research.

Clemson University Roles and Responsibilities:

Dr. Thomas R. Kurfess of the Clemson University International Center for Automotive Research provided the academic project oversight. Doctoral candidate Michael Arant at CU-ICAR provided the student labor on the project. Clemson University had a leading role in all project tasks.

National Instruments Roles and Responsibilities:

NI provided direct financial support through the contribution of software components (LabVIEW). NI also provided assistance and guidance on simulation and model development.

Project Description

The goal of the "U21: Co-Simulation of Heavy Truck Tire Dynamics & ESC (Phase B)" research was to adapt the research done in Phase A on passenger cars to commercial trucks. As it was anticipated that articulated commercial vehicles would be significantly harder to control than passenger cars, the current work addresses only yaw stability of commercial vehicles. It is recognized, and shown in this research, that roll control is also important with the conclusion that roll control is needed in the next research phase. The work done here is considered as a stepping stone activity toward a full roll and yaw stability system in the HCVS research.

The research here documents the potential for yaw stability control of class 8 tractor and semi-trailer vehicles. Included in this investigation is an analysis of brake control strategies (tractor brakes only, entire vehicle brakes, and selection of optimal trailer brake pressure) for tractor yaw control. Finally, the effect of trailer load and load placement on yaw stability response was evaluated.

As with the Phase A research, the stability algorithm development used a non-linear vehicle simulation package as the "true" vehicle as opposed to an actual test vehicle. This was done for cost and time reasons as it was much quicker and cheaper to use a model for the vehicle rather than instrumenting and running an actual test many hundreds of times. In the Phase A work, Limroth used CarSim® by MSC (Mechanical Simulation Corporation 2009a) while the Phase B work used TruckSim® by MSC (Mechanical Simulation Corporation 2009b). The control and vehicle modeling process is illustrated in Figure 1 below.

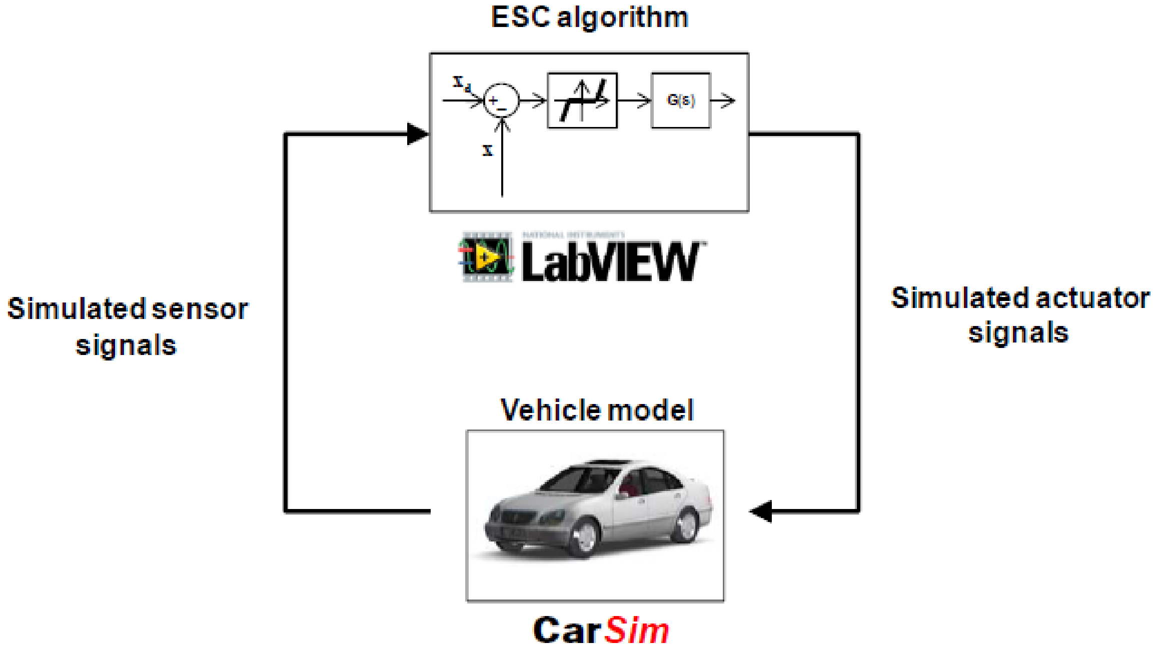

Figure 1. Diagram. ESC System Diagram (Limroth 2009)**.**

Chapter 2 – Results of "U13: Co-Simulation of Heavy Truck Tire Dynamics and Electronic Stability Control Systems (Phase A)"

The basic approach to yaw stability used in this work was the same as that developed by Limroth in 2009 (Limroth, Kurfess & Law 2009). In the previous work Limroth developed a three layer control strategy with a built in hierarchal order of importance. In this case, the anti-lock brake system (ABS) had the primary control, with the driver brake demand second in line, followed by the stability control system. In this way, the tires are monitored against wheel lock (ABS), the driver has the ability to stop when needed, and the stability system can intervene when the driver is not trying to stop and an instability situation exists.

The work done by Limroth has been documented in the report: "U13: Co-Simulation of Heavy Truck Tire Dynamics and Electronic Stability Control Systems (Phase A)" (Limroth, Kurfess & Law 2009), and Limroth's Dissertation (Limroth 2009). As such, the details of the yaw stability system will not be re-presented here. The review of the yaw controller here is limited to a few key ideas used in "U21: Co-Simulation of Heavy Truck Tire Dynamics & ESC (Phase B)".

Passenger Car Work

As noted in chapter 1, the existing research was limited to passenger cars. More specifically, the work dealt with a two axle front wheel drive sedan. The state of the true vehicle (yaw rate and lateral velocity) was measured and compared to a simple model of the vehicle. Deviations of the true vehicle or, in this case the CarSim® model, from the desired response of the driver prompted the stability system to intervene with differential braking to adjust the vehicle's yaw. The stability system was modeled as illustrated below (Figure 2).

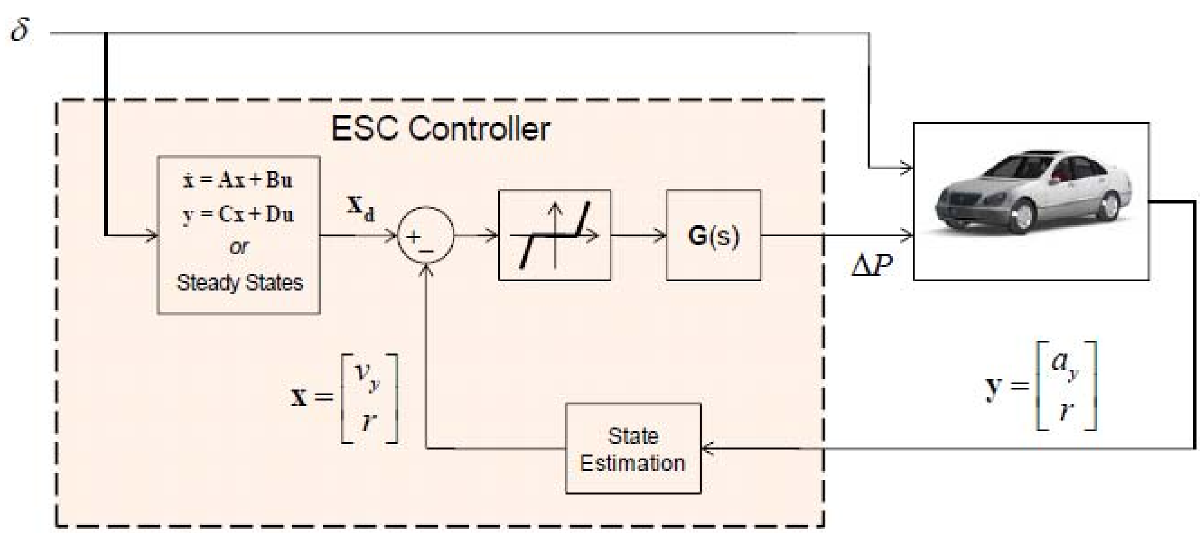

Figure 2. Diagram. Yaw Control Flow Diagram (Limroth 2009)**.**

The vehicle model used for assessing driver intent was a typical bicycle model as shown in Figure 3. When the actual vehicle's behavior differed from the bicycle model's behavior, a corrective action was applied to the actual vehicle to bring it back into alignment with the supposed driver intent.

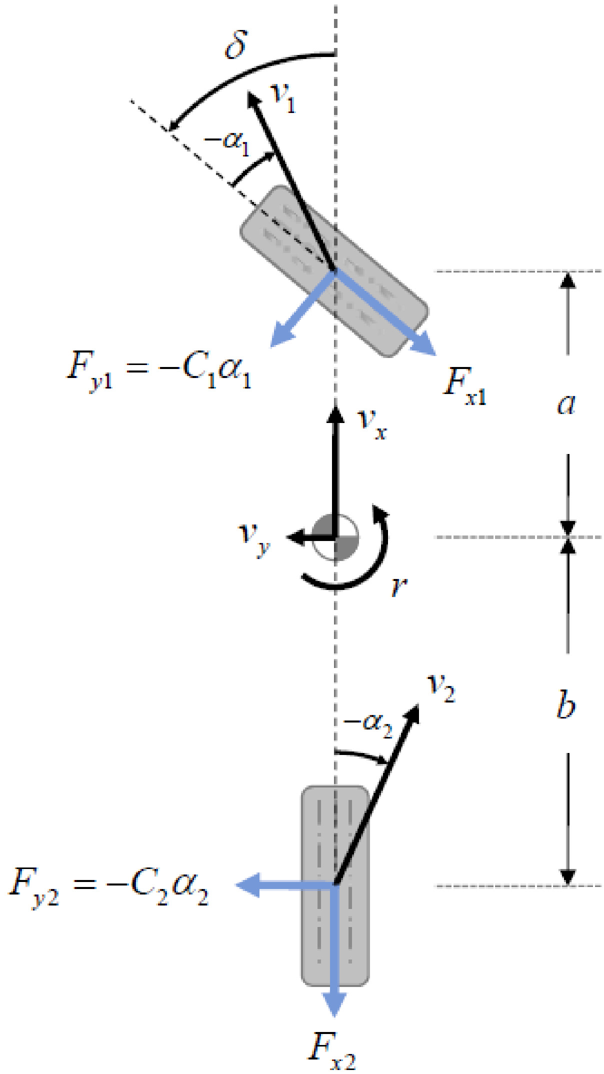

Figure 3. Diagram. Bicycle Model of Passenger Car (Limroth 2009)**.**

Yaw Stability Operation

The ESC controller uses the response of the vehicle, or in this case, the response of the TruckSim® (Mechanical Simulation Corporation 2009b) model to estimate key vehicle and environmental parameters needed to accurately prescribe needed stability corrections. The model uses data from non-limit (normal driving) situations to estimate the vehicle's mass, cornering potential (tire cornering stiffness), and traction limits.

The algorithm can also use this information to predict when the vehicle might become unstable and begin to intervene before the stability limit is reached. The complete controller flow chart is pictured in Figure 4.

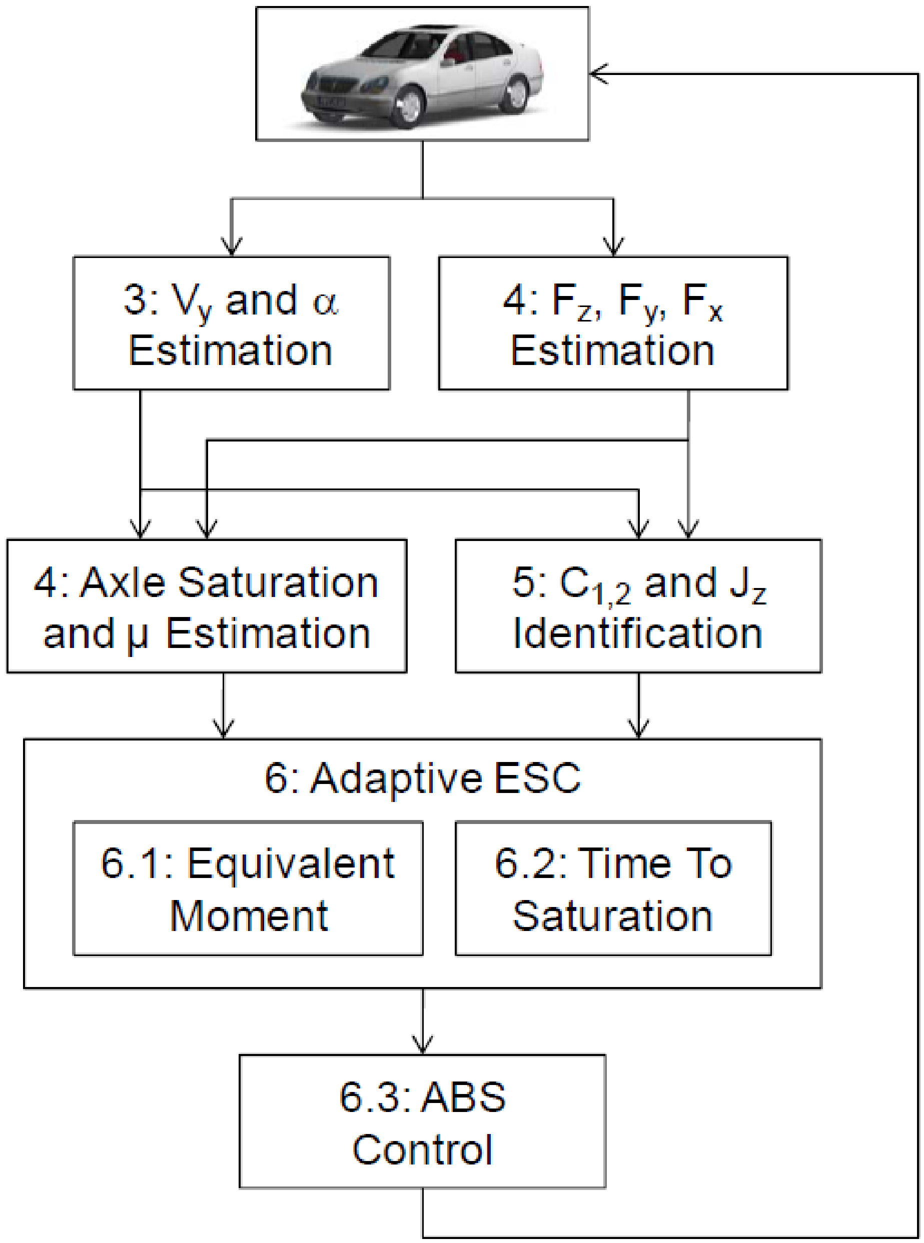

Figure 4. Diagram. Yaw Stability Control Flow Chart (Limroth 2009)

Note that the ABS controller is at the bottom. This controller supersedes all other braking commands in order to maintain wheel traction and prevent wheel lock-up.

Predicting Loss of Stability and Corrective Actions

The yaw stability algorithm uses the estimated vehicle and environmental parameters to predict when stability might be lost. This prediction is called the Time To Saturation (TTS) value. It is based on the rear axle slip angle and the peak estimated slip angle generated from the tire cornering stiffness, the tire load, and the road friction. When an oversteer event is predicted or observed, the system responds with a countering yaw moment through the application of braking forces to individual wheels (Figure 5). Again, the ABS has the priority for determining the braking applied to any wheel.

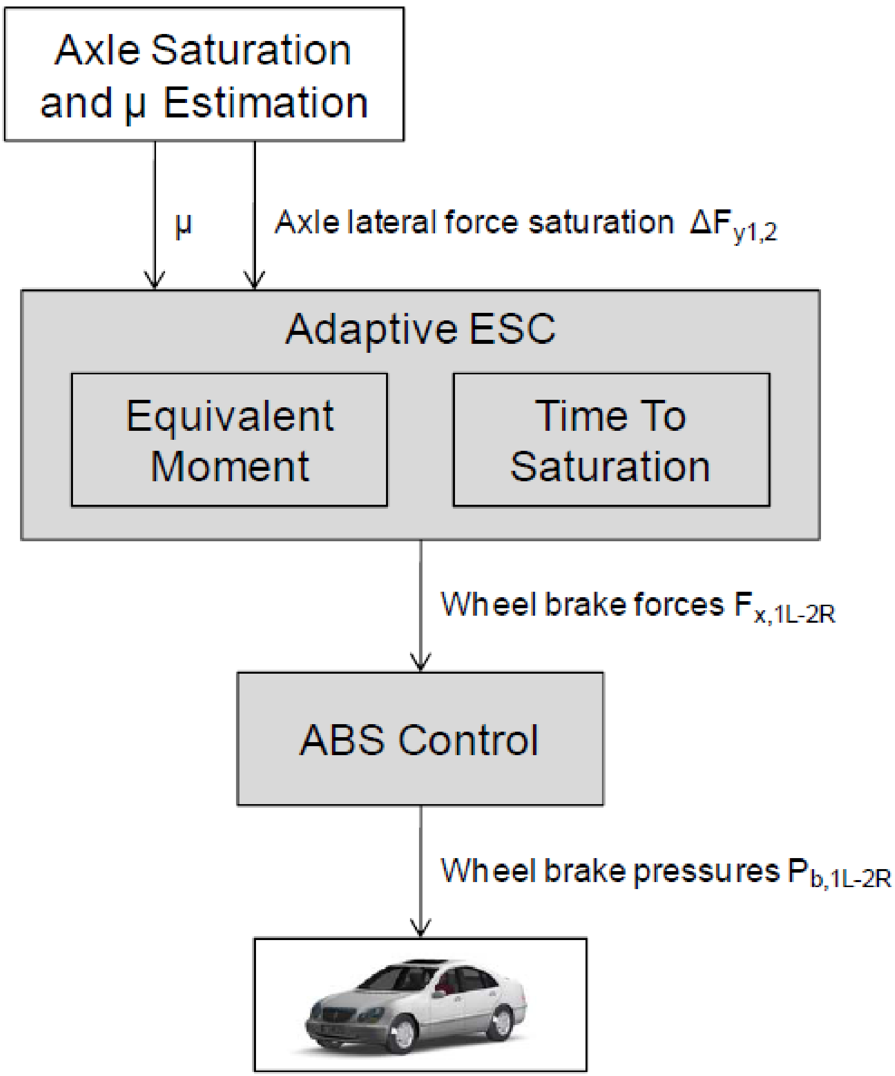

Figure 5. Diagram. ESC Action (Limroth 2009)**.**

Stability Assessments

The results of the "U13: Co-Simulation of Heavy Truck Tire Dynamics and Electronic Stability Control Systems (Phase A)"(Limroth, Kurfess & Law 2009) research indicated that the controller strategy was successful in reducing path divergence of a vehicle (Figure 6) as well as reducing the demand on the driver through the reduction of required steering input to complete the maneuver (Limroth 2009).

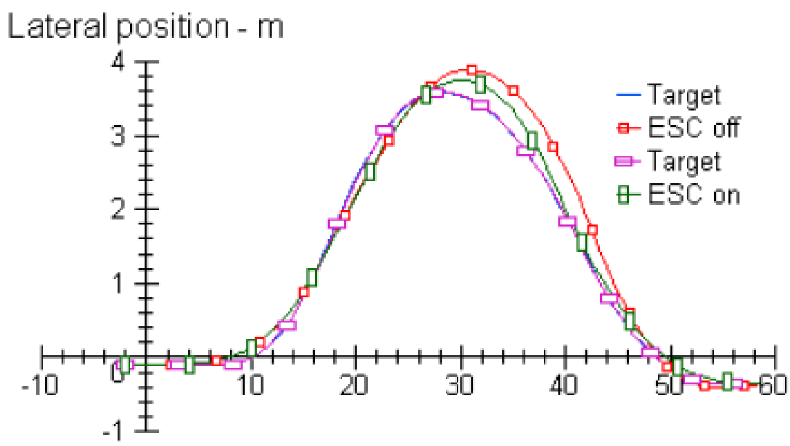

Figure 6. Graph. Phase A Double Lane Change Path (Limroth 2009)**.**

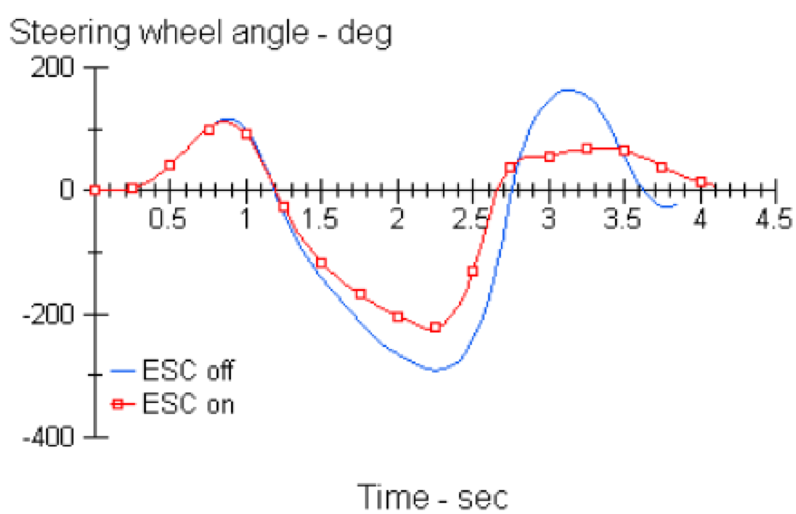

Figure 7. Graph. Phase A Double Lane Change Steering Input (Limroth 2009)**.**

Based on the positive results from Phase A, the ESC algorithm was adapted for use with a tractor and semi-trailer in Phase B.

Chapter 3 – Adapting Work to a Tractor and Semi-Trailer

When migrating a controller from a passenger car to a commercial truck, there are several issues that need to be addressed. Among the more important issues involved in the conversion of the Phase A ESC model to manage the stability of a truck were:

- The significant change in vehicle mass and inertia
- The recognition that the mass and inertia can change dramatically with cargo load
- The inclusion of a second drive axle (for use with 3 axle tractors)
- The inclusion of trailer brakes to the control strategy

Each of these points was addressed in the development of the new tractor ESC controller. Some of these were implemented in the initial model development (mass and inertia effects) while others were added later and used to assess the sensitivity of the controller to the parameter. The modifications to the controller are documented below.

Updating the ESC Model for a Tractor Semi-trailer

The first activity in converting the ESC controller to manage a truck was to update the vehicle parameters (mass, CG location, inertia, etc.). To do this, three separate models were developed for the different vehicle configurations:

- A bobtail, or tractor only configuration.
- An empty trailer configuration. This configuration was also used when modeling a rear trailer only load as the vertical load seen by the tractor is the same for the unloaded and rear only trailer payload only case.
- A loaded trailer configuration. This configuration was also used when modeling a front trailer only load as the vertical load seen by the tractor is the same for the loaded and front only trailer payload only case.

While the existing ESC model from Phase A did have the ability to account for load changes, the method used resulted in a re-calculation of the CG location with a change in payload. As the process for determining the CG location of a multi-unit vehicle is not the same as for a single unit car, the load function of the Phase A model was not used and each vehicle case was developed in a separate model. The models were the same except for the vehicle parameters used.

ESC Controller Activation

For all of the ESC models developed, the controllers can be run with and without the ESC system active. Thus the steering used with the ESC controller on (Figure 8) is the same as with the ESC controller off (Figure 9) providing a true assessment of the effect of the ESC system. Switching the ESC off simply sets the controller output brake demands to zero for all wheel positions.

