Validation of a Moving Base Driving Simulator for Subjective Assessments of Steering and Handling

Master's Thesis in Automotive Engineering

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Vehicle Dynamics
CHALMERS UNIVERSITY OF TECHNOLOGY
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Cover:
VI-Grade Driver in Motion Moving Base Driving Simulator installed at Volvo Car Corporation.

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Abstract

An important step in automotive development to evaluate the steering and handling characteristics of a vehicle is through physical subjective assessments and testing. This allows for a thorough understanding of how the vehicle behaves when driving and how it will be experienced by the customer. However, as physical subjective assessments and testing require real vehicles to be driven on a real track, it is rather inefficient time-wise, costly, and sensitive regarding repetitiveness and to surrounding conditions, compared with using digital development tools. Due to these drawbacks, the general trend in the automotive industry is to move an increasing amount of the development of vehicle steering and handling dynamics from using physical tools and methods to digital ditto. This does however require that the digital tools used provide reliable and trustworthy results, a validation of which is the main purpose of the thesis project presented in this report.

The focus here is to validate the partly digital development tool that is the Moving Base Driving Simulator existing at Volvo Cars. This is performed by generating virtual vehicle models of a physical vehicle through measurements in a kinematics and compliance rig. The measurements are performed with three different antiroll bar configurations, thus generating three different vehicle models. The vehicle models are validated by simulating them driving certain manoeuvres, and driving the same manoeuvres in the physical environment in the same vehicle specimen as is used throughout the whole project. After tuning and validation, the virtual vehicle models are used as input to the Moving Base Driving Simulator. Performing a physical subjective assessment in the same vehicle as was measured in the kinematics and compliance rig, and another subjective assessment in the Moving Base Driving Simulator with the same layout, allows for a validation of the simulator by comparing the results. The project is thus covering all major steps included in vehicle dynamics development including kinematics and compliance measurements, generation, analysis and simulations of virtual vehicle models, physical objective measurements, and finally subjective assessments in a physical vehicle and in a driving simulator. The outcome of all stages are presented in this report and shows for example that 94% of the assessed handling characteristics and 78% of the steering characteristics change in the same direction in the physical and virtual subjective assessments when changing the antiroll bar configuration of the vehicle.

Key words: Vehicle Dynamics, Steering, Handling, Moving Base Driving Simulator, Subjective Assessments, Physical testing for Objective Metrics, Kinematics and Compliance measurements, Validation

Contents

Preface

The current trend in the automotive industry is for physical subjective assessments and testing to be replaced with corresponding digital development tools. The main purpose of the study presented in this master thesis report is to evaluate one of these digital development tools, namely a Moving Base Driving Simulator and the vehicle models used to control it. The study has been performed at the department of vehicle dynamics at Volvo Car Corporation in Gothenburg, Sweden and at the test track in Hällered during January to June 2015.

The report is split in two parts, a main section and an appendix. The main section, in which you are currently reading, contains the most relevant information regarding the thesis project. Information that is considered as additional, together with data that is to be kept within Volvo Car Corporation is added in the appendix. Therefore, the appendix should be treated as secret and is only available within Volvo Car Corporation.

Performing the project would not have been possible without the help and support from our supervisor Gaspar Gil Gómez and examiner Professor Bengt Jacobson. Special thanks to Volvo Car Corporation and the department of vehicle dynamics, managed by Stefan Karlsson, for allowing us to perform our master thesis within such an interesting and challenging topic and for providing us with the resources necessary to do so. Also, thanks to Max Boerboom for helping with VI-CarRealTime and explaining various vehicle dynamics related topics, Carl Sandberg for helping with VI-CarRealTime, theoretical explanations and the driving simulator, Per Hesslund for helping out with and realizing the K&C measurements and physical testing, Egbert Bakker for supervising the methodology and explaining vehicle dynamics related topics, Sergej Abyzov for performing the physical testing and processing the data, Peter Töppner Nilsson for operating the driving simulator, Axel Jonson for help with Sympathy for Data and the tire models, Daniel Hedendahl for supporting with Sympathy for Data, Adj. Professor Gunnar Olsson for feedback on the report, Per Carlsson for providing data about the vehicle used, Marcus Ljungberg for helping with the power steering system, Patrik Johansen for performing the physical vehicle configuration changes, David Dahlgren for providing information about the steering system, and Egbert Bakker, Mattias Davidsson, Eric Olsson, Per Carlsson and Kenneth Ekström for participating as drivers during the subjective assessments.

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Abbreviations

ABS	Anti-lock Braking System
ARB	Antiroll Bar
CoG	Centre of Gravity
CR	Constant Radius
CRT	Car Real Time
DiM	Driver in Motion
ESC	Electronic Stability Control
FLH	Front Left Hand
FRH	Front Right Hand
FR	Frequency Response
HPG	Hällered Proving Ground
HSS	High g Swept Steer
K&C	Kinematics and Compliance
LSS	Low g Swept Steer
MBDS	Moving Base Driving Simulator
MoI	Moment of Inertia
OM	Objective Metrics
RLH	Rear Left Hand
RRH	Rear Right Hand
SA	Subjective Assessment
SfD	Sympathy for Data
SPMM	Suspension Parameter Measurement Machine
SWA	Steering Wheel Angle
SWD	Sine With Dwell
SWT	Steering Wheel Torque
VCC	Volvo Car Corporation

1 Introduction

The following chapter provides a brief introduction to the project, explaining why it is performed, how it is performed and which areas of research it covers.

1.1 Background

The development phase of the vehicle handling and steering characteristics is nowadays mostly based on physical testing of Objective Metrics (OM) and Subjective Assessments (SA). However, because of reasons that are investigated and discussed further on in this thesis, replacing a certain amount of physical testing with digital development tools provides several advantages.

The main digital development tool referred to in this thesis is softwares capable of simulating the same manoeuvres and approximately predicting the same vehicle response as during physical testing. Also, the SAs performed through physical testing can, if desired, to a certain level be replaced by SAs in a Moving Base Driving Simulator (MBDS). To what extent digital development tools can be used depend on their accuracy which therefore should be verified before further work can be performed.

During vehicle development, it is of high value to be able to predict the performance and properties of vehicles for which a multi-body dynamic digital model is not available. As with any physical testing, the general trend also in this area is for more of the physical work to be replaced with digital development tools. Being able to generate a digital model of such a vehicle that can be tested objectively in a virtual environment and subjectively in a driving simulator with a known accuracy and trustworthiness allows for several opportunities that would have been unavailable without these tools.

"The hope is to be able one day to predict, during the design phase and with the help of simulations, the driver's perceived feeling of vehicles and thus be able to reduce the development time and cost, as well as improve the vehicle performance", Gil Gómez (2015).

The increased complexity of the involved systems, and the continuously increasing quality standards and competitiveness makes the need for efficient use of digital development tools and knowledge of their accuracy even more imperative.

1.2 Problem motivating the project

Developing and verifying vehicle handling and steering characteristics by physical testing is relatively inefficient time wise and economically. Compared to digital development tools, physical testing does also introduce difficulties with repeatability when performing the same test multiple times under the same conditions.

Increasing the usage of virtual vehicle models relative to that of physical vehicles can make significant improvements to the development process of the vehicle handling and steering characteristics. This does however require that the models used are accurate and correctly represents a real vehicle. Inaccurate models can still give results that are assumed to be good but when the resulting designs and decisions are to be implemented in a real vehicle, they might give a result totally different from what is desired. Before using vehicle models as a method for important decision making, their accuracy should be verified.

This requirement is definitely valid if especially studying the application of a driving simulator. For it to be a useful tool in vehicle dynamics development, it must be known to what extent the behaviour of a driving simulator corresponds with that of a real vehicle.

1.3 Envisioned solution

A potential method to improve the efficiency of the development process of vehicle handling and steering characteristics would be to replace stages of the physical testing and SAs with digital development tools based on Objective Metrics (OMs).

Verifying the accuracy of the digital development tools used can be performed by generating a vehicle model based on data from measurements of a physical vehicle in a Kinematics & Compliance (K&C) rig. This model can then be tested virtually to generate OMs, which can be compared to the OMs generated from testing the physical vehicle. A method to verify the suitability of a MBDS to reproduce the vehicle handling and steering feel is to perform a SA with the MBDS running the same vehicle model as previously created, and another SA using the same drivers and questionnaire with the same physical vehicle as which the vehicle model is generated from.

By generating the vehicle model from measurements performed in a K&C rig, and establishing a framework of methods for efficient model generation from measured data, the performance of vehicles for which a multi-body dynamic digital model is not available can be evaluated. If the performed validations show this methodology to be highly accurate, the time needed for usage of the physical vehicle can ideally be reduced to only the time it takes to perform the K&C measurements, thus allowing major economical improvements.

1.4 Objective

The main purpose of this study is to validate the accuracy of a vehicle model generated from K&C measurements, and the representativeness of the MBDS to reproduce the driving experience of a real vehicle. This will yield the suitability of these tools to replace the traditional development methods and whether the predicted efficiency improvements can be reached or not.

1.5 Deliverables

The aim of the thesis project is to deliver answers to the following questions:

- How can a vehicle model in VI-CarRealTime be created from measurements of a physical vehicle in a K&C rig?

- How do changes in the antiroll bar configuration affect the outcome of K&C measurements?

- How well do OMs generated from a VI-CarRealTime model based on K&C measurements correlate with OMs obtained from physical testing?

- To what extent can the performance of vehicles for which a virtual multi-body dynamics vehicle model is not available, be assessed from vehicle models based on K&C measurements?

- How well does a SA performed in a MBDS using a vehicle model based on K&C measurements correlate with a SA performed in the same physical vehicle?

1.6 Limitations

- The verification of the accuracy of the virtual models is limited to the one representing a V40.

- Because of limitations in the availability of expert drivers for the SA, the number of drivers is limited to a relatively low amount; which consequently might reduce the statistical significance of the study.

- The vehicle model used in the MBDS is dependent on the current performance of the simulator. Optimization of the algorithms controlling the MBDS, such as motion cuing, will not be performed.

- The data obtained from the K&C measurements is limited to what is possible to measure with the rig located at Hällered proving ground, and what is possible to measure within the available timeframe.

- The manoeuvres performed to obtain the vehicle DNA, both virtually and physically, are limited to: constant radius, frequency response, high g swept steer, low g swept steer, on centre steering, sine with dwell and vehicle yaw stability.

- The areas and tracks used for the SAs are limited to what is virtually available in the MBDS.

- The testing performed including maneuvers and evaluation is limited to what is considered by the current standard at Volvo Car Corporation to be within the areas of steering and handling.

2 Theory

The following chapter explains the theory that is necessary to know in order to understand the following parts of this report.

2.1 Subjective assessments

A passenger vehicle is designed to be driven by and to transport people, and should thus be designed after what people find desirable. How a vehicle is experienced is however a subjective feeling, something that cannot be fully measured by objective means. This introduces the need for subjective testing during the development phase of new vehicles.

As explained by Gil Gómez, et al (2015) "Cars are driven by people… A passenger vehicle is therefore not only a device that has to deliver a minimum performance or transport people safely from point A to point B. It is also a machine designed to have a constant interaction with its driver and its passengers – to put it briefly, *a machine to be felt*. Consequently, the driving experience becomes one of the vehicle's most important characteristics. Vehicle dynamics, and more specifically steering and handling, thus cannot yet be totally understood only through equations and performance criteria. These objective parameters are necessary to understand and improve the system *'vehicle'*; however, to understand the system '*vehicle-driver',* driving feel cannot be ignored."

One significant methodology used during the development of steering and handling of new vehicles at Volvo Car Corporation is for the engineers to tune the properties of the relevant components according to their subjective feelings when driving the vehicles. This methodology ensures that the driving characteristics follow the formulated plans of how the steering and handling is to be experienced by the customer. The drawbacks of these types of tests are however not to be ignored. Tuning component properties for steering and handling during the development stage requires availability of full vehicle prototypes. As the components also are tuned rather than directly calculated, several iterations and different versions are most likely required. As can be understood, coupled with this process comes a high requirement for equipment, facilities, tools, time and money. These factors all justify why striving for replacing parts of the physical subjective testing with more efficient methods is justified.

Research regarding how parts of physical subjective testing can be replaced by objective measurements and digital development tools are currently ongoing, for which this thesis is providing support.

2.2 Objective testing

Apart from subjective assessments, an important part in vehicle dynamics development is objective testing where a vehicle is tested in order to obtain measured values of certain metrics that characterises the behaviour of the vehicle.

Huber and Drews (2009) motivates the need of objective measurements as: “the development engineer today needs highly conclusive and repeatable evaluation criteria. With regard to the interaction between the operator, the vehicle and the environment, the objective to be pursued is a design of the vehicle that provides optimum support for the driver’s skills. To achieve this, it is necessary to actually make handling properties describable and to support these descriptions with measurements.”

As objective testing can be performed for a significant amount of different purposes, it can also be performed in different ways. One is for a human driver to control a vehicle equipped with various sensors and data acquisition systems that gathers information and data about the behaviour and characteristics of the vehicle. If exact repeatability and for the vehicle to be driven in a highly accurate manner is desired, a more advanced setup can be used, including robots to control the vehicle. Such robots can be connected to and control the physical controls of the vehicle such as steering wheel, pedals and gear lever.

Objective testing is often executed by performing one or a selection of several defined manoeuvres. The definition of the manoeuvres can follow multiple different standards such as those internally specified by different vehicle manufacturers or international standard like ISO. Some international manoeuvre standards that are relevant in the current project include Steady-state Circular Driving Behaviour (ISO 4138:2012), Lateral Transient Response (SS-ISO 7401:2011) and Sine with Dwell Stability Control Testing (ISO/DIS 19365).

If the vehicle is equipped with robots to control its motion, these will in most cases allow for an extraction of time step data regarding for instance throttle, brake, and clutch pedal position, steering wheel angle, steering wheel turn rate, steering wheel torque and current gear. If the vehicle is also equipped with sensors and data acquisition systems, further information of the performance of the vehicle can be obtained, such as velocities, accelerations, and yaw, pitch and roll motions.

Some measurements from objective testing that are used to a significant amount in this report include lateral acceleration, yaw rate, slip angle and roll angle. Studying the notation of vehicle motions shown in Figure 1, lateral acceleration and roll angle are self-explanatory. Yaw rate is the angular velocity of the yaw motion of the vehicle. Jacobson (2013) explains slip angle as “the angle between tyre longitudinal direction and the tyre translational velocity (wheel hub velocity)”.

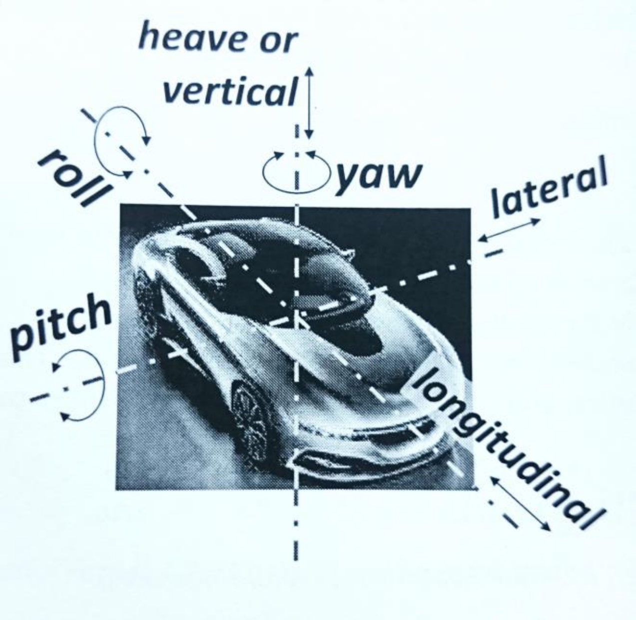


Figure 1 - Notation of vehicle motions. [Jacobson (2013)]

2.3 Moving Base Driving Simulator

One significant solution to consider when investigating digital tools to replace physical subjective testing is a driving simulator. A typical driving simulator uses a virtual model to represent the vehicle behaviour and a virtual environment to display the surroundings. Depending on the driver input and the road conditions, the appropriate behaviour of the vehicle is calculated and performed by the software. The interface between the driver and the simulator is ideally similar to the controls used in a real vehicle.

According to VI-Grade (2015), a driving simulator can be designed in two different types, static and dynamic. In a static simulator, the platform in which the driver sits is kept stationary. In a dynamic simulator, the platform moves accordingly to the behaviour of the simulated virtual vehicle. The main purpose of a dynamic driving simulator is for the driver to feel the movements of the body in the same way as in a physical vehicle. The purpose of the software used for a dynamic simulator is thus not only to simulate the virtual vehicle, but also to move the physical vehicle body in a manner that provides the driver with a driving feel as realistic as possible.

The driving simulator in focus for this thesis is the one recently obtained by Volvo Car Corporation, named Driver-in-Motion, DiM, designed by VI-Grade, and engineered and manufactured by Saginomiya. The DiM is a dynamic moving base driving simulator where the driver can not only see the behaviour of the vehicle but also feel it. As shown in Figure 2, the vehicle body in which the driver sits is resting on a hexapod of six electro-mechanically actuated cylinders. The hexapod is resting on a base plate which moves horizontally on airpads. The movement of the base plate is controlled by a tripod system with three electro-mechanically actuated horizontal cylinders. This setup allows the vehicle body to move with nine degrees of freedom. VI-Grade (2015)

Figure 2 - The moving base driving simulator used at Volvo Cars.

To be able to replace parts of the physical testing with the usage of a driving simulator, it is beneficial to have similar environments available. For this reason, the surface of real tracks is laser scanned, transformed into virtual models and imported into the diving simulator.

As the scope of the current project is to investigate both handling and steering characteristics, realistic motions of the steering system used in the driving simulator are thus of great importance. To obtain a feeling in the steering wheel as realistic as possible, an electric motor that adds torque to the wheel is mounted behind it. Controlling the behaviour of the motor and consequently the torque feedback to the driver is performed using a mathematical model in Matlab Simulink. Depending on the current velocities, accelerations, and steering wheel angle of the simulated vehicle model, the appropriate torque level from the motor is calculated by the Simulink model.

2.4 VI-Grade CarRealTime

The virtual vehicle model used in the driving simulator is created and simulated in the software VI-CarRealTime, also developed by VI-Grade. Modelling of a vehicle in VI-CarRearTime is made based upon lookup tables where the behaviour and performance of all relevant components and systems are summarized in a matrix dataset as shown in Figure 3. The values in the lookup tables are then used as input to the algorithms governing the predictions and calculations of how the vehicle model will behave during the simulations.

The simulated vehicle body has six degrees of freedom, three rotations and three translations. Apart from that, each wheel does also have six degrees of freedom since the software considers the bump steer and the camber gain in all four wheels.

VI-CarRealTime has integrated functions that allow for modelling of systems such as ESC and ABS, although these are not utilized in the current project.

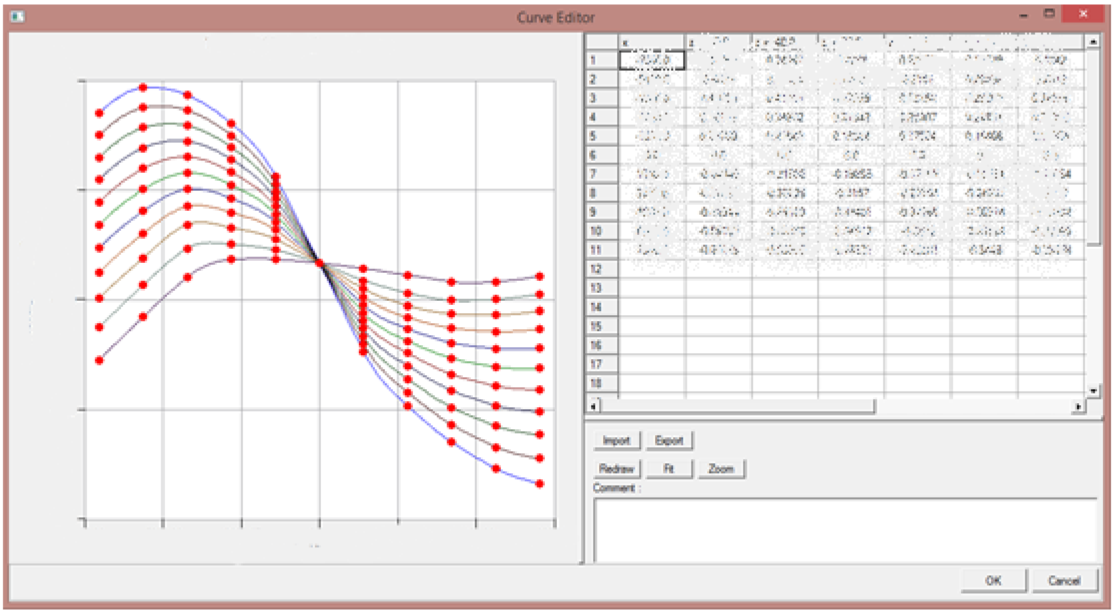


Figure 3 - Example of lookup table in VI-CarRealTime. Values hidden for secrecy.

The fact that the vehicle model consists of datasets rather than geometrical bodies, as in several similar simulation softwares, allows the simulations in VI-CarRealTime to be performed faster than real time. This is obviously vital for making the software suitable for usage in a driving simulator.

VI-CarRealTime contains a driver model and does therefore not require a simulator to run. It can thus be used as a standalone software for simulating vehicle driving characteristics. This means that a vehicle model under development can be tuned and modified on a regular computer in the same environment as it will be used when running it in the driving simulator.

2.5 Data processing

One issue that appears when analysing or displaying data from within the area of vehicle dynamics, even if it is objectively measured, is what to use and how to display it. Common equipment used during physical testing or softwares used for simulations can easily extract hundreds of values and parameters that represent the behaviour of a vehicle. When comparing different vehicles or the effect on certain changes on one vehicle, having to study all these hundreds of parameters is not only highly time requiring but makes it also difficult to understand and to overview. In order to solve this, a decision has to be made of which parameters are the most representative of the vehicle behaviour and how these easily can be displayed and compared.

In the current project, this is performed by generating a so called DNA fingerprint, which is a compilation of metrics divided into different sections. These metrics are calculated from the data that is either physically measured or virtually simulated.

The software used in the current project to calculate the relevant metrics is an open source solution optimized and created for data processing named Sympathy for Data. A system in Sympathy for Data for generating the DNA fingerprint from simulations performed in VI-CarRealTime did however not exist. One does thus have to be generated during the current project.

2.6 Kinematics and Compliance measurements

Kinematics and compliance characteristics of a vehicle suspension system are crucial in order for engineers to determine the performance of the vehicle in areas such as ride, steering and handling. K&C rigs are used to accurately determine the kinematics characteristics of the vehicle suspension and steering geometries but also the compliance characteristics of all the suspension components, elastomeric bushes, anti-roll bars, springs, bump stops and body.

Holdmann et al. (1998) explains the terms as: “Kinematics means the movements of the wheel relative to the body that result from spring travel. Compliance steer results from additional forces in the contact area of the tires. These forces caused by lateral or longitudinal accelerations of the vehicle deform the suspension parts and its bushings and lead to additional camber and toe angles.”

The Suspension Parameter Measuring Machine (SPMM 4000) built by Anthony Best Dynamics is used in this research to gather the needed K&C data. This machine subjects the vehicle to a variety of forces and displacements by controlling the centre table that holds the body and the wheel station on which the wheels are standing, as shown in Figure 4 and Figure 5. Data such as forces on the contact patch, centre wheel displacement and wheels angles are logged during the Kinematics and Compliance tests.

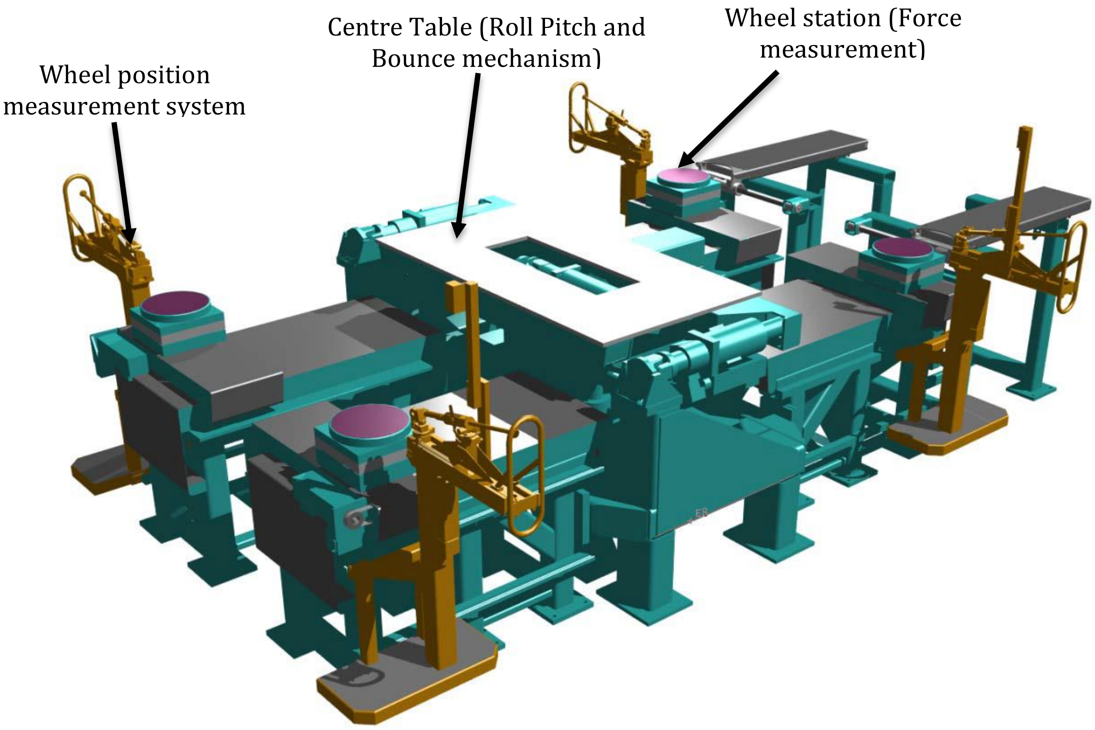


Figure 4 - SPMM 4000 K&C measurement machine.

