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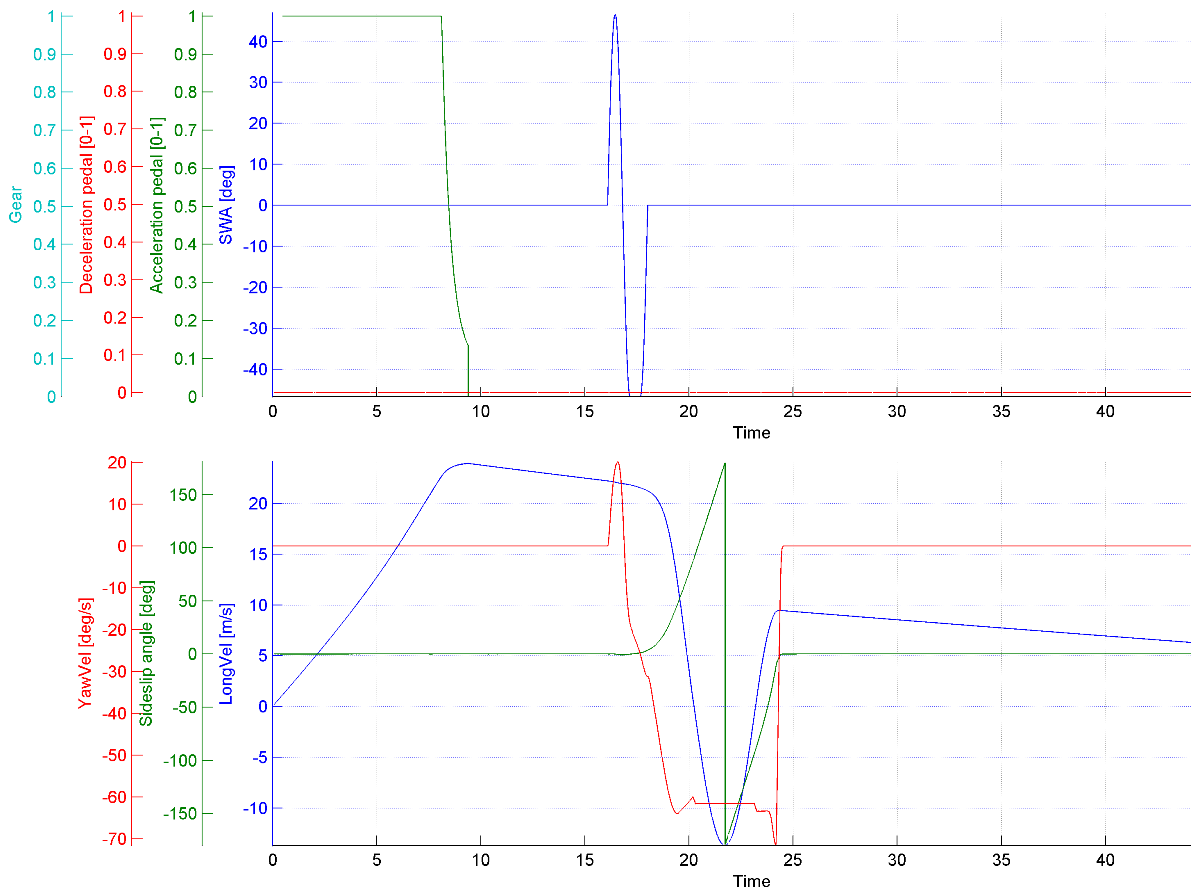

Test Procedures and Evaluation Tools for Passenger Vehicle Dynamics

Master's thesis in Automotive Engineering

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Department of Applied Mechanics
Division of Vehicle Engineering and Autonomous Systems
Vehicle Dynamics Group
CHALMERS UNIVERSITY OF TECHNOLOGY
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Cover:
Example of summary graphs produced using the analysis tool written within this master thesis work.

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Abstract

Both within education and research it is necessary to be able to ensure that the real or virtual vehicle used, behaves as supposed. In order to verify this a massive set of test procedures is needed. However, to create a ruff overview showing the basic behaviour, some test procedures are implemented into an evaluation tool. The user of this tool is presented the results in a form of a report with numbers and diagrams

Within this thesis a set of test procedures have been selected and implemented in an evaluation tool divided in to virtual test and analysis in order to both be able to use it for simulations as well as for post processing of real test data.
This report focuses on the choice and implementation of a limited number of test procedures as well as the design of the evaluation tool developed.
The tests that have been implemented are: Steady state cornering, Sine with dwell, Continuous sinusoidal input and Straight ahead acceleration.
Other tests that were discussed and were suitable to be implemented at a later stage are: Step input, Random input, Sinusoidal input, one period, Pulse input, Braking with split coefficient of friction, Brake in turn and Straight braking.
In order to give the user freedom to adjust the tests based on current requirements, all test procedure constants, e.g. times, velocities and distances, have been parametrized using an excel reference document to ensure good adaptability
The tool developed within this test is easy to set up and supports batch processes which enables it to run several simulations using different models. This have been done with one model from the research project Balance Active and Passive Safety (BAPS).
The evaluation tool is based on an combination of Matlab and Simulink.
The results from the analysis part of the tool are presented as an pdf document.

The purpose with creating this tool is to provide a method to easily and quickly get results on the behaviour of a real vehicle or a vehicle model during a few standard tests. This purpose is fulfilled with the tool created within this thesis.

Keywords: Test Procedures, Vehicle verification, Model verification, Vehicle dynamics

Preface

The work with the master thesis has been conducted at the Division of Vehicle Engineering and Autonomous Systems under supervision by Bengt Jacobson and Gunnar Olsson.

This thesis have been written at the Division of Vehicle Engineering and Autonomous Systems facilities.

Acknowledgements

First and foremost would like to express my gratitude to my examiner Professor Bengt Jacobson for all his interest, important input and good ideas regarding my thesis. I would like to thank Gunnar Olsson for his valuable input regarding the design, layout and choice of test manoeuvres, Ulrich Sander for all the help with the BAPS model and its vehicle parametrisation and Vehicle dynamics at Volvo Cars, for the productive discussions regarding the choice of test procedures.

I would as well like to thank all my friends within Chalmers Student Union, FestU, KL, and Balliancen that I have had the privileged to work and spend time with during my studies. An extra acknowledgement goes to Björn, for all cooperation during our courses, Karin for all good discussions and help with proofreading, and of Andreas for all good times during my time in Gothenburg.

Finally would as well like to thank Louis Tellier for all interesting and beneficial discussions, as well as all the fun times at the department during this thesis.

Nomenclature

Abbreviations

BAPS	Balance Active and Passive Safety	[Bapa]
BMAP	Brake Mean Effective Pressure	
rpm	Revolutions Per Minute	
FMU	Functional Mock-up Unit	[Fmi]
FMI	Functional Mock-up Interface	[Fmi]
ESC	Electronic stability control	

Matlab variables

$StopSignal$	Stop signal for simulation
$Time$	Time vector
SWA	Steering wheel angle
$Throttle$	Acceleration pedal position
$Brake$	Deceleration pedal position
$LongAcc$	Longitudinal acceleration
$LatAcc$	Lateral acceleration
$YawAcc$	Yaw acceleration
$LongVel$	Longitudinal velocity
$LatVel$	Lateral velocity
$YawVel$	Yaw velocity
$X\_position$	Vehicle position along environment X-axis
$Y\_position$	Vehicle position along environment Y-axis
Psi_angle	Vehicle angle compared to staring position
$PitchAcc$	Pitch acceleration
$PitchVel$	Pitch velocity
$PitchAng$	Pitch angle
$RollAcc$	Roll acceleration
$RollVel$	Roll velocity
$RollAng$	Roll angle
$alphaFL$,FR,RL,RR	Tyre slip angle
$FxWheelFL$,FR,RL,RR	Wheel force along tire X-axis
$FzWheelFL$,FR,RL,RR	Wheel force along tire Y-axis

Contents

1 Introduction

This master thesis is written within the Automotive engineering master program at Chalmers University of Technology. It focuses on the choice and implementation of a limited number of test procedures as well as the design of the evaluation tool developed within this thesis work.

The meaning with creating this tool is to provide a method to easily and quickly get results on the behaviour of a real vehicle or a vehicle model during a few standard tests.

The tool developed within this thesis work should be possible to use both on more advanced research models as well as simpler educational models.

In order to formulate and verify requirements on complete vehicle dynamics behaviour a massive set of test procedures are needed. Same test procedures are preferable used for verification with virtual model in real vehicles. Again same procedure are preferably used when validating a virtual model vs the real vehicle.

1.1 Objective

The two aims of this Master Thesis are:

- to define a set of test procedures for evaluation of a passenger vehicle, real or virtual, from a vehicle dynamics perspective, to be used in education or research.
- set up a verification tool based on these test procedures.

Deliverables

- Determine a set of test procedures that can be used in order to evaluate the overall dynamics properties of a vehicle. The chosen test procedures should reflect commonly used types of vehicle requirements.
- Reproduction of test procedures in simulation environment using Matlab. The simulation framework should provide easy set up and import of models.
- A script that generates a pdf report after each test with results of each requirement and saves needed data.

1.2 Limitations

In order to ensure the feasibility within the given time frame, several limitations has been made within this master thesis.

Test procedures limitations

The following limitations has been made in order to limit the types and amount of test procedures that will be included in this thesis work.

- Limited amount of test procedures, five to ten
- No advanced tracks
- No advanced driver models
- To ensure the result quality no subjective tests will be included.
- Only lateral and longitudinal dynamics will be considered.
- No tests that requires unreasonable advanced models or model environment, e.g. side winds or ADAS sensors.
- No tests that requires steering wheel force feedback.

Model limitations

In order ensure that the tool can be used with different types of models, some overall limitations have been declared.

- Limited number of model inputs,
  - Steering wheel angle
  - Acceleration pedal position, value between 0-1
  - Deceleration pedal position, value between 0-1
- When using the parametric models from the BAPS research project [Bapa] they will be regarded as black box models. No changes will be made to the vehicle model.
- In and outputs as decided in this thesis. The decision is inspired by the model from the BAPS project.

Choice of platform

The platforms used in this masters thesis are Matlab [MAT13] and Simulink [Sim13], this due to that the final tool should be accessible for student as well as staff at Chalmers University of Technology without the need of investments in additional licences. A Matlab/Simulink solution is as well FMI compliant which opens the possibility of using models from multiple platforms [Fmi]. Using an FMI solution requires however a licence from Modelon.

2 Background and Theory

When designing a vehicle an extensive set of vehicle requirements and verification methods are used. Within research projects and education there is as well a need for requirements and verification procedures, even if not as extensive. Since research and education often focuses on a specific function in the vehicle it is important to have a more generic requirement set in order to ensure the overall behaviour of the vehicle. In order to verify a vehicle, real or virtual, it is necessary to have test procedures related to the requirements. If validating, or verifying, a virtual vehicle is conducted through comparison with test results from a real vehicle. Same set of test procedures should be used for both real and virtual vehicles.

2.1 Literature review

In order to use relevant test procedures a literature study has been preformed. Within this study the following sources have been evaluated in order to determine relevant test manoeuvres.

- Swedish Standards Institute containing ISO standards
- SAE International Digital Library
- FMVSS, Federal Motor Vehicle Safety Standards (Sine with dwell FMVSS216)
- EuroNCAP (information regarding ESC standard)
- NHTSA (information regarding ESC standard)
- ISO/TC 22 Road vehicles (Relevant parts regarding passenger cars.)
- Motor sport Magazines (e.g. Acceleration 0 - 100 km/h)

The general result from the review was that it were possible to find ISO standards containing tests as well as legislations such as FMVSS216. However it were significantly harder to obtain information comparing different tests as well as evaluating the tests and discussing advantages and disadvantages regarding them.

During the literature review information regarding different ways to export the simulation or test results from Matlab to a pdf document were investigated, as well as methods to coordinate simulations between Matlab and Simulink.

2.2 Development tools

Within this thesis work several programs have been used. The programs that are essential for running the evaluation tool are: Matlab, Simulink and a Latex installation, e.g. MikTex.

MathWorks
For all simulations and post processing Matlab [MAT13] and Simulink [Sim13] have been used. Matlab have been used to prepare the simulations, change settings and execute a batch process using a simulink model. The post processing have been preformed using Matlab and the results were exported to a *.tex* document in order to be compiled to a pdf-document from Matlab using MiKTex [MiK].

Dymola
The platform used for the BAPS model, presented in chapter 5, is the modelling and simulation environment Dymola [Dym13]. This has as well resulted in the use of FMI Toolbox for MATLAB/Simulink [FMI13]

MiKTex
To compile *.tex* files the Latex installation MiKTex [MiK] has been used together with the following latex packages: babel, verbatim, inputenc, microtype, mathtools, booktabs, float and geometry.

2.3 Models

In order to ensure that the tool can be used with different types of vehicle models, four different vehicle models have been used for this thesis work. All vehicle models except the BAPS models has been built within this thesis work.

Single track model
A simple bike model based on values from a parametrisation of Saab 9.3, with a tire model based on Pacejkas "Magic Formula" tire model [Pac02] have been used. This model does not account for roll or pitch behaviour.

Two Track Model
The two track model used in this thesis is based on models created during the Vehicle Dynamic Advances course at Chalmers University of Technology [Doc]. It is using reference values from a SAAB 9.3 and with a longitudinal force output described in equation 2.1, where F_{Output} is the longitudinal output force on the tires, $C_{MaxLongForce}$ is the maximum longitudinal output force and $P_{AccelPedal}$ is the acceleration pedal position (value between 0 and 1 where 1 is full throttle). It can be used as a tricial model of the drive train. The tire model used in this two track model is based on Pacejkas "Magic Formula" tire model [Pac02].

$$F_{Output} = C_{MaxLongForce} \cdot P_{AccelPedal} \tag{2.1}$$

Two Track Model with Drive-train
Based on the previous explained two track model, an modified version with a more realistic power-train have been designed.

It is equipped with a very simple engine based on a example BMAP curve from a sedan vehicle as well as a gearbox designed without delays and which changes gears at pre determined engine rotational speeds. This model has been designed to test acceleration cases in order to be able to evaluate different typed of drive-trains and gearboxes.

Two Track Model with ESC
This is a second modification of the previous presented two track model but with ESC. The ESC is designed to compensate for the yaw velocity error by adding braking forces to specific wheels if the yaw error exceeds a boundary condition.

BAPS model

Balancing Active and Passive Safety (BAPS) [Bapa] is a research project between Autoliv, Volvo Car Corporation, VTI, Chalmers and Semcon. The main objective with this project is "to develop a methodology for the estimation of how much present and future active and passive safety measures, and combination of these, will reduce the risk for people involved of sustaining injuries of different severities" [Bapb].

An Functional Mock-up Unit (FMU) from the BAPS project have been used as one of the vehicle models within the work of this masters thesis. This both to evaluate the model as well as verify the compatibility of the evaluation tool.

During this project the BAPS model will be treated as an black-box model. No modifications will be made to the model.

This model have been used with several sets of parameters, the different parametrizations are presented in Appendix C

The parameters altered during the simulations with the BAPS model are shown in Table 2.1. This set of parameters have been provided from the BAPS project.

Table 2.1: Parameters adjusted for each parametrization during the simulations of the BAPS model.

Parameter:	**Unit:**
Weight	[kg]
Distance CoG FrAxle	[m]
Distance CoG ReAxle	[m]
Height CoG	[m]
Track Width Front	[m]
Track Width Rear	[m]
Inertia about x-axis	[kg·m^2]
Inertia about y-axis	[kg·m^2]
Inertia about z-axis	[kg·m^2]

3 Selection of test procedures

In this section the methods and selection of a suitable set of test procedures will be discussed. The target with the set of test procedures are to supply a ruff overview of a, real or virtual, vehicle and conclude which test procedures to implement in the evaluation tool.

3.1 Method & Development Process

In order to select the most beneficial test manoeuvres for implementation in the tool, two purposes with the tests were considered, tests that can be used to validate a real vehicles behaviour and that can be used to verify a vehicle model and show the models limitations.

Within this masters thesis an attempt to get a ruff overview of the vehicle or models behaviour will be conducted by using only a few tests. By preforming five to ten tests it is not possible to get a complete overview of a vehicles behaviour.

The used test manoeuvres should preferably be possible to preform both in simulations and during testing of a real vehicle, in order to be able to compare simulation and test data.

Considered test manoeuvres

The following tests were considered to be used as test manoeuvres on the information found regarding them during the literature review. Some of the tests that will be discussed are not ISO standards and this will be taken in to account when choosing which test manoeuvres to implement. At this stage all test manoeuvres using the surroundings, e.g. test of lane departure warning, have been removed.

Steady state cornering *ISO 4138*	Steady state manoeuvres reveals important information about the vehicles behaviour. The results from this manoeuvre are uses as reference values in several other test manoeuvres such as a sine with dwell [Nat07] and Continuous sinusoidal input. This manoeuvre revels the vehicle under/over-steer behaviour, roll angle at steady state, steering as function of lateral acceleration and side slip as function of lateral acceleration. The steady state cornering manoeuvre can be preformed in three different ways, using constant radius, constant velocity or constant steering angle. More information regarding the manoeuvre is available in:[ISOe]
Sine with dwell *FMVSS126 S7.9*	Test of over-steer intervention and responsiveness. Used to test ESC. ISO standard is under development. Efficient manoeuvre to excite an over-steer response from a vehicle [FEO05] More information regarding the manoeuvre is available in:[Nat07]
Fishhook *NHTSA*	This manoeuvre original designed to quantify on-road, untripped roll overs properties. It might not provide the inputs needed for evaluating vehicle with ESC. More information regarding the manoeuvre is available in:[FEO05]
Sine steer increased amplitude	Base on Sinusoidal input, one period, but with a 1.3 times larger amplitude the second half cycle. Similar results as Sine with dwell, however inconstant results of different vehicles [FEO05].
Double lane change *ISO 3888-1*	To determine behaviour at a double lane change and the road holding ability of passenger cars. More information regarding the manoeuvre is available in:[ISOc]
Sinusoidal input, one period *ISO 7401 (ISO 8725)*	Lateral acceleration related to steering wheel angle and yaw velocity related to steering wheel angle, in the time domain. Vehicle transient response to one period of sinusoidal steering input. Not fully representative to real driving but similar to lane change manoeuvres. More information regarding the manoeuvre is available in:[ISOf]
Obstacle avoidance *ISO 3888-2*	Defines behaviour of vehicle at a severe lane change in order to avoid an obstacle. More information regarding the manoeuvre is available in:[ISOd]
Step input *ISO 7401*	Lateral acceleration related to steering wheel angle and yaw velocity related to steering wheel angle, in the time domain.Gives transient response to step input, including response times and overshoots. More information regarding the manoeuvre is available in:[ISOf]
Pulse input *ISO 7401*	Lateral acceleration related to steering wheel angle and yaw velocity related to steering wheel angle, in the frequency domain. Provides frequency response (gain and phase angle functions) More information regarding the manoeuvre is available in:[ISOf]
Random input *ISO 7401* *(ISO 8726)*	Lateral acceleration related to steering wheel angle and yaw velocity related to steering wheel angle, in the frequency domain. Applies where the vehicle behaviour is assumed to be linear. Provides high amount of information over a limited range of lateral acceleration correlating to normal public road driving. More information regarding the manoeuvre is available in:[ISOf]

Continuous sinusoidal input ISO 7401	Lateral acceleration related to steering wheel angle and yaw velocity related to steering wheel angle, in the frequency domain. More information regarding the manoeuvre is available in:[ISOf]
Stopping distance at straight-line braking with ABS ISO 21994:2007	Straight line braking from 100 kph down to 0 kph. Gives information about braking distance. It does as well show the stability of the vehicle at straight line braking. If the vehicle does not have ABS brakes this test can still be used to get this information. More information regarding the manoeuvre is available in:[ISOb]
Braking with split coefficient of friction ISO 14512	The purpose of this test is to determine course holding and directional behaviour. The results are compared to the vehicle steady state cornering behaviour [ISOe]. More information regarding the manoeuvre is available in:[ISOa]
Brake in a turn ISO 7975	Results in information regarding yaw stability change in path and change in lateral acceleration compared to steady state. More information regarding the manoeuvre is available in:[ISOg]
Power off reaction of a vehicle in a turn ISO 9816	Gives information about how the vehicle behaves when releasing the acceleration pedal during cornering More information regarding the manoeuvre is available in:[ISOh]
Acceleration 0-top speed	Provides information regarding drive-train, traction control, shifting properties, time 0-100 kph, time 402 m and acceleration margin.
Accelerating with split coefficient of friction	Similar procedure to "Braking with μ-split, ISO 14512". This test could provide information regarding directional stability and yaw stability.
Accelerating in a turn	Similar procedure to "Brake in a turn, ISO 797". Results in information regarding yaw stability change in path and change in lateral acceleration compared to steady state.

Within this thesis there have been a focus on lateral dynamics since that is the main focus area of the vehicle dynamics group at the division of Vehicle Engineering and Autonomous Systems. The has contributed to the decision that it is suitable to have one test trigging the ESC system. In order to ensure the longitudinal dynamics it were considered suitable to have one acceleration test.

Based on the limitations discussed in section 1.2 Limitations several tests were discarded, e.g. even thou double lane change is an efficient way to test the transient behaviour of a vehicle or model it is not selected in order to avoid dependency of advanced driver models. The selection of tests are further discussed in section 3.2 Selection of tests.

3.2 Selection of tests

Due to the limitation of five to ten tests it is not possible to get a complete overview of the behaviour. However when limited to this amount of tests, a ruff overview can be provided. This give the user an idea of the behaviour and for example the information needed to determine if a model behaves in reasonable way and is working. When choosing test procedures a target have been to focus on all areas of the vehicle, from acceleration, braking, steady state cornering, evaluate the vehicle stability and ESC system as well as evaluate the transient behaviour.

It were as well considered the necessary of that the selected tests could be preformed both on virtual and real vehicles.

Except with regard to the Sine with dwell manoeuvre there have been a considerable shortage of information regarding how efficient different manoeuvres are to evaluate behaviours as well as comparison between different manoeuvres. This have resulted in that the decisions have been largely based on discussions with Bengt Jacobsson at Chalmers University, Gunnar Olsson at LeanNova and Chalmers as well as discussions with representatives for Handling and Braking at Volvo Cars.

The chosen tests within this thesis are shown in table 3.1. Due to the time limitation, not all test procedures have been implemented which will be further discussed in section 3.2.1

Table 3.1: Chosen test procedures and which test procedures that have been implemented in the evaluation tool.

Test procedure:	**Implemented:**
Steady state cornering	Yes
Acceleration 0-max speed	Yes
Sine with dwell	Yes
Continues Sinusoidal input.	Yes
Step input	No
Random input	Only post process
Sinusoidal input, one period.	No
Pulse input	No
Braking with split coefficient of friction	No
Brake in turn	No
Straight braking	No

3.2.1 Implemented test procedures

The implementation of tests have been done in accordance with existing standards. More detailed information regarding how the test procedures are implemented in the Evaluation tool are availiable in section 4, Evaluation tool.

Several of the tests have specified standard conditions, e.g. Steady state cornering with constant speed is in the standard case driven at 100 kph however can be changed in 20 km/h increments according to the standard [ISOe]. Another adjustable parameter when running Steady state cornering with constant speed is the increase in steering wheel angle. Similar adjustable parameters can be found in all test procedures and therefore all test procedures implemented in this thesis needs to have several parametrised settings in order to supply the user with relevant information.

Another type of adjustable parameters that occurs for all implemented tests are adjustable PID regulators for acceleration pedal, deceleration pedal and for steering wheel. In the acceleration pedal case the PID regulator is needed since many test procedures are initialized or preformed at constant predefined speed. While using a model with a regular engine behaviour a standard parametrization can be used, but if necessary the parametrization can be adapted based on the model.

The adjustable parameters which are specific for each test will be described in the remaining subsections in sections 3.2.1.

Steady state cornering

In order to have a stable and simple control, steady state cornering with constant speed have been chosen. Resulting in the need of only one regulator to control the acceleration pedal position in comparison with constant radius turn where two regulators are needed, one for steering and one for acceleration pedal. By using two regulator there is an increased risk for designing an unstable system since the desired steering angle is dependent of the velocity, and the longitudinal velocity is affected by the steering angle. The manoeuvre with constant steering angle will only be correct if the steering is completely linear, which makes it unsuitable.

During steady state cornering in the virtual testing part of the evaluation tool it is possible for the user to select several test speeds, e.g. to run the test at 80, 100 and 120 kph. Apart from the test velocity the user can as well as adjust the steering input magnitude and duration in order to control the change in lateral acceleration.

Sine with dwell

In order to be able to evaluate the stability of a vehicle as well as the ESC system a Sine with dwell manoeuvre have been used. The chosen manoeuvre is based on FMVSS126 [Nat07] since this manoeuvre have produces consistent results and shown to be an efficient way to trigger an over-steer behaviour according to NHTSA [FEO05].

The Sine with dwell manoeuvre implemented in the virtual testing part of the evaluation tool allows the user to change test velocity, the size of the steering wheel angle increments, aswell as change the turn frequency, dwell length and maximum steering wheel angle.

In order to determine the steering wheel angle used in a Sine with dwell manoeuvre the results from steady state cornering is used.

Acceleration

This test provides information about the behaviour of the vehicles or models power-train, both regarding acceleration capabilities and gearbox behaviour. It were implemented as the second test manoeuvre due to its simplicity to simulate. This have resulted in the possibility at an early stage test to run multiple test manoeuvres in a simulation and thereby ensure that the chosen way of implementation of test procedures works.

The implementation of the acceleration test manoeuvre allows the user to either search for top speed or to find a specific speed, e.g. if only 0-120 is interesting in a study there is no point in spending simulation time to find the top speed.

Continuous sinusoidal input

In order to evaluate the frequency response of a model there is three different test methods: puls input, random input and continuous sinusoidal. The reason for using continuous sinusoidal input instead of random or pulse input is that it is possible to program in an efficient and representative way, as a difference to random input. It consists as well of a sweep containing several different frequencies which is beneficial compared to puls inputs single frequency.

Due to very similar analysis methods for random and continuous sinusoidal input, there is a possibility to use the same analysis part of the evaluation tool on the logged data from a random input test.

The implementation of continuous sinusoidal input allows the user to adjust test velocity, low and high frequency, step size, as well as the number of periods that should be preformed at each frequency.

4 Evaluation Tool

As stated in section 1.1 Objectives, an framework for simulation, referred to as Virtual test, and a data analysis and report script, referred to as Analysis, should be produced within this thesis work. Figure 4.1 shows the interaction between these two deliverables. Both the simulation part and the post analysis part should work independently of each other. The results from the virtual testing preformed by the framework for simulation should be possible to replace with results from real tests.

In order to build a structured tool a clear and well organized file structure have been used. This structure is presented in figure E.1 in Appendix E.

4.1 Virtual test

This section will discuss the development process, design targets and the results of the virtual testing part of the evaluation tool written within this thesis.

For clarity of this chapter the following definitions are needed.

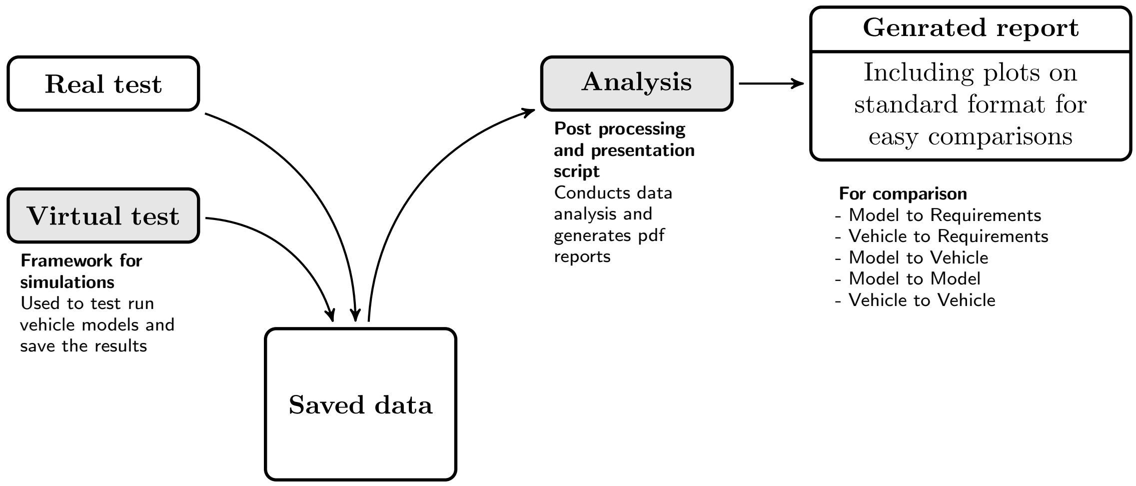

Figure 4.1: *Verification of real vehicles, models with respect to requirements.*

Vehicle model	The model of a vehicle, without driver or logging tools. With inputs such as Steering wheel angle, throttle position and brake. Outpus such as Lateral acceleration, longitudinal acceleration and position.
Simulink interface	Within this thesis it is defined as the simulink blocks containing logging code and the virtual driver.
Simulink model	This refers to the complete simulink file, including both the simulation interface and the vehicle model.

4.1.1 Method & Development Process

As stated in section 1.2, Limitations, the platforms used in this thesis-work are Simulink and Matlab. To have an efficient tool that allows further development the following key features have been regarded:

Usability — An very important property is that the tool should be attractive to use in order to verify a model or to quickly check the behaviour of a model. It is necessary that it is easy to set up and operate, otherwise the potential users will not be motivated to use this tool.

Adjust ability — The tools needs to be compatible with different models . Also test parameters needs to be adjustable.

Debugging of model — All information needed to run a test case should be possible to included in the simulink file. This provides the possibility to run the simulink model separately in order to debug the model as well as verifying new test cases.

Allow accelerated simulations — To ensure that many tests can be preformed in a efficient way with for example different parameter settings, it is important that the tool can be executed in simulinks accelerated mode. To ensure this all input settings needs to be pre defined. However the possibility of using accelerated mode is depending on the vehicle model as well.

Allow future development — In order to allow future development and addition of new test scripts it is necessary to have a standardised way of implementing the test scripts as well as clear program structure in order to enable other persons then the original author of the evaluation tool to understand and implement additional test scripts in to the tool.

Data storage	All data from the simulations needs to be automatically stored using an clear structure and then saved. The data structure needs to provide a possibility for post processing of the data at a later stage.
Allow batch processes	In order to simulate several models or parametrizations the simulation tool needs to allow batch processes. This results in that the entire evaluation tool should be designed in order to allow this.
Allow FMU models	The virtual test tool should allow the user to import FMU models based on international standardized format FMI. These models can be used in several different programs such as Dymola, Matlab/Simulink and CarMaker [Fmi].
Only require standard uni. licenses	The tool for virtual testing should not require special licenses. Matlab/Simulink as well as MS Office are assumed to be available. LaTeX with standard user-packages are also assumed to be available.

In order to ensure a clear and efficient structure of the scripts activity based flowcharts have been used. The flowcharts have been based on the Activity Diagrams within the OMG Unified Modeling Language Specification v 1.5 [Uml].

4.1.2 Results regarding virtual test

In this section the final virtual test scripts designed and results are presented.

Tool layout

The over all layout of the simulation framework have been based on the key features mentioned in section 4.1.1. In order to reduce the complexity for the user a specific set-up and initialisation script is being used as shown in figure 4.2.

This provides the user with an efficient method of changing vehicle model, use batch scripts to change model settings and select test manoeuvres to preform. It has however the disadvantage of a slightly more complicated script structure.

The run part shown in figure 4.2 controls the selection of model, test and settings to be used and loads the model and changes it settings in order to run the selected test. All tests using a specific model with a specific parametrization are executed before the current model is closed and the next model is loaded. Using this solution the loading time of models were reduced and as well as its contribution to the over all simulation time.

In order to ensure that the Simulink interface can run without recompiling the Simulink models for each test the input settings are specified as a predefined vector that is assigned to a constant block in the Simulink interface. This as well results in that the Simulink can run as a stand alone model during development of new test manoeuvres as well as during debugging of vehicle models.

By specify the test manoeuvres as functions outside Simulink it is possible to add or change a manoeuvre without having to do any adjustments to the Simulink files. This ensures that the same test manoeuvre code is used for all models when simulating several models at once and reduces the risk of issues with different code versions. The alternative to using external Matlab functions would be to build the functions with Simulink blocks, however it would most likely result in that not only the current test case, but all test cases, would calculate there driver input information and only the information from the current test would be used. The disadvantageous with the current design with external Matlab functions is that the Simulink model can not run unless the folders containing the Matlab functions are added to Matlabs file paths.

An important design change during the development were to export the test settings each run instead of only once per test. The reason for it were to enable the possibility to check previous data and if necessary abort a test, e.g. Sine with dwell, when it has failed to pass a test. Resulting in the possibility to check each run if the model passes a criteria before it start the next run. The possibility to access previous runs is necessary for several tests manoeuvres since many of them uses a steering angle based on a specific lateral acceleration at a certain velocity.

