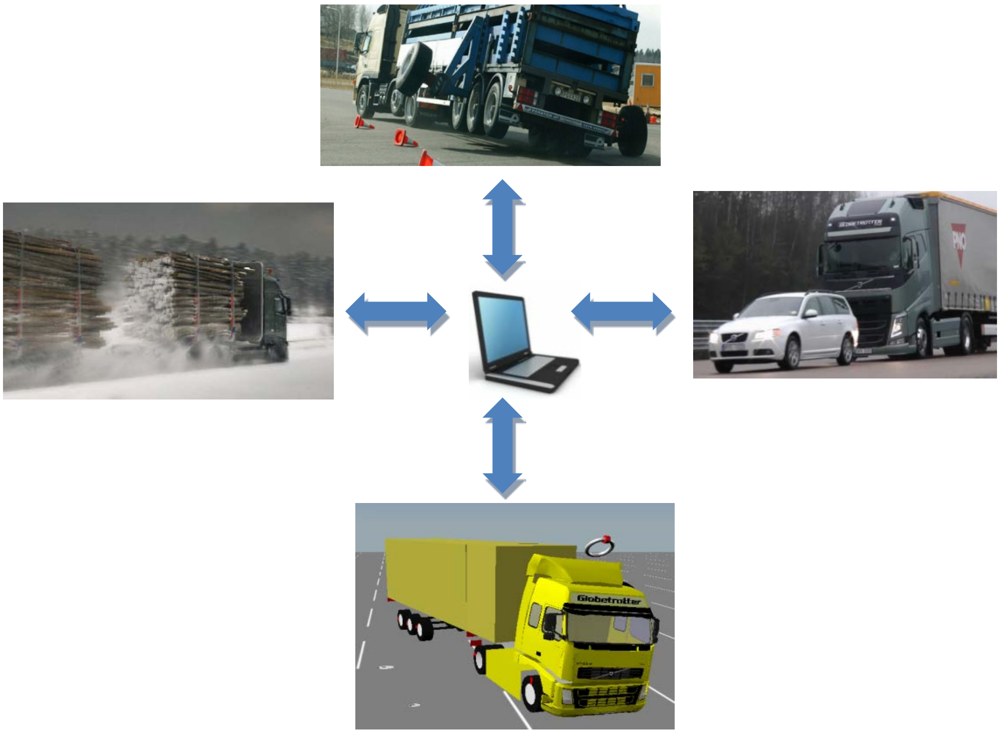

Function development and verification environment for active safety functions of heavy commercial vehicles

Master's Thesis in Automotive Engineering

SACHIN JANARDHANAN

Department of Applied Mechanics
Division of Vehicle Engineering and Autonomous systems
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CHALMERS UNIVERSITY OF TECHNOLOGY
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ABSTRACT

Introduction of active safety functions in the heavy vehicle industry to meet the legislations and continuous development of new functions is a major task considering performance, cost and time. In order to introduce these features in a short time period, with affordable costs including validation makes it necessary to find an alternative approach to existing practices of development process. Based on the advanced engineering studies on model based product development, within Volvo Group Trucks Technology, a proposal was to have a simulation environment capable of integrating the entire range of functional systems represented by physical models and motion controllers followed by implementing software in loop simulations for the verification of the motion control systems.

The aim of this thesis was to generate a simulation environment to support function development of new active safety functions and verification of Electronic Braking System (EBS) functions by integrating existing in-house tools within Volvo Group Trucks Technology and the complied software code (EBS-7) from the supplier. Simulation environment was developed with a focus on modularity to cover diverse variant based product offering and supporting quick function development with the help of MATLAB/Simulink. Finally, the simulation environment was verified for its function, stability and accuracy by using simplified test cases and further validated by correlating the simulation results with real test measurements.

The simulation results and correlation with the real truck test measurements indicate the ability of simulation environment to serve as a tool for the future function development of safety functions and verification of Electronic Braking System functions.

Key words: Heavy vehicle, Model based development, Function development, Electronic Stability Control (ESC), Software in Loop (SIL), Controller Area Network (CAN), Truck.

Contents

Preface

This thesis work has been conducted as a partial requirement for the Master of Science degree in Automotive Engineering at Chalmers University of Technology, Gothenburg, Sweden in cooperation with Volvo Group Trucks Technology, Sweden. The entire project was carried out at Chassis strategies and Vehicle Analysis group, Volvo group Trucks Technology in Gothenburg from February to July 2013.

As the thesis work involved integrating different systems and areas of expertise, there were many contributors for the completion of this work. Firstly I would to acknowledge my supervisors at Volvo Group Trucks Technology namely Leo Laine and Per Olsson for their technical support and valuable guidance. I have always learnt something new during the discussions and technical sessions. A special thanks to Rickard Andersson from the Advanced Technology Research group for his guidance to deal with Global Simulation Platform (GSP). I also appreciate the continuous support from Niklas Fröjd to handle the Volvo Transport Models (VTM) and for useful discussions related to longitudinal dynamics.

This work would have been incomplete without the expertise and support of my supervisor Kristoffer Tagesson and examiner Bengt Jacobson from Chalmers University, who took their time and guided me to visualize the problem in detail. Kristoffer played a dual role of supervisor at Chalmers as well as at Volvo Trucks. I would also like to express my appreciation to Stefan Edlund, Inge Johansson and the entire team of Chassis strategies and Vehicle Analysis, for their inputs and support throughout the entire duration of the thesis.

Finally I would like to thank my family and all the well-wishers for their backing throughout this work.

Göteborg July 2013

Sachin Janardhanan

Notations

a_{y-ss}	Steady state lateral acceleration threshold	m/s^2
g	Acceleration due to gravity	m/s^2
k_u	Understeer gradient	rad/g
L	Wheelbase	m
R	Radius of the curvature	m
v_x	Longitudinal velocity	m/s
δ_{fw}	Steering angle at the front wheel	rad
δ_{swa}	Steering wheel angle	rad

Abbreviations

AEB	Advanced Emergency Braking
CAN	Controller Area Network
EBS	Electronic Braking System
ECU	Electronic Control Unit
EMS	Engine Management System
ESC	Electronic Stability Control
GSP	Global Simulation Platform
HMI	Human Machine Interface
LDW	Lane Departure Warning
MSDM	Motion Support Device Management
SIL	Software in Loop
TCS	Traction Control System
TEA	Truck Electronic Architecture
TECU	Transmission Electronic Control Unit
TSC	Torque Speed Control
TS&VMM	Traffic Situation and Vehicle Motion Management
VMCU	Vehicle Master Control Unit
VTM	Volvo Transport Model

1 Introduction

Today almost all of the active safety functions and driver assistance features in the heavy commercial vehicles are based on softwares embedded in the motion controllers. The developers of these functions often work independently focussing on the detailed development of the concerned systems. With the growing number of functions which involve communication between different system based controllers an integrated development approach becomes very important.

In this thesis work an integrated simulation environment is developed using software in loop controllers, to enhance the current limitations of software based product development process, provide support for development of new functions and serve as a verification tool. The development of control functions are not a part of this work and only involve verification of the supplier provided software functions. In this study the Electronic Braking System (EBS) system is specifically verified for its functionality using test cases and henceforth referenced by EBS-7, which is the latest version of software used in Volvo trucks. The Truck Electronic Architecture is also referenced using TEA2+, the latest electronic architecture used in Volvo Trucks.

The reader is also assumed to have sufficient knowledge in the operation of Electronic Stability Control (ESC) function, Controller Area Network (CAN) communication protocols and vehicle dynamics. In this study the definition of Electronic Stability Control includes both directional control and roll over stability control, although this may not be the same in the references cited and often based on the context.

This chapter presents the background, purpose and limitations of the simulation environment.

1.1 Background

Based on results of the safety benefits of Electronic Stability Control (ESC) function on passenger vehicles and study of various accident statistics on heavy vehicles, European Union has made it mandatory for the heavy vehicles to be fitted with ESC system [1]. Electronic stability control (ESC) for heavy vehicles includes the rollover protection systems in addition to the directional control (understeer and oversteer) normally found in the passenger cars. Further two additional safety related features namely the Advanced Emergency Braking (AEB) and Lane Departure Warning (LDW) systems are to be made mandatory on heavy vehicles from the year 2014 as per legislation passed by European Union [8].

The current function development process is highly dependent on isolated testing of the subsystems and feedback from physical verification of the vehicle in the late stages of development [11]. However to meet the mandatory regulations for all the heavy vehicles along with diverse variant offerings it would be time consuming and complex to follow the conventional development process. In addition the continuous introduction of new software functionalities, manufacturer's goal to deliver a safe product and limited resources including field test possibilities for the entire product range add to the complexity of development process, cost and time. The development of active safety and driver assistance features also involves integrating various systems together and it becomes necessary to verify their combined effect during the development to identify any integration errors and functionality issues [11]. For example the Roll Over Protection functionality would require the Engine Management System (EMS) system, Transmission Electronic Control Unit (TECU) and Electronic Braking System (EBS-7) to function together harmoniously and as an integrated system to have predictable rollover stability control. Based on earlier studies and product development experiences within Volvo Group Trucks Technology, a solution for such a function based product development process would be to generate a model based simulation environment integrating all the required systems [11]. The model based product development could be realized by a merged simulation platform which includes the required functional systems for motion control and with corresponding softwares in loop. Additionally the amendments to the regulations R13 and R13-H by Economic Commission of Europe (ECE), to include the computer simulations as a method to detect effectiveness of directional and roll over stability of heavy vehicle combination is a key driver for this development [8].

1.2 Objective

The purpose of this thesis is to generate an integrated simulation and verification environment by merging different simulation platforms, used for discrete functionalities, namely Volvo Transport Models (VTM) and Global simulation platform (GSP) along with EBS-7 software and CAN communication protocols of the TEA2+ system architecture used in Volvo Trucks. The VTM platform includes detailed physical models for the chassis and vehicle dynamics based systems and the GSP including detailed physical models and controllers of the powertrain systems majorly developed for fuel economy evaluations. The simulation environment is developed to include Software in Loop simulation capabilities. Additionally automation of CAN protocols was focused to avoid repetition and to reduce human errors in manual signal creation.

Finally to validate the functioning and accuracy of the simulation environment, test cases verifying the EBS-7 functionalities are performed.

1.3 Limitations

The scope of the thesis work is limited due to the following constraints:

- The automated signal generation is not programmed for the entire Truck Electronic Architecture (TEA2+). Only the communication networks, from TEA2+, necessary for the functioning of the EBS-7 are focused upon.
- Light versions of Engine Management System and Transmission Electronic Control Unit are used instead of actual software used in the truck based controllers due to non-availability of the software on time. These light versions limit the verification of Drag Torque Control function and Brake Blending functions of the EBS-7 software.
- All the test cases do not have real time measurements to verify the accurate functionality of the EBS-7 software.
- The physical plant model of VTM is validated only for few driving scenarios and does not consider the effects of variation in ambient temperature and friction of the road surface etc.
- The development and verification of traffic situation, environment sensors and the Driver Assistance Control functions like AEB and LDW are not in the scope of this study.

2 Literature Review

Information and literature from different facets were explored for the generic development of the environment considering future implementations. This chapter highlights the data that were explored in the areas of legal regulations, model based development of the active safety functions and electronic braking system functions.

2.1 Legislations and Application

Active safety systems also referred as “Primary safety system” reduces the risk of the potential vehicle crashes and injuries to vehicle occupants. The scope of introduction of these safety functions in the respective industry (heavy or passenger vehicles) is driven by need for improved vehicle safety, legislations and technological improvements in the infrastructure. Electronic stability control (ESC), one of most potential active safety functions was first introduced in passenger vehicles around 1995 and nearly in 2005 into the heavy vehicles industry.

Accident statistics and analysis in different countries like United States, Australia and across Europe indicate that implementation of ESC (referring to directional control loss) in vehicles can reduce single passenger vehicle crashes by nearly 30% [6, 13, 15]. Analysis performed by Volvo accident research team indicates that the frequencies of heavy trucks driving off the road with or without roll instability accounts to 35% of the traffic accidents involving single heavy trucks in Western Europe causing serious to fatal injuries [1]. Hence based on the positive proven effect of ESC in the passenger vehicles and voluntarily fitted heavy vehicles, the UNECE in Nov 2007 reached an agreement to revise the ECE Regulation 13, by requiring the heavy vehicles to have ESC as a mandatory fitment. The regulation ECE-R13 applies to all common categories of heavy vehicle types to be equipped with ESC (refers to both yaw and roll control) from 2010, with priority given to heavy truck/trailer combinations and touring coaches [18]. In addition the new Regulation, (EC) No. 661/2009, also requires all vehicle categories including heavy trailers seeking type approval from 2011 to have mandatory ESC fitment and as a mandatory fitment on all new vehicles from November 2014 [8]. The regulation also mandates fitment of new technologies namely the Lane Departure Warning systems and Advanced Emergency Braking systems from 2013 on new type of vehicles and 2015 on all new vehicles [3]. Similarly the NHTSA in United States has already submitted the notice for rulemaking and will establish a new Federal Motor Vehicle Safety Standard No.136 that requires all the heavy trucks to be fitted ESC systems [14].

In order to improve the implementation rate of the ESC systems, UNECE has supported the cause by making amendments in the Regulation No: 13 supporting the use of computer simulations. The regulation ECE R-13 and 13 H states: “The effectiveness of the directional and/or roll-over stability control function of power Driven vehicles and trailers of categories M, N and O, may be determined by computer Simulation” [8].

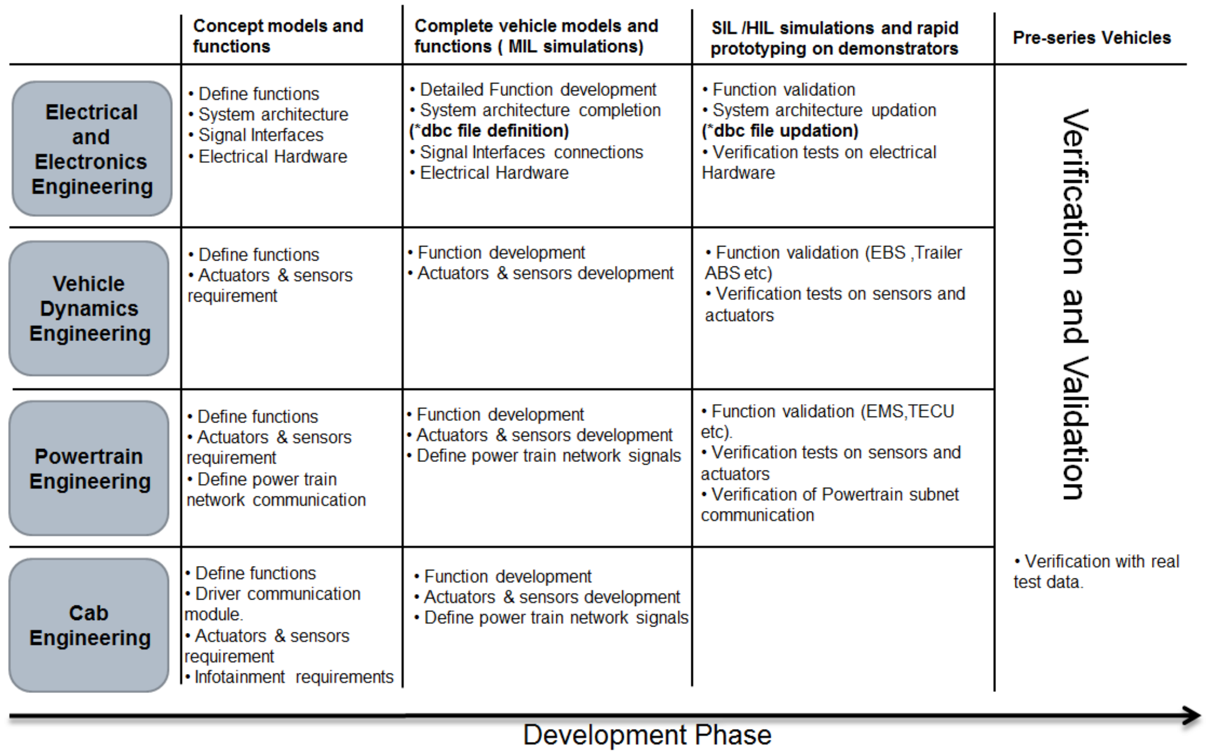
2.2 Model Based development with software in loop

With the increase in the introduction of electronic based driver assistance features and active safety systems in road vehicles, the Original Equipment Manufacturers (OEM) are constantly improving the methods of development of integrated mechatronic system to have reliable product [9]. The rapid introduction of these function based electronic control systems like ESC, LDW, AEB, etc., increase the complexity of the development in terms of communication architecture, integration and verification, in addition to the association with safety critical systems like brakes, steering etc. Hence the integrated development of these emerging functions becomes very necessary to achieve the required functionality with required quality, safety and cost after the vehicle integration [7]. This integrated development and verification is greatly supported by model based development using Model in Loop and Software in Loop approaches in the early stages and followed by hardware in loop during the later stages [10].