Figure 5 - Vehicle installed in the SPMM 5000 K&C measurement machine.

The steering characteristics are measured by making a sweep from one side of the steering rack limit to the other and measuring both the steering wheel travel but also the wheels displacements and angles. For this purpose the steering wheel is controlled by a steering robot, Figure 6, which is also needed in order to prevent the steering wheel from displacing during all the other tests and thus being able to measure the steering system compliance. There is also a robot to control the brake pedal and apply braking force on the four wheels when the measurement requires it.

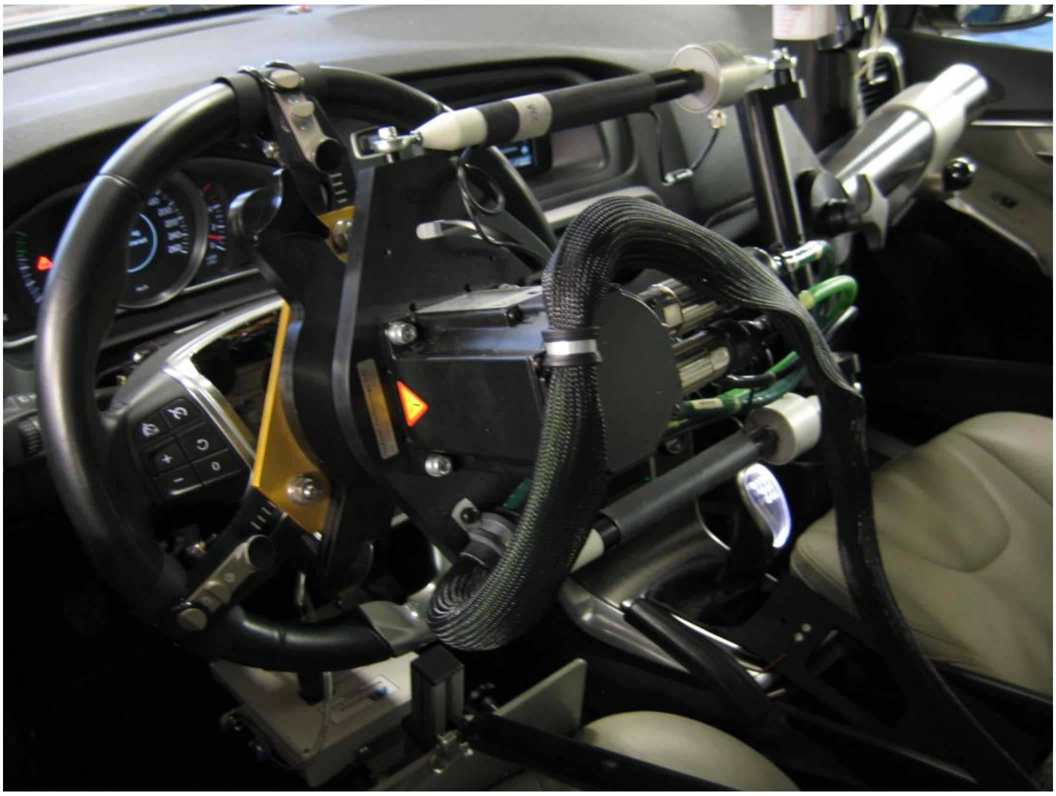


Figure 6 - Steering robot used during K&C measurements.

Even though the tests are dynamic, the machine applies forces and moments to the suspension slowly in order to not excite any dynamic forces originating from inertias, dampers or elastomers. The tests are therefore quasi-static and in some of them the movements can barely be appreciated by the human eye. Because of this, the data generated from the kinematics and compliance measurements is not sufficient to generate a fully functioning virtual vehicle model and must be complemented with the characteristics of for instance dampers and power steering system. The machine is also capable of measuring centre of gravity and moment of inertia of the vehicle.

3 Method

The workflow followed throughout the thesis project is as in Figure 7:

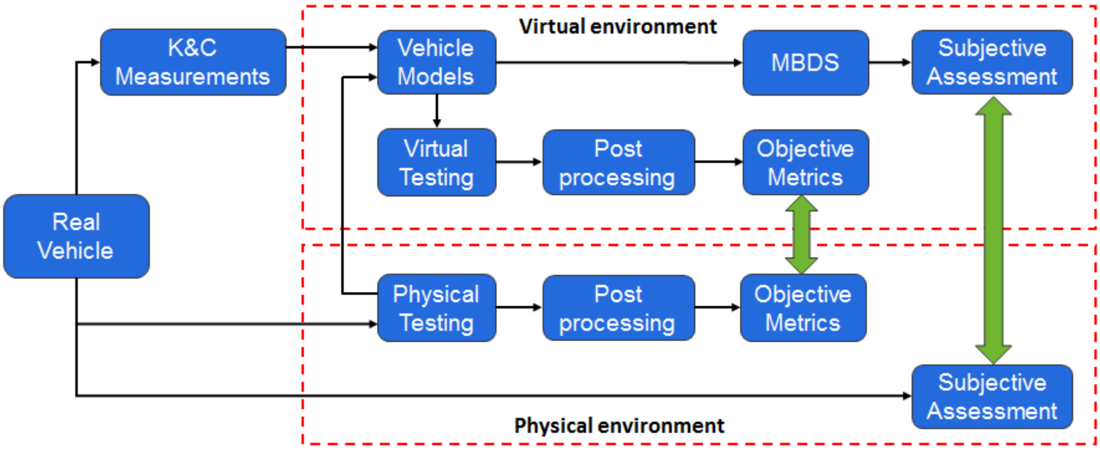


Figure 7 - Schematic of the workflow followed throughout the project.

The block “real vehicle” in the schematic above refers to the 2012 Volvo V40 D2 that is used throughout the project. The motivation to select this model is as it has been used earlier in the research aiming at correlating objective metrics with the outcome of subjective assessments, a research to which this thesis project is providing support. Selecting the same vehicle allows the data collected and analysis performed to be compared with that obtained from the mentioned research and also for it to be used in that research. Much attention is paid towards always using the same vehicle specimen throughout every stage of the project and ensuring that it always has the same corner weights, tyres, tyre pressures and fuel load. As explained further in section 3.3.1.2, the antiroll bar configuration of the physical vehicle is altered which allows for relative comparisons and generates multiple vehicle models; the standard configuration, one without the front antiroll bar, one without the rear antiroll bar, and one completely without antiroll bars.

As can be seen, the schematic is divided into a physical and a virtual environment. This is performed to clarify that the project basically can be split into two parts where the purpose of each is to deliver results that can be directly compared with those from the other environment, allowing for direct validation. The validations that are to be performed are denoted with green arrows in the schematic above. As explained earlier, the main purpose of the thesis is to validate the driving simulator. This is performed by the validation of the two subjective assessments, with the one in the virtual environment being performed in the driving simulator and the one in the physical environment in the V40 that the vehicle model used in the simulator is generated from. To ensure the accuracy of the vehicle model used in the virtual environment, this is validated as well. To perform this validation, the vehicle model is simulated to generate a number of metrics. These metrics are then compared with the metrics generated from physical testing. Vehicle performance data from the physical testing is also used when creating the virtual vehicle model to ensure a realistic behaviour.

Comprehensive explanations of the different parts of the project are presented in the following sections.

3.1 Preparatory stages

As shown in the schematic of the project workflow in Figure 7, the initial major steps to be performed must either be the kinematics and compliance measurements, physical testing or physical subjective assessments. Due to the fact of the current project started in January, this turned out to cause slight issues. Everything performed in the physical environment requires the testing environment to fulfil certain criteria such as dry tarmac and ambient temperature above a threshold value to be comparable with the simulations performed in the virtual environment. Therefore, while waiting for the weather to be acceptable, as much as possible of the other parts of the project had to be prepared. These preparations followed the simple flowchart showed in Figure 8.

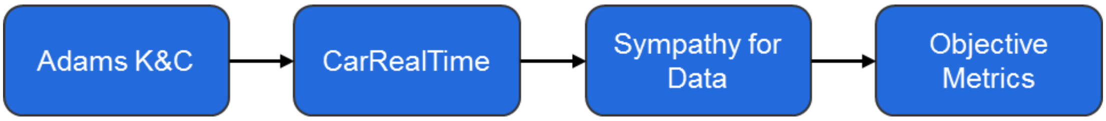


Figure 8 - Schematic of the preparatory workflow followed.

Using a model of a similar Volvo V40 built in MSC Adams allows the manoeuvres in VI-CarRealTime and the flows in Sympathy for Data to be prepared. The available Adams model deviates slightly from the physical vehicle specimen used in the project as it is equipped with a different powertrain and chassis configuration, but it is the closest available model that can be used for preparation. The kinematics and compliance of the Adams model are measured virtually and its output data can therefore be considered an approximation if compared with the output of physical kinematics and compliance measurements. When the model is imported in VI-CarRealTime, it allows an investigation of the ease and possibility to generate the different manoeuvres and to gain understanding of the simulation environment. Simulating the Adams vehicle in VI-CarRealTime does then allow for the flows in Sympathy for Data to be prepared for the formats used as output from VI-CarRealTime. Lastly, completing the procedure shown in Figure 8 will provide objective metrics in a DNA fingerprint which later can be compared with the DNA fingerprints generated from the vehicle measured in the physical kinematics and compliance rig. Comparing both sets of metrics will allow for a validation of the correctness of the methodology.

3.2 Vehicle model generation and validation

One important part of the project upon which much time was spent was to generate, validate and adapt the virtual vehicle model that is used in the driving simulator. The methods used to fulfil the requirements set on this virtual vehicle model are explained in the following section.

3.2.1 Virtual environment

As explained earlier, the thesis project can be split into two parts, one related to the virtual environment and one regarding the physical environment. The following sections describe the work performed in the virtual environment to generate, tune and adapt the vehicle model.

3.2.1.1 K&C measurements

To be able to generate a virtual model of the V40 that is used in the thesis project, properties and performance of how the suspension system, body, and related components behave during driving must be known and formulated; consequently, some sort of dynamic measurements must be performed. In the current situation where VI-CarRealTime is used due to its capability of integration in the driving simulator, the most suitable method to perform these dynamic measurements is by using a rig measuring the kinematics and compliance of the suspension system. Such a rig is available at Volvo Car Corporation and is, as stated in the theory chapter, an Anthony Best SPMM 4000.

The effect in kinematics and compliance of having the anti-roll bar connected or not is uncertain without testing it. An exhaustive study of the needed K&C tests is thus performed to understand which metrics that could be affected by the ARB configuration of a vehicle. Also, a physical study of how the ARB is installed in the vehicle is performed in order to better understand how it possibly can affect the K&C measurements. During the physical study of the vehicle it was observed that the front and rear antiroll bars in the Volvo V40 have the rubber bushing vulcanised to the bar and to the mounting. This results in an increased stiffness of the suspension even when bouncing the vehicle completely horizontally. In order to be on the safe side and also to further study the effect of the antiroll bar on the K&C measurements, it was decided to measure the vehicle fully without ARBs, with only the front ARB mounted, with only the rear ARB mounted, and in its standard configuration.

3.2.1.2 K&C to CRT

The process of generating a vehicle model from physical K&C measurement had been accomplished in the past at Volvo Cars and therefore a compilation of required measurements do exist. However, the models generated so far are of relatively low complexity and are for instance missing tie rod and kingpin kinematics of the steering system, resulting in no torque feedback to the steering wheel at all. Furthermore, when these models were generated, the compliance tests were only performed at a single bounce level.

It has been decided to increase the accuracy of the models generated in order to reduce the deviation from reality, and also because steering characteristics are to be analysed. This requires more complex models and thus more K&C measurements. The vehicle model generated from Adams is generated from a larger range of different K&C measurements and is therefore used as an example to decide which extra measurements that are required.

3.2.1.2.1 Required K&C tests

After comparing the existing models at Volvo Cars and the VI-CarRealTime model generated from Adams, the extra needed tests were identified. It was decided to include compliance measurements at different bounce levels and also asymmetric bounce levels for left and right wheels in order to capture the opposite wheel dependency on each axis. Single events in compliance for left and for right wheels independently were also decided to be included in favour of an increased accuracy.

The data from the virtual Adams K&C measurements that is used to generate the model in Vi-CarRealTime is obtained by measuring the vehicle in eleven different suspension bounce levels for each relevant parameter. Due to limitations of VI-CarRealTime, the number of bounce levels is limited to a maximum of three, and asymmetric bounce levels are not possible to implement in the model when generating it from real K&C measurements.

To decide which three bounce levels to use, the compliance lookup tables of the model generated from Adams were studied. As can be observed in Figure 9, the track change under lateral forces at different bounce levels is not linear even though the bounce level changes linearly.

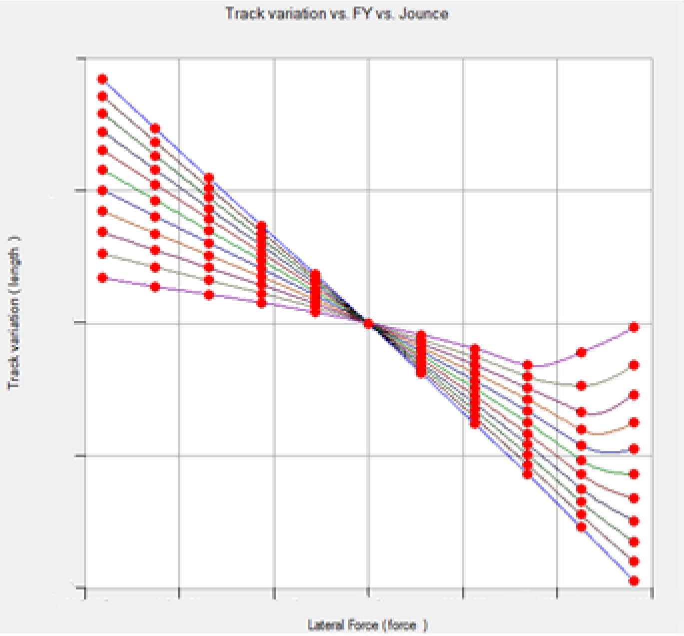


Figure 9 - Example of lookup table with eleven bounce levels. Values hidden for secrecy.

This means that by choosing the highest possible, lowest possible and steady state bounce levels, a small error is introduced due to the linear interpolation used between the data sets. However, taking the changing shape of the curves at different bounce levels into account, the best way to predict the behaviour is to take the boundary lines rather than leaving the software to make spline extrapolations. Another approach is to try to investigate the most commonly reached maximum and minimum bounce levels under the performed manoeuvres and define those as the boundary values. This was seen as a complex task that might lead to errors if the bounce levels change during the subjective assessments, for example due to the road surface conditions. The first method is therefore the one of choice when performing the measurements and generating the virtual vehicle models.

Table 1 shows the needed measurements in order to generate a vehicle model which a precision that is deemed to be acceptable in the current project. As can be observed, there is a fourth configuration with both antiroll bars disconnected “OFF-OFF” in which only a roll test is performed. This test is needed to calculate the auxiliary anti roll force generated by the antiroll bars, which is required when at a later stage the different virtual vehicle models are generated. The second column, “ON-ON”, shows the standard configuration of the vehicle and the tests that are to be performed for one configuration. The third and fourth column, “OFF-ON” and “ON-OFF”, shows which of these tests that is to be performed again if the vehicle configuration is modified.

Table 1 - Required K&C measurements.

Test name	ON-ON	OFF-ON	ON-OFF	OFF-OFF	3 bounce levels
Vertical bounce all car	x	x	x		No
Vertical bounce only rear	x	x	x		No
Roll test	x			x	Yes
Longitudinal compliance in phase (braking)	x	x	x		Yes
Longitudinal compliance out phase (braking)	x	x	x		Yes
Longitudinal compliance in phase (strapped wheels)	x	x	x		No
Longitudinal compliance out phase (strapped wheels)	x	x	x		No
Longitudinal compliance single, braking (right wheels)	x	x	x		Yes
Longitudinal compliance single, braking (left wheels)	x	x	x		Yes
Longitudinal compliance single, strapped wheels (right wheels)	x	x	x		No
Longitudinal compliance single, strapped wheels (left wheels)	x	x	x		No
Aligning torque in phase	x	x	x		Yes
Aligning torque out phase	x	x	x		Yes
Aligning torque single (right wheels)	x	x	x		Yes
Aligning torque single (left wheels)	x	x	x		Yes
Lateral compliance in phase	x	x	x		Yes
Lateral compliance out phase	x	x	x		Yes
Lateral compliance single (right wheels)	x	x	x		Yes
Lateral compliance single (left wheels)	x	x	x		Yes
Steering ratio	x	x	x		No
MoI and CoG	x				No

3.2.1.2.2 Controlled parameters

The tire casing stiffness differs between different tire models. Therefore, it was decided to in VI-CarRealTime use the same Bridgestone tire model that the tire manufacturer used to determine the parameters of the magic tire formula. The vehicle weight and its weight distribution will greatly affect the moment of inertia and centre of gravity, and can significantly affect the K&C measurements. Thus, another parameter to be controlled is that the corner weights of the vehicle are the same during the K&C, the physical testing and the physical subjective assessments.

When assessing a vehicle subjectively, the vehicle will be driven so severely that the tires will become saturated at some point. This implies that compliance measurements should be performed applying the highest possible forces on the wheel stations without causing the tires to slip, considering that this force is within a reasonable range of the application in which the vehicle model is to be used. This was explained to the operators of the K&C rig and at each bounce level the maximum force level was tested before performing the measurements.

3.2.1.2.3 Vehicle model generation

Once the data of all the vehicle setups has been gathered and before the vehicle model generation wizard in VI-CarRealTime can be used, a renaming of the files is needed. The vehicle wizard uses a K&C configuration file to understand which tests are used to build the vehicle model. This file must be modified in order to include the single event tests and the tests at maximum and minimum bounce levels. If more details of the vehicle model generation are needed, refer to Appendix A where the process is described in detail.

After the vehicle model has been generated, all relevant parameters are not necessarily introduced correctly. These must then be introduced manually. If information about which parameters were changed is desired, refer to Appendix A where all the changed and added parameters are described in detail.

3.2.1.3 Model validation in time step

Once a vehicle model is successfully generated from the kinematics and compliance measurement data, it must be tuned to ensure desirable functionality and performance in the driving simulator. Obviously, the aim for the virtual vehicle model is for it to be as close to its physical counterpart as possible. The method of choice to ensuring this is by comparing the properties of the vehicle model with the measurements performed during the physical testing.

To eliminate potential sources of error from the manoeuvres being performed slightly differently, the exact inputs for the steering and pedal robots used during the physical testing are extracted from the testing data and used as inputs for manually built manoeuvers in VI-CarRealTime. This does thus eliminate the source of error originating from the manoeuvres being implemented differently.

Garrott, et al. (1997) mentions: “A simulation's predictions will, in general, only be correct within some portion of the physical system's operating range. An obvious example of this is that a vehicle dynamics simulation's predictions may be correct for low lateral acceleration manoeuvres but become progressively worse as lateral acceleration increases and non-linear effects become more important." In order to cover as much as possible of the operating scope of the vehicle during each manoeuvre, the validation with time step data is performed using the runs with the highest and lowest amplitude of a certain metric as input for the simulated manoeuvres.

3.2.1.3.1 CarRealTime custom manoeuvres from physical testing data

When performing physical testing, all information from the steering robot, pedal robot and additional measurement units should be stored in .bcd-files. The target is for these to be converted into .txt-files which are much more easily readable. For this purpose, a flow in Sympathy for Data is obtained which converts the .bcd-files to obtain the extension .txt. The input to the flow is a .log file which points to all .bcd-files that are included in the current manoeuvre.

Once the .txt-file is generated, it is imported into a Matlab-script which extracts the data that is relevant as input to the custom manoeuvres in VI-CarRealTime, and introduces that data in a .dcd-file. When the .dcd-file is available, the VI-EventBulider is used to generate the custom event, meaning the manoeuvre built to replicate the inputs used in physical testing. A flowchart to aid the understanding of process is found in Figure 10.

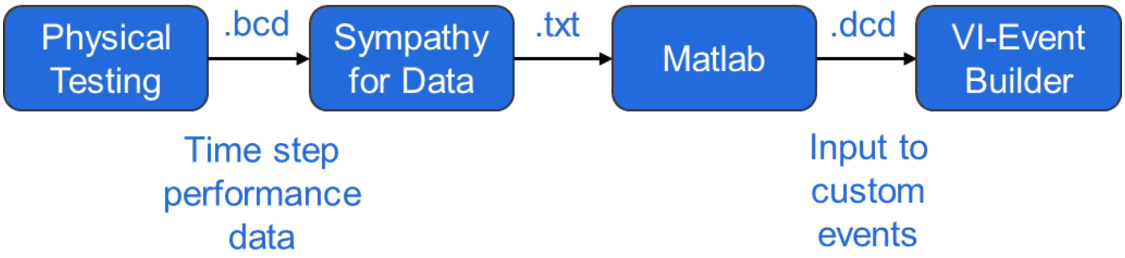


Figure 10 - The process to generate custom events from physical testing data.

For the current application, the data extracted to the .dcd-file and thus introduced in the custom event is selected as time and steering wheel angle, ensuring that the simulated vehicle will use the same steering input as during the physical testing.

Another important factor is obviously the longitudinal velocity of the vehicle. For the manoeuvres where the longitudinal velocity is defined as constant, the target velocity is set as constant in the event. For the manoeuvres that are defined with an initial velocity, and that are supposed to be performed with no throttle applied, the solution is not as straight forward. The first solution applied to this was to implement the measured time step data of the longitudinal velocity, similar to what is performed for the steering wheel angle. When running a simulation with this, it was however seen that the model was working intensively to be as close to this velocity as possible, resulting in it applying more throttle or braking during the manoeuvre if the current velocity deviated too much from the one introduced. Sudden acceleration or braking does obviously have a significant effect on the dynamics of the vehicle and thus also on the result of the simulation.

To solve this issue, the time step data of the longitudinal velocity was replaced with providing an initial velocity and specifying the level of throttle, brake and clutch as zero throughout the full manoeuvre, leaving the vehicle with only engine brake. The correlation of the longitudinal velocity between the physical vehicle and the virtual one does in this case then depend on how well the powertrain and other friction elements are modelled. Even though this method does not result in the longitudinal velocity being exactly identical with that in physical testing during each time step, the result is still much more accurate than when introducing the velocity variation as time step data, resulting in the vehicle suddenly accelerating or braking.

When the custom event is successfully created it is saved as a .vdf-file. Using the .vdf-file as a file driven manoeuvre in VI-CarRealTime and running the simulation finally allows the vehicle model to be simulated using the same input as in the physical testing.

3.2.1.3.2 Metric comparison

As mentioned, the actual tuning of the vehicle model is performed by comparing certain metrics obtained from the simulation with corresponding ones from the physical testing. For this purpose, a Matlab script is generated which imports the .csv-file that becomes available when running simulations in VI-CarRealTime, and the .txt-file that is generated with Sympathy for Data from the .bcd-file from physical testing. Once the necessary files are imported, the script plots measured data against simulated data for a selection of metrics namely lateral acceleration, yaw rate, side slip angle, roll angle, and steering wheel torque.

To ensure that the model is tuned to operate in a range of manoeuvres as wide as possible, the metrics compared are obtained from five different manoeuvres, coupled with two driving cases for each manoeuvre, such as high and low lateral acceleration, high and low longitudinal velocity, etcetera. Using five different manoeuvres with five different metrics from each, and with two cases of each metric, a total of fifty graphs are generated. These graphs are then compared by visually studying the accuracy between the datasets obtained from simulation and physical testing. A comparison of fifty datasets can obviously be difficult to overview but as each configuration change normally affects a certain amount of or category of metrics, this method ensures that no performance range is ignored.

By creating a fingerprint in VI-CarRealTime that consists of all .vdf-files of the relevant manoeuvres and generating a Matlab script that runs VI-CarRealTime in batch, all fifty graphs can be generated by the simple press of a button.

3.2.1.3.3 Model modification

Depending on the outcome of the generated plots, actions are taken upon the parameters of the vehicle model that are assumed to affect the metrics for which a significantly visible deviation is present. It is however important to remember that it is desired to keep the number of modifications to each vehicle model to a minimum.

In the current case of the thesis project, slight modifications were however necessary. The major reason for this is the tyre model used which is generated from physical measurements performed by one of the major tyre manufacturers. The model is unfortunately highly unstable during some manoeuvres and does thus require some modifications to even be able to use in the driving simulator, as explained in Section 4.2.2.

3.2.1.3.4 Alternative vehicle models

As an additional part of the current project, alternative methods to generate the vehicle models than directly from kinematics and compliance measurements are investigated. Generating the vehicle models without the front and rear antiroll bar respectively can be performed by significantly quicker and easier means than measuring the vehicle with these configuration changes in the kinematics and compliance rig. Vehicle models with corresponding configuration changes can be generated directly in VI-CarRealTime by virtually disconnecting the antiroll bar of the model generated from the standard vehicle. In practise, this means changing the auxiliary antiroll force of one of the current axis to zero. Comparing the performance and properties of these virtually modified vehicle models with those of the vehicle models generated from the physical kinematics and compliance measurements allows for an investigation of the need to perform these additional measurements.

Another method to obtain a vehicle model that can be used in simulations and in the driving simulator would be through virtual kinematics and compliance measurements. In the current project, such a vehicle model is, as explained, obtained from Adams K&C.