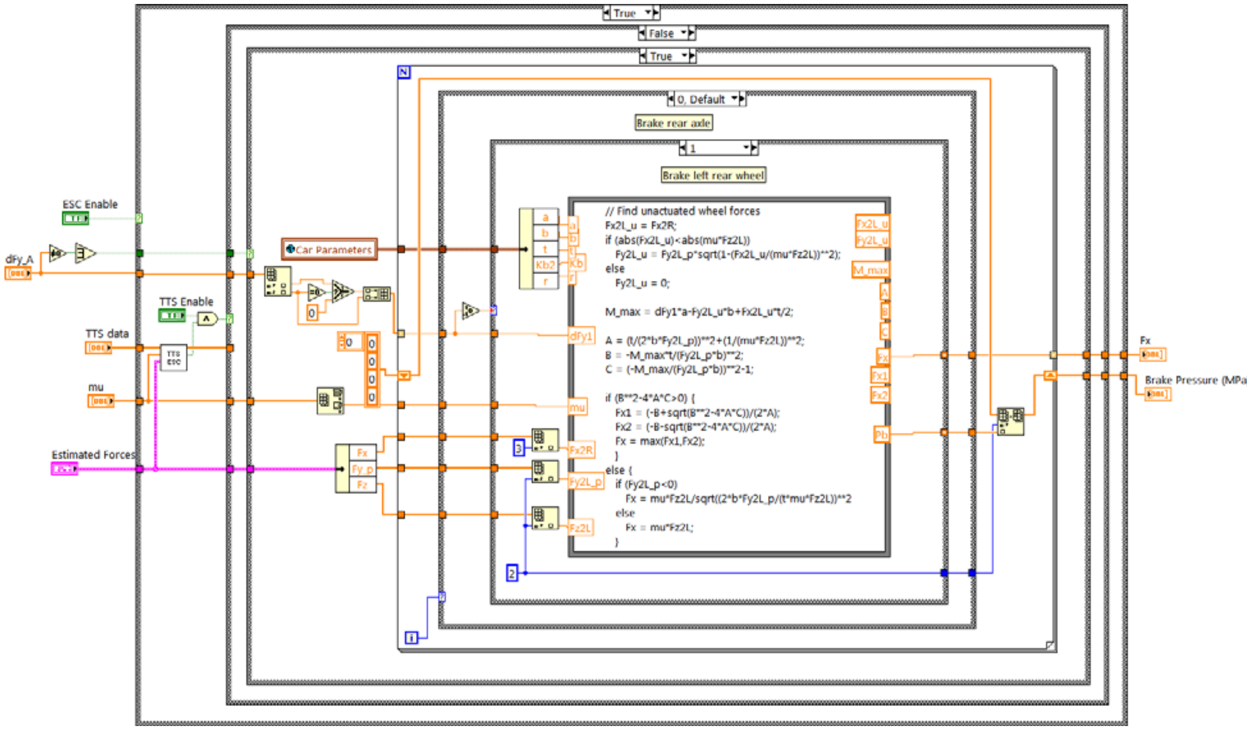

Figure 8. Diagram. ESC Controller Enabled.

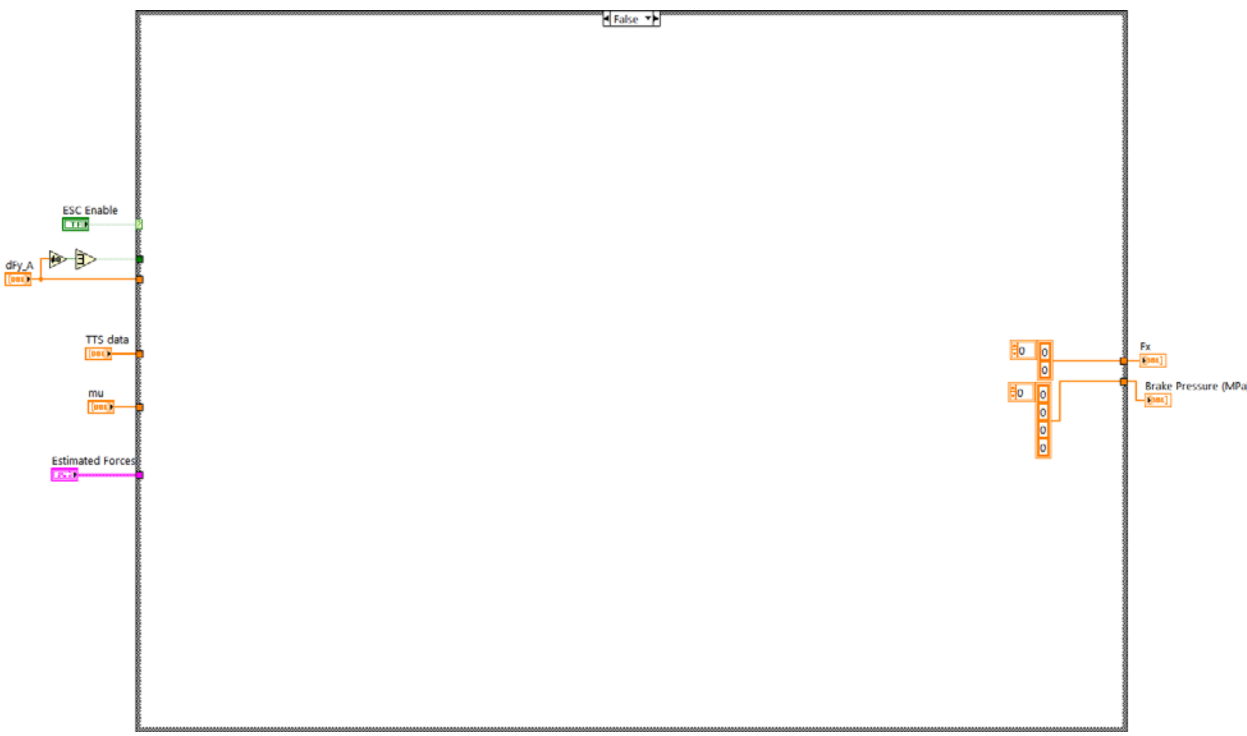

Figure 9. Diagram. ESC Controller Disabled.

Building a Bobtail TruckSim® Model with LabVIEW ESC

The bobtail model was very close to the Phase A car model with the only significant change to the brake allocation module. As is the typical industry approach to brake control of 6x4 vehicles, the two left and two right side drive wheels were controlled as a unit. For illustration, Figure 10 shows the controller brake output where the two left drive wheels see the same brake command and the two right drive wheels see the same brake command. The brake channel order from top to bottom is left steer, right steer, left front drive, right front drive, left rear drive, and right rear drive. As can be seen, the controller acts like a two axle controller with the rear axle duplicated for the tandem drive. The brake supply input to the left is the ESC demand to activate the brakes.

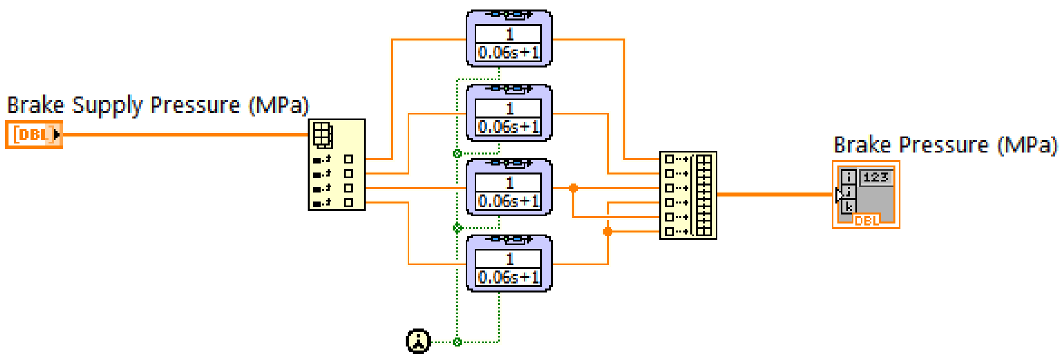

Figure 10. Diagram. Bobtail Brake Control.

Building a Tractor Control Only TruckSim® Model with LabVIEW ESC

The next model developed was for a complete tractor and trailer which required ESC brake commands for the trailer as well as the tractor. Typically, the trailer ESC commands would be incorporated into the overall vehicle's brake controls so that the driver or the ESC system could activate the trailer brakes. However, since only free rolling maneuvers were being used for this analysis, driver brake demand was not needed. For expediency the trailer brakes were set-up such that they could only be activated by the ESC system. If combined brake and turn maneuvers need to be assessed in the future, then the trailer brake logic used here would be insufficient as there is no mechanism for the driver to command brakes to the trailer.

For the first round of full tractor and trailer modeling, the controller was assumed to have no ability to activate the trailer brakes. As such, the trailer brakes were set to zero for all cases. The resulting ESC brake output structure is the same as for the bobtail with the addition of four trailer brake channels at the bottom of the stack (Left front trailer, right front trailer, left rear trailer, right rear trailer) (Figure 11). Each of the trailer channels is set to zero in this case.

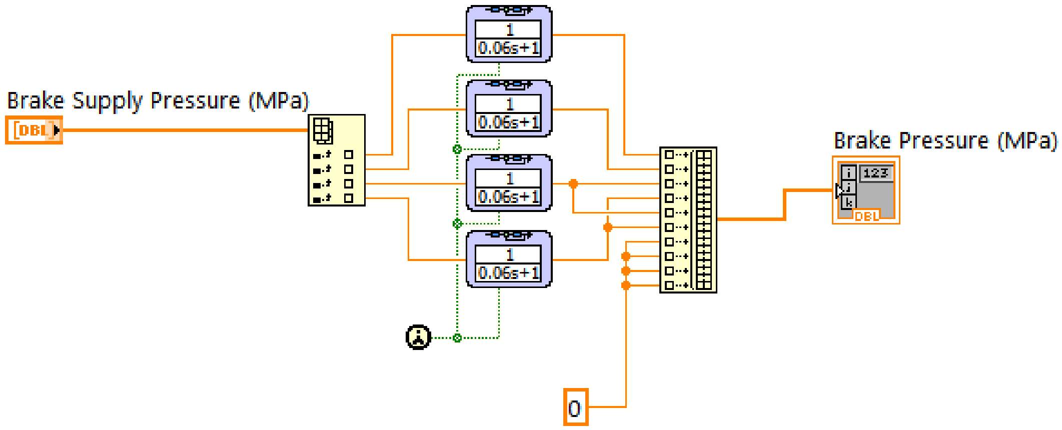

Figure 11. Diagram. Tractor Trailer Control without Trailer Brakes.

Building a Tractor Control with Trailer Brakes TruckSim® Model with LabVIEW ESC

The final model developed took the previous tractor and trailer model and added trailer brakes to assist stability control. Several methods were tried with the most effective being the following (Figure 12). As the fifth wheel connection is always behind the tractor's CG location, the effect of applying the trailer brakes is to return the tractor back to a straight ahead driving condition. In other words, the trailer brakes are useful for restoring a case where the tractor is yawing out of control (in either direction) but not useful for a case where more yaw is needed (in which case the rear axles of the tractor are braked to induce yaw).

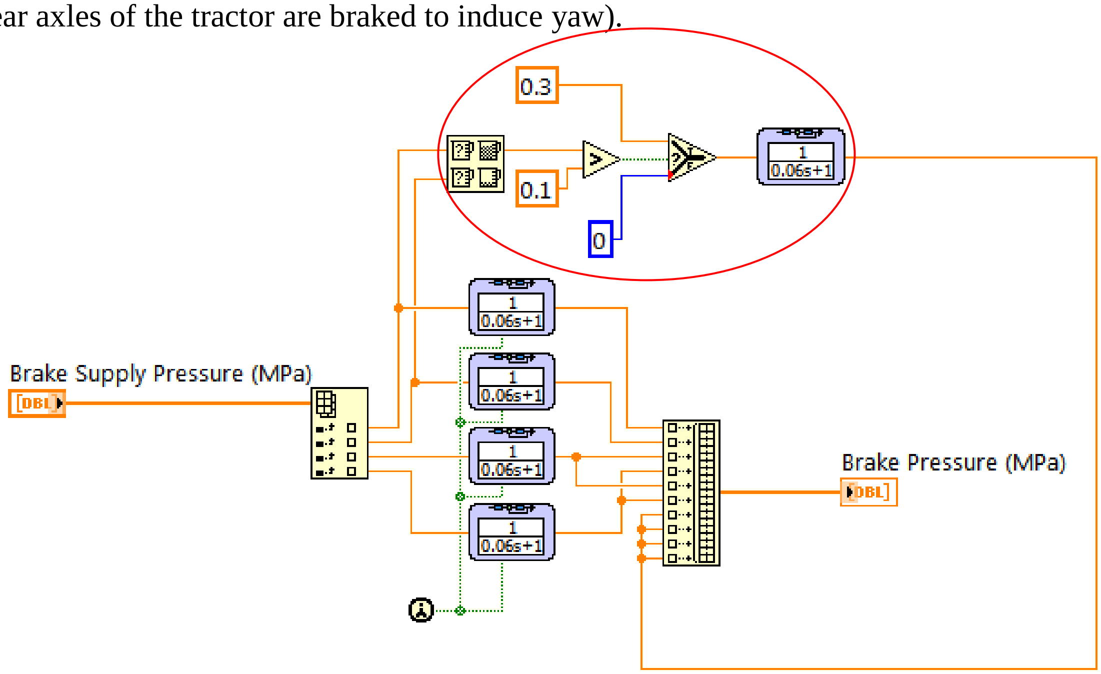

Figure 12. Diagram. Tractor Trailer Control with Trailer Brakes.

The idea behind this controller is that the steer axles should be the first responder to a yaw divergence condition as they are directly attached to the tractor. But they can also serve as an indicator to the trailer brakes to activate at the same time. This is reflected in the section enclosed in the red oval. Also note that the trailer brakes use a line pressure of 0.3 MPa which is well below the 0.8 MPa peak pressure possible. The selection of 0.3 MPa is discussed in the results section in chapter 4.

Additionally, it should be observed that the trailer brakes activate with either front wheel position. With the fifth wheel plate located behind the CG, it does not matter which direction the tractor is yawing toward, the trailer brakes act to resist the yaw divergence of the tractor. To prevent the trailer from cycling on and off during minor corrections, the trailer brakes have an activation threshold of 0.1 MPa front wheel pressure. With full brake pressure being about 0.8 MPa, this constitutes a small threshold for activation. Note that all four trailer brakes see the same input as there is little value in differential braking of the trailer wheels.

Finally, as with the no trailer brake case before, this method does not permit the driver to activate the trailer brakes via the brake pedal. It is a viable control method for assessing the vehicle response to free rolling tests where the only brake demand is from the ESC controller. It would not be a sufficient control strategy for a combined brake and turn maneuver.

Dual Control Systems (Tractor Control and Trailer Control)

The significant problem with the trailer brake strategy used here is that only the tractor's dynamic state is observed and, as a result, the actions taken to enhance stability of the tractor do not necessarily improve the stability of the trailer. Attempts were initiated to manage information on the stability of each unit (tractor and trailer) such that the controller could act to restore stability to whichever unit was diverging. Unfortunately, none of the methods applied worked well as the precedence of activation between the tractor's needs and trailer's needs could not be managed well. As a result, this activity is left for a later research activity.

Chapter 4 –General Assessment of Modeling and Control Development

The approach used in this analysis of stability control development was to model a bobtail vehicle with and without ESC and then the full tractor and trailer in 12 different scenarios generated using three controllers (no ESC, tractor only brakes, full brakes) and four load conditions (empty, front load, rear load, full load). The entire set of analysis cases were assessed using a lane change maneuver and an exit ramp maneuver.

All of the modeling results documented in this report were developed using a ground coefficient of friction (mu) of 0.5. This is roughly equal to wet asphalt though the mu of wet asphalt varies considerably with binder selection, rock content, and age. This decision was made as high ground mu values are typically associated with dry pavement and the general stability limit of commercial vehicles on dry pavement is in rollover rather than yaw instability. Lower mu values associated with snow did not result in significant qualitative differences relative to wet asphalt modeling and the quantitate differences were largely related to the lower speeds associated with lower mu testing.

To make the results easier to review, the bobtail and empty tractor semi-trailer results are presented in detail. The effect of load on the full tractor and trailer is treated separately so that the load condition effect is easier to see.

Stability Maneuver Selection

The two stability maneuvers used to assess the ESC performance were the double lane change and a 500 foot radius exit ramp. The lane change maneuver was derived from a TruckSim® (Mechanical Simulation Corporation 2009b) lane change maneuver while the ramp steer maneuver was generated by the author.

The lane change maneuver consisted of a 70 meter by 4 meter lead-in segment followed by a 30 meter by 4 meter offset and a 50 meter by 4 meter return segment. The offset of the center segment was 3.5 meters (Figure 13). This course was effective in testing both the initial steer response and the counter-steer response of the vehicle. The steering controller tried to maintain the same set path through the cones for all cases.

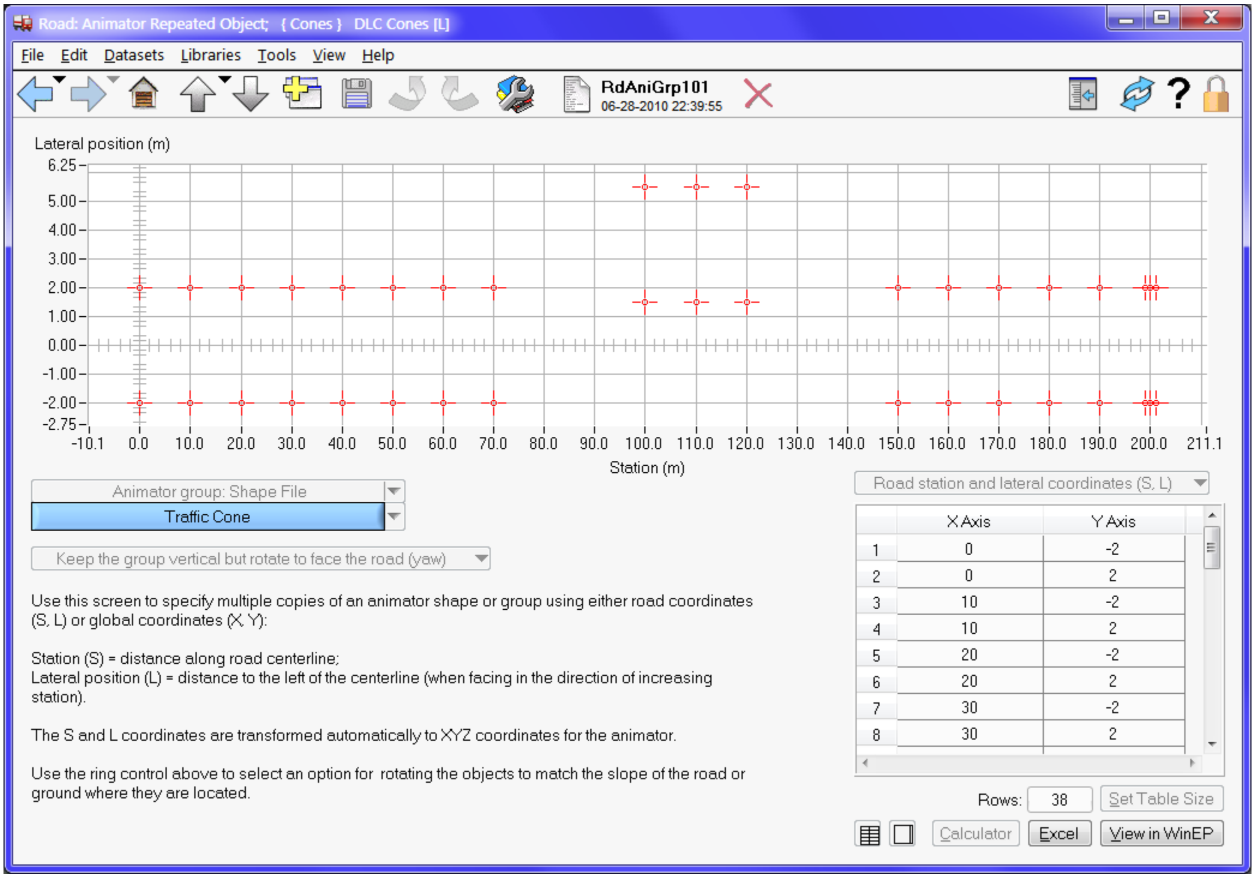

Figure 13. Chart. Lane Change Maneuver (Mechanical Simulation Corporation 2009b)**.**

A second lane change maneuver based on stability control work done by NHTSA was also instigated (Barickman, Elsasser). The NHTSA maneuver was quite similar to the lane change maneuver above with the NHTSA maneuver having the gates slightly further apart and the second gate offset by 4 meters as opposed to the 3.5 meters used here. As the two lane change maneuvers were quite similar and the TruckSim® (Mechanical Simulation Corporation 2009b) maneuver also had the driver intent path defined, the TruckSim® version was selected.

The exit ramp was a simple flat 500 foot radius arc with a 25 meter straight lead in segment. The steering controller attempted to maintain a path around the center of the road profile shown in Figure 14.

Figure 14. Illustration. Exit Ramp Circuit (Mechanical Simulation Corporation 2009b)**.**

The purpose of the two different maneuvers was to test the ESC behavior in transient (lane change) and steady state (exit ramp) conditions.

Bobtail Vehicle Analysis (Lane Change)

The first simulations developed were the bobtail lane change cases as this vehicle arrangement most closely resembled the prior passenger car research. In this analysis, the vehicle speed was set to 115 km/hour as at this speed the ESC controlled vehicle was able to respect all of the cones while the non-ESC vehicle could not (Figure 15). In all figures and plots, the blue is the nominal vehicle and the red is the ESC-enable vehicle.

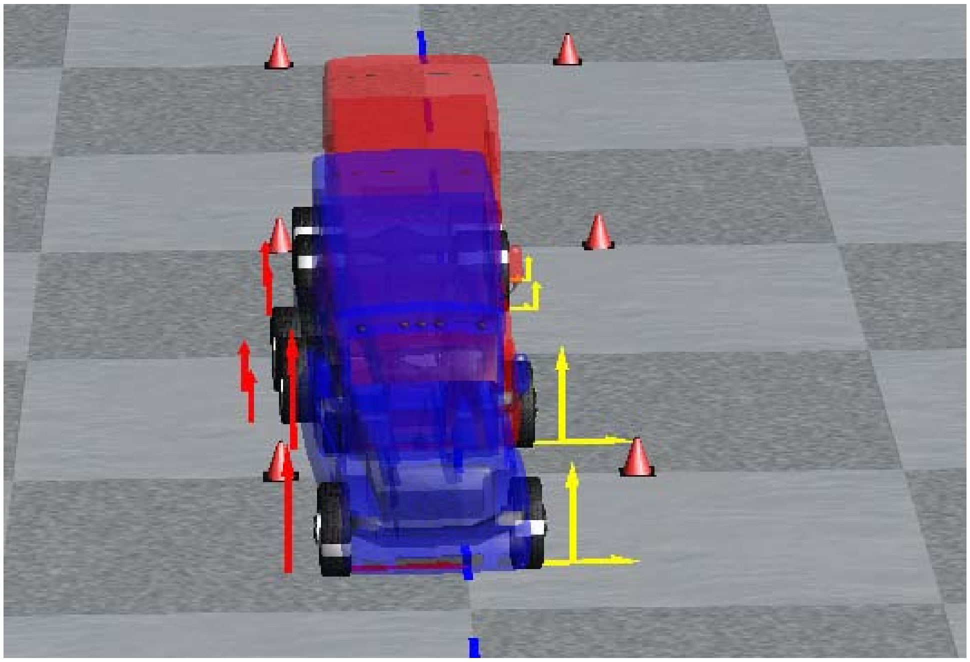

Figure 15. Illustration. Bobtail Lane Change.