The integrated model based product development gives an opportunity to verify early concept phase function development, improve it over the development phase and verify its detailed function before manufacturing, without adding significant cost, delivery time and at the same time improving the quality [7]. Model based development also establishes a common platform for different development groups (electrical, mechanical, hydraulics) in an organization and external suppliers to interact and support in the common development process. A comprehensive development procedure in a vehicle project with software based functionalities and its verification is indicated in figure 2.1.

Based on the study as in [11], a proposal for utilization of Model based development in different stages of a product development process in a simplified representation is shown in figure 2.2. A brief overview is described here:

- CONCEPT PHASE: Early phase preliminary system level simulations and full vehicle concept simulations. The behaviour of a new subsystem, addition to the existing system or plant could also be evaluated using Model in Loop. Simplified algorithm of functions could be simulated along with physical models before detailed development.
- DEVELOPMENT PHASE: The stage after the concept phase could use the model based development using Software in Loop for detailed development of the communication architecture, fault tracing and verification of bugs in the software and issues with the system architecture. This stage could be accomplished in different development loops to match with the development phase of the overall system. Supplier based softwares could be verified in this stage before final development of the production code.
- VERIFICATION AND HOMOLOGATION: Finally the model based development system could be merged with Hardware in loop simulators to verify the integrity of the system architecture and functionality of the softwares using hardwares.



	Concept models and functions	Complete vehicle models and functions (MIL simulations)	SIL /HIL simulations and rapid prototyping on demonstrators	Pre-series Vehicles
Electrical and Electronics Engineering	• Define functions • System architecture • Signal Interfaces • Electrical Hardware	• Detailed Function development • System architecture completion **(*dbc file definition)** • Signal Interfaces connections • Electrical Hardware	• Function validation • System architecture updation **(*dbc file updation)** • Verification tests on electrical Hardware	Verification and Validation
Vehicle Dynamics Engineering	• Define functions • Actuators & sensors requirement	• Function development • Actuators & sensors development	• Function validation (EBS ,Trailer ABS etc) • Verification tests on sensors and actuators	
Powertrain Engineering	• Define functions • Actuators & sensors requirement • Define power train network communication	• Function development • Actuators & sensors development • Define power train network signals	• Function validation (EMS,TECU etc). • Verification tests on sensors and actuators • Verification of Powertrain subnet communication	
Cab Engineering	• Define functions • Driver communication module. • Actuators & sensors requirement • Infotainment requirements	• Function development • Actuators & sensors development • Define power train network signals		• Verification with real test data.

*** dbc file** – Data base file used to read and define data flow the on the CAN communication.

Figure 2.1- Integrated software based function development in a vehicle project

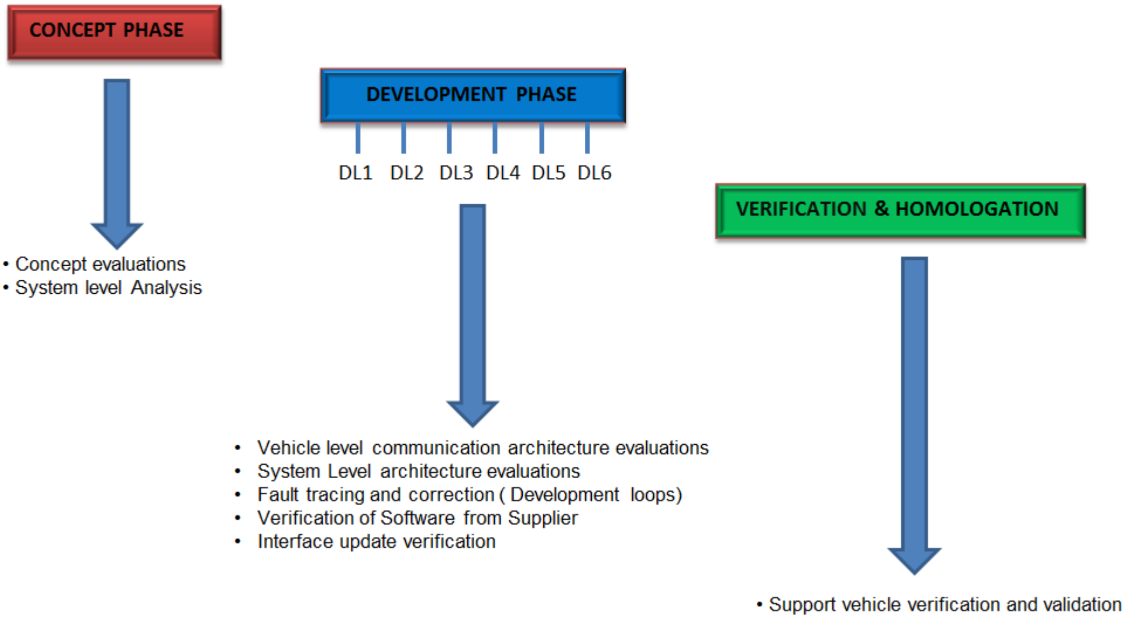


Figure 2.2-Simplified view of use of simulation environment in vehicle development

2.3 Electronic Braking System software functions

The most regular driver assistance and stability control functions activated by the Electronic Braking System software (EBS-7) are listed below with their applications:

- Traction Control System (TCS) – This function is usually activated on a low friction surface when the tractive force on the wheel is limited. Depending on the friction level on a drive axle which could be even or split, the TCS function acts differently. On even low friction the EBS-7 limits the torque sent out by the engine which is governed by the slip limiting torque of the wheel on the low friction surface. In split friction case the wheel on the low friction surface is braked while the high friction level wheel pulls out the vehicle from the situation.

- Drag Torque Control – is usually activated to prevent the drag or braking torque effect on the wheels caused by the engine and endurance braking devices usually on a downhill. This function controls the engine torque and cuts the engine retarder and driveline torque from delivering too negative torque preventing braking of the wheel and hence the slip.

- Cruise Control – This function helps in maintaining constant cruise speed by controlling engine speed to match that of the varying road profile.

- Brake Blending – The brake blending functions reduces the load on the friction brakes by parallel activation of the endurance brakes (engine retarder or driveline retarder). The balancing act of how much torque is applied by the service brakes and the endurance brakes is performed by the EBS-7 software depending braking demand.

- Antilock Braking System (ABS) – This function prevents the wheel slip by continuously monitoring the wheel speeds during a braking situation. By regulating the brake pressures to the individual wheels during braking, they are prevented from being locked.

- Yaw Control (part of ESC) – This function stabilizes the vehicle in low and mid friction conditions and prevents the unstable yaw motion of the truck in understeer and oversteer conditions. The stabilizing effect is achieved by braking the inner wheel during understeer conditions and the outer wheel in an oversteer situation.

- Roll Stability Protection (part of ESC) - The roll stability protection function of the EBS-7 prevent vehicle rollover under various driving situations and vehicle configurations (within the limits of physics). This function is mainly needed for mid to high friction level surfaces. The roll stability determines the maximum speed that the vehicle can be driven in a curve situation. The vehicle speed is controlled by regulating the engine and brake torques.

3 Simulation architecture

3.1 Development of the simulation environment

The integrated Software in Loop simulation platform represents a simplified view of the complete vehicle system and its environment of operation as shown in figure 3.1. It is developed by integrating the following simulation platforms and softwares:

- Volvo Transport Models (VTM) – This platform incorporates the vehicle plant models including tractor trailer combinations and rigid trucks. It includes detailed longitudinal, lateral and vertical dynamic models of the complete truck/tractor-trailer combination covering major components like frame, steering system, suspensions, axles, wheels and the cab excluding the motion actuators. The entire vehicle dynamics model is enclosed in the vehicle plant subsystem of the simulation environment as shown in the figure 3.1.
- Global Simulation Platform (GSP) – The GSP platform includes the detailed models of the powertrain systems extending from the engine to differential. All the controllers and actuators concerned with the respective actuator systems are included within GSP. The actuators from GSP platform and the brake actuator models are enclosed in the Motion Support Device Management subsystem of the simulation environment represented in the figure 3.1.
- Softwares – The Software in Loop version of the EBS-7 software is enclosed in EBS Controller unit located within the Traffic Situation and Vehicle Motion Management subsystem indicated in the figure 3.1. Additionally light version of engine and transmission controllers separated with their interfaces from GSP is used. In figure 3.1, the Traffic Situation and Vehicle Motion Management subsystem houses all the involved Electronic Control Units and the entire communication architecture.

The requisite of modularity, ease of use, function development support and alignment to the development process were the main factors driving such a simplified representation. In order to have reduced human interventions while creating the signals and feeding the parameters, effort has been made to automate the entire process. The automation is carried out using Matlab function scripts.

The simulation architecture is subdivided into Human Machine Interface (HMI), Traffic Situation and Vehicle Motion Management (TS&VMM), Motion Support Device Management (MSDM), Vehicle Plant and the Sensor Noise subsystems. An additional advantage of such architecture is the capability to simulate controllers, actuators and plant models at different sampling rates representing the real functioning as in a truck. A very clear distinction can also be made between different types of the signals whether they are CAN based, other digital signals or actual physical signals based on mechanics.

The overview of the architecture and the subsystems are detailed as follows:

- Human Machine Interface: The HMI subsystem represents the driver-machine communication interface which sends driver requests and observes the vehicle status. Basic open loop driver requests like throttle, steer and brake requests are sent through this subsystem. In addition other CAN based requests to trigger the functions within different Electronic Control Units are also communicated. This subsystem could also be enhanced to include driver model (open/closed loop) sending out requests.

- Traffic Situation and Vehicle Motion Management: The Traffic situation and vehicle motion management encloses the intelligence of the complete environment (controllers) and is the main communication channel between the driver and actuators. Based on the driver request and feedback of vehicle states this subsystem processes the output to the actuators as directed by the respective controllers. This subsystem represents a simplified version of the network of Electronic Control Units and their communication which are necessary for the functioning of the EBS-7, EMS and TECU softwares. CAN protocols like SAE J1939, ISO 11992 and internal Volvo protocols are used and automated using .dbc files. These .dbc files represents the communication protocols as found in the Truck Electronic Architecture and are version controlled which gives an opportunity to verify the communication structure, controller functionalities and integration errors during development loops.

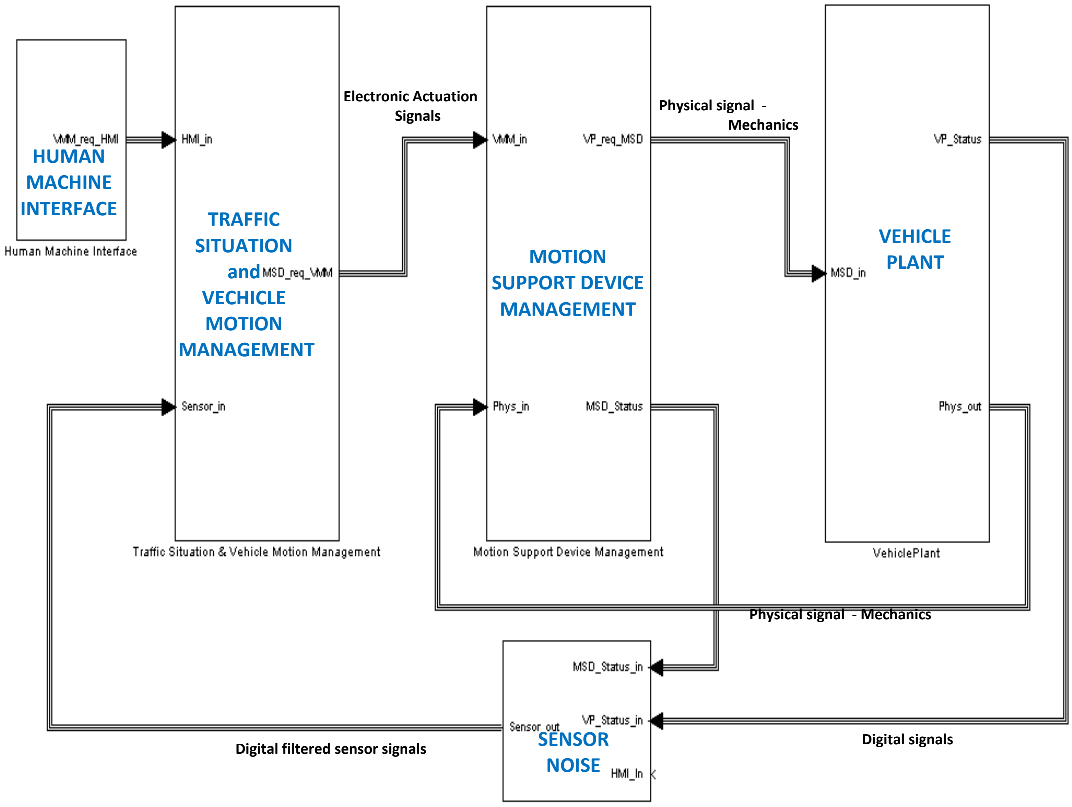


Figure 3.1-Simulation environment architecture

The simplified representation of the Traffic Situation and Vehicle Motion Management sub-systems is shown in figure 3.2. This network of communication sends the status of the different parameters and variables which are necessary for the EMS, TECU and the EBS-7 to activate respective control functions and deliver the control signals to the actuators.

The figure 3.3 highlights the functioning of the entire network in which the Electronic Control Units (ECU) receive requests from driver, status of vehicle systems and other controllers over CAN bus. The ECU's communicate directly over J1939 bus and other sub networks, while the other signals like vehicle states, driver inputs and actuator status are converted by respective sensors into electronic signals and then sent over CAN bus. On the reception of the required signals, the ECU's respond according to the software programmed by sending the actuator requests and other status signals over CAN bus.