Using these additional vehicle models is not according to the specified methodology in the current project as it deviates from the statement of using the same vehicle specimen throughout the whole project. The vehicle model with standard configuration obtained from Adams K&C, together with the two vehicle models where the antiroll bar configuration is virtually modified in VI-CarRealTime will however still be used as reference models as it allows for a comparison and investigation of the different methodologies.

3.2.1.4 Model implementation in MBDS

The main factor to take into consideration when implementing a vehicle model in the driving simulator is the stability of the model, mainly because of safety reasons to not cause any damage to the simulator or discomfort to the person driving it. Transferring the vehicle model from VI-CarRealTime to the simulator should be a rather swift operation including copying the model, compile it to the required format and load it into the simulator.

The process of ensuring stability of the model is to begin at low pace that slowly increases. The initial step performed when validating the stability of the models used in the current project was to ensure the stability of the steering. This was performed by driving at an infinitely long straight road with the platform motions switched off, and with the driver performing slow and low steering inputs. When the steering was proven stable, the platform motions were activated but with a downscaled behaviour. Proven stable use also with this configuration allowed the track to be changed to Handling track two at Hällered Proving Ground which is what will be used during the subjective assessments, and the platform motions to be increased to fully realistic behaviours.

3.2.1.5 CRT manoeuvre implementation

As shown in the schematic in Figure 7 that displays the methodology used to reach the final results of the project, the first validation performed is with the purpose to obtain the correlation of the vehicle models used. To perform this, the objective metrics in the DNA fingerprint generated from the physical testing, are compared with those in the DNA fingerprint generated from the virtual vehicle model. In order to allow for this, the manoeuvres that are performed in the physical testing must be performed exactly the same when simulating the virtual vehicle model. The manoeuvres performed during the physical testing are all executed according to standard procedures that are developed internally at Volvo Cars. These manoeuvre standards specify not only how the manoeuvres should be performed, but also exact numbers or ranges within which certain input parameters such as steering wheel angle, throttle position, longitudinal velocity should be kept. The standards does also state which value or range of values the measured output metrics such as lateral acceleration and steering wheel turn rate should reach for the test to be valid.

The seven manoeuvres selected to be the most representative for the steering and handling characteristics and that are reasonable to use within the scope of the current project can to some extent be designed from standard manoeuvres that are pre-installed in VI-CarRealTime. These manoeuvres are connected to a GUI that allows the user to adapt certain input parameters to the simulation such as longitudinal velocity, initial gear, throttle position, steering wheel angle, steering wheel turn rate and target lateral acceleration. Modifying these parameters to fit the Volvo Cars standard ones is however rather time consuming as each requires comprehensive tuning to be performed for each vehicle model. Some of the Volvo Cars standard manoeuvres are also not possible to obtain exactly as in the description.

After some research it was luckily found that it internally in Volvo Cars do exist manoeuvres that are programed to correspond to the Volvo Cars standard ones. As these manoeuvres were generated with an older version of VI-CarRealTime, their functionality and accuracy cannot be guaranteed. Before using these manoeuvres for generation of the DNA fingerprint their correctness must therefore be ensured. Because of the issues occurring when modifying the VI-CarRealTime pre-installed manoeuvres explained above, the most appropriate solution was decided as modifying the manoeuvres available at Volvo Cars to function properly with the current version of VI-CarRealTime. Using the Volvo Cars standard manoeuvres do require slight tuning for different models to fit the specified standards but significantly less than when modifying the VI-CarRealTime pre-installed ones.

3.2.1.6 Data processing

Due to issues with the integrated steering model in VI-CarRealTime, to obtain desirable steering functionality in the vehicle models, external input from a controller modelling the steering assist in Simulink is required. Since several different models are simulated, it was decided to automate this process by generating a script that runs Simulink in batch with VI-CarRealTime. By loading the manoeuvres from VI-CarRealTime using the batch script, all manoeuvres are run with the external steering using a simple press of a button. The output data from this is generated as .csv-files that contain numerous data of the performance of the simulated vehicle during the manoeuvre.

This output data from the simulated manoeuvres is the source for calculating the vehicle DNA fingerprint. As described in section 2.5, this is performed by using Symphaty for Data. The .csv-files from the simulated manoeuvres are used as input to the Sympathy for Data flows, which after running generates the metrics used for the DNA fingerprint.

Obtaining reasonable metrics from the .csv-files generated from the simulated manoeuvres in VI-CarRealTime was however far from plug and play. Firstly, a separate flow importing the data had to be created which renames the measured parameters to the names used in the Symphaty for Data flows and which combines the imported data with the metadata containing general information about the simulated vehicle. Secondly, the metadata had to be updated to include correct information about the simulated vehicles such as wheelbase, corner weights and positioning of the measurement sensors. The third task needed to perform was to convert the units of the input parameters to what is used in Sympathy for Data. This turned out to be a more problematic task than it might seem as VI-CarRealTime is not consistent with the units used in the software when running simulations and when outputting simulated data.

3.2.2 Physical environment

The second environment present in the thesis project is the physical one where real cars are used in a real life environment. The main purpose of utilizing this environment is to allow for validation of the virtual tools that are used.

3.2.2.1 Physical testing for objective metrics

To obtain comparable data of how the physical vehicle behaves during certain manoeuvres, it is objectively tested. The physical testing is performed using the same vehicle specimen with the same tyres, tyre pressures, corner weights and fuel load as during the kinematics and compliance measurements and subjective assessments. In this type of testing, the vehicle is equipped with robots controlling steering, throttle and brake, as can be seen in Figure 11. The robots are programmed to give such inputs such as the vehicle follows the behaviour as is specified in a set of predefined manoeuvres. Using the robots ensures repeatability and that the manoeuvres are performed according to the specifications of each manoeuvre. To measure the performance and current state of the vehicle such as velocity, acceleration and position, an Inertial Measurements Unit, IMU, is used, as shown in Figure 12. The output data from the IMU is used partly as input to the robots to know the current state of the vehicle, but is also possible to extract for usage once the testing is finished.

Figure 11 - Driving robots used during physical testing.

Figure 12 - Inertial Measurement Unit.

As mentioned earlier in the report, the data from the physical testing is used both to generate manoeuvres and comparable data to use to validate the model in time step data and to create the DNA fingerprint used for validation of the model in delta.

3.3 Subjective Assessments

The probably main part of the project is the subjective assessments that allow for the final validation of the driving simulator. The assessment is divided in two parts, one physical performed in a real vehicle, and one virtual performed in the driving simulator using the vehicle model generated from the physical vehicle. Since much effort is applied into keeping as much as possible similar between the vehicle model used in the driving simulator and the physical vehicle, comparing the outcome of the assessments will provide an understanding of how similar the simulator manages to replicate the characteristics of the physical vehicle.

3.3.1 Physical SA

During the complete physical subjective assessment, the same V40 D2 with the same specifications as during the physical testing and kinematics and compliance measurements is used.

3.3.1.1 Assessment evaluation method

Submitting the driver ratings of the different vehicle characteristics and to determine what the drivers actually should assess is performed using a questionnaire with a standard layout used at Volvo Car Corporation. This questionnaire is then printed so that the drivers easily can fill in the grades by hand when in the car. As the subjective assessments performed in the current project are not performed with the main purpose of actually evaluating the different vehicles, but to study the differences of the grades put in the physical and virtual assessments, and, as is explained further in Section 3.3.1.3, only one track is used for the assessment, a limited version of the questionnaire is used, as shown in Table 2.

Table 2 - Questionnaire used during the subjective assessments.

For confidentiality, the table can only be found in Appendix C.

During the subjective assessments performed in this thesis project, it is also investigated how the standard questionnaire can be improved. For this purpose, the questionnaire used includes several modifications. By input from the drivers and analysis of how the performed changes might affect the result, this will allow an investigation of whether these changes were for the better or not.

The subjective assessments are performed in cooperation with another thesis project, aiming at developing an iPad-application of the questionnaire for submission of the assessment grades, Vestlund (NA). To provide also this project with usable data from the assessments, some of the runs are to be evaluated on the traditional paper form, and some in the iPad-application.

3.3.1.2 Vehicle configurations

A factor with major importance of the assessments is how many vehicles that are used. Often, subjective assessments are performed as a comparison of multiple vehicles. Using several vehicles in the assessment will allow for a deeper understanding of how the driving simulator manages to resemble different types of vehicles. More vehicles will also usually result in more data, providing a statistically more relevant result. More vehicles will however also require a longer time to complete the assessment, so it is important to find the optimal compromise for the current project. To obtain multiple vehicles but maintain a relatively low complexity of the project, it was in the current case decided to use only one vehicle but to change its chassis configuration to through that generate vehicles with different behaviour. The aim of when determining what physical components to change in order to generate the different vehicle configurations was to select components that can easily and quickly be changed, but does still provide a relatively large impact on the driving behaviour of the vehicle. The best solution to fulfil these criteria was decided as changing the antiroll bars of the vehicle. The contribution of the antiroll force to the dynamics of the vehicle can be eliminated by simply removing the connection between the antiroll bar and the suspension arm. In the case of the current 2012 V40, this is performed by removing just one screw on each side in the rear, and two screws including a small linkage arm in the front. The vehicle can without any problems be driven with the disconnected antiroll bars mounted in place in the vehicle. A slight exception to that is the front antiroll bar that must be strapped in a lifted position to not make contact with the lower suspension arms during bounce. Overall, changing this antiroll bar configuration is a matter of a few minutes for both axes.

Since the vehicle is equipped with two antiroll bars, connecting or disconnecting these in different combinations can in total generate four differently configured vehicles. The question is then how many differently configured vehicles to use during the subjective assessments. For statistical purposes, the ideal would be to obviously use all for configurations. However, after some investigation it was understood that running a vehicle completely without antiroll bars might results in highly distorted and unexpected vehicle behaviour. For safety reasons it was therefore decided to use the configurations including standard vehicle, disconnecting the front antiroll bar but keeping the rear antiroll bar connected, and disconnecting the rear antiroll bar but keeping the front antiroll bar connected as shown in Figure 13.

Figure 13 - Vehicle configurations used.

As mentioned previously, some of the assessments are to be evaluated on paper, and some in the iPad-application. Based on this, it was decided to run each configuration twice and to assess half of the vehicles on paper and half in the iPad. In this way, more vehicles are generated, compared with the three different configurations. Even though the six vehicles do not have unique configurations, running each configuration two times does partly generate more vehicles, giving more data and through that a broader and more statistically correct data set, and does partly allow for investigations of how consistently the drivers provide their grades. Ideally, two identical vehicles should ideally obviously also be assessed identically. If this is not the case, the reliability of the assessments can be questioned. This method will therefore allow for evaluating not only the different vehicle configurations but also how consistent the drivers provide their grades, and thus their ability to experience configuration changes. The changes between the different configurations and the fact that each configuration is used twice will obviously be kept secret from the drivers.

The next factor to decide is in which order the different configurations are to be used and which of the configurations to assess on paper and in the iPad. To perform this, five different reasonable options are identified:

1. Completely randomize the order of the configurations and which to assess on paper and in the iPad.
2. Randomize the configurations and decide to assess the first three on paper and the last three in the iPad, or the other way around.
3. Randomize the configurations and decide to assess each configuration once on paper and once in the iPad.
4. Decide the order of the configurations and randomize which to assess on paper and in the iPad.
5. Decide the complete order of the configurations and the assessment method.

Completely randomize the order of the configurations and assessment methods could be appropriate from a statistical viewpoint. This might however lead to both runs of one configuration being assessed on only paper or in the iPad, which will not provide comparable results of whether the iPad-application affects the outcome of the assessment and if the drivers provide different grades if using the paper or iPad. Using a completely randomized order of the configurations might also include a bias as the drivers will have different references. For instance, driving a vehicle that behaves “neutrally” in a certain aspect right after having driven a vehicle that behaves far from what is desired, the “neutral” vehicle might seem better than if driven right after the vehicle that behaves worst. As the main purpose of the subjective assessments is to compare the potential differences of the physical and virtual assessments, comparable data with the same bias is a necessity. Based on this reasoning, it was decided to assess each configuration once on paper and once in the iPad and to change the configurations in the same order in all assessments. For the drivers not being able to hint that each configuration is assessed with both methods, the first three configurations are to be assessed on paper and the last three on the iPad. This results in the three configurations being performed in the same order two times during each assessment. Rather than randomizing this order, it was decided to use the order from which the bias from the previously driven configuration will have the lowest impact on each grading.

From driving the three differently configured vehicles in advance, it was learnt that the driving behaviour of the vehicle configuration without the front antiroll bar was more different from the standard vehicle than that of the vehicle without the rear antiroll bar. From this, the vehicle configurations could be ranked as the original vehicle being the “best” in terms of a majority of the studied aspects, the one with the rear antiroll bar disconnected being “average”, and the configuration without the front antiroll bar being the “worst”. It was decided not to have an extreme configuration initially as this might increase the bias towards the others. Therefore the “average” configuration without the rear antiroll bar is the first one used. Of the remaining two, the “worst” configuration without the front antiroll bar is selected as the second and the “best”, being the standard vehicle and the one remaining as the third and last. The reason for this is to obtain a balance between the configurations as the “worst” one will not seem quite as bad if performed directly after the “average” than if performed directly after the “best” configuration.

3.3.1.3 Track selection

The location of the physical subjective assessments is selected to be Hällered Proving Ground. To ensure repeatable and comparable conditions between different assessments, a closed track is necessary. As it turned out to be no problem to perform the assessments at the facility, the decision was simple. The next decision was to decide at which track or tracks to perform the assessments. This decision had to be determined by which tracks that are available in the simulator. As Handling track two and the Country road both are laser scanned and imported into the simulator, these are ones available for the assessments. The current project investigates steering and handling, and as the country road mainly is used to evaluate ride, while the handling track two is used to, as obviously can be deduced from its name, evaluate vehicle handling, it was selected for the assessments to be performed solely at handling track two. For evaluating vehicle handling, handling track two is the closest to ideal from what is available at Hällered but for steering this is unfortunately not the case. The reason for this is because steering evaluation ideally requires a long straight road, why it normally is evaluated at the main track. Handling track two does have a straight section but it is not as long as what is desired to ideally evaluate all the steering related characteristics that are asked for. One solution to this would be to allow the drivers during the physical assessments to drive a few laps at the main track to properly evaluate the steering, but this track is however not available in the driving simulator. This could be solved by, in the simulator, instead of the main track using the infinitely long straight road that is available. Another factor to take into consideration here is the time required to perform the assessments. Several of the potential drivers are expert drivers with a crammed schedule and the longer the assessments take, the smaller is the possibility of their participation. Since the purpose of the assessments is not to actually evaluate the performance of the vehicle, but to compare the potential differences of when driving the same vehicle model at the same track in reality and in the simulator, and to not lose time when switching between different tracks, at was decided to use only handling track two. The drivers were then told to evaluate the straight ahead steering as good as possible on the straight section of the track.

3.3.1.4 Selecting drivers

Another important factor to determine before starting with the subjective assessments is which drivers and how many that should participate. A low amount of drivers is obviously very efficient, but also gives low statistical correctness of the results. A high amount of drivers provides more statistically trustworthy results but might not be able to fit within the limited timeframe of the project.

As the purpose of the assessments is not to actually evaluate how good the different vehicle configurations are, but to investigate the differences of when driving at Hällered and in the simulator, using highly experienced drivers is not necessary. Even drivers who have no or very little previous experience in vehicle dynamics evaluation can provide valid results of the differences between the different assessments. The statistical significance of the results provided by an unexperienced driver can however be lower than for an experienced driver.

Possible differences in the results from an unexperienced driver can be because the driver actually perceives the vehicles differently or simply because he or she is not fully sure of what they are actually assessing. Using unexperienced drivers is also generally less time efficient as they have to spend time learning how to assess the different aspects. The issue though is that the availability of experienced drivers is much lower than of drivers with no or very little experience of vehicle dynamics evaluation. Based on this, it was decided to utilize as many expert drivers as possible.

3.3.1.5 Implementation routine

To obtain fully comparable results and thus eliminating all potential differences between the different subjective assessments, it was decided to develop a routine of how to perform the assessments. The first step was to go through the evaluation questionnaire with the driver, explain the implemented modifications and the meaning of all characteristics that are to be evaluated. This procedure was performed the same, independent of the experience level of the driver. After this, the drivers were told about the assessment methods and that they would be driving six different configurations of the same vehicle.

A mechanic and a lift were booked in order to quickly and safely change between the different configurations. When each of the changes was performed, one of the members of the thesis project drove the vehicle to the test track with the driver in the passenger seat. The reason for this is that the road from the workshop to the track is not available in the simulator and driving this road during the physical assessment will therefore provide the driver with information that is not possible to obtain during the virtual one.

To obtain an understanding of how the plans of how to perform the assessments actually will work out and to eliminate any errors and thus lost time during the actual assessments, the full procedure of changing configurations, driving the vehicles, and going through the questionnaire was performed before the actual assessments began. This mainly showed that the planned implementation routine was realistic and provided an understanding of how much time that would be required for assessments. It was also seen that a driver that is not totally new to subjective assessments and the questionnaire used should be able to assess the requested characteristics within three laps of Handling track two, including in and out lap. The drivers were therefore told to have three laps available and to perform the manoeuvres the driver finds necessary to be able to evaluate all characteristics. If the driver was not able evaluate everything within the give distance, an extra lap was allowed and preferred compared to leaving some characteristics unevaluated. The reason for why the number of laps is aimed at being kept to a minimum is because driving simulators are associated with motion sickness. To keep the results from the different assessments comparable, the drivers should drive the same amount of laps on the track as in the simulator.

Another factor kept during the subjective assessments was to always have someone sitting in the passenger seat. The reason for this is partly because the vehicle model used in the simulator is generated with the load level curb +2, meaning one person in each of the front seats, and partly because this allowed the person in passenger seat to take notes of how the driver assessed the different characteristics. These notes will after the assessments make it possible to compare how the drivers were assessing the different characteristics in the simulator and on the track. From this comparison, conclusions can be drawn of whether there are any trends of how different drivers assess the different characteristics in the simulator and on track. If a driver also assesses one characteristic in a significantly different manner between different runs, the gathered information can be used to determine if potential differences are because of a different driving style.

When the assessment of each vehicle configuration was finished, the person in the passenger seat looked through the questionnaire and ensured that each question was correctly filled in. Once the questionnaire was determined to be correctly submitted, the vehicle was driven back to the workshop. As the assessment is finished, whoever drives the car back is irrelevant. When the car is back in the workshop, the driver is told to leave before the change to the following configuration begins.

3.3.2 Virtual SA

As told initially in this chapter, the aim is for as much as possible to be similar and comparable between the physical and virtual assessments. Keeping everything identical is however not possible due to the nature of the different environments. This is described further in the following sections.

3.3.2.1 Assessment evaluation method

The method used to evaluate the subjective assessments is selected slightly differently between the physical and virtual assessments. The virtual subjective assessment it is decided to be evaluated only by using the questionnaire in the iPad application. The main reason for this decision originates from the drawback of using the paper questionnaire as it requires a significant amount of time consuming manual work, while extracting the data from the iPad application is a matter of a few minutes. As the virtual subjective assessments were performed in the closing stages of the project when the available time was rather limited, and as the data collected during the physical subjective assessments were told to be enough for the thesis developing the application to investigate effects of evaluating the assessments manually or digitally, it was decided to use only the iPad application.

Using only the iPad-application to evaluate the virtual subjective assessments is however not without disadvantages as half of the physical assessments for each driver were evaluated on paper and half in the iPad. If a difference does exist regarding the outcome of evaluations performed on paper and in the iPad application, the results from the virtual assessment might not be fully comparable with those from the first three vehicle configurations used in the physical subjective assessment. The fact that all vehicle configurations are evaluated on the same sheet when using the paper as evaluation method, and that each vehicle configuration is evaluated in a separate session in the application is another disadvantage of using the iPad. When talking with the drivers, it has been understood that they mainly evaluate the vehicle configurations in delta, meaning for each evaluation they compare with the previous ones. It is possible to in the application switch between different sessions to compare with previous evaluations but that is far from as intuitive as when using the paper. Even though these drawbacks exist, using solely the iPad application to evaluate the virtual subjective assessments is still considered as a better alternative due to the significant ease to extract the data.

3.3.2.2 Vehicle configurations

Since the physical subjective assessment uses the same three configurations twice for each driver, the plan was to have the same structure also for the virtual subjective assessments. However, five different vehicle models are possible to generate from the kinematics and compliance measurements, namely the standard configuration, one measured without the front antiroll bar, one without the rear antiroll bar, one modified version of the standard vehicle where the front antiroll bar is disabled in VI-CarRealTime, and one modified version of the standard vehicle where the rear antiroll bar is disabled in VI-CarRealTime. A standard naming for these models can be found in Table 3. Using the same methodology for the physical and virtual subjective assessments would in this case then mean to select three of the five vehicle models and have each driver driving them twice. The question that then occurs is which of the five models to choose. One solution could be to choose the three showing the most desirable results after the model validation in time domain, as explained in Section 4.3. However, since more than three vehicle models are available, and more than three vehicle configurations are to be driven this could allow for also a subjective comparison of the different vehicle models.

Table 3 - Standard naming for vehicle models.

Model Name	Origin of model parameters
ON-ON ref	Standard vehicle measured in K&C rig
OFF-ON ref	Standard vehicle measured in K&C rig with front antiroll bar disconnected in VI-CarRealTime
ON-OFF ref	Standard vehicle measured in K&C rig with rear antiroll bar disconnected VI-CarRealTime
ON-ON Adams	V40 model imported from Adams K&C to VI-CarRealTime
OFF-ON KnC	OFF ON vehicle measured in K&C rig
ON-OFF KnC	ON OFF vehicle measured in K&C rig

Another vehicle model that potentially could be interesting to compare with the ones available is the one from Adams. This model is not generated from the same vehicle specimen as the others, but could still be interesting to compare as this opens up for the possibility to investigate any obvious subjective differences between a model generated from Adams K&C, and models generated from physical kinematics and compliance measurements. Including also the Adams to be driven in the simulator results in six different vehicle models, which obviously is suitable for the assessment methodology. Since the need of driving the same configuration twice is not as evident in the virtual subjective assessment as during the physical ditto due to the same evaluation method being used throughout the whole assessment, it was decided as the most appropriate solution to use all the six different vehicle models and thus compare all of them both objectively and subjectively.

3.3.2.3 Track and driver selection

As one of the main reasons for performing the assessments at Handling track two at Hällered Proving Ground was that it is available also in the driving simulator, this track is obviously also used for the virtual subjective assessments. Since also the main purpose of the entire thesis project is to compare the physical subjective assessment with the virtual one, having any driver performing in just one of the two assessments is in comparison rather pointless. All the drivers participating in the physical subjective assessment were therefore also taking part of the virtual assessment.

3.3.2.4 Implementation routine

Having certain routines for the procedure of how each of the subjective assessments should be performed did during the physical assessments show to be a relatively efficient method to minimise deviations between the different sessions. A similar routine was thus developed for the virtual subjective assessments.

As the questionnaire already was explained to the drivers during the physical subjective assessment, this was not performed again. The drivers were simply told to look through it and ask if anything seemed unclear. Answering the questionnaire was performed by the drivers while seated in the simulator.

Changing between different vehicle models is in the driving simulator a matter of just a few seconds so in the ideal assessment the driver remains seated in the cockpit during the full duration. However, when performing the assessments, it was understood that some drivers might suffer from motion sickness when driving the simulator. The drivers were therefore told to ideally remain seated during the full assessment, but if they felt any discomfort, it is better for them to leave the simulator and take a break.

Just as during the physical subjective assessment, the drivers were told to be allowed to take three laps of the track, with a bonus lap as a possibility if everything could not be evaluated after the standard three.

One addition to the implementation routine that was added to the virtual subjective assessment was to ask the drivers about they experienced the different vehicle models. Interviewing the drivers allows for a deeper understanding of the advantages and disadvantages of the driving simulator as a development tool and will provide an extra dimension to the understanding compared with only studying the values from the questionnaires. After each vehicle model, the drivers were asked about their general perception of the model, in other words how they liked it, and if it was a real vehicle, what changes of the mechanical components of the car they would perform in order to improve its characteristics. After the third vehicle configuration the drivers were asked to formulate a comparison of the performance of the three vehicles. After the sixth vehicle configuration the drivers were asked to formulate a similar comparison of the fourth, fifth, and sixth configurations, followed by a question to rank all six models of how much they liked driving it. The questions are selected to be as few as possible but still provide a good understanding of how the driver are experiencing the different vehicle models, the driving simulator in general, the configuration changes performed and connections with the physical assessments. As mentioned above, it was recommended for the drivers to be seated in the driving simulator during the full assessment session. The interviews where therefore mainly conducted through the communication system that is installed between the simulator cockpit and the control room.

4 Results

The outcomes of the methods performed, as described in the previous chapter, are explained in the following sections.

4.1 K&C measurements

As explained in the methodology section, one step in the process of obtaining a virtual vehicle model of the physical vehicle used in the project is to measure its characteristics and behaviour in a kinematics and compliance rig.

4.1.1 Outcome of measurements

All the planned tests were conducted in exception of the longitudinal compliance tests with strapped wheels at the -60 mm and +60 mm bounce levels. The reason for this is because the strapped wheel tests becomes highly time consuming when being performed at different bounce levels since the tension of the straps needs to be adjusted continuously. This missing data will of course reduce the precision of the model but since the longitudinal dynamics characteristics are not under study, it was decided to create the models without this data.