The results of the bobtail testing using the lane change maneuver showed that the ESC system was able to slightly reduce the steering demands on the driver by lowering the required steering input for the return lane section (160 to 250 meters) which was the section of the maneuver where the uncontrolled vehicle exited the cones (Figure 16).

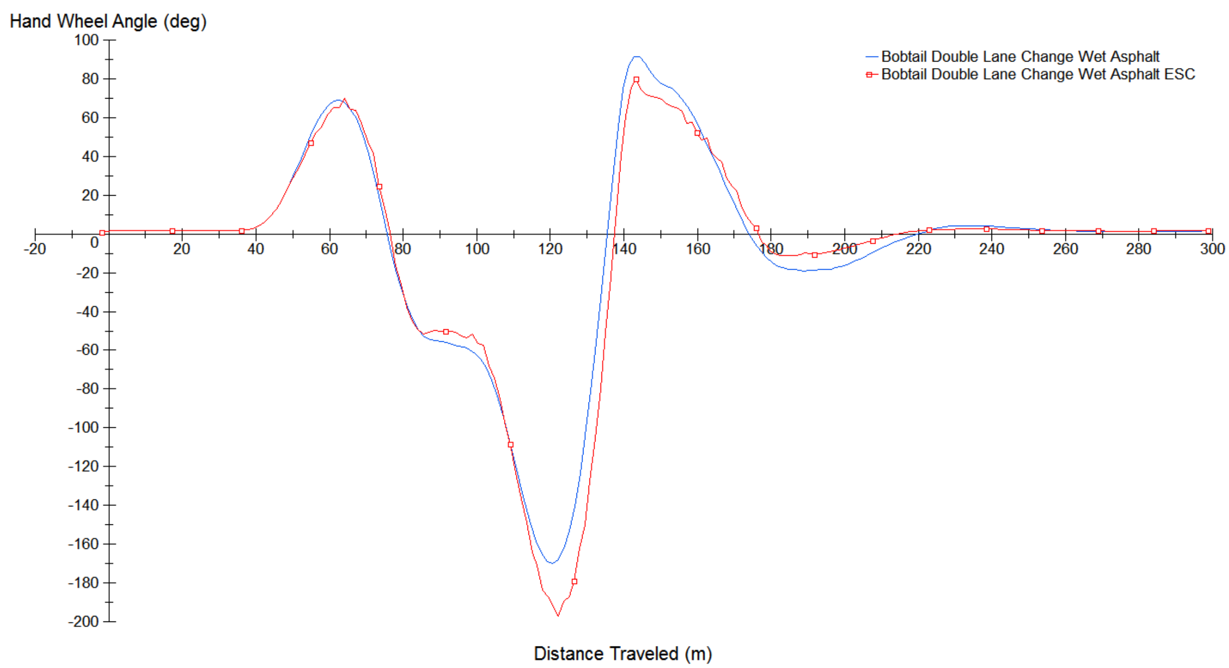

Figure 16. Graph. Bobtail In Lane Change – Steering Input.

The ESC system was also effective at reducing the lateral acceleration levels seen by the vehicle (Figure 17) as well as the yaw rate magnitudes (Figure 18). This was particularly true for the more demanding latter part of the maneuver.

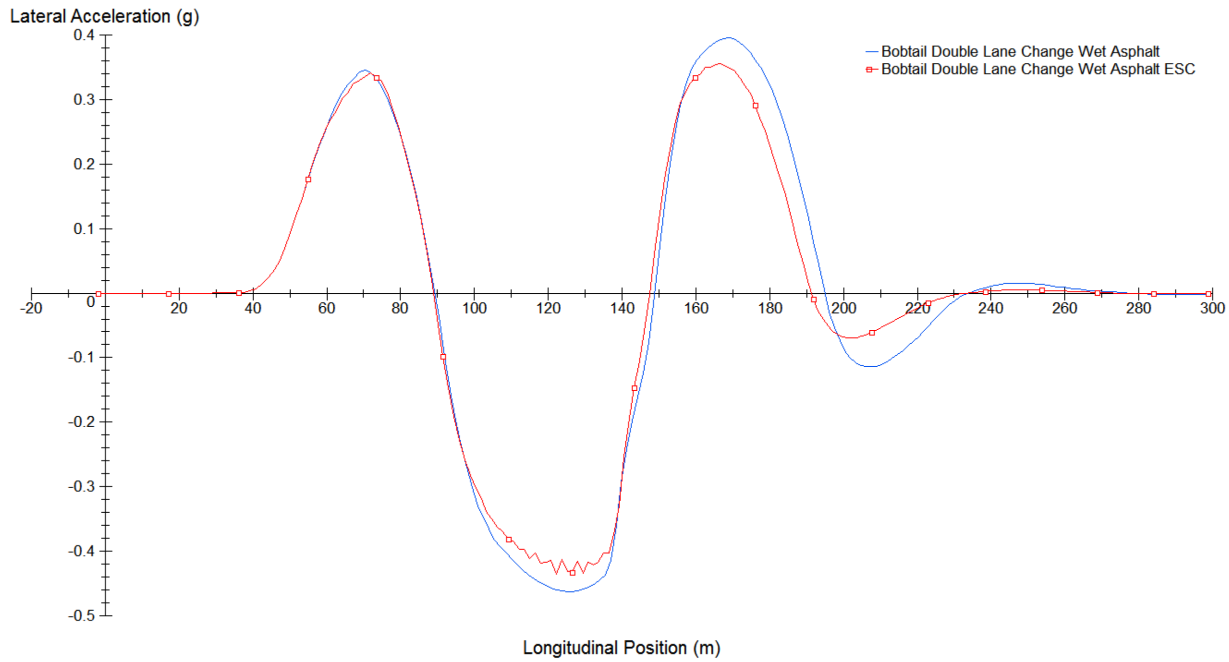

Figure 17. Graph. Bobtail In Lane Change – Observed Lateral Acceleration.

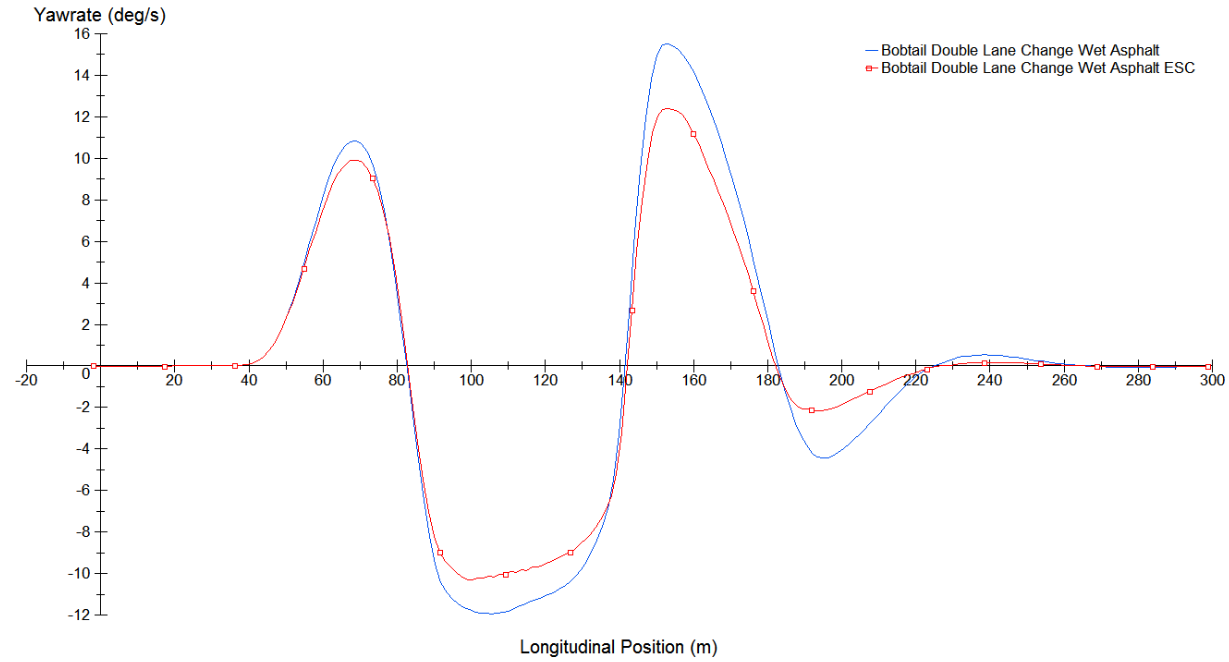

Figure 18. Graph. Bobtail In Lane Change – Observed Yaw Rate.

The ESC system also improved the vehicle's path following for the most part with minor negative effects of the ESC controller observed at the end of the first lane change (140 meter mark). The reduction in vehicle performance with the ESC system at the 140 meter mark was due to the fact that the ESC system reduced the vehicle's turning potential in this region when attempting to mitigate a yaw divergence condition (Figure 19). This resulted in the vehicle failing to make the turn toward the last gate as quickly as the non-ESC case.

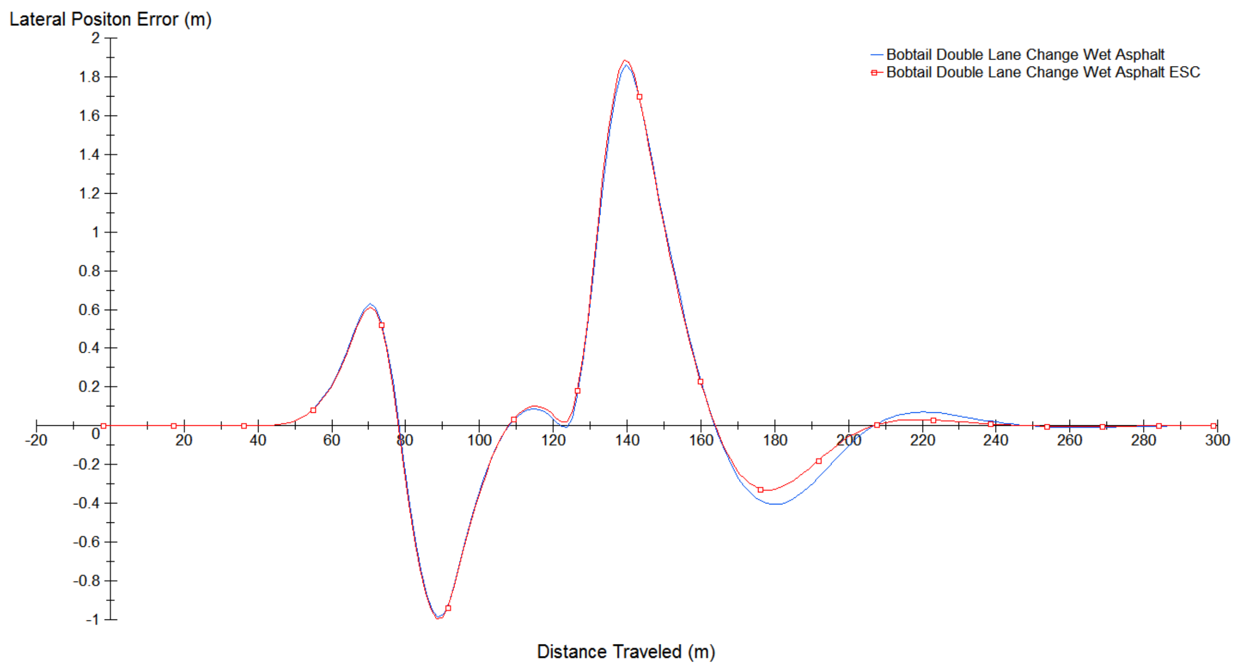

Figure 19. Graph. Bobtail In Lane Change – Observed Path Error.

In this analysis, the vehicle was able to generate the needed front axle cornering force to negotiate the maneuver without the need for the ESC system to generate a supplemental turning moment (documented by the lack of rear axle brake input). This indicates that the vehicle could generate the needed moments to initiate a turn through steer effects only. However, the vehicle did require ESC support in reducing unwanted yawing which can be observed through the activation of the front axle brakes when entering and exiting each lane (Figure 20). For reference, the wheel position notation is as follows:

Left Front (Steer)	L1
Right Front (Steer)	R1
Left Middle (Lead Drive)	L2
Right Middle (Lead Drive)	R2
Left Rear (Rear Drive)	L3
Right Rear (Rear Drive)	R3

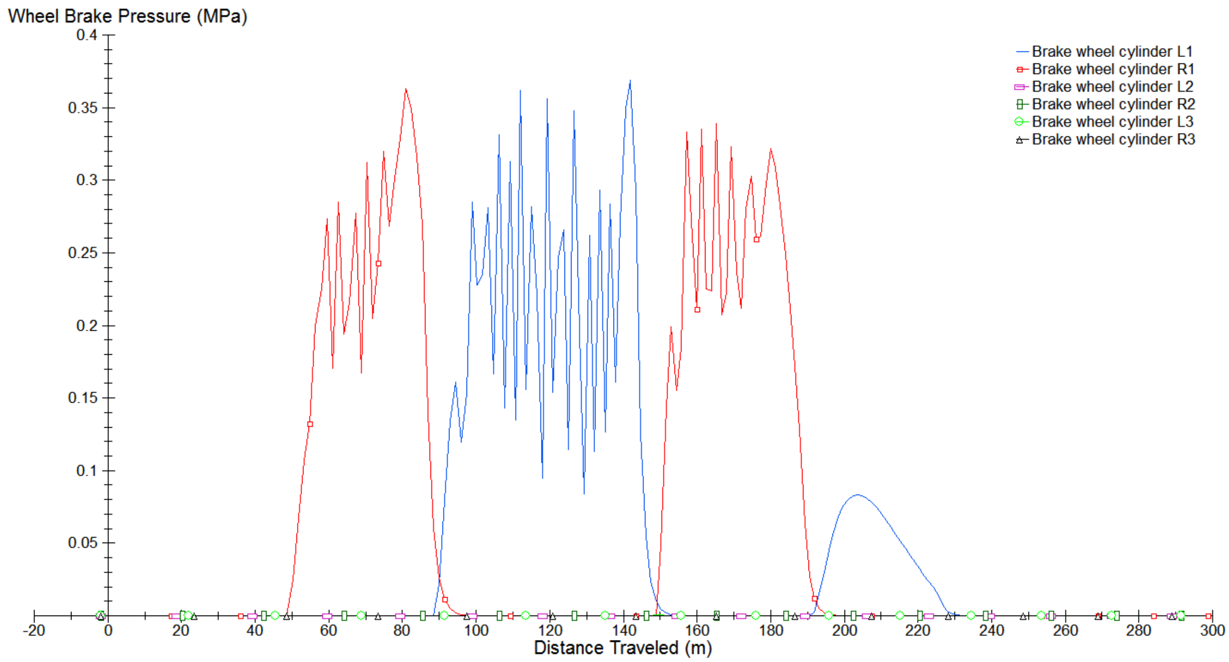

Figure 20. Graph. Bobtail In Lane Change – Observed Brake Control.

Using the ESC controller, the bobtail tractor could manage the lane change maneuver a few km/hour faster than the non ESC case. This is not a large margin, but is in line with the results observed in Phase A with the passenger car. The real benefit of the ESC is not in increasing the permissible speed, but rather in the reduction in driver demand during the most challenging portions of the maneuver. With the ESC system making corrections automatically, the need for the driver to make quick and accurate corrections to maintain stability is lessened. Of course, there is the obvious benefit that the ESC system will make corrective actions should the driver fail to make them on his own.

Bobtail Vehicle Analysis (Exit Ramp)

The bobtail exit ramp maneuver was run at 100 km/hour with and without ESC. Each vehicle case was able to maintain a safe position on the road with the ESC case actually reducing the vehicle's ability to maintain the desired path at the entrance to the turn due to front axle braking (Figure 22). The image below (Figure 21) is of the non-ESC vehicle (blue) and the ESC vehicle (red). The vehicle colors match the plots of the vehicle performances as well.

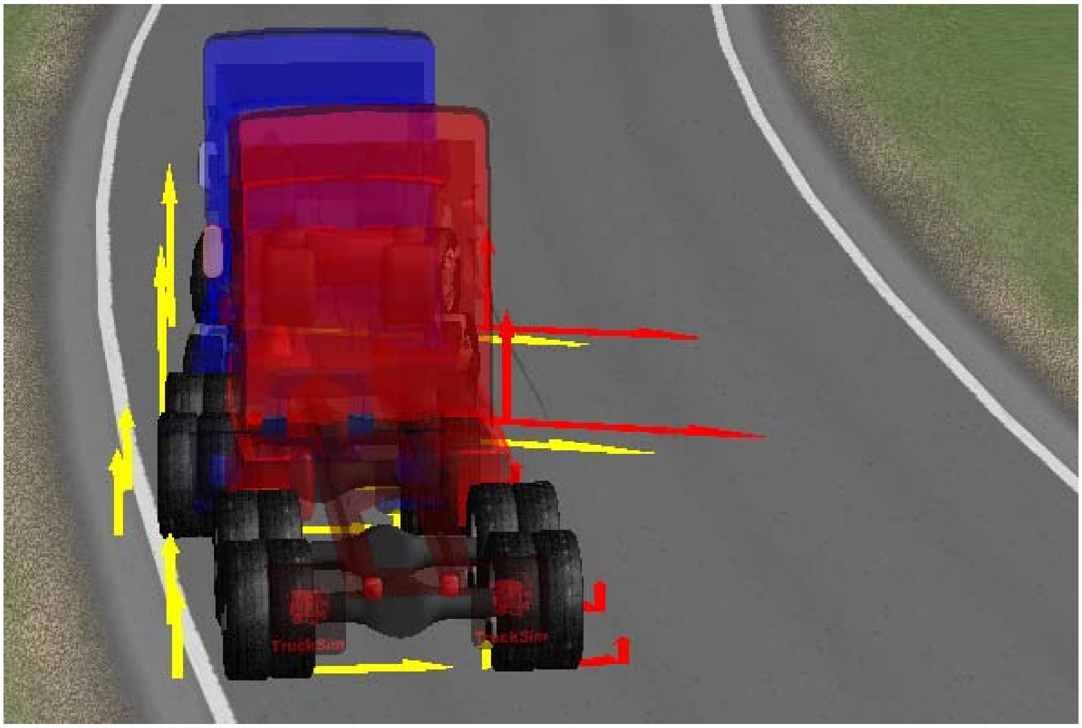

Figure 21. Illustration. Bobtail In Exit Ramp – Maneuver.

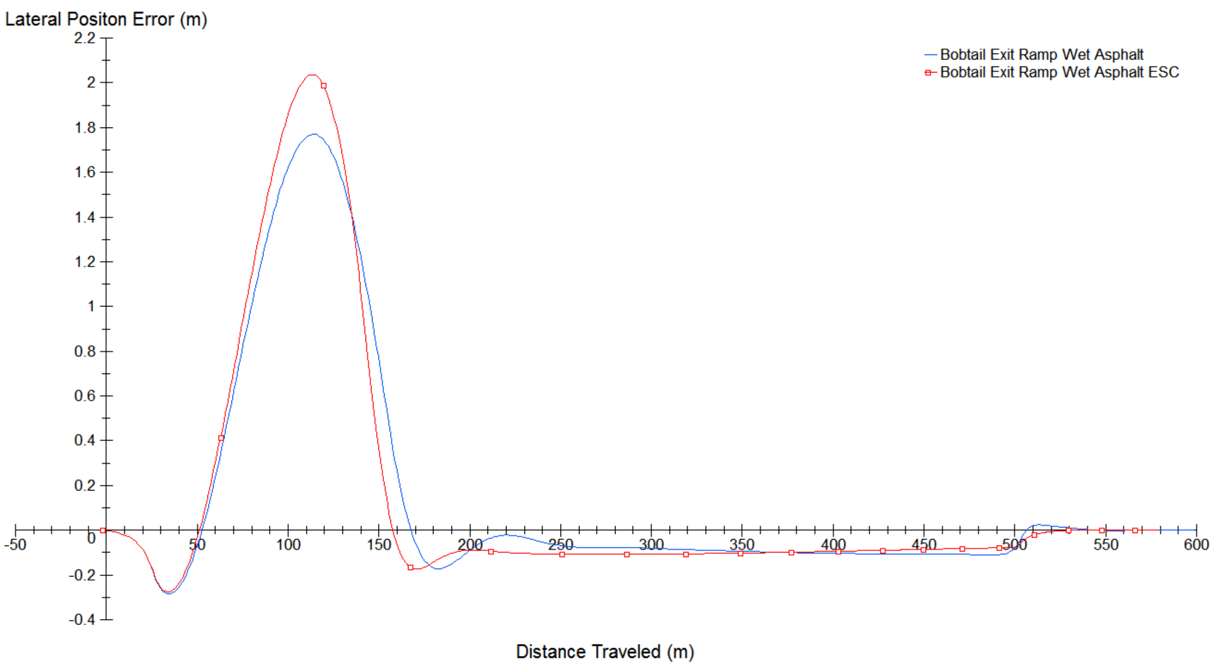

Figure 22. Graph. Bobtail In Exit Ramp – Observed Path Deviation.

Both vehicles exhibited significant lateral off-tracking (Figure 22) as the vehicles tried to negotiate the entrance to the ramp. As the vehicle began to oversteer, the ESC controller activated the front left brake (Figure 23) to mitigate the yaw deviation of the tractor. This resulted in a reduction of the ESC equipped vehicle's yaw rate (Figure 24) but it also produced an even greater deviation from the desired path (Figure 22) as the vehicle lost front cornering power. This is in line with expectations where the ESC system is essentially trading path control for yaw stability. The assumption here is that the better option would be to plow off the road head first rather than slide off sideways and risk a tripped rollover in the soft soil.

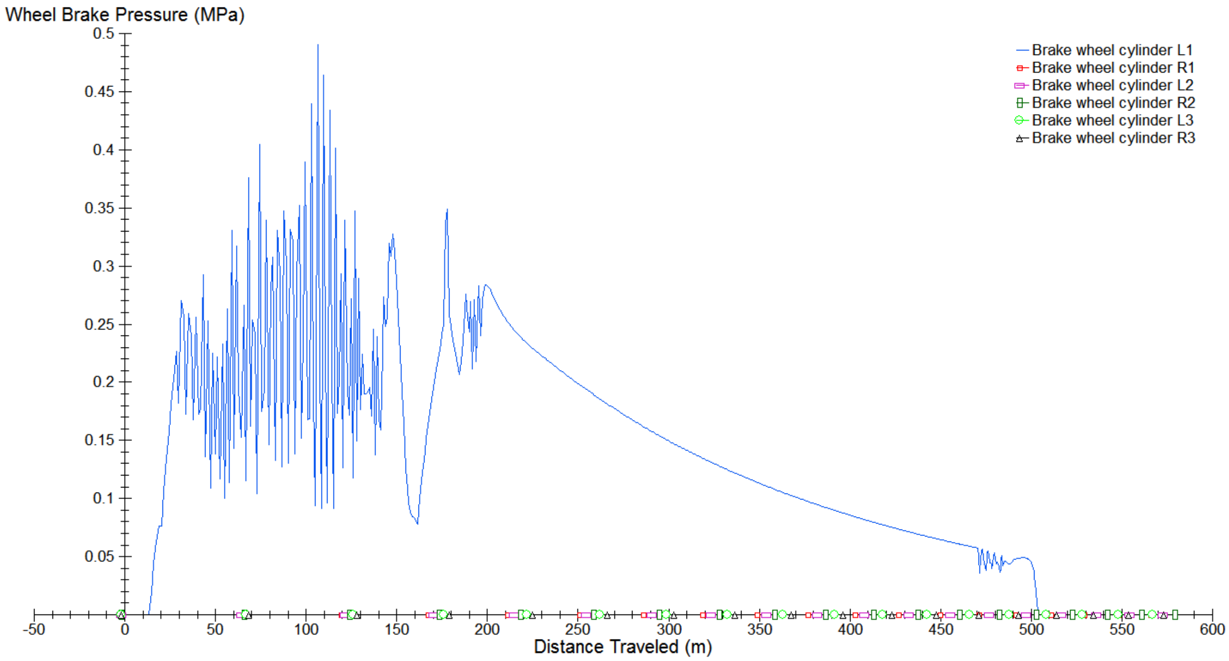

Figure 23. Graph. Bobtail In Exit Ramp - Observed ESC Brake Response.