After all tests are preformed for a model, all relevant data is saved. The reason for saving after each model is to ensure that a batch processes can run several models without occupying to much of the RAM. The results

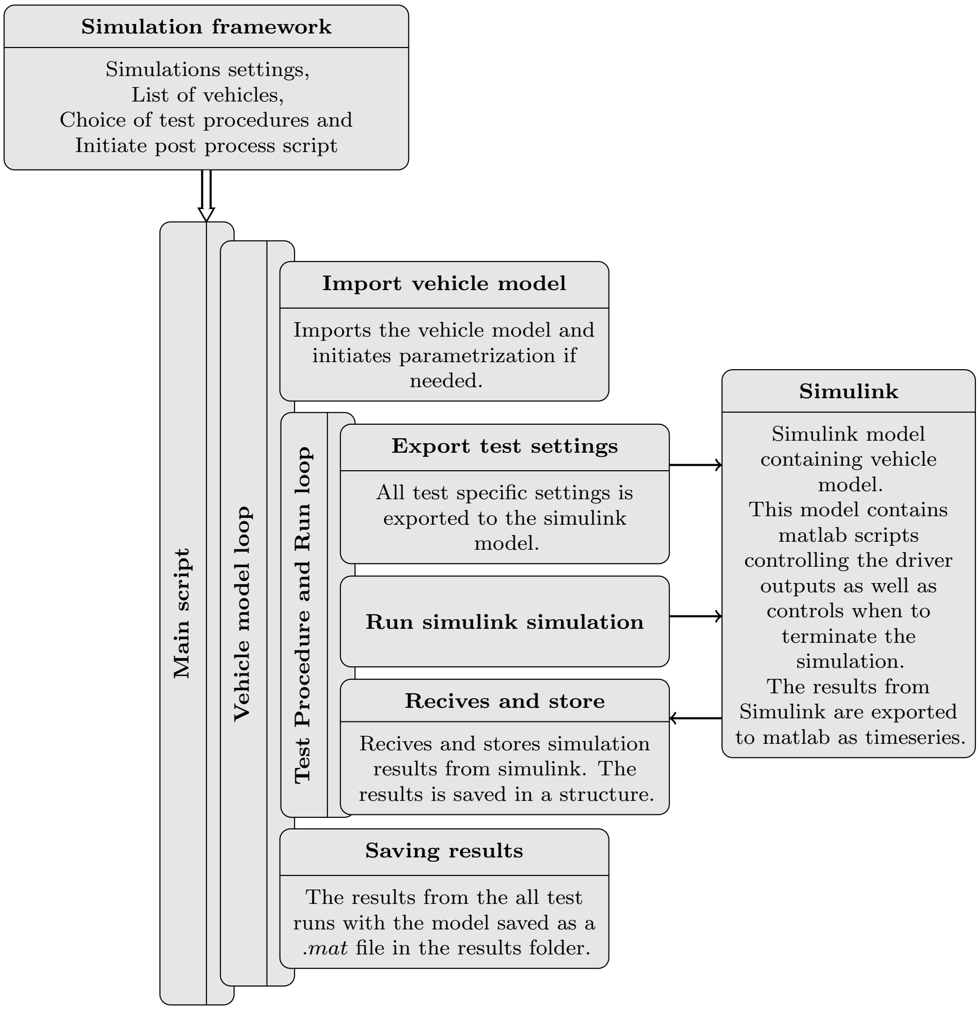

Figure 4.2: *Figure showing the overall layout of the simulation framework tool as well as its simulation loops and interaction with the simulink model.*

for each model is saved as an *.mat* file with a array of structures containing all saved data from a test run, as well as information about the test manoeuvre.

Adjust ability

In order to have a good adjust-ability an excel document containing the adjustable parameters for all test have been used. The benefit of using an excel file is that it is providing an good overview of the settings and its contents can easily be changed. When running the tool, the valus from the adjustable parameters are imported from the excel file to matlab.

Even if excel requires a specific licence it is considered to be standard at most companies as well as universities. If no license is accessible it is as well possible to access the document through open source programs.

Model interface

The model interface have been designed based on three blocks as shown in figure 4.3. This is done in order to ensure that it is easy to change model and make necessary set-ups. The input block creates and sends the driver inputs to the vehicle model block. The vehicle model block sends the behaviour information on to the logging block, which after the simulation exports it to Matlab. The logging block sends as-well necessary feedback signals back to the input block.

In order to change vehicle model, it is only needed to replace the vehicle model block with new block

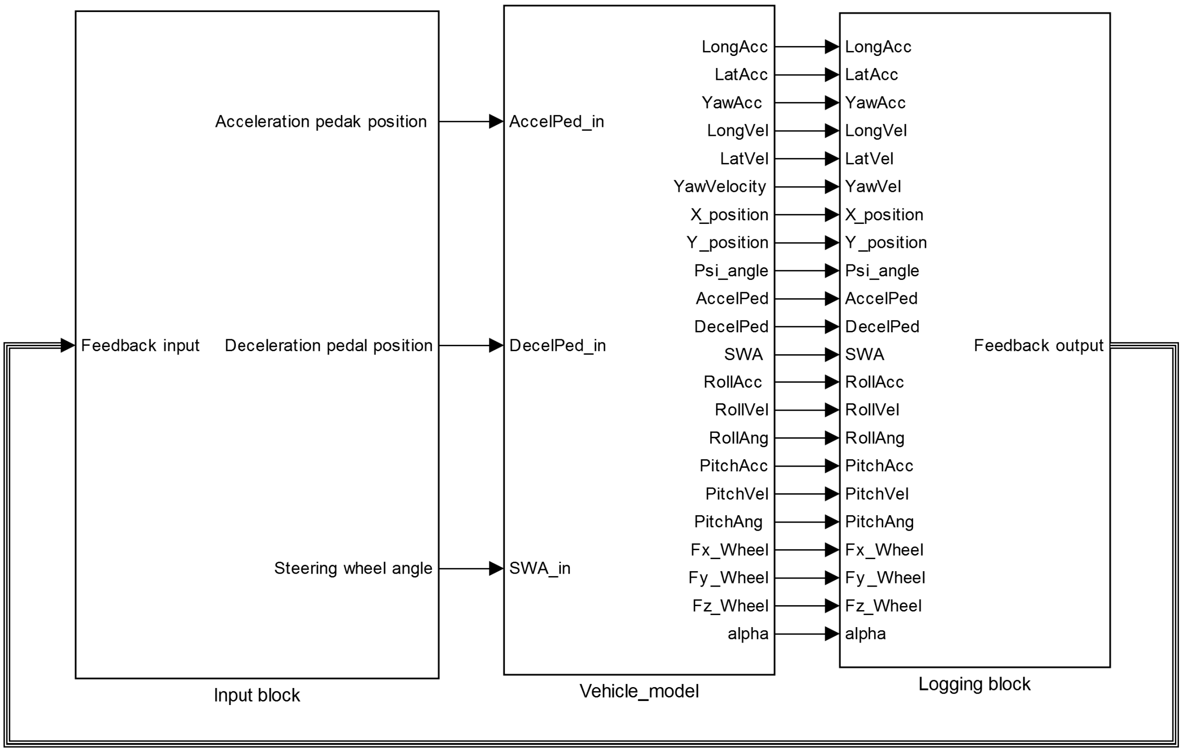

Figure 4.3: *Figure showing the simulink model contaning both simulink interface and vehicle model.*

containing the same in and out-puts. This makes it easier for the user to change and adapt a model without affecting the way the test is preformed. The disadvantages with this type of solution is that it is slightly more complicated to add more output signals and that there is no inputs from the surrounding environment, as stated in Limitations (section 1.2).

If a variables is not specified in the model, e.g. Gear, it should be set to NaN in order to ensure that both simpler and more advanced models can be used.

Accelerated simulation

In order to avoid algebraic loops so that accelerated and rapid acceleration mode can be used, a memory box is mounted on the main feedback loop. This results in a possibility to avoid errors due to algebraic loops when using accelerated simulations, but with the disadvantage of using information from last simulation step when calculating the current input signals. This disadvantage is however being considers to be very small due to small simulation steps.

Allowing future development

In order to ensure the possible of continuing to add test procedures to this evaluation tool, the scripts have been clearly divided for each test. The procedure needed is to create the script controlling the behaviour of the vehicle, add it to the main input function, add this to the script file, containing a list of all tests, and add the specific settings to the excel file. All input and output signals to the test scripts have the same size independently of what test is run in order to reduce the need of recompiling the simulink model. It will still require that the programmer have a large understanding of matlab and simulink as well as take the time needed to understand the program, however thanks to this simplification, the need of understanding all evaluation tool scripts should be significantly reduced.

4.2 Analysis

In this section of the report the design of the auto-generated reports as well as the design of the post processing script will be regarded. There is a large value in establish a standardized format for review of the test results, which is why the auto-generated report is a very important feature of the tool.

4.2.1 Method & Development Process

In order to ensure that the results are presented as standardized as possible the existing ISO standards that were discussed in Chapter3 were used when writing the post processor.

The key features that have been regarded when writing the post processing and presentation part of the evaluation tool is the following:

Option of using plot windows	In order to allow the user to view and zoom in on a graph if needed, this option is important. However if this option is not activated by the user no plots should be displayed in order to improve the calculation speed
Export to pdf	The final results needs to be exported to a pdf document so it easily can be printed or distributed.
Export graphs	All graphs needs to be exported in format suitable for use in a presentation.
Export evaluation plots	In order to easily debug a model or to further investigate its behaviour, evaluation plots containing all logged variables should be presented in a recognisable way for easy evaluation.
Auto-generating of reports	When running virtual tests it should be possible to automatically post process the results immediately after running the simulations without further need of setup.
Adjustable settings	The tool should allow the user to make adjustments to whether to plot evaluation plots or to save all graphs.

4.2.2 Results regarding analysis

Design of auto generated reports

The auto generation of reports have been written so that it creates a separate report for each vehicle. The disadvantage with this solution is that is is harder to compare two specific vehicle since the user needs to take the two reports, find the graph to compare, and do it manually. However this results in the possibility to compare reports that have been generated at different instances as well as comparing as many different reports as the user would like.

The reports are generated in the same way independently if the information used for the report is from a simulation of a model or from real vehicle testing.

In order to ensure that the test conditions for a specific test can be known when evaluating the result, the path or reference number of the file where the test conditions have been recorded can be displayed on the front page of the report. If now reference is defined, a line will be displayed allowing the user to manually add the reference.

The tests manoeuvres that are based on ISO tests will be presented based on the specifications in the ISO standard. The reason for this is as mentions in section 4.2.1 to ensure that the results are presented in a standardized way, in order for the user to read and understand the results.

In those test manoeuvres that are not specified as a standard, the choice of graphs and information that is presented are based on available information regarding the manoeuvre as well as the author experience from courses as well as meetings within this thesis work.

In order to provide the user with as much important information as possible, two pages showing the logging signals have been added. Giving the user more extensive information about the vehicles behaviour

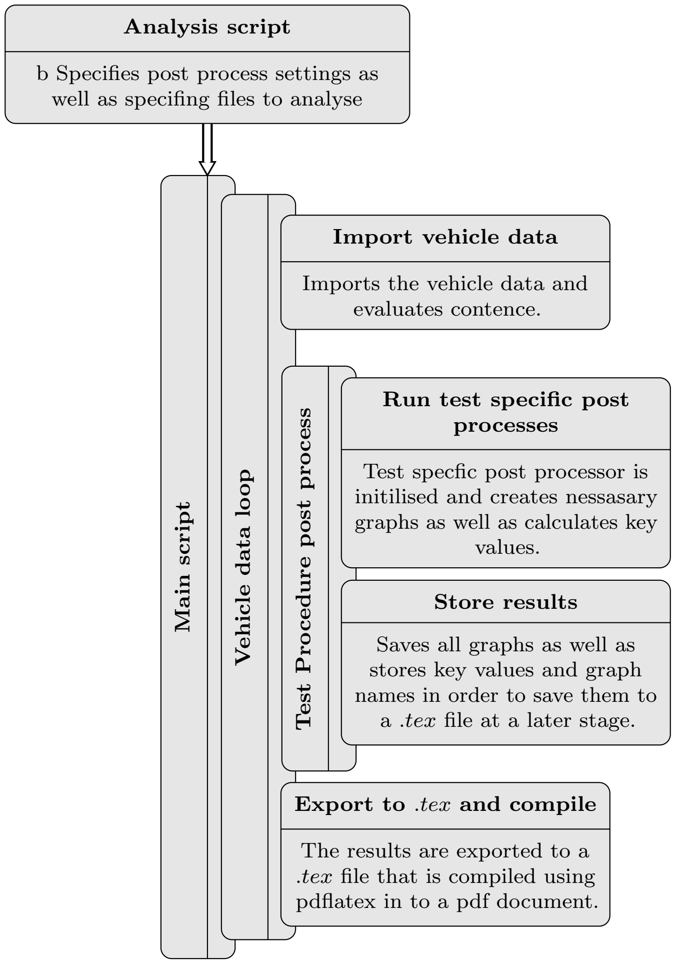

Figure 4.4: *Figure showing the overall layout of the Analysis part of the Evaluation tool.*

Design of post processing tool.

As stated in section 1.2, Matlab have been used as a standard platform, however in order to export the results in an efficient way to a pdf document other licence free software as Latex were early considered due to there flexibility. In figure 4.4 the script structure is described.

The chosen design of the post processor are a matlab script that calculates all needed information, creates plots which it saves, and then exports the information to a *.tex* file that is compiled using PdfLatex. This results in an easily printed or distributed pdf document for each tested vehicle containing information from all preformed tests. Example of reports can be found in Appendix A and B.

When post processing results from simulations the search path to the *.mat*. file is needed. This file contains information about what type of runs that is stored in the file, if this information is missing a pop up window will occur and ask the user for needed information. This is to ensure that the stored data are post processed in the right way, giving the user the possibility to directly post process the results if using the simulation tool.

In order to be able to import results from tests with a real vehicle a script converting the test data to the data structure used in this thesis is needed. Within this thesis a script for importing logged test data from the Saab 9.3 possessed by the vehicle dynamics department have been written in order to ensure this possibility.

When post processing the results the tool evaluates one vehicle at a time and then steps thou the different test manoeuvres specific post process scripts.

As described in section 4.2.1 one important feature were to have the ability to access graphs if requested. This have been solved by creating a possibility of choosing whether to save the graphs after the pdf document is created or if all *.png* files that contains the graphs should be removed.

5 Simulations with BAPS model

This chapter describe the setup of the BAPS model as well as presenting results from simulations using the Evaluation tool.

5.1 Set up options

Before being able to run the BAPS model it is nessasary to conecting the FMU to the simulink interface as shown in figure 5.1. It is as well several parameters that needs to be altered depending of what vehicle specifications to use during the simulation.

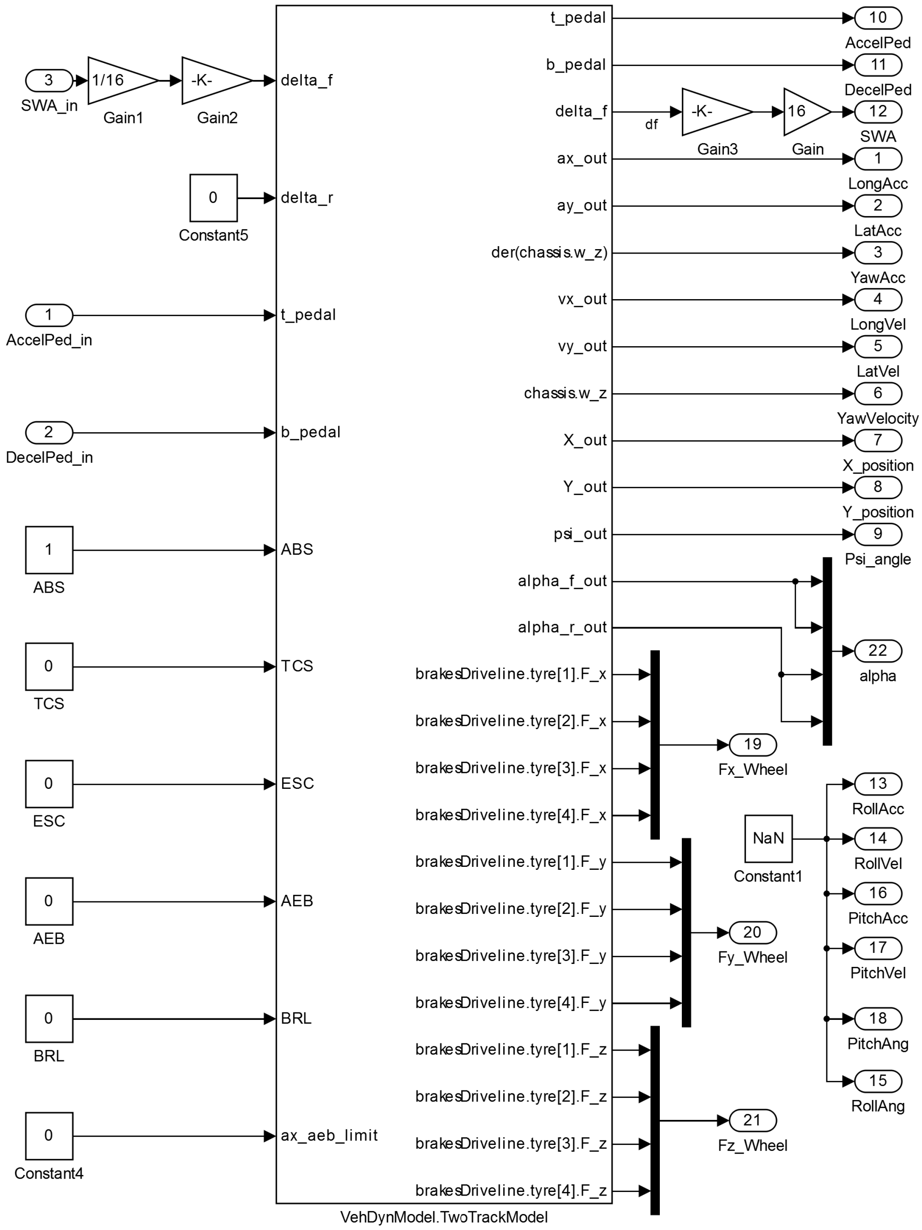

Figure 5.1: *Figure showing the BAPS model (FMU) connected to the simulink interface. This figure represents the Vehicle block in figure 4.3*

5.1.1 Parametrized vehicles

In order to test run the BAPS model set of vehicles have been provided by the BAPS project. The parameters provided of these are not complete parametrisations of vehicles and are not completely representing the original vehicles, however they are sufficient in order to verify the evaluation tool and the possibility to run a batch script. The different parametrisations used within this thesis are presented in table C.1 in Appendix C

5.1.2 Adjustable safety systems

This model have some Active Safety functions. Of these, ESC, ABS and TCS can be tested in the tool in present thesis. But another of them is AEB (Automatic Emergency Brake) is an ADAS (Advanced Driver Assistance System) function and can consequently not be tested since the tool does not support information about the vehicles environment. Table 5.1 shows what systems that can be used.

Table 5.1: Active Safety functions in BAPS model and whether they can be used within the evaluation tool.

Safety system:	**Supported:**	**Comments:**
ESC	Yes	
ABS	Yes	Not been tested within this thesis
TCS	Yes	Not been tested within this thesis
AEB	No	No information regarding surrounding environment available.

5.2 Results from the simulations with the BAPS model

The simulations using the BAPS model showed that it is possible to run batch simulations in an efficient way, as well as the compatibility with FMU models.

However the simulations were preformed without ESC, which resulted in an misleading result regarding the FMVSS 126 legislation. It should as well be noted that the model is not designed in order to evaluate frequency responses, which results in unreliable results.

The results from these simulations are presented in Table D.1.

6 Conclusions

This thesis have developed an evaluation tool enables the users to easily verify and check a model as well as easily post process logged data.

This possibility is beneficial both for research and educational purpose.

Within research it gives an efficient method to easily verify multiple vehicle models, as have been done with the BAPS model. This can show if the vehicle model is a good representation of a real vehicle in order to increase the reliability of the research results.

In education this thesis work can as well provide a useful tool for rapid simulations in order to compare variables e.g. different trackwidths.

As an example, a beta version of the tool were successfully used in two other MSc theses, [San14] and [Kar14].

6.1 Future work

It would be beneficial to develop several more test scripts in order to be able to get a better overview of a virtual or real vehicle. A recommendation of test procedures for future implementation are presented in table 6.1. The reason why this tests are recommended are in order to complete the overview of the vehicle behaviour and thereby increase the usefulness of the evaluation tool.

Table 6.1: Proposed test procedures for future implementation.

Test procedure:
Step input
Sinusoidal input, one period.
Pulse input
Braking with split coefficient of friction
Brake in turn
Straight braking
Random frequency response

This type of tool could as well be beneficial to present as an open source solution and make it available online. It could result in designers that uses the tool supplies scripts for different test procedures, as well as scripts for different types of result analysis.

Similar tools could as well be beneficial for evaluation of trucks, truck combinations, electric bikes and minicars, e.g. urban personal vehicles.

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A Example report BAPS model

Test object: Volvo_XC90_2011

Test conditions: ________________________

Reference number: BAPS 30-Nov-2014

Testdate: 2014-11-30 12:57:07

Contents

1 Steady State Cornering, SS-ISO 4138:2012

This test is preformed using steady state cornering according to SS-ISO 4138:2012. The used method within this case is the Constant speed method. The centripetal acceleration is obtained using the product of yaw velocity and horizontal velocity, as is described in section 9.2 b in SS-ISO 4138:2012

Table 1: List of runs and active tests

Run	Test type	Reason for ending
1	Steady State Cornering	Break due to high change in lateral acc.
2	Steady State Cornering	Break due to high change in lateral acc.

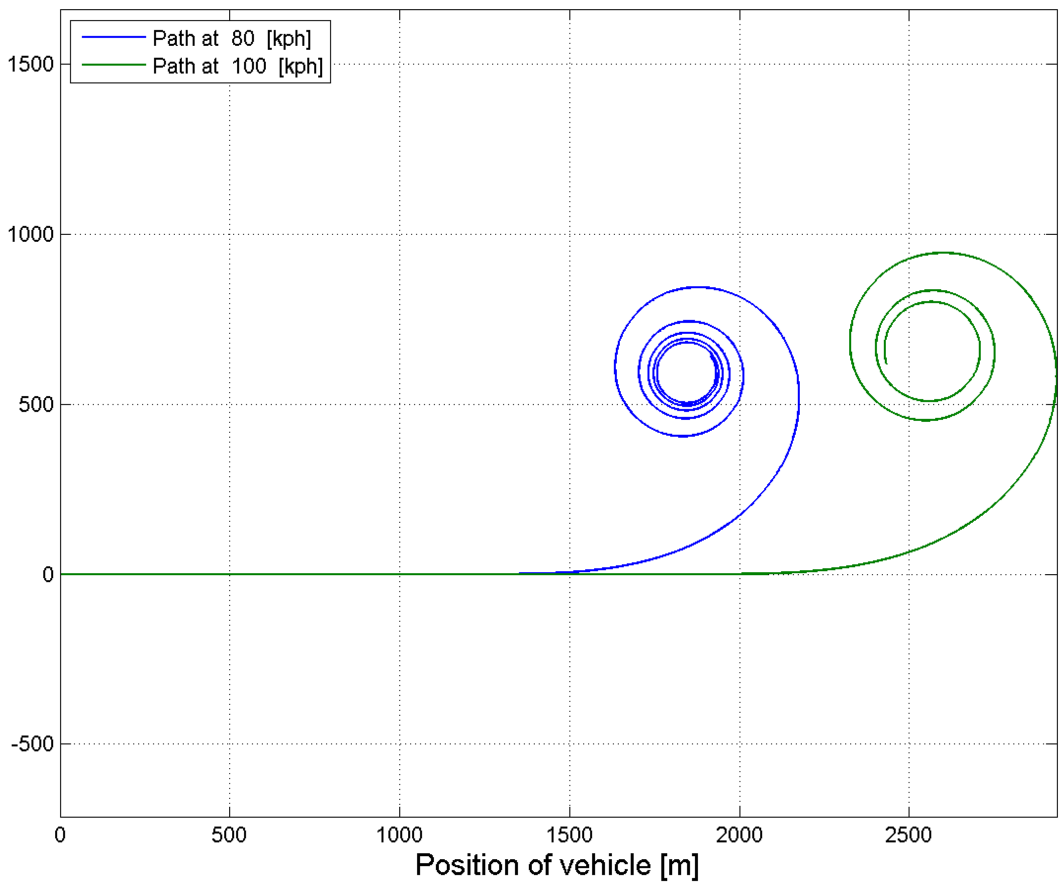


Figure 1: Displays the path for the different runs. All mesurements are in meters.

1.1 Longitudinal Velocity during test

This plot is not defined in ISO 4138:2012 Steady state cornering, however it is presented in order to display the variations in speed that occurs during this test.

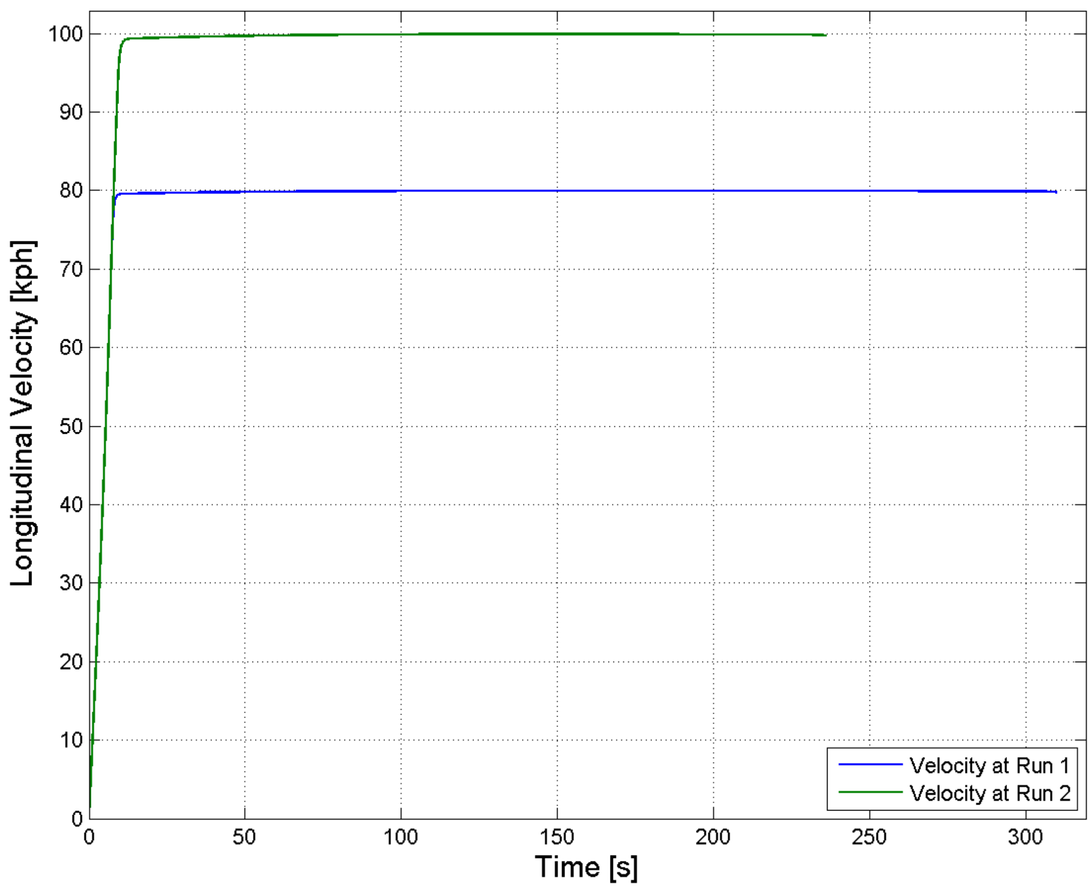


Figure 2: Longitudinal velocities during Steady State Cornering test. The maximum velocities were: Run 1: 80 [kph]. Run 2: 100 [kph]. And the final velocity were: Run 1: 80 [kph]. Run 2: 100 [kph].

1.2 Steering angle as function on lateral acceleration

Presented according to Steady State Cornering SS-ISO 4138:2012.

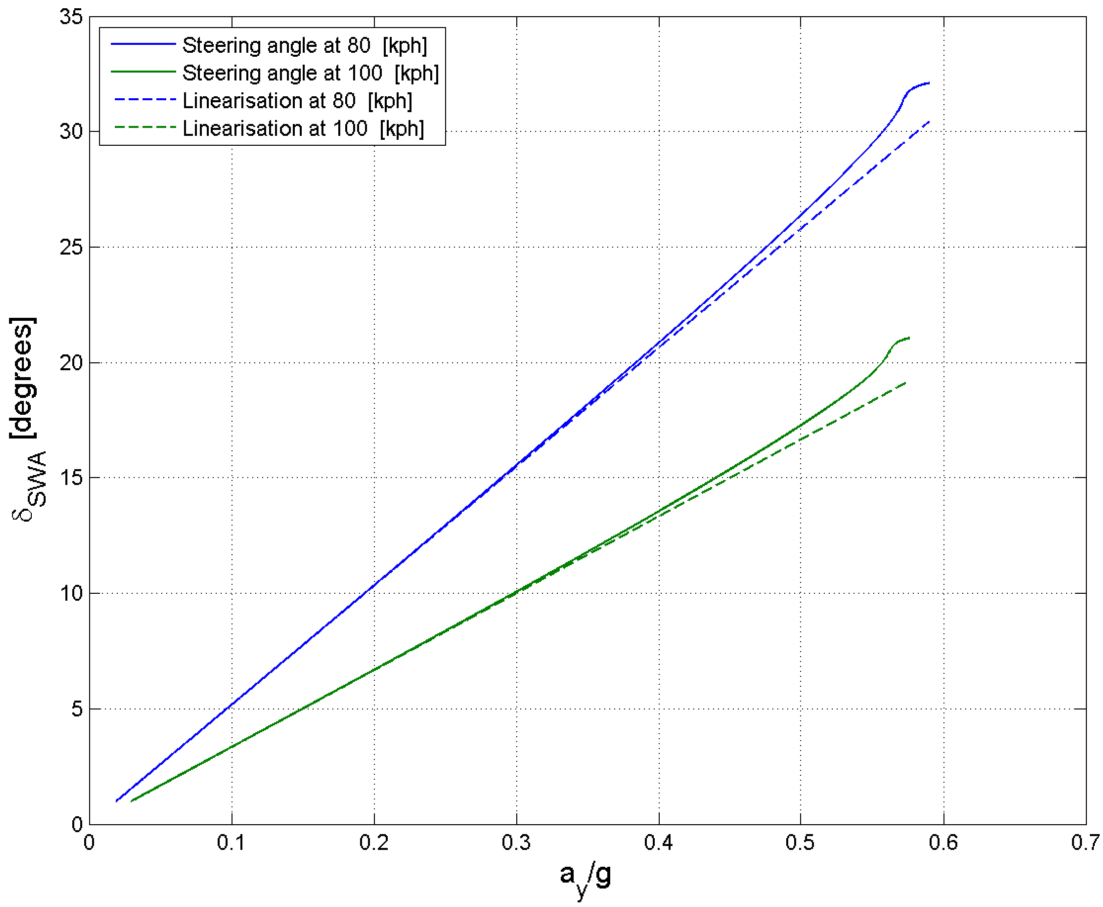


Figure 3: Steering angle as function of lateral acceleration in g. The graph shows as well the linearisation of the different runs. The displayed velocities in the legend is the maximum speed during the test.

1.2.1 Steering angle gradient as function on lateral acceleration

The gradient is calculated based on the change during one sample step divided with acceleration change during this sample and the corresponding acceleration vector is calculated as mean value during that the sample step.