4.1.2 Analysis of results

Before the measurements in the kinematics and compliance rig were performed, it was discussed whether it really was necessary to measure the complete vehicle three times. As the three different configurations involves the configuration of the front and rear antiroll bar, a potential idea was that if the antiroll bar configuration does not affect the performance and properties of the opposite axis, it should be enough to measure the standard vehicle, and one with both antiroll bars disconnected. The characteristics that are related to one of the axes can then be obtained from the measured vehicle with the same configuration of the current axis. For instance, the characteristics of the vehicle with the front antiroll bar disconnected and the rear antiroll bar connected could then be obtained by taking the values for the front axis of the vehicle with no antiroll bars connected and the rear axis from the standard vehicle.

A similar question was if it really is necessary to measure the characteristics that do not involve vehicle roll for all three different configurations. Ideally, whether the antiroll bar is connected or not should not necessarily affect measurements including only wheel bounce. If this really is the case in practice is however yet to be determined.

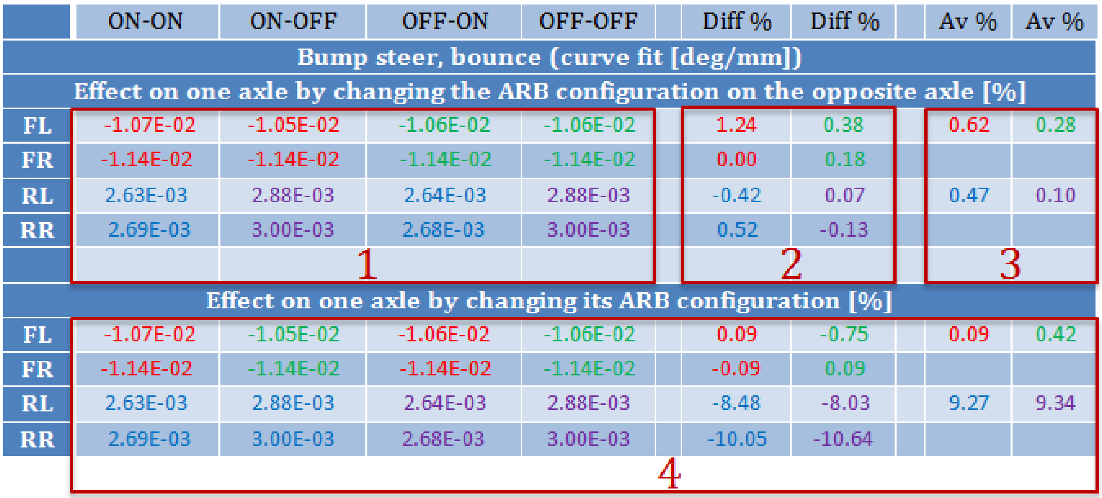
The purpose of these questions is to be able to minimize the amount of measurements, partly to save time and money for the current project but mainly for knowledge for future measurements.

The questions were discussed with several people with knowledge within the subject. The answers of whether a simplified and shortened measurement program would give the same results were however not fully determent and even if most could argue for one or the other of the cases, a totally definite answer could not be found. For this reason, it was decided to not only use the measurements from the kinematics and compliance rig to generate the virtual vehicle models but to also analyse the results to allow for researching the questions.

The standard kinematics and compliance test in the Anthony Best SPMM rig involves the measurement of 94 different metrics. Analysing all of these does obviously introduce challenges with overviewing all data and the time required to perform all comparisons. To make the study more feasible, it was decided to analyse the metrics by just comparing the fit curves which are calculated in the linear range of the metric. The fit curves can be compared with a linear regression and are automatically calculated by the software that post processes the measurement data. These curves are then compared for each wheel, axis or vehicle side, depending on the metric analysed.

To obtain numerical values from the analysis, the slope of the fit curves are compared over the different configurations for the different measurement points. As an example, in Table 4, the effect on the bump steer during bounce when having the antiroll bar connected or disconnected in the analysed axis and the effect of connecting and disconnecting the antiroll bar in the opposite axis is investigated. To easier understand how the values for comparison are calculated, the table is divided in four sections. In section one, each row represents the slope of the curve fit for each wheel, with the first row being front left, second front right, third rear left, and fourth rear right. Each column in section one represents each of the four configurations, and thus each of the four vehicles that have been measured, with the first column displaying the "ON-ON" configuration, the second the "ON-OFF" configuration, the third the "OFF-ON" configuration, and the fourth the "OFF-OFF" configuration. As can be understood, for the purpose of this investigation, four differently configured vehicles are measured, while for the generation of the virtual vehicle models, only the first three ones will be used.

Table 4 - Analysis of bump steer measurements.



	ON-ON	ON-OFF	OFF-ON	OFF-OFF		Diff %	Diff %		Av %	Av %
Bump steer, bounce (curve fit [deg/mm])										
Effect on one axle by changing the ARB configuration on the opposite axle [%]										
FL	-1.07E-02	-1.05E-02	-1.06E-02	-1.06E-02		1.24	0.38		0.62	0.28
FR	-1.14E-02	-1.14E-02	-1.14E-02	-1.14E-02		0.00	0.18			
RL	2.63E-03	2.88E-03	2.64E-03	2.88E-03		-0.42	0.07		0.47	0.10
RR	2.69E-03	3.00E-03	2.68E-03	3.00E-03		0.52	-0.13			
		1				2			3	
Effect on one axle by changing its ARB configuration [%]										
FL	-1.07E-02	-1.05E-02	-1.06E-02	-1.06E-02		0.09	-0.75		0.09	0.42
FR	-1.14E-02	-1.14E-02	-1.14E-02	-1.14E-02		-0.09	0.09			
RL	2.63E-03	2.88E-03	2.64E-03	2.88E-03		-8.48	-8.03		9.27	9.34
RR	2.69E-03	3.00E-03	2.68E-03	3.00E-03		-10.05	-10.64			
					4					

As the header above section one of Table 4 mentions, the purpose of the investigation performed in section one is to understand the effect on the current axle by changing the antiroll bar configuration on the opposite axle. For this purpose, the values in section two are calculated as the percentage difference between the values where the configuration of the opposite axle is changed. For example, the value in the upper left corner of section two corresponds to the difference experienced in the front left wheel when changing the configuration of the rear axle. This is also the case for the value in the upper right side of section two but with the difference that the one in the left corner is calculated with the front antiroll bar connected, and the value in the right corner calculated with the front antiroll bar disconnected. To better understand the origin of each calculated value a colour coding is introduced where the colour of the value in section two is the percentage difference between the values on the same row with the same colour.

The values in section three are the average of the values of the same colour in section two, yielding the average value for the complete axle. For example, the red value in section three is the average percentage difference of the slope of the linear regression for the bump steer during bounce in the front axle when changing the configuration of the rear axle.

The methodology used to calculate the values in section four is the same as in the first three but instead of investigating the effect of changing the antiroll bar on the opposite axle, the effect of changing the configuration on the current axle is investigated.

With the difference between the linear curves fits calculated, a more exhaustive comparison of the metrics that show a difference greater than 4 % is performed. For this purpose, a Matlab script is generated that allows not only the slope of the regression line to be analysed, but for the metric to be compared in its whole range. This provides a better understanding of the origin of the measurement differences.

To perform the investigation, metrics that provide a significant difference between the different configurations are investigated further. A selection of these is presented in the following sections.

4.1.2.1 Wheel rate during bounce

As can be seen in Table 5, changing the antiroll bar configuration of the studied axle results in a slope difference of the regression line of around 4 to 6% in all configurations and axles.

Table 5 - Analysis of wheel rates measurements.

	ON-ON	ON-OFF	OFF-ON	OFF-OFF	Diff %	Diff %	Av %	Av %
Wheel rates, bounce (curve fit [N/mm])								
Effect on one axle by changing the ARB configuration on the opposite axle [%]								
FL	33.50	33.32	32.54	32.14	0.54	1.24	0.36	0.62
FR	32.80	32.74	31.18	31.18	0.18	0.00		
RL	27.18	25.69	27.05	25.71	0.48	-0.08	0.69	0.06
RR	27.09	25.60	26.85	25.59	0.89	0.04		
Effect on one axle by changing its ARB configuration [%]								
FL	33.50	33.32	32.54	32.14	2.95	3.67	4.07	4.34
FR	32.80	32.74	31.18	31.18	5.20	5.00		
RL	27.18	25.69	27.05	25.71	5.80	5.21	5.81	5.07
RR	27.09	25.60	26.85	25.59	5.82	4.92		

In Figure 14, the complete dataset of wheel rate versus bounce are plotted for the rear left wheel when changing the configuration of the rear antiroll bar with the front antiroll bar connected. The same is valid for Figure 15 but with the difference of having the front antiroll bar disconnected.

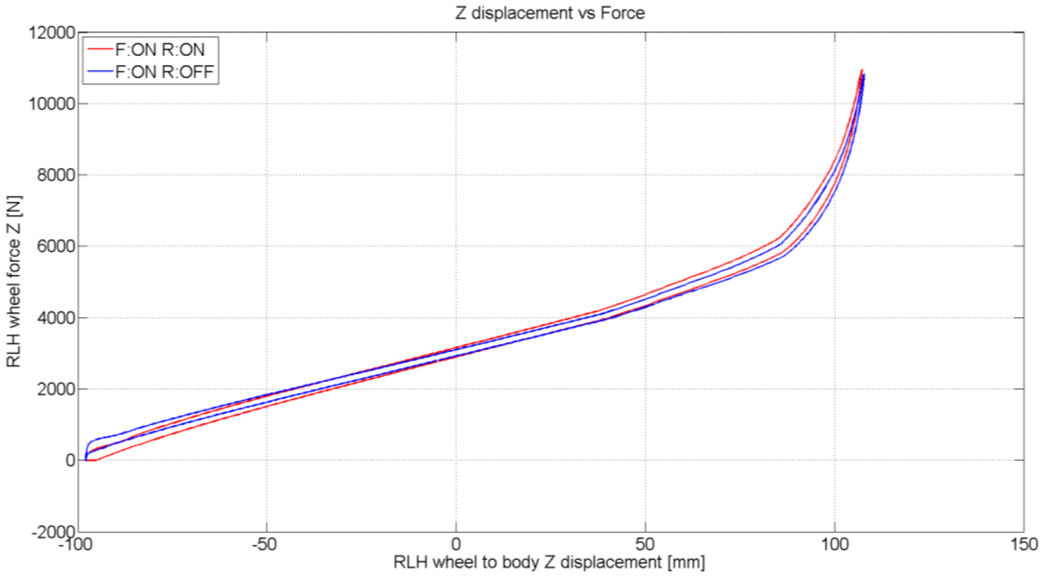


Figure 14 - RLH vertical wheel force change, ON-ON vs ON-OFF

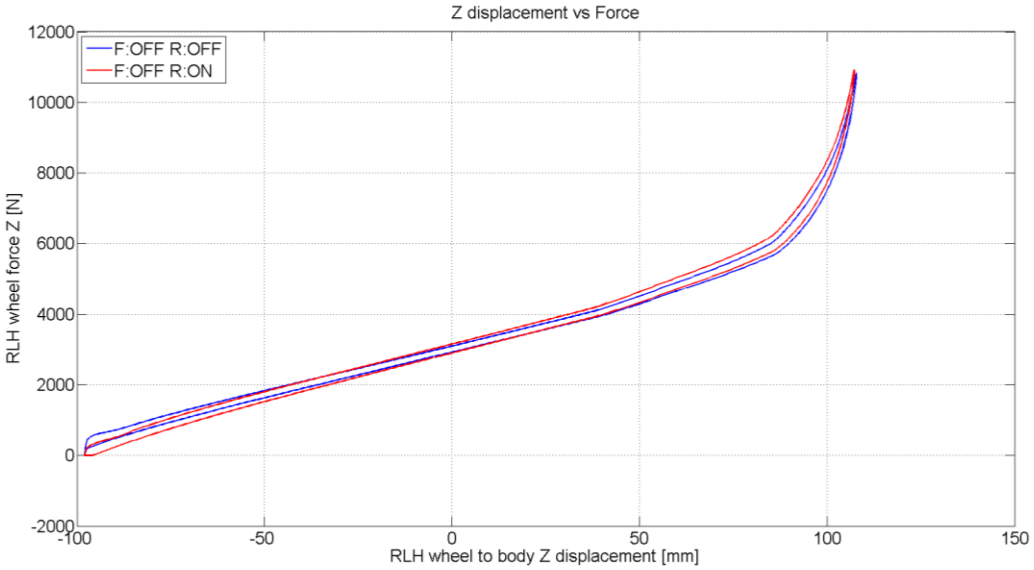


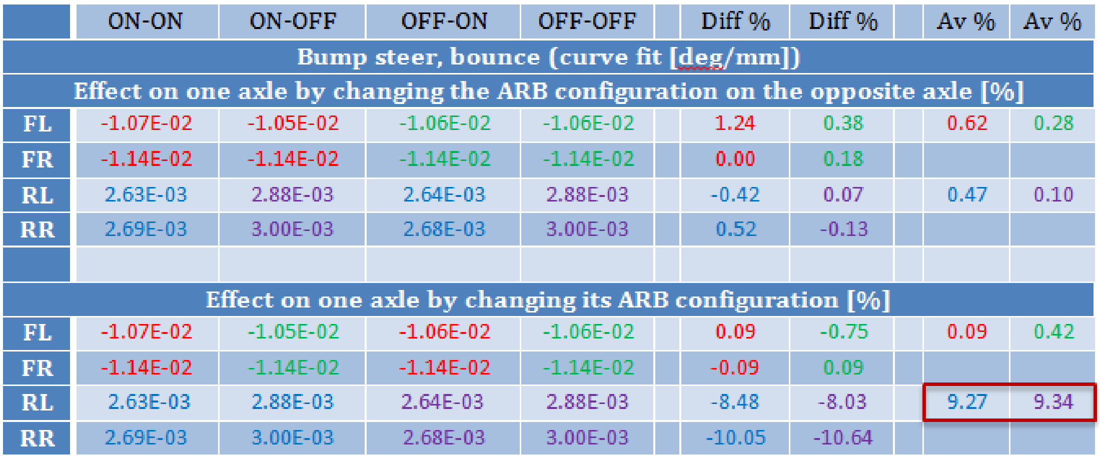
Figure 15 – RLH vertical wheel force change, OFF-OFF vs OFF-ON

As explained in section 3.2.1.1, the rubber bushing that holds the antiroll bar in place is vulcanized. This characteristic therefore affects the normal forces of the wheels when the car is bounced.

4.1.2.2 Bump steer during bounce

Another metric that is found to be affected by the antiroll bar setup is the bump steer during bounce. As can be seen in Table 6, the rear axle suffers changes of up to more than 9% when the antiroll bar is disconnected in the rear axle.

Table 6 - Analysis of bump steer measurements.



	ON-ON	ON-OFF	OFF-ON	OFF-OFF		Diff %	Diff %		Av %	Av %
Bump steer, bounce (curve fit [deg/mm])										
Effect on one axle by changing the ARB configuration on the opposite axle [%]										
FL	-1.07E-02	-1.05E-02	-1.06E-02	-1.06E-02		1.24	0.38		0.62	0.28
FR	-1.14E-02	-1.14E-02	-1.14E-02	-1.14E-02		0.00	0.18			
RL	2.63E-03	2.88E-03	2.64E-03	2.88E-03		-0.42	0.07		0.47	0.10
RR	2.69E-03	3.00E-03	2.68E-03	3.00E-03		0.52	-0.13			
Effect on one axle by changing its ARB configuration [%]										
FL	-1.07E-02	-1.05E-02	-1.06E-02	-1.06E-02		0.09	-0.75		0.09	0.42
FR	-1.14E-02	-1.14E-02	-1.14E-02	-1.14E-02		-0.09	0.09			
RL	2.63E-03	2.88E-03	2.64E-03	2.88E-03		-8.48	-8.03		9.27	9.34
RR	2.69E-03	3.00E-03	2.68E-03	3.00E-03		-10.05	-10.64			

As shown in Table 6, Figure 16 and Figure 17, the configuration of the front antiroll bar has little effect on the result of the rear right wheel. The result is therefore consistent for the different front axle configurations and it can be concluded that the rear antiroll bar affects the rear toe angle both statically and dynamically and that the front axle configuration does not affect the toe angles of the rear axle.

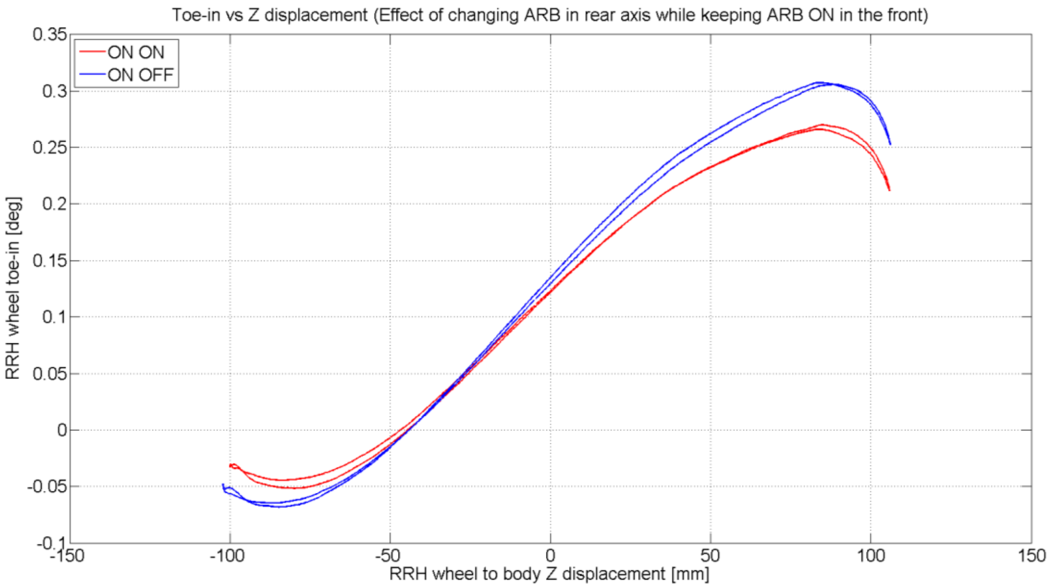


Figure 16 - RRH toe angle change, ON-ON vs ON-OFF.

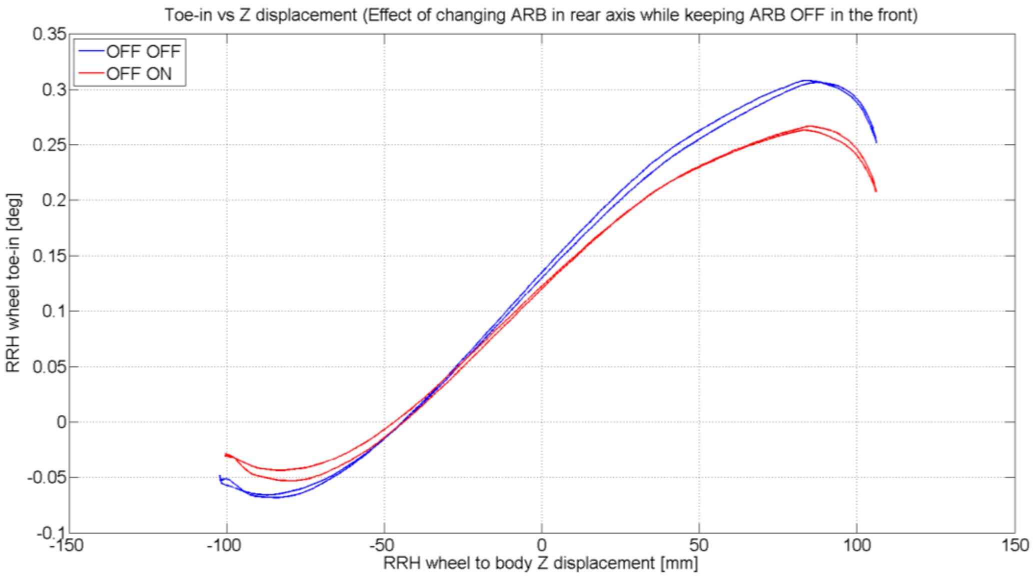


Figure 17 - RRH toe angle change, OFF-OFF vs OFF-ON.

The reason for this change can be motivated by the force of the antiroll bar not being applied completely perpendicularly to the suspension arm and therefore creating a lateral force that changes suspension geometry. This change could be due to the elasticity of the rubber bushings in the suspension system and of the vehicle body, resulting in deflection of the suspension hard points.

4.1.2.3 Wheel recession during bounce

The longitudinal displacement of the rear wheels is significantly changed when the antiroll bar is disconnected in rear axle. As can be observed in Table 7, the change reaches up to 13%, and the configuration of the front axle has very little effect on the measurement when changing the rear axle configuration.

Table 7 - Analysis of wheel recession measurements.

	ON-ON	ON-OFF	OFF-ON	OFF-OFF		Diff %	Diff %		Av %	Av %
Wheel recession, bounce (curve fit [mm/mm])										
Effect on one axle by changing the ARB configuration on the opposite axle [%]										
FL	-5.77E-03	-5.88E-03	-6.05E-03	-6.05E-03		-1.89	0.05		1.49	0.39
FR	-8.03E-03	-8.12E-03	-8.25E-03	-8.19E-03		-1.10	0.73			
RL	-4.22E-02	-4.82E-02	-4.26E-02	-4.81E-02		-0.78	0.29		0.66	0.17
RR	-3.82E-02	-4.43E-02	-3.84E-02	-4.43E-02		-0.55	-0.05			
Effect on one axle by changing its ARB configuration [%]										
FL	-5.77E-03	-5.88E-03	-6.05E-03	-6.05E-03		-4.66	-2.78		3.63	1.79
FR	-8.03E-03	-8.12E-03	-8.25E-03	-8.19E-03		-2.61	-0.81			
RL	-4.22E-02	-4.82E-02	-4.26E-02	-4.81E-02		-12.46	-11.52		13.11	12.42
RR	-3.82E-02	-4.43E-02	-3.84E-02	-4.43E-02		-13.76	-13.32			

When studying Figure 18 it is clear that both dynamic and static longitudinal displacement of the right rear wheel is affected when changing the rear antiroll bar. The change reaches a maximum of around 1mm when being close to the bounce limits of the suspension. An explanation for this effect can be the same as for the bump steer change in the previous section.

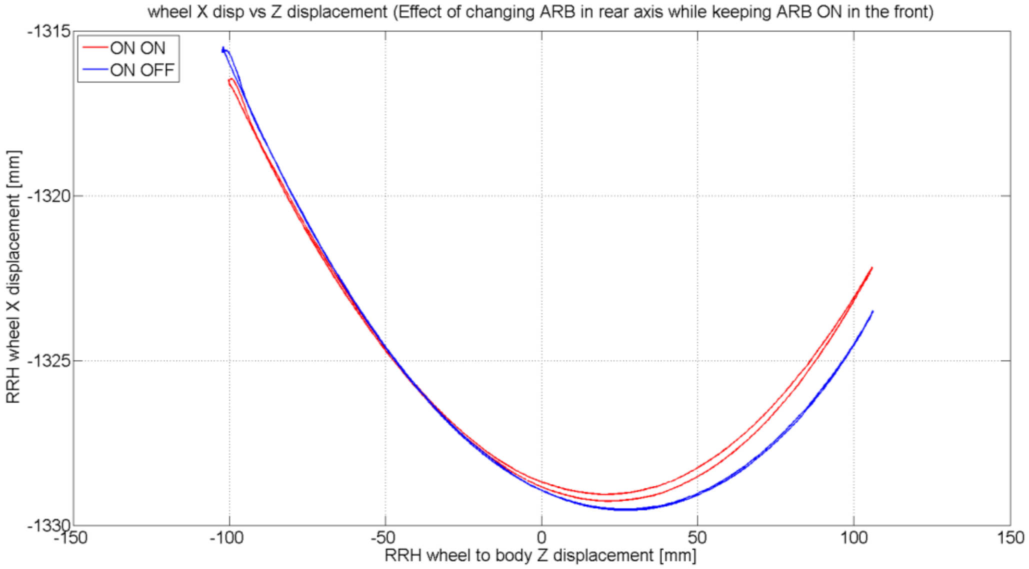


Figure 18 - RRH longitudinal wheel displacement, ON-ON vs ON-OFF.

4.1.2.4 Track width change during bounce

The variation of the track width during bounce seems to be a case where the differences are mainly caused by the tolerances of the machine performing the measurements. When analysing the regression lines, a reasonable difference cannot be found for changes of the antiroll bar configuration in the same or the opposite axle as can be seen in Table 8. As shown here, changing the configuration of the rear antiroll bar while keeping the front antiroll bar on, affects the slope of the regression line for the front track width change with a variation of over 18%. However, changing the configuration of the front antiroll bar while keeping the rear antiroll bar on, has no effect on the slope of the regression line for the front track width change, thus yielding an unrealistic and unreasonable result.

Table 8 - Analysis of track change measurements.

	ON ON	ON OFF	OFF ON	OFF OFF		Diff %	Diff %		Av %	Av %
Track change, bounce (curve fit [mm/mm])										
Effect on one axle by changing the ARB configuration on the opposite axle [%]										
Front	2.73E-02	3.35E-02	3.05E-02	3.28E-02		-18.57	-6.84		18.57	6.84
Rear	1.68E-01	1.68E-01	1.68E-01	1.65E-01		0.00	2.19		0.00	2.19
Effect on one axle by changing its ARB configuration [%]										
Front	2.73E-02	3.35E-02	3.05E-02	3.28E-02		-10.52	2.38		10.52	2.38
Rear	1.68E-01	1.68E-01	1.68E-01	1.65E-01		-0.18	2.00		0.18	2.00

When observing the plots of the front track width change in Figure 19 to Figure 22, it is noticeable that the change is of a maximum of almost 2mm. After reading the manual of the Anthony Best kinematics and compliance rig used, Table 9, it was found that the accuracy in track width measurements is 1mm.