The sudden drop in yaw rate (Figure 24) at 150 meters for the vehicles is due to the sudden drop in steering input (Figure 25) generated as the driver quickly removes steering input to prevent a yaw divergence situation from arising.

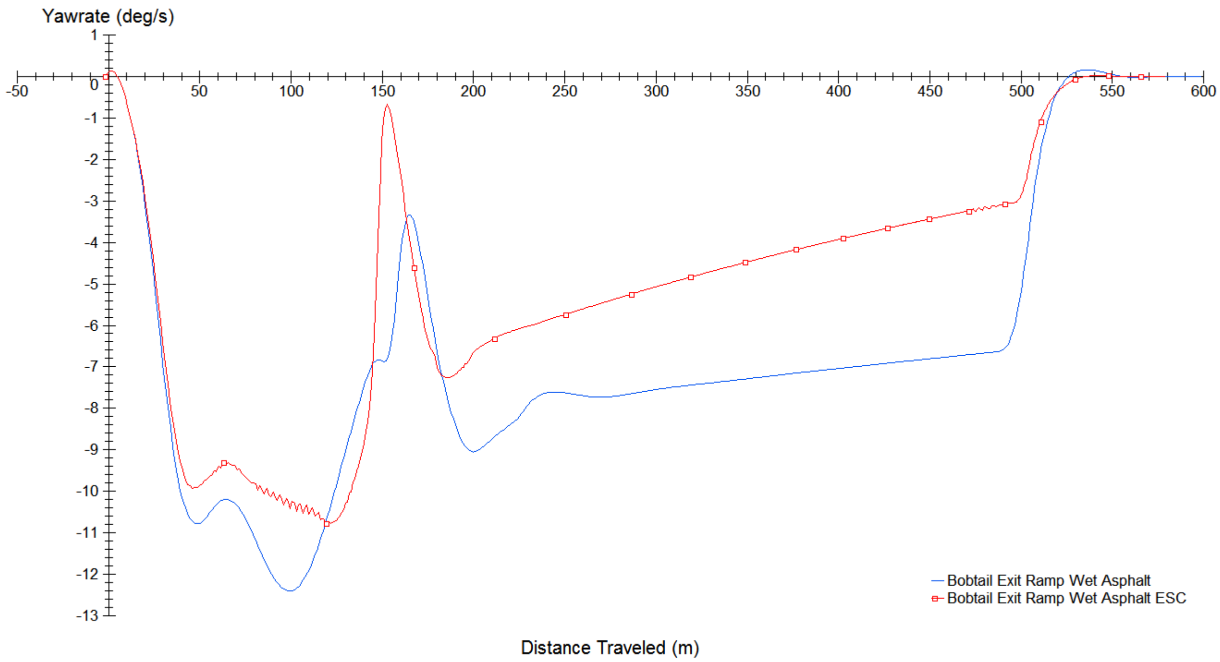

Figure 24. Graph. Bobtail In Exit Ramp - Observed Yaw Rate.

In an effort to reduce the path radius error observed in the initial part of the maneuver, the driver continually increased the steering angle to the vehicle attempting to generate a larger yaw rate. This exaggerated steering input was even larger for the ESC-enabled tractor as the driver sensed that the tractor was not turning sufficiently to maintain the desired path. But the higher driver steering input could not overcome the ESC stability corrections (Figure 23) and the ESC vehicle continued to push outward in the turn (Figure 22).

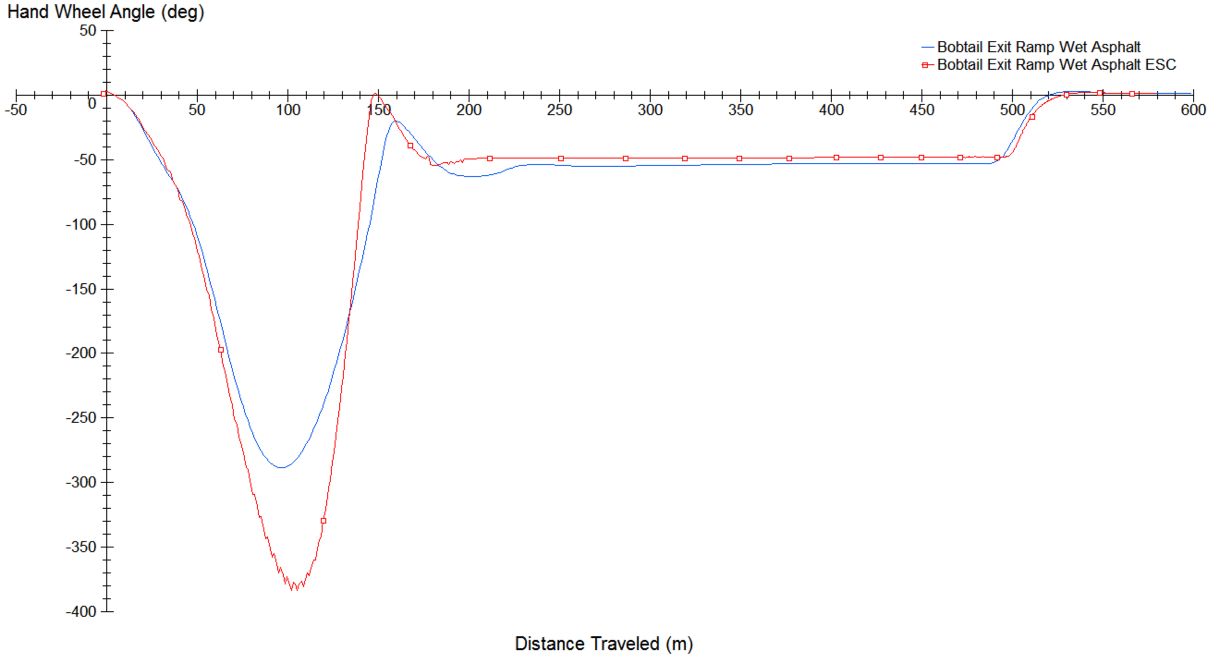

Figure 25. Graph. Bobtail In Exit Ramp - Measured Steering Input.

The combined braking force from the large front wheel steering input and the differential braking for the ESC case in red resulted in the vehicle slowing down during the maneuver (Figure 26). The vehicle subsequently lost lateral acceleration as a result of the velocity reductions (Figure 27). When the ESC-controlled vehicle had slowed enough, the ESC system recognized that the yaw instability situation had passed and released the brakes around 500 meters into the maneuver (Figure 23).

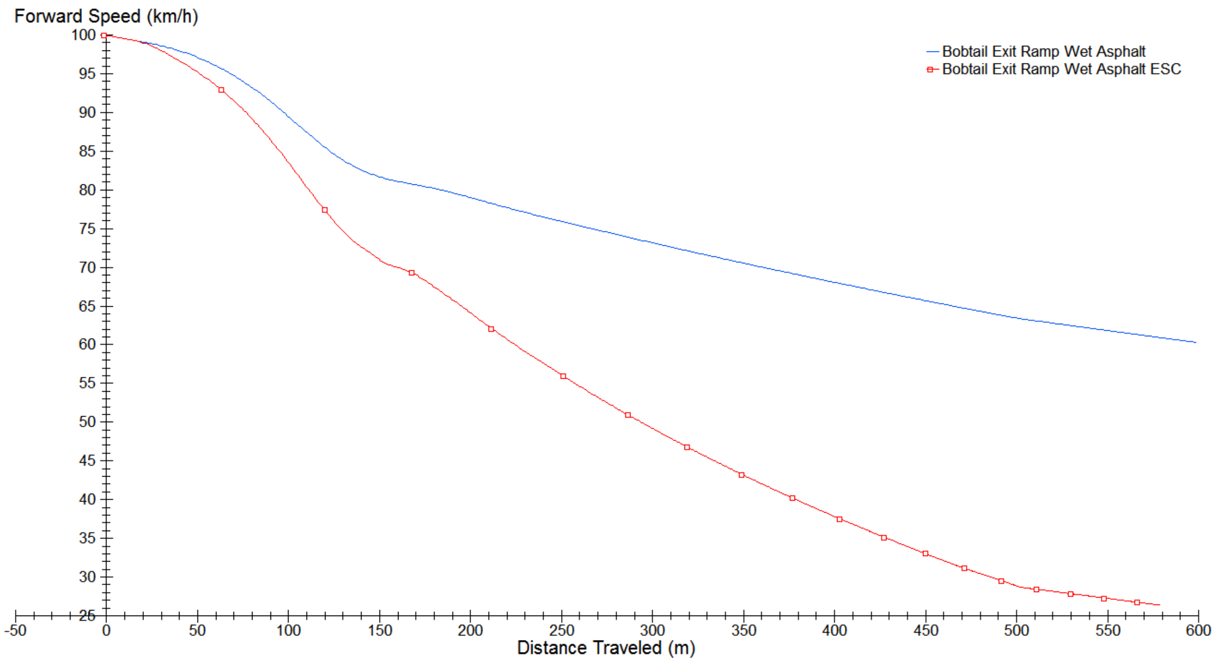

Figure 26. Graph. Bobtail In Exit Ramp - Observed Vehicle Speed.

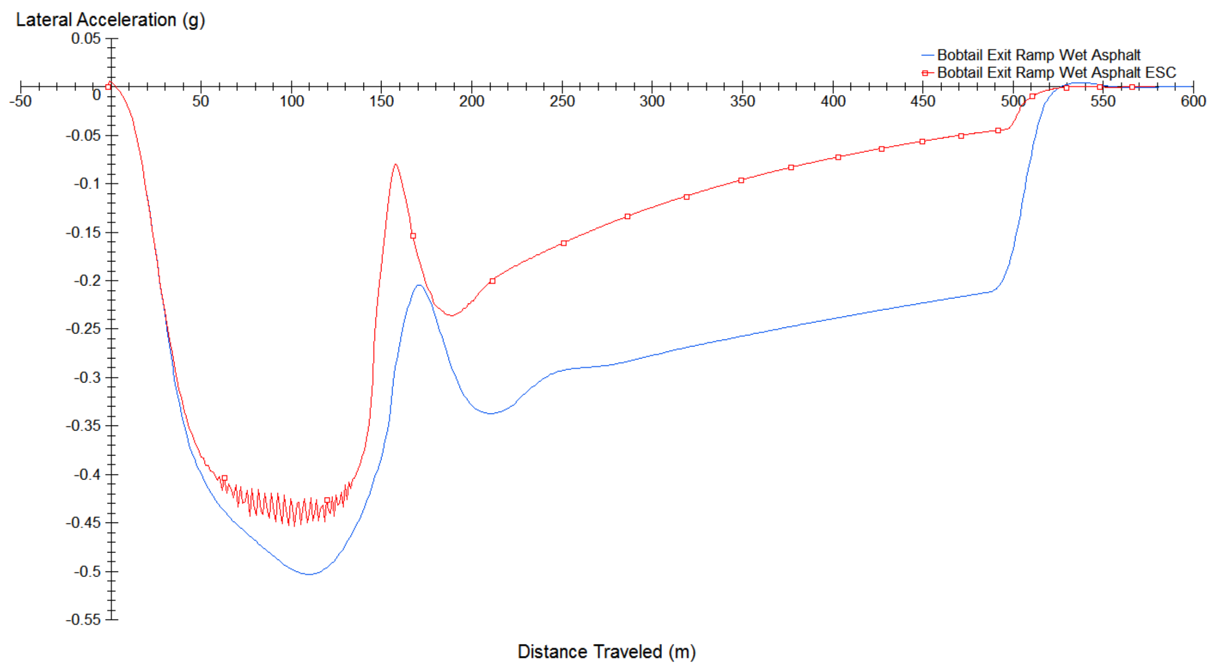

Figure 27. Graph. Bobtail In Exit Ramp - Observed Lateral Acceleration.

Initial Tractor and Semi-Trailer Analysis (Lane Change with Empty Trailer)

Generally, tractor and semi-trailer accidents fall in to two classes: rollovers which generally occur with loaded vehicles on dry pavement and jackknife or swing-out events which tend to occur with unloaded vehicles and wet or slippery roads. As the area of study here is on yaw stability, the target case for investigation of a complete tractor and semi-trailer was an empty vehicle on wet asphalt (mu of 0.5). While snow and other surfaces can yield even lower frictional values (0.1 to 0.25 range), the research focused on wet asphalt. The reasoning for the concentration on wet asphalt was that the lower mu cases evaluated produced very similar qualitative vehicle responses and the quantitative differences were largely a function of the lower speeds used for very low mu road surfaces.

The illustration in Figure 28 below shows the same empty vehicle executing the lane change maneuver with three different ESC controllers. The blue truck represents the no ESC case as before. The red truck represents an ESC controller that only activates the tractor brakes (see Figure 11 for controller definition). The purple truck represents a full ESC system where the trailer brakes are activated to restore tractor yaw divergence when applicable (see Figure 12 for controller definition). In general, the best vehicle performance was observed with the complete ESC system using the trailer brakes.

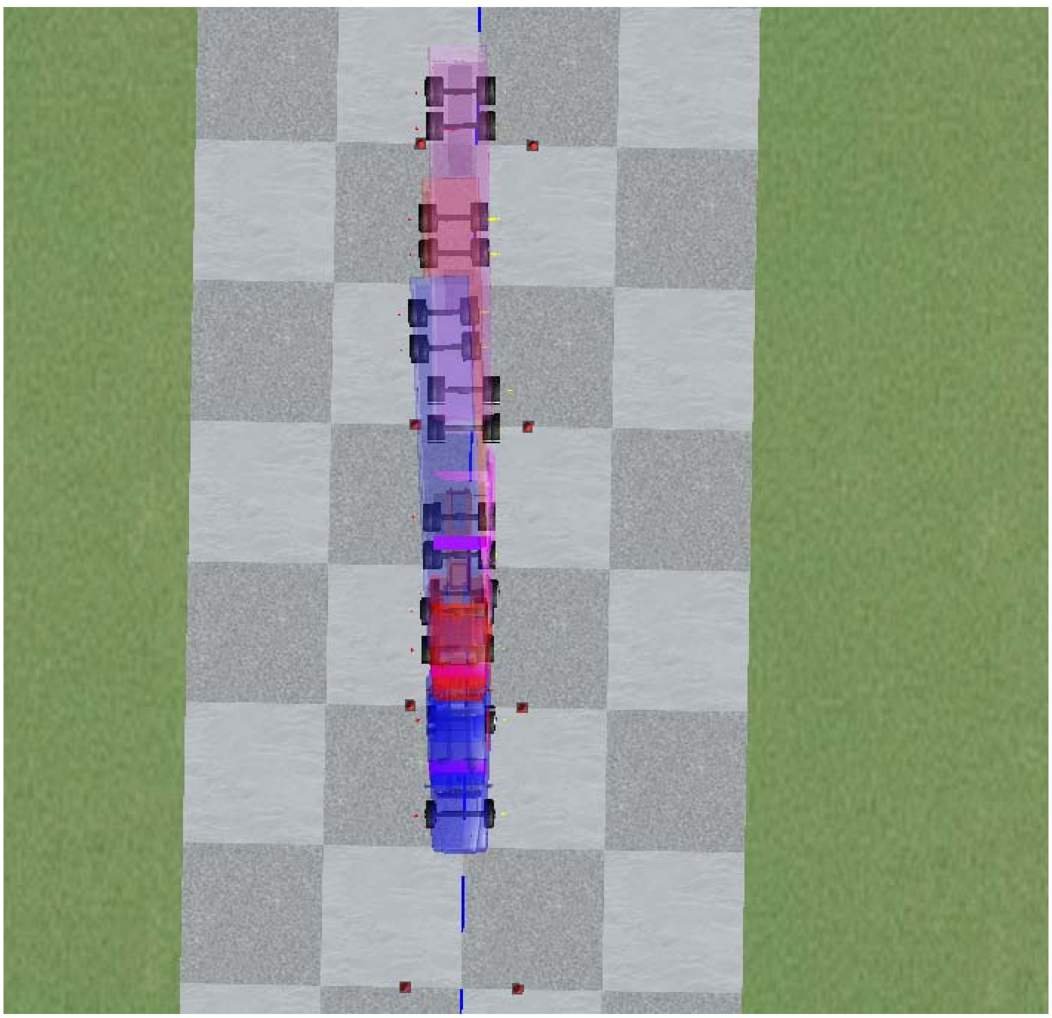

Figure 28. Illustration. Empty Tractor Trailer Lane In Change (Low Trailer Brake Pressure).

Trailer Brake Pressure

Close inspection of the full ESC controller in Figure 12 will show that when the trailer brakes are activated to maintain stability, the trailer brake pressure is limited to 0.3 MPa. For reference, full brake is 0.8 MPa so the 0.3 MPa peak pressure is significantly below maximum potential brake pressure. The logical question here would be why 0.3 MPa is used as the maximum ESC enable pressure. The reason is that the selection of the peak trailer brake pressure is a function of the road surface (mu) and the trailer load. With increasing load or mu, the tires can develop more grip permitting larger in-plane forces to be generated and a higher pressure to be used.

During the lane change maneuver, the trailer must generate lateral forces to follow the tractor's path. If excessive brake demands are made, the lateral force is traded for longitudinal force resulting in significant path deviations for the trailer. As the tractor cannot "see" the trailer, it does not recognize that the trailer is swinging out and does not release the brakes to restore the trailer to the proper path. For illustration of this effect, Figure 29 is the exact same vehicle and maneuver with the trailer brakes set to 0.6 MPa.

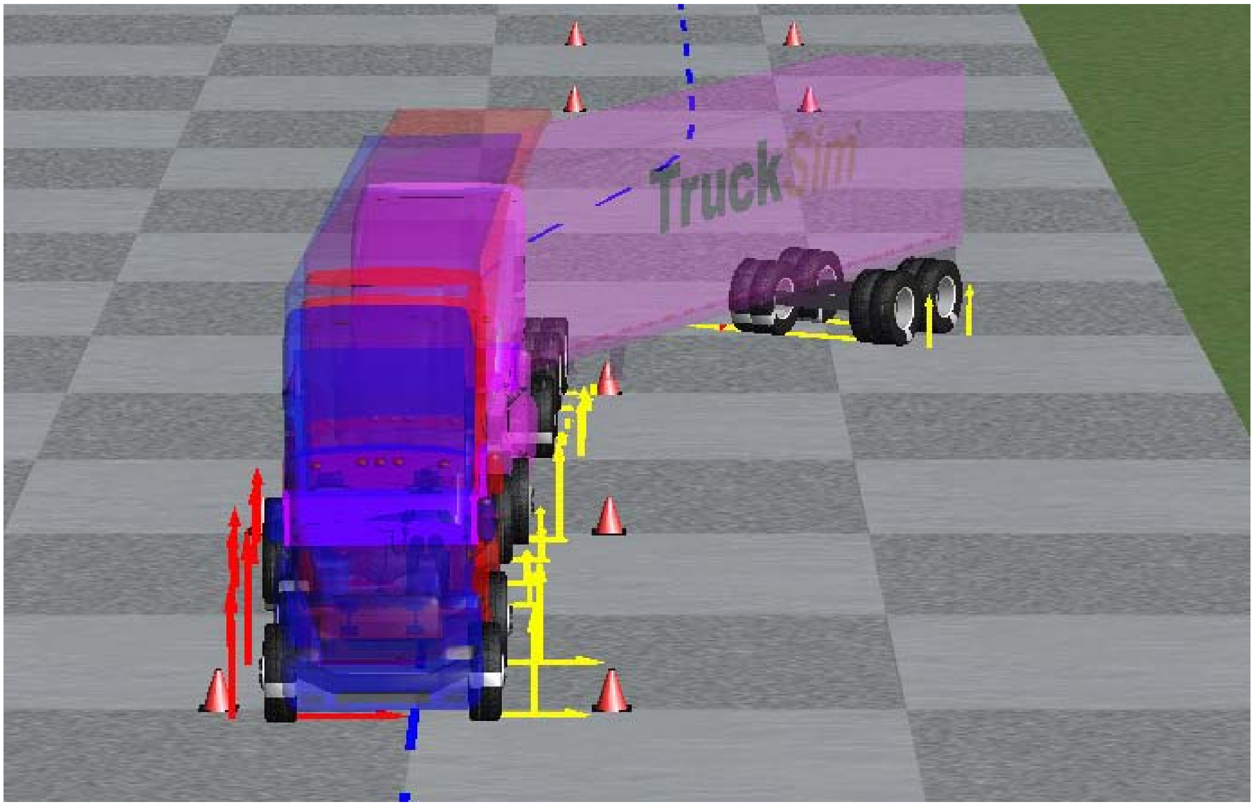

Figure 29. Illustration. Empty Tractor Trailer In Lane Change (High Trailer Brake Pressure).

There were three options for solving this problem of over-braking the trailer: Reduce the peak pressure to the trailer to a "nominally safe" level (method used here), infer the trailer's behavior by monitoring its effect on the tractor and adjusting trailer braking as needed (method used by industry), or adding sensors to the trailer to report the trailer's behavior to the tractor and adjusting trailer braking as needed (proposed solution for future work).

The appropriate trailer brake pressure was assessed by running a simulation with a deliberately low trailer brake pressure and simulation with a tractor only brake controller. Figure 30 documents the tractor ESC only brake response (red truck in Figure 28) and Figure 31 documents the tractor and low trailer brake ESC response (purple truck in Figure 28). Here it can be noted that the peak brake pressure sent to the steer wheels was on the order of 0.3 MPa for both models.

Figure 30 documents the activation of the front left brake (blue) and the front right brake (red) for the tractor only controller. Note that the remaining brakes in Figure 30 are all zero. Figure 31documents the inclusion of the trailer brakes (axles 4 and 5) for the complete ESC controller. Note that all four trailer brakes (L4, R4, L5, and R5) see the exact same brake command and thus have the same curves. As noted before, the tractor drive axles were not activated and thus there is no brake pressure for L2, R2, L3, or R3 in either Figure 30 or Figure 31.