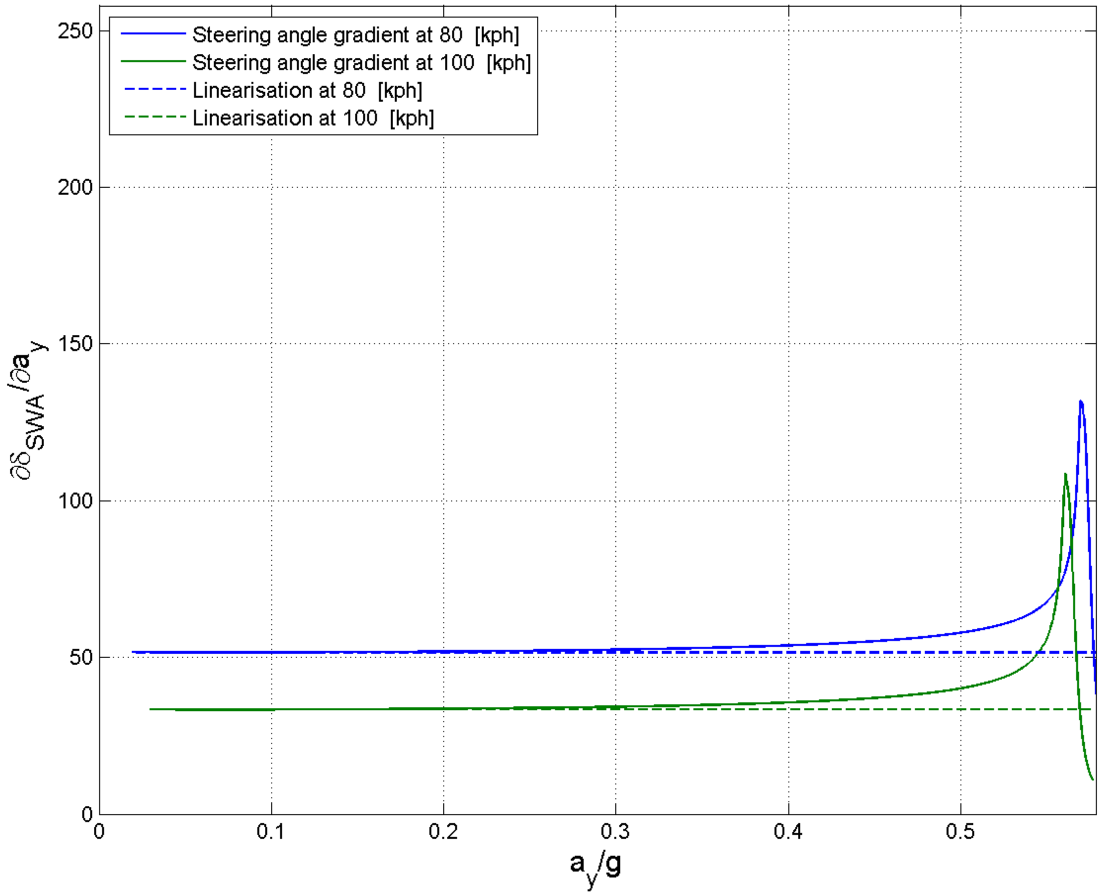


Figure 4: Steering angle gradient as function of lateral acceleration.

When using the reference speed of 80 [kph] the linearisation is represented by $51.59 * (a_y/g)$. When using the reference speed of 100 [kph] the linearisation is represented by $33.33 * (a_y/g)$.

1.3 Sideslip angle as function on lateral acceleration

Presented according to Steady State Cornering SS-ISO 4138:2012.

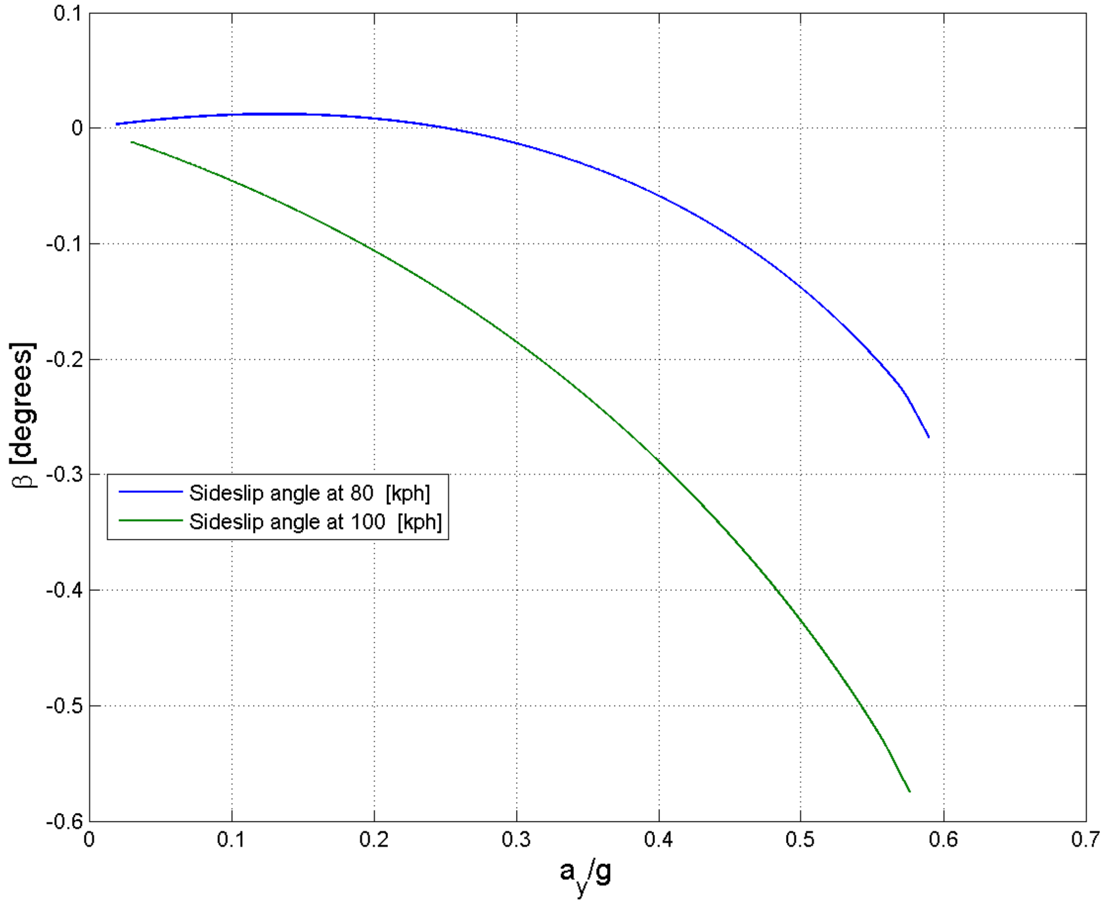


Figure 5: Side slip angle as function of lateral acceleration.

1.4 $(\alpha_r - \alpha_f)$ in relation to a_y/g

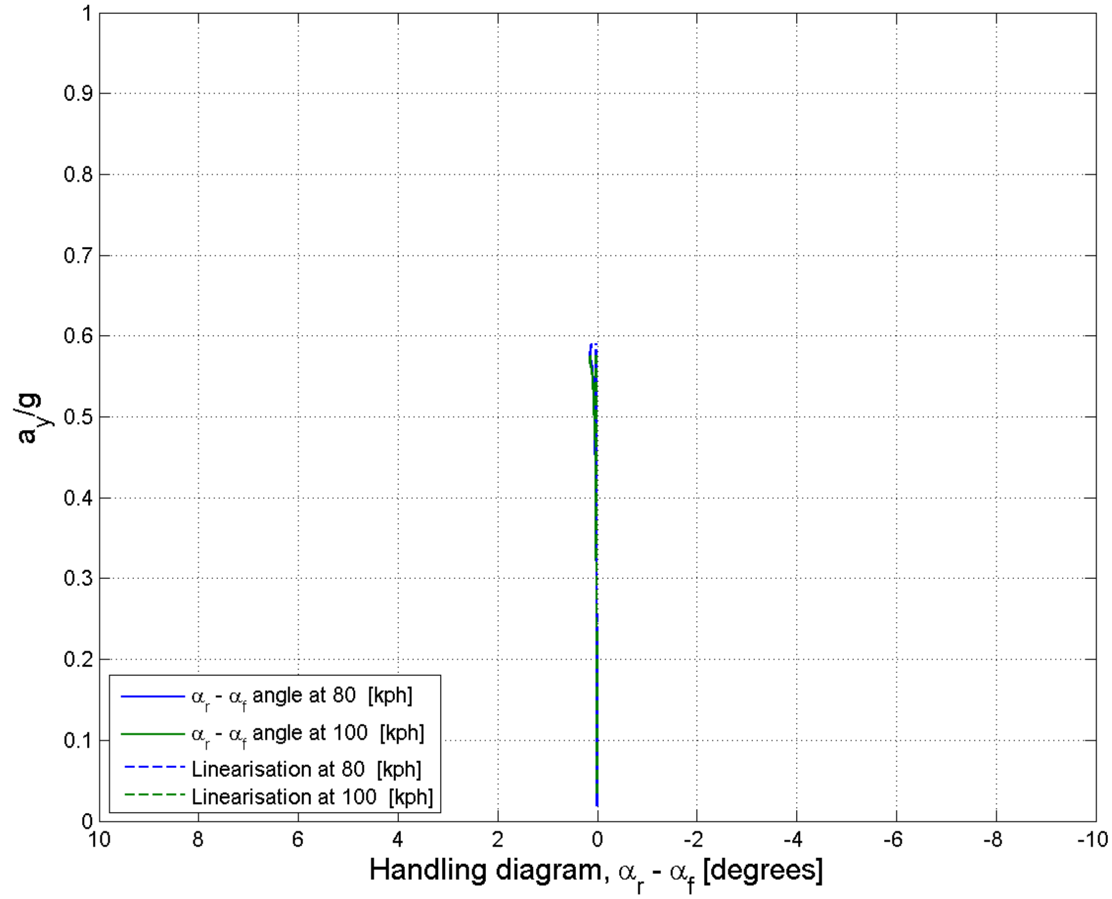


Figure 6: Showing the relation between slip angles and lateral acceleration as well as the linearisation.

When using the reference speed of 80 [kph] the linearisation is represented by $0.04 * (a_y/g)$.

When using the reference speed of 100 [kph] the linearisation is represented by $0.04 * (a_y/g)$.

2 Straight Ahead Acceleration

Table 2: List of runs and active tests

Run	Test type	Reason for ending
3	Straight Ahead Acceleration	Break due to too low longitudinal acc.

2.1 Longitudinal Velocity during test

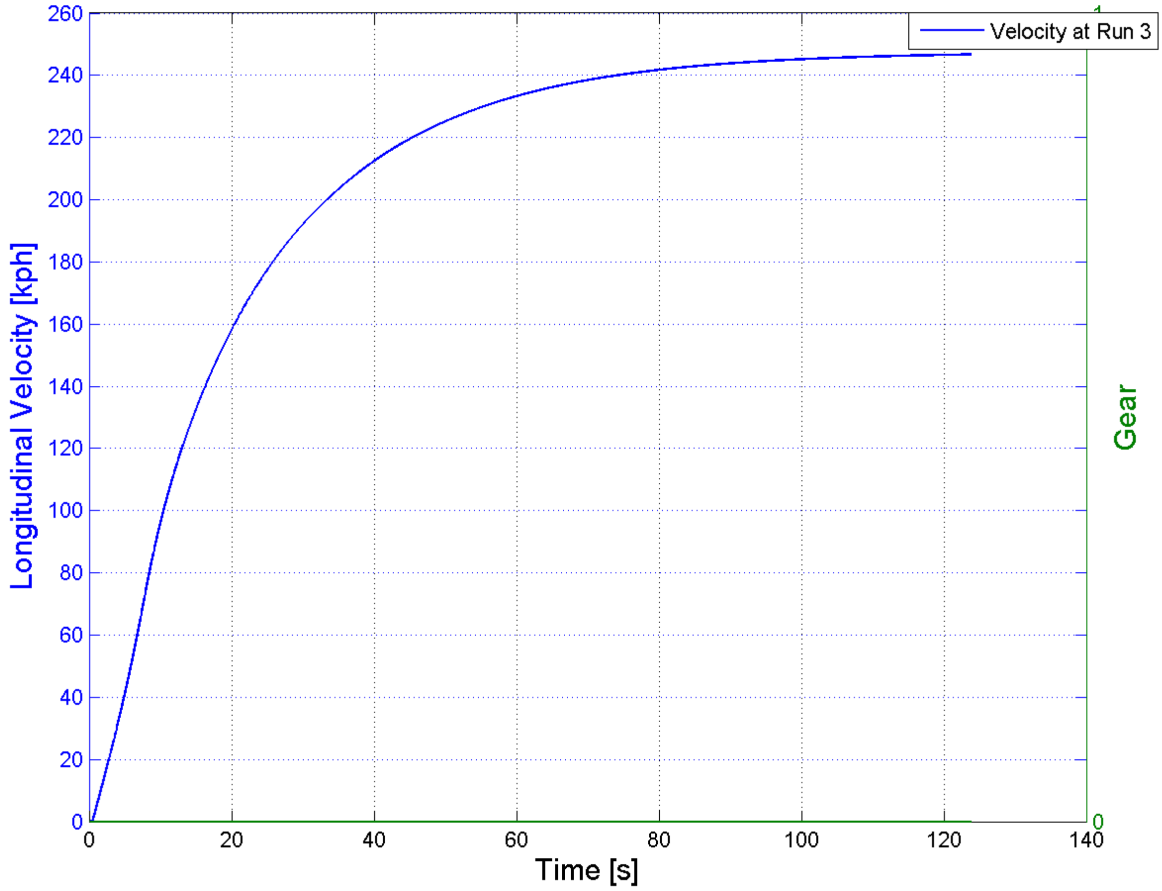


Figure 7: Longitudinal velocities acceleration test. The maximum velocity during the test were: Run 3: 247 [kph].

Table 3: Displayes time between two velocities during ongoing full acceleration.

Velocity change	Time, Run: 3
0-60 [kph]	6.79 [s]
0-100 [kph]	10.48 [s]
80-120 [kph]	4.56 [s]

Table 4: Time for traveling the 402 meters.

Distance	Time, Run: 3
402 [m]	18.09 [s]

2.2 Longitudinal Acceleration during test

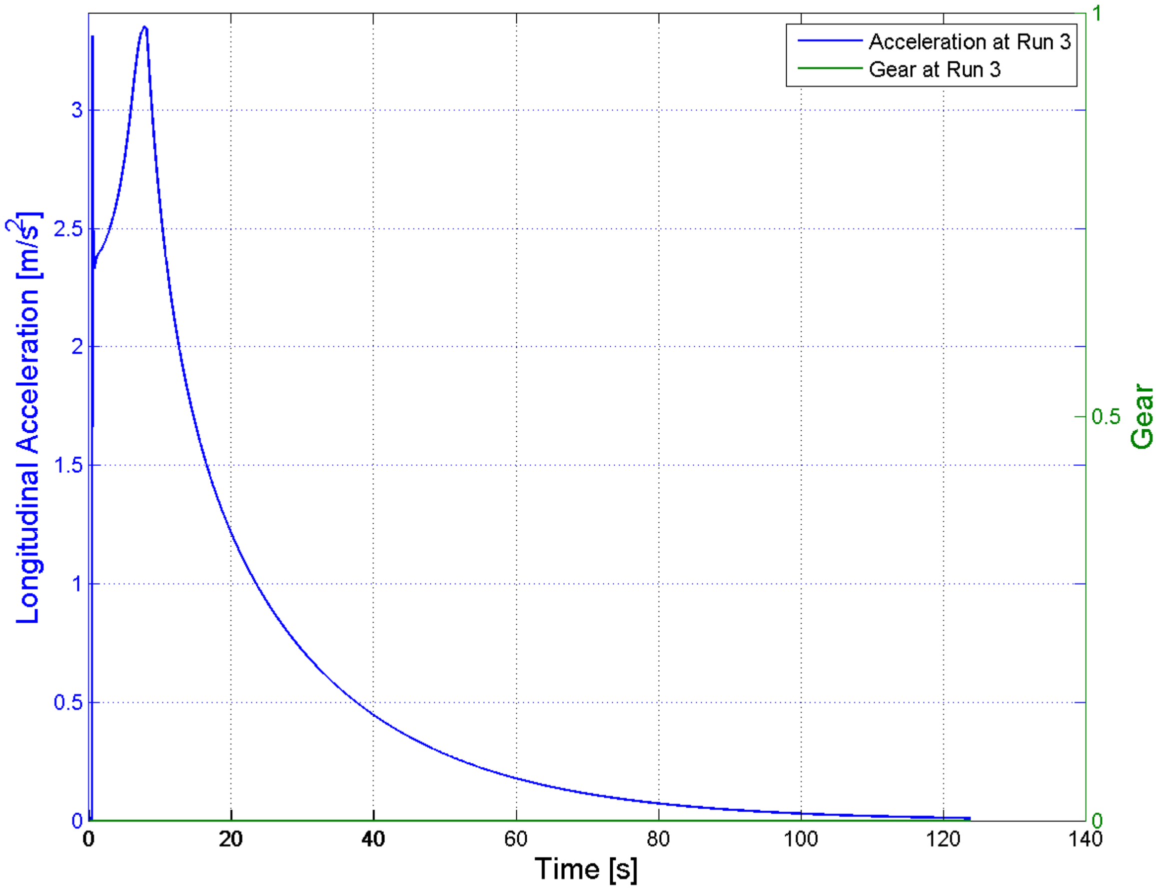


Figure 8: Longitudinal acceleration during test.

2.3 Acceleration at different velocities

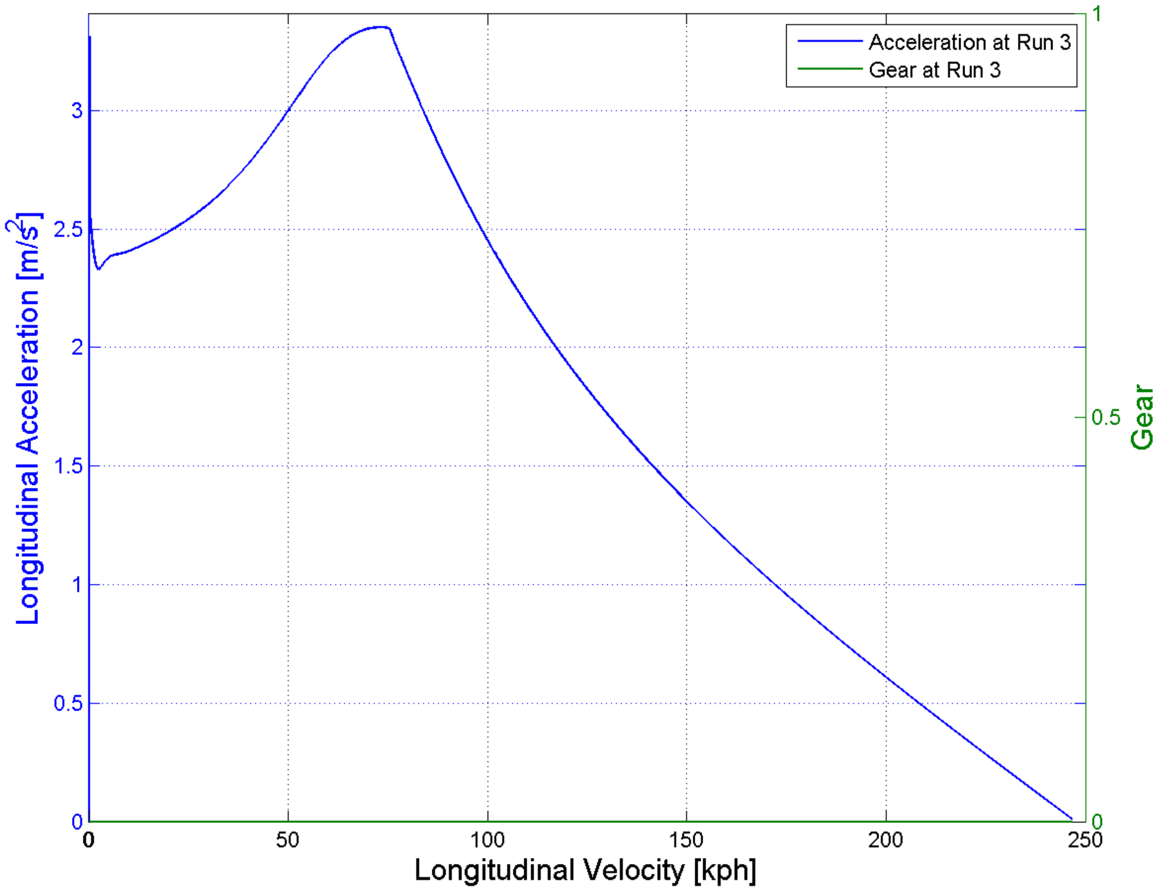


Figure 9: Longitudinal acceleration as a function of longitudinal velocity.

3 Sine With Dwell, FMVSS 126

This results are based on Laboratory Test Procedure for FMVSS 126, Electronic Stability Control System (TP-126-03, 9th Sept. 2011). The methods to calculate key-values ate displayed in section 13.10 in TP-126-03.

Table 5: List of runs and active tests

Run	Test type	Reason for ending
4	Sine with dwell	Break due to manoeuvre done.
5	Sine with dwell	Break due to manoeuvre done.
6	Sine with dwell	Break due to manoeuvre done.
7	Sine with dwell	Break due to manoeuvre done.

Table 6: Displays results from all sine withdwell test manoeuvre in terms of: Run number, Peak steering wheel angle, Peak yaw velocity, Yaw velocity criteria 1.00 seconds after completion of steering, Yaw velocity criteria 1.75 seconds after completion of steering, Lateral movement criteria.

Run	SWA	YawVel	COS+1.00[s]	COS+1.75[s]	Lat.movement
4	23	-0.20	Pass	Pass	Fail
5	31	-0.26	Pass	Pass	Fail
6	39	-0.34	Pass	Pass	Pass
7	47	-0.55	Fail	Fail	Pass

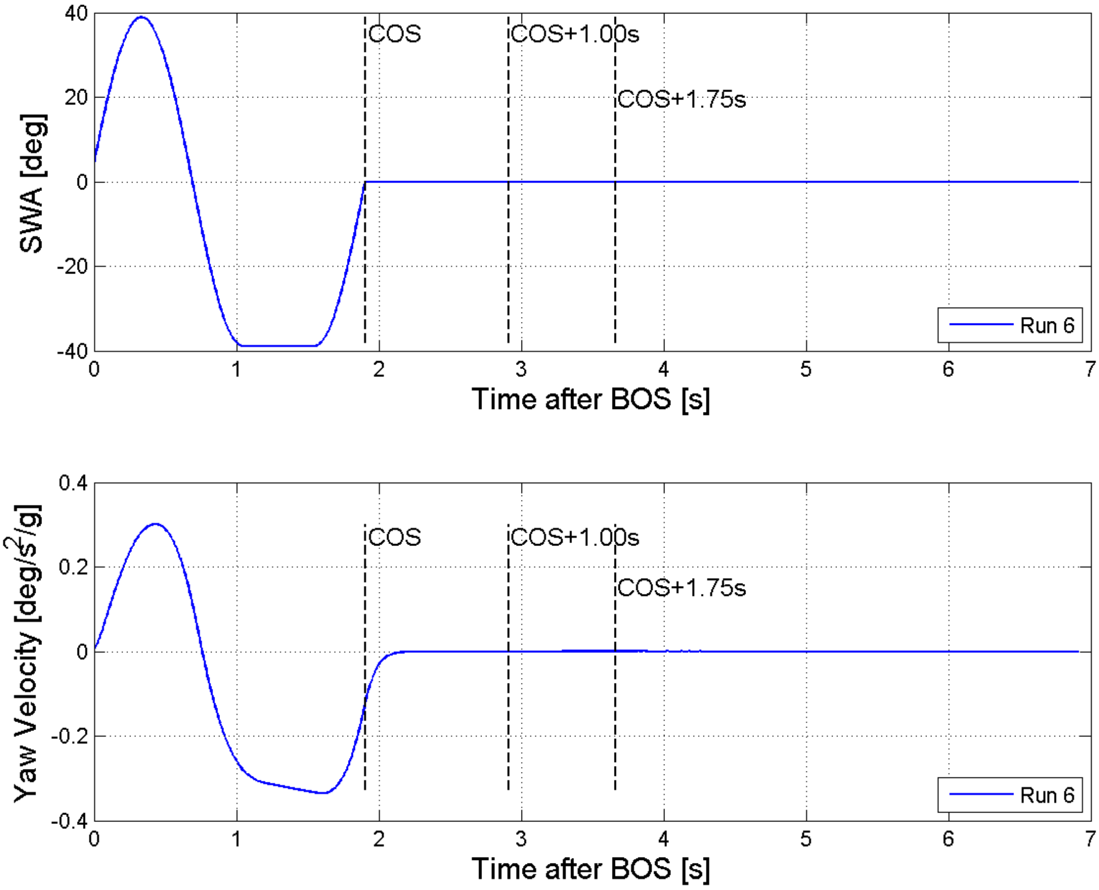


Figure 10: Steering wheel angle as well as Yaw velocity as a function of time after Beginning of steer (BOS). COS+Time shows time after Completion of steer (COS) which is used as test criteria.

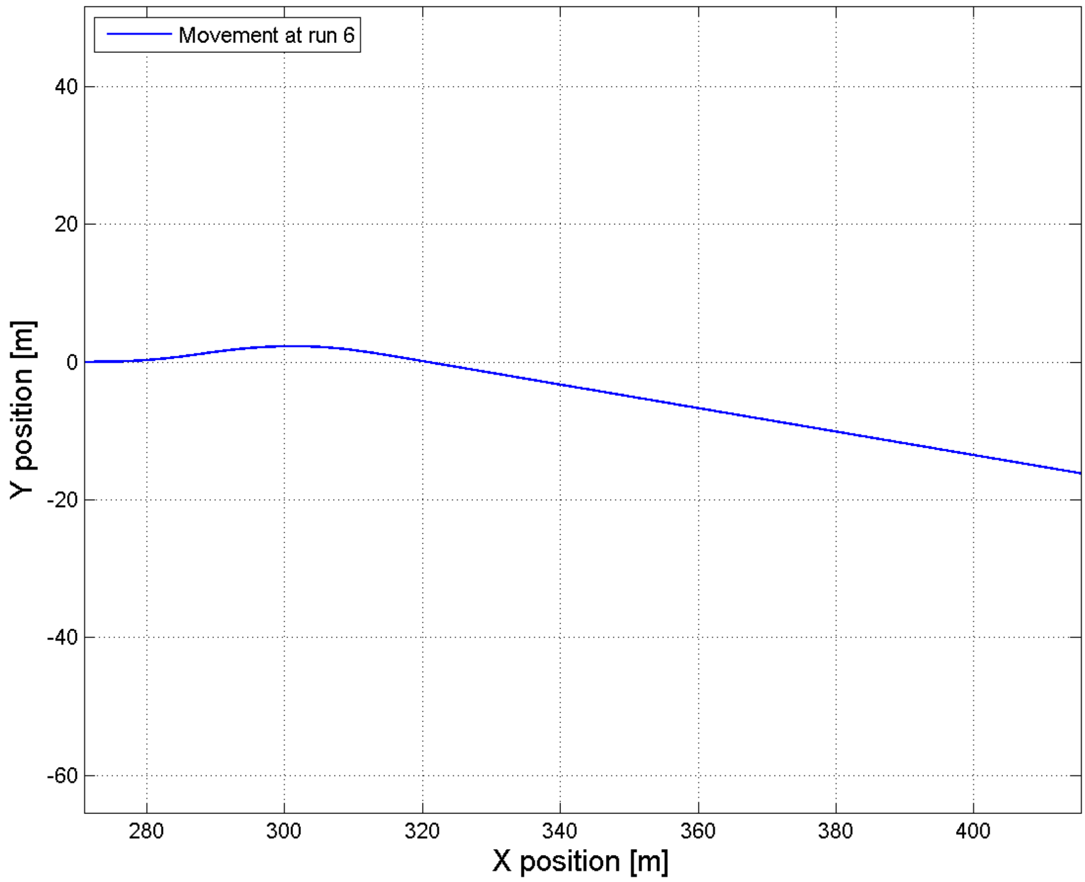


Figure 11: Vehicle movement during manoeuvre in Run 6.

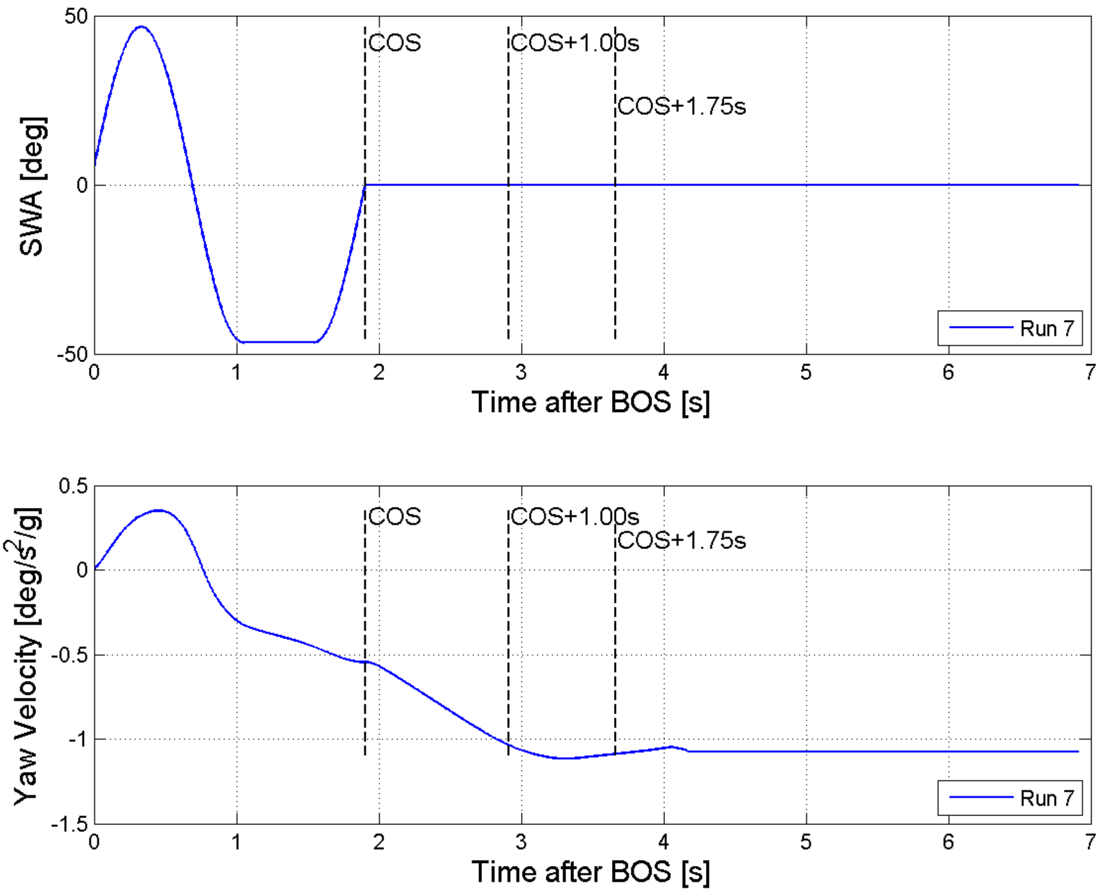


Figure 12: Steering wheel angle as well as Yaw velocity as a function of time after Beginning of steer (BOS). COS+Time shows time after Completion of steer (COS) which is used as test criteria.

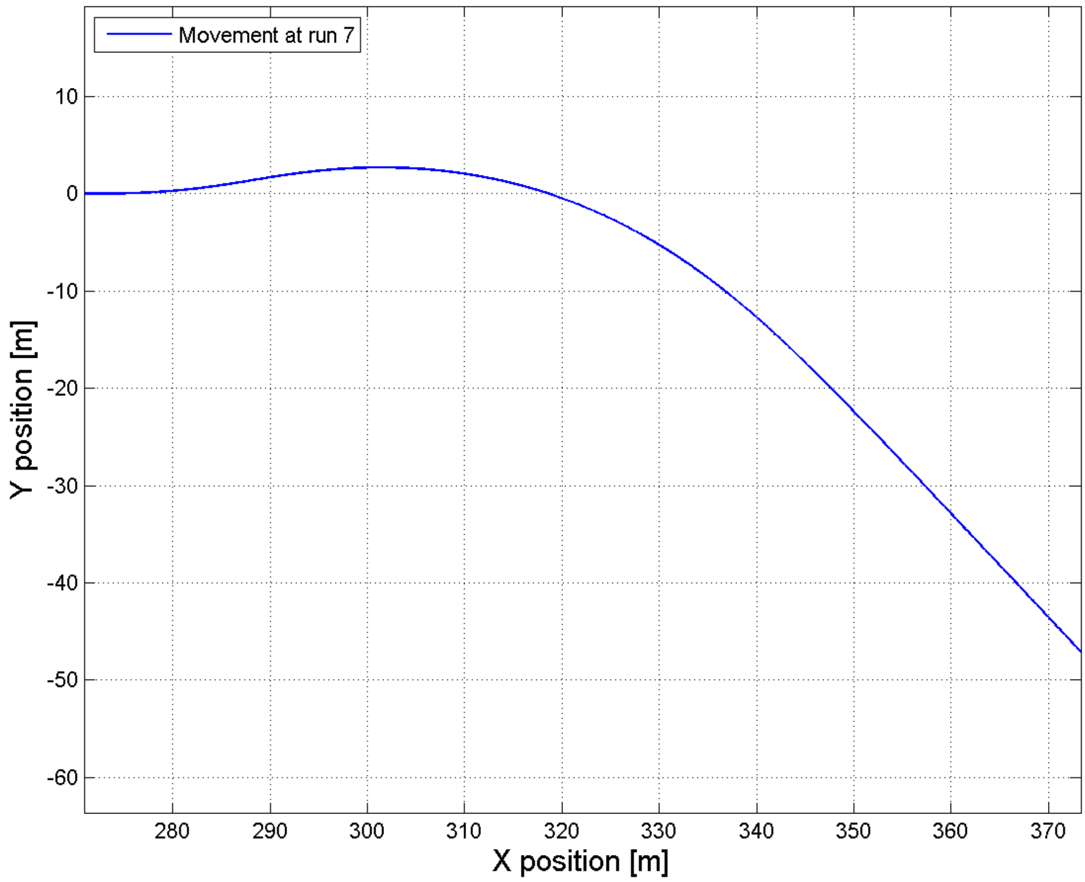


Figure 13: Vehicle movement during manoeuvre in Run 7.