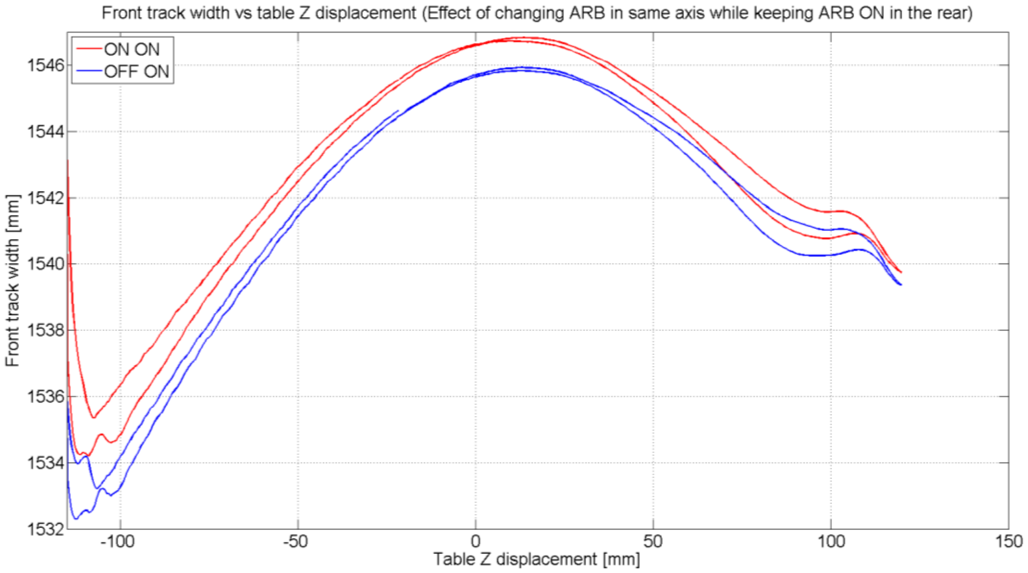


Figure 19 - Front track width change, ON-ON vs OFF-ON.

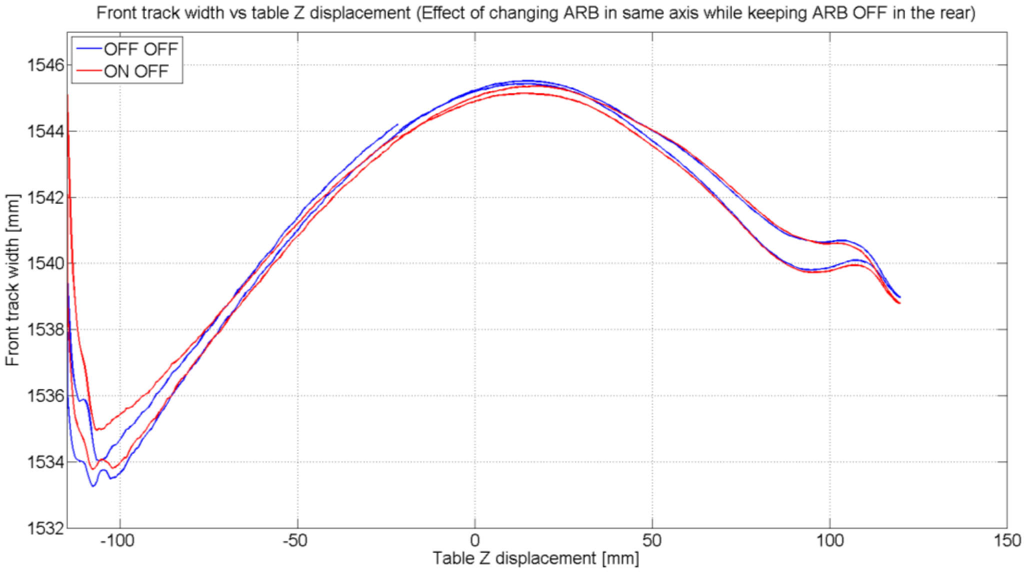


Figure 20 - Front track width change, OFF-OFF vs ON-OFF.

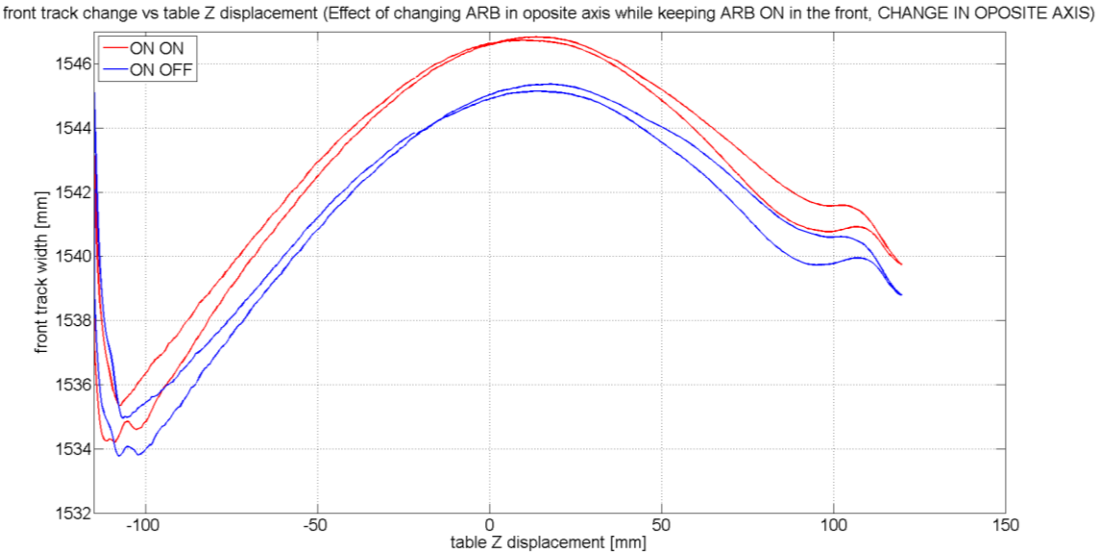


Figure 21 - Front track width change, ON-ON vs ON-OFF.

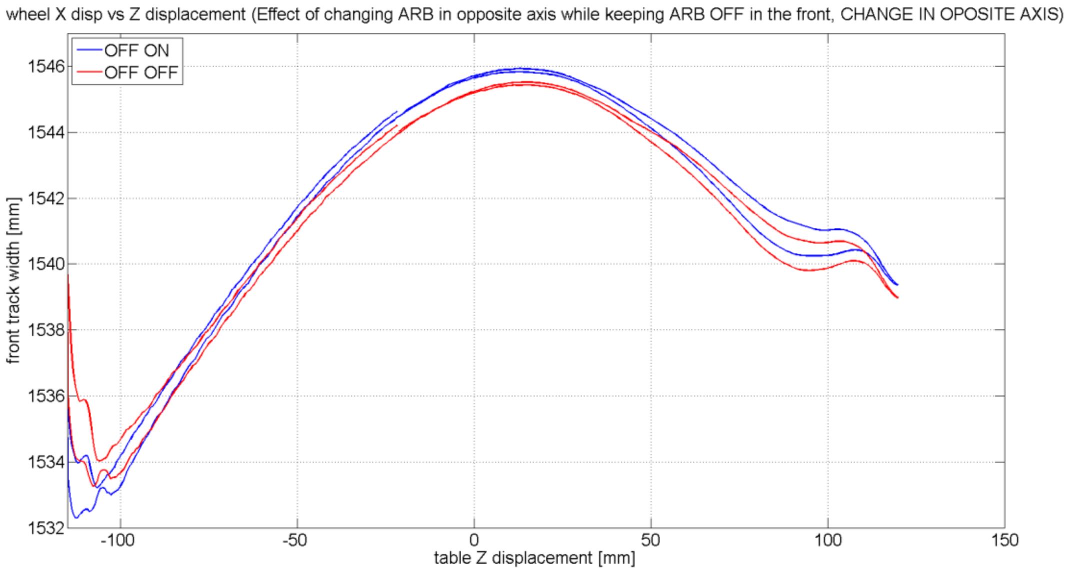
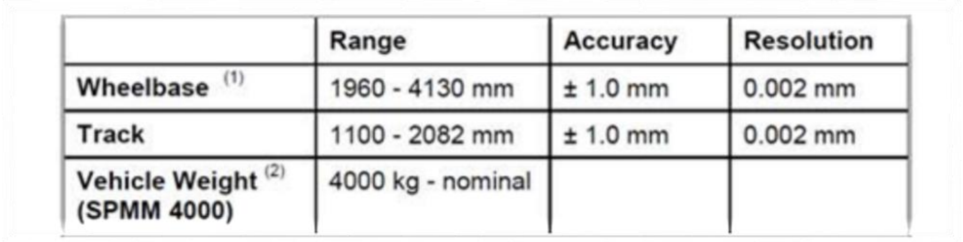


Figure 22 - Front track width change, OFF-ON vs OFF-OFF.

Table 9 - Specifications of the K&C rig used. Anthony Best Dynamics Ltd. (2010)



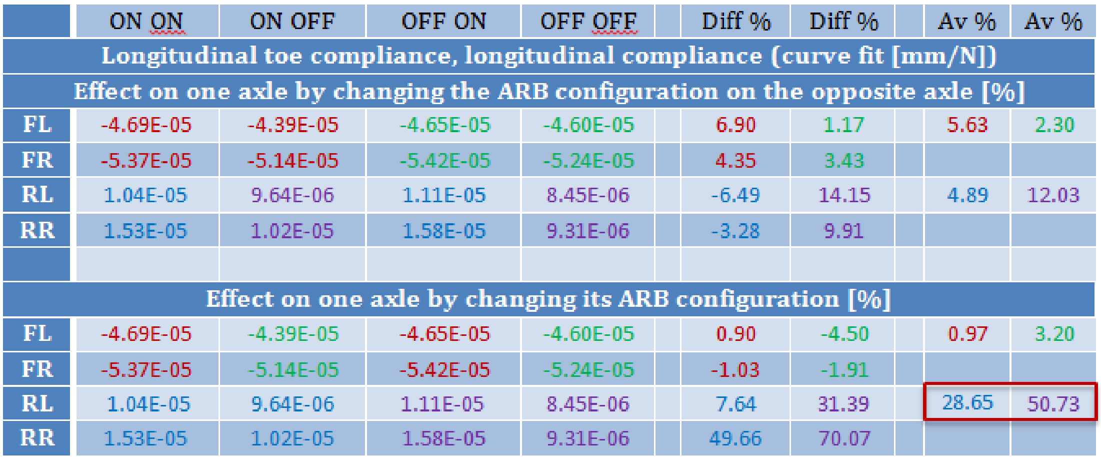
	Range	**Accuracy**	**Resolution**
Wheelbase (1)	1960 - 4130 mm	± 1.0 mm	0.002 mm
Track	1100 - 2082 mm	± 1.0 mm	0.002 mm
Vehicle Weight (2) **(SPMM 4000)**	4000 kg - nominal		

As the measurements do not show any reasonable consistency in the effect of changing the configuration of the antiroll bar in the same or in the opposite axis, the main source of variation is assumed to be the accuracy of the machine.

4.1.2.5 Longitudinal toe compliance

As can be observed in Table 10, having the antiroll bar connected or not has significant effects on the toe change of the wheels. The greatest effects are observed in the rear axle when the antiroll bar is removed in this same axle.

Table 10 - Analysis of longitudinal toe compliance measurements.



	ON ON	ON OFF	OFF ON	OFF OFF		Diff %	Diff %		Av %	Av %
Longitudinal toe compliance, longitudinal compliance (curve fit [mm/N])										
Effect on one axle by changing the ARB configuration on the opposite axle [%]										
FL	-4.69E-05	-4.39E-05	-4.65E-05	-4.60E-05		6.90	1.17		5.63	2.30
FR	-5.37E-05	-5.14E-05	-5.42E-05	-5.24E-05		4.35	3.43			
RL	1.04E-05	9.64E-06	1.11E-05	8.45E-06		-6.49	14.15		4.89	12.03
RR	1.53E-05	1.02E-05	1.58E-05	9.31E-06		-3.28	9.91			
Effect on one axle by changing its ARB configuration [%]										
FL	-4.69E-05	-4.39E-05	-4.65E-05	-4.60E-05		0.90	-4.50		0.97	3.20
FR	-5.37E-05	-5.14E-05	-5.42E-05	-5.24E-05		-1.03	-1.91			
RL	1.04E-05	9.64E-06	1.11E-05	8.45E-06		7.64	31.39		28.65	50.73
RR	1.53E-05	1.02E-05	1.58E-05	9.31E-06		49.66	70.07			

When studying Figure 23 which represents the toe change in the rear right wheel when varying the configuration of the rear antiroll bar while keeping the front antiroll bar connected, and Figure 24 which represents the toe change in the rear right wheel when varying the configuration of the rear antiroll bar while keeping the front antiroll bar disconnected, it is clear that the deformation of the suspension linkages are affected by the antiroll bar, both in the static toe setup and in the dynamic toe change under longitudinal forces.

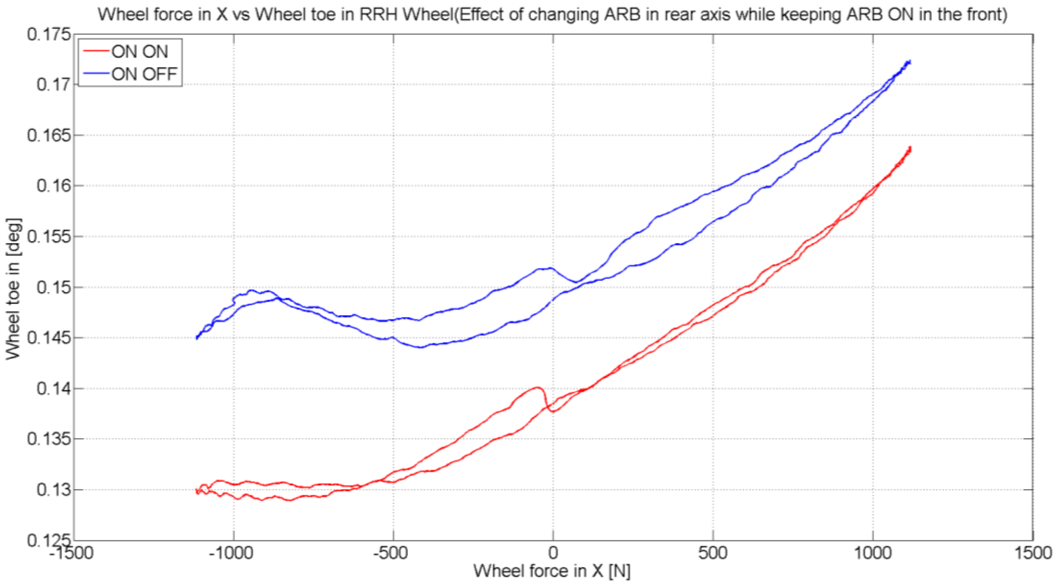


Figure 23 - RRH toe angle change, ON-ON vs ON-OFF.

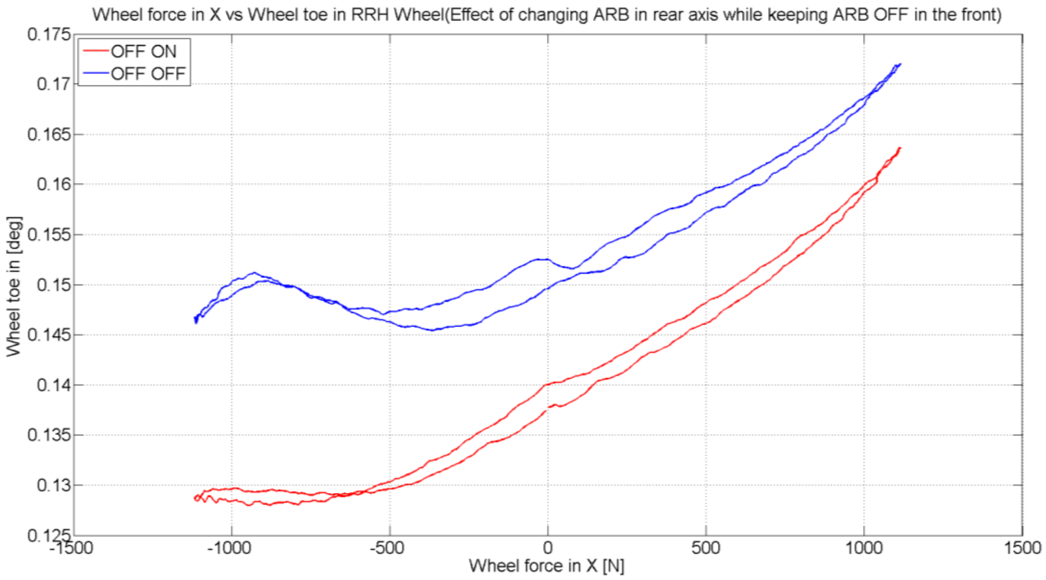


Figure 24 - RRH toe angle change, OFF-ON vs OFF-OFF.

4.1.3 Averaged results

In order to better understand how the antiroll bar configuration of the vehicle measured in the kinematics and compliance rig affects the results, certain numerical values are calculated. These values are obtained by comparing the average slope in the linear range of each measurement. The value of this curve fit is then compared with the corresponding one from the measurements where the antiroll bar configuration is altered.

Comparing the results of all analysed measurements, yields an average difference of just 3.98% when changing the antiroll bar configuration of the opposite axle. Changing the antiroll bar configuration of the current axle, affects the resulting values by on average 24%. The axle where the antiroll bar configuration has the largest impact on the results is the rear, with an average difference of 34% between the measurements performed with and without the antiroll bar.

4.2 Vehicle model generation

Generation of the vehicle models from the kinematics and compliance measurements showed positive results. Using the built-in wizard in VI-CarRealTime for importing data from a kinematics and compliance rig allowed for a relatively straight forward process although certain tweaks and modifications of the generated models were required for them to function desirably. However, one rather large issue that became apparent after the generation of the models was the instability of the steering system, as explained in Section 4.2.2. There were also issues with the initially generated antiroll bars, which are explained in the following section.

4.2.1 Antiroll bar

The antiroll bar generated by the vehicle generating wizard is shown to be incorrect. As can be observed in Figure 25, the lookup table shows values that are not symmetric in both directions. Also, the values are extremely high as can be seen when comparing them with the lookup table of the auxiliary antiroll force of the model generated from Adams K&C, in Figure 26.

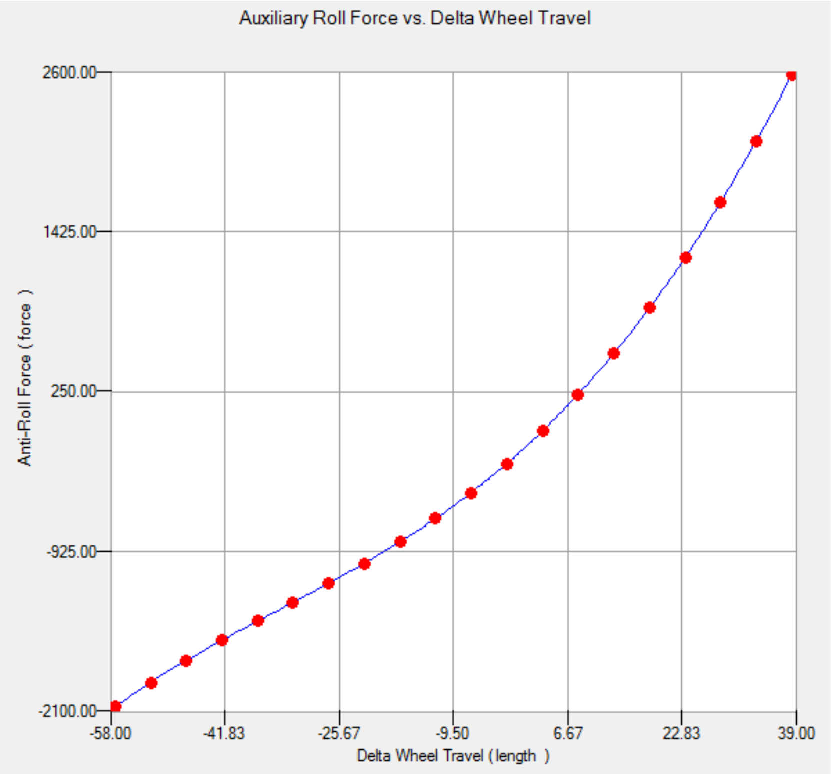


Figure 25 - Auxiliary antiroll force in front suspension of the ON-ON ref model.

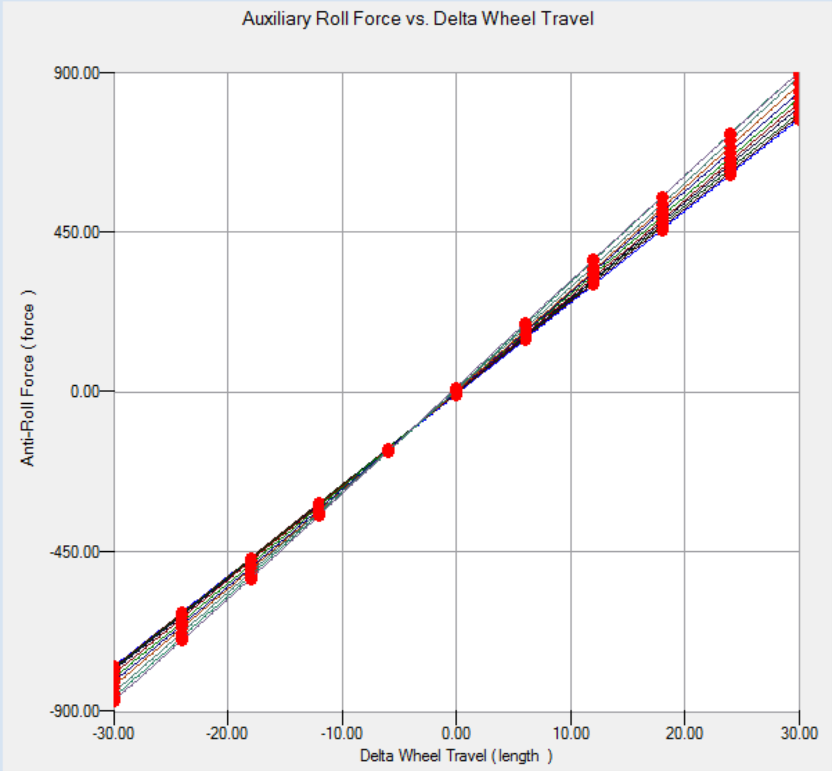


Figure 26 - Auxiliary antiroll force in front suspension of the ON-ON ref model

To reach a more realistic behaviour, it was the decided to use the antiroll bars of the model from Adams and adjust their stiffness in order to match the roll behaviour of the physical vehicle, as measured during the physical testing.

4.2.2 Power steering control

Figure 27 shows the steering wheel torque over time when running the manoeuvre constant radius where a corner with a constant radius is to be taken while increasing the velocity. As shown, the system is highly unstable and seems to enter a resonance mode.

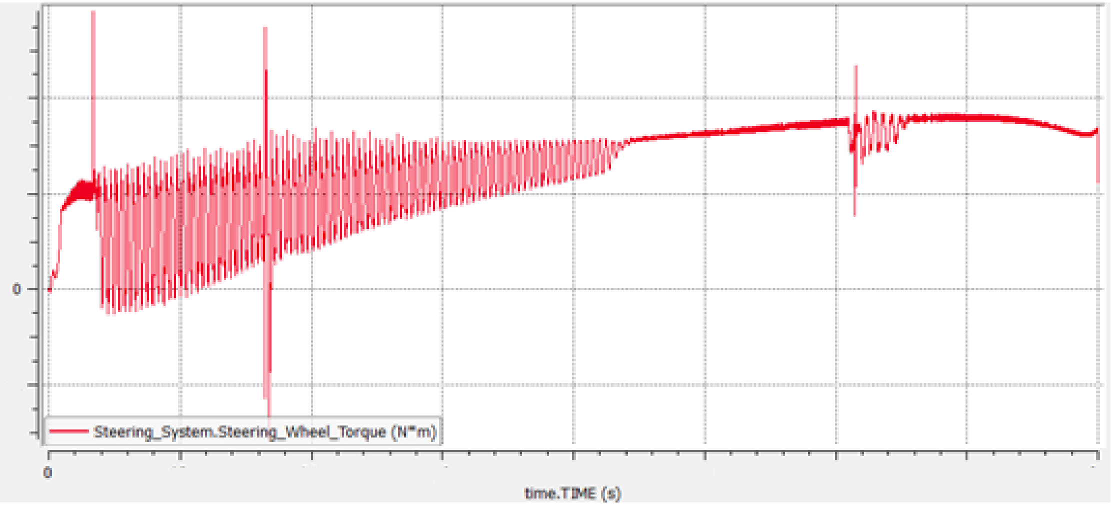


Figure 27 - Initial SWT during CR. Values hidden for secrecy.

Using a model as unstable as this, in the driving simulator will severely affect the outcome of the assessments. Improving the system was therefore required. After discussions with VI-Grade and experts in the area, it was possible to narrow down potential reasons for the instability to be either the steering system or the tire model.

By studying Luty (2011) explaining: “lower tire cornering resistance can decrease an amplitude of lateral force oscillations whilst greater tire relaxation length can decrease an amplitude and also can increase phase shift of lateral force oscillations”, it was decided to reduce the relaxation length of the tire model and that way exit the resonance mode. Implementing this change yielded smaller improvements than expected so it was therefore decided to also improve the modelling of the power steering system.