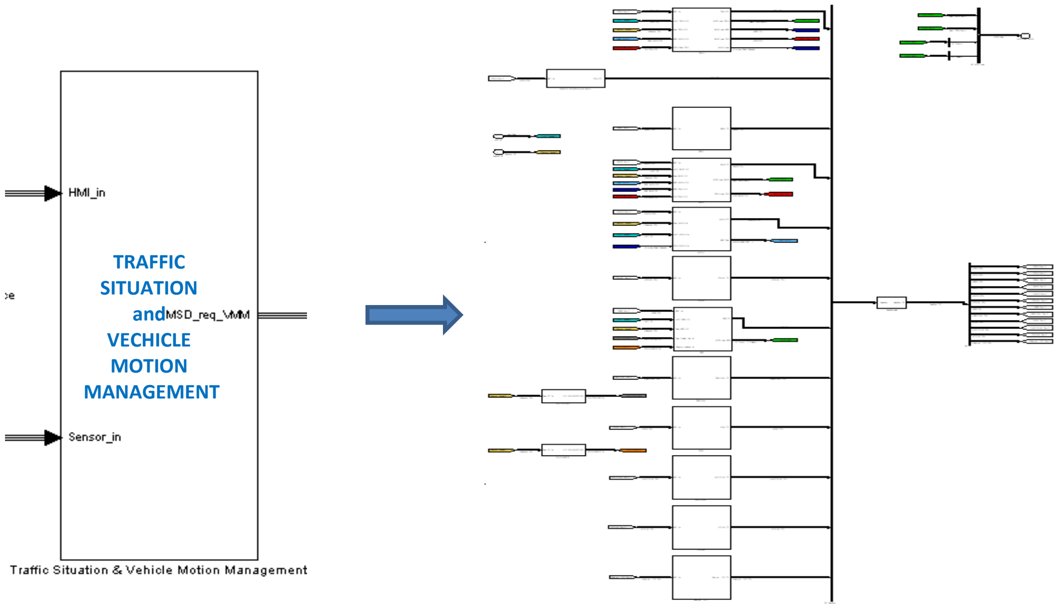


Figure 3.2-Traffic Situation and Vehicle Motion Management subsystem overview

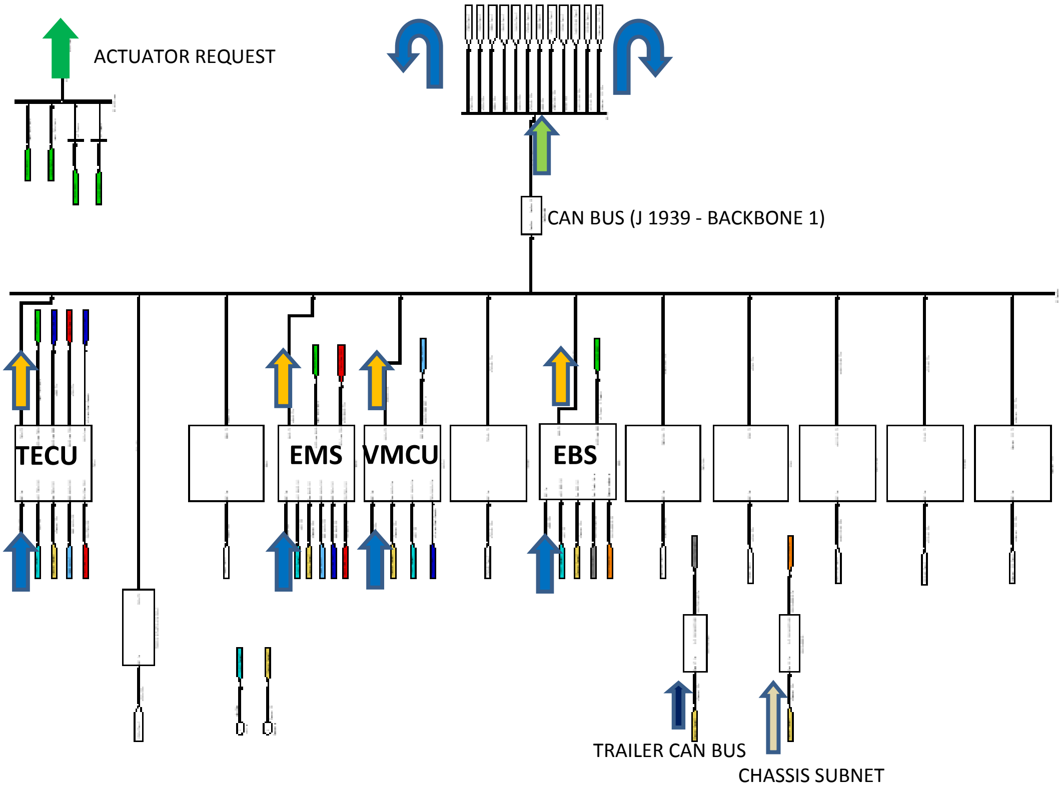


Figure 3.3-Communication within Traffic Situation and Vehicle Motion Management subsystem

The information over the CAN bus could be accessed by different ECU’s at the same time indicating the possibility of peer to peer communication for arbitration of request. For example the engine torque output status from the EMS is transmitted on to the CAN bus, is accessed both by TECU and EBS-7 to perform their operations. The TECU requests engine torque for smooth gear shifts by limiting the engine torque and the EBS-7 needs the engine torque to send torque limitations to EMS during critical situations like Traction Control activation. For the EMS to decide which ECU has the highest priority at a given situation, a torque speed control arbitrator is generally built in the respective controllers. A simplified Torque Speed Control arbitrator was developed to complement the light version of the Engine Management System that was used in the simulation platform. For an ECU to respond to different torque or speed requests sent by peer ECU’s, an arbitrator is used to decide which request should be processed first based on priorities and type of requests whether speed or torque control/limit.

- Motion Support Device Management: The Motion Support Device Management subsystem is the interface between the mechanical world of Vehicle Plant and electronic world of controllers. It includes all the actuators namely the engine including auxiliaries, clutch, transmission, differential and brake systems. The respective controller (ECU) requests sent in the form of electronic actuation signals (solenoid valve request, flip flops etc.) are processed by the corresponding actuators converting electronic input or request into mechanical output. The final output from this subsystem is the torque on to the wheels of Vehicle Plant. Each subsystem represents the detailed physical model of the corresponding motion actuators as shown in the figure 3.4.

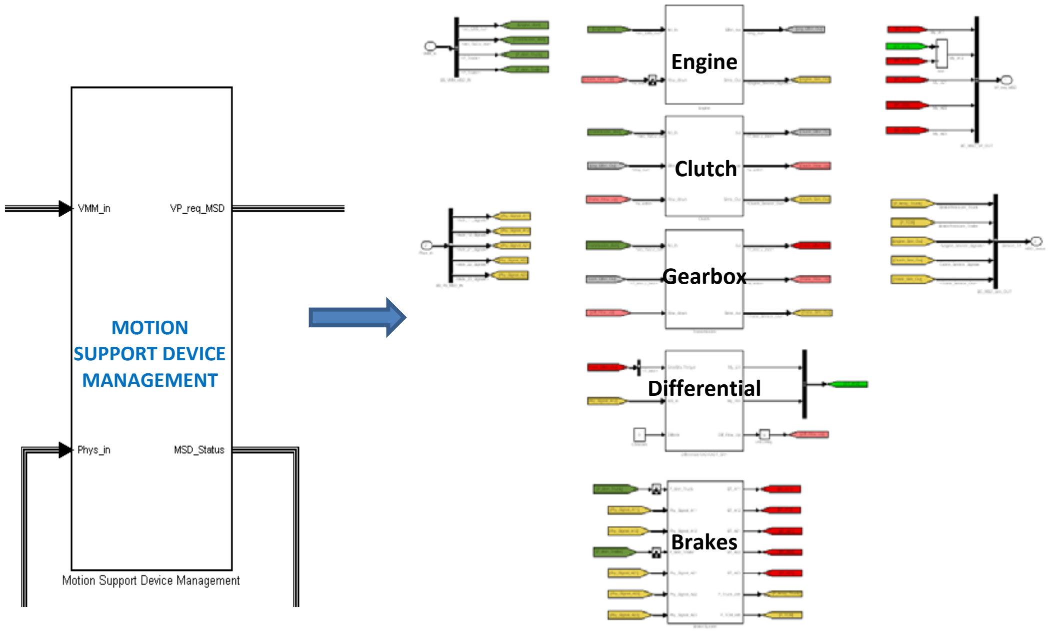


Figure 3.4-Motion Support Device Management subsystem

Inorder to ensure smooth transfer of power from the engine the power network is maintained as shown in figure 3.5, by sending the torque and inertia values down the from engine to differential and differential speeds back up to the engine. This subsystem also requires the feedback of the rotational speeds and accelerations of the wheels from the Vehicle Plant to ensure smooth transfer of power back to the wheels.

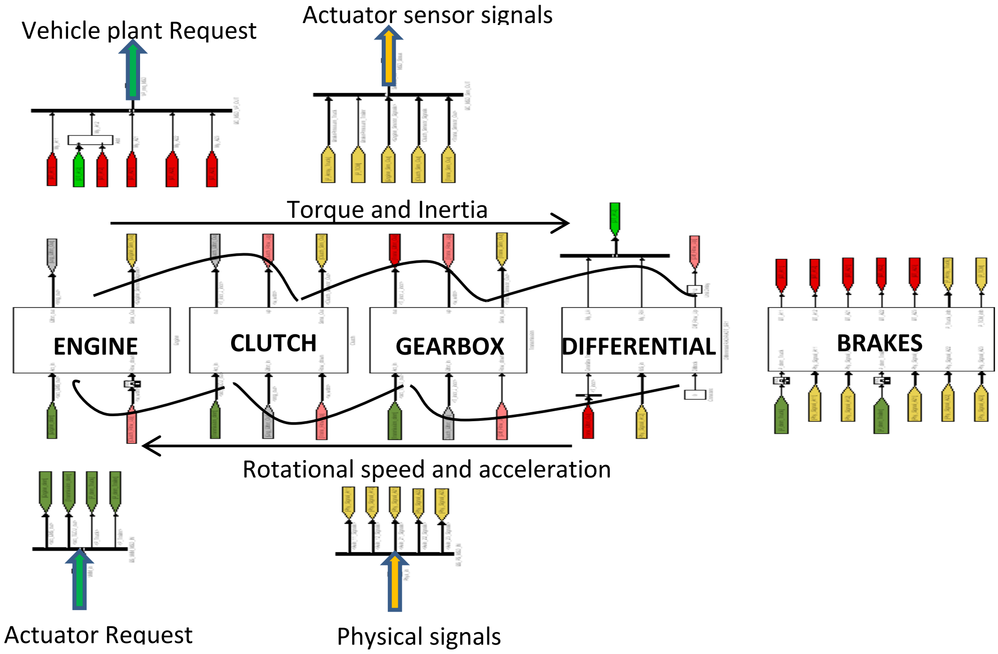


Figure 3.5-Motion Support Device Management structure

- Vehicle Plant: A 4X2 Tractor semitrailer template was the chosen from the VTM library and the parameters adapted to suit that of a test truck FH-713 used for winter test measurements as indicated in Appendix A. This subsystem receives torque requests from the Motion Support Device Management subsystems and steering input from the driver.

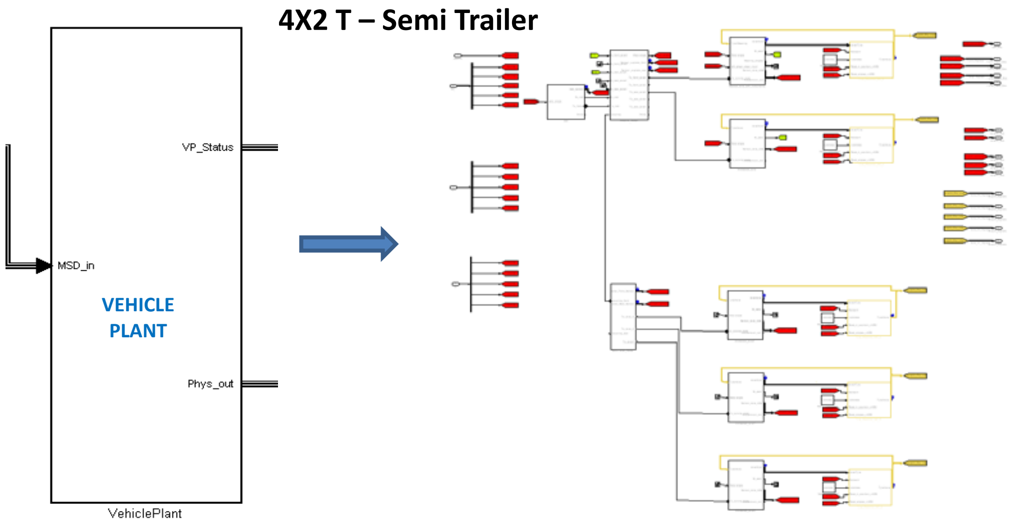


Figure 3.6- Vehicle plant subsystem

3.2 Verification method for simulation environment

The simulation environment is validated for integration, by verifying the results of the Software in Loop simulations with the EMS, TECU and EBS-7 software. For few test cases the results are also compared with the winter test measurement results in order to verify the accuracy of the simulation environment.

3.2.1 Model preparation and tuning

The integrated simulation environment is prepared for simulation by the modifying the parameters for the 4X2 Tractor semitrailer template from VTM library as per in Appendix A and feeding the parameters for the respective systems. The driver inputs of steering wheel position, accelerator pedal position, and brake pedal position are fed in according to the test cases with inclusion of measurement data for relevant tests. The peak friction co-efficient and the cornering stiffness scaling of each axle in the vehicle plant are tuned according the earlier study performed by Sundström and Laine [16]. Factors like variability of tyre friction co-efficient and ambient temperature are not included in the simulation environment. The parameters concerned with the EBS-7 software are modified based on the test cases using supplier provided application. A first order filter is added at the output of the transmission to handle the numerical instability and to have smooth transition of inertia at the output of the transmission.

3.2.2 Verification of EBS functions

In order to achieve reliable and uniform results from the simulation environment, all the EBS-7 functionalities are verified for truck specification as per FH-713, in Appendix A.

The EBS-7 software is verified for the following test cases:

3.2.2.1 Traction Control

- Even friction: This test is intended to verify traction control activation by observing the torque speed limit communication of the EBS-7 to the Engine Management System. By ramping up to full throttle (100%) on low friction conditions from standstill, the response of the vehicle is observed. In order to simulate the low friction conditions the longitudinal and lateral peak friction coefficients of the drive axle tire are scaled down by 0.38.
- Split friction: The split friction condition is modeled with the left side of the vehicle on the high friction side and right side of the vehicle on the low friction side ($\mu=0.38$). This situation of traction control functionality is verified by observing the brake pressures sent by EBS-7 on the left and the right drive wheels.

As there were no test results available for both the cases, simulation results were not validated.

3.2.2.2 Low friction straight line braking

The vehicle is driven with an initial speed of 60km/h and sudden brakes are applied to mimic the panic situation until the vehicle stops on a surface with friction co-efficient of 0.3. The intention of this test case is to verify the ABS functionality of the EBS-7 software by observing the brake pressures on each wheel of the tractor. The driver inputs to this simulation are taken from the winter test measurements and test case no 14 is selected from the list of measurements carried out in 2011.

3.2.2.3 Modified Sine with Dwell

This test method is performed to evaluate the effectiveness of the yaw stability control of the EBS-7 for a vehicle driven on a low friction surface (μ=0.3) with a defined longitudinal speed and amplitude of steering wheel input. The steering wheel input is in the form of a sine wave for the first half and continues with a dwell on the second phase to complete the test. The frequency of steer is between 0.2-0.5Hz and the dwell time is set to be in the range of 0.5-1s. The yaw stability factors obtained with reference to peak yaw rate and responsiveness factor from the lateral displacement of first axle of the tractor are subsequently evaluated and compared with the reference values. The test method is detailed in [12] and is a modified version according to heavy vehicle dynamics. The driver inputs are taken from measurements.

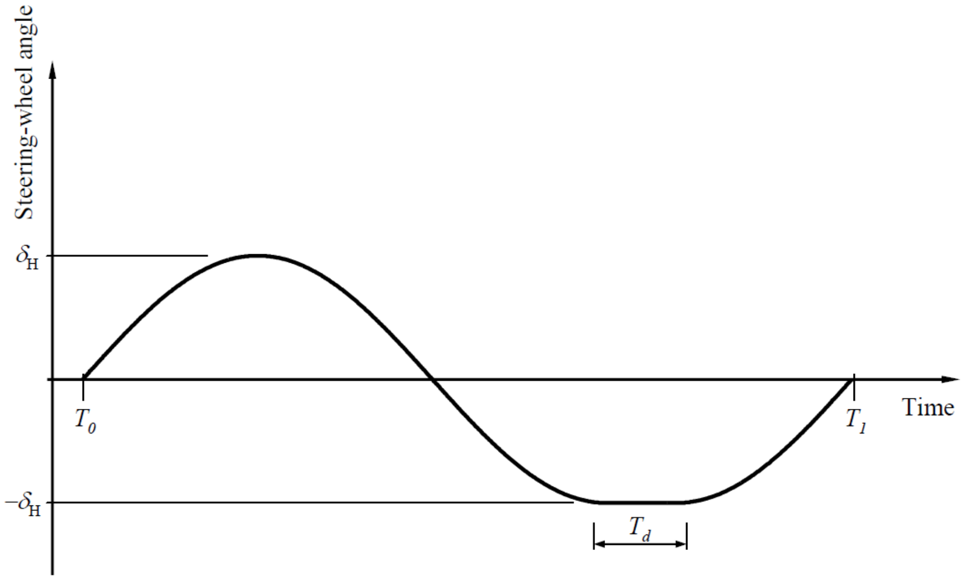


Figure 3.7- Steering Wheel Angle input for sine with dwell test

3.2.2.4 High Speed Closing Curve

This test verifies the roll over stability control of a vehicle on high friction surface and at a constant longitudinal velocity on a path with constantly increasing curvature. The yaw stability effects are also considered since they may also occur near threshold values. In this test the vehicle initially travels at a constant longitudinal speed of 60km/h and then ends with a circular curve. The transition from straight line to circular path produces a jerk and should be in the range of 1.2-1.5 m/s³. The final Steering Wheel Angle is calculated so as to produce a lateral acceleration 1.5 times the steady state threshold for a given curvature radius in Appendix B.2. The ramp from zero to final steering value determines the value of jerk. As vehicle reaches the steady state threshold for a given speed the roll over stability control function of EBS-7 should be activated to prevent the rolling situations. Steering Wheel Angle input is evaluated for the defined longitudinal speed of 60km/h and a steady state turning radius of 48m as shown in Appendix B.2. The detailed test method is described in the ISO standard - ISO/DIS 11026 for heavy commercial vehicles. This test is carried out with no measurements to which simulation results are correlated.