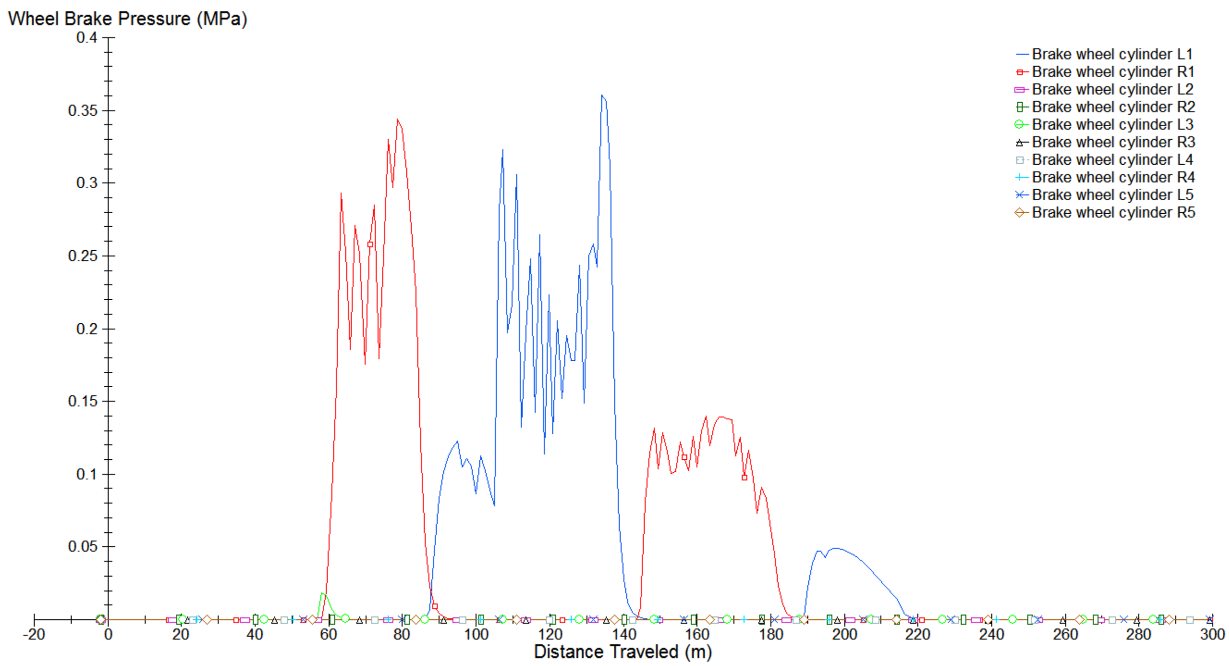

Figure 30. Graph. Empty Tractor Trailer In Lane Change – Brake Pressures for Tractor Only ESC Control.

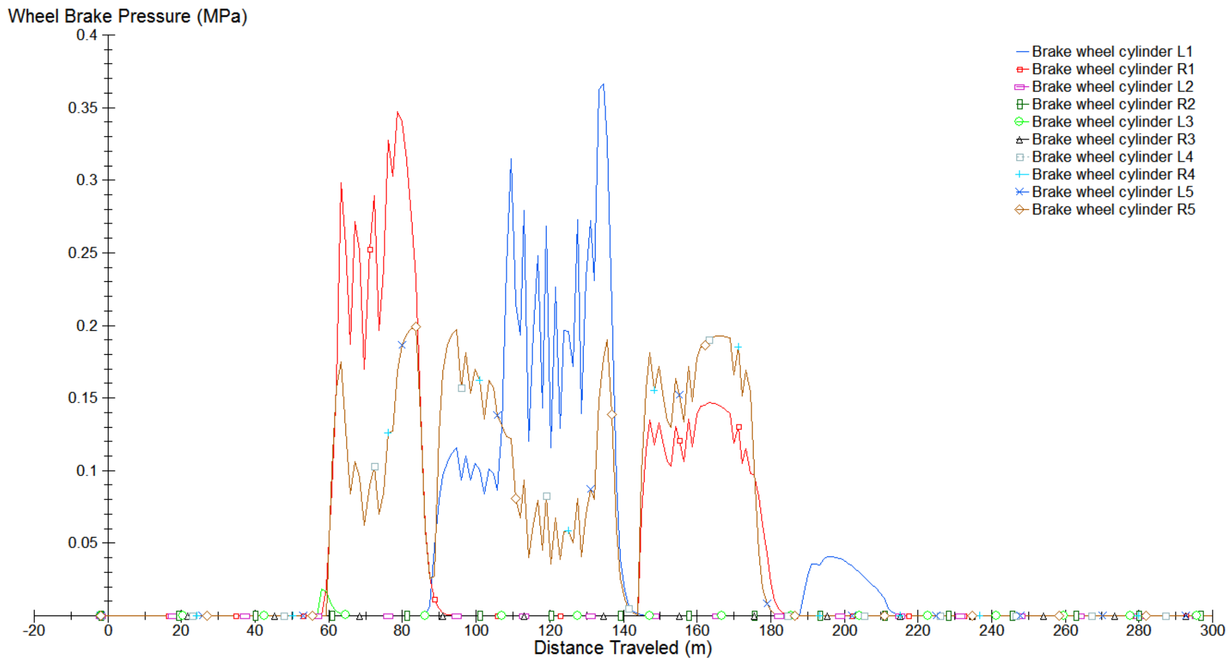

Figure 31. Graph. Empty Tractor Trailer In Lane Change – Brake Pressures for Tractor and Trailer ESC Control (Low Trailer Brake).

The optimal trailer brake demand for this test condition was then set at 0.3 MPa and the model re-evaluated (Figure 32). In this case (Figure 32) the trailer ESC braked controller (purple) did not experience a large yaw divergence and, in fact, had the smallest yaw divergence of the three cases. The resulting brake response was then checked to make sure that the brake demands were balanced (Figure 33). The result was a good estimate of the optimal trailer brake pressure for full ESC application.

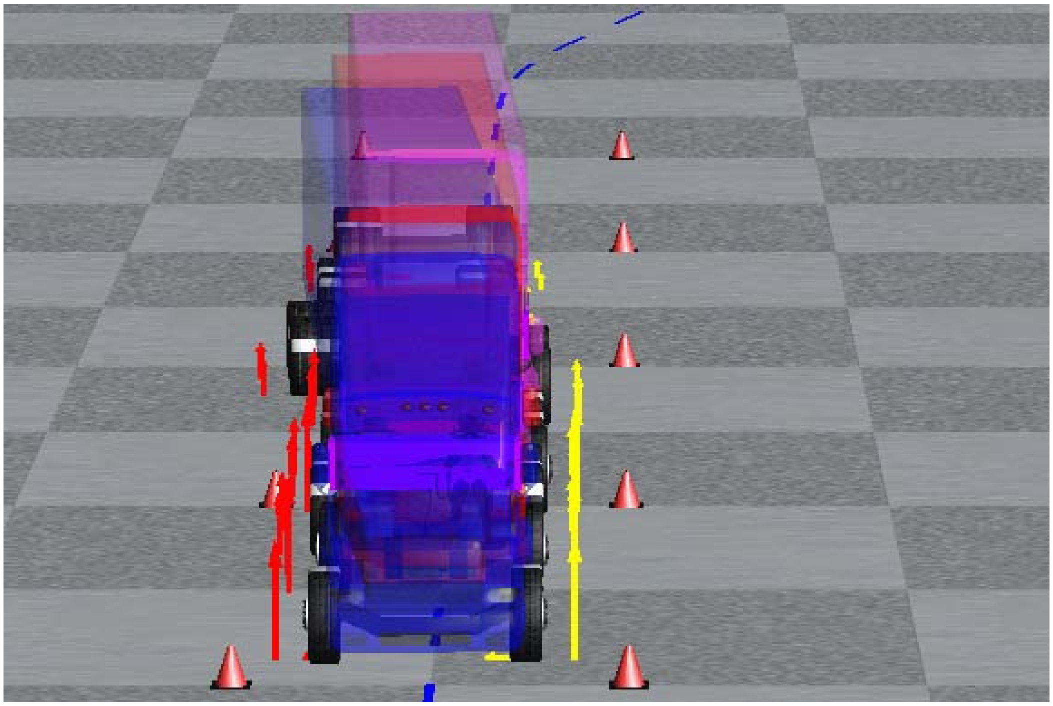

Figure 32. Illustration. Empty Tractor Trailer In Lane Change (Optimal Trailer Brake Pressure).

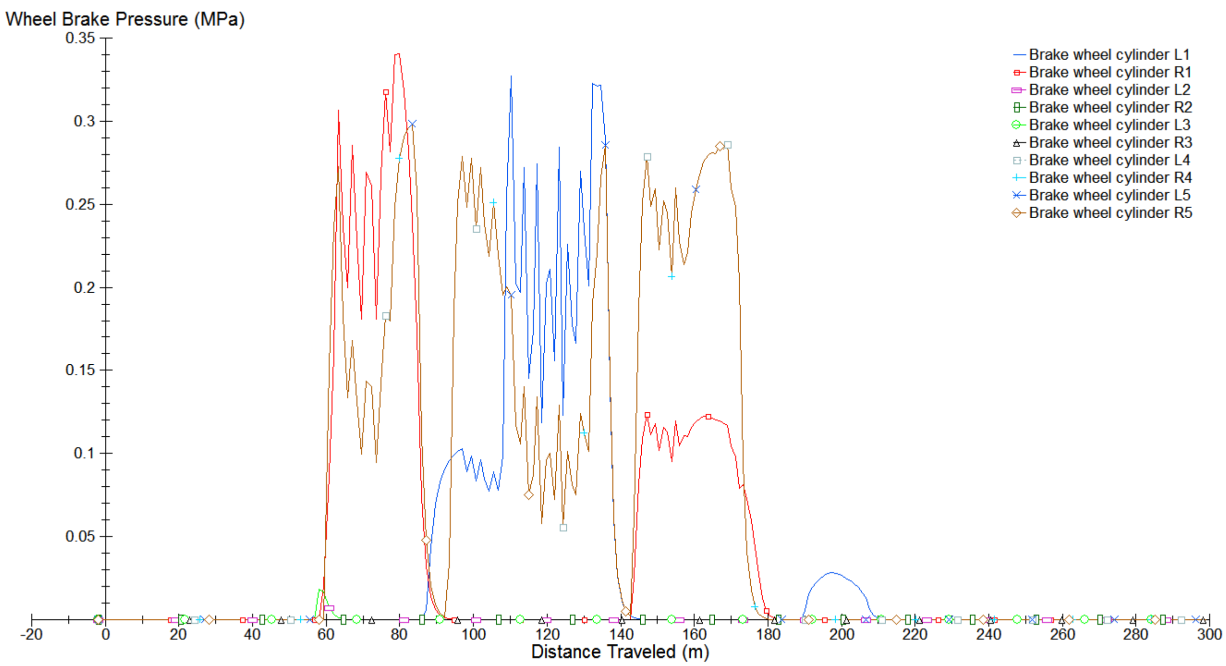

Figure 33. Graph. Empty Tractor Trailer In Lane Change – Brake Pressures for Tractor and Trailer ESC Control (Optimal Trailer Brake).

For reference, the 0.3 MPa pressure used here was developed with a road mu of 0.5. A trailer brake pressure limit of 0.15 MPa was determined using the same method when the road mu was set to 0.25 (snow).

Tractor and Semi-Trailer Analysis (Lane Change with Empty Trailer)

While the addition of the optimized trailer brakes in the ESC controller does not result in dramatic performance improvements, it is clear from the tractor path deviation plot (Figure 34) that the additional trailer braking (purple curve) does help stabilize the tractor and improve the vehicle's performance.

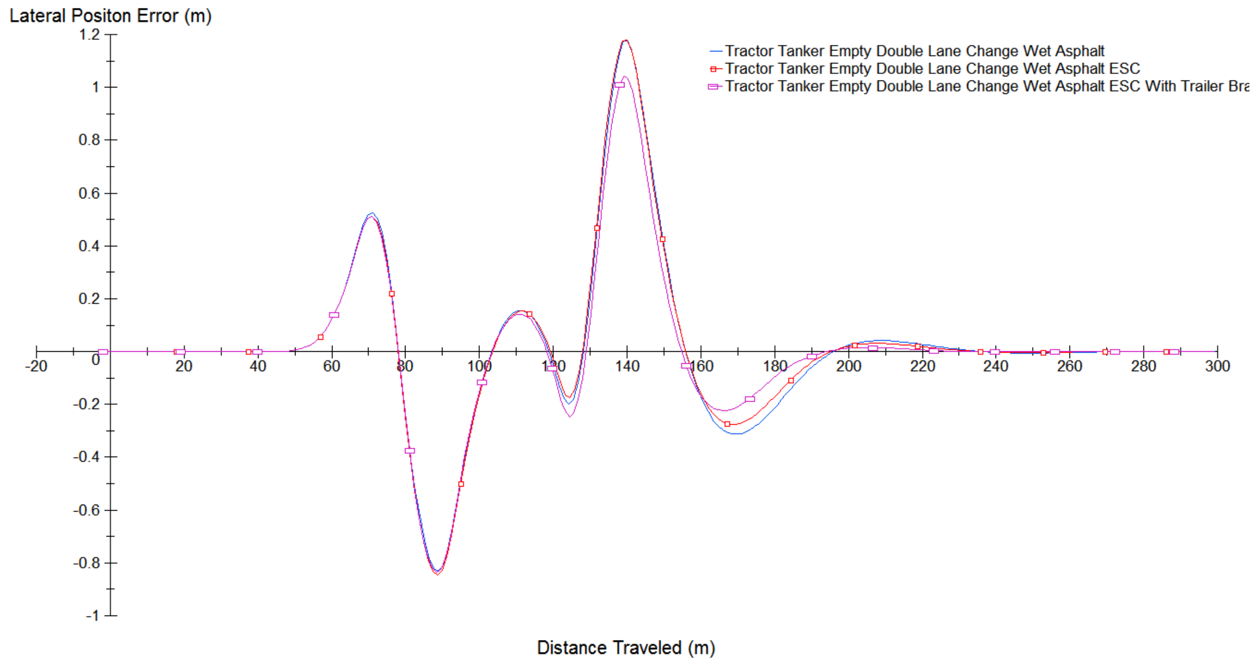

Figure 34. Graph. Empty Tractor Trailer In Lane Change – Tractor Path Deviation.

The ESC systems also indicated a slight reduction in driver input requirements for the empty tractor trailer as shown in Figure 35. Again, the addition of the trailer brakes further improved the vehicle's performance relative to the tractor brake only case.

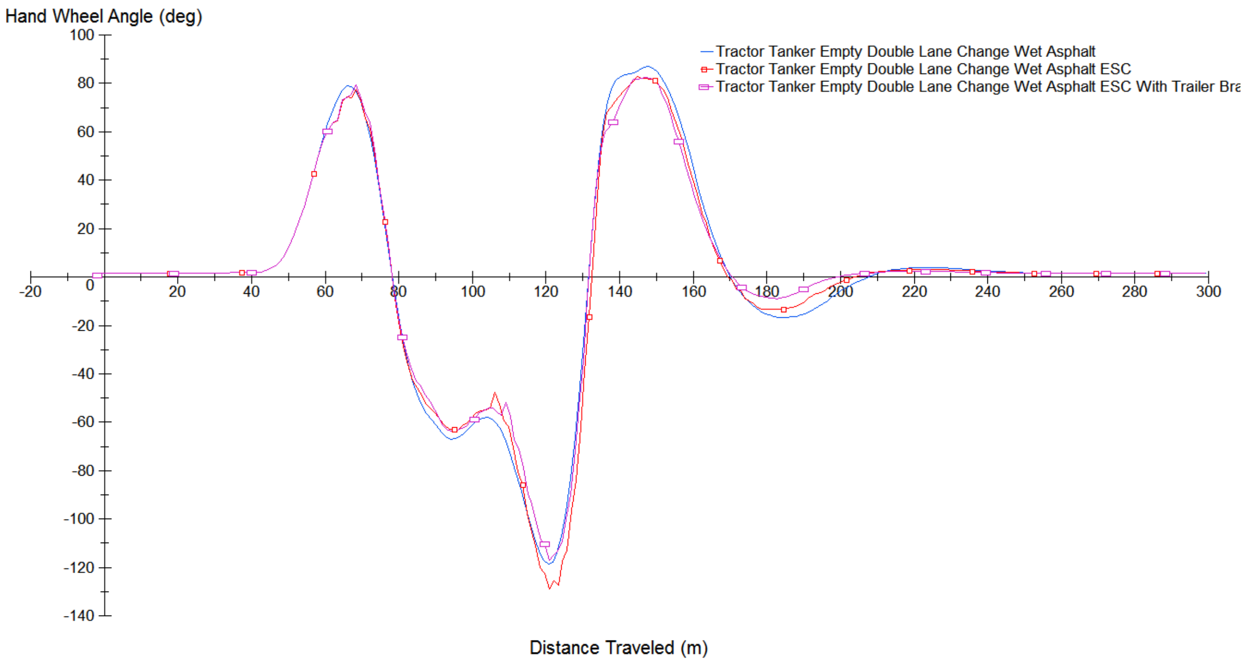

Figure 35. Graph. Empty Tractor Trailer In Lane Change – Measured Steering Input.

The most notable effect of the addition of trailer braking to the ESC system can be seen in the tractor's lateral acceleration (Figure 36) and yaw rate (Figure 37) responses. In the latter part of the lane change maneuver, where the tractor is returning to the original lane, the trailer brakes play a significant role in resisting the yaw divergence of the tractor.

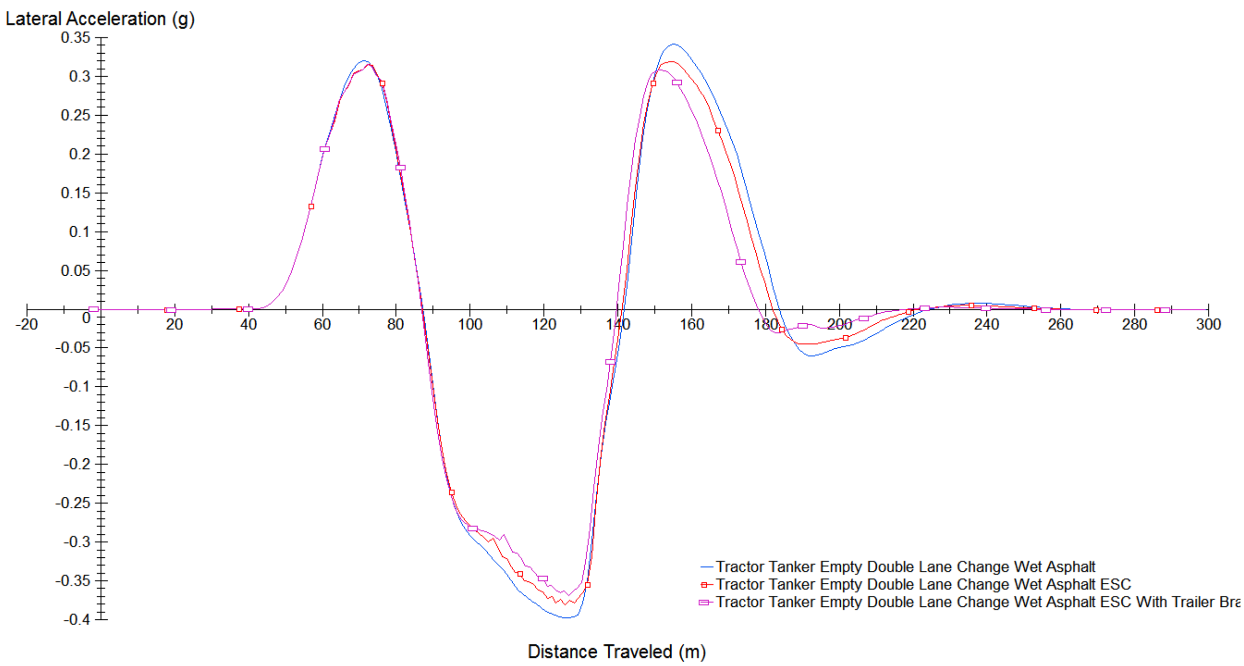

Figure 36. Graph. Empty Tractor Trailer In Lane Change – Observed Lateral Acceleration.

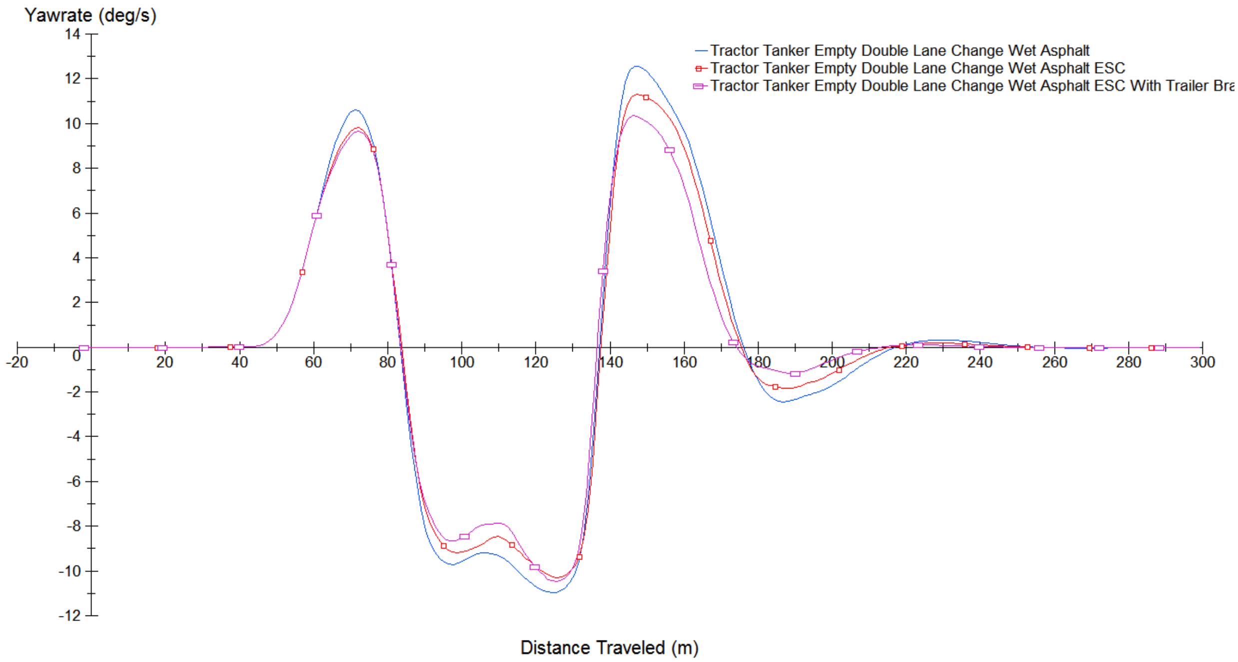

Figure 37. Graph. Empty Tractor Trailer In Lane Change – Observed Yaw Rate.

The effects of the ESC controller on tractor behavior documented above can be qualitatively understood (Figure 38) by observing that the non-ESC vehicle (blue) has the greatest lateral offset and the largest yaw angle relative to the desired path (blue dashed line). Addition of tractor-only ESC control (red) reduces both the lateral offset and the yaw angle error. Finally the full ESC control (purple) has the least error in offset or heading angle.