The modelling of the power steering system in VI-CarRealTime consists of a large amount of different parameters and the improvements of the system were performed with the aim of ensuring the correctness of all parameters. Finding corresponding values and characteristics of all these parameters did however turn out to be more difficult than expected. Tuning the system by using values that seemed reasonable did also turn out to be an unsuccessful method why alternative solutions were sought.

A reasonable solution was found as modelling the power steering system using Matlab Simulink. The Simulink model is generated with a general approach where the corresponding boost curves of the current vehicle easily can be imported. Based on the current steering wheel angle, lateral acceleration, steering rack force and longitudinal velocity, the model generates an appropriate steering wheel torque as shown in Figure 28.

For confidentiality, the figure can only be found in Appendix C.
Figure 28 - Schematic view of the Power Steering Simulink controller.

Using this external model resulted in a more stable system but the torque values were rather different from the ones obtained from the physical testing. This difference was however expected as the Simulink is generated to provide a driving feel quite realistic rather than to correlate with certain metrics. To improve the correlation of the studied metrics, the measurements from the physical testing were studied. From this, it was identified that the required steering wheel torque was mainly depending on the lateral acceleration of the vehicle. A scaling factor of the steering assist that is directly coupled to the current lateral acceleration is therefore introduced as can be observed in Figure 28.

After calibrating the power steering model, used together with an improved tire model, a significantly more stable and more closely correlating system was reached. As shown in Figure 29, the stability is still not fully ideal but the status is considered acceptable within the scope of the project. Comparing Figure 27 with Figure 29 shows generally different trends of the overall change of the steering wheel torque. The reason for this is that the less advanced steering system results in different steering wheel torque output.

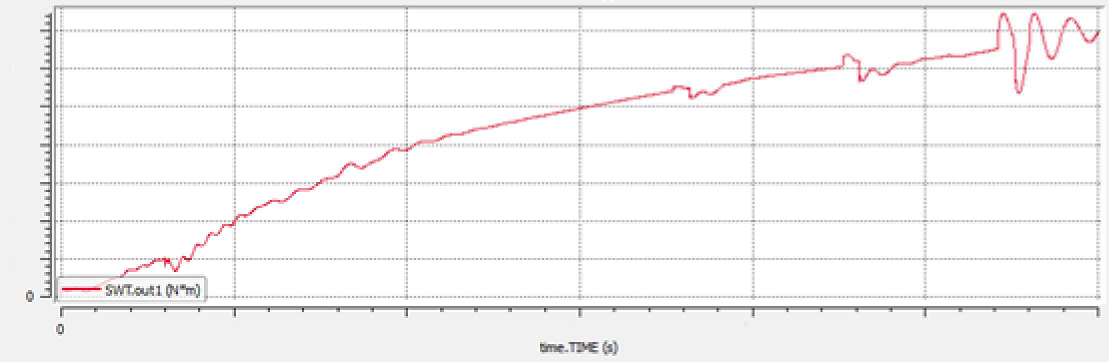


Figure 29 - SWT during CR of modified model. Values hidden for secrecy.

4.3 Model validation in time domain

Once all the models are generated and simulated with the physical testing data as input, it is necessary to go through the model and correct parameters that are incorrect or add new ones in order to improve the model fidelity. Unfortunately, there is not a unified criterion to decide when a model is correct enough to consider it validated. In order to decide when the model is accurate enough, the usage of the model and which vehicle dynamics characteristics that are to be evaluated were always kept in mind.

The validation is decided to be performed using the same parameters for all the vehicle models. It could be possible to tune each model independently to match the parameters under study as good as possible. However, this method would not be correct in order to prove the validity of the decided methodology in this research. Also, the fact that not all the possible driving situations are studied in the compared time step data might lead to unbalanced results between models which are not an effect of the antiroll bar configurations. For the same reason, it is also decided to not use values that are far from what is expected from reality.

A logical method to check the correctness of the generated vehicle models would be to go through every single lookup table and parameter and check that the created values seem reasonable. This can however be an extremely complex and time consuming task that is considered not suitable for this research. It is considered more adequate to check that the generated tables have the correct sign convention but without looking into the exact values. After simulating the models, it is easier to understand which parameters are in need of a deeper study.

4.3.1 Methodology validation

In order to prove the validity of the decided methodology, a comparison of the six different vehicle models is performed. The plan is to first study if a model generated from measuring a vehicle in a K&C rig emulates reality more accurately than a model generated from a multi-body dynamics software K&C tool, in this case MSC Adams. Second, it is also intended to research if the effect of having the antiroll bar connected or not affects the K&C measurements in an extent that affects the vehicle dynamics behaviour significantly. The results of the methodology validation are presented in Section 4.3.3.

4.3.2 ON-ON ref initial status

Only the status of the ON-ON model is analysed in this section. If results from the other models are desired, refer to Appendix B.

Figure 30 shows a sine with dwell manoeuvre performed at low amplitude and low lateral acceleration with the ON-ON configuration vehicle. At this stage no changes to the vehicle model, the tire model or the power steering model are performed. Figure 31 shows the same manoeuvre on the same vehicle but applying a steering wheel angle amplitude six times larger.

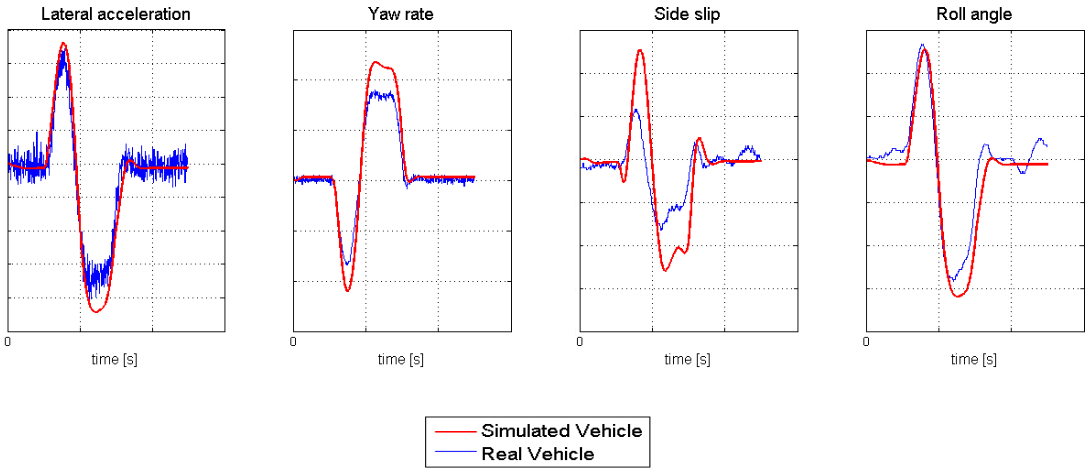


Figure 30 - Low amplitude SWD with ON-ON ref.

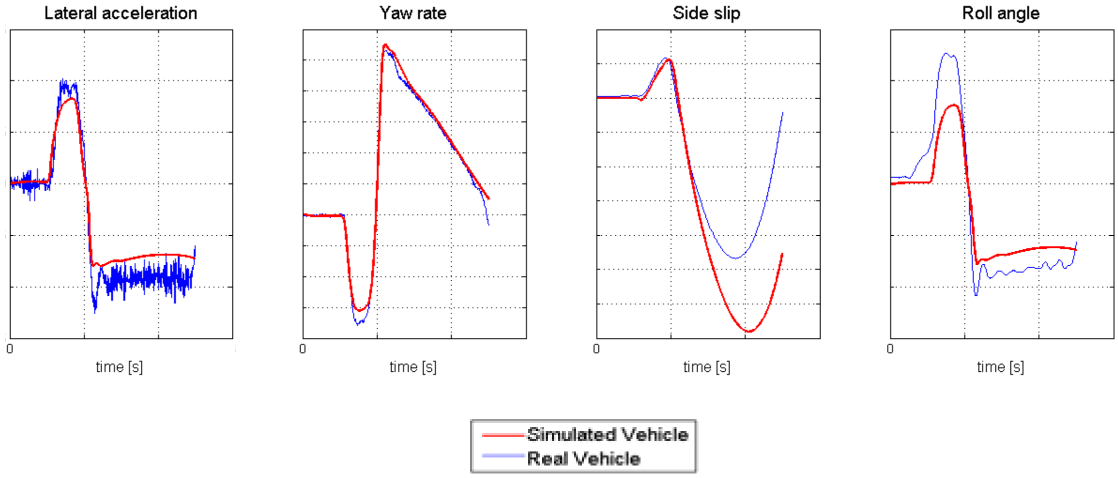


Figure 31 - High amplitude SWD with ON-ON ref.

By comparing Figure 30 with Figure 31, it can be observed that the lateral acceleration exceeds the real values at low amplitude steering wheel inputs and does not reach the desired values at high amplitude steering. Based on these differences, it is decided to study the peak lateral friction coefficient of the tire model and the steering geometry tables.

The steering system was found to be correct but all the mechanical properties of the steering components such as stiffness and inertia of the steering column components were missing. The lateral peak friction coefficient of the tires was found to be μ=0.8, which had been modified by Volvo Cars for some research purposes. The antiroll bar tables were also studied and non-symmetric values for positive and negative roll were found. Also, the values were found to be unrealistically high.

The Figures in Appendix B, shows the result of the remaining analysed manoeuvres. By studying them, it can also be understood that the peak friction coefficient, the steering characteristics and the auxiliary antiroll force are not properly defined in the models.

In the CR manoeuvre shown in Figure 32, the side slip angle of the real vehicle has rather odd values up to a certain moment when it stabilizes and shows more logical values. This is because the lateral velocity component is calculated by integrating the lateral acceleration. This gives inaccurate values when the lateral acceleration is low, which in combination with low longitudinal velocities results in unrealistic side slip values.

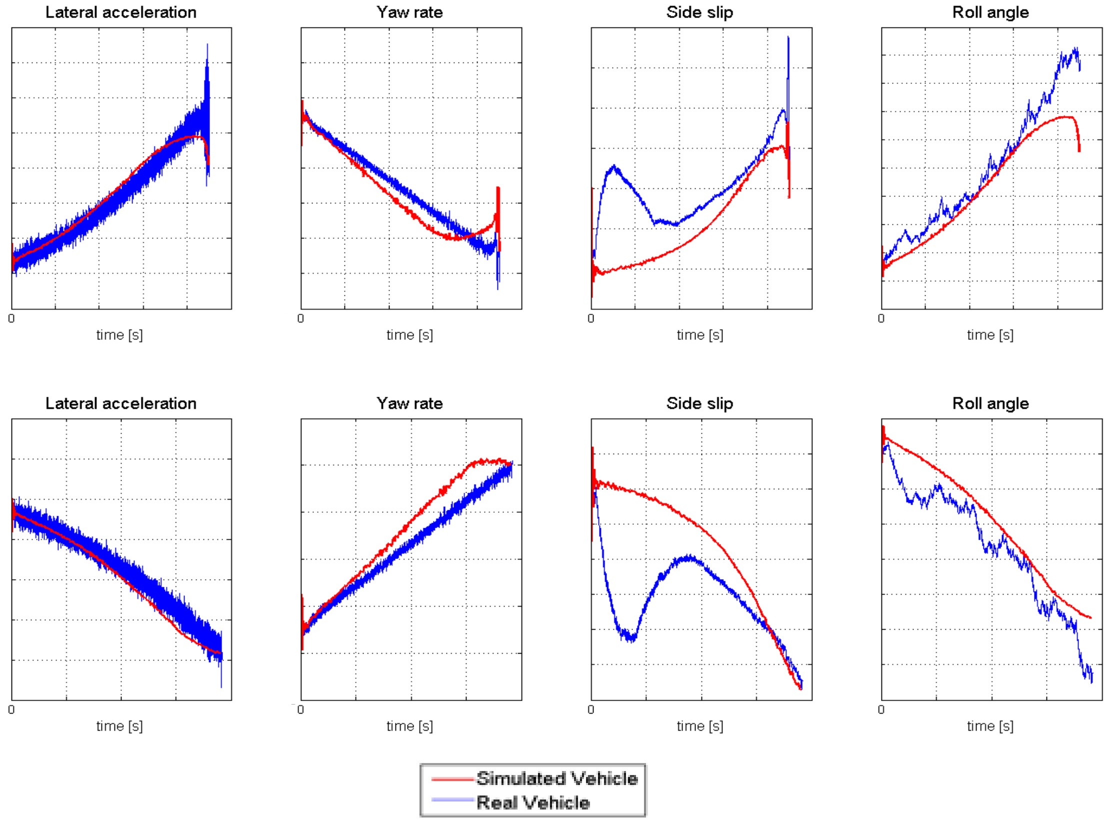


Figure 32 - CR with ON-ON ref.

4.3.3 Final model status

In this section, the changes performed to the vehicle and tire model are explained and the simulation results compared in time step data are shown. However, in order to not repeat the same plots more than once, the final status of the OFF-ON and ON-OFF configurations models are shown in Section 4.3.3.2 and Section 4.3.3.3.

After identifying potentially incorrect and missing parameters, several iterations of changes are performed to the tire and vehicle models in order to find a model that emulates the reality as close as possible.

For a good understanding of the effect of each changed parameter, a simulation of all the manoeuvres was performed after every change in the models. To keep the focus of the report to what is relevant and to the defined research scope, the results from each of the different iterations are not covered in depth.

As a first step, the mechanical properties of the steering system are gathered and introduced in VI-CarRealTime. It was then observed that all the low lateral acceleration manoeuvres were correlating much better. However, the high lateral acceleration manoeuvres did not improve, so a need of increasing the lateral peak friction coefficient of the tires becomes evident. After a few iterations, the lateral and longitudinal peak friction coefficients were set to a value of one. At this point, the antiroll bars were substituted by the ones from the model generated from Adams K&C as they seemed more realistic.

Apart from the mentioned changes, the peak relaxation length of the tire model must be changed as mentioned in Section 4.2.2 in order to ensure the stability of the model in the simulator. Changing this parameter does also affect the simulation results and the results presented in this section do include the change of this parameter together with all the ones mentioned before.

4.3.3.1 ON-ON ref & ON-ON Adams

Figure 33 and Figure 34 shows the results of the model "ON-ON ref", the model "ON-ON Adams" and the real vehicle in ON-ON configuration.

As can be appreciated, after correction of the "ON-ON ref" vehicle model and the tire model, the simulation matches the data gathered from the physical testing much more accurately.

It is also evident that the model generated form K&C correlates much better with the real data than the model generated from Adams. This is noticeable at any condition: high and low lateral accelerations and in transient and steady state manoeuvres as the ones shown in Figure 33 and Figure 34.

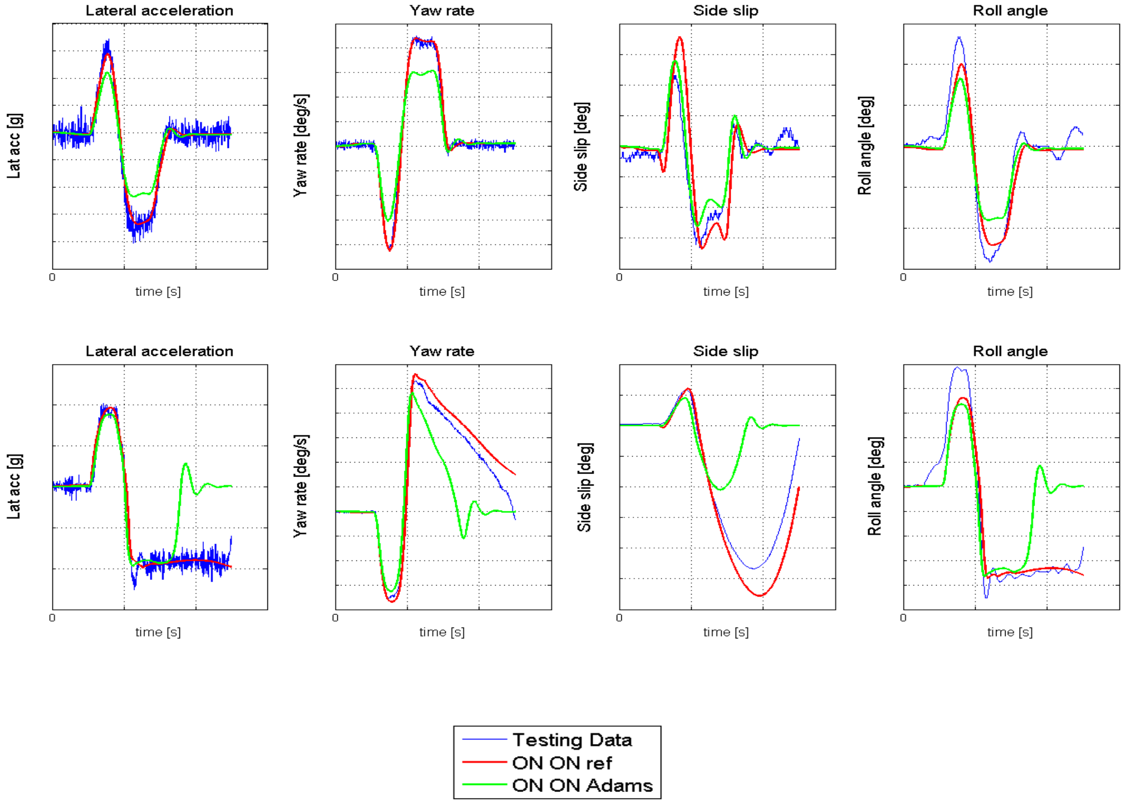


Figure 33 - SWD with ON-ON ref & ON-ON Adams.

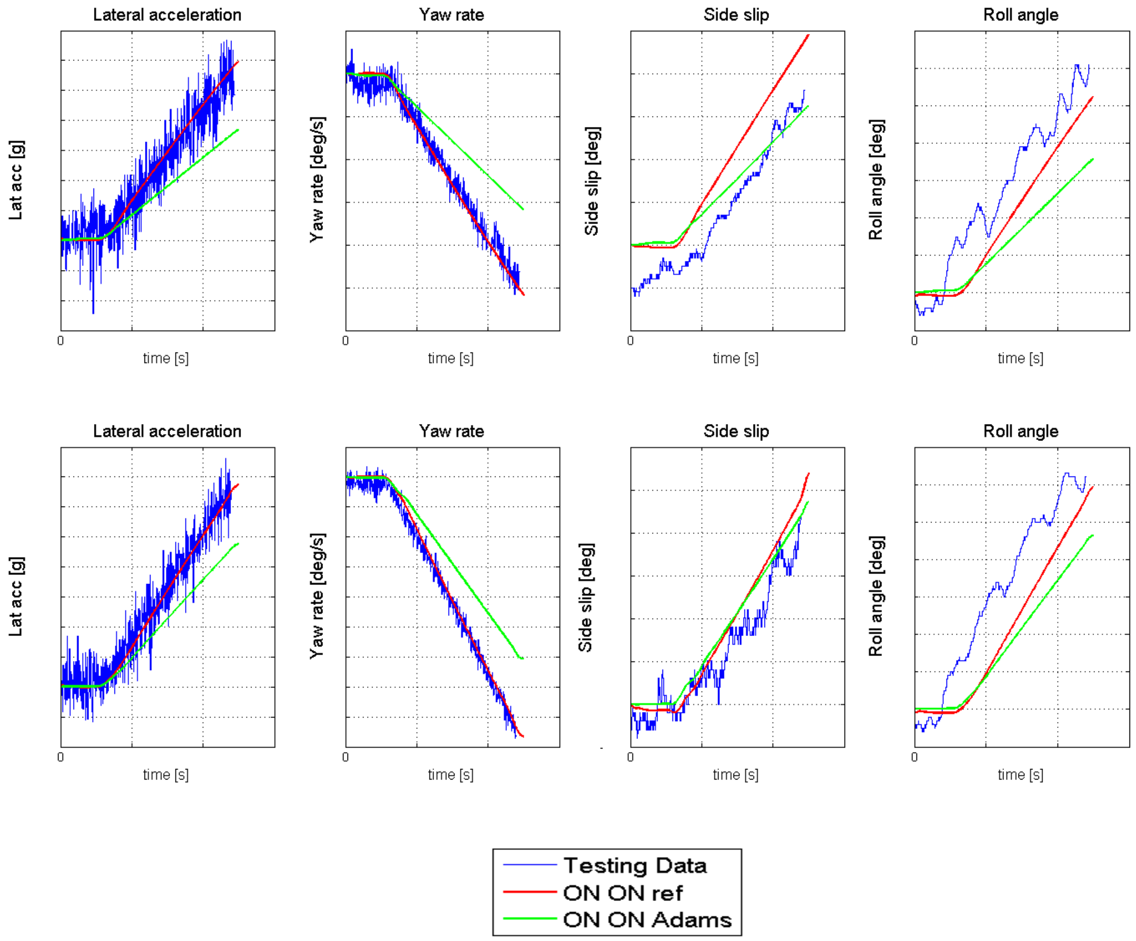


Figure 34 - LSS with ON-ON ref & ON-ON Adams.

4.3.3.2 OFF-ON ref & OFF-ON KnC

Figure 35 shows the results of the model "OFF-ON ref" and "OFF-ON KnC" compared with the data gathered from the physical testing in that same configuration.

The differences between these two models are rather small and they are assumed to be due to differences in the K&C measurement generated when having the front antiroll bar connected or not. The rest of the manoeuvres analysed showed also very small differences. These can be found in Appendix B.

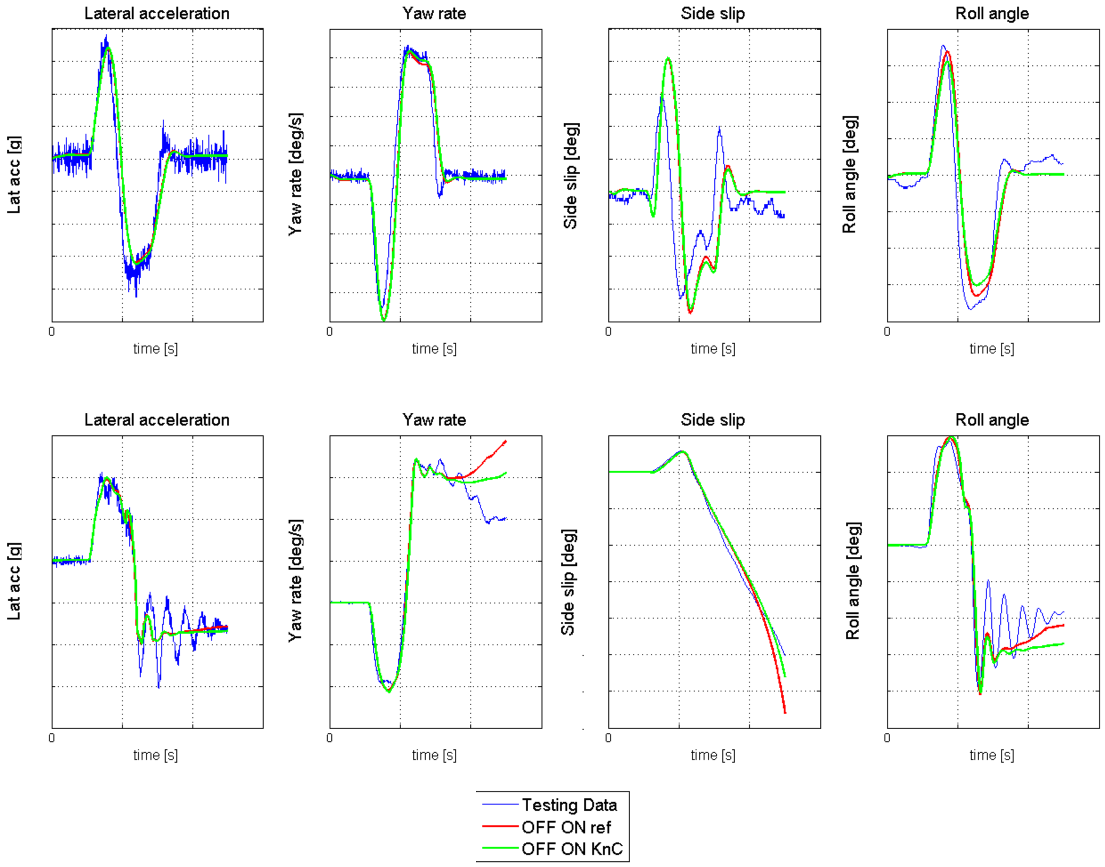


Figure 35 - SWD with OFF-ON ref & OFF-ON KnC.

4.3.3.3 ON-OFF ref & ON-OFF KnC

Figure 36 shows the results of the model “ON-OFF ref” and “ON-OFF KnC” compared with the data gathered from the physical testing during two sine with dwell manoeuvres. The rest of the manoeuvres show smaller differences between the models. This can be seen in Appendix B.

The differences between these two models are slightly larger than for the OFF-ON configuration. The larger deviation is assumed to be due to the differences in the K&C measurement generated from having the rear antiroll bar connected or not, where, as shown in the K&C results, the rear axle is the one that is mostly affected by the ARB configuration.