4 Verification and Discussion

4.1 Traction Control

4.1.1 Even friction

The input of accelerator pedal to full throttle position (100% - accelerator pedal position) results in gradual wheel speed increase. Around 7s the wheels starts to slip due to low friction resulting in abrupt increase of drive wheel speeds as in figure 4.1.2.

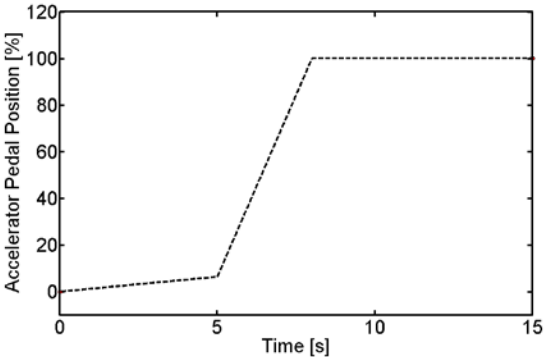


Figure 4.1.1-Driver input

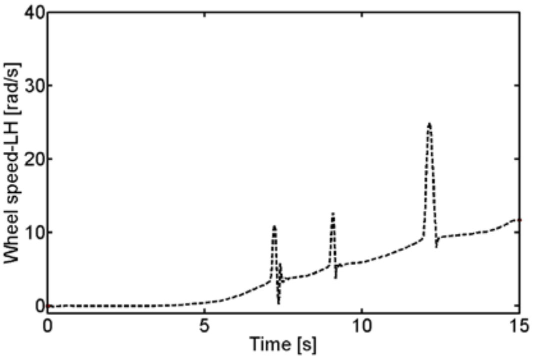


Figure 4.1.2- Tractor rear left wheel

On observation of the rate of increase in the wheel speeds and engine speed the EBS-7 activates the Traction Control function by limiting the engine torque output at 7.15s as in figure 4.1.3 which reduces the wheel speed. The first engine control mode flag highlighting a value 3 (Engine torque limitation) is an indication of Traction Control activation and is active until 8s which reduces the wheel speeds.

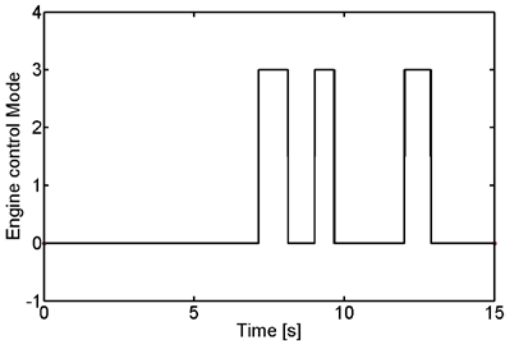


Figure 4.1.3- Torque limitation flag

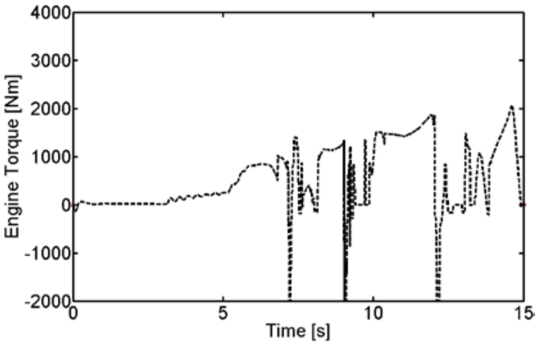


Figure 4.1.4-Engine torque-Actuator

After the torque limitation, wheels speeds settle to gradual increase (based on friction co-efficient) switching off the Traction Control functionality. A similar activation of Traction Control function is observed around 9s and 12s due to increase in wheel speeds resulting from wheel slip. The activation of the Traction Control helps in maintaining constant increase in the longitudinal vehicle velocity on a low friction surface without any major interruptions as shown in figure 4.1.5, which is tracked by the EBS-7 by observing the rate of wheel speed increase and other parameters.

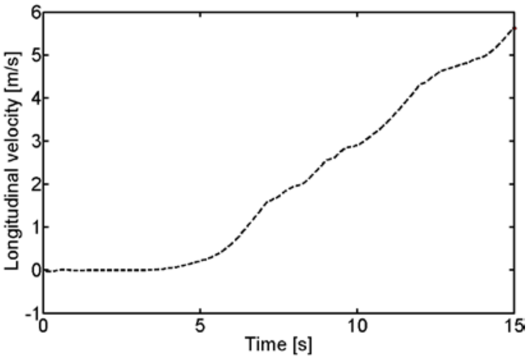


Figure 4.1.5-Longituinal velocity

An engineering judgement of the simulation give that the result is reasonable, but a firmer verification cannot be made due to lack of measurement data.

4.1.2 Split friction

The Traction Control function on a split friction case is verified in a similar manner as even friction with the same accelerator input from standstill as in figure 4.1.1. However on detecting a split friction condition brake pressures are requested depending on vehicle parameters and states by the Traction Control function.

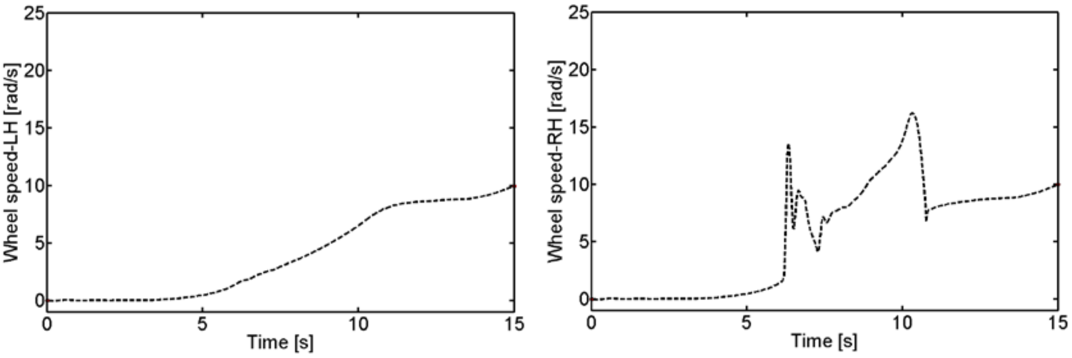
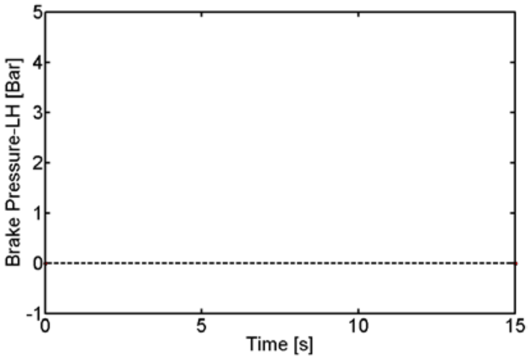


Figure 4.1.6- Tractor rear left wheel *Figure 4.1.7- Tractor rear right wheel*

Figure 4.1.6 and 4.1.7 indicate the wheel speeds on the high friction and low friction sides of the vehicle. The sudden increase of rotational wheel speed on the right hand side due to low surface friction activates the Traction Control function at 6.25s mitigating the situation by applying brake pressures on the side with higher wheel speed rate.

The activation of Traction Control by applying brake pressures results in gradual increase vehicle speed as in the figure 4.1.10, by detecting wheel slip and controlling the wheel speeds and other vehicle states.



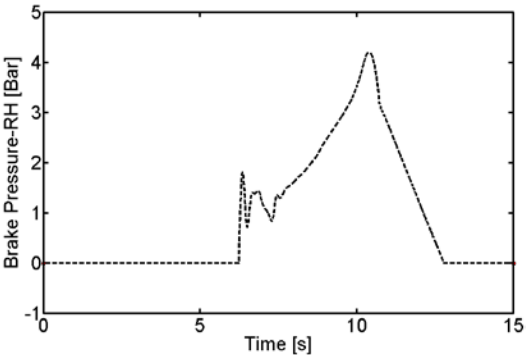


Figure 4.1.8-Tractor rear left wheel

Figure 4.1.9-Tractor rear right wheel

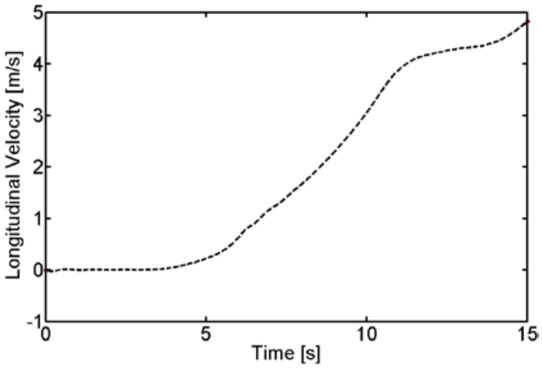


Figure 4.1.10-Longitudinal velocity

An engineering judgement of the simulation give that the result is reasonable, but the lack of measurements limits the verification of the instant and duration of brake application correlation by the EBS-7 software.

4.2 Low friction straight line braking

Straight line low friction braking investigates the ABS functionality of the EBS-7 software and is verified against the measurement data. The simulation is adjusted with same initial longitudinal velocity and brake input as per measurements without any input on the accelerator pedal position.

The longitudinal vehicle velocity and individual wheel speed characteristics are the primary indication of the ABS activation, which shows comparable tendencies between measurements and simulation results as in figure 4.2.2 and figure 4.2.3. The accuracy of simulated wheel speeds is not similar to the measurements possibly due to the absence of tyre and surface friction variability in the simulation environment, the adjustment of initial vehicle velocity and absence of correlated rolling resistance modelling as per measurements. Other factors like the tyre relaxation dynamics and phase difference in the driveline dynamics could reason for the overshoots and out of phase difference in the simulations.

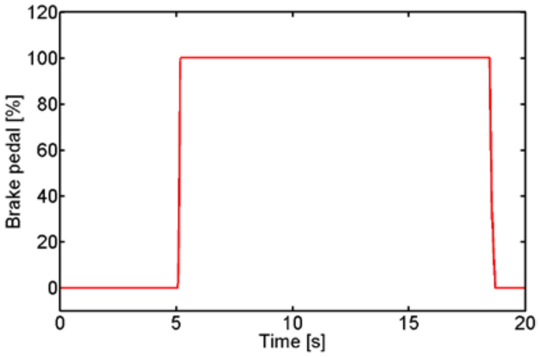
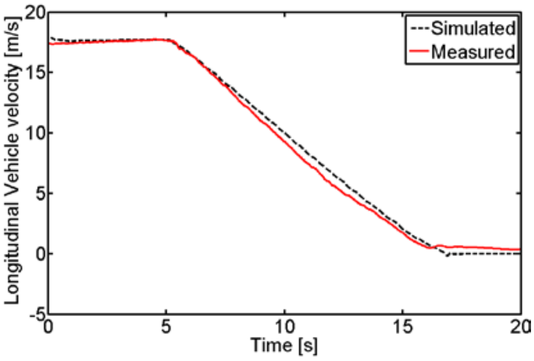


Figure 4.2.1-Driver input from measurement



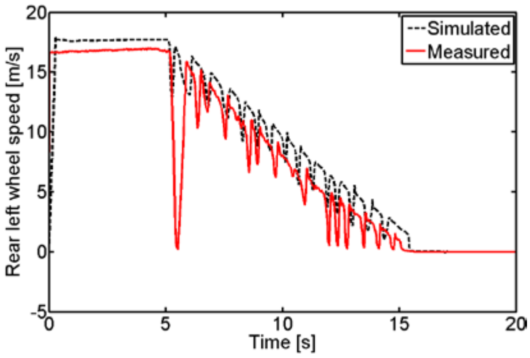
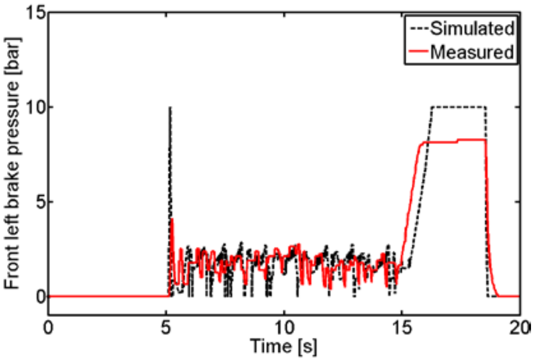


Figure 4.2.2-Longitudinal velocity *Figure 4.2.3-Tractor rear left wheel*

The plot of brake pressures in fig.4.2.4 and 4.2.5 indicates the brake actuation resulting due to the input of wheels speeds fed in to the EBS-7 and shows similar tendencies as per measurements. This pulse pattern of brake pressures are a clear indication of ABS functionality while driver input from the brake pedal is 100%.



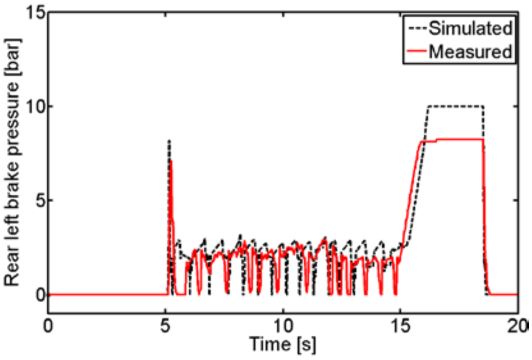


Figure 4.2.4-Tractor front left wheel

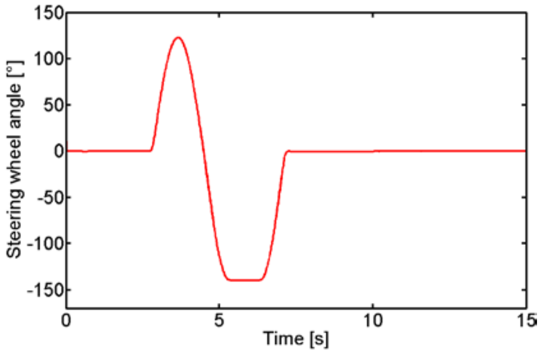
Figure 4.2.5-Tractor rear left wheel

The EBS-7 activates the ABS functionality by sending the required brake pressure depending on the tyre slip and reduces the vehicle stopping distance on low friction.

Comparison between measurement and simulation is judged as good enough for early Development Phase.

4.3 Modified Sine with Dwell (f=0.3Hz, Dwell=1.0s, 55kmph)

This lateral dynamics based test is primarily performed to induce the yaw instability in the vehicle motion by reaching lateral stability limits on the axles. The test case no: 79 winter test measurements is referred for the simulations. The input amplitude of 135deg for the steering wheel is directly taken from the measurements and accelerator pedal position is adjusted to match the longitudinal vehicle velocity before the start of the manoeuvre in the simulation.