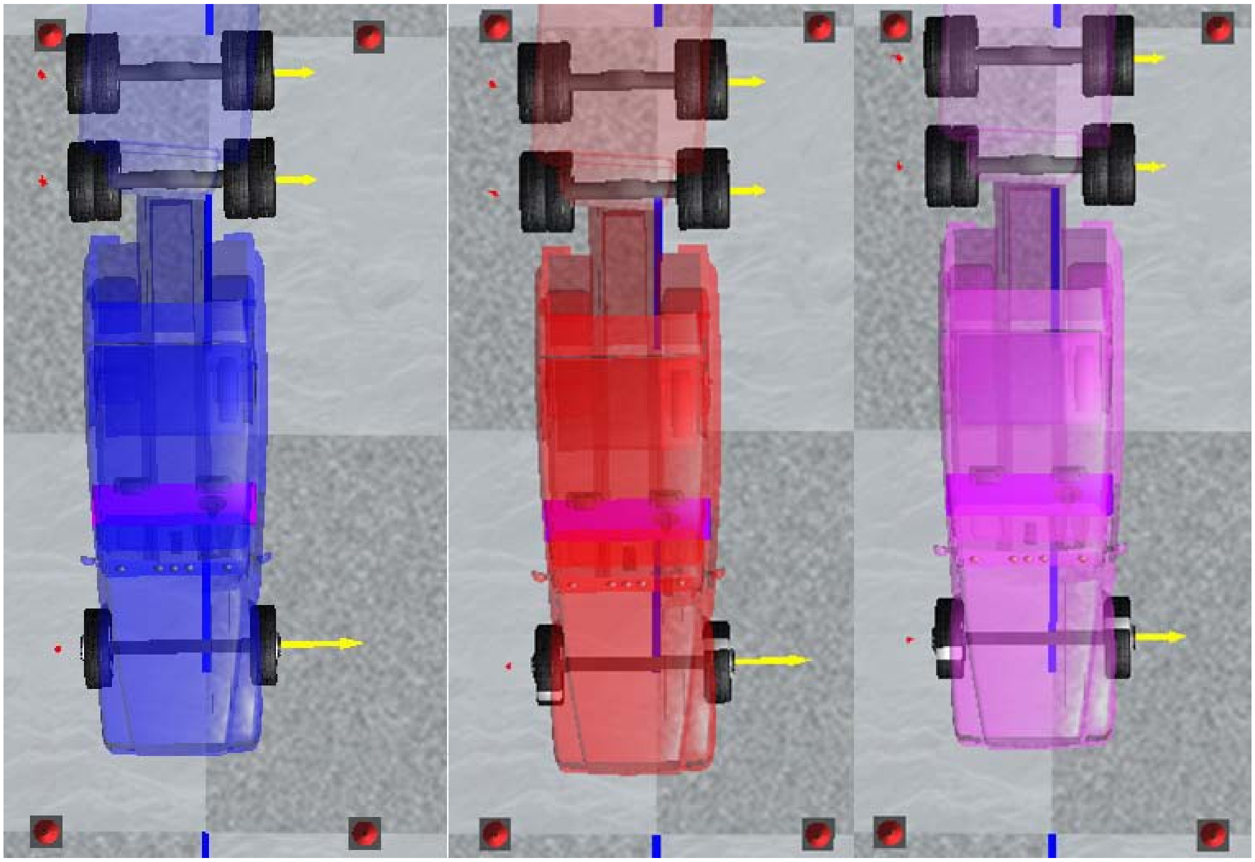

Figure 38. Illustration. Empty Tractor Trailer In Lane Change - Top View.

The careful reader will note that the above analysis was based on the tractor's behavior and not the trailer. There are three reasons for this limitation of the analysis.

1. There is no "desired" reference path for the trailer.
2. The tractor cannot "see" the trailer so control of the trailer is an unrealistic demand for the controller.
3. The manual tuning of the trailer brake pressure has the potential to affect the relative performance as brakes are applied and released.

The result was that trailer performance was assessed by observing how closely it followed the tractor's path. In all ESC cases, the empty trailer performed acceptably with improvements in trailer tracking generally in line with the tractor improvements.

Tractor and Semi-Trailer Analysis (Exit Ramp with Empty Trailer)

Like the lane change maneuver, the results of the simulations of the empty tractor trailer using the exit ramp indicated that the ESC systems did improve the yaw stability of the vehicle. The simulation results, illustrated in Figure 39, also showed that the full tractor and trailer brake ESC system gave the best results.

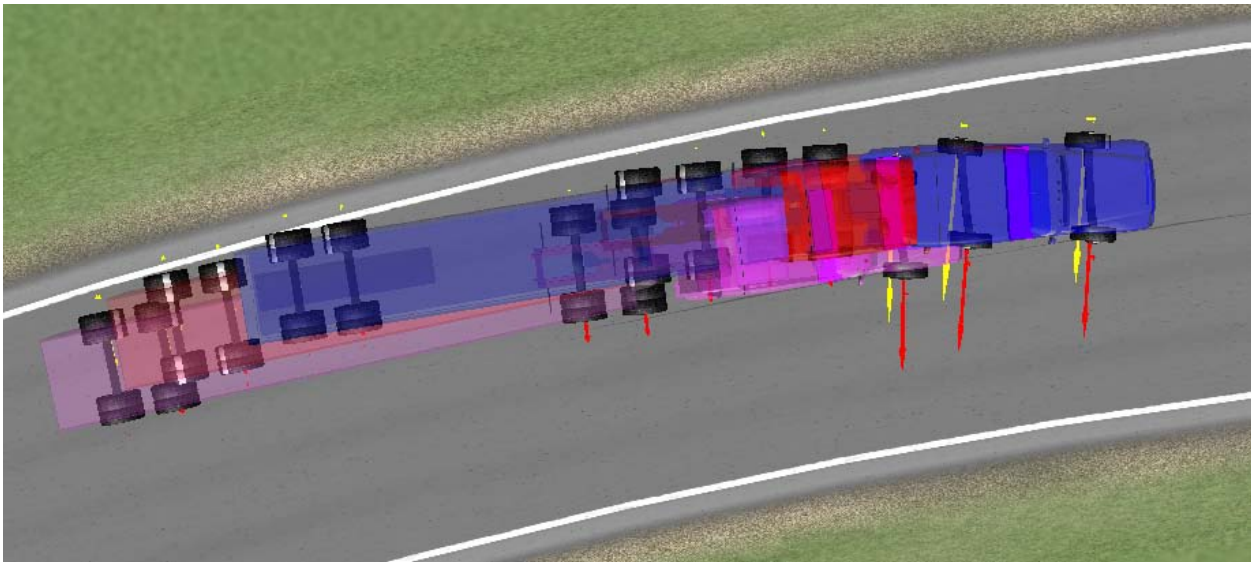

Figure 39. Illustration. Empty Tractor Trailer In Exit Ramp.

In the tractor brake only system (Figure 40), the only ESC activation was the left front wheel as the system tried to counter the excessive yaw development of the tractor in the beginning of the maneuver. For the tractor and trailer ESC system (Figure 41), the trailer brakes were activated as well. Since the same track surface conditions were used for the exit ramp and the lane change, the trailer brake pressure was again set at 0.3 MPa.

For the tractor only brake case (Figure 40) the front left wheel brake quickly builds to the 0.3 MPa peak and then oscillates as the vehicle tries to balance brake demand with steering demand. When the vehicle controller reaches a stable balance of yaw control and heading control (300 m), the front brake demand begins to taper off. For the tractor and trailer brake case (Figure 41), the front left brake and trailer brakes quickly build to the 0.3 MPa peak. However, the trailer brakes cycle downward as the controller tries to balance the yaw control and heading change demands (trailer brakes resist the needed heading change). Once the vehicle begins to stabilize and sufficient lateral force is developed to maintain the desired path, the trailer brakes are fully applied to mitigate yaw divergence. All brake demands are removed once the vehicle reaches a stable operating condition.

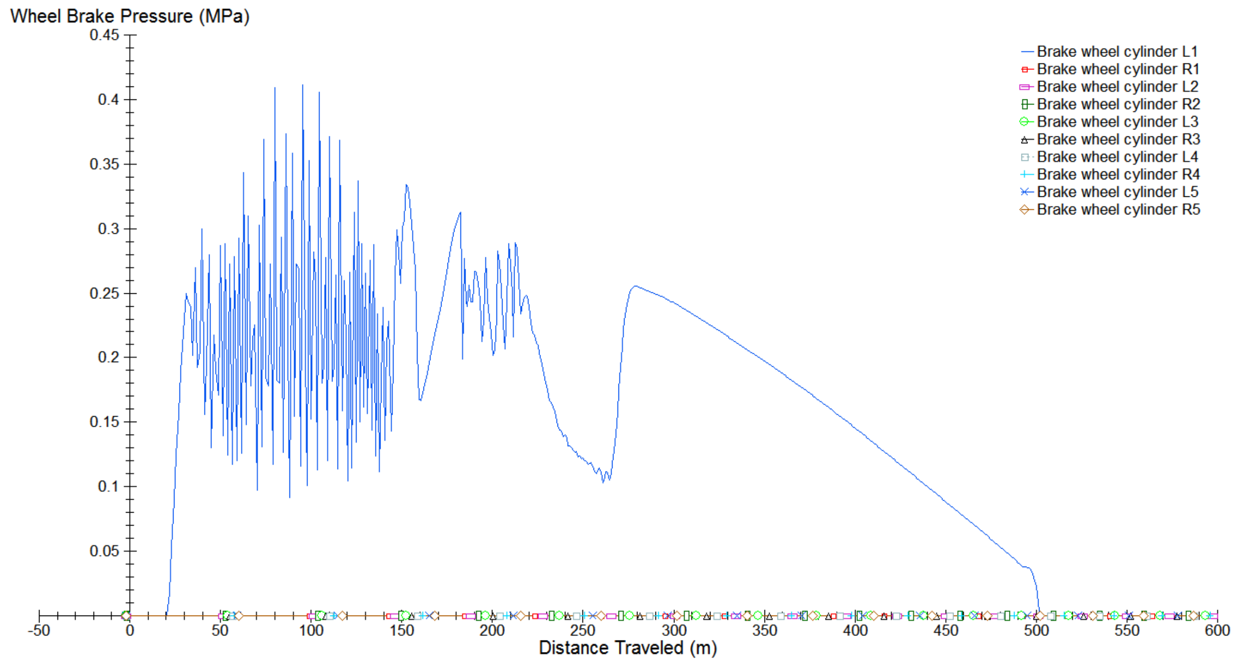

Figure 40. Graph. Empty Tractor Trailer In Exit Ramp – Brake Pressures for Tractor Only ESC Control.

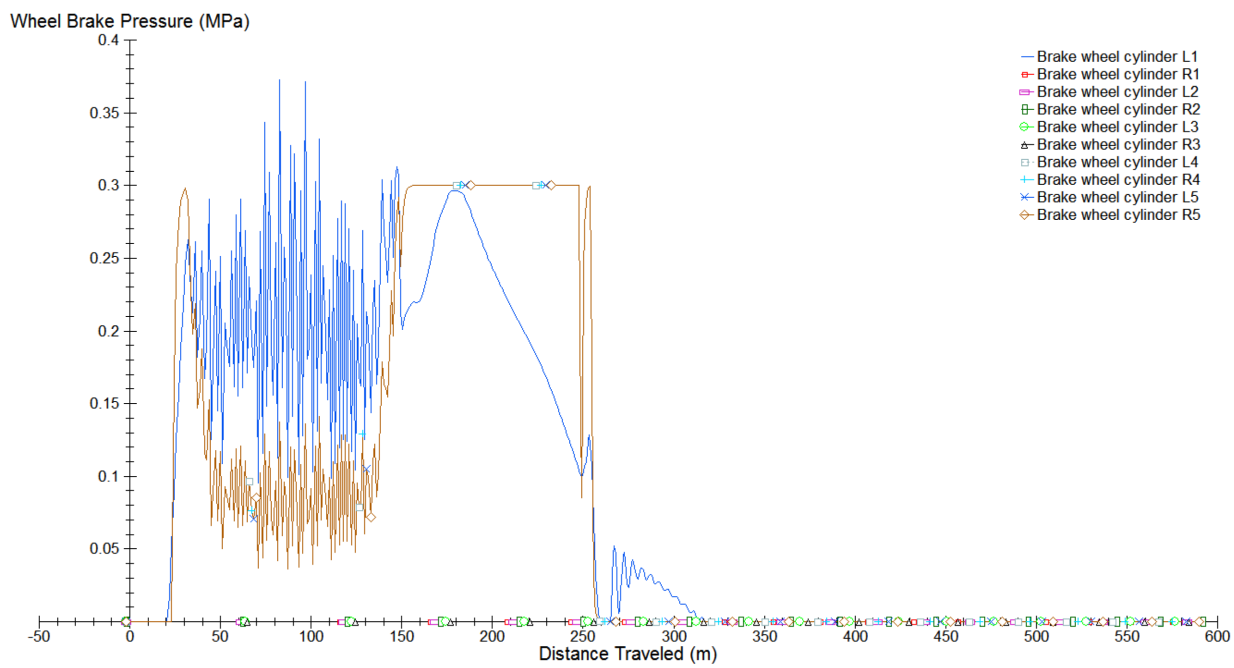

Figure 41. Graph. Empty Tractor Trailer In Exit Ramp – Brake Pressures for Tractor and Trailer ESC Control.

Not surprisingly, the ESC systems resulted in the vehicle losing speed through the turn with the speed loss proportional to the number of brakes being activated (Figure 42). Note the significant drop in speed for the full ESC case at 150 meters as the trailer brakes reach full pressure (Figure

41). Also note the speed reduction in the non-ESC case as the steer wheels generate a braking force along with a lateral force as a consequence of the tire heading differing from the vehicle heading (tire slip angles).

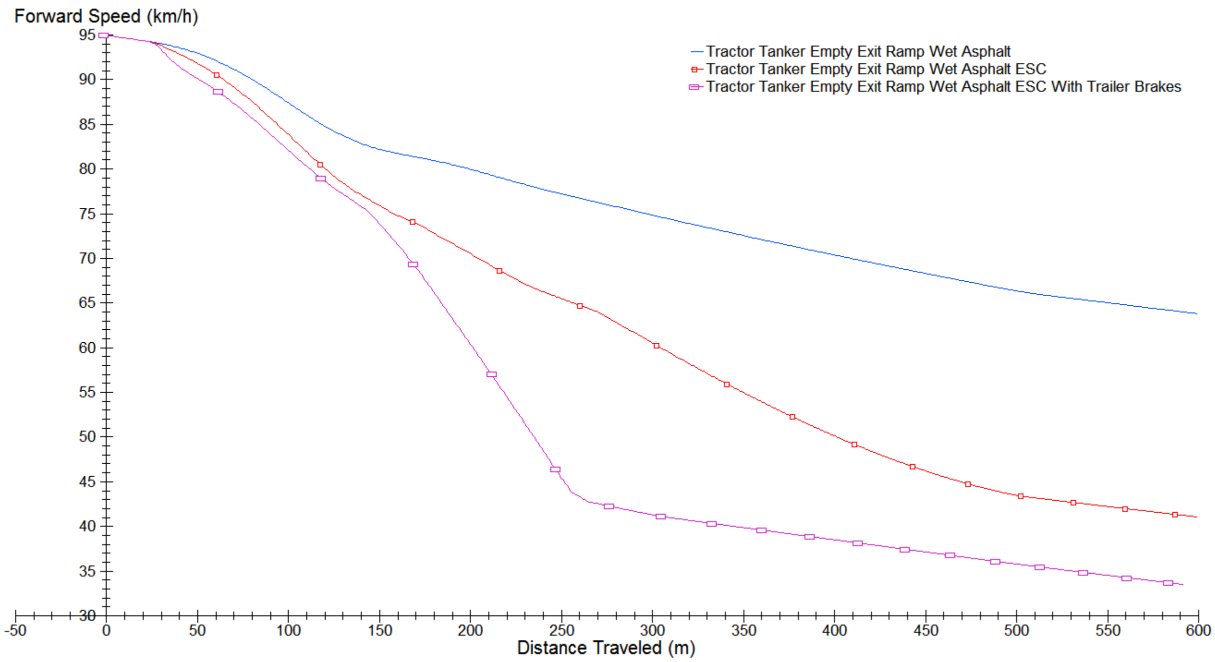

Figure 42. Graph. Empty Tractor Trailer In Exit Ramp – Observed Vehicle Speed.

While the vehicle animation (Figure 39) made it appear that the largest path deviation occurred with the non-ESC case, the largest path deviation of the tractor actually occurred with the tractor-only ESC (Figure 43) as the controller applied the front left brake reducing the vehicle's cornering potential. This result matched the general behavior of the bobtail testing as the ESC intervention on the bobtail case also caused the tractor to deviate further from the desired course. With the addition of the trailer brakes, the needed yaw moment to control the tractor could be generated in part from the trailer. This shift of restoring yaw moment to the trailer brakes allowed the front brake demand to drop by approximately 0.05 MPa. This permitted an increase to the front axle cornering potential and a better path-following curve (Figure 43).

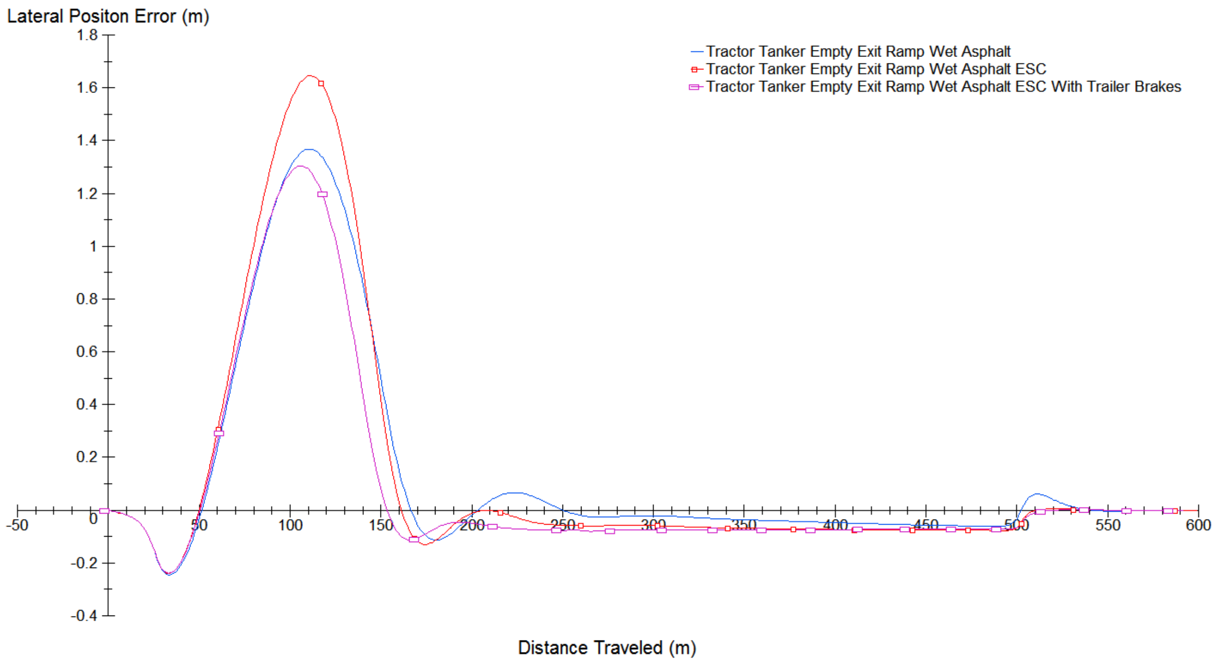

Figure 43. Graph. Empty Tractor Trailer In Exit Ramp – Observed Path Deviation.

With each of the ESC systems, the driver noted that the ESC controller was acting to reduce the turning potential of the vehicle and compensated for the reduced turning potential with an increased steering angle for the first part of the turn (Figure 44). As the full tractor and trailer ESC system resulted in a smaller path deviation than the tractor-only system, the driver responded with a smaller increase in steering input for the tractor and trailer ESC controller relative to the tractor-only ESC controller.

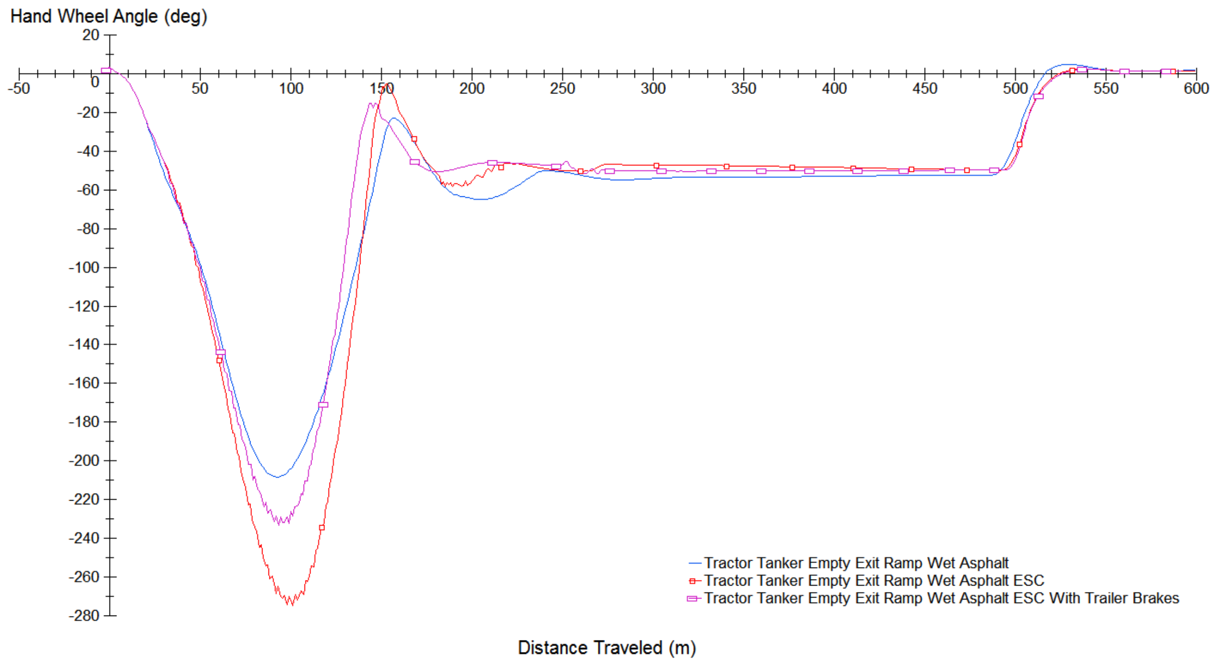

Figure 44. Graph. Empty Tractor Trailer In Exit Ramp – Measured Steering Input.

Finally, Figure 45 shows that the combined tractor and trailer brake ESC system does the best job of managing the vehicle's yaw rate.