4 Frequency response, SS-ISO 7401:2011

This results are based on Frequency response from SS-ISO 7401:2011 It is valid according to SS-ISO 7401:2011 for evaluating Continuous sinusoidal input or Random input.

Table 7: List of runs and active tests

Run	Test type	Reason for ending
8	Continuous sinusoidal input	Break due to end of simulation time.

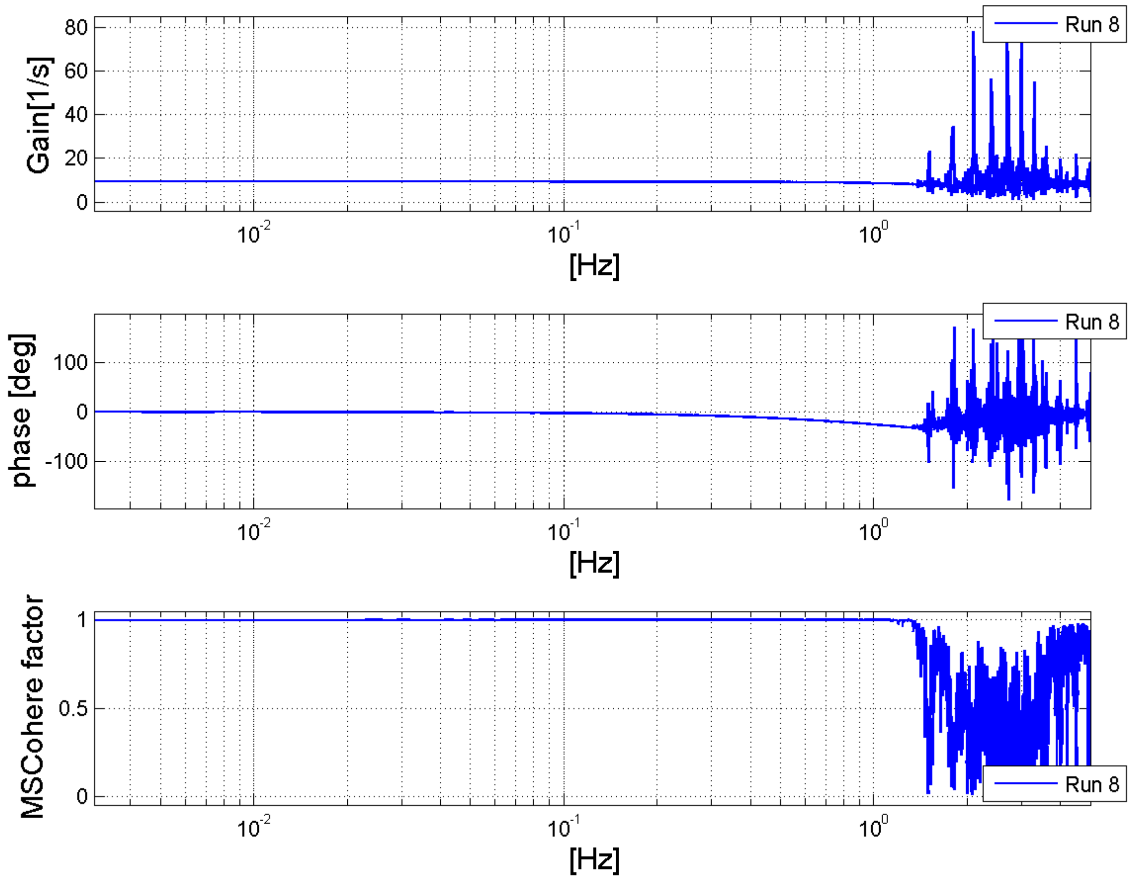


Figure 14: This graph presents steering wheel angle, phase angle and coherence as a function of frequecy.

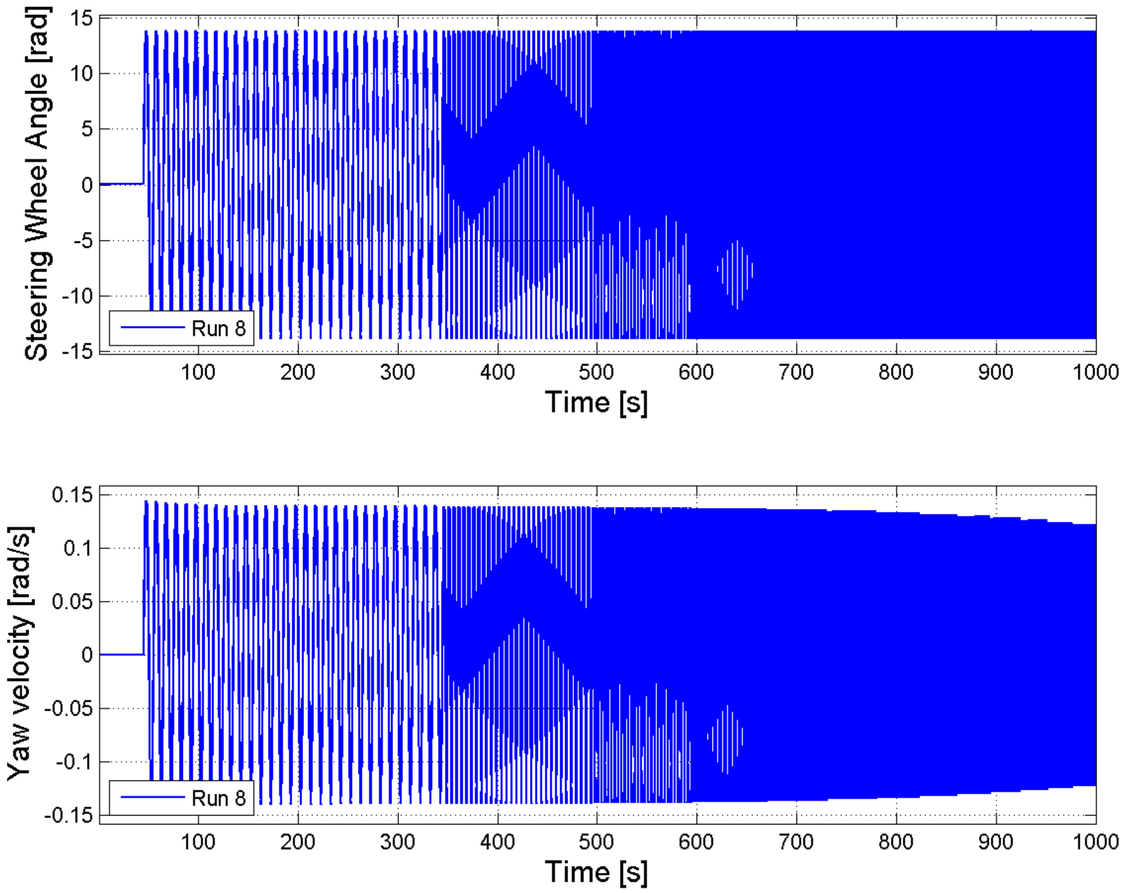


Figure 15: Steering wheel angle as well as Yaw velocity as a function of time after Beginning of steer (BOS). COS+Time shows time after Completion of steer (COS) which is used as test criteria.

B Example report SAAB Sim whith ESC and EVAL

Test object: Model Saab 9.3

Test conditions: ________________________

Reference number: model_4wheel_engine_ESC 01-Dec-2014

Testdate: 2014-12-01 21:20:22

Contents

1 Steady State Cornering, SS-ISO 4138:2012

This test is preformed using steady state cornering according to SS-ISO 4138:2012. The used method within this case is the Constant speed method. The centripetal acceleration is obtained using the product of yaw velocity and horizontal velocity, as is described in section 9.2 b in SS-ISO 4138:2012

Table 1: List of runs and active tests

Run	Test type	Reason for ending
1	Steady State Cornering	Break due to end of simulation time.
2	Steady State Cornering	Break due to end of simulation time.

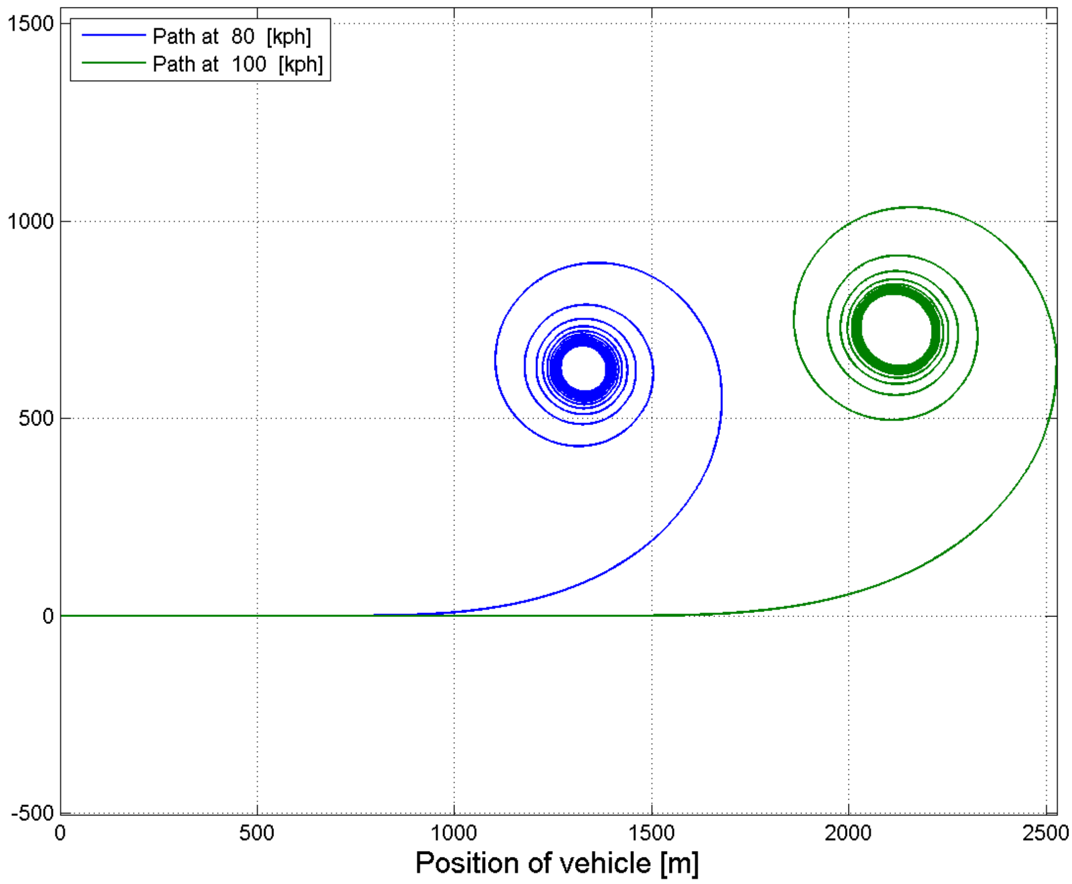


Figure 1: Displays the path for the different runs. All mesurements are in meters.

1.1 Longitudinal Velocity during test

This plot is not defined in ISO 4138:2012 Steady state cornering, however it is presented in order to display the variations in speed that occurs during this test.

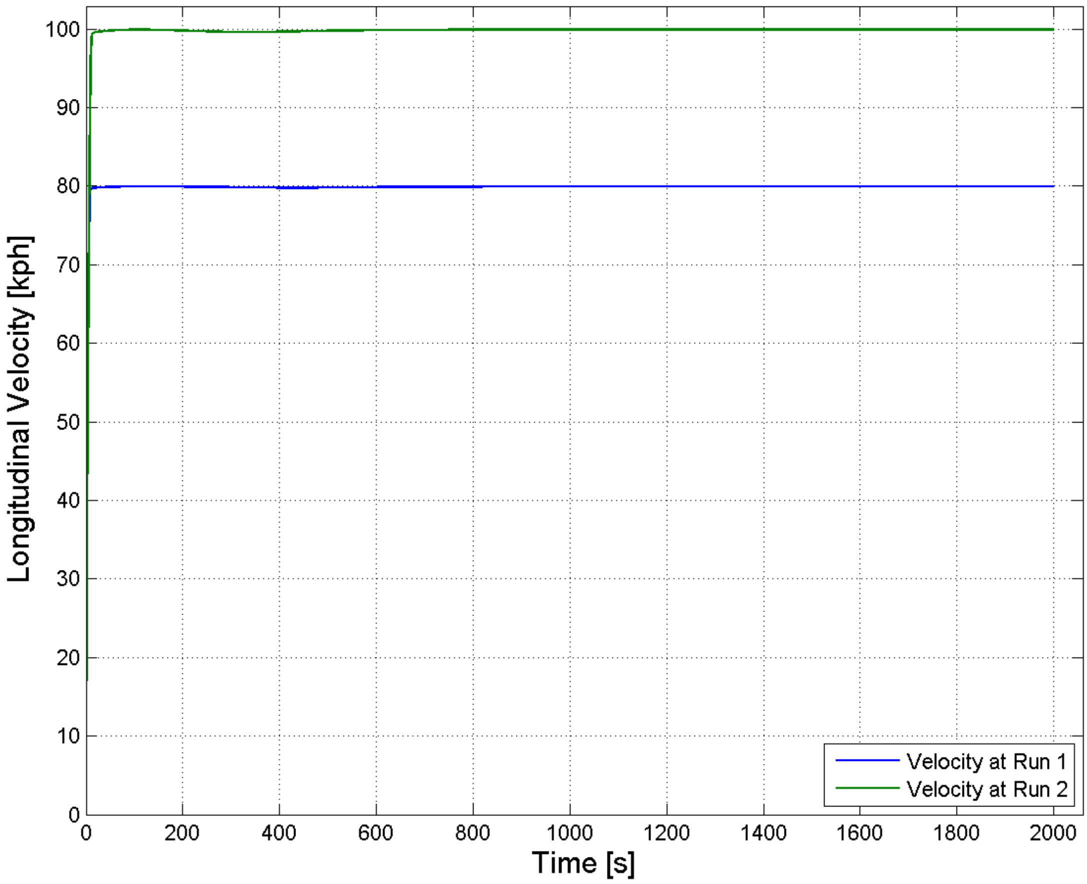


Figure 2: Longitudinal velocities during Steady State Cornering test. The maximum velocities were: Run 1: 80 [kph]. Run 2: 100 [kph]. And the final velocity were: Run 1: 80 [kph]. Run 2: 100 [kph].

1.2 Steering angle as function on lateral acceleration

Presented according to Steady State Cornering SS-ISO 4138:2012.

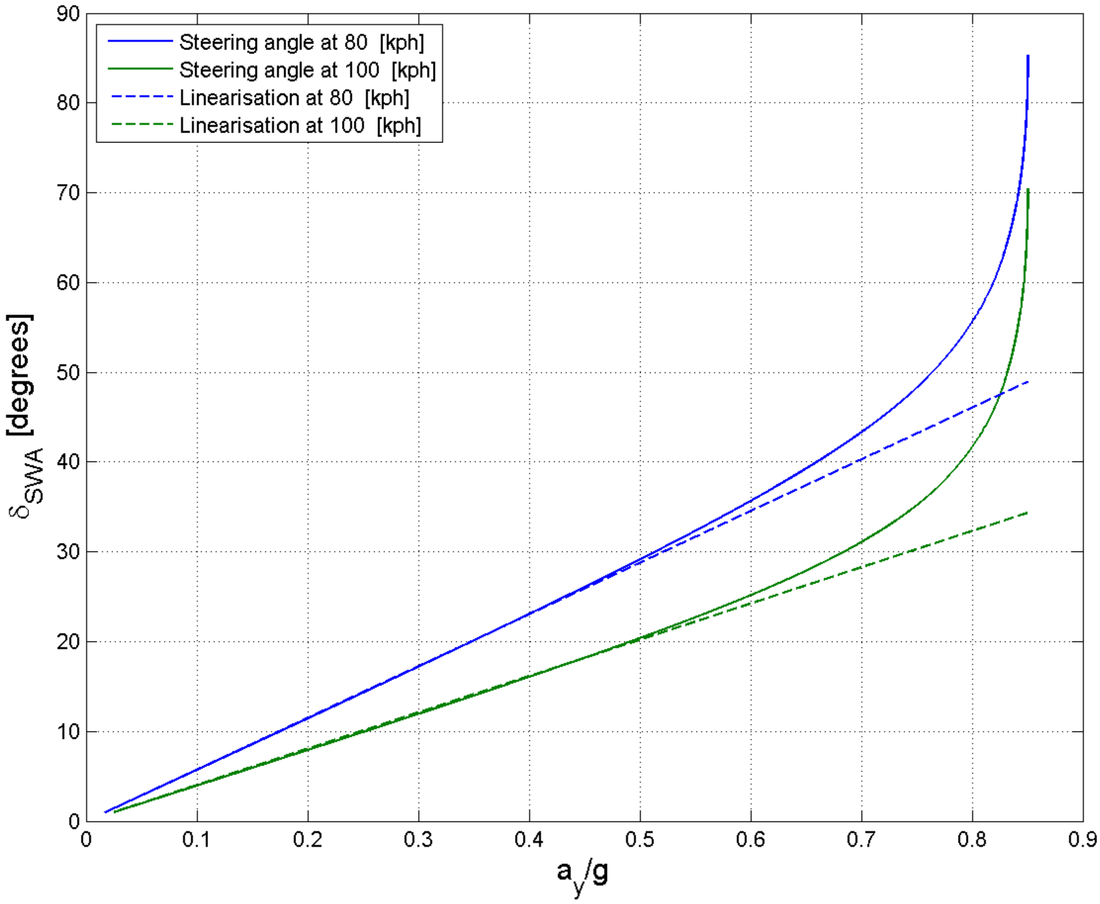


Figure 3: Steering angle as function of lateral acceleration in g. The graph shows as well the linearisation of the different runs. The displayed velocities in the legend is the maximum speed during the test.

1.2.1 Steering angle gradient as function on lateral acceleration

The gradient is calculated based on the change during one sample step divided with acceleration change during this sample and the corresponding acceleration vector is calculated as mean value during that the sample step.

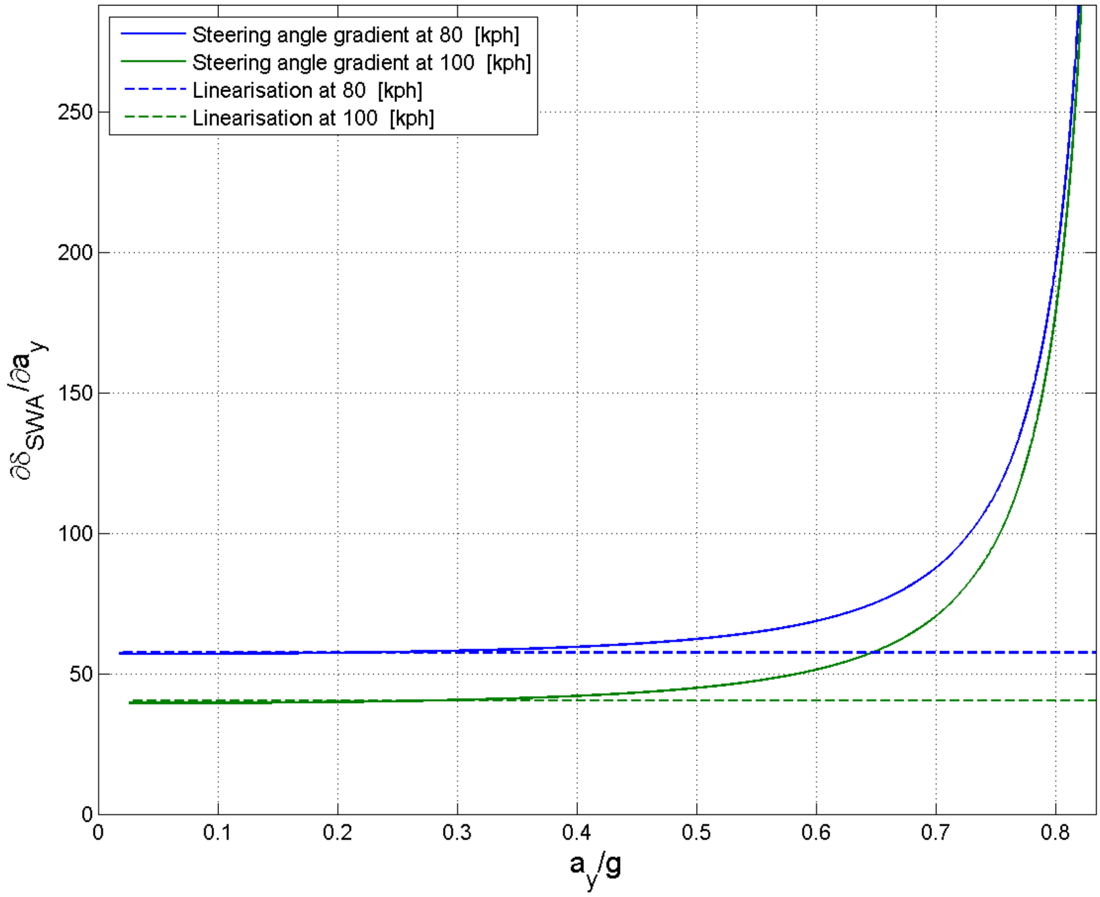


Figure 4: Steering angle gradient as function of lateral acceleration.

When using the reference speed of 80 [kph] the linearisation is represented by $57.58 * (a_y/g)$. When using the reference speed of 100 [kph] the linearisation is represented by $40.41 * (a_y/g)$.

1.3 Sideslip angle as function on lateral acceleration

Presented according to Steady State Cornering SS-ISO 4138:2012.

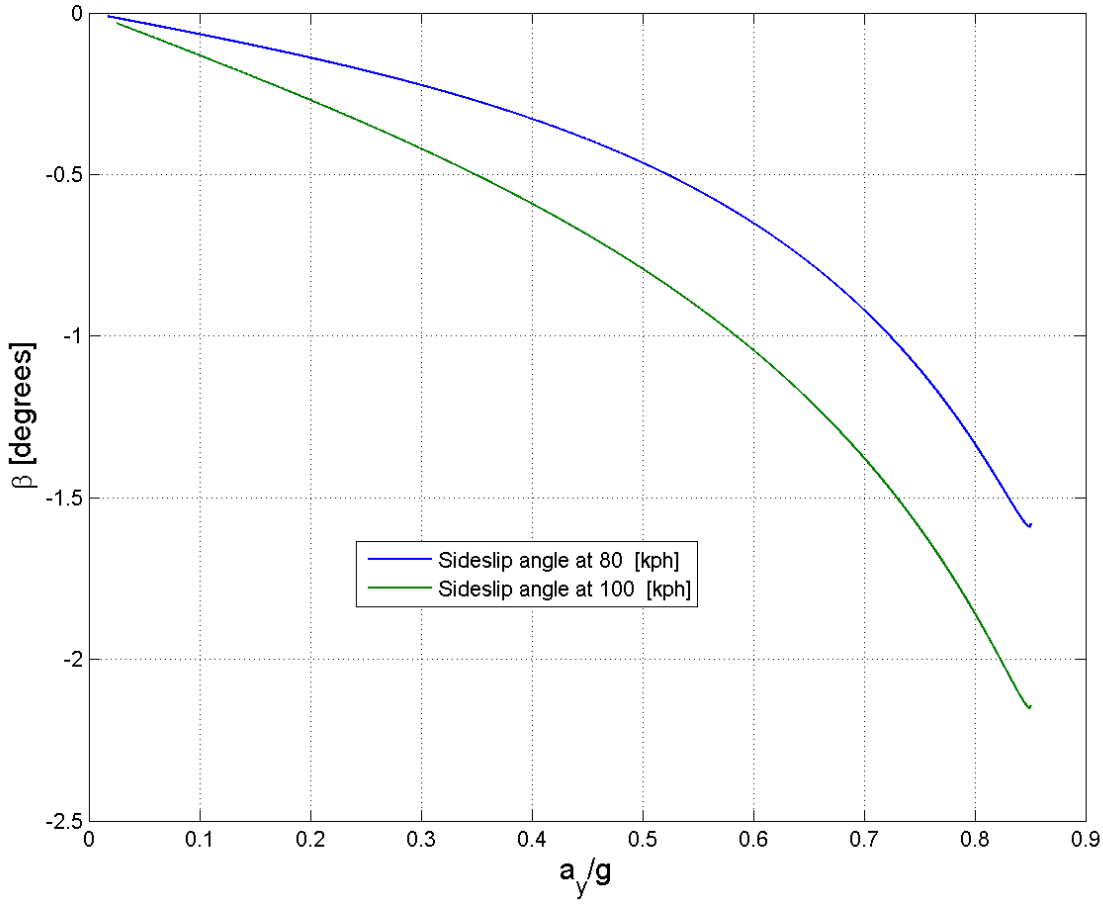


Figure 5: Side slip angle as function of lateral acceleration.

1.4 $(\alpha_r - \alpha_f)$ in relation to a_y/g

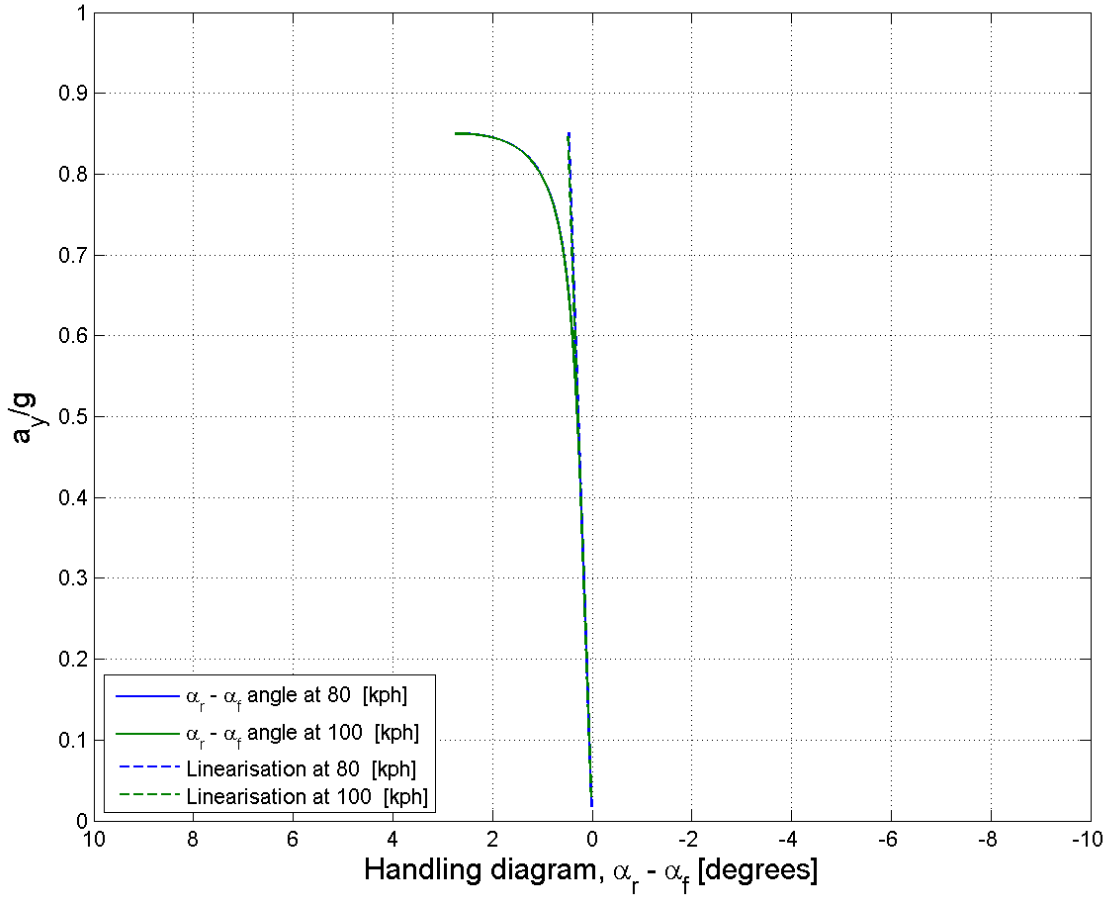


Figure 6: Showing the relation between slip angles and lateral acceleration as well as the linearisation.

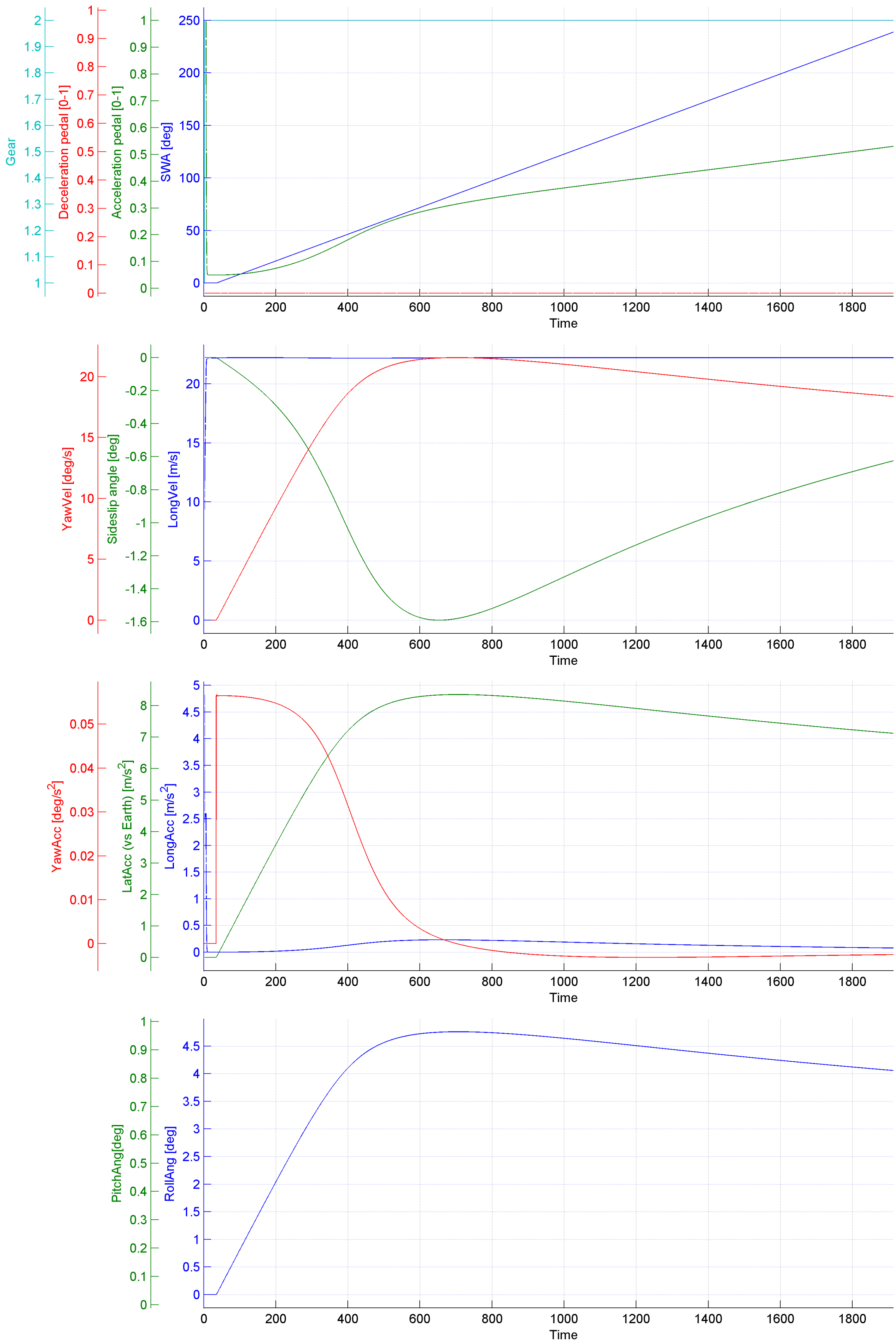
When using the reference speed of 80 [kph] the linearisation is represented by $0.55 * (a_y/g)$.

When using the reference speed of 100 [kph] the linearisation is represented by $0.57 * (a_y/g)$.