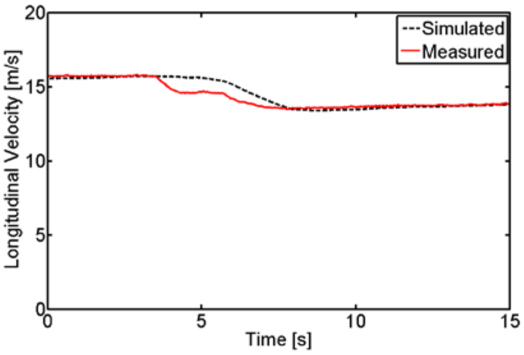


Figure 4.3.1-Measured Driver input-SWA

Figure 4.3.2-Longitudianl velocity

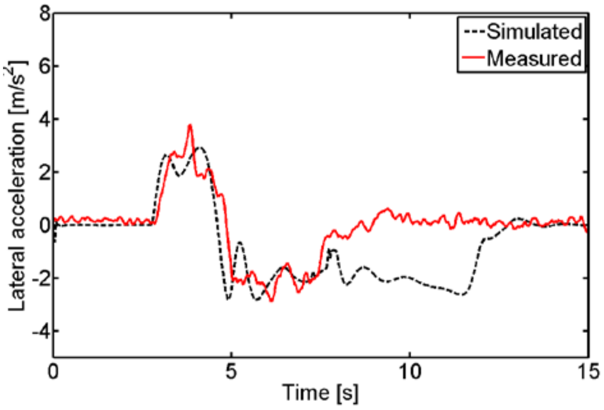
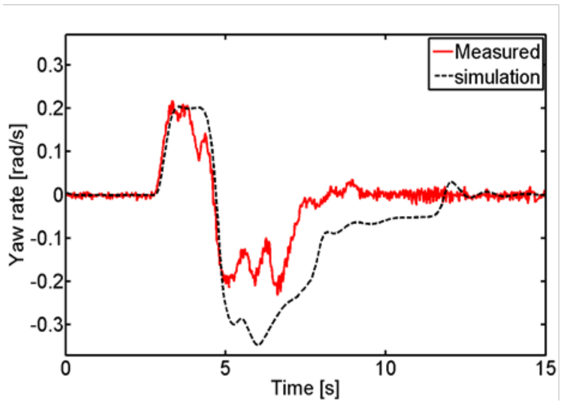


Figure 4.3.3-Tractor Lateral acceleration

The longitudinal velocity on low friction surface combined with frequency of steering input generates high lateral acceleration and induces yaw motion on the tractor and trailer when the axles start to slip as in figures 4.3.4 and 4.3.5. The yaw rate of the tractor follows the similar pattern as per measurements until the beginning of dwell, after which the yaw rate of measurements indicates a sign of understeer which is absent in the simulation output. Similarly there is delayed response of the trailer yaw rate in simulation and it becomes prominent after the dwell failing to converge quickly to a zero yaw rate and thereby indicating a different dynamic response to the measurement. The deviation of the tractor yaw rate from simulation in the later part of the manoeuvre indicates the sign of oversteer and could be identified by the ESC activation flags.



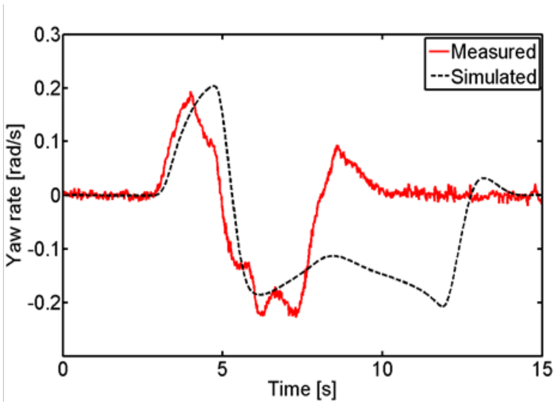
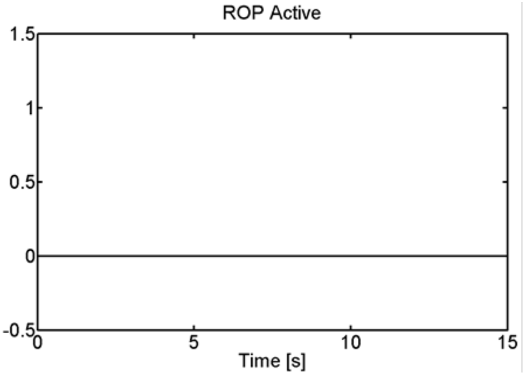


Figure 4.3.4-Tractor yaw rate *Figure 4.3.5-Trailer yaw rate*

The observation of the Roll Over Protection (ROP) and Yaw Control (YC) activation by the ESC function indicates a difference between the measurements and the simulations. The ROP flag from measurement data in figure 4.3.8 gets activated during the early part of the manoeuvre that is absent in the simulation, explaining the difference in the longitudinal velocity of the vehicle due to engine torque limitations in the early part as in figure 4.3.2. Inactivity of the ROP in the simulation environment can be attributed to the lower lateral acceleration as compared to the measurements, possibly reaching the threshold, which could be observed at around 3.5s. At the same instant the Yaw Control flag gets activated in the simulation environment as in figure 4.3.7, indicating tyre slip. Yaw Control activation is also seen later in the measurements corresponding to instant of the understeer behaviour seen in the yaw rate curve. Similarly two activation of Yaw Control is seen in the simulation plots in fig.4.3.7, during the later stages of the manoeuvre indicating the oversteer phenomenon.



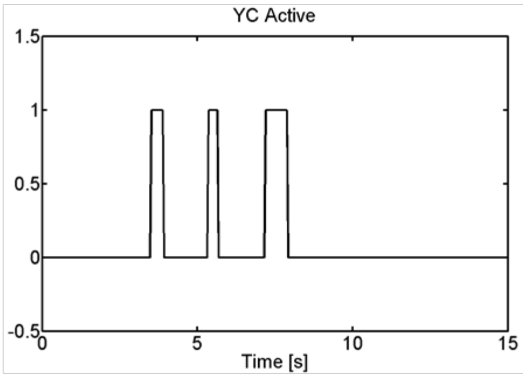
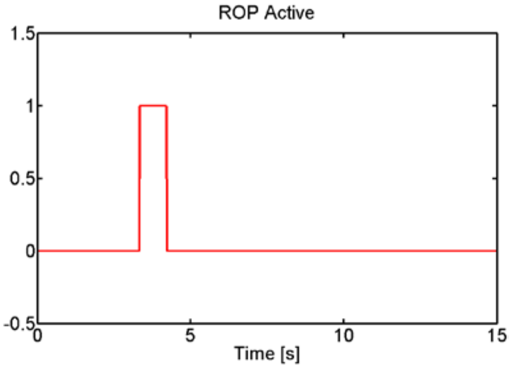


Figure 4.3.6- Simulation output *Figure 4.3.7- Simulation output*



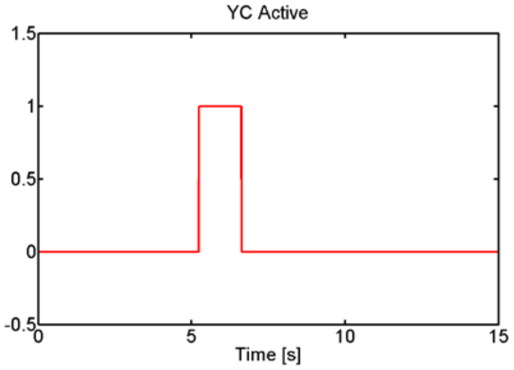


Figure 4.3.8- Measurement output *Figure 4.3.9- Measurement output*

The possible deviation of the yaw rate and lateral acceleration behaviour in the simulation environment could be explained by the factors like inaccuracy in tire road interaction modelling, driveline dynamics effects, sensor measurement deviances, eccentricity of lateral tyre relaxation dynamics and parameters in the EBS-7 software. The non-activation of ROP during the simulation compared to the activation of ROP in measurements is a clear indication of tyre road interaction which could be attributed to the tyre cornering stiffness differences between the simulation and measurements.

By observation of the yaw rate and the brake pressure actuation plots, the mode of ESC actuation, whether it is oversteer or understeer, could be detected. All other cases of changes in vehicle behaviour apart from brake actuation by the ESC may be possibly due to engine control.

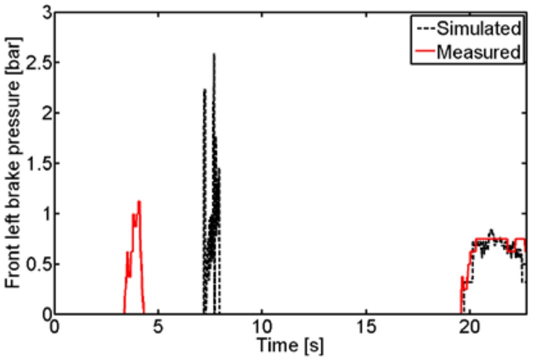


Figure 4.3.10- Tractor front left wheel

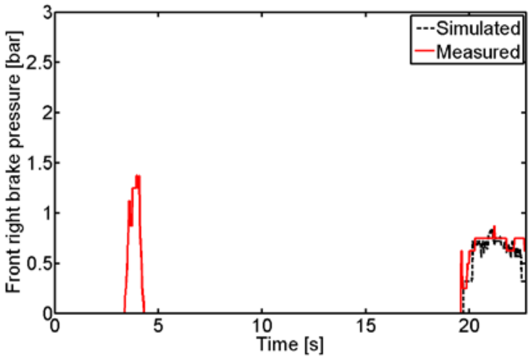


Figure 4.3.11- Tractor front right wheel

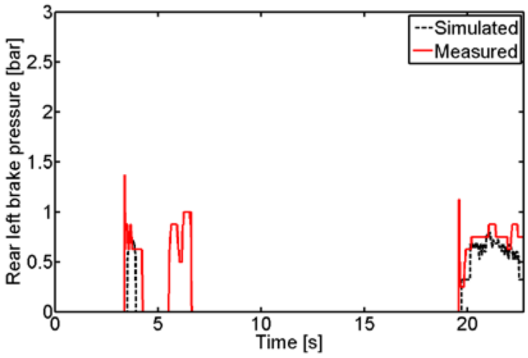


Figure 4.3.12- Tractor rear left wheel

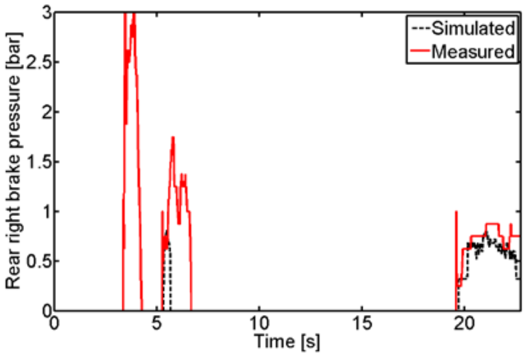


Figure 4.3.13- Tractor rear right wheel

The Comparison between measurement and simulation is judged as good enough for early loops of Development Phase.

4.4 High Speed Closing Curve

The roll stability control function of the EBS-7 is tested using the high speed closing curve test by evaluating the reduction in longitudinal speed, brake actuation and activated control flags. The accelerator pedal is depressed from standstill to achieve a speed of 60km/h and maintained around that speed before feeding the steering input at 35s to produce the required jerk of around 1.2 m/s³.

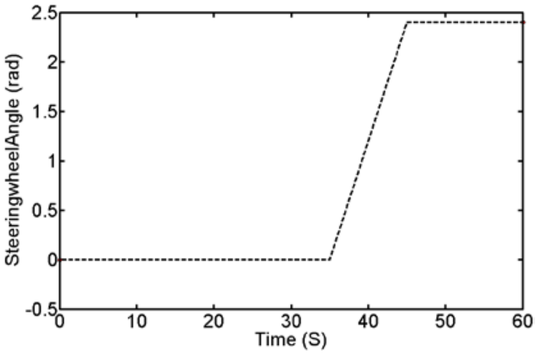


Figure 4.4.1-Driver input-SWA

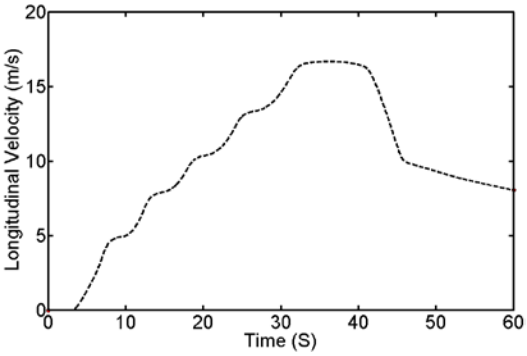


Figure 4.4.2-Longitudinal velocity

The plot in figure 4.4.3 indicates a proportional increase in lateral acceleration to the steering input and achieves a maximum value of 4.1 m/s².

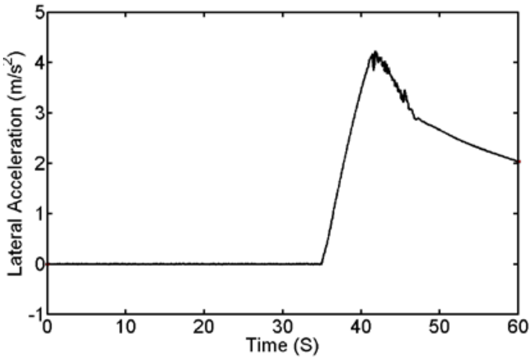


Figure 4.4.3-Tractor lateral acceleration

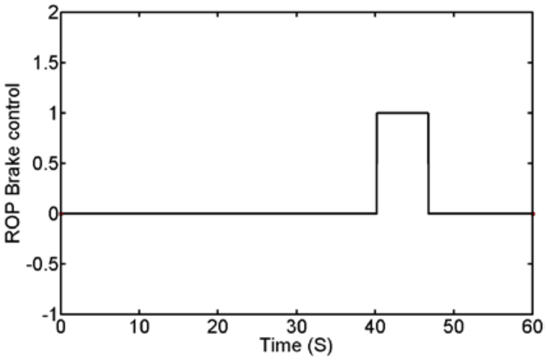


Figure 4.4.4-ROP activation flag

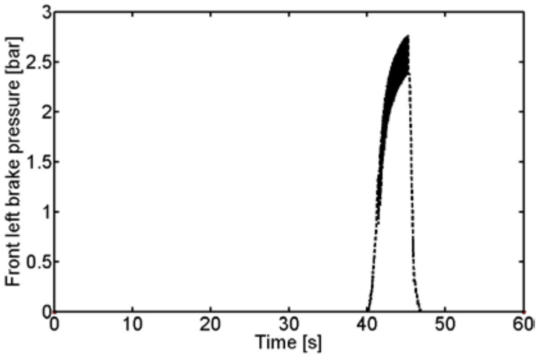


Figure 4.4.5-Tractor front left wheel

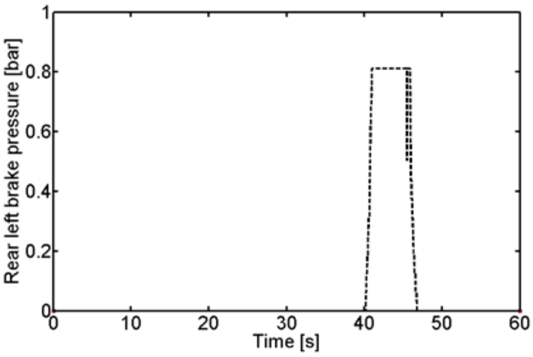


Figure 4.4.6- Tractor rear left wheel

As soon as the EBS-7 detects the lateral acceleration values higher than the steady state threshold in this case at 40s, the Roll Over Protection controller is activated shown by the ROP brake control flag and the corresponding brake actuation pressures. In this simulation case the yaw controller is also activated at the same instant as the yaw rate also reaches the threshold value as shown in figures 4.4.7 and 4.4.8.