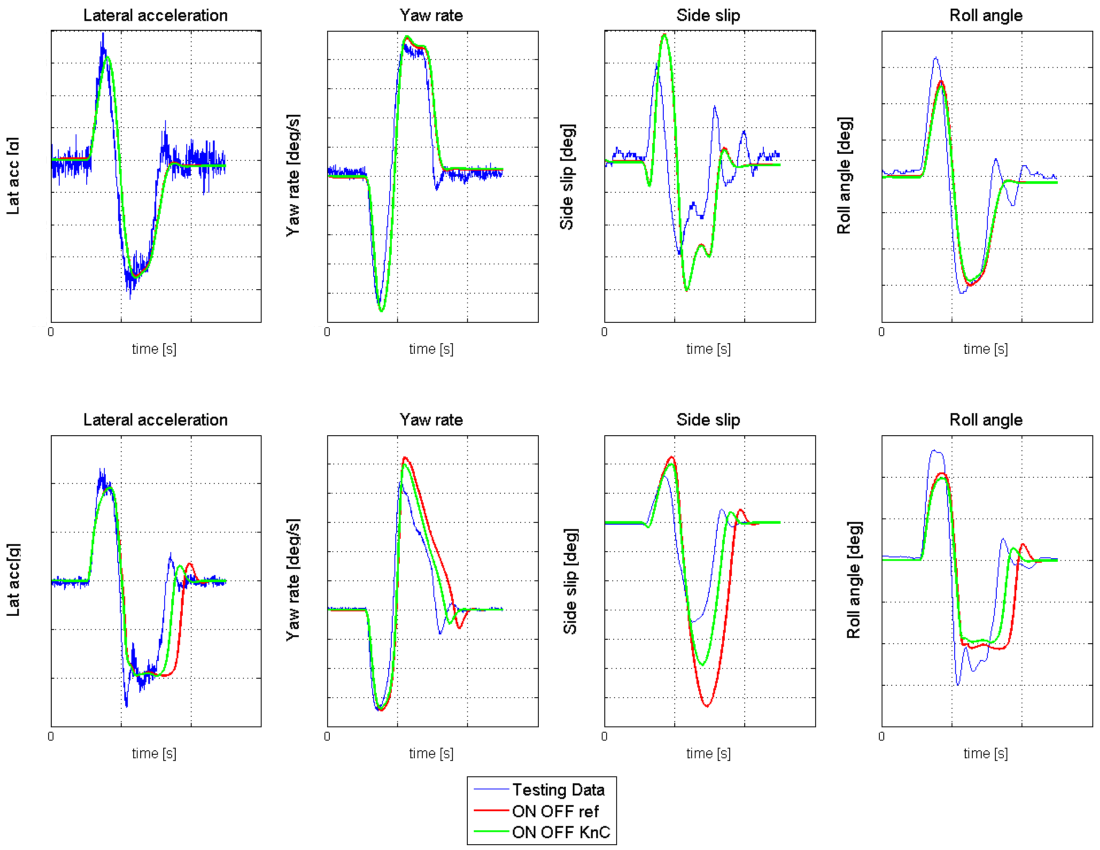


Figure 36 - SWD with ON-OFF ref & ON-OFF KnC.

4.4 Correlation of objective metrics

To get an understanding of how well the virtual vehicle models correlate with the results obtained from the physical testing, a comparison was performed. As explained in the method section, this is performed by comparing the objective metrics generated from simulating the vehicle models with the objective metrics obtained from physical testing.

The vehicle models are compared with physical testing in time step data, as explained in Section 4.3, which obviously do give an understanding of the correlation between the two, but it is decided to also compare the metrics as this also relatively easily allows a comparison in delta.

4.4.1 Analysis of objective metrics using DNA fingerprint

One way to analyse the obtained objective metrics is by using the DNA fingerprint. Here, six different data sets are compared. Three of these are obviously the tree different vehicle configurations measured physically. The remaining three are selected as the vehicle models generated directly from the kinematics and compliance measurements as these showed the closest correlation in the time step validation.

Running the implemented manoeuvres in VI-CarRealTime, coupled with the batch script to include the Simulink power steering model turned out to be a rather swift process. Importing the generated data from the simulations to the metric calculation flows in Sympathy for Data did also work well. One issue with the Sympathy for Data flows is however that not all metrics included in the steering and handling DNA fingerprints are generated. The reason for this is that the flows adapted to the data from VI-CarRealTime were obtained at a relatively early stage when the development of the DNA fingerprint from the flows was still under work. At the point of the final DNA fingerprints to be generated, flows that produce the complete DNA fingerprint are available. Adapting these flows to function properly with the data from VI-CarRealTime did however turn out to require more time than was available during the closing stages of the project. To ensure sufficient time for everything that was planned for during the project, it was decided to use the available flows and compare the metrics that are generated. The DNA fingerprints from the simulations are also not complete as they are generated from several more manoeuvres than those selected in the current project. A fragment of the DNA fingerprint containing the metric values of all three configurations from physical testing and simulations of the virtual models can be found in Figure 37. Note that all metric names and numerical values are hidden due to confidentiality. The full DNA fingerprint with the metric names displayed can be found as Figure 37 in Appendix C.

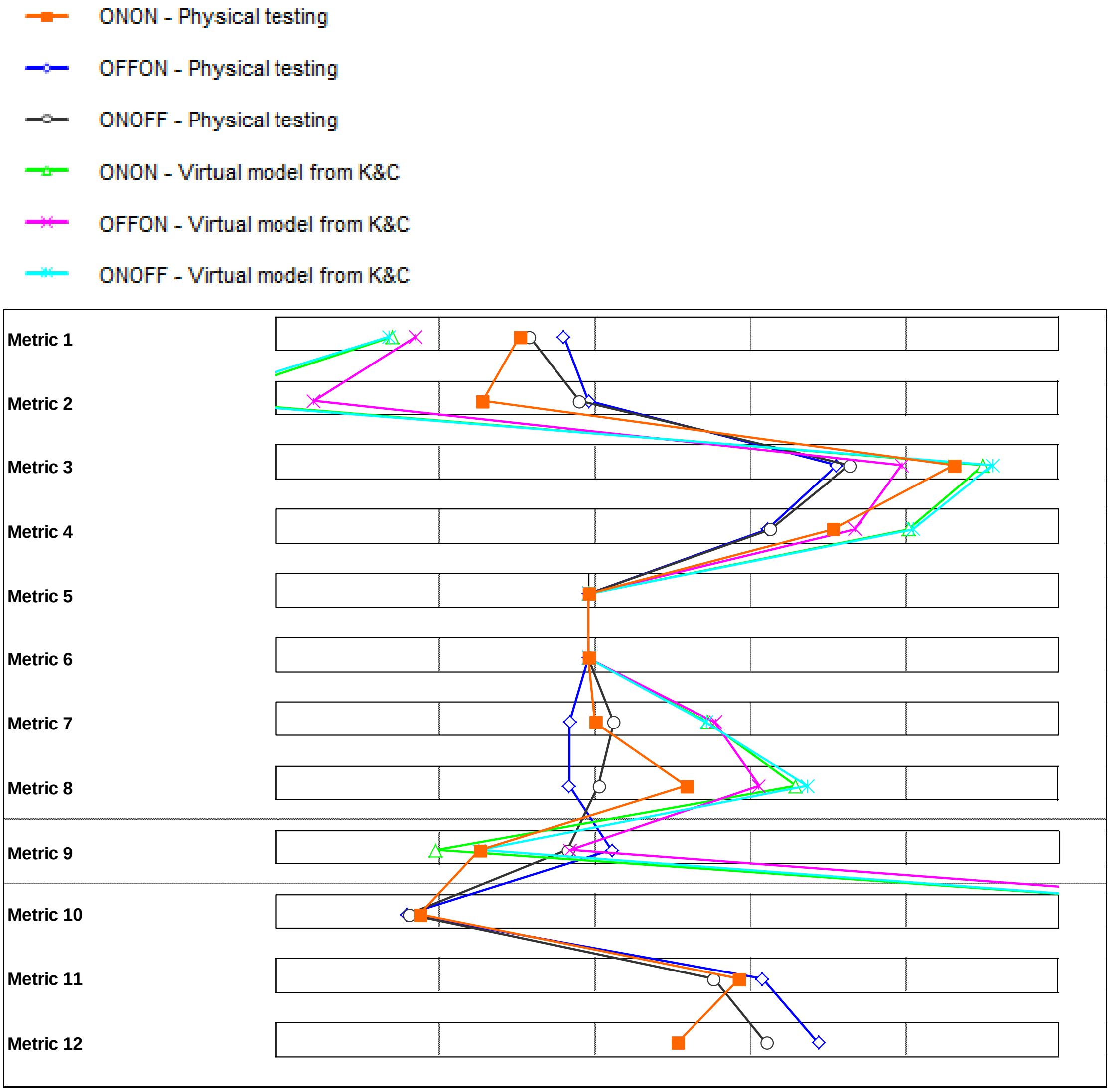


Figure 37 - Fragment of the steering DNA fingerprint.

As seen in the DNA fingerprint in Figure 37, of the metrics that are available for all six configurations, some are fairly close while others are far from near. The reason for the differences between the ones with highly deviating values is however in most cases known as these can be traced to the fact the steering model used is far from ideal.

Another aspect to this is that the exact values are not the most important factor when evaluating the vehicle models. When using a digital development tool such as the driving simulator, it is usually not the exact behaviour that is to be resembled, but the difference when making changes. For this reason, a more relevant comparison would be how similar each metric from the simulated configurations is to the ones obtained from physical testing. Such a comparison is performed in the following section.

4.4.2 Delta analysis of objective metrics

To improve the understanding and readability, the validity of the models obtained from the delta validation is explained separately for handling and steering metrics.

The ON-ON configuration is selected as reference and the change on the metrics is analysed for the physical vehicle and for the virtual one. The effect of removing the front and rear antiroll bars is analysed individually.

4.4.2.1 Handling metrics

Figure 38 and Figure 39 show the percentage change in the studied handling metrics when removing the rear and front ARB in reality and in CAE. The metric names are hidden for secrecy. Uncensored versions can be found in Appendix C.

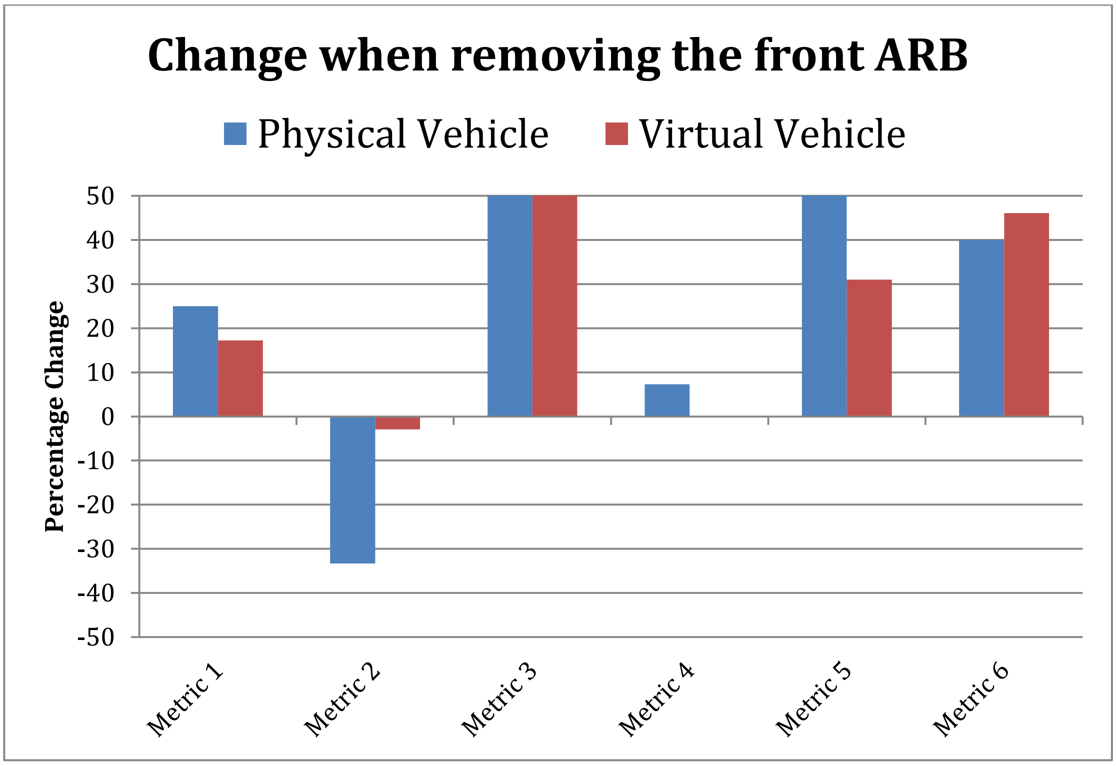


Figure 38 - Percentage change when removing the front ARB.

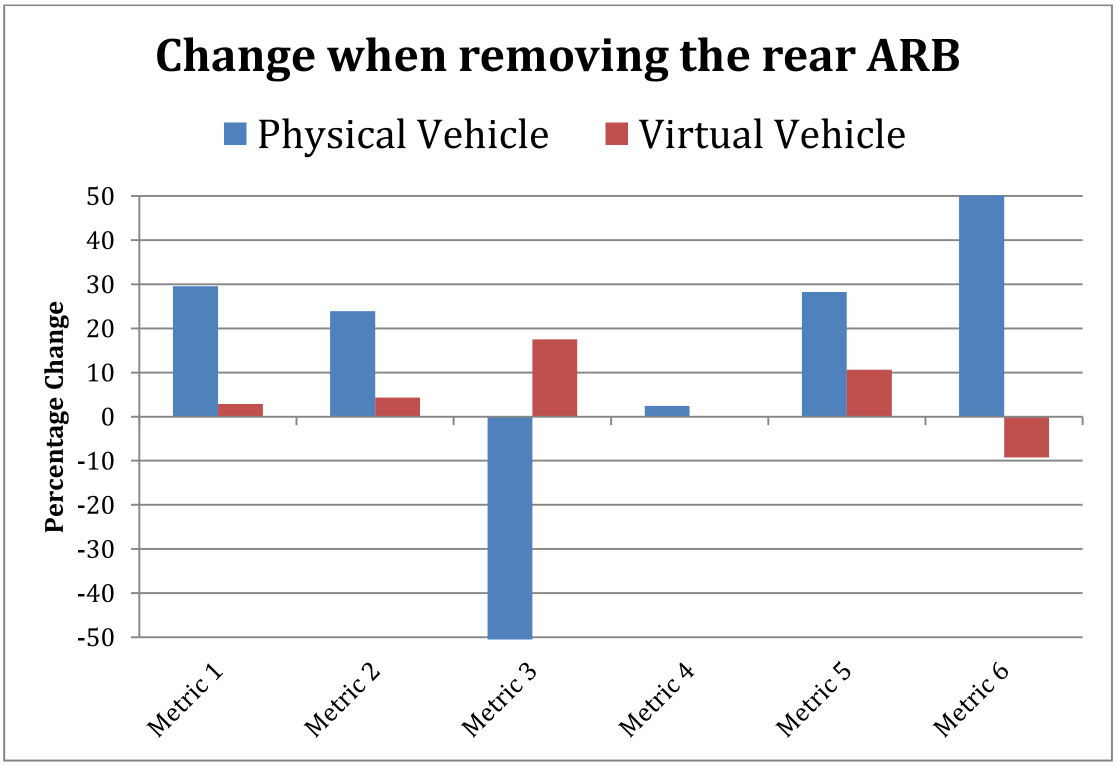


Figure 39 - Percentage change when removing the rear ARB.

As can be observed in Figure 38 and Figure 39, for 83% of the metrics, the changes are predicted in the same direction during both the physical and virtual testing. Of those who change in the same direction, the average deviation is of 15.9 percent points.

4.4.2.2 Steering metrics

Figure 40 and Figure 41 show the percentage change in the studied steering metrics when removing the rear and front ARB in reality and in CAE. The metric names are hidden for secrecy.

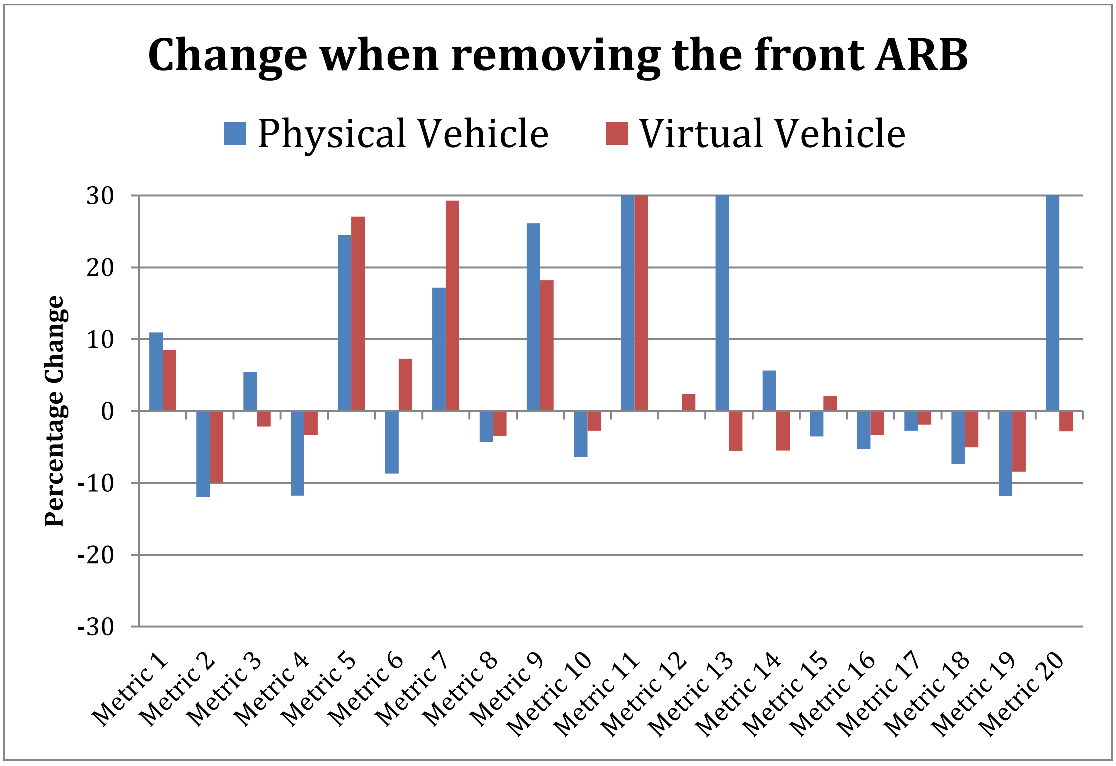


Figure 40 - Percentage change when removing the front ARB.

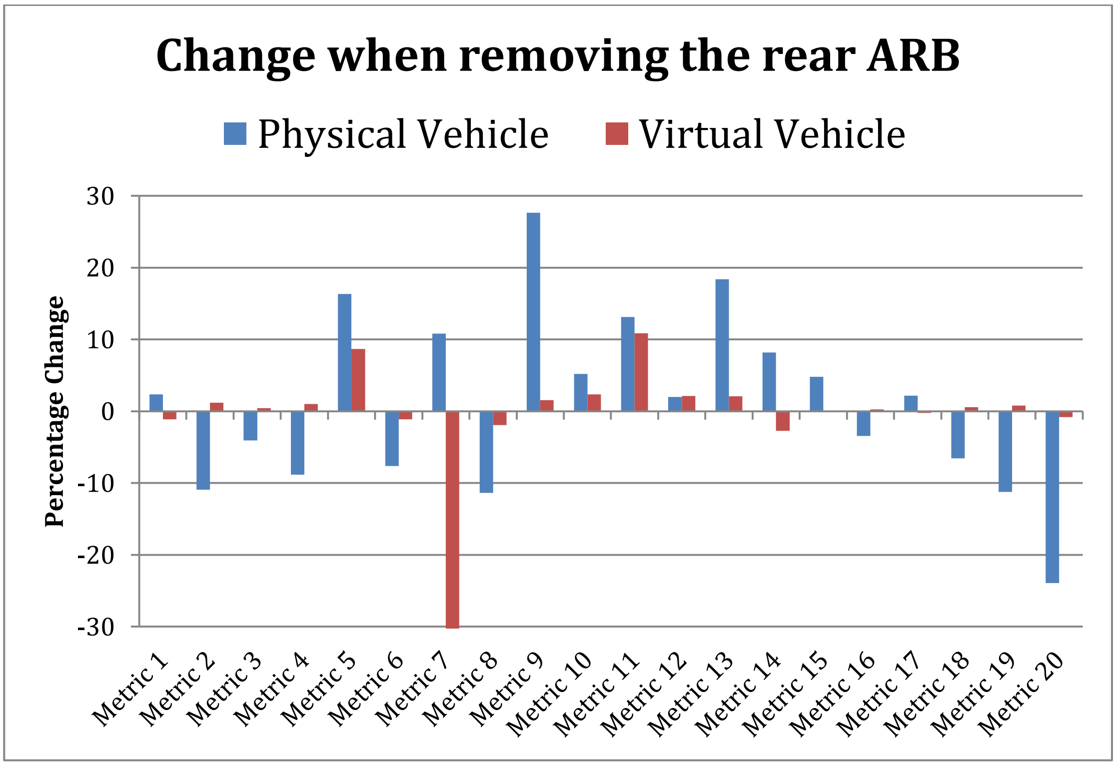


Figure 41- Percentage change when removing the rear ARB.

As it can be difficult to get an idea of the quality of the validation in delta by just studying the figures, it can be said that 62% of the steering DNA metrics predict the changes in the same direction in reality and in CAE. Of those metrics, the average deviation is of 6.3 percent points.

4.5 Model implementation in the MBDS

Implementing the generated vehicle models in the driving simulator turned out to be a rather swift and straight forward process. No major issues were encountered in the process of importing the vehicle models in the software used by the driving simulator and their overall stability did also show acceptable results. The operation was however not fully problem free. As told in Section 4.2, generating the vehicle models did initially yield issues with the stability of the power steering system. These issues were corrected for an improved stability when simulating the models offline of the simulator. When implementing the vehicle models in the simulator, the driver did still experience instability in the steering system when it was entering a resonance for small steering wheel inputs.

To solve this issue, the parameters that control the feedback to the steering wheel in the driving simulator were modified. Studying Zaremba and Davis (1995) reveals that the stability should be possible to improve by increasing the damping of the system. Performing this did however show the contrary as the steering became more unstable when increasing the damping. It was therefore tried to do the exact opposite, to decrease the damping which unexpectedly also increased the stability. The low damping in the system was remained but the time available did unfortunately not allow for a deeper study of the behaviour.

Other minor changes to the controller of the steering system in order to improve its stability include the torque build up in the centre region of the steering range. These changes will influence steering related aspects of the subjective assessments but the stability of the model is considered to have higher priority. Performing the mentioned modifications resulted in a far more stable system but the overall subjective feel is however still not fully correlating with that of the physical vehicle. The mentioned changes are considered to be what is reasonable to perform within the scope and timeframe of the current project but the system do need further future modification to exactly resemble the steering feel of the physical vehicle.

4.6 Subjective assessments

As told when explaining the methodology used in the project, the different vehicle configurations and vehicle models used are assessed in both a physical environment, as in a real car on a real track, and a virtual environment, meaning in the driving simulator. The results of these assessments are explained in the following sections.

4.6.1 Physical SA

The overall outcome of the physical subjective assessments shows a positive result where the planned configuration changes and implementation routines were possible to perform ad follow. The probably largest difference between the planning and implementation was the required time. Before the beginning of the assessments, the full procedure was performed to understand for how long each driver had to be booked. The assumed time turned out to be an underestimation as the drivers spent much more time and effort filling in the questionnaire than expected. The estimated maximum time of three hours turned out to be closer to at least four hours.

Another lesson learned from the physical subjective assessments is to never underestimate the impact of the weather when performing a task that requires dry conditions. Around three fourths of the initially planned subjective assessments had to be cancelled and rescheduled due to poor weather conditions.

4.6.2 Virtual SA

Also the virtual subjective assessment showed overall positive results regarding implantation and planning. Implementing the vehicle models and ensuring stability turned out to be quicker and less troublesome than expected. Modifying the Simulink model used to control the steering feedback was also a swift accomplishment. One general problem of all coupled systems in the driving simulator is however the steering. The torques and forces delivered as feedback from the steering system have a rather unrealistic behaviour. The range of constant torque level around zero steering wheel angle is larger than in the real vehicle, with an adjacent torque build up also larger than in the real vehicle. If the steering is excited with small steering inputs in this range, it also has a tendency to enter an oscillating motion that has to be discouraged by the driver. These steering related issues were however all much more significant the first time the vehicle models were installed in the simulator. Much effort was put into reducing these issues, which to some extent was successful, but due to the time limitations in the project, at one stage the improvements had to be discontinued. These issues will obviously have an impact on the outcome of the subjective assessments, but it is a known issue that will be taken into consideration when analysing the results.

As the virtual subjective assessments are not depending on as many external factors as the physical one, such as the weather, the initial planning could be held to a much larger extent. The major factor to affect the time required to perform the subjective assessments was in this case the tendency of the drivers to be affected by the motions of the simulator. The presence of motion sickness for some people was known before the subjective assessments were performed but the execution of these showed how much issues this can cause for the ones affected. One driver was not able to drive the vehicle model without the front antiroll bar due to its tendency to oversteer. The motion sickness he obtained from driving the model made him unable to continue the assessment for the rest of the day. Other drivers did however seem completely unaffected by motion sickness. The youngest driver participating in the study managed to drive all six vehicle models in one run without taking any pauses and without any present motion sickness. Analysing if the issues of motion sickness can be derived from the age of the drivers is however not considered to be within the scope of the current project.

4.6.2.1 Responses from driver interviews

As described further in Section 3.3.2.4, to obtain a deeper understanding of how the drivers experience the driving simulator, they were interviewed after having driven each of the six different vehicle models. The following sections provide a compilation of the answers.

4.6.2.1.1 General driving feel

The first question asked to the drivers after having driven each vehicle model was how it felt to drive the vehicle. The answers to this question are summarised in Table 11, where the configuration of the different vehicle models are as is specified in Table 3.

Table 11 - Driver responses on general driving feel.

For confidentiality, the table can only be found in Appendix C.