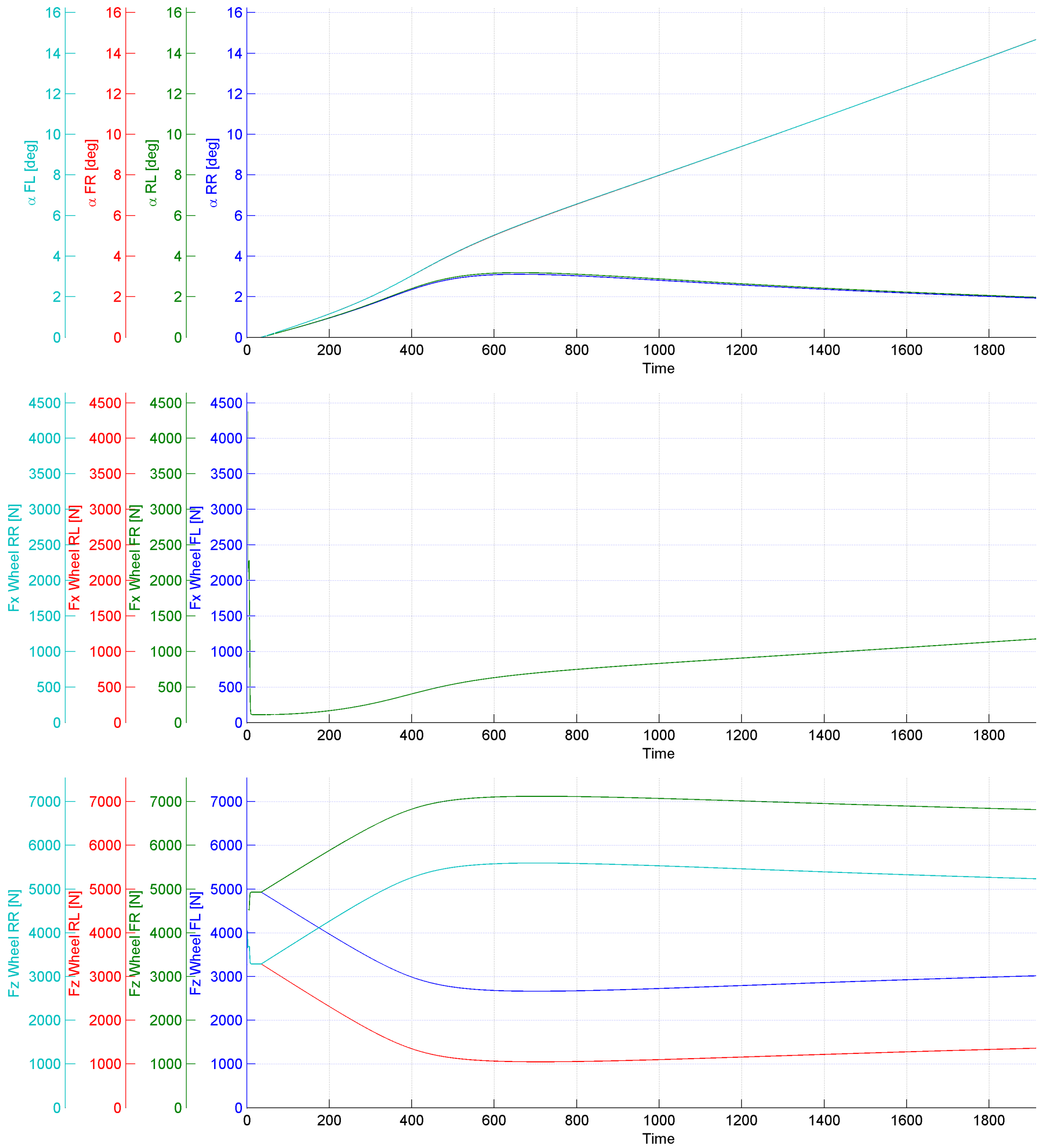
1.5 Test Evaluation plots:

Show summary of key values in order to verify the results.

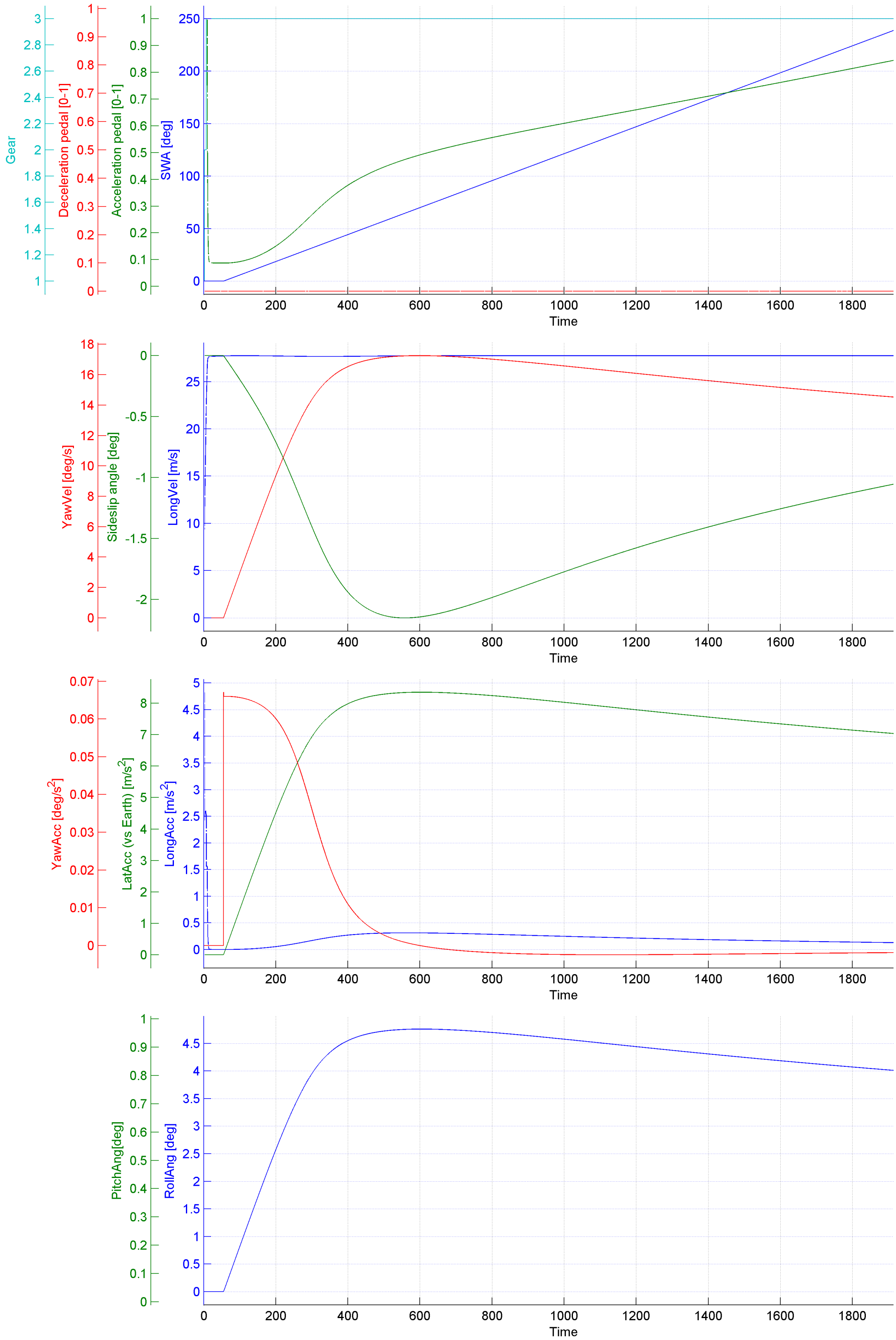
1.5.1 Evaluation plot from run:1



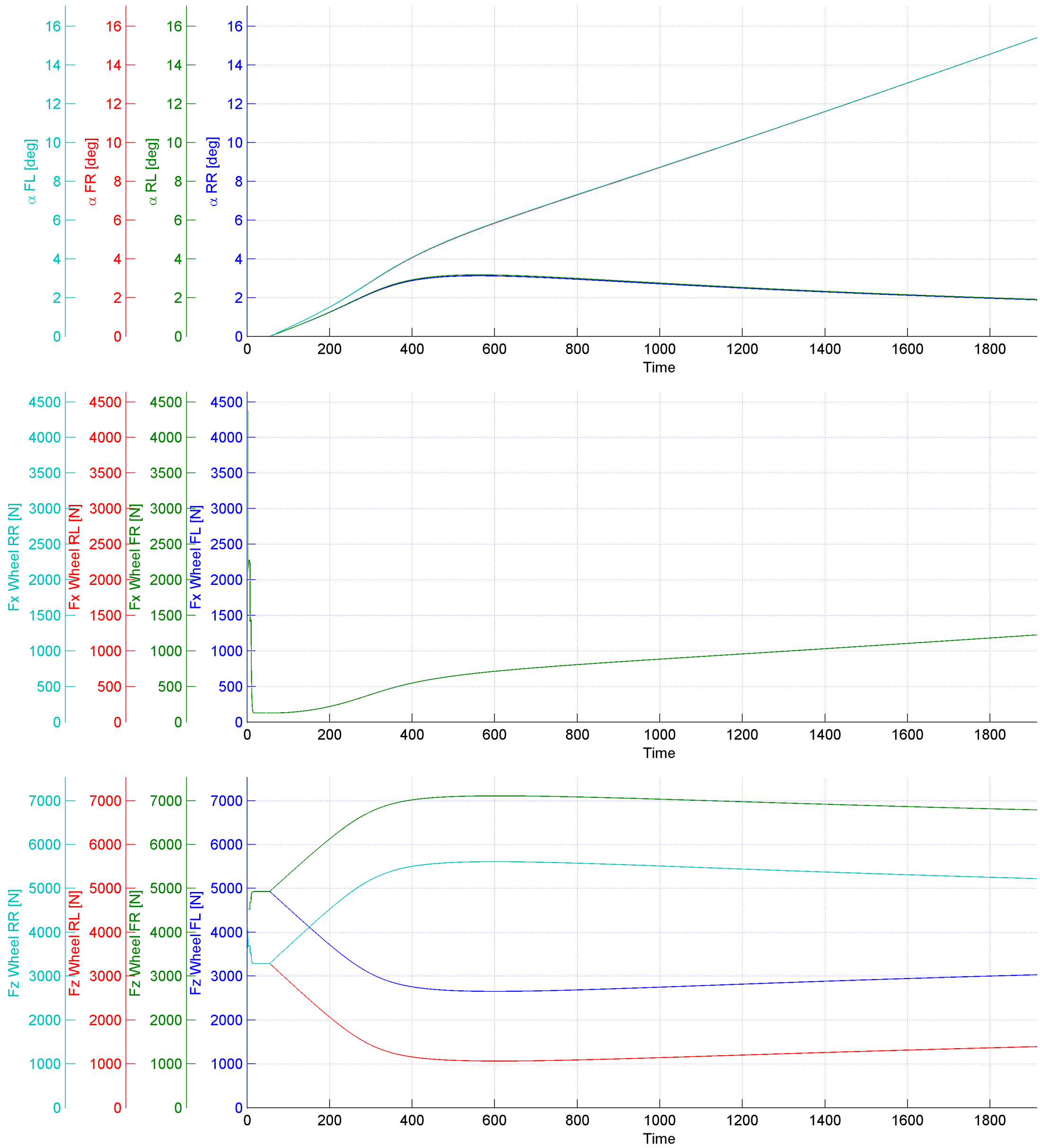
1.5.2 Evaluation plot from run:1



1.5.3 Evaluation plot from run:2



1.5.4 Evaluation plot from run:2



2 Straight Ahead Acceleration

Table 2: List of runs and active tests

Run	Test type	Reason for ending
3	Straight Ahead Acceleration	Break due to too low longitudinal acc.

2.1 Longitudinal Velocity during test

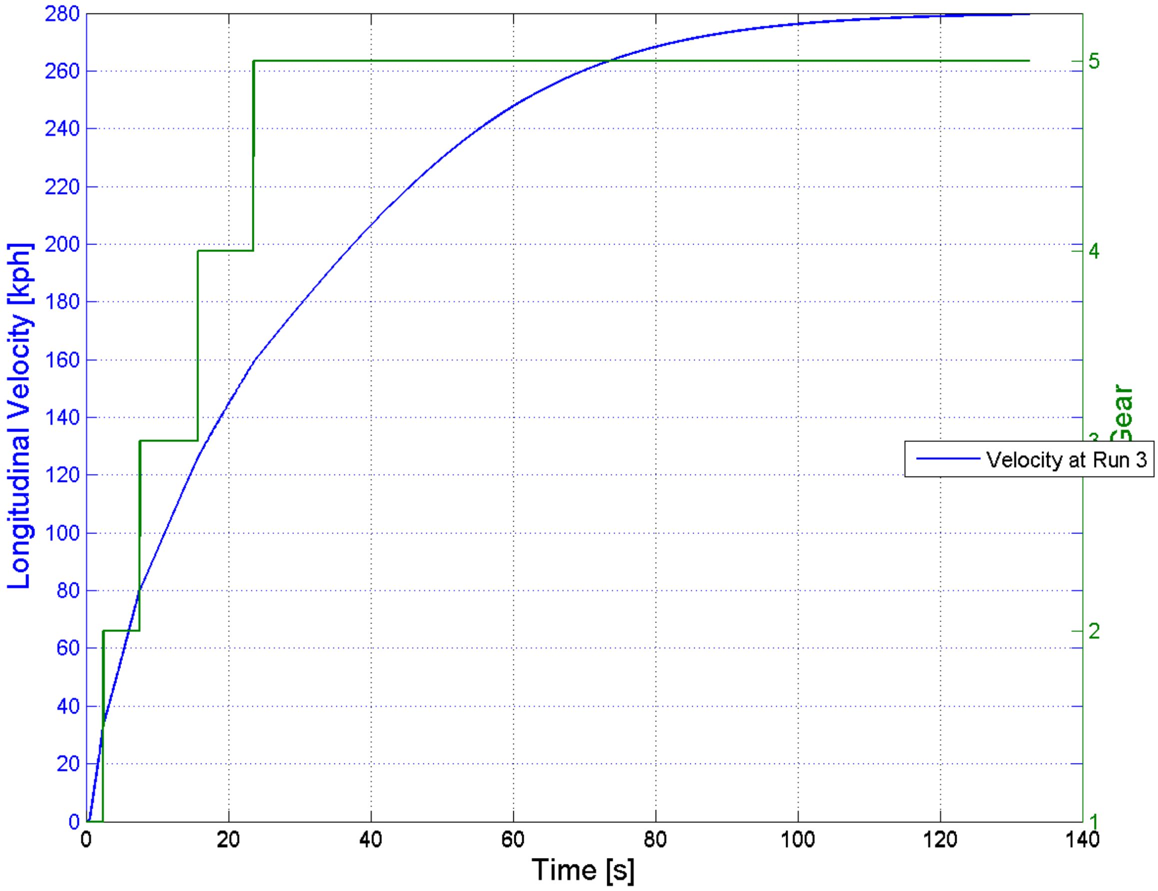


Figure 7: Longitudinal velocities acceleration test. The maximum velocity during the test were: Run 3: 280 [kph].

Table 3: Displayes time between two velocities during ongoing full acceleration.

Velocity change	Time, Run: 3
0-60 [kph]	5.39 [s]
0-100 [kph]	11.04 [s]
80-120 [kph]	7.05 [s]

Table 4: Time for traveling the 402 meters.

Distance	Time, Run: 3
402 [m]	17.88 [s]

2.2 Longitudinal Acceleration during test

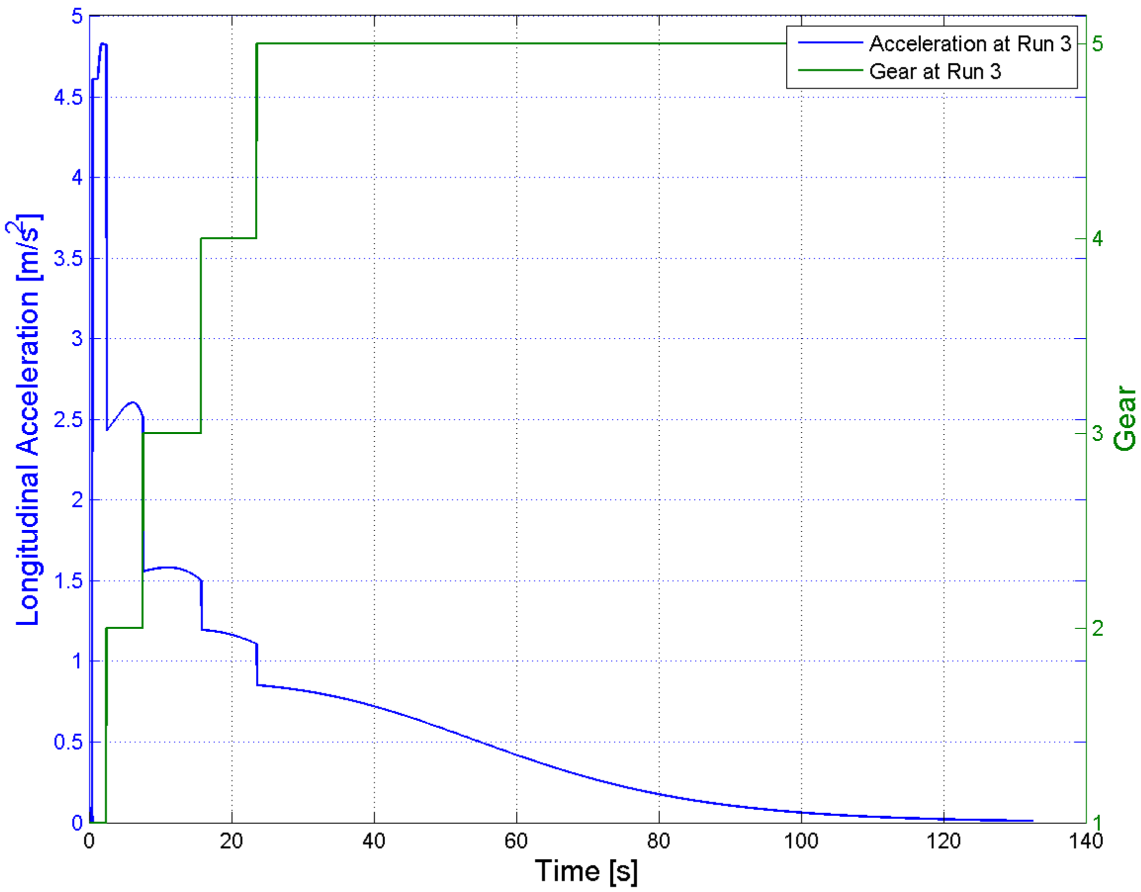


Figure 8: Longitudinal acceleration during test.

2.3 Acceleration at different velocities

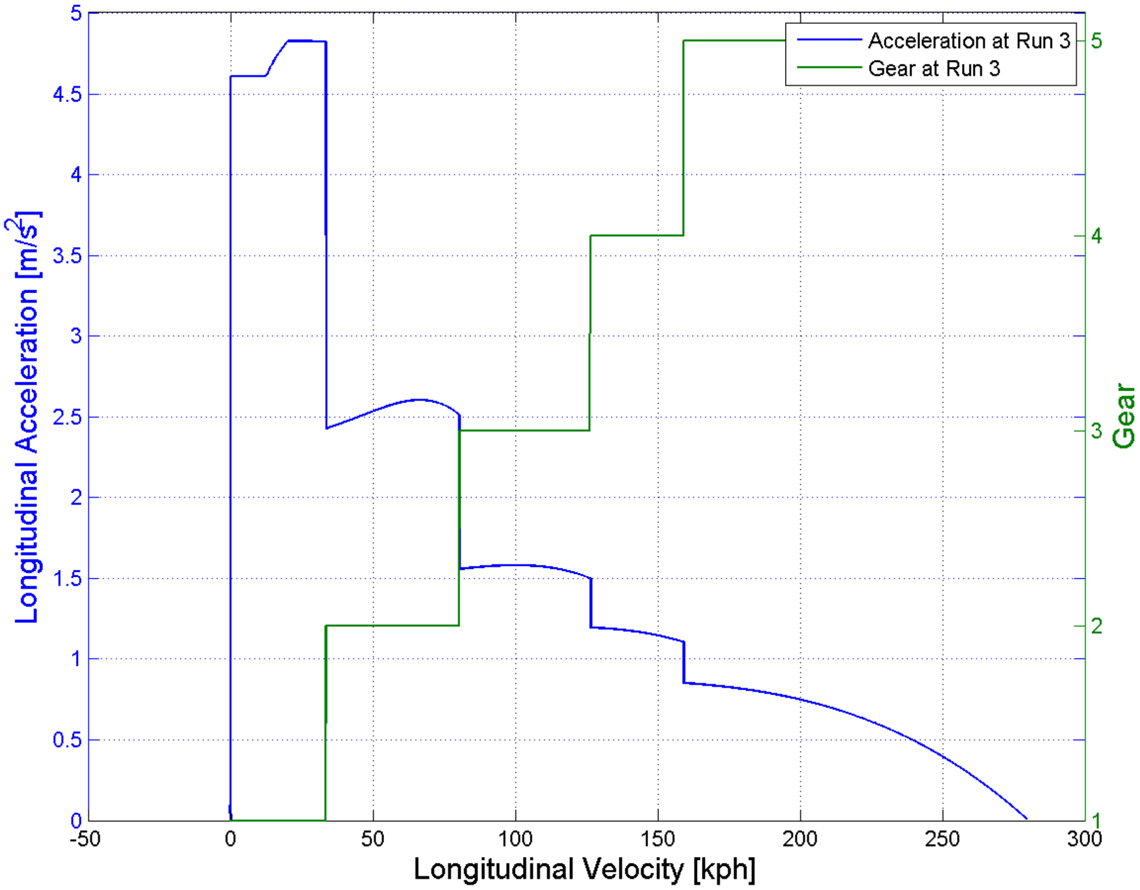
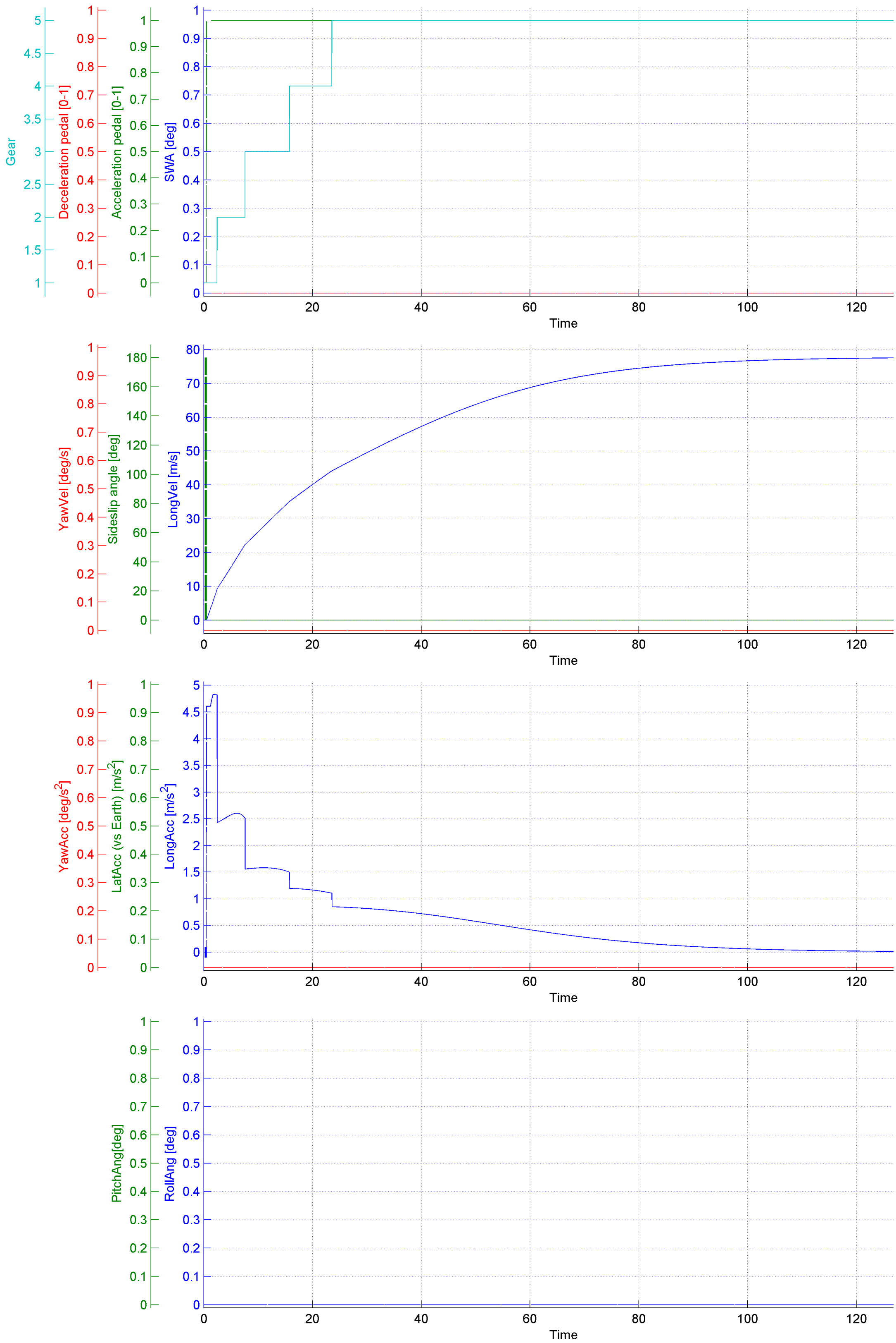


Figure 9: Longitudinal acceleration as a function of longitudinal velocity.

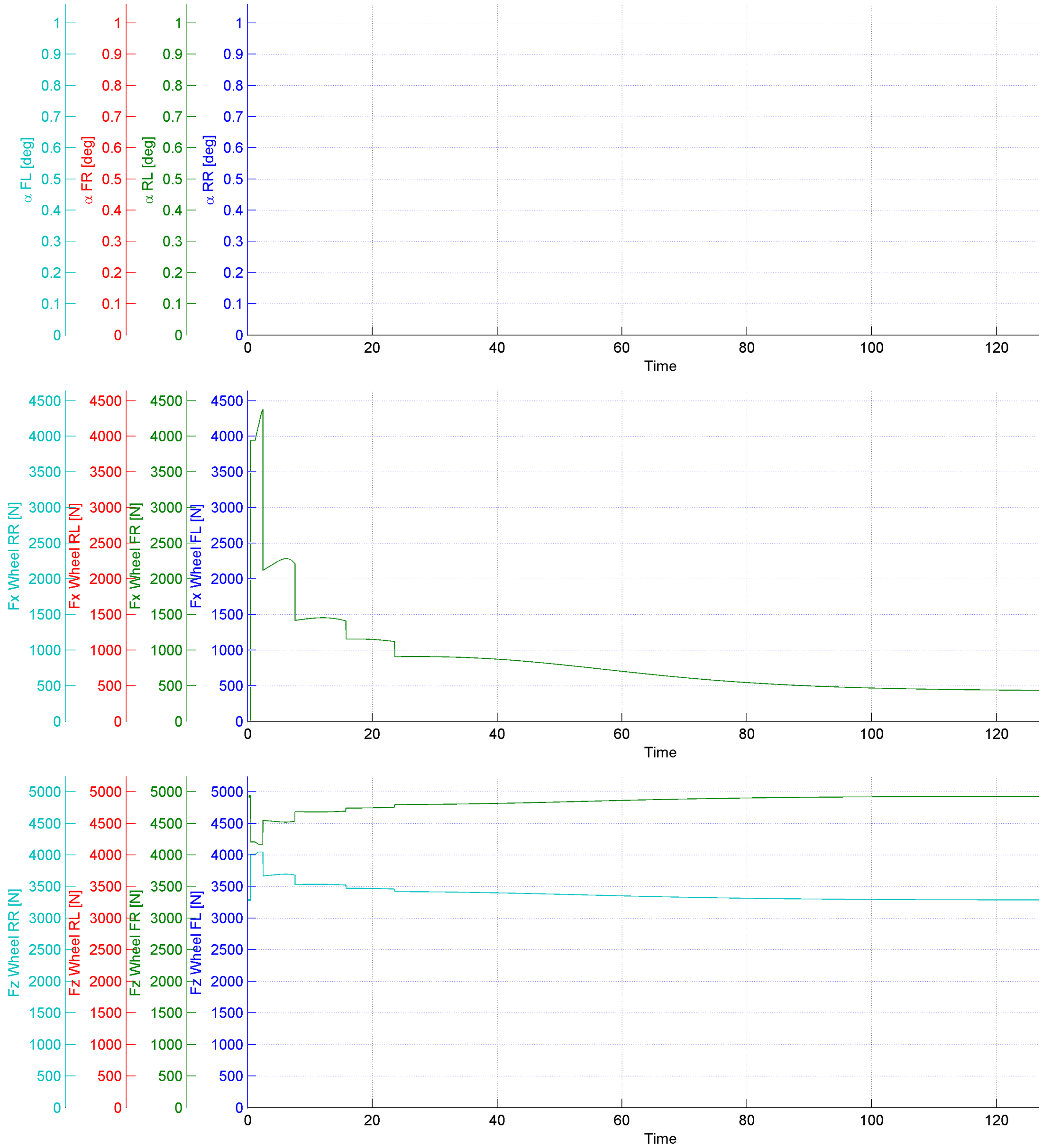
2.4 Test Evaluation plots:

Show summary of key values in order to verify the results.

2.4.1 Evaluation plot from run:3



2.4.2 Evaluation plot from run:3



3 Sine With Dwell, FMVSS 126

This results are based on Laboratory Test Procedure for FMVSS 126, Electronic Stability Control System (TP-126-03, 9th Sept. 2011). The methods to calculate key-values ate displayed in section 13.10 in TP-126-03.

Table 5: List of runs and active tests

Run	**Test type**	**Reason for ending**
4	Sine with dwell	Break due to manoeuvre done.
5	Sine with dwell	Break due to manoeuvre done.
6	Sine with dwell	Break due to manoeuvre done.
7	Sine with dwell	Break due to manoeuvre done.
8	Sine with dwell	Break due to manoeuvre done.
9	Sine with dwell	Break due to manoeuvre done.
10	Sine with dwell	Break due to manoeuvre done.
11	Sine with dwell	Break due to manoeuvre done.
12	Sine with dwell	Break due to manoeuvre done.
13	Sine with dwell	Break due to manoeuvre done.
14	Sine with dwell	Break due to manoeuvre done.
15	Sine with dwell	Break due to manoeuvre done.
16	Sine with dwell	Break due to manoeuvre done.
17	Sine with dwell	Break due to manoeuvre done.
18	Sine with dwell	Break due to manoeuvre done.
19	Sine with dwell	Break due to manoeuvre done.
20	Sine with dwell	Break due to manoeuvre done.
21	Sine with dwell	Break due to manoeuvre done.
22	Sine with dwell	Break due to manoeuvre done.
23	Sine with dwell	Break due to manoeuvre done.
24	Sine with dwell	Break due to manoeuvre done.
25	Sine with dwell	Break due to manoeuvre done.
26	Sine with dwell	Break due to manoeuvre done.
27	Sine with dwell	Break due to manoeuvre done.
28	Sine with dwell	Break due to manoeuvre done.
29	Sine with dwell	Break due to manoeuvre done.
30	Sine with dwell	Break due to manoeuvre done.
31	Sine with dwell	Break due to manoeuvre done.
32	Sine with dwell	Break due to manoeuvre done.
33	Sine with dwell	Break due to manoeuvre done.

Table 6: Displays results from all sine withdwell test manoeuvre in terms of: Run number, Peak steering wheel angle, Peak yaw velocity, Yaw velocity criteria 1.00 seconds after completion of steering, Yaw velocity criteria 1.75 seconds after completion of steering, Lateral movement criteria.