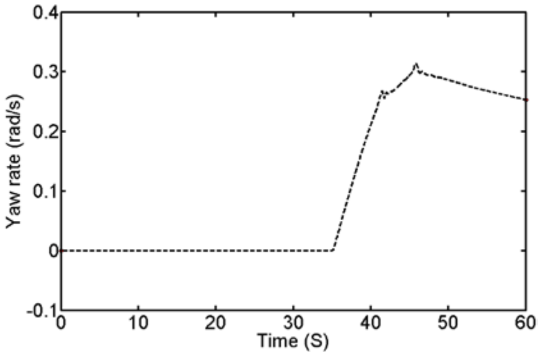


Figure 4.4.7-Tractor yaw rate

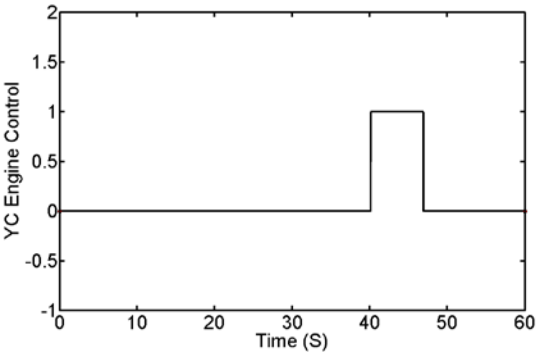


Figure 4.4.8-Yaw control activation flag

Since the ROP controller is regulating the brake actuation and the yaw controller takes control of the engine by sending the torque limitation requests.

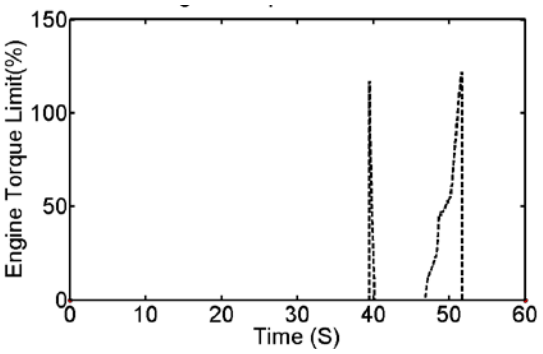


Figure 4.4.9-Engine torque limitation

The second torque limitation in figure 4.4.9 is purely from yaw controller which demands engine torque limitation before activating the ESC and diffuses the critical situation by reducing the speed inorder to avoid lateral instability. The reference to the results indicate a co-ordinated action by the EBS-7 and hence the result of a reduced longitudinal vehicle velocity.

An engineering judgement of the simulation give that the result is reasonable, but a firmer verification cannot be made due to lack of measurement data.

5 Conclusion

An integrated simulation environment covering the entire range of heavy commercial vehicles, that has capability to support development of active safety functions and verify the EBS-7 software using Software in Loop was the requisite from this thesis work.

The reference to earlier studies and brainstorming sessions, directed to simulation architecture with separated controllers and actuators. This network of controllers referred as Traffic Situation and Vehicle Motion Management indicate the capability to manage the vehicle motion as per the requirement of the function and add traffic situation capabilities to receive feedback from the traffic environment. Such a network provides the opportunity to develop new functions by establishing a communication structure as per the function requirement and using appropriate controllers. Automation of the signal generation using the .dbc files, which are revision controlled also supports in achieving the aim of quick development and avoiding manual signal generation and thereby reducing errors. A similar approach is used for the actuator systems giving the capability to use different models of variants representing different systems and evaluate the response for development of new systems. These separated controllers and actuators also simplify the representation of their physical features enabling them to operate at different processing rates to mimic the reality. The above indicated advantages were the main decision points for the structure of the simulation environment.

The results of simulation also qualify the verification environment to be used as a tool for the verification of the simple EBS-7 functions and support development of integrated active safety functions. This is further supported by acceptable degree of correlation with the measurements obtained from winter tests. Observation of the tendencies from the results also identify that the EBS software is functioning as per measurements although not accurate, giving a good base for verifying the EBS-7 software’s for simple functions. The deviation from the measurements could be reasoned majorly due to the lack of accuracy in the physical models of actuator systems, absence of variable environmental conditions and variation in modelling the communication protocols between the controllers. Further the use of the light versions of engine management and transmission management software within the simulations and the difference between the parameters used in simulation and those in the measurement vehicle affect the nature of the results and accuracy. However appropriate tuning of the parameters, gives the required results indicating that there is no major change that needs to be performed on the architecture. Additionally the influence of bugs in the software is also a factor which should not be disregarded as they significantly affects the response expected. The feeding of the software related parameters needs to be performed with utmost importance as they mainly affect the functionality.

Hence it becomes very critical to understand and collectively consider the influence of all these effects on the vehicle behaviour as they have significant role to play in the development of integrated active safety functions and driver assistance features.

6 Future work

The following features and development is necessary on the simulation environment to achieve the accuracy and perform as per the functional requirement:

- Extended automation to cover the entire TEA2+ architecture used in Volvo trucks. In the current work only the backbone 1 (SAE J1939 bus) and portions of the other network concerned for the activation of the EBS-7 were automated.
- Inclusion of detailed communication protocol features like operating rates, cycle time of messages and signals needs to be encompassed for the accuracy and processing of the softwares.
- Integrating the production softwares used for the EMS and TECU to have predictable and reliable output from the actuators. The light versions of softwares used in the present work limit the verification for the brake blending and drag torque control functionalities. These two functions are important to verify as they represent the simplest integrated control and coordination of actuators namely engine and the brake.
- Extended verification of the simulation environment by verifying a wide range of test cases is necessary, to include the influence of driveline dynamics. Additionally the tire road interaction was validated only for few test cases and more work needs to be done on this.
- Automated parameterization would be desirable to avoid manual errors of feeding the parameters to the software. This should also be co-ordinated with corresponding automation of physical models.
- Include noises in the feedback signals to mimic the situations as in real world scenarios and signal processing.
- In order to verify functions which use environment sensors, the ECU(s) connected to environment sensing has to be represented. This can be done in different ways, from simple "replay" of logged signals from environment sensing to extending the vehicle model to include also other objects or integrating with other tools.

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A Appendix: Test truck specifications

Vehicle combination name	Tractor 4x2 plus 3-axle semitrailer- FH713
Tyres on tractor	Michelin M+S 315/70R22.5
Tyres on trailer	Summer 385/65R22.5

Axle	**Position [m]**	**Left wheel [kg]**	**Right wheel [kg]**	**Total axle load [kg]**
Axle1	0	3320	3200	6520
Axle2	3.58	4720	4760	9480
Axle3	9.1	2680	2800	5480
Axle4	10.40	2780	2600	5380
Axle5	11.75	2680	2740	5420

Table A.1- Truck specification used for winter test measurement, 2011

B Appendix: Simulation Analysis and Results

The additional calculation and results from the simulations are indicated in this section.

B.1 Traction Control

B.1.1 Even Friction

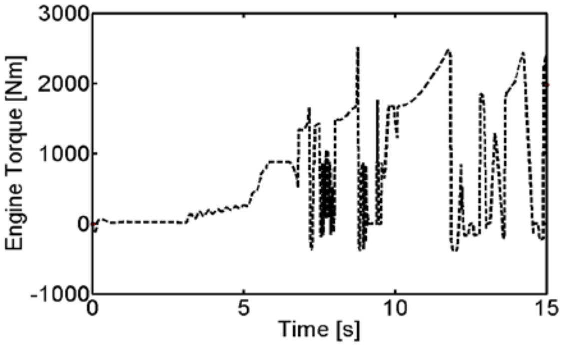

Figure B.1.1.1-Engine Torque- CAN

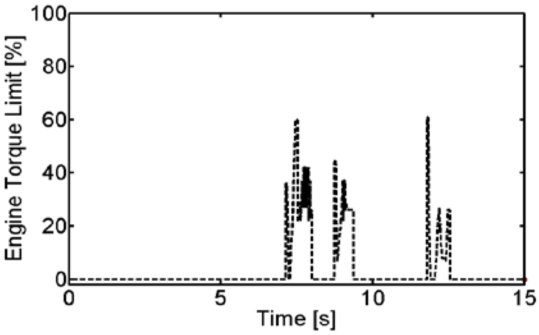

Figure B.1.1.2-Engine Torque Limit

The figure B.1.1.1 indicates the engine torque values sent by the engine controller over CAN network. Figure B.1.1.2 refers to the engine torque limitation sent by the EBS-7 over CAN to the EMS.

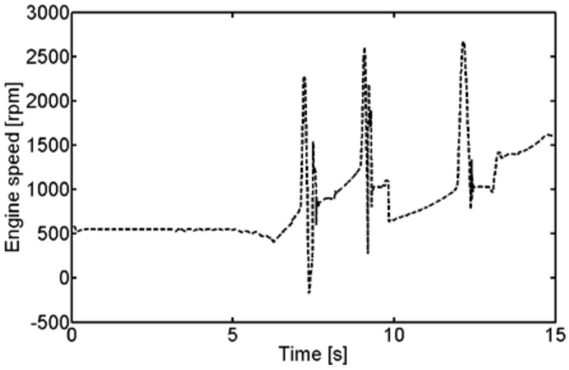

Figure B.1.1.3-Engine speed- Actuator

B.1.2 Split Friction

The engine statuses from the actuator and over CAN from controller are indicated in the figures B.1.2.1, B.1.2.2 and B.1.2.3.

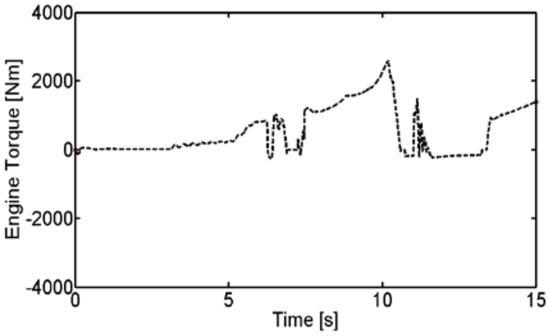

Figure B.1.2.1-Engine Torque- Actuator

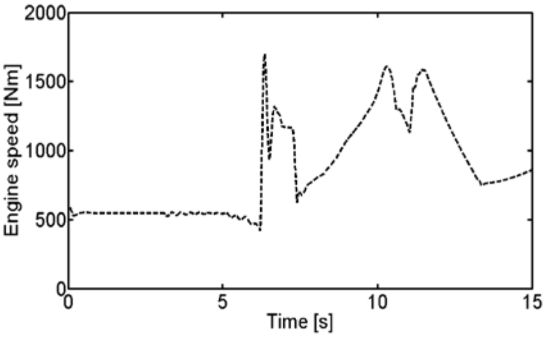

Figure B.1.2.2-Engine speed- Actuator

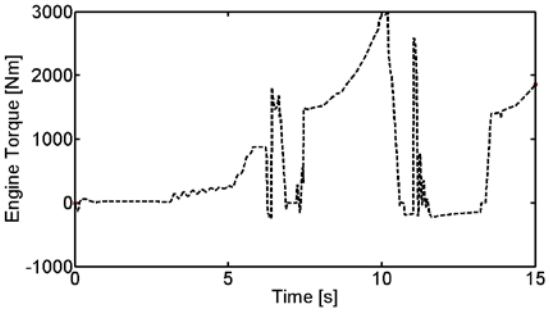

Figure B.1.2.3-Engine Torque- CAN

B.2 Low friction straight line braking

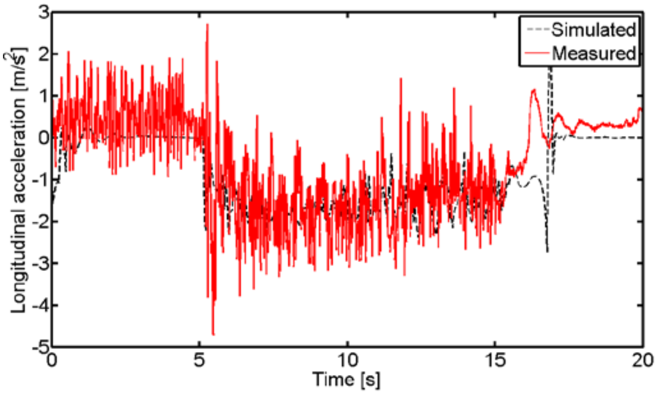

Figure B.2.1- Tractor longitudinal acceleration

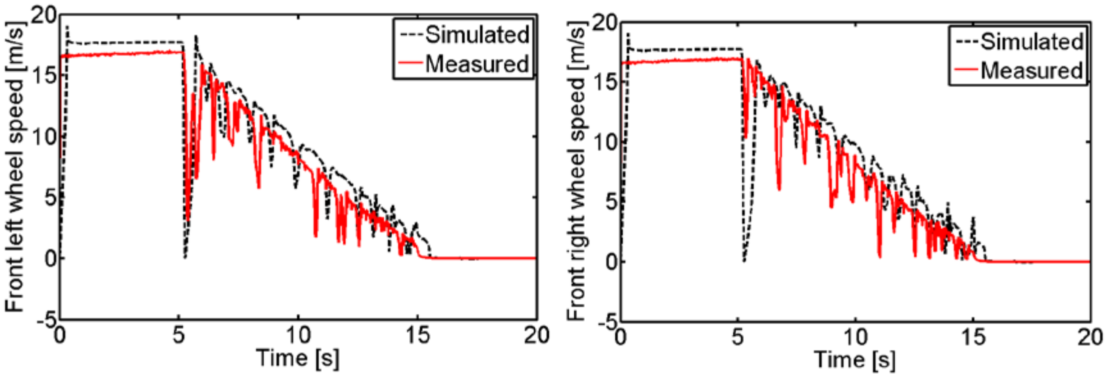

Figure B.2.2- Tractor front left wheel *Figure B.2.3- Tractor front right wheel*

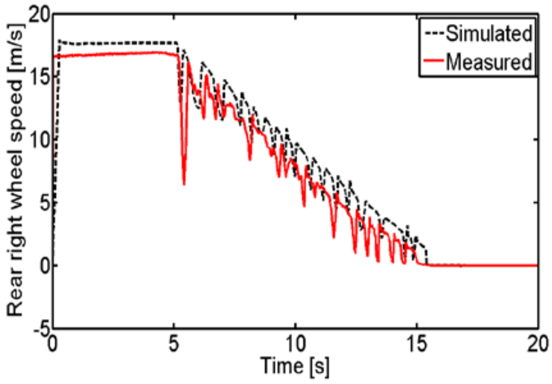

Figure B.2.4- Tractor rear right wheel

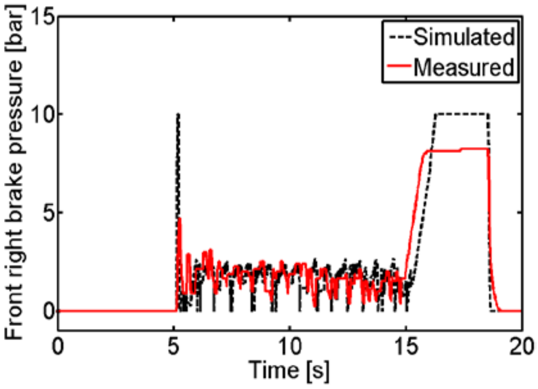

Figure B.2.5-Tractor front right wheel

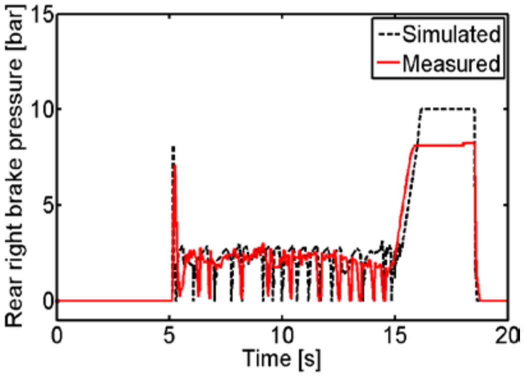

Figure B.2.6- Tractor rear right wheel

B.3 Modified Sine with Dwell

Figures B.3.1 and B.3.2 indicate the engine torque status from the actuator and the engine torque limit sent by the EBS-7 over CAN for the test case no: 79. The engine torque limitation is requested by the EBS-7 only after the dwell part of the steering when oversteer is observed.