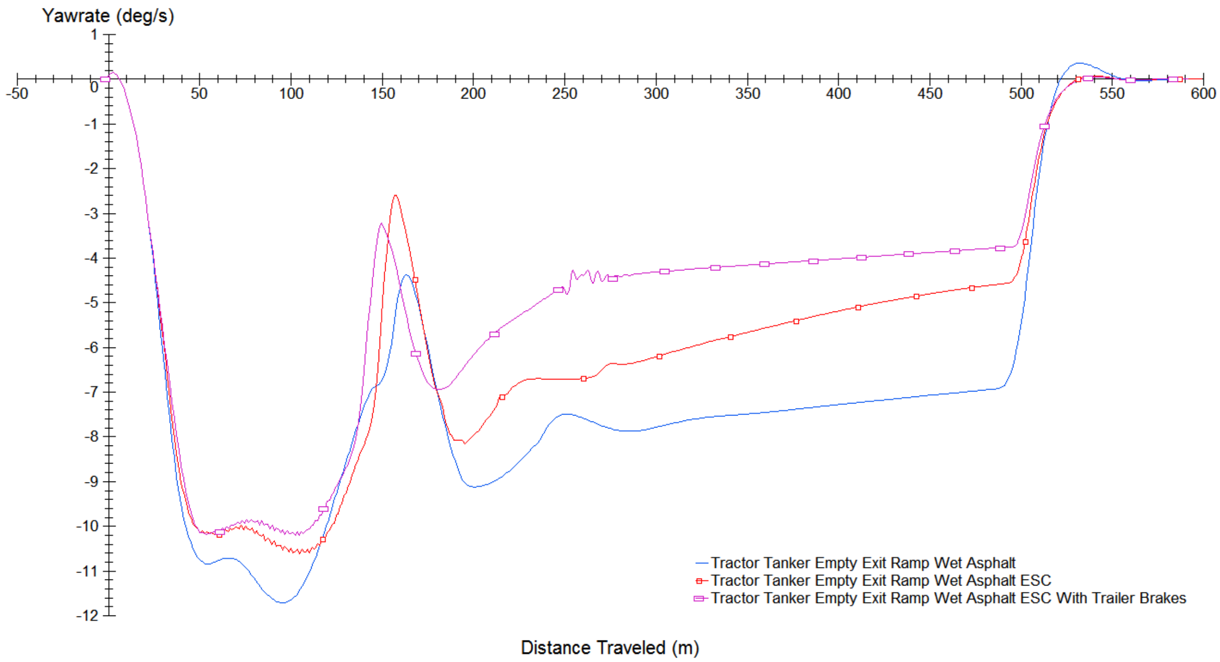

Figure 45. Graph. Empty Tractor Trailer In Exit Ramp – Observed Yaw Rate.

Computational Requirements (Solver Time)

While the controller strategy developed here does result in improvements to the vehicle's stability for both maneuvers, there is a significant problem with the controller. Specifically, the controller is too expensive computationally. The nominal time for the vehicle to complete the lane change maneuver is 13 seconds. The controller requires approximately 20 seconds to execute the lane change simulation. Similarly, the exit ramp maneuver requires 44 seconds for the vehicle to complete the circuit but the controller takes over 50 seconds to develop the proper control responses.

Any real world implementation of a controller requires that the controller be able to calculate appropriate responses and implement those responses before the vehicle's condition changes. Consequently, the current controller is not suitable for real time implementation on a vehicle. The current controller takes approximately 125% of the simulation time to solve and a production system would need to be on the order of 50% of the maneuver time.

Chapter 5 – Assessment of Controller and Load Effects

As commercial vehicles are generally not run in an empty configuration, the yaw stability controller was assessed with different loads. As the addition of load changes the mass and CG location of the tractor, new models were made for the loaded simulations to reflect the changes to the vehicle's operating condition. The changes, however, were limited to defining new vehicle parameters. The controller logic remained unchanged.

The results of the loaded vehicle simulations were then used to evaluate if the controller strategy was robust. The significant short coming of this approach was that the yaw-only controller modeled here managed only yaw stability with the result that roll stability limitations could and did affect the analysis results.

Fully Loaded Vehicle

Upon completion of the empty vehicle analysis, the same set of maneuvers and controllers were reassessed using a tractor and trailer with a DOT legal limit of 80,000 lb (36,360 kg). As anticipated, the loaded vehicle exhibited wheel lift for all three ESC scenarios (Figure 46) during the lane change maneuver which reduced the trailer's cornering potential such that the trailer diverged significantly from the tractor's path (Figure 47).

Figure 46. Illustration. Loaded Tractor Trailer In Lane Change - Wheel Lift .

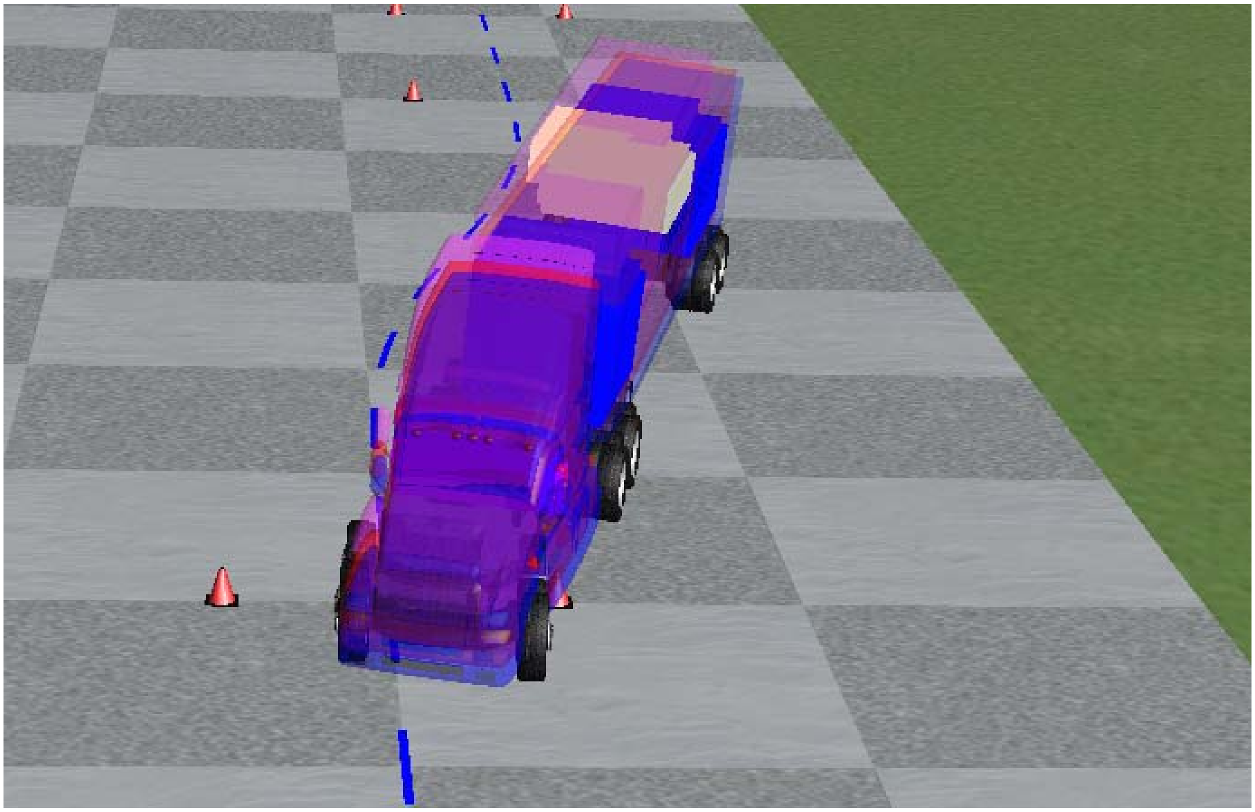

Figure 47. Illustration. Loaded Tractor Trailer In Lane Change - Trailer Path Divergence.

While the analysis of the simulations did provide results in line with the empty vehicle case for the tractor, the wheel lift events produced simulation responses that were quite noisy due to the wheels bouncing on the ground (approximately 160 meters into the maneuver). Figure 48 is the driver steering input for the three ESC cases where the full tractor and trailer braking case is again the best. But the results are generally useful in a qualitative sense only as there is a clear issue with roll stability that is not being managed.

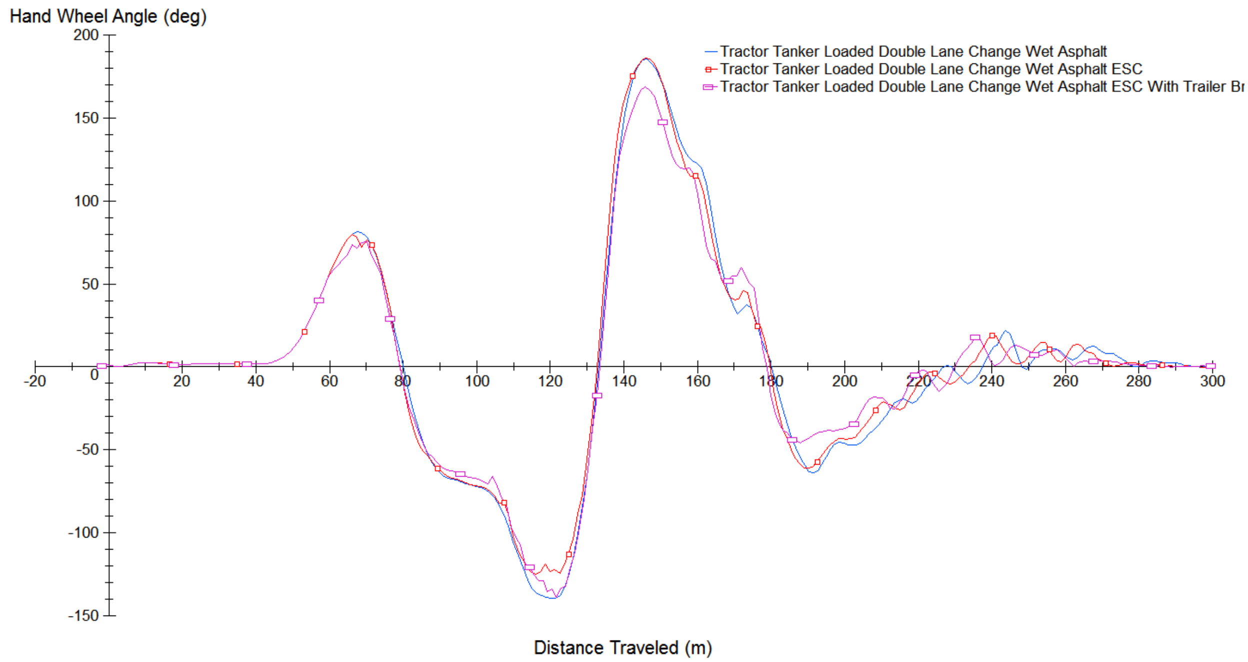

Figure 48. Graph. Loaded Tractor Trailer In Lane Change – Measured Steering Input.

Not surprisingly, when the loaded vehicle exit ramp case was assessed, wheel lift was again observed for all ESC cases (Figure 49). Coupled with the trailer wheel lift was a loss of trailer traction which subsequently led to significant yaw deviations of the trailer (Figure 50) relative to the tractor after 6 meters of travel into the turn.

Figure 49. Illustration. Loaded Tractor Trailer In Exit Ramp - Wheel Lift.

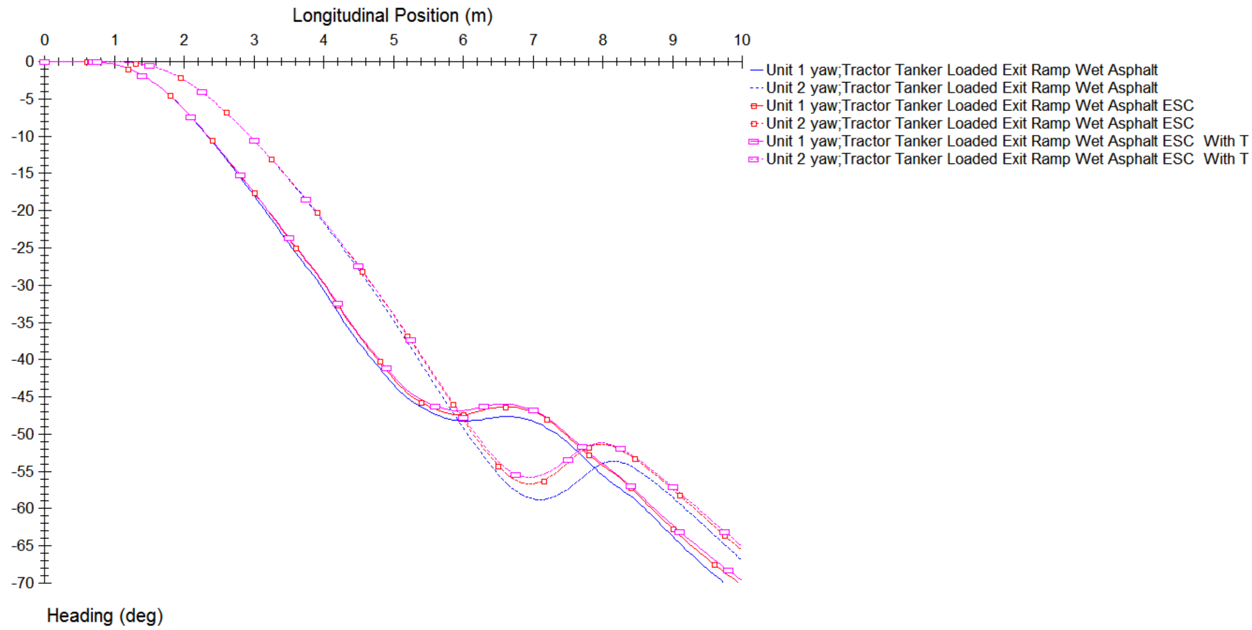

Figure 50. Graph. Loaded Tractor Trailer In Exit Ramp – Observed Trailer Swing.

As was the case with the loaded lane change analysis, the yaw stability controller did appear to provide some benefit in the exit ramp maneuver, such as in yaw rate control (Figure 51). But the results are not particularly reliable as the roll instability is having a significant effect on the vehicle's dynamic behavior.

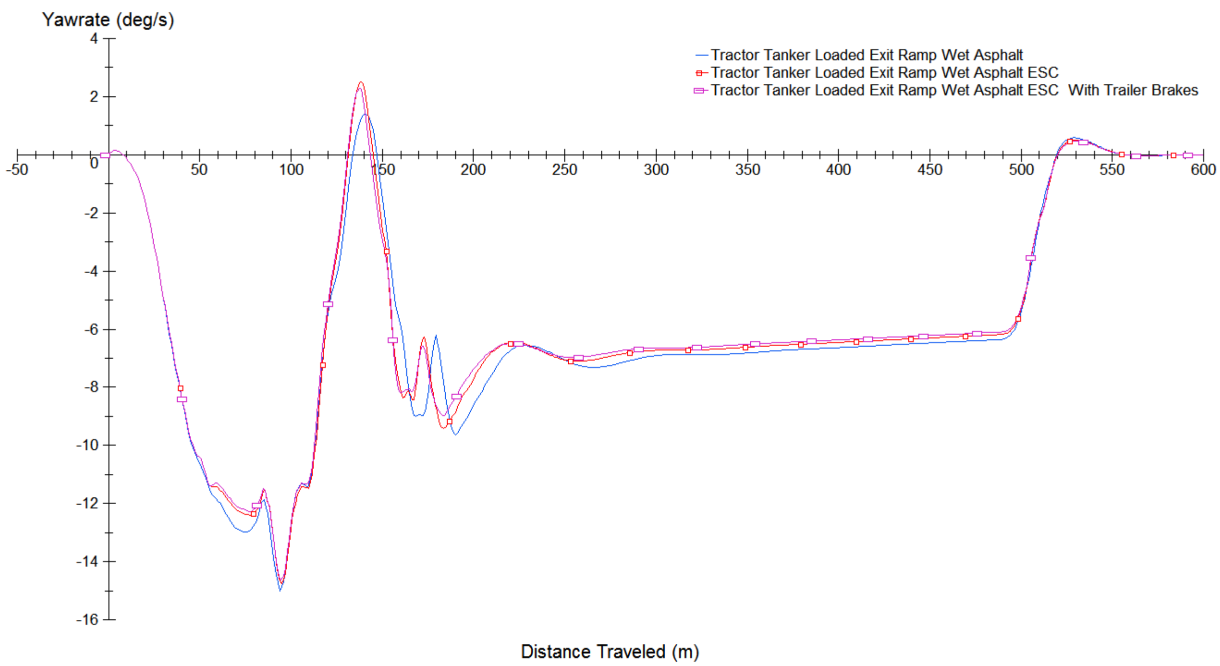

Figure 51. Graph. Loaded Tractor Trailer In Exit Ramp – Observed Yaw Rate.

The conclusion of the loaded vehicle modeling was that without the inclusion of roll control, the existing yaw controller was not suitable for a loaded tractor and semi-trailer.

Front Load Vehicle

The remaining two load cases assessed with the ESC controllers are not generally seen on public roads. To maintain equal tractive forces at all wheel ends, it is desired to have the tractor drive and trailer axles relatively equally loaded. This arrangement also has the benefit of producing lower CG heights as the mass is spread along the length of the trailer rather than piled on one end. However, to test the ESC controllers, the extreme loading conditions where loads are concentrated at the trailer ends were evaluated.

For the front only load (Figure 52), the expected vehicle behavior was observed where the tractor experienced significant yaw deviations. As the trailer is free to rotate about the fifth wheel, the trailer changed heading much more slowly than the tractor. This produced a situation where the trailer tended to push the tractor into large yaw divergence situations. While the stability was poor for all cases, as can be seen by the jackknife tendency in Figure 52, the tractor and trailer brake ESC case was marginally better at maintaining the desired path in the lane change maneuver (Figure 53).

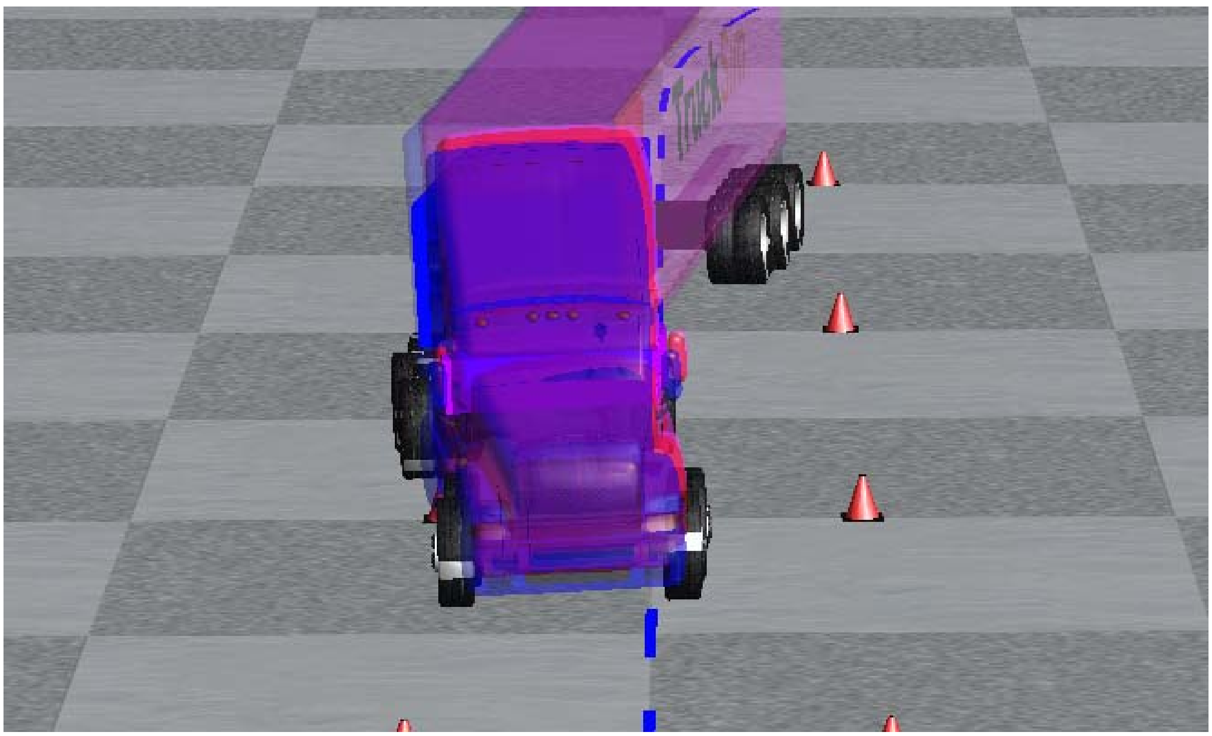

Figure 52. Illustration. Front Load Tractor Trailer In Lane Change – Yaw.

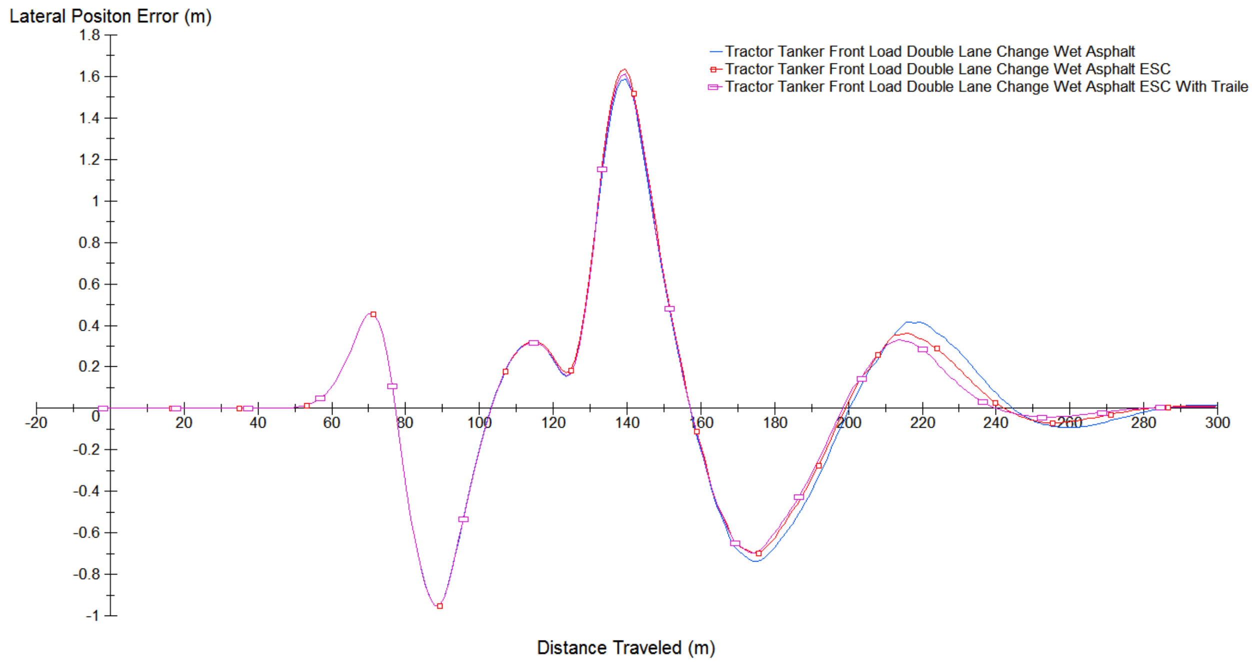

Figure 53. Graph. Front Load Tractor Trailer In Lane Change Path – Observed Path Deviation.

With no load on the rear of the trailer and a significant overturning moment from the front mass, the rear of the trailer lifted regardless of the ESC controller input as can be seen in Figure 54. Note this wheel lift occurred as the model assumed a rigid trailer chassis.