Run	**SWA**	**YawVel**	**COS+1.00[s]**	**COS+1.75[s]**	**Lat.movement**
4	26	-0.18	Pass	Pass	Fail
5	34	-0.24	Pass	Pass	Fail
6	43	-0.29	Pass	Pass	Pass
7	52	-0.34	Pass	Pass	Pass
8	60	-0.38	Pass	Pass	Pass
9	69	-0.42	Pass	Pass	Pass
10	77	-0.46	Pass	Pass	Pass
11	86	-0.50	Pass	Pass	Pass
12	95	-0.54	Pass	Pass	Pass
13	103	-0.58	Pass	Pass	Pass
14	112	-0.60	Pass	Pass	Pass
15	121	-0.62	Pass	Pass	Pass
16	129	-0.64	Pass	Pass	Pass
17	138	-0.64	Pass	Pass	Pass
18	146	-0.64	Pass	Pass	Pass
19	155	-0.63	Pass	Pass	Pass
20	164	-0.61	Pass	Pass	Pass
21	172	-0.60	Pass	Pass	Pass
22	181	-0.58	Pass	Pass	Pass
23	189	-0.56	Pass	Pass	Pass
24	198	-0.54	Pass	Pass	Pass
25	207	-0.52	Pass	Pass	Pass
26	215	-0.49	Pass	Pass	Pass
27	224	-0.47	Pass	Pass	Pass
28	232	-0.46	Pass	Pass	Pass
29	241	-0.45	Pass	Pass	Pass
30	250	-0.44	Pass	Pass	Pass
31	258	-0.43	Pass	Pass	Pass
32	267	-0.42	Pass	Pass	Pass
33	275	-0.42	Pass	Pass	Pass

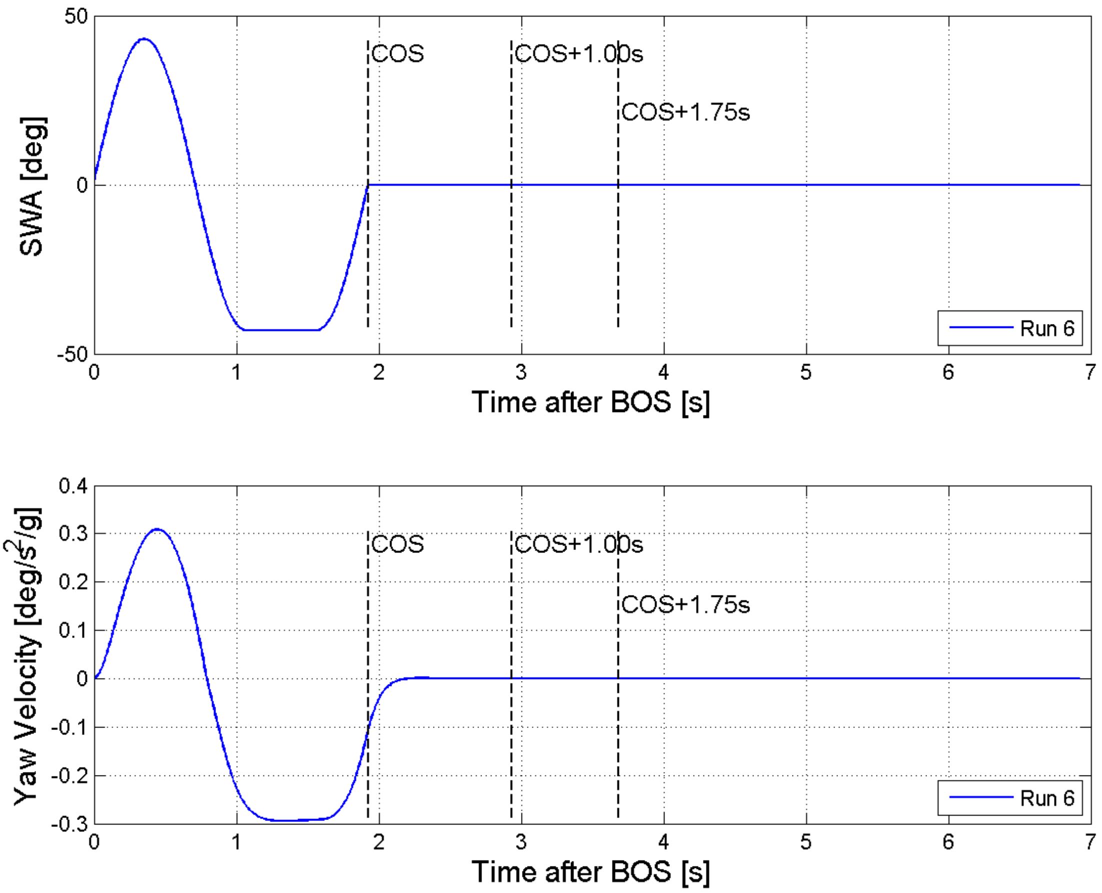


Figure 10: Steering wheel angle as well as Yaw velocity as a function of time after Beginning of steer (BOS). COS+Time shows time after Completion of steer (COS) which is used as test criteria.

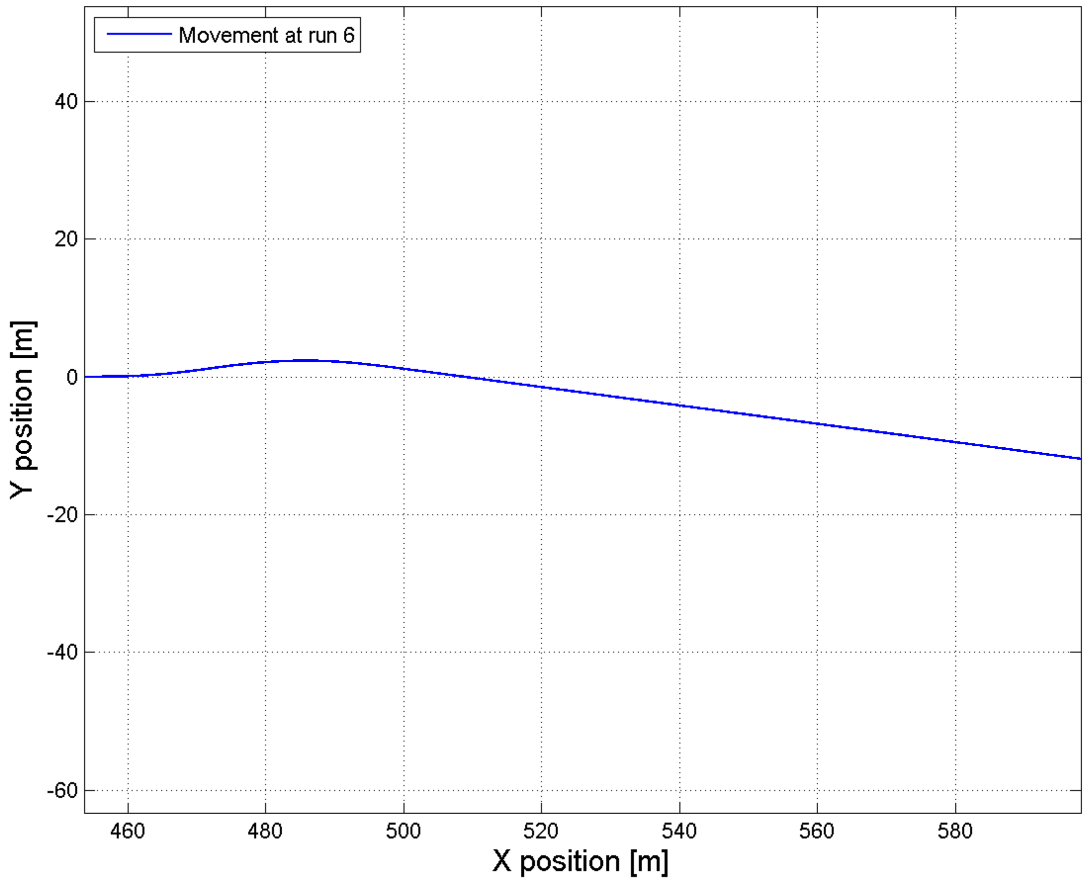


Figure 11: Vehicle movement during manoeuvre in Run 6.

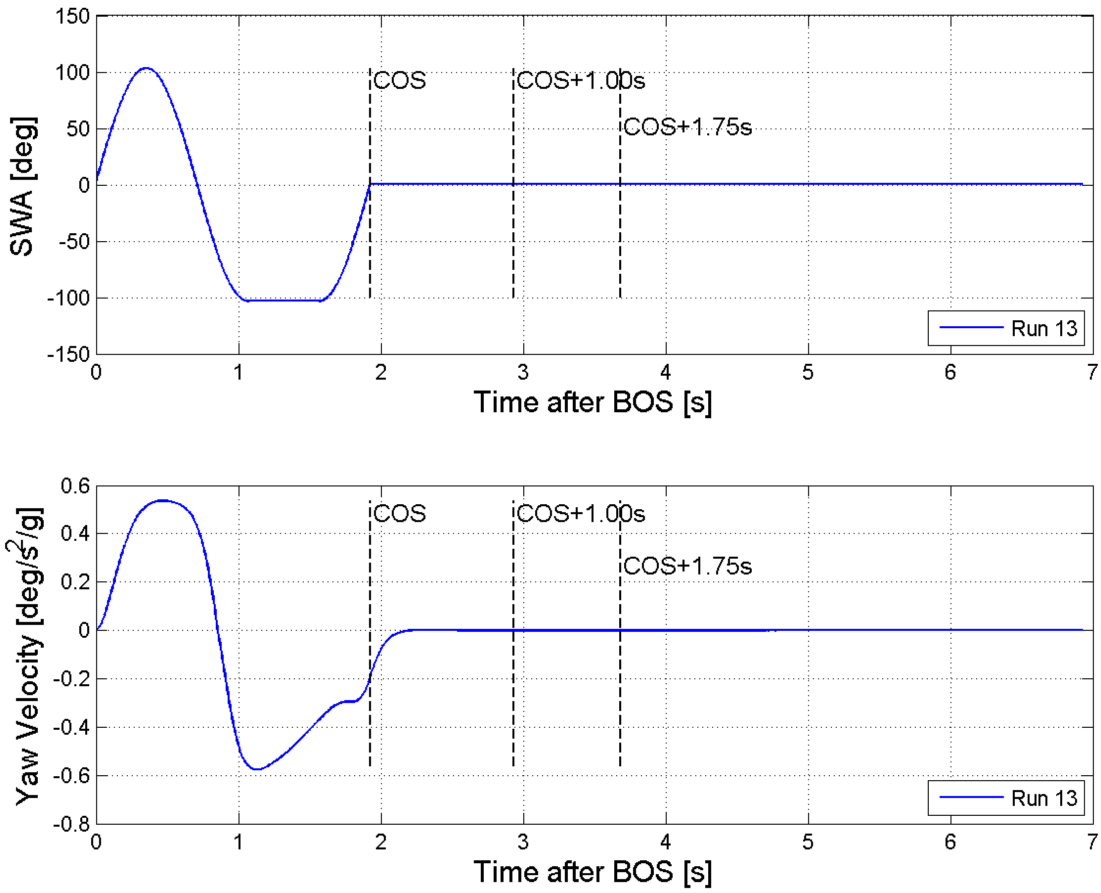


Figure 12: Steering wheel angle as well as Yaw velocity as a function of time after Beginning of steer (BOS). COS+Time shows time after Completion of steer (COS) which is used as test criteria.

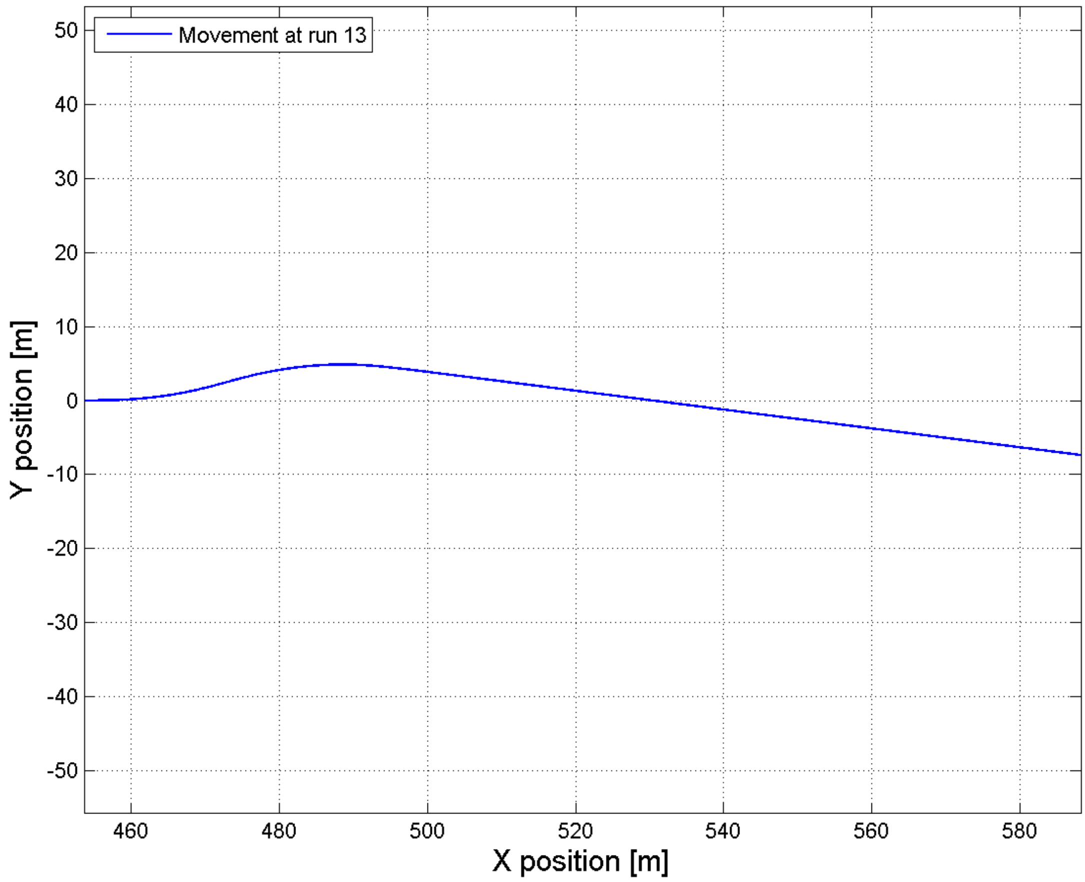


Figure 13: Vehicle movement during manoeuvre in Run 13.

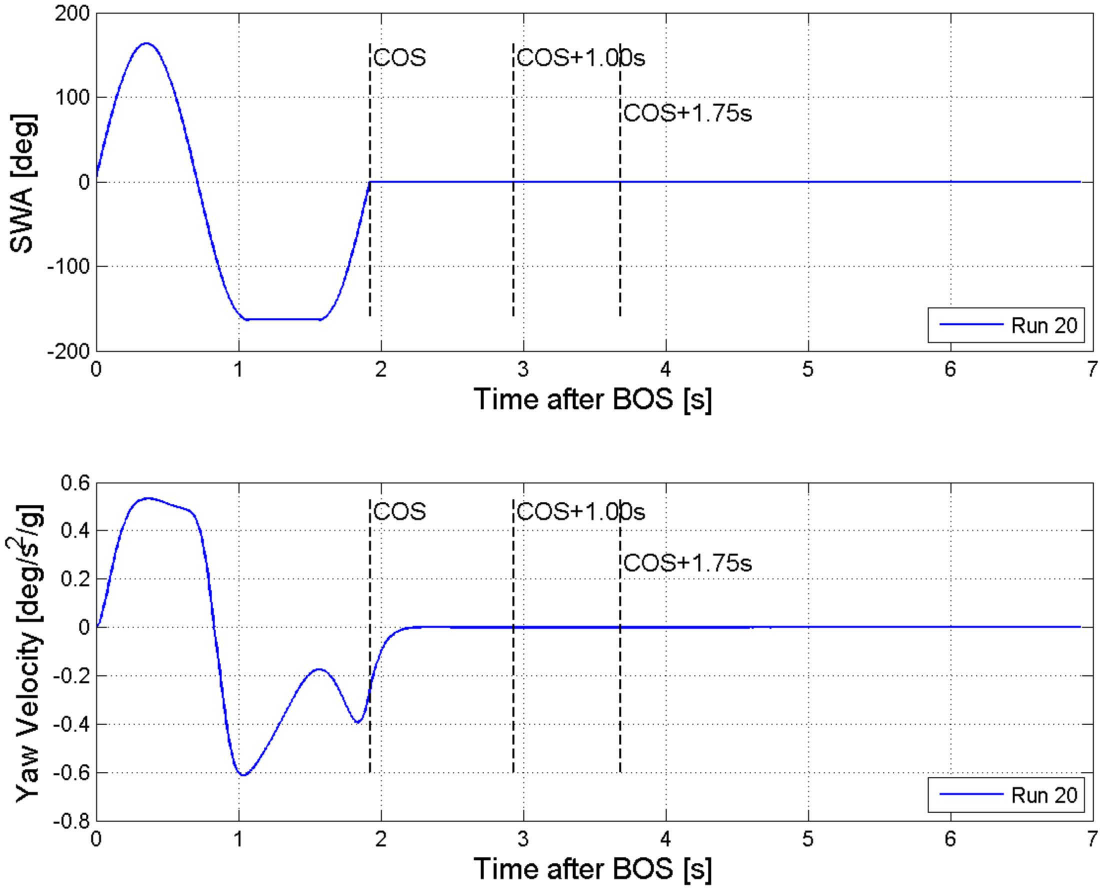


Figure 14: Steering wheel angle as well as Yaw velocity as a function of time after Beginning of steer (BOS). COS+Time shows time after Completion of steer (COS) which is used as test criteria.

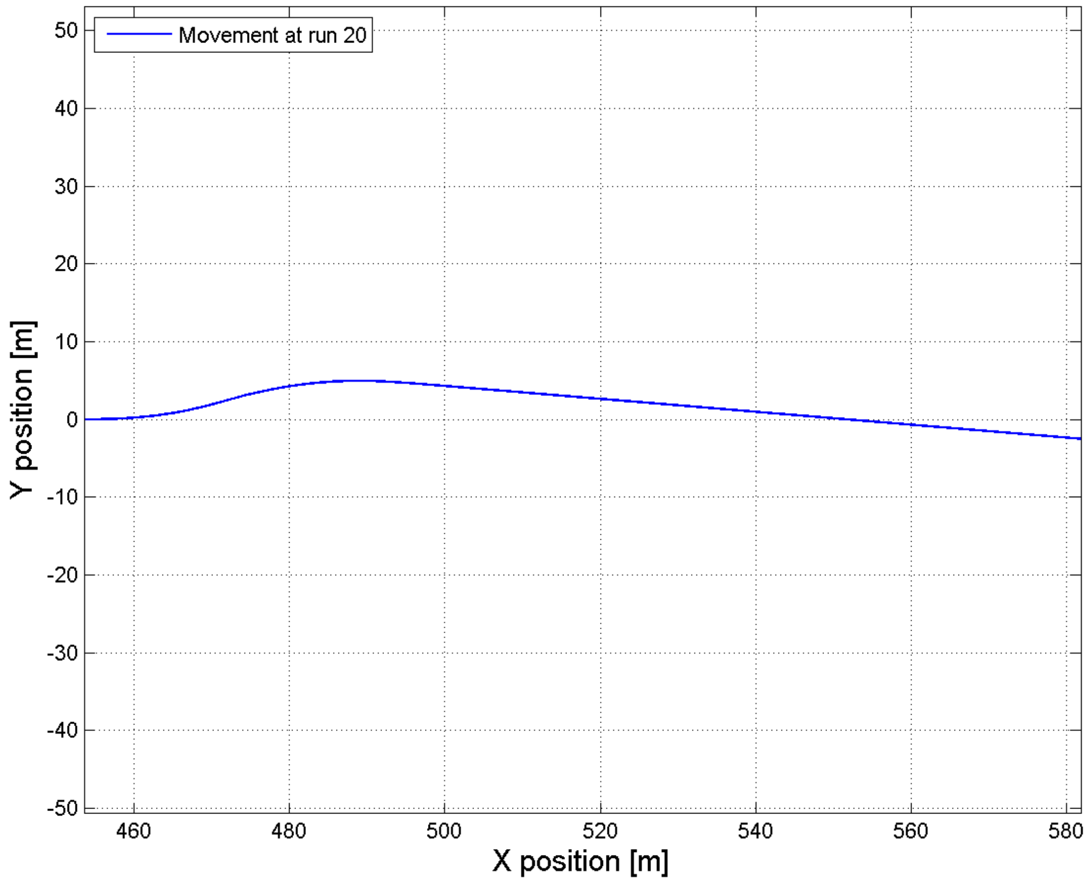


Figure 15: Vehicle movement during manoeuvre in Run 20.

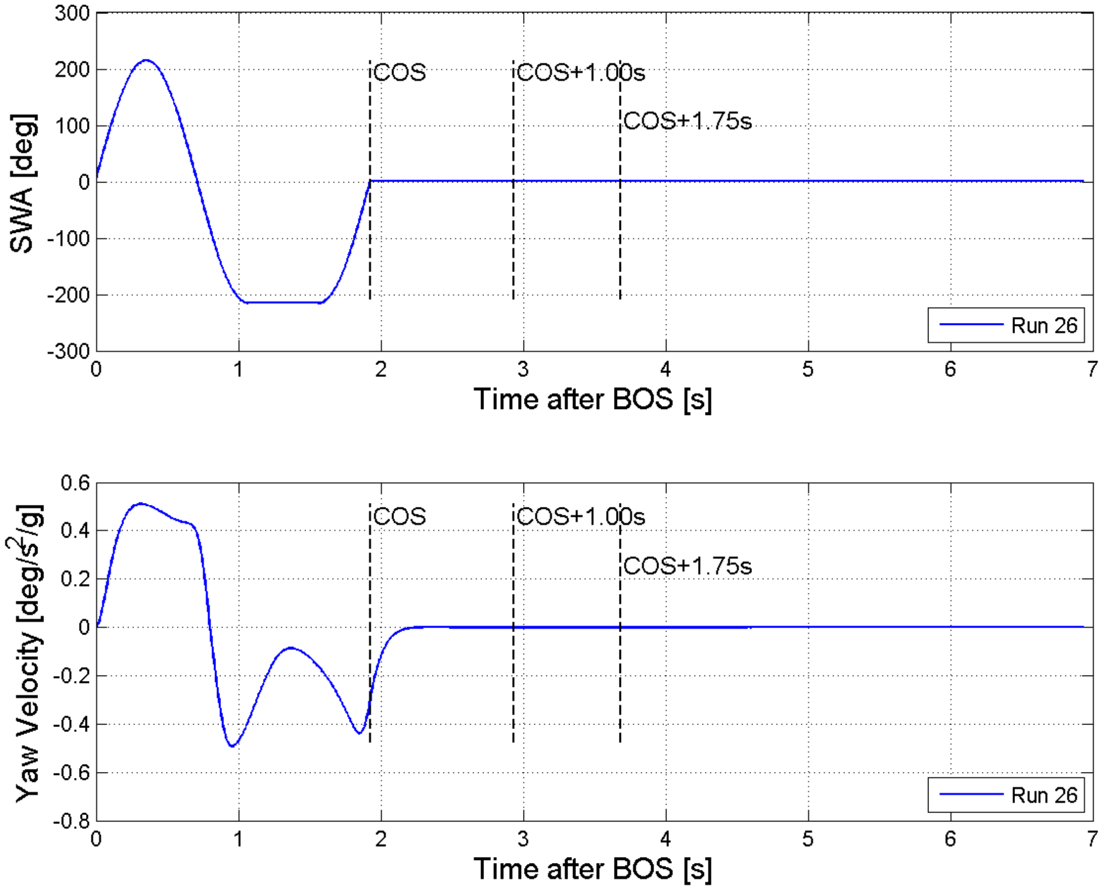


Figure 16: Steering wheel angle as well as Yaw velocity as a function of time after Beginning of steer (BOS). COS+Time shows time after Completion of steer (COS) which is used as test criteria.

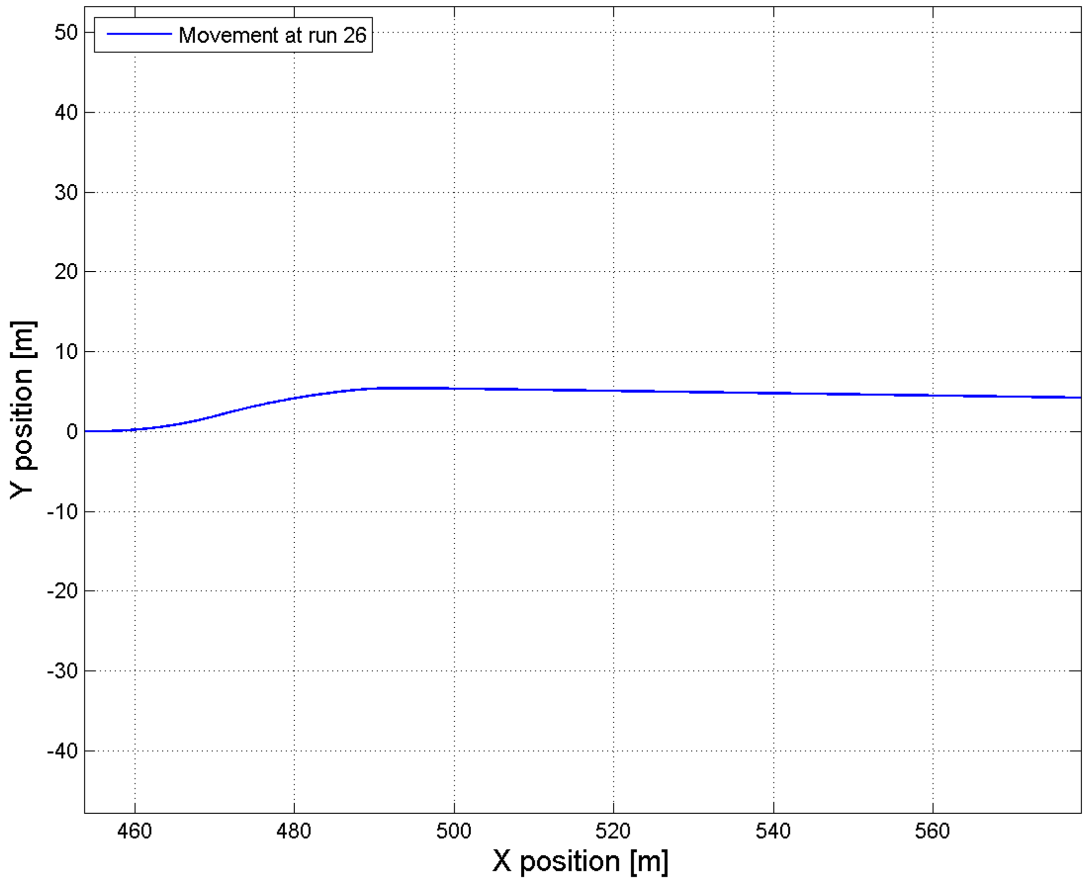


Figure 17: Vehicle movement during manoeuvre in Run 26.

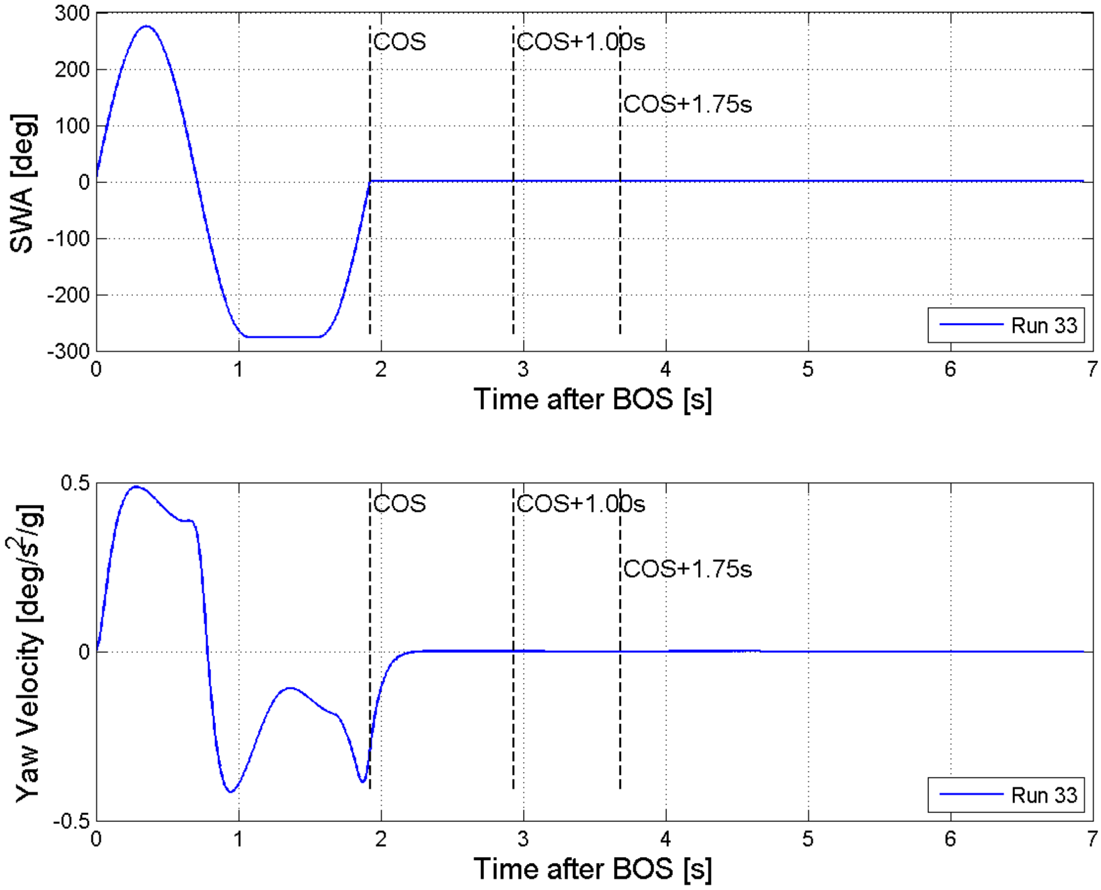


Figure 18: Steering wheel angle as well as Yaw velocity as a function of time after Beginning of steer (BOS). COS+Time shows time after Completion of steer (COS) which is used as test criteria.