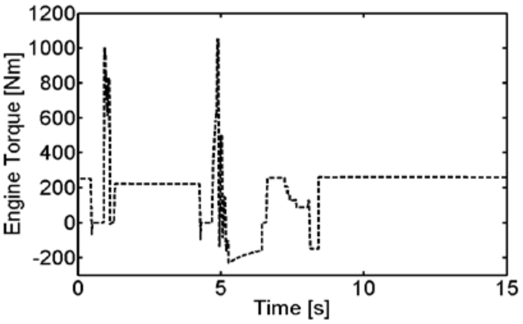

Figure B.3.1-Engine Torque-Actuator

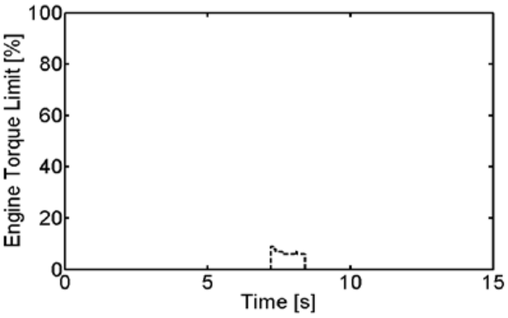

Figure B.3.2-Engine Torque limit-CAN

The table B.3.1 indicates the simulation results for the steering wheel inputs swept from 55deg to 135deg as per the Modified Sine with Dwell test [12] and is carried out for the ESC on and off conditions. The tire road friction characteristics were tuned to be same as that of the 2011 winter test conditions in [16] and the initial steering wheel input was calculated based on the friction level for steady state turning as per [12] and a tuning factor.

The yaw stability factors and articulation angles for the modified sine with dwell test are the criteria which determine the yaw stability of the vehicle combination on a low friction surface for a particular steering wheel angle input. The values highlighted in red indicate the cases in which the tractor trailer combination failed the test. Observation of the values for the yaw stability factors for both tractor and trailer indicate that for the ESC-off conditions the vehicle combination does meet the yaw stability requirement for steering wheel angles above 115deg with the vehicle combination jack knifing for the steering wheel angles of 120deg and higher. For the ESC-on case the yaw stability factor does not meet the criteria for a steering wheel angle input of 135deg which indicates the limitation of the ESC function and an improvement in yaw stability of 20deg compared to the ESC-off case.

Table B.3.1- Results from the Modified sine with dwell test simulations

SWA	**ESP Off=1 On=2**	**Maximum Yaw velocity**	**Response criteria**	**Final yaw angle**	**Yaw Stability Factor (Tractor unit)**		**Yaw Stability Factor (Trailer unit)**		**Max art. Angle**
δ_H **[deg]**		$\left\lvert\dot{\psi}_{1,peak}\right\rvert$ **[rad/s]**	$d_y\left(\frac{0.5}{f}+T_0\right) > 1.5$ **[m]**	$\psi_{1,final}(6+T_1) < 0$ **[rad]**	$\frac{\lvert\dot{\psi}_1(1+T_1)\rvert}{\lvert\dot{\psi}_{1,peak}\rvert} < 0.7$	$\frac{\lvert\dot{\psi}_1(2+T_1)\rvert}{\lvert\dot{\psi}_{1,peak}\rvert} < 0.35$	$\frac{\lvert\dot{\psi}_2(1+T_2)\rvert}{\lvert\dot{\psi}_{1,peak}\rvert} < 0.9$	$\frac{\lvert\dot{\psi}_2(2+T_2)\rvert}{\lvert\dot{\psi}_{1,peak}\rvert} < 0.45$	**[deg]**
55	1	0,1440	1,6299	-0,1399	0,0226	0,0002	0,0265	0,0005	4,23
60	1	0,1569	1,7638	-0,1509	0,0221	0,0004	0,0284	0,0004	4,66
65	1	0,1696	1,8938	-0,1611	0,0221	0,0009	0,0314	0,0002	5,10
70	1	0,1818	2,0190	-0,1703	0,0228	0,0016	0,0363	0,0001	5,56
75	1	0,1932	2,1384	-0,1782	0,0246	0,0023	0,0439	9,11E-05	6,03
80	1	0,2037	2,2509	-0,1848	0,0267	0,0028	0,0554	7,85E-05	6,51
85	1	0,2131	2,3554	-0,1906	0,0277	0,0022	0,0713	9E-05	7,01
90	1	0,2215	2,4514	-0,1966	0,0252	0,0003	0,0913	0,0001	7,52
95	1	0,2293	2,5383	-0,2050	0,0173	0,0050	0,1140	0,0002	8,07
100	1	0,2367	2,6162	-0,2195	0,0042	0,0107	0,1367	0,0014	8,68
105	1	0,2443	2,6852	-0,2461	0,0012	0,0111	0,1506	0,0067	9,37
110	1	0,2518	2,7460	-0,2943	0,0619	0,0090	0,0976	0,0255	10,12
115	1	0,2589	2,7993	-0,3814	0,1260	0,0084	0,3282	0,0761	10,87
120	1	0,2649	2,8461	-0,5813	0,7088	0,0959	0,8209	0,3012	11,55

125	1	0,2694	2,8869	-2,0183	0,8182	0,9724	0,7442	0,7027	>90
130	1	0,2723	2,9227	-2,0390	0,8274	0,9996	0,7212	0,6722	>90
135	1	0,2733	2,9540	-2,0246	0,8059	0,9789	0,7254	0,6827	>90
55	2	0,1440	1,6299	-0,1399	0,0226	0,0002	0,0265	0,0005	4,23
60	2	0,1569	1,7638	-0,1509	0,0221	0,0004	0,0284	0,0004	4,66
65	2	0,1696	1,8938	-0,1611	0,0221	0,0009	0,0314	0,0002	5,10
70	2	0,1818	2,0190	-0,1703	0,0228	0,0016	0,0363	0,0001	5,56
75	2	0,1932	2,1384	-0,1782	0,0246	0,0023	0,0439	9,11E-05	6,03
80	2	0,2037	2,2509	-0,1848	0,0267	0,0028	0,0554	7,85E-05	6,51
85	2	0,2131	2,3554	-0,1906	0,0277	0,0022	0,0713	9E-05	7,01
90	2	0,2215	2,4514	-0,1966	0,0252	0,0003	0,0913	0,0001	7,52
95	2	0,2293	2,5383	-0,2050	0,0173	0,0050	0,1140	0,0002	8,07
100	2	0,2367	2,6162	-0,2195	0,0042	0,0107	0,1367	0,0014	8,68
105	2	0,2443	2,6852	-0,2461	0,0012	0,0111	0,1506	0,0067	9,37
110	2	0,2518	2,7460	-0,2943	0,0619	0,0090	0,0976	0,0255	10,12
115	2	0,2589	2,7993	-0,3669	0,0225	6,37E-06	0,2414	0,0663	10,87
120	2	0,2649	2,8461	-0,4210	0,3805	0,0215	0,6171	0,0749	11,55
125	2	0,2701	2,8877	-0,4702	0,4410	0,0343	0,8111	0,0205	12,18
130	2	0,2795	2,9291	-0,5243	0,2988	0,0050	0,7269	0,2529	14,20
135	2	0,2908	2,9652	-0,5869	0,2708	0,3186	0,6460	0,6910	16,40

The plots in figure B.3.3-B.3.5 gives an indication of the vehicle agility and behaviour in addition to the effectiveness of the Electronic Stability Control function for different steering wheel inputs based on the Modified Sine with Dwell test simulations. The ranges of results are based on simulations in table B.3.1.

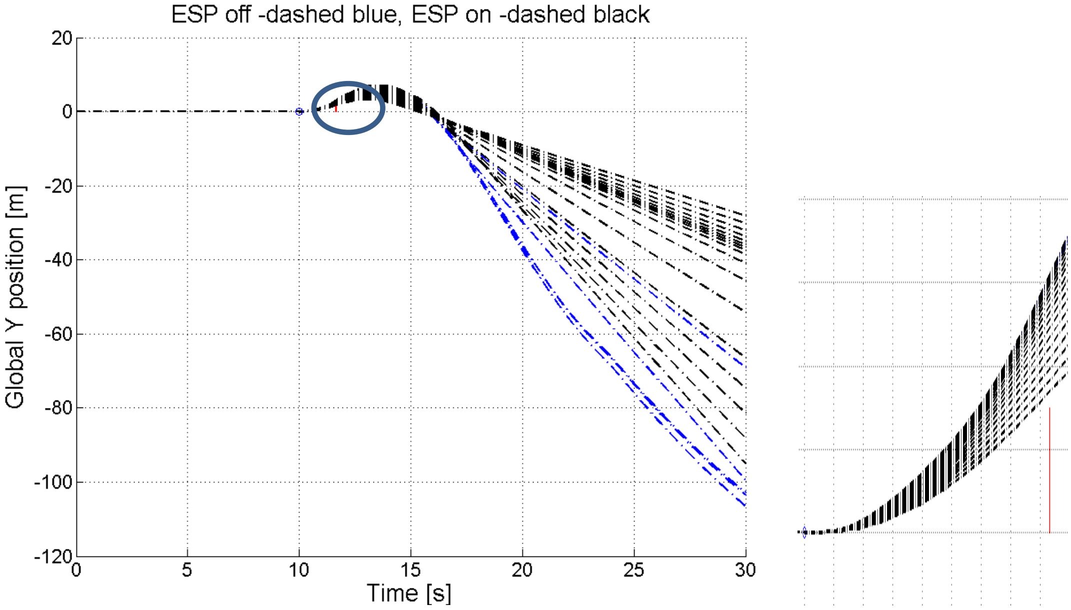

Figure B.3.3- Responsiveness of the tractor unit for different steering inputs

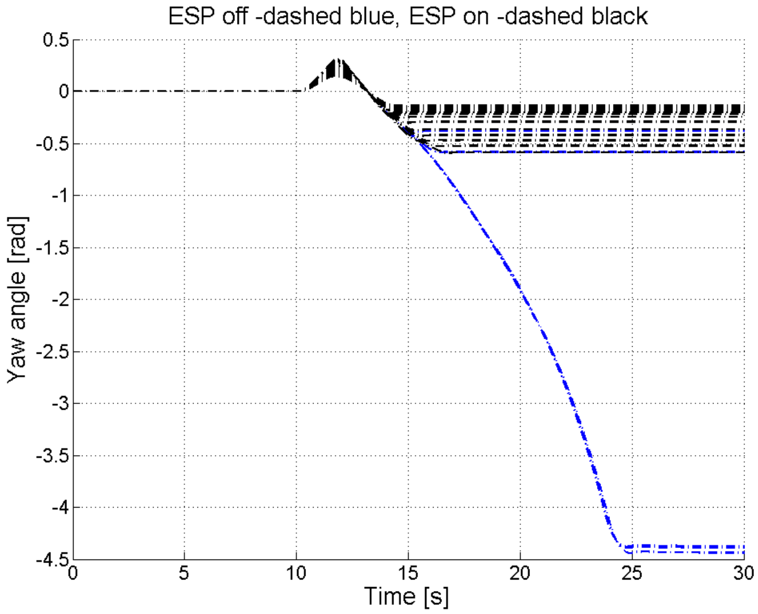

Figure B.3.4- Yaw angle of the tractor unit for different steering inputs

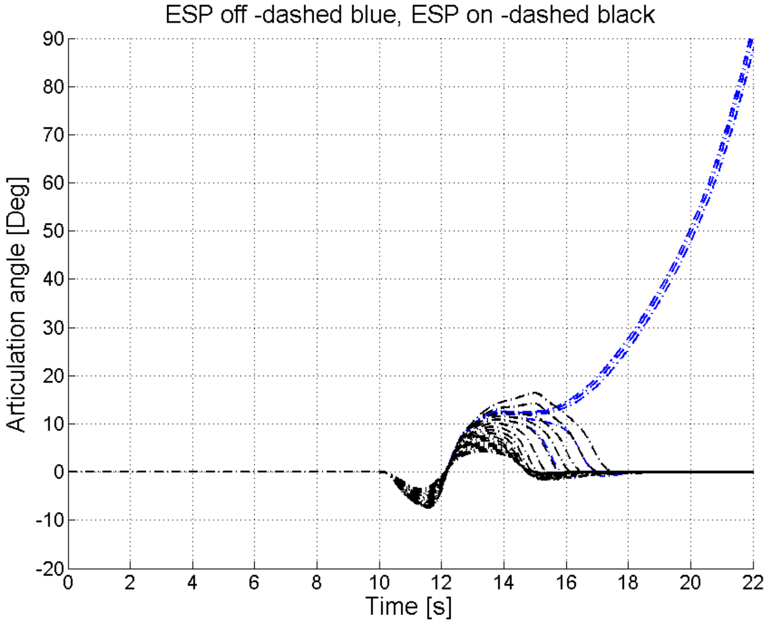

Figure B.3.5- Articulation angle between the tractor and trailer unit

The figures B.3.6-B.3.14 indicate the yaw rate response of the tractor and trailer units for the ESC on and off conditions.