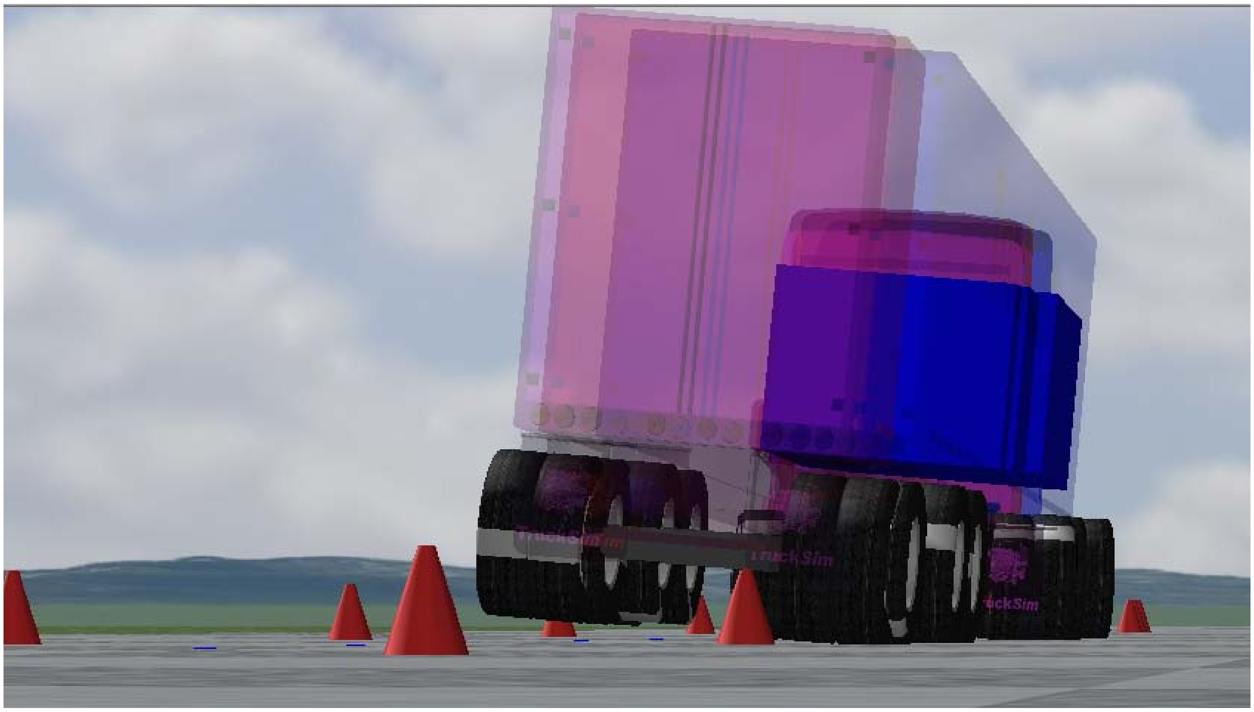

Figure 54. Illustration. Front Load Tractor Trailer In Lane Change - Wheel Lift.

The wheel lift and set down can be seen as noise in the steering input (Figure 55) where the chatter in the 180 to 240 m section is from the trailer lifting and returning to the ground.

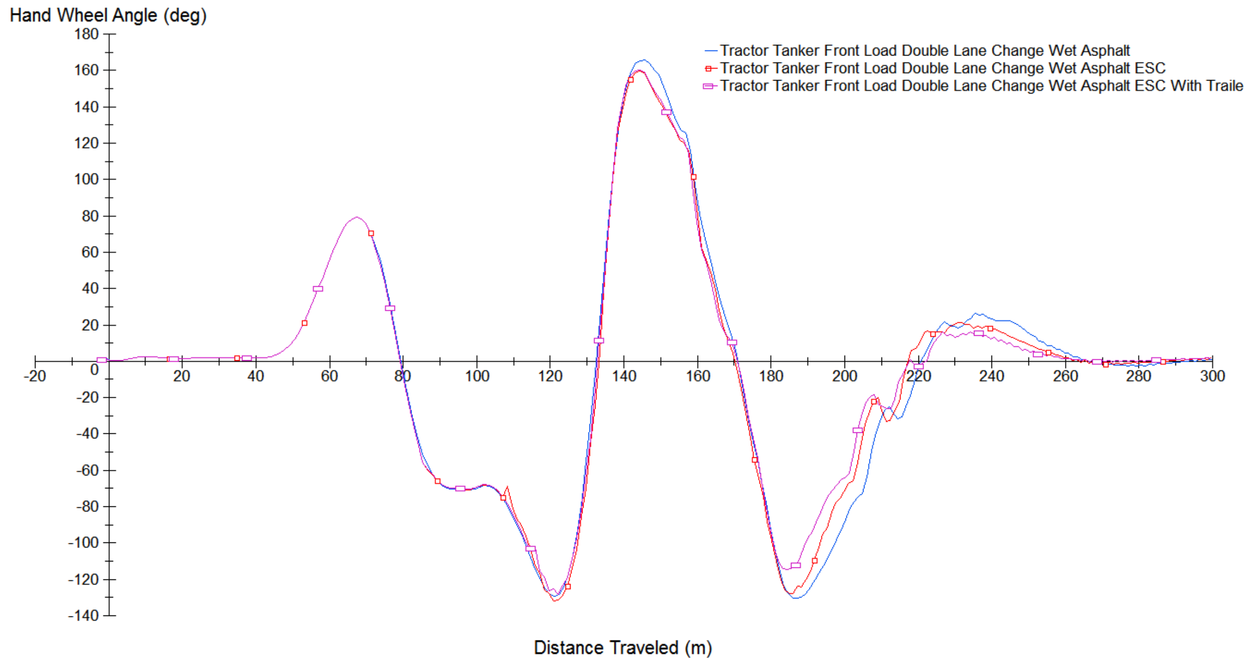

Figure 55. Graph. Front Load Tractor Trailer In Lane Change – Measured Steering Input.

In the exit ramp maneuver, the tractor again experiences a large yaw divergence (Figure 56). While the ESC system does help with controlling the yaw divergence, it cannot compensate completely as the inner drive wheels are near lift off. This case also shows an interesting product of the combined tractor and trailer braking approach. When the wheel loads at the rear of the trailer are very light compared to the drive axle loads, the trailer braking cannot generate significant forces and the difference between the tractor-only ESC and tractor and trailer ESC becomes negligible as seen in Figure 57.

Figure 56. Illustration. Front Load Tractor Trailer In Exit Ramp – Yaw.

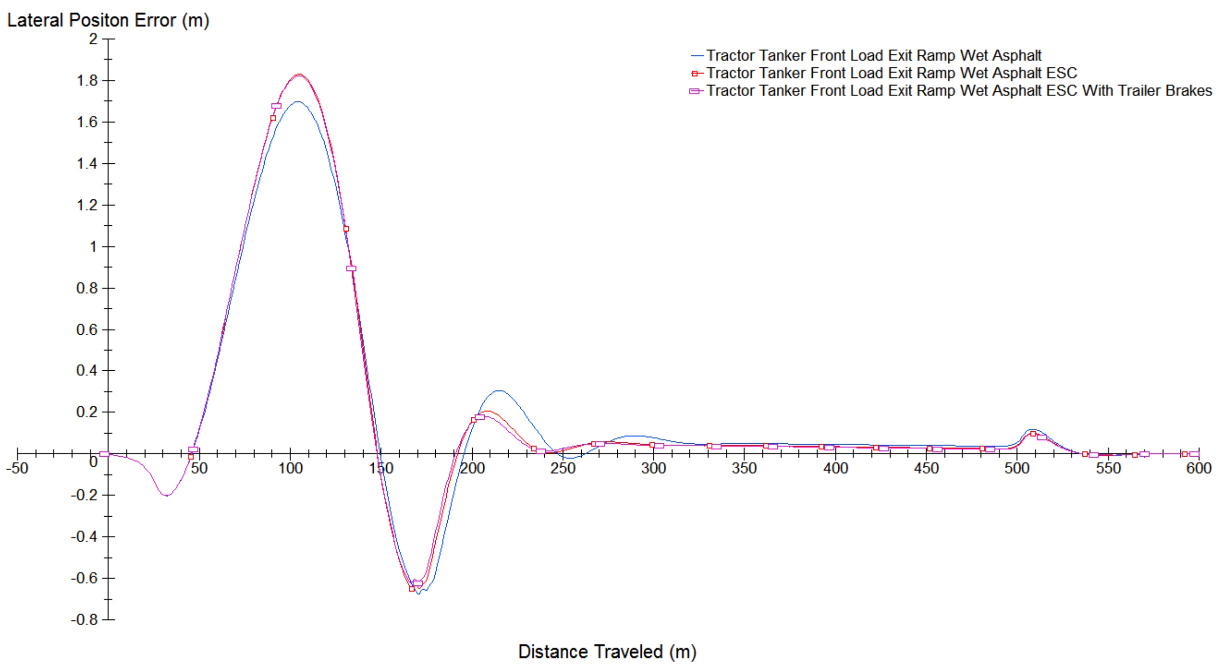

Figure 57. Graph. Front Load Tractor Trailer In Exit Ramp - Observed Path Deviation.

Rear Load Vehicle

For the rear loaded vehicle condition, the ESC system struggled to maintain stability as the controllers did not account for roll stability. In this case, the tractor and trailer braking ESC controller generally performed better than the tractor only brake system as the rear biased loading resulted in significant trailer braking potential. The main issue observed with this loading case was that the ESC system could not "see" the trailer's performance and thus took no action to improve the trailer's performance as can be seen in Figure 58 where all three ESC cases had significant trailer swing-out.

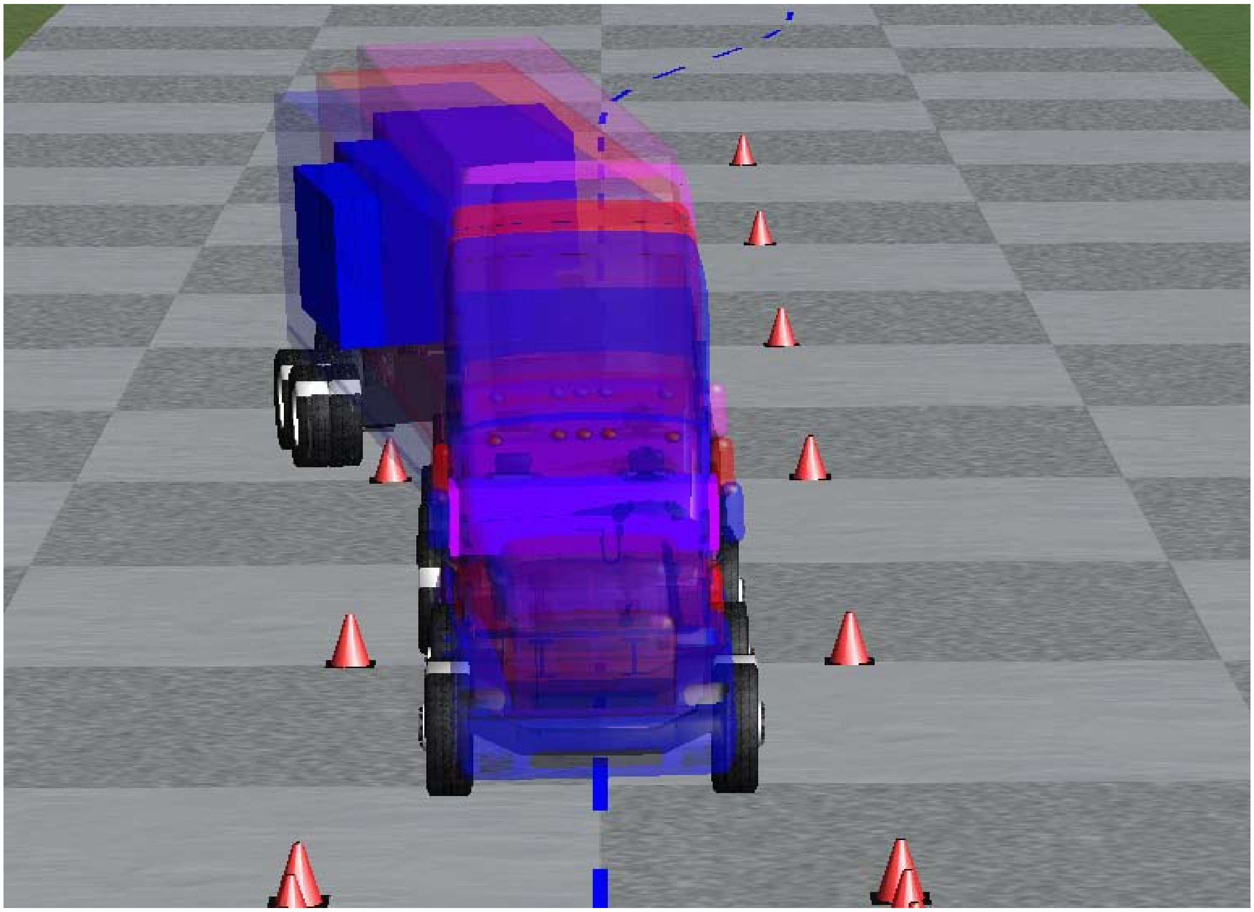

Figure 58. Illustration. Rear Load Tractor Tanker In Lane Change - Swing Out.

Figure 59 and Figure 60 document the slight improvement in tractor behavior for the tractor and trailer ESC brake system around the 140 meter mark where path deviation was the most significant. Of course, the trailer's performance is not as good with all cases having significant lane departure for the trailer. The conclusion here is that for a trailer only load case, there is not much that the tractor based ESC system can do to improve stability.

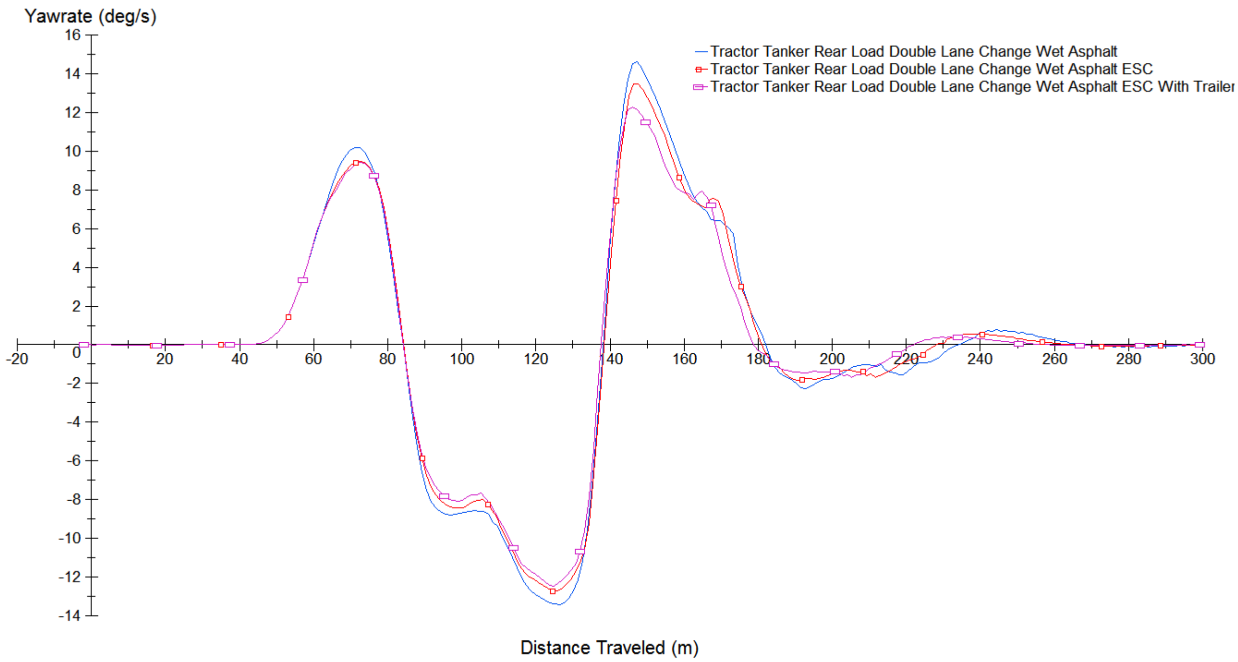

Figure 59. Graph. Rear Load Tractor Tanker In Lane Change - Observed Yaw Rate.

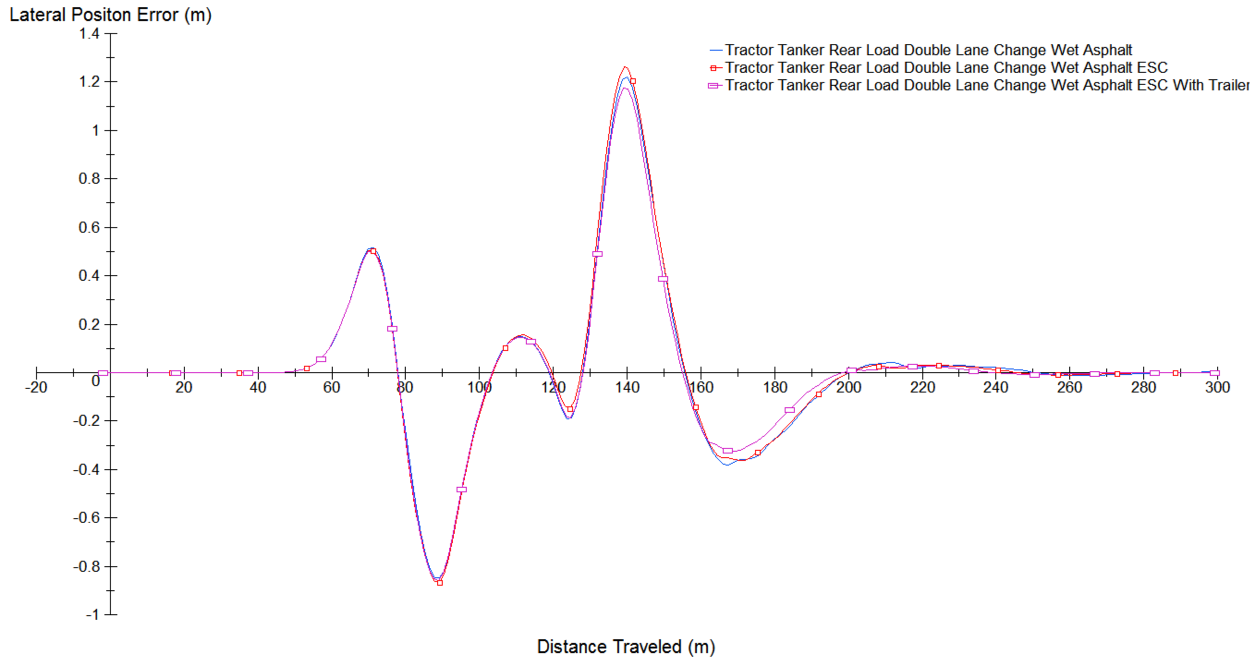

Figure 60. Graph. Rear Load Tractor Tanker In Lane Change - Observed Path Deviation.

Finally, the exit ramp maneuvers for the rear loaded trailer reproduced the general conclusions observed in the lane change testing (Figure 61). The added tractive potential at the rear of the trailer helped improve the ESC's ability to control the tractor (Figure 62) but without some mechanism for observing the trailer's behavior, the system could not correct for trailer instability.

Figure 61. Illustration. Rear Load Tractor Tanker In Exit Ramp.

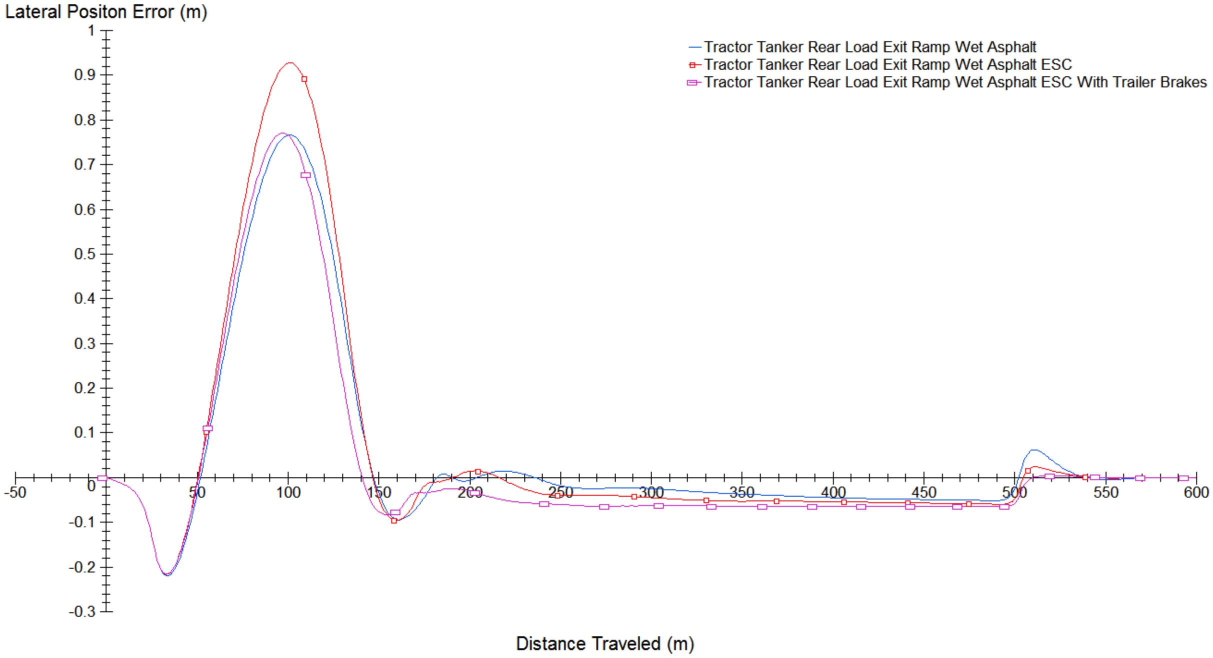

Figure 62. Graph. Rear Load Tractor Tanker In Exit Ramp - Observed Path Deviation.

Chapter 6 – Conclusions and Future Work

The purpose of this research was to investigate the applicability of applying existing ESC strategies from the passenger car world to commercial vehicles. As such, it was known that the resulting stability control simulations would not and could not account for all sources of instability in an articulated vehicle. The reasoning behind performing this exercise was to document the needed improvements to the stability controls for future ESC development for commercial vehicles. The result is the identification of three key areas where advancements will be needed.

Trailer Sensors

The current yaw stability approach is insufficient for managing both the tractor's and trailer's yaw stability needs. While the controller can be successful in some cases, such as when there is equal loading of the trailer, it was not successful in managing cases with unequal loading of the trailer. This points to the need for a better method for predicting the trailer's behavior based on measured reactions at the tractor, or the implementation of sensors on the trailer to measure the dynamic behavior of the trailer.

Need for Roll Stability

As a class 8 commercial vehicle is just as likely to be subject to roll instability as it is to yaw instability, the controller needs to be able to manage and mitigate rollover risk as well as yaw instability. This is not just a practical issue based on the need to protect from all instability sources. It is particularly important as roll instability can actually compromise the ability to correct for yaw instability. The difficult part of this task will be in assessing whether the roll or yaw risk is greater and then in applying the appropriate restorative actions.

Need for System Control of Tractor and Trailer with Inter-Unit Communication

Both of the preceding needs in the development of a better tractor semi-trailer stability system are critical to the success of a class 8 ESC system. However, there is some flexibility in how to accomplish the task. The most straightforward approach would be to place yaw and roll controllers on each unit of the vehicle. In this way, each unit would be able to detect an instability event and react to it as needed. However, it is proposed that the better solution would be to have a single controller manage the entire vehicle as this would eliminate the potential for the trailer unit to take an action that is not beneficial for the tractor (and vice versa). If a single controller strategy is to be employed, then there will need to be a method for the units of the vehicle to communicate and, if multiple controllers are used to implement a single strategy, coordinate with each other.

Chapter 7 - References

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