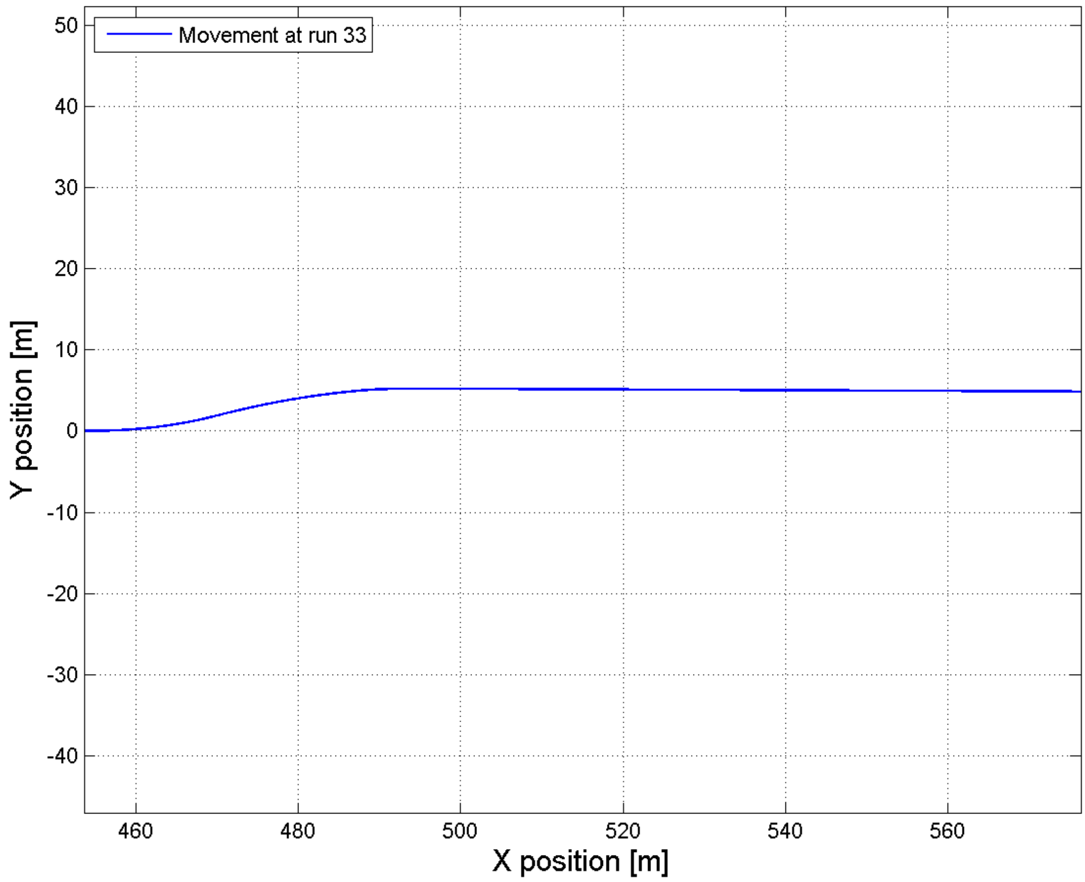
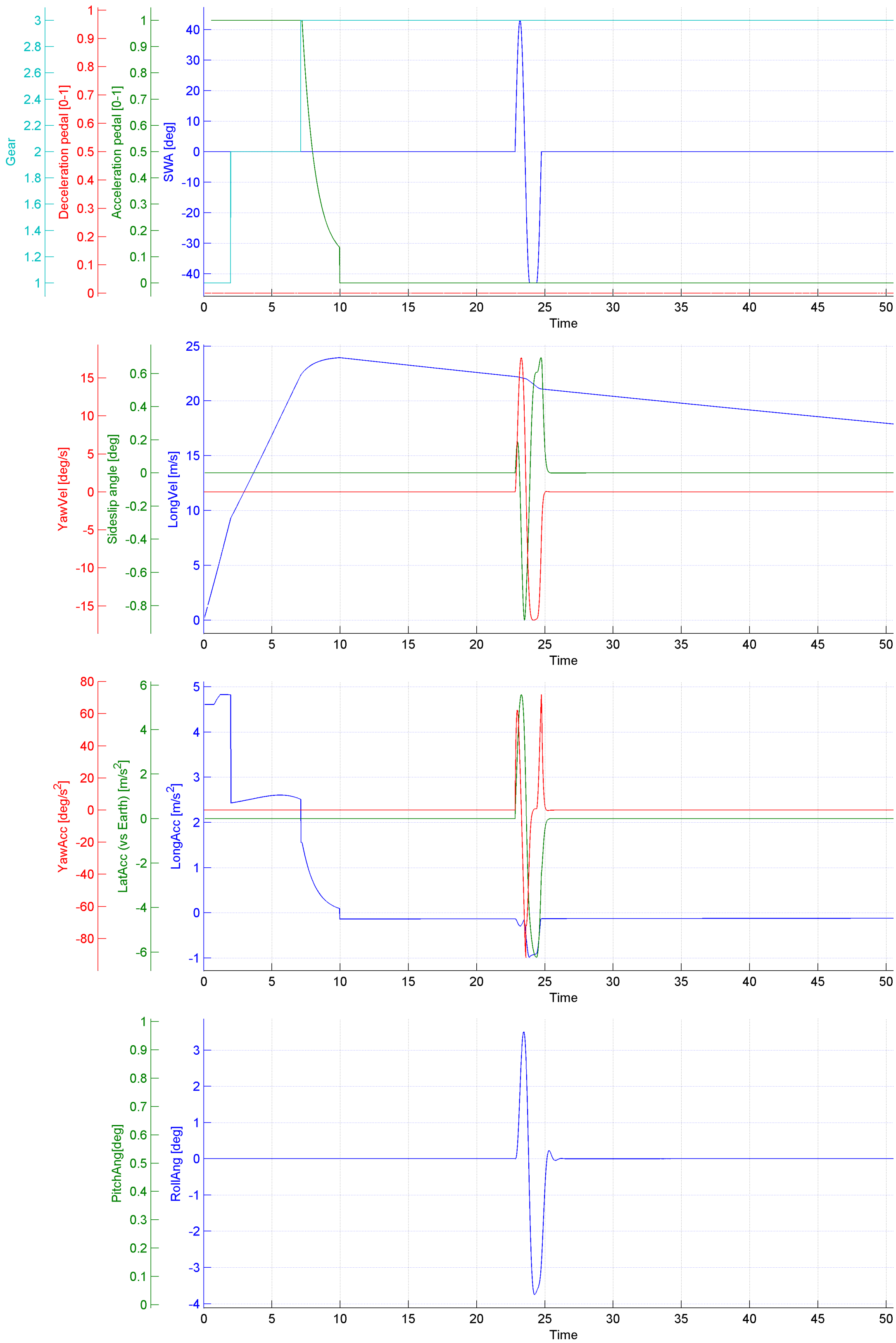


Figure 19: Vehicle movement during manoeuvre in Run 33.

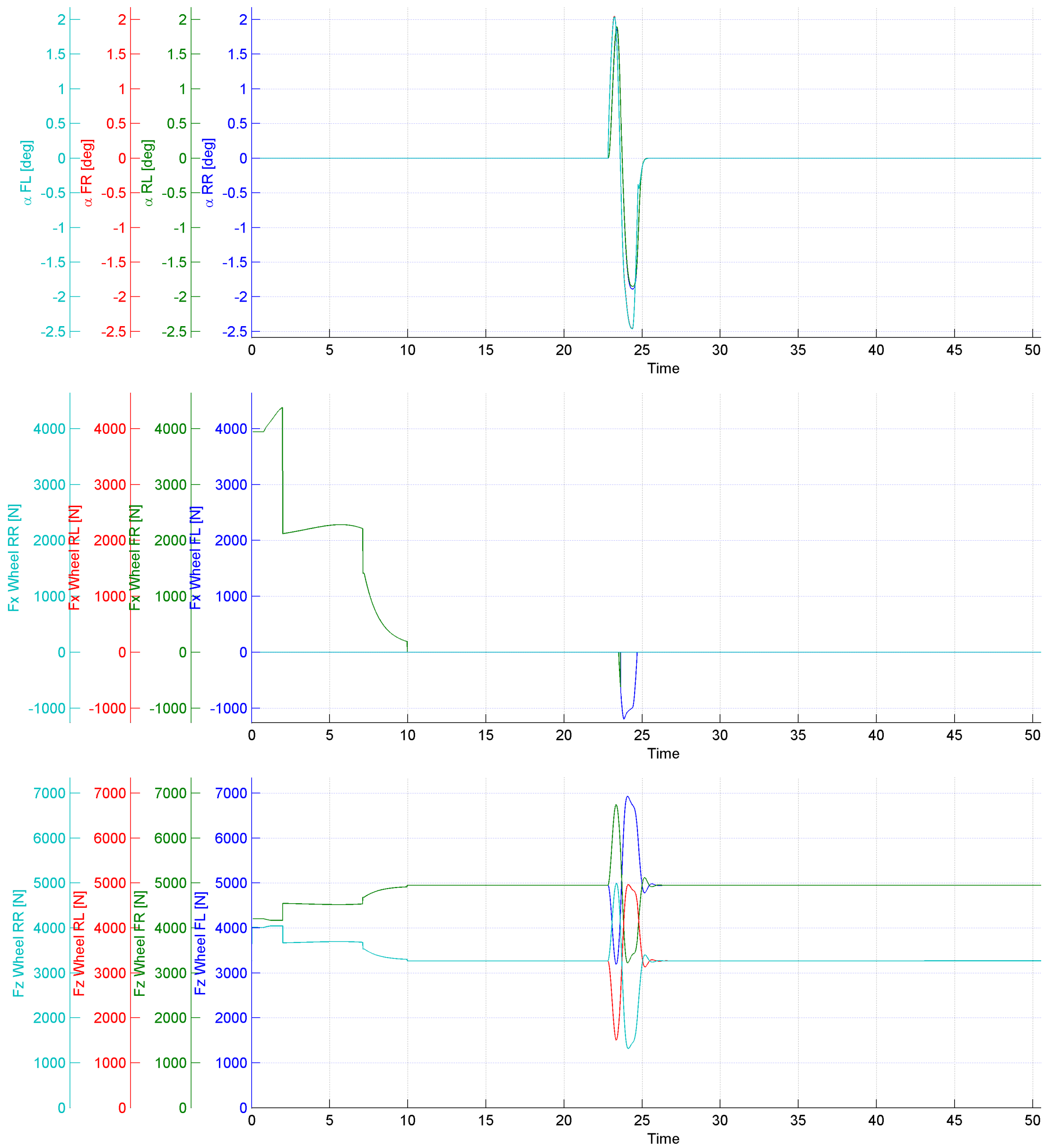
3.1 Test Evaluation plots:

Show summary of key values in order to verify the results.