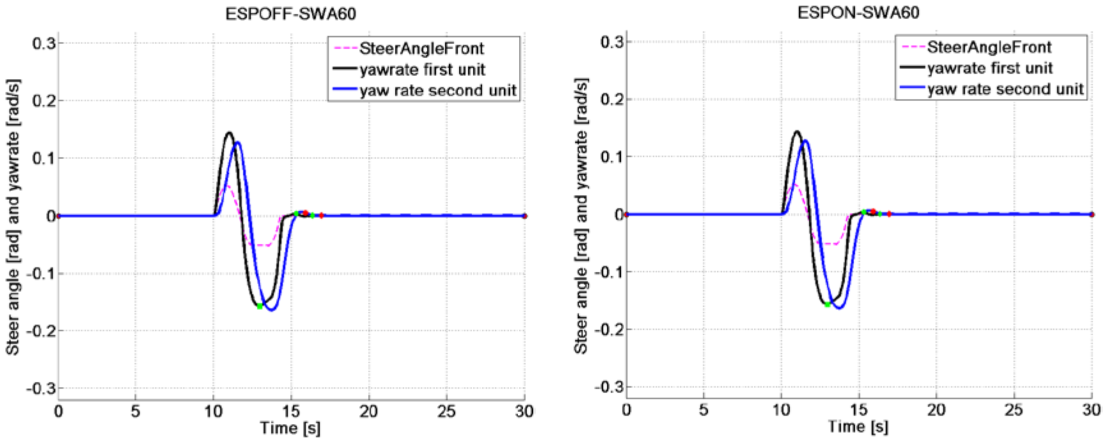

Figure B.3.6- Yaw rate response, SWA=60 deg, ESC off/on

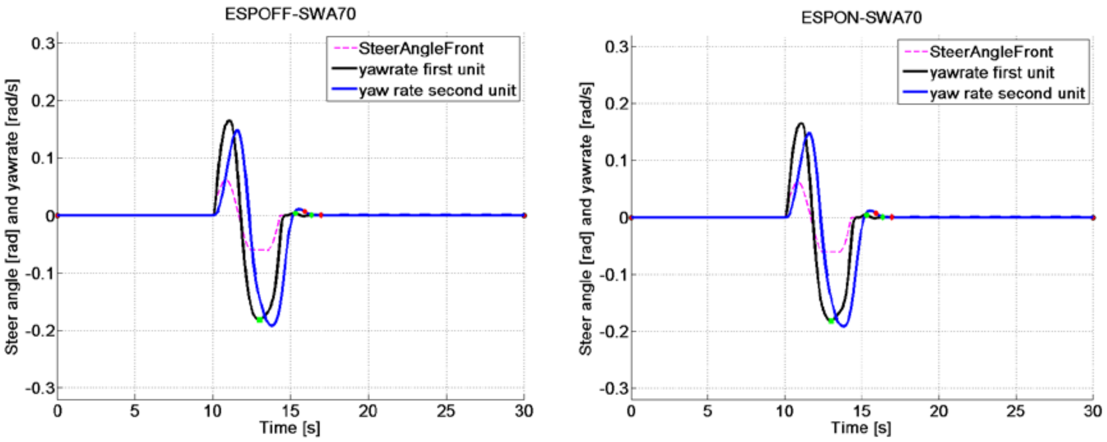

Figure B.3.7- Yaw rate response, SWA=70 deg, ESC off/on

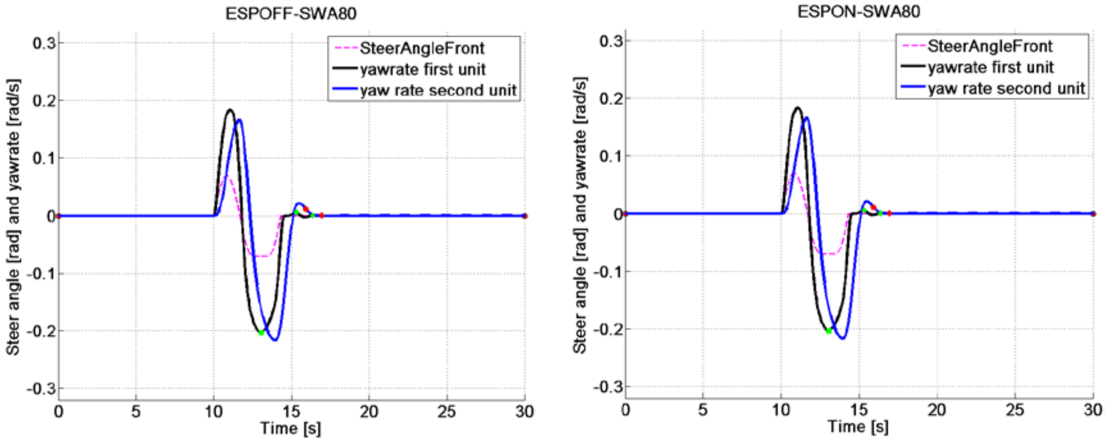

Figure B.3.8- Yaw rate response, SWA=80 deg, ESC off/on

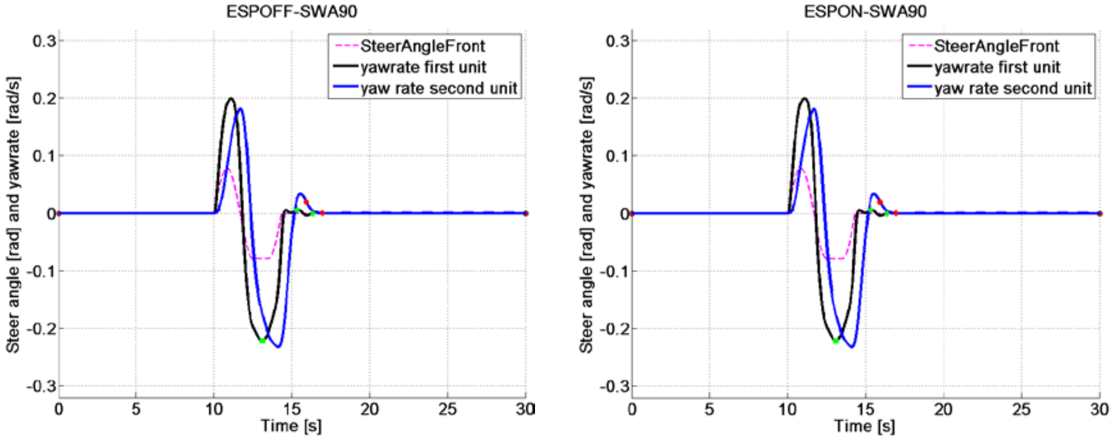

Figure B.3.9- Yaw rate response, SWA=90 deg, ESC off/on

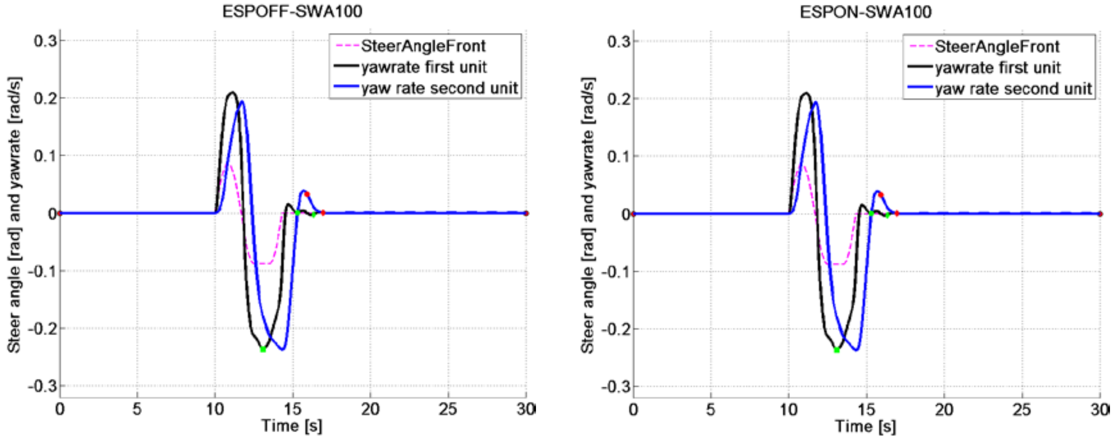

Figure B.3.10- Yaw rate response, SWA=100 deg, ESC off/on

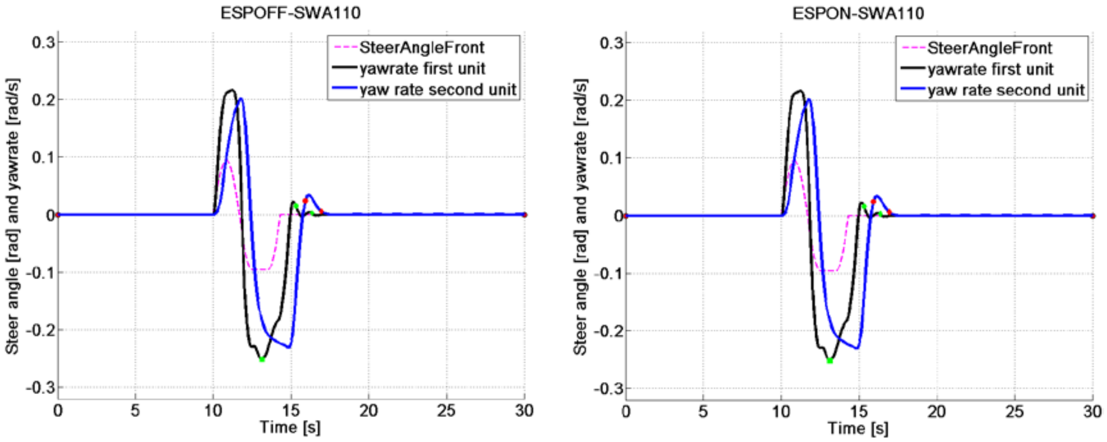

Figure B.3.11- Yaw rate response, SWA=110 deg, ESC ESC off/on

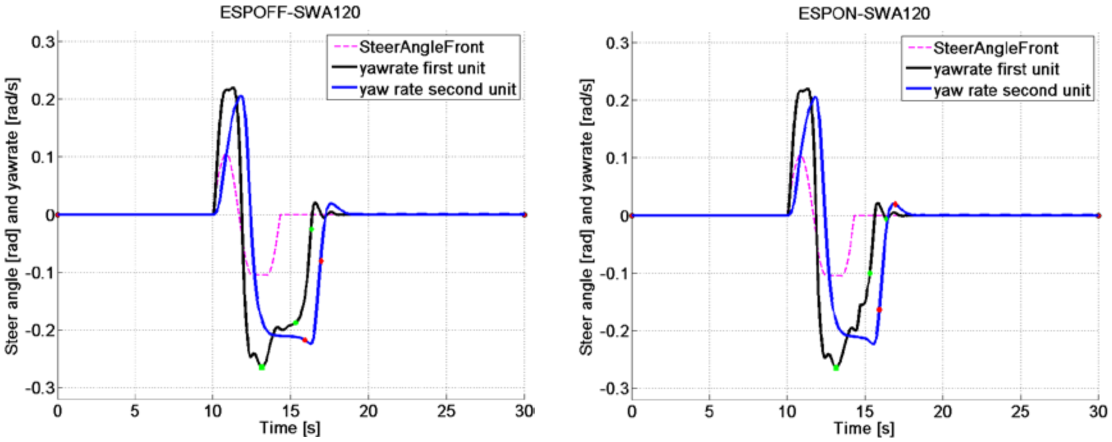

Figure B.3.12- Yaw rate response, SWA=120 deg, ESC off/on

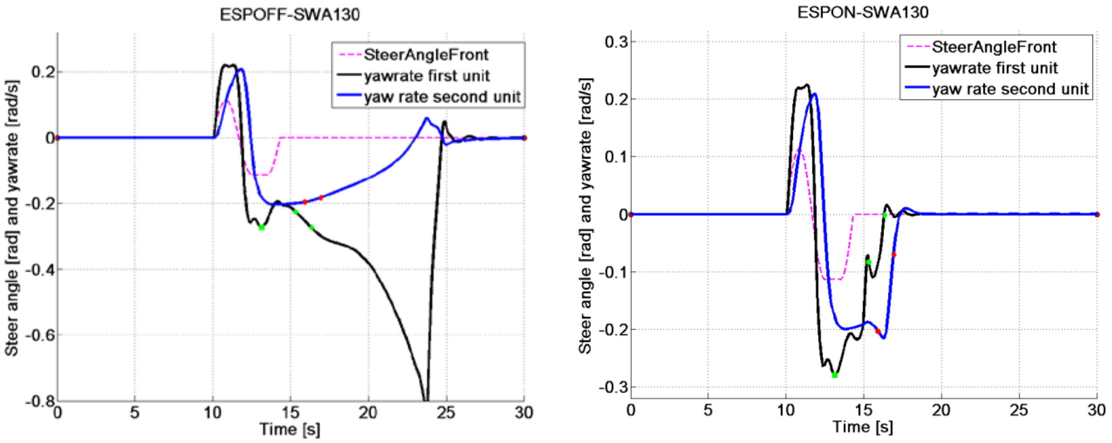

Figure B.3.13- Yaw rate response, SWA=130 deg, ESC off/on

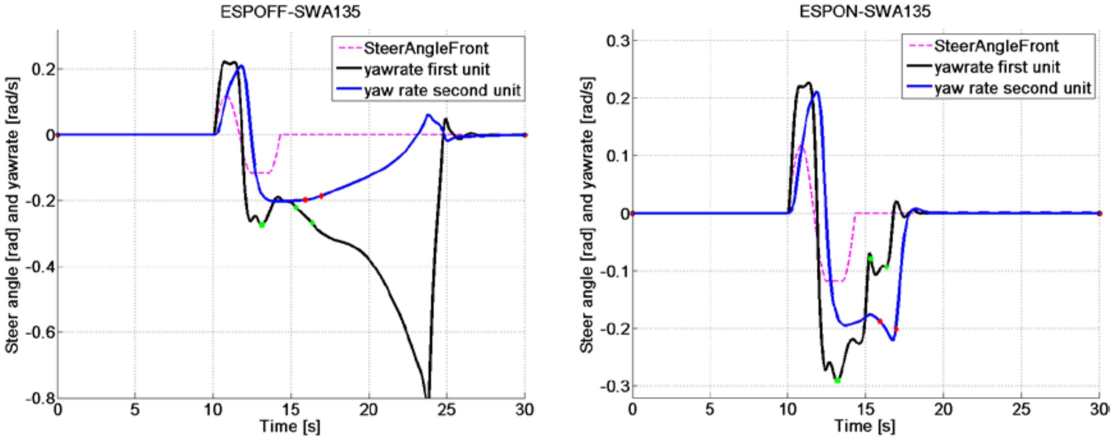

Figure B.3.14- Yaw rate response, SWA=135 deg, ESC off/on

B.4 High Speed Closing Curve

B.4.1 Steering Wheel Angle calculation

The input of Steering Wheel Angle required for the manoeuvre is calculated and by considering certain assumptions.

As the final requirement of the test is to achieve a closing curve, the steering angle required for this final steady state condition can be assumed. Reference to [17] indicates that the roll over threshold of a heavy truck with a high centre of gravity is nearly 0.4g of lateral acceleration. Based on the ISO/DIS 11026 standard the steering input should be nearly 50% greater than the steady state condition to achieve the required jerk at the given speed.

Hence with a constant longitudinal velocity of 16.67m/s the radius for the manoeuvre could be estimated.

$$1.5 * a_{y-ss} = \frac{{v_x}^2}{R} \qquad \text{(Eq.B.4.1)}$$

Hence assuming $a_{y-ss} = 0.4g$ yields a value of R=48m.

The normalized cornering stiffness of the front tire=5N/rad/kg and rear axle=20N/rad/kg are taken from representative truck measurement. From these values and considering the effects of other compliances and effects, the understeer gradient achieves a value of 0.07rad/g.

Using these factors the front steering wheel angle can be calculated using equation B.4.2:

$$\delta_{fw} = \frac{L}{R} + k_u * \frac{{v_x}^2}{R*g} = 0.12\text{rad} \qquad \text{(Eq.B.4.2)}$$

Translating this front wheel angle to steering wheel angle using a steering gear ratio 1:20 gives a value of δ_{swa} = 2.4rad.

B.4.2 Simulation Results

The figures B.4.2.1 and B.4.2.2 indicate the actuator engine torque and speed.

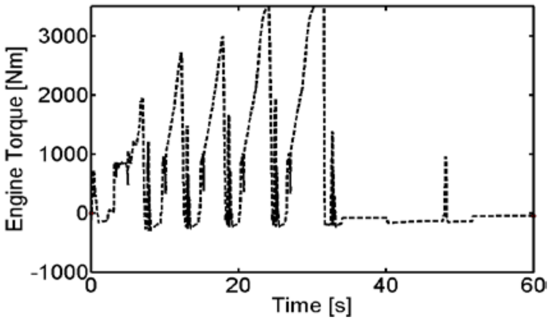

Figure B.4.2.1-Engine Torque-Actuator

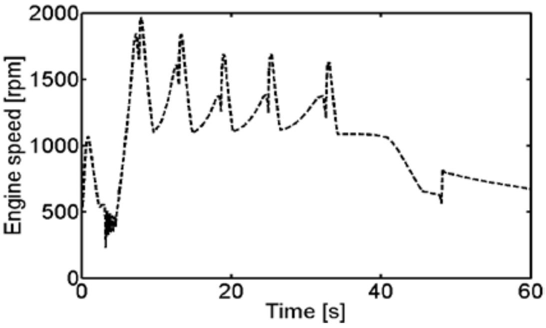

Figure B.4.2.2-Engine speed- Actuator

The brake pressures on the right hand side of the tractor are highlighted in the figures B.4.2.3 and B.4.2.4.

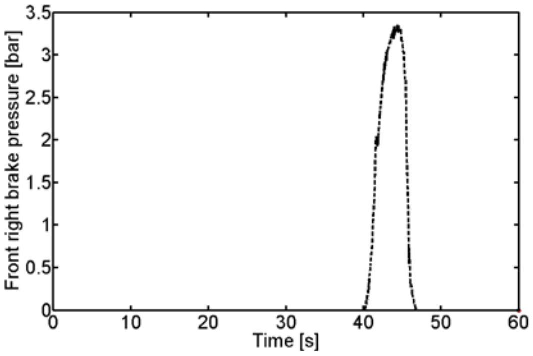

Figure B.4.2.3-Tractor front Right wheel

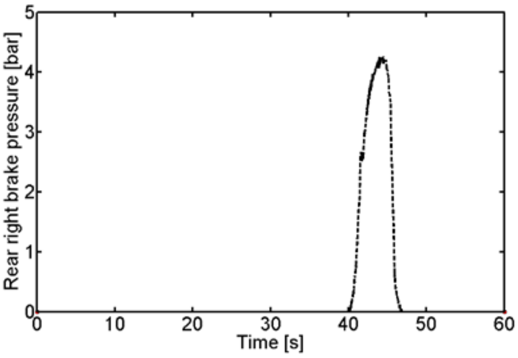

Figure B.4.2.4-Tractor rear right wheel