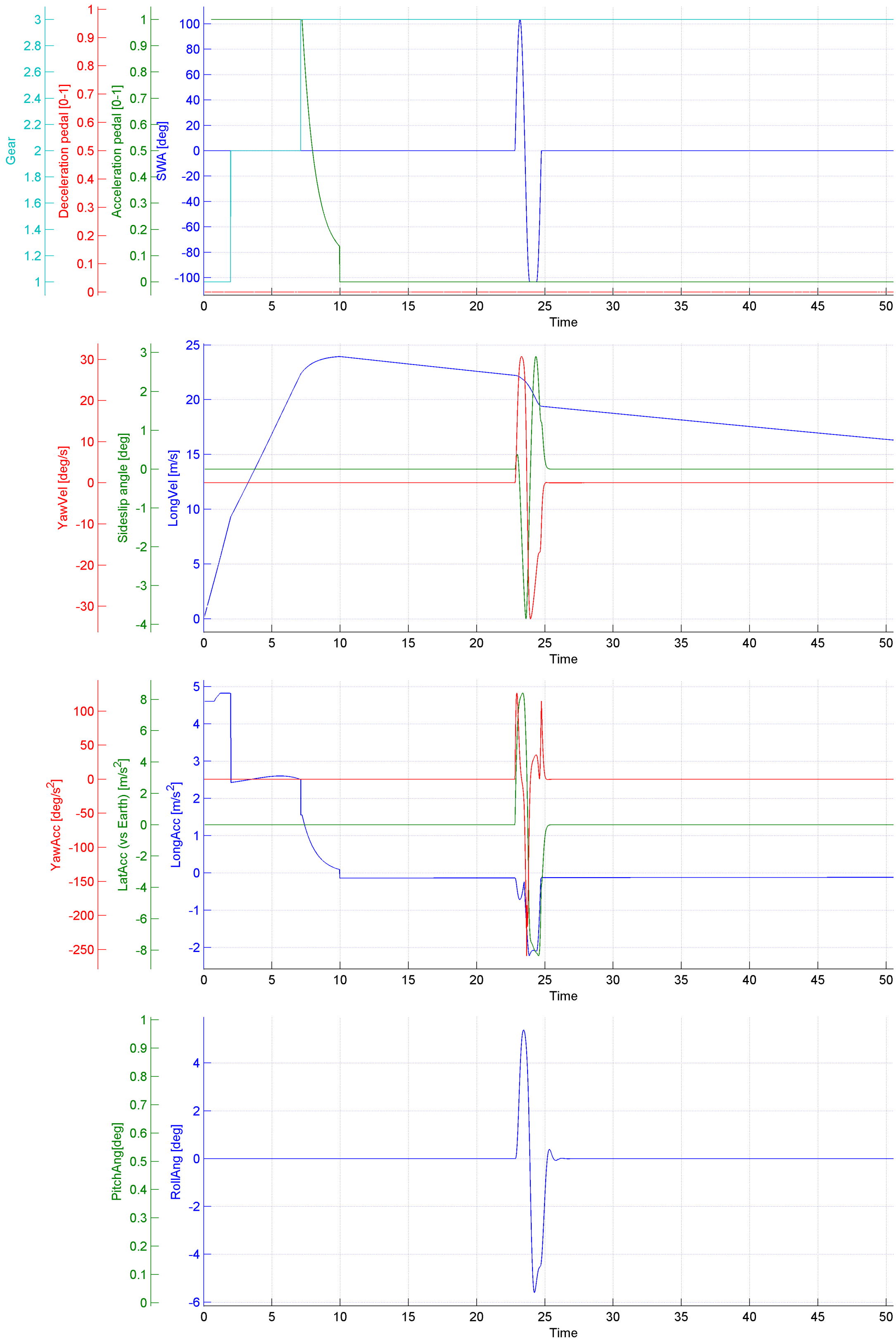
3.1.1 Evaluation plot from run:6



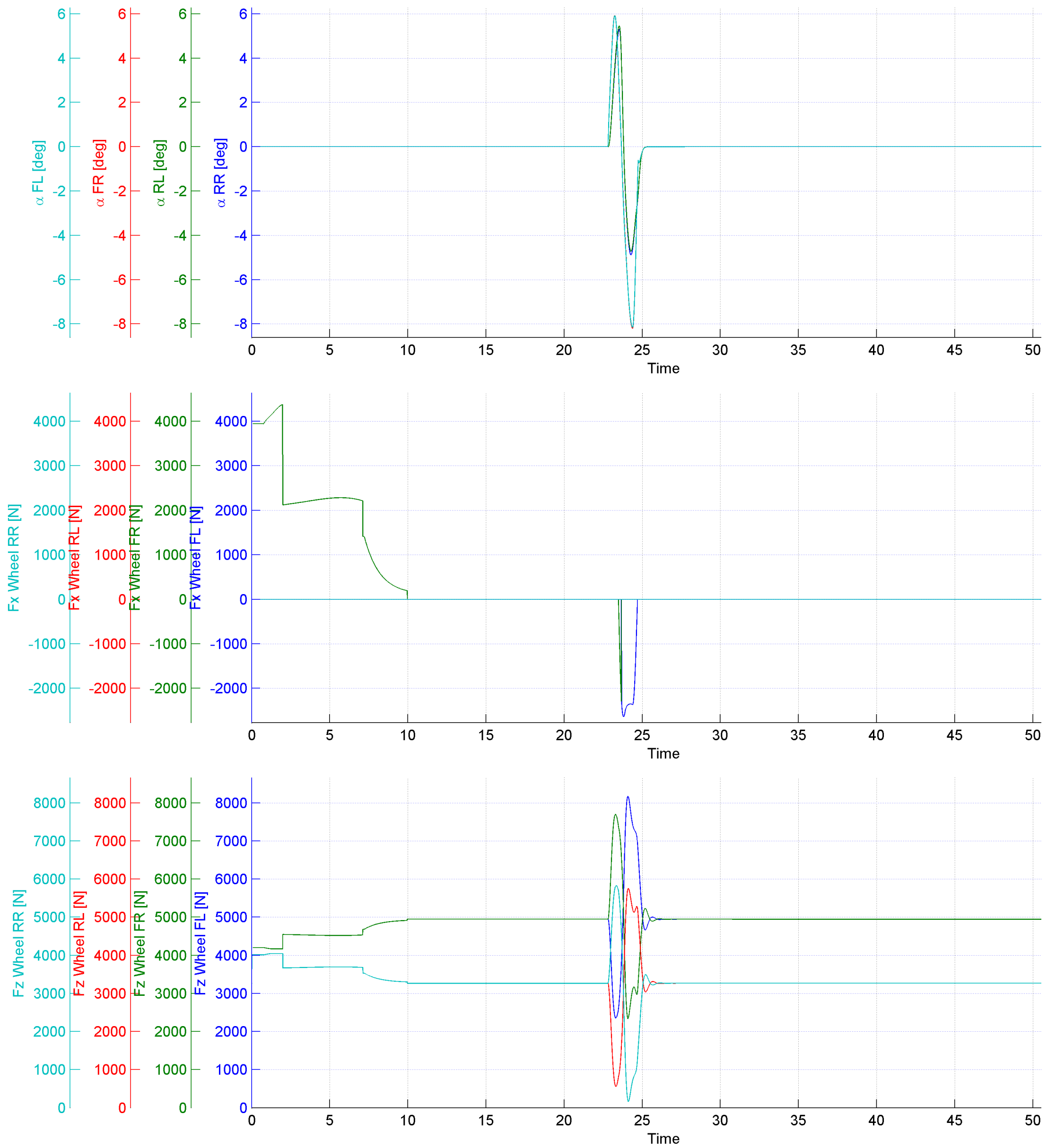
3.1.2 Evaluation plot from run:6



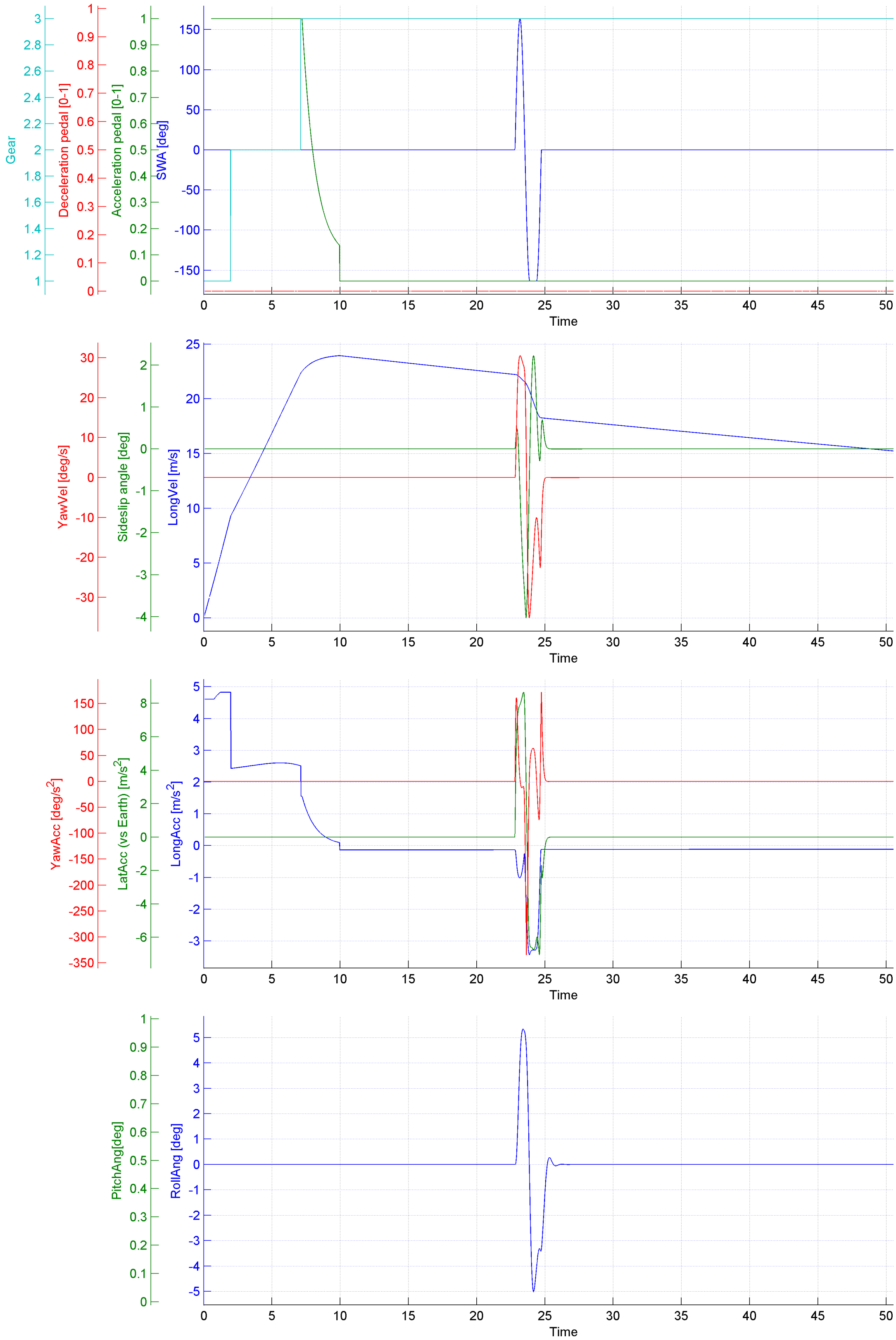
3.1.3 Evaluation plot from run:13



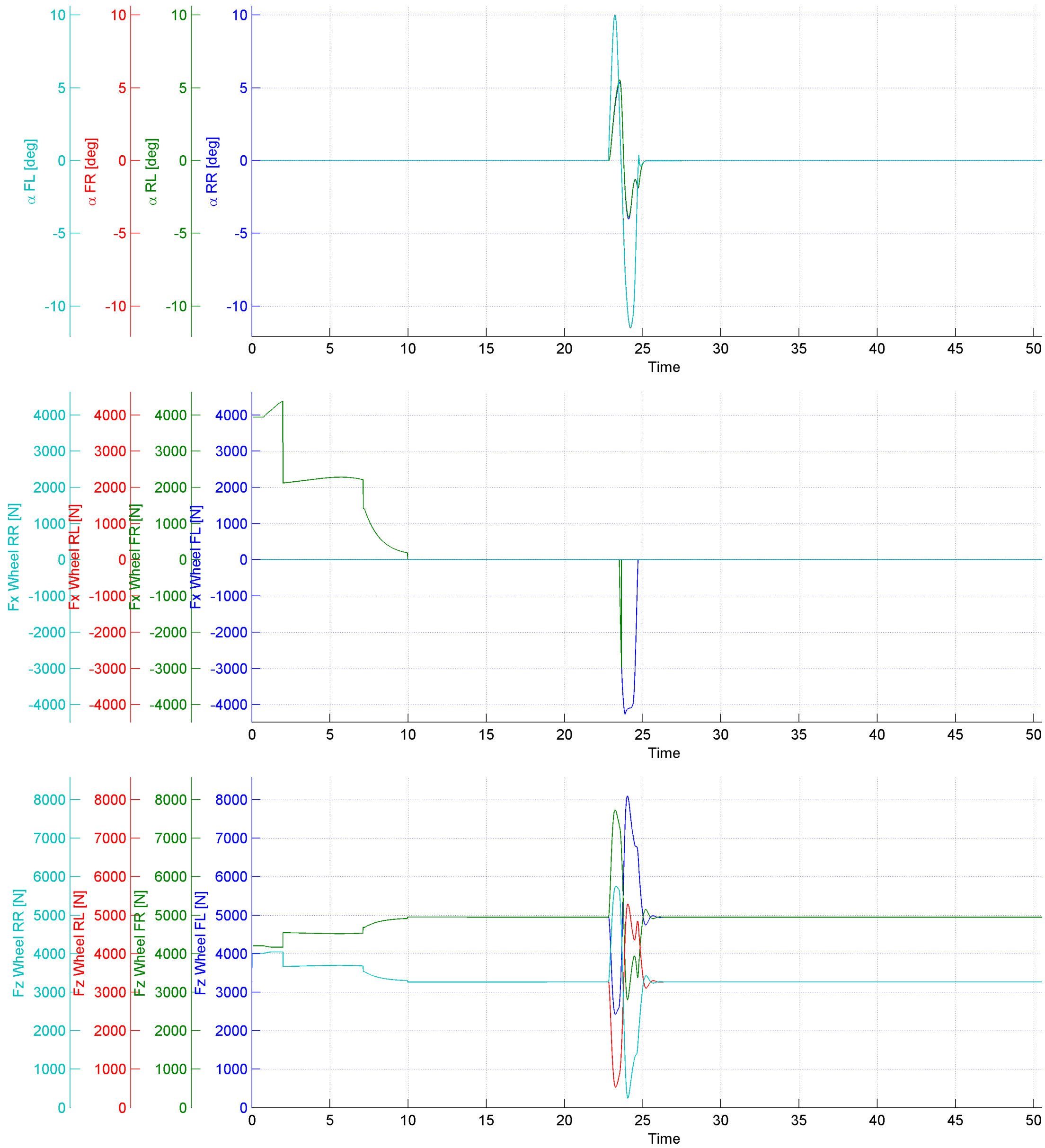
3.1.4 Evaluation plot from run:13



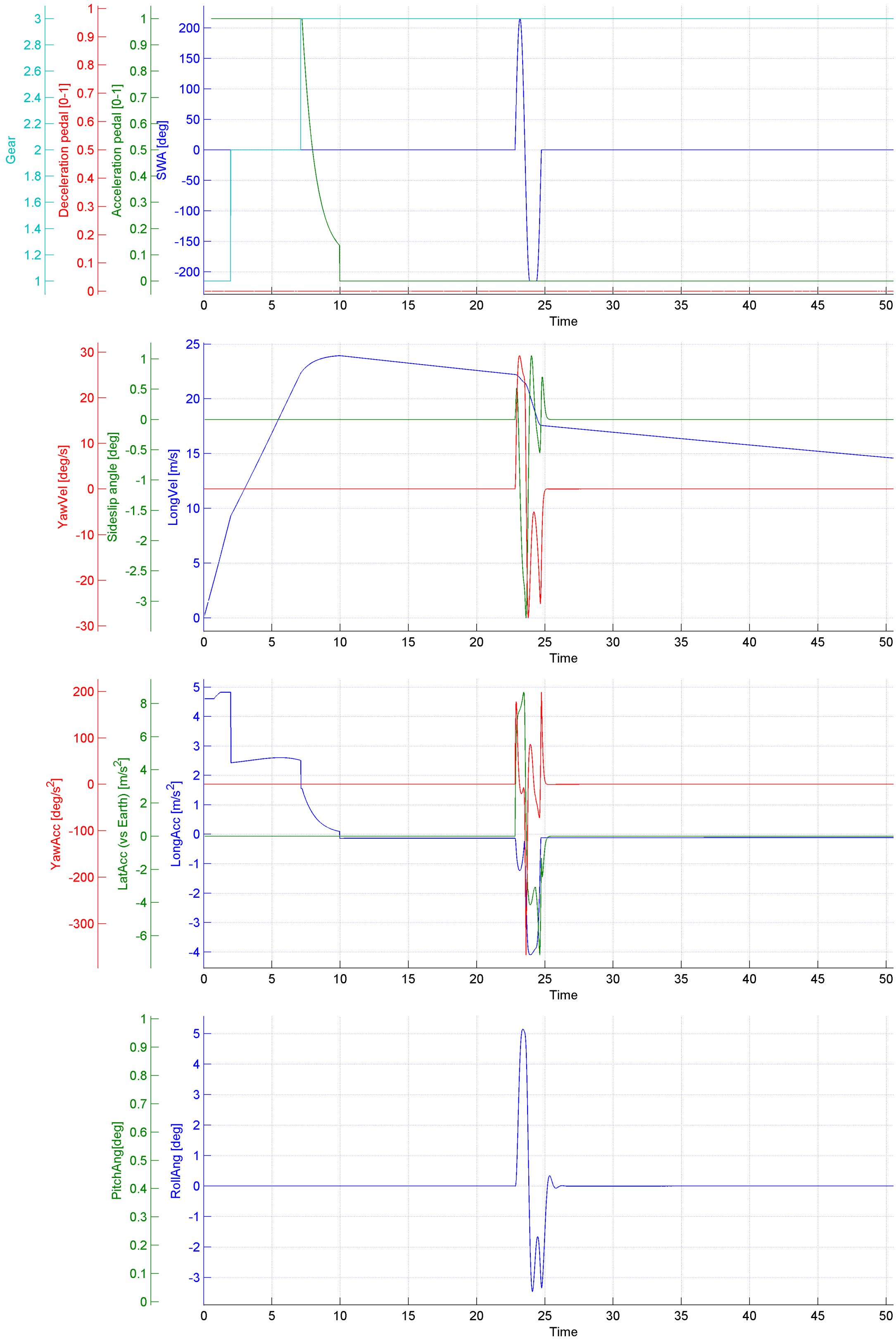
3.1.5 Evaluation plot from run:20



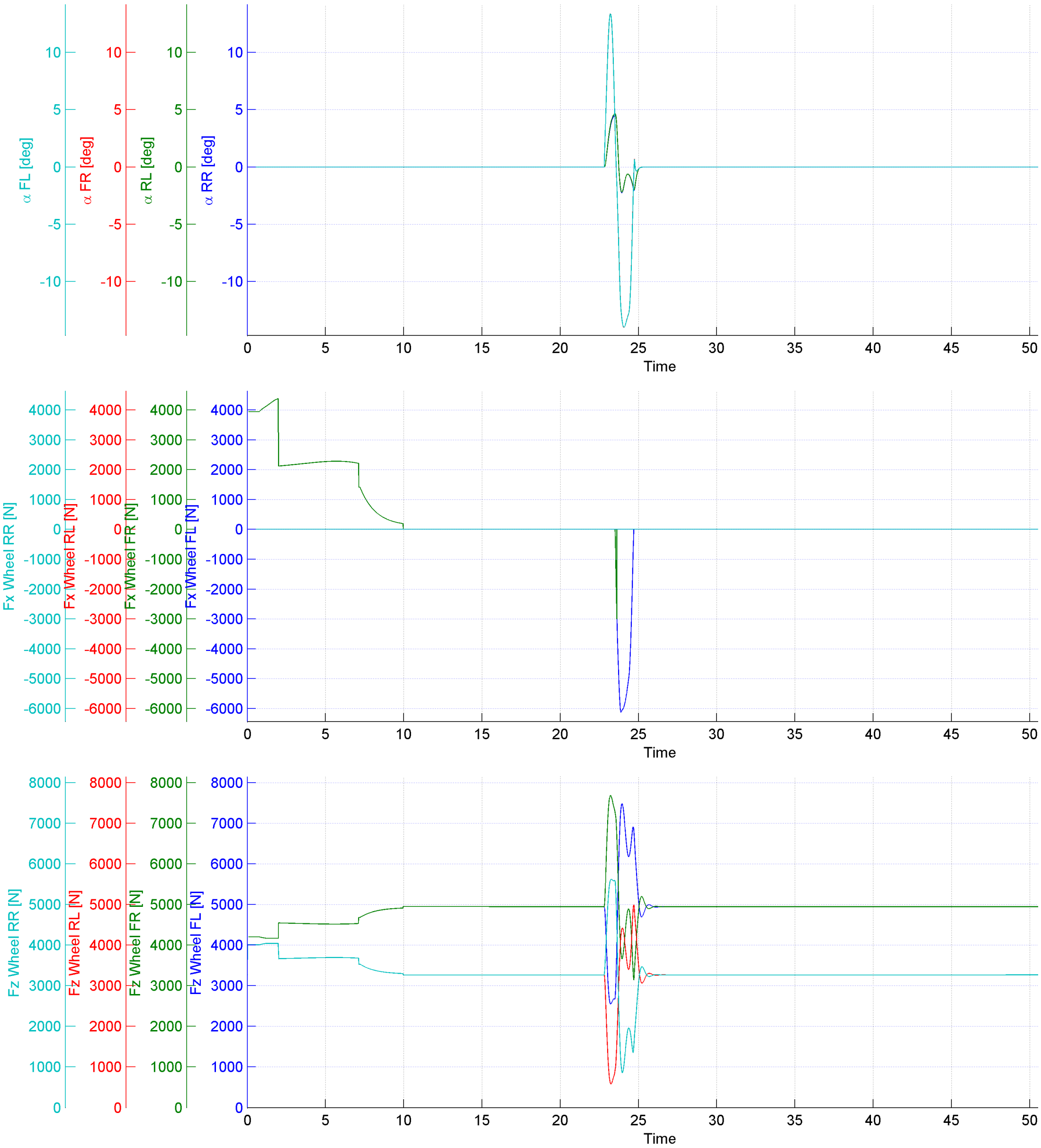
3.1.6 Evaluation plot from run:20



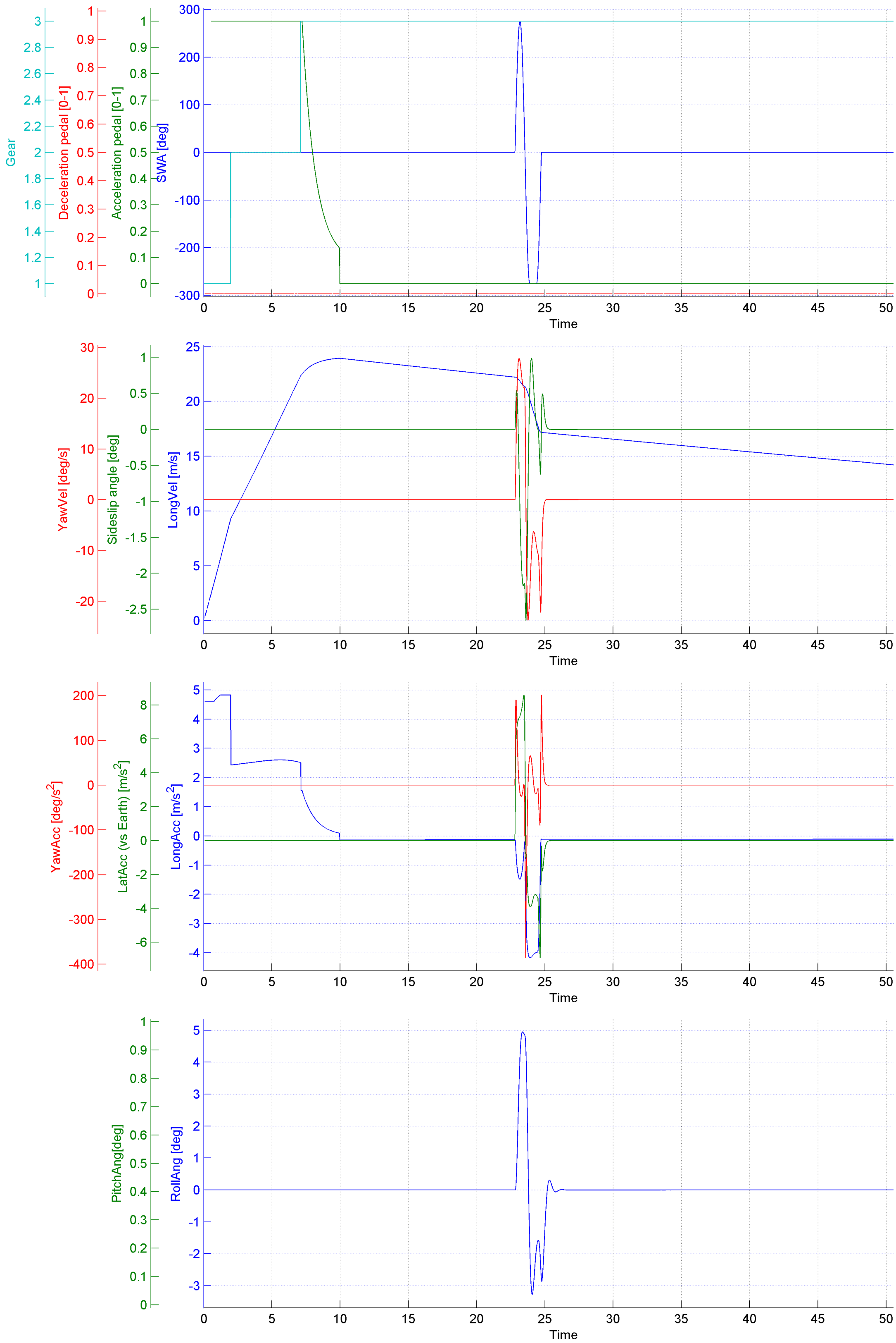
3.1.7 Evaluation plot from run:26



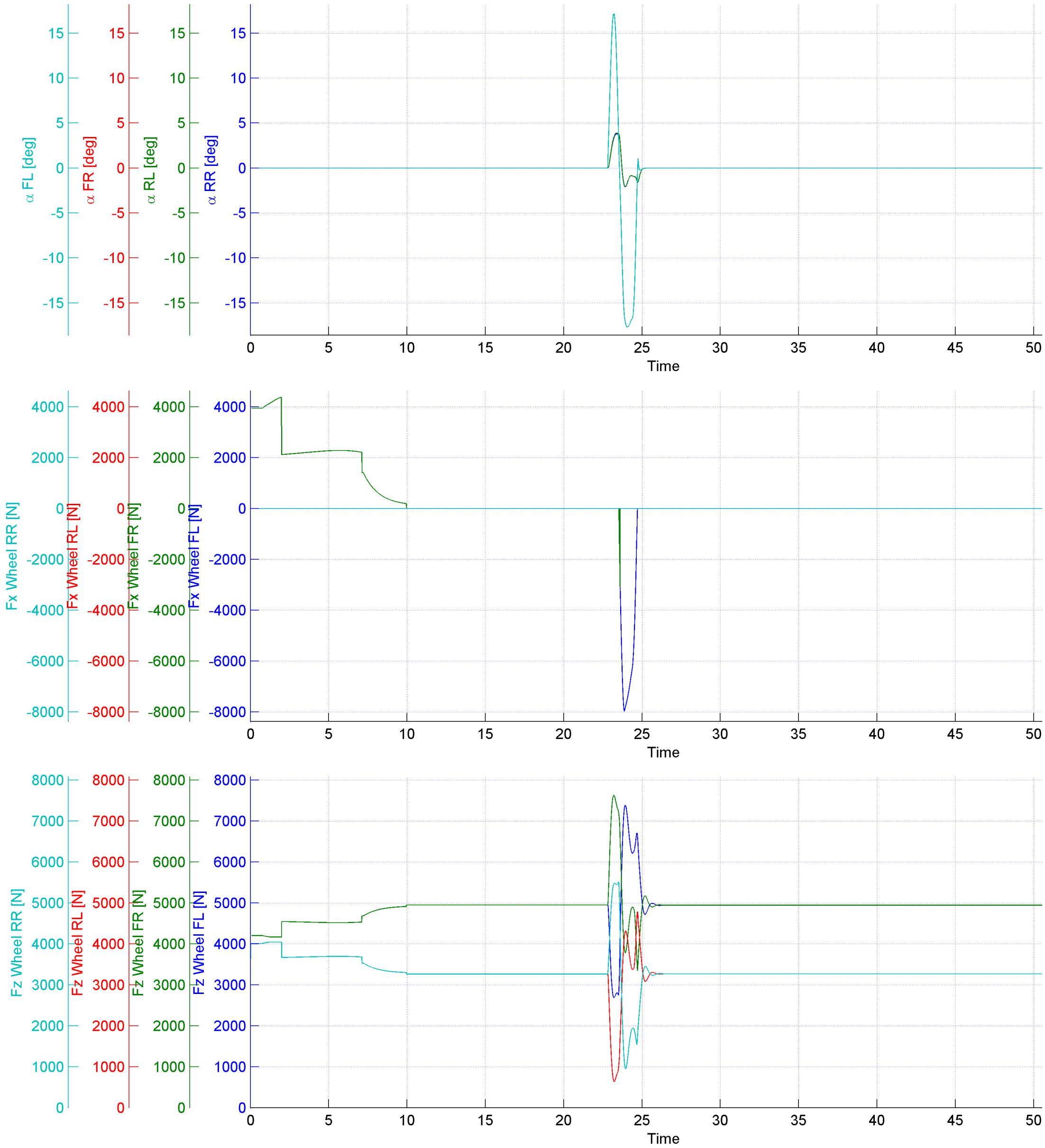
3.1.8 Evaluation plot from run:26



3.1.9 Evaluation plot from run:33



3.1.10 Evaluation plot from run:33



4 Frequency response, SS-ISO 7401:2011

This results are based on Frequency response from SS-ISO 7401:2011 It is valid according to SS-ISO 7401:2011 for evaluating Continuous sinusoidal input or Random input.

Table 7: List of runs and active tests

Run	Test type	Reason for ending
34	Continuous sinusoidal input	Break due to end of manouvre.

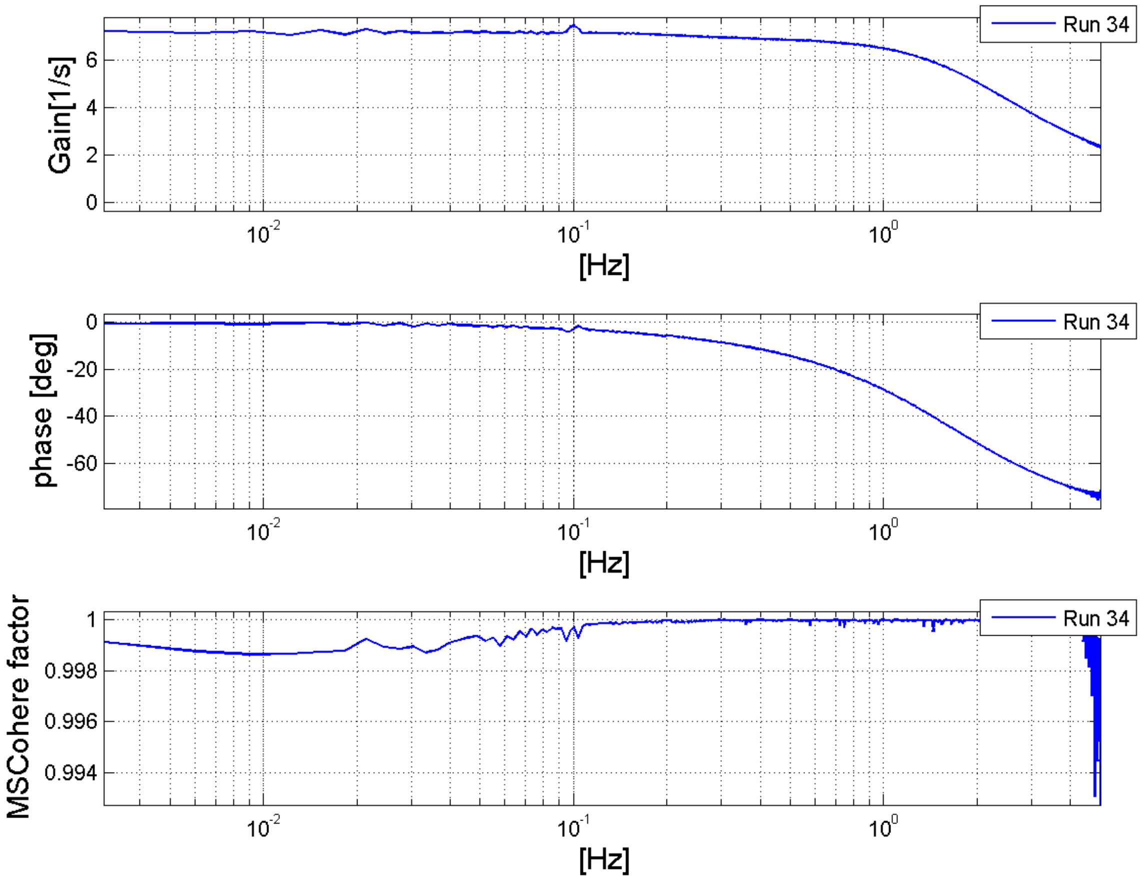


Figure 20: This graph presents steering wheel angle, phase angle and coherence as a function of frequecy.

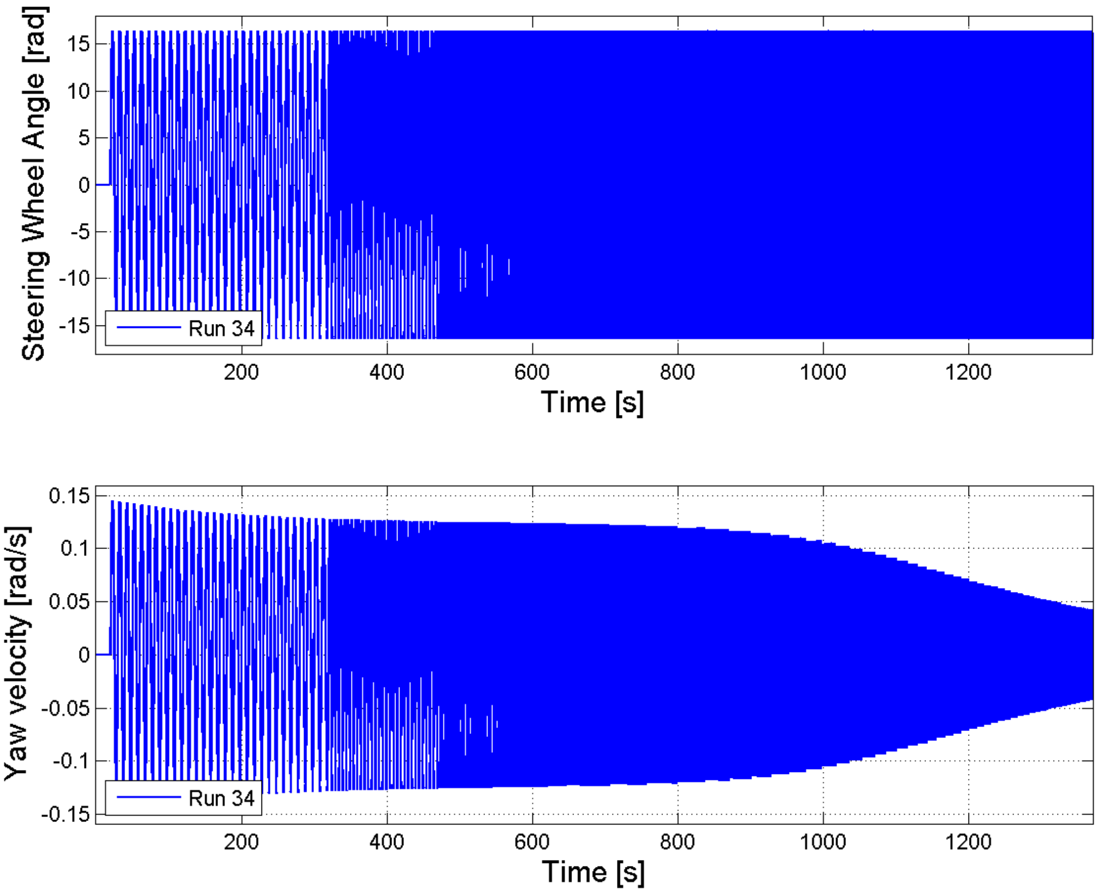
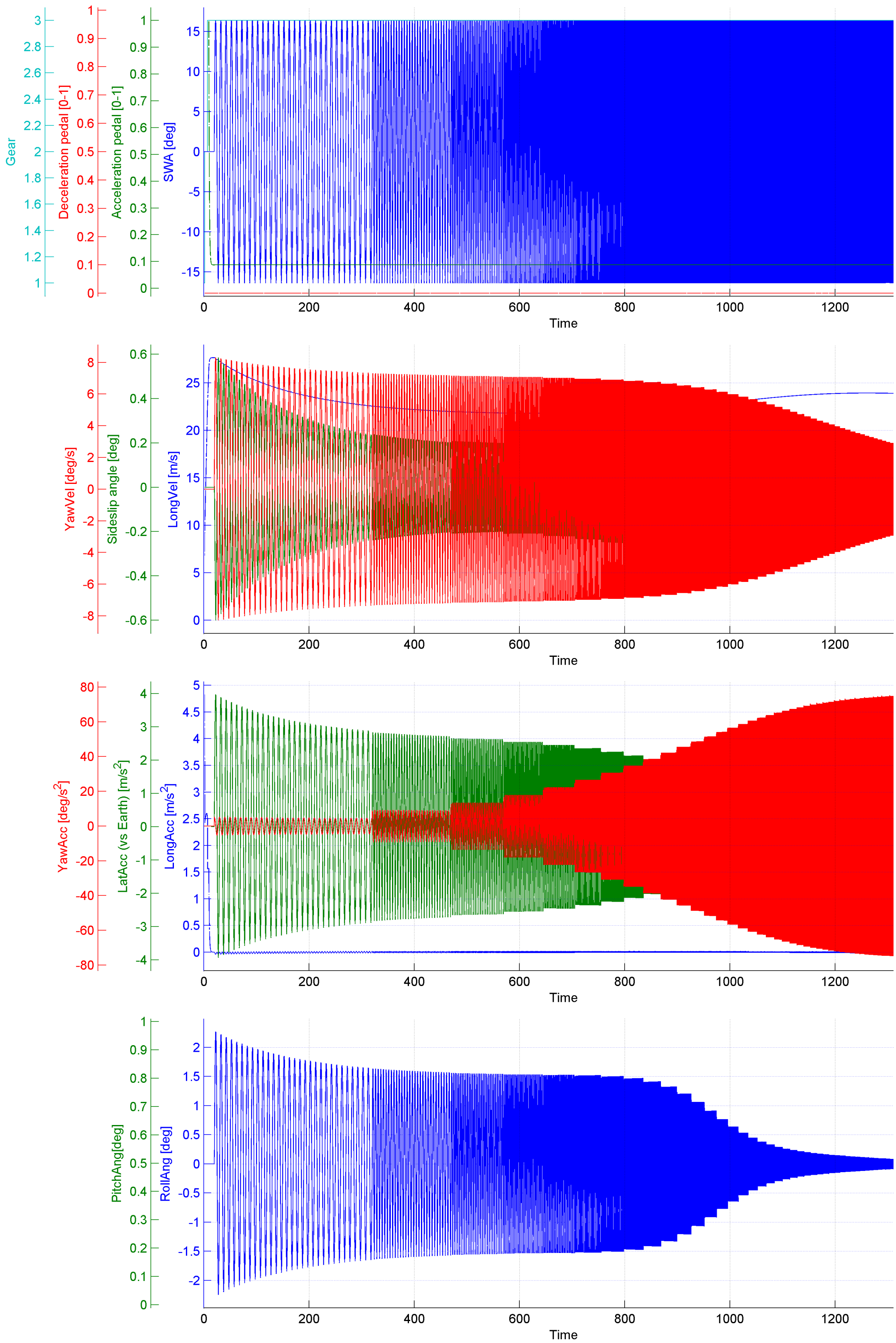


Figure 21: Steering wheel angle as well as Yaw velocity as a function of time after Beginning of steer (BOS). COS+Time shows time after Completion of steer (COS) which is used as test criteria.

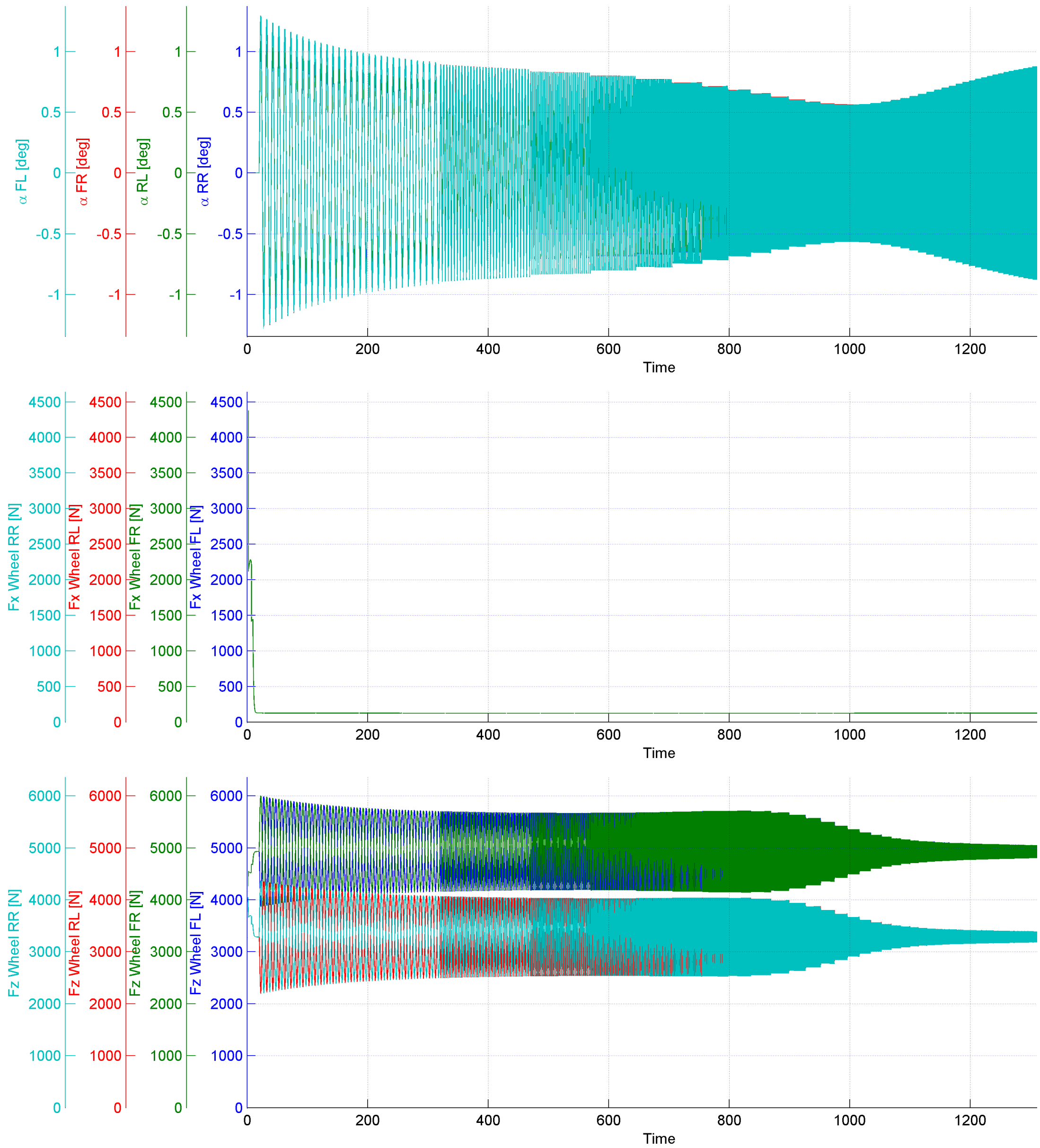
4.1 Test Evaluation plots:

Show summary of key values in order to verify the results.

4.1.1 Evaluation plot from run:34



4.1.2 Evaluation plot from run:34



C Parametrization of BAPS model

Table C.1: Parametrizations used together with BAPS model.

Make, Model and Model Year	Weight [kg]	Distance CoG FrAxle [m]	Distance CoG ReAxle [m]	Height CoG [m]	Track Width Front[m]	Track Width Rear[m]	Inertia about x-axis [kg·m^2]	Inertia about y-axis [kg·m^2]	Inertia about z-axis [kg·m^2]
BMW 535i 2011	1646	1.508	1.338	0.603	1.600	1.600	982	3273	3273
Volkswagen Passat 2 0TDI 2011	1687	1.443	1.386	0.626	1.552	1.552	990	3301	3301
Mercedes Vivaro 2011	1830	1.536	1.475	0.781	1.615	1.615	1218	4059	4059
Fod Kuga TDCI 2011	1466	1.426	1.214	0.692	1.574	1.574	753	2510	2510
Skoda Yeti Tdi 4x4 2011	1552	1.368	1.165	0.685	1.541	1.541	728	2425	2425
Volvo XC90 2011	1863	1.396	1.396	0.720	1.634	1.634	1027	3422	3422
Skoda Fabia Kombi TSI 2011	1060	1.297	1.247	0.613	1.417	1.417	503	1678	1678
Skoda Octavia 2011	1354	1.354	1.301	0.595	1.541	1.541	699	2331	2331
Suzuki Swift 2011	1023	1.096	1.141	0.616	1.490	1.490	373	1244	1244
Smart for 2 2011	765	0.830	0.736	0.637	1.283	1.283	137	458	458
BMW 1er 2011	1242	1.380	1.176	0.612	1.471	1.471	597	1991	1991
BMW X3 2011	1613	1.350	1.350	0.673	1.581	1.581	866	2887	2887
Citr en C3 2011	968	1.122	1.168	0.621	1.470	1.470	374	1246	1246
Opel Astra Sports Tourer 2011	1387	1.392	1.338	0.625	1.544	1.544	757	2523	2523
Volkswagen Sharan 2011	1547	1.438	1.382	0.696	1.569	1.569	905	3016	3016
BMW 530 D Gran Turismo 2011	1998	1.452	1.452	0.634	1.611	1.611	1237	4122	4122
Seat Ibiza 1 2 Ecomotive 2011	1249	1.147	1.194	0.584	1.446	1.446	501	1670	1670
Mercedes CLS 350 CDI 2011	1730	1.568	1.335	0.582	1.581	1.581	1071	3569	3569
Volkswagen Passat Variant 2011	1452	1.414	1.358	0.628	1.537	1.537	818	2726	2726
Opel Astra 2011	1471	1.392	1.338	0.625	1.533	1.533	806	2687	2687
Volkswagen Polo TDI 2011	1045	1.130	1.177	0.595	1.463	1.463	409	1363	1363
Volkswagen Touareg Hybrid 2011	2101	1.422	1.421	0.700	1.624	1.624	1251	4170	4170
Honda Jazz 2011	1016	1.110	1.156	0.622	1.495	1.495	383	1278	1278
Volkswagen Golf VI 2011	1095	1.244	1.196	0.597	1.512	1.512	481	1602	1602
Seat Alhambra 2011	1605	1.410	1.410	0.686	1.598	1.598	939	3130	3130
BMW 3er Kombi 2011	1492	1.448	1.184	0.582	1.530	1.530	747	2489	2489
Volkswagen Caddy 2011	1492	1.448	1.184	0.582	1.530	1.530	747	2489	2489

D Batch run results using BAPS model

Table D.1: Results summary for test objects.

Test object:	Max Lateral Acc at 80[kph]	Max Lateral Acc at 100[kph]	Linearisation of SWA constant 80.00	Linearisation of SWA constant 100.00	Acceleration time 0-60 [kph]	Acceleration time 0-100 [kph]	Acceleration time 80-120 [kph]	Acceleration time 402 [m]	Complient with FMVSS 126	Max SWA to pass at COS+1.00[s]	Max SWA to pass at COS+1.75[s]	Min SWA to pass lateral movement	Frequency when Gain below 95% of SSC	Max Gain during test
BMW 535i 2011 BAPS 10 Jun 2014	0.94	0.64	55.99	37.40	7.37	11.07	4.11	18.43	Pass	271	271	42	1.07	155.97
Volkswagen Passat 2 0TDI 2011 BAPS 10 Jun 2014	0.64	0.62	53.30	34.85	7.00	10.58	4.15	18.11	-	56	56	40	0.92	110.51
Mercedes Vivaro 2011 BAPS 10 Jun 2014	0.57	0.52	56.63	36.96	6.99	10.69	4.49	18.24	-	43	43	43	0.91	114.76
Fod Kuga TDCI 2011 BAPS 10 Jun 2014	0.73	0.53	53.32	36.07	7.82	11.83	3.97	18.82	-	57	57	41	1.24	139.52
Skoda Yeti Tdi 4x4 2011 BAPS 10 Jun 2014	0.55	0.52	51.28	34.83	7.77	11.71	4.05	18.82	-	47	47	39	1.33	134.51
Volvo XC90 2011 BAPS 10 Jun 2014	0.59	0.58	51.59	33.33	6.79	10.48	4.56	18.09	-	39	39	39	0.86	80.61
Skoda Fabia Kombi TSI 2011 BAPS 10 Jun 2014	0.58	0.56	48.13	31.58	7.50	11.67	3.93	18.43	-	44	44	36	0.93	109.17
Skoda Octavia 2011 BAPS 10 Jun 2014	0.66	0.64	50.17	32.88	7.25	10.95	3.66	18.12	Pass	273	273	38	0.93	112.26
Suzuki Swift 2011 BAPS 10 Jun 2014	0.62	0.61	40.46	25.87	7.26	11.30	3.80	18.13	-	30	30	30	0.75	127.43
Smart for 2 2011 BAPS 10 Jun 2014	0.47	0.45	32.94	22.93	8.46	13.81	5.40	20.13	-	20	20	25	1.49	171.88
BMW 1er 2011 BAPS 10 Jun 2014	0.62	0.56	51.71	35.13	7.92	12.19	4.02	18.92	Pass	276	276	39	1.30	123.14
BMW X3 2011 BAPS 10 Jun 2014	0.61	0.59	49.90	32.26	6.95	10.46	3.99	17.98	-	45	45	38	0.84	139.34
Citr en C3 2011 BAPS 10 Jun 2014	0.61	0.59	41.42	26.49	7.29	11.43	3.91	18.21	-	31	31	31	0.75	123.22
Opel Astra Sports Tourer 2011 BAPS 10 Jun 2014	0.63	0.61	51.51	33.71	7.24	10.90	3.69	18.12	-	54	54	39	0.92	182.45
Volkswagen Sharan 2011 BAPS 10 Jun 2014	0.58	0.56	53.14	34.74	7.16	10.75	3.89	18.14	-	48	48	40	0.92	119.85
BMW 530 D Gran Turismo 2011 BAPS 10 Jun 2014	0.66	0.65	53.55	34.57	6.61	10.45	4.90	18.09	-	56	56	40	0.82	101.33
Seat Ibiza 1 2 Ecomotive 2011 BAPS 10 Jun 2014	0.64	0.63	42.27	26.98	7.05	10.69	3.51	17.83	-	32	32	32	0.75	150.87
Mercedes CLS 350 CDI 2011 BAPS 10 Jun 2014	0.78	0.79	58.68	40.05	7.47	11.25	4.29	18.62	Pass	273	273	44	1.14	131.27
Volkswagen Passat Variant 2011 BAPS 10 Jun 2014	0.62	0.61	52.28	34.20	7.19	10.79	3.75	18.10	-	47	47	39	0.92	142.90
Opel Astra 2011 BAPS 10 Jun 2014	0.62	0.61	51.50	33.70	7.17	10.77	3.78	18.09	-	47	47	39	0.92	109.31
Volkswagen Polo TDI 2011 BAPS 10 Jun 2014	0.64	0.62	41.67	26.62	7.21	11.18	3.74	18.04	-	31	31	31	0.75	122.31
Volkswagen Touareg Hybrid 2011 BAPS 10 Jun 2014	0.60	0.59	52.51	33.92	6.60	10.61	5.16	18.23	-	40	40	40	0.82	101.61
Honda Jazz 2011 BAPS 10 Jun 2014	0.62	0.60	40.98	26.19	7.26	11.31	3.82	18.13	-	31	31	31	0.75	125.03
Volkswagen Golf VI 2011 BAPS 10 Jun 2014	0.63	0.62	46.30	30.43	7.48	11.60	3.87	18.39	-	49	49	35	0.95	141.57
Seat Alhambra 2011 BAPS 10 Jun 2014	0.60	0.59	52.07	33.64	6.94	10.45	3.97	17.96	-	47	47	39	0.83	155.80
BMW 3er Kombi 2011 BAPS 10 Jun 2014	0.80	0.62	55.15	37.35	7.90	11.93	4.01	18.92	Pass	273	273	41	1.35	98.20
Volkswagen Caddy 2011 BAPS 10 Jun 2014	0.52	0.51	48.50	31.81	7.37	11.13	3.74	18.27	-	37	37	37	0.96	116.64

E Folder strucutre of Evaluation tool

Both within education and research it is beneficial to be able to ensure that the vehicle used, real or virtual, behaves as it should. In order to verify this a set of test procedures is needed. By implementing these test procedures in to an evaluation tool the user is presented with an efficient method to verify a model through simulation way and analysis of the results.

Within this thesis a set of test procedures have been selected and implemented in an evaluation tool divided into virtual test and analysis in order to both be able to use it for simulations as well as for post processing of real test data. This report focuses on the choice and implementation of a limited number of test procedures as well as the design of the evaluation tool developed.

Within this thesis Steady state cornering, Sine with dwell, Continuous sinusoidal input and Straight ahead acceleration have been implemented in to the evaluation tool. This gives the user an partial overview. Preferably several more test procedures should be implemented in the tool in order to get a more comprehensive view of the vehicles behavior. A recommendation for future work is to implement: Step input, Random input, Sinusoidal input, one period, Pulse input, Braking with split coefficient of friction, Brake in turn and Straight braking.

In order to give the user freedom to adjust the test procedures based on his specific requirements, all test procedures have been implemented using reference document with parametrizations for each test procedure. This is done in order to to ensure good adaptability

The tool developed within this test is easy to set up and supports batch processes which enables it to run several simulations using different model. This have been done with one model from the research project Balance Active and Passive Safety (BAPS). The evaluation tool is based on an combination of Matlab and Simulink. The results from the analysis part of the tool are presented as an pdf document.

The purpose with creating this tool is to provide a method to easily and quickly get results on the behavior of a real vehicle or a vehicle model during a few standard tests. This purpose is fulfilled with the tool created within this thesis.

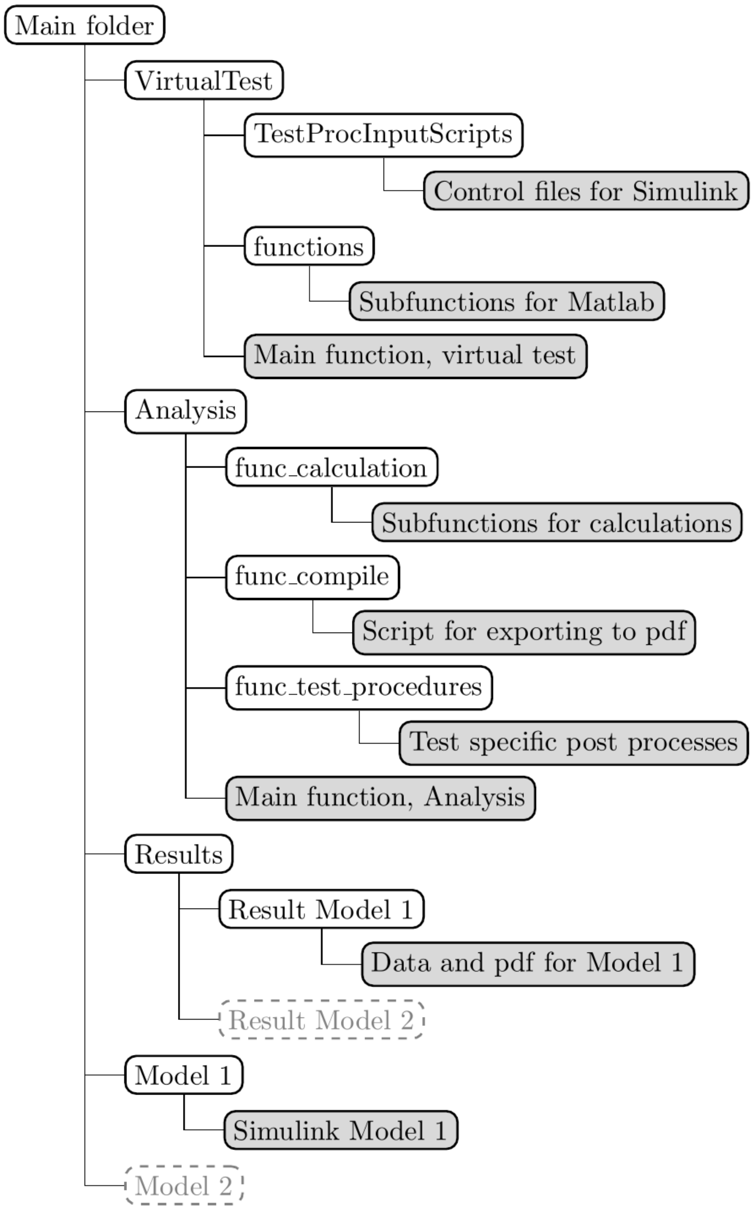


Figure E.1: *File and folder structure for Evaluation tool*