4.6.2.1.2 Improvement suggestions

The second question asked to the drivers after having driven each of the different vehicle models was which physical components they would change, or how they would change them, in order to improve the characteristics of the vehicle, if they were driving a physical vehicle with the same properties as the currently simulated one. This allows for an understanding of how well the driving simulator to some extent can be used as a replacement for physical tuning through subjective assessments. As the different vehicle models are generated from measuring the same vehicle with different antiroll bar configurations, the correct answers would therefore be to increase the contribution of the rear antiroll bar for the first and fourth model, increase the contribution of the front antiroll bar for the second and fifth model, and no changes for the third and sixth model. The answers to these questions are compiled in table 12.

Table 12 - Driver suggestions on improvements.

ON-OFF KnC	Add friction and damping in steering Add rear antiroll bar Decrease rear antiroll bar
OFF-ON KnC	Loosen rear antiroll bar or stiffen front antiroll bar
ON-ON ref	Nothing obvious Tuning friction and damping of power assist system Tighten bleeds of dampers
ON-OFF ref	Increase rear antiroll bar Minor increase of front antiroll bar
OFF-ON ref	Increase front antiroll bar Decrease rear dampers
ON-ON Adams	Difficult to evaluate Increase rear dampers

4.6.2.1.3 Configurations comparisons

After having driven the third vehicle configuration the drivers were asked to compare their experience of the first three vehicles. The same question was given after the sixth vehicle configuration where the drivers were asked to compare the fourth, fifth and sixth vehicles. The results are summarised in Table 13 where the order in which the models are referred to is the same as how they are presented in Table 11 and Table 12.

Table 13 - Comparisions of the different vehicle models.

ON-OFF KnC, OFF-ON KnC & ON-ON ref	#2 more oversteered than #1 #2 feels better than #1 but still not fully natural Steering in #3 is better than #2 & #1 but still not good #3 feels best #1 not good, too understeered poor transitional stability of #2 #2 more consistent oversteer than #1 #2 has better ability control the oversteer than #1 #2 has more realistic steering than #1 #2 rolls more than #1 #3 easiest to control Unpredictable behaviour of #3
ON-OFF ref, OFF-ON ref & ON-ON Adams	#4 feels close to #1 #5 feels like #2 but with better steering #5 is unstable under braking but not as much as #2

4.6.2.1.4 Configuration rankings

After having driven all six different vehicle models, the drivers were asked to rank the models from best to worst after how much liked their behaviour and characteristics. The results can be seen in table 14.

Table 14 - Driver rankings of the vehicle models.

Driver 1	3,5,4,2,1,6
Driver 2	3,6,2,4,5,1

4.6.3 Correlation of assessment results

Performing all the previously mentioned stages of the project does finally allow for a study of the correlation between the virtual and physical subjective assessments which yields the validity of the driving simulator. The correlation study is performed by comparing all of the subjective grades given by the drivers in the different assessments. In the questionnaire used, a total of 26 questions were asked, divided into eight for handling characteristics and 18 for steering characteristics.

As explained in Section 3.3.1.2, each vehicle configuration is driven twice to allow for an investigation of the consistency of the drivers and how using the questionnaire in paper form and in the form of an iPad-application can affect the results. Performing these investigations is however not within the scope of the current project. The rating of each vehicle characteristic is therefore averaged between the two runs with each vehicle configuration.

As described in Section 3.3.2.2, six different vehicle models are used in the subjective assessment in the driving simulator. Due to the limited time in the current project, only the three vehicle models generated directly from the kinematics and compliance measurements are analysed in this section. The reason for this selection is as these models showed the best correlation in the model validation explained in Section 4.3.

The overall correlation is investigated by comparing the subjective values set by the drivers in both of the subjective assessments for all of the different characteristics. For each characteristic, the subjective value set by the drivers in the standard vehicle configuration is then compared with the one set when removing the front and rear antiroll bar of the vehicle respectively. This gives a percentage difference for each characteristic between the configurations for the physical subjective assessment and for the virtual ditto.

Since the probably most important property of the driving simulator is for it to correctly resemble the direction in which a certain change of the vehicle configuration affects its characteristics, the most important trend here is that the difference of the vehicle configuration results in that the subjective values set by the drivers changes in the same direction for both the virtual and subjective assessments. The ideal is obviously if the exact set values are the same but in the current case this is considered secondary.

The percentage change of the different handling characteristics when removing the rear antiroll bar can be found in Figure 42. Figure 43 shows the same for when removing the front antiroll bar. This is also shown in Figure 44 and Figure 45 but for steering characteristics. For confidentiality reasons, the names of the different characteristics are hidden. Uncensored versions of these figures can be found in Appendix C.

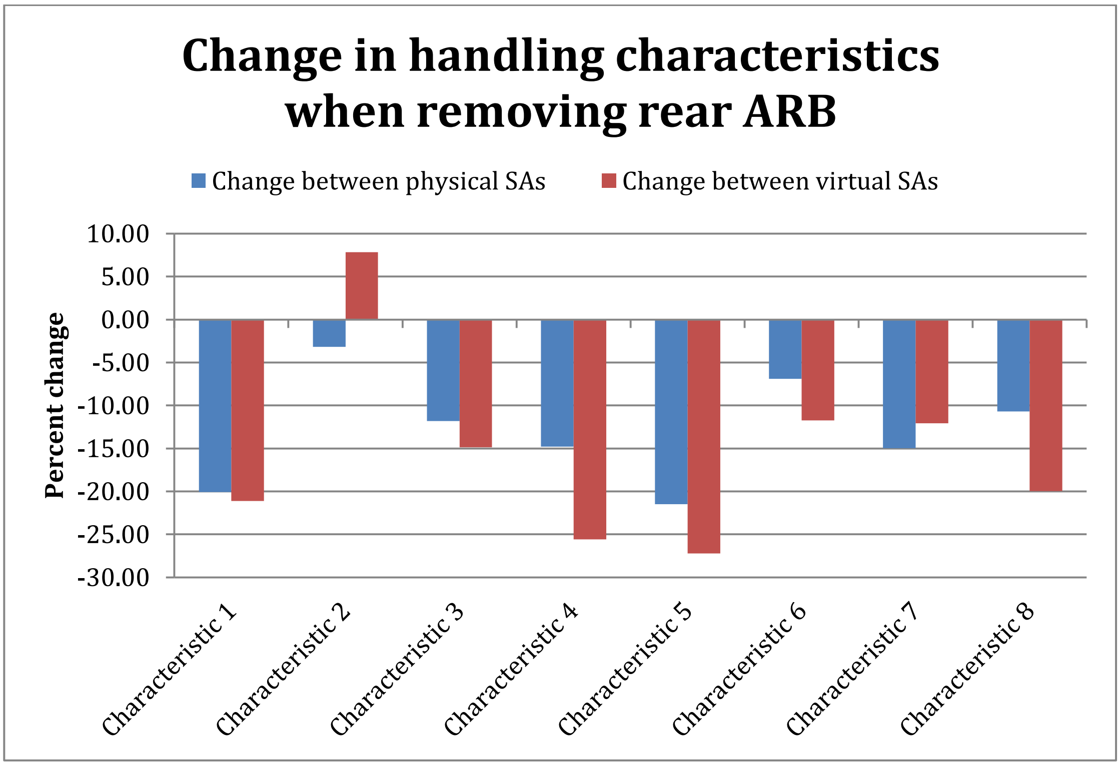


Figure 42 - Change in handling characteristics when removing rear ARB.

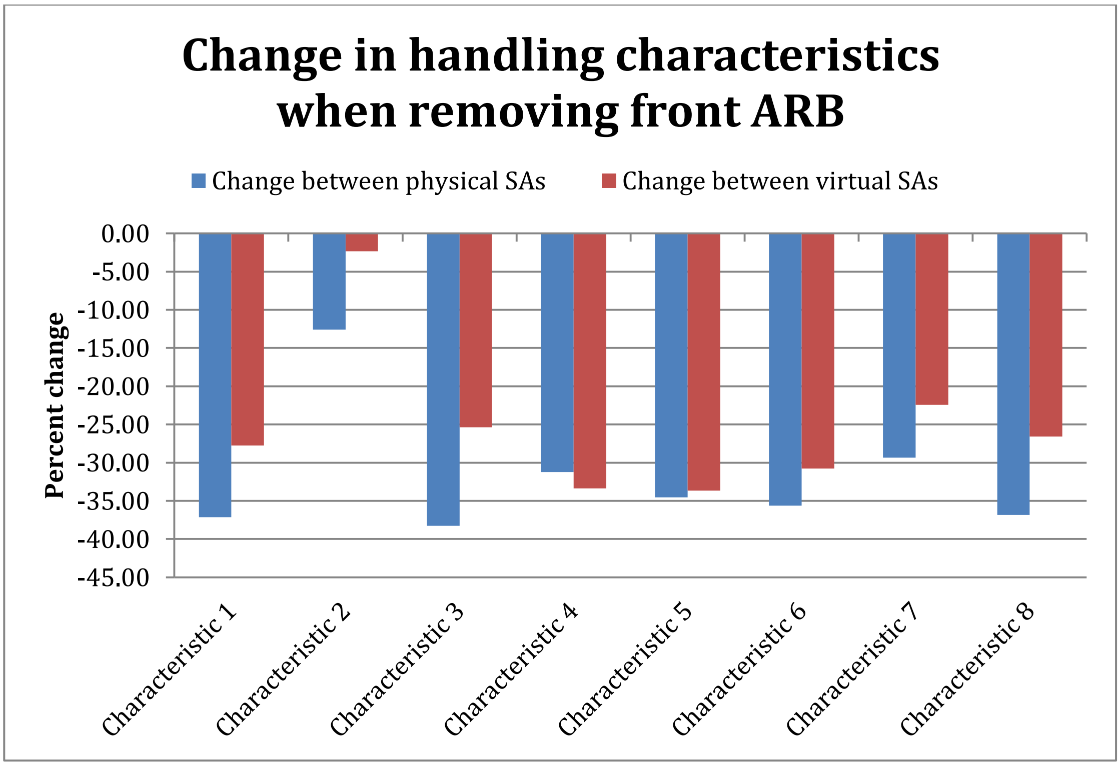


Figure 43 - Change in handling characteristics when removing front ARB.

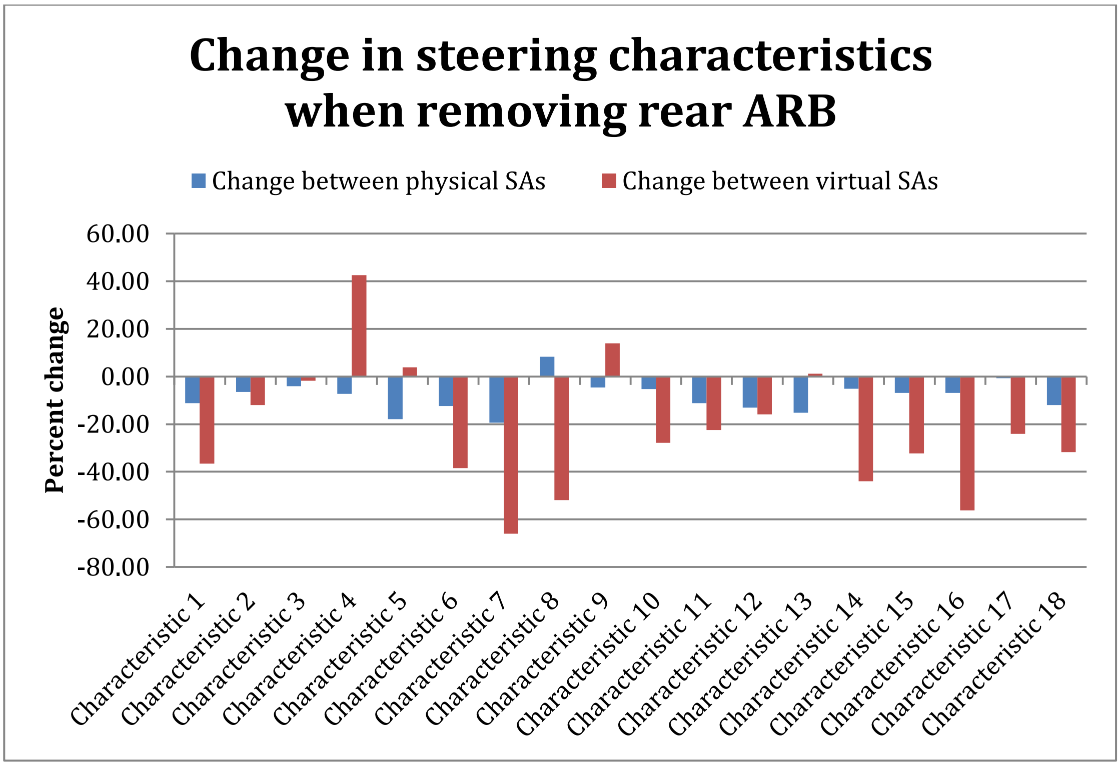


Figure 44 - Change in steering characteristics when removing rear ARB.

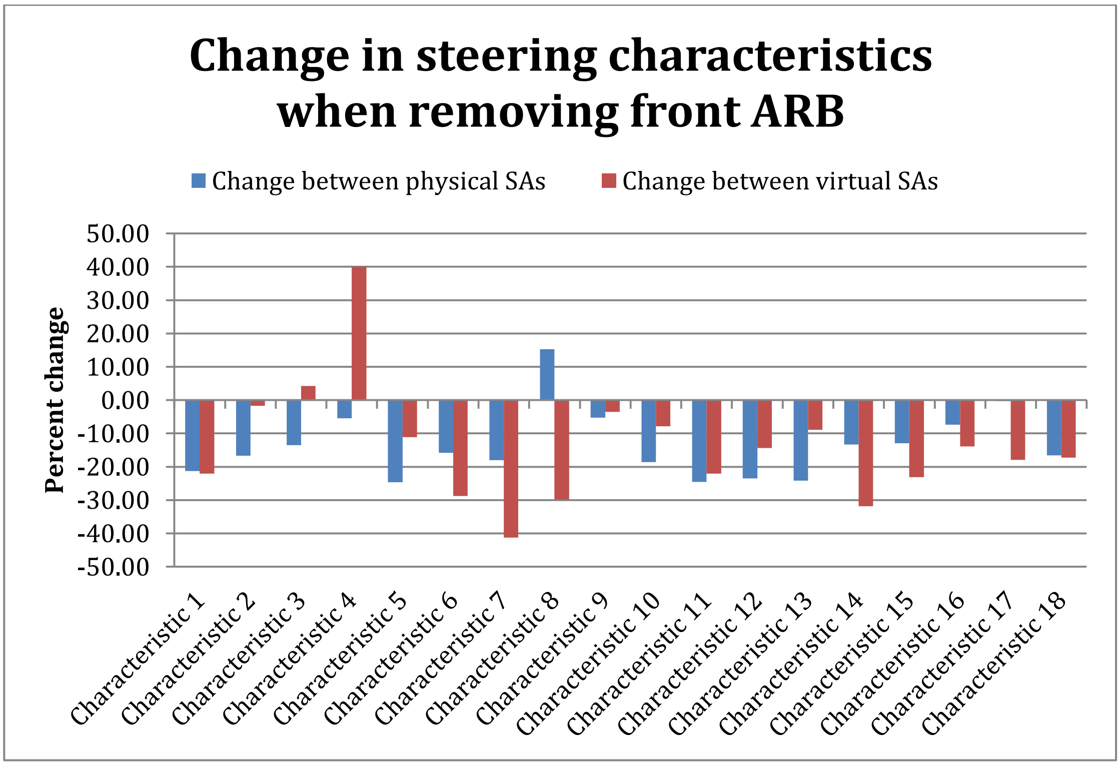


Figure 45 - Change in steering characteristics when removing front ARB.

By comparing the differences shown in Figure 42 to Figure 45, it can be obtained that in handling, 94% of the characteristics change in the same direction. The same value for the steering characteristics is 78%. Of the characteristics that change in the same direction, the deviation is on average 6.3 percent points for handling and 18.7 percent points for steering.

5 Conclusions and future work

With the thesis project presented in this report performed and all the mentioned steps gone through, certain experiences and knowledge has been gained. Based on this knowledge, conclusions can be drawn about the outcome and performance of the research including recommendations of how the research could be continued in the future. This is presented in the following chapter.

5.1 Project conclusions

By studying the results obtained from all the steps performed in the current project, certain conclusions can be drawn. These are presented in the following sections.

5.1.1 Kinematics and compliance measurements

As explained in previous sections, the main purpose of the kinematics and compliance measurements is to generate a virtual vehicle model of the physical vehicle that is used in the project. However, as no definitive answer could be reached of how much the configuration of the antiroll bars affects the result, a further study of this was performed.

From the brief study performed, it can be concluded that having the antiroll bar connected or not does not in a significant manner affect the K&C measurements of the opposite axle. However, having the antiroll bar connected or not does affect the outcome of the K&C measurements of the same axle.

To draw any conclusions about the need of performing the tests has however appeared to be rather difficult as the measured differences are in such small ranges that the effect on the vehicle dynamics performance cannot be definitely predicted. In order to obtain more reliable data that allows any conclusions to be drawn in the subject, it was decided to investigate the issue further by generating virtual vehicle models directly from the kinematics and compliance measurement data and compare these with models generated by modifying the antiroll bar configuration in the software from the vehicle measured in the ON-ON configuration.

5.1.2 Overall model validation

The obvious question that becomes apparent when performing a validation is when the model is assumed to actually be valid. Garrott et al. (1997) defines validity as: “a computerized, mathematical model of a physical system, such as a handling and control vehicle dynamics simulation, will be considered to be valid if, within some specified operating range of the physical system, a simulation's predictions of the system's responses of interest to specified input(s) agree with the actual physical system's responses to the same input(s) to within some specified level of accuracy”. Applying this on the current project does thus yield a requirement to specify the level of accuracy. The initial focus was to find a numerical value of how accurate is “accurate enough”. However, when implementing the virtual vehicle models and changing the incorrect parameters, the apparent overall accuracy of the models were, especially in the time step validation, assumed as rather good. As the aim of the used methodology also is for the vehicle models to require as few modifications as possible, and as the project is within a limited time frame, the reached accuracy of the vehicle models were under the given constraints assumed to be good enough.

This is motivated by Klemmer, et al. (2011) stating: "since the effort and the runtime of a model increases with the level of detail, a model should not be more detailed than required, matching the needs of the model application".

It is however important to remember that the assumed level of validity only is valid within the scope of the current project. Garrott et al. (1997) does also explain: "a second significant point contained in the definition of simulation validation is that it is valid only for specified inputs/outputs groups. For example, for a handling and control simulation, simply because the simulation has been shown to be valid for braking and steering control inputs does not imply that the response to a road disturbance (such as a bump in the road) will be correctly predicted. Similarly, a simulation that successfully predicts lateral sprung mass acceleration might fail to predict vertical sprung mass acceleration." In the current project this means that the resulting level of accuracy is for instance not necessarily the same for the vehicle dynamics characteristics of ride, which are not within the scope of the project.

5.1.2.1 Model validation in time step

The use of time step data for the validation of the vehicle models is shown to be the most efficient method time wise since the obtained data from the simulation can be directly plotted against the physical testing data. This allows for multiple iterations in a rather short time.

This validation method is also the most suitable when modifications to the model are to be performed. The reason for this is because by analysing the vehicle behaviour over time, clearer conclusions can be obtained than if comparing absolute values of certain metrics, as in the delta validation. The trace of a metric allows for the engineer to understand which vehicle parameters could be revised and if needed, modified.

The last but not least important reason for using this method is because the exact same input that was introduced to the vehicle in physical testing can be introduced to the simulated vehicle, and therefore the complete deviation is solely caused by the vehicle model.

5.1.2.1.1 Methodology validation

Using a model generated from real K&C measurements instead of one from Adams K&C should be more accurate in theory. Since the model of a Volvo V40 T5 with Sport chassis is available, it is decided to compare it with the model generated from real K&C and by that validate that part of the methodology.

As can be seen in Section 4.3.3.1, the ON-ON ref correlates much more accurately with the physical testing data than the ON-ON Adams model. The higher accuracy of the ON-ON ref model is consistent through all the manoeuvres. Therefore, it can be concluded that a model generated from real K&C measurements is more accurate.

In Section 4.1.2, the effect from the ARB on the K&C measurements is analysed. As explained in Section 4.1.3, the ARB has an effect on the K&C measurements and mostly in the rear axle. The effect of those changes on the vehicle dynamics performance of the vehicle models are covered in Section 4.3.3.2 and Section 4.3.3.3.

From those results it can be concluded that for the transient manoeuvres like the SWD the OFF-ON KnC and ON-OFF KnC models are more accurate than the OFF-ON ref and ON-OFF ref models. However, this behaviour turns out to be the opposite in the more steady state manoeuvres such as CR, HSS and LSS. The difference in these cases is however less significant than it is for the SWD manoeuvre. It becomes difficult to extract a clear validation of this part of the methodology and it is therefore decided to run all the six models in the simulator and study which ones are closer to the real vehicle regarding the subjectively assessed aspects.

5.1.2.2 Model validation in delta

If studying the results from the validation of the time step data, the results from the delta validation might come as a surprise as they do not show as close correlation with the physical measurements as those from the time step validation. This does however not necessarily mean that the models in reality are highly inaccurate or unsuitable for the current application. What must be taken in consideration here is that the generation of the delta validation is far more complex than the one performed in time. As explained in the methodology, the time step validation uses the output from the physical testing as input for the manoeuvres performed. The resulting output values from both the physical and virtual environments are then directly plotted against each other. The methodology is partly selected for being as efficient as possible and to minimise the sources of error. This can be compared with the procedure required to perform the validation in delta. Here, the manoeuvres are pre-programmed which to some extent has to be adapted to each vehicle model. The comparison of the results is performed based on metrics that, from the physical testing are obtained from Matlab Toolbox, and from the simulations are extracted using custom adapted flows in Sympathy for Data. Potential differences between the scripts used in the softwares could cause differences between the calculated metrics.

One possibility to eliminate the sources of error originating from the manoeuvres would have been to use the output data from the physical testing as input to the simulated manoeuvres, as in the time step validation. However, if the behaviour of the vehicle model is not exactly identical to that of the physical vehicle, which is not going to be the case, the resulting output parameters from the simulations will differ from those from physical testing. As the standard manoeuvre descriptions require the parameters to reach a certain value or be within a certain range, this may then cause the output metrics from the manoeuvre to be unacceptable.

Another issue with studying the metrics used in the DNA fingerprint, compared with the time step data, is that many of the metrics are obtained at a single point. The models used can thus be slightly off compared with physical testing at and around the exact point, but close during the rest of the range, something that will not be known when studying a single metric.

5.1.3 Virtual subjective assessment driver interviews

Analysing the interview responses from the virtual subjective assessments that are summarised in Table 11 to Table 14 can be performed to an almost unlimited extent. As the available time in the current project is highly limited, the more obvious conclusions are presented in the current section.

Studying the answers to the first question as shown in Table 11 shows that the drivers seem to be able to assess the different models more carefully the longer time they have been using the driving simulator. If this however is because the drivers become more used to the environment or because the initially used vehicle models are less suitable for more precise evaluations are yet to be investigated. Such an investigation is however not within the scope of the current project.

The second question, as summarised in Table 12, shows rather positive results. For all of the models deviating from the standard one, the drivers correctly suggested changes to its antiroll bar configuration in the right direction. The only exception to this is the driver suggesting to decrease the rear antiroll bar of the first vehicle model, which is measured without the rear antiroll bar. The same driver did however suggest the remaining antiroll bar configurations correctly so this is assumed to be a communication mistake. The answer of no obvious suggested changes to the third vehicle model is as well a highly positive result, showing both the ability of the driving simulator to resemble the behaviour of the different vehicle models, and the ability of the drivers to identify the driving characteristics of a production vehicle.

The responses to the third and fourth question, as shown in Table 13 and Table 14, yields somewhat conflicting results between the different drivers. That the third vehicle model, generated directly from the measurements of the standard vehicle, is the preferred one seems definite. The ranking of the fifth and sixth is however completely different. As the remaining models show more similar results, the rather different evaluations of the fifth and sixth models are assumed to be of personal preference of the drivers. It can also be seen that the drivers were keener to compare the first three models than the latter three. The reason for this could be that the drivers become somewhat exhausted after a lengthy evaluation session. Towards the end of the assessment the drivers were also commenting it being slightly difficult to tell all different vehicle models apart.

5.1.4 Validation of Subjective Assessment data

With the title of the thesis including validation of a moving base driving simulator, this is obviously a key part of the project. This validation is, as explained in Section 4.6.3, performed by comparing the results of the physical and virtual subjective assessments. As also can be seen in Section 4.6.3, 94% of the handling characteristics assessed during the subjective assessments changes in the same direction when altering the vehicle configuration. With the ones changing in the same direction showing an average deviation of only 6.3 percent points, the results can be summarised as rather good, at least for such major changes as the antiroll bar configuration. Since the corresponding numbers for the steering characteristics are 78% prediction in the correct direction and an average deviation 18.7%, the representation of the moving base driving simulator of changes in the steering characteristics can be considered as not quite as good. This was however somewhat expected due to the simplified controller used for the steering wheel torque and for the initial instability of the steering torque feedback system in the driving simulator.

To summarize, the current status of the moving base driving simulator in focus in the current study is that it is more precise and useful to assess handling characteristics than to assess steering characteristics. Its ability to resemble changes of the handling characteristics shows positive results, although there is still room for improvement. To be a useful tool to assess steering characteristics, further improvements are required.

5.1.5 Coverage of deliverables

- **How can a vehicle model in VI-CarRealTime be created from measurements of a physical vehicle in a K&C rig?**
  Generating a vehicle model in VI-CarRealTime from measurements performed in a kinematics and compliance rig has shown successful results, and by using the in VI-CarRealTime built in wizard, a relatively straight forward process. The probably most difficult aspect is to know exactly what to measure and how to measure in the kinematics and compliance rig. This is explained more closely in Section 3.2.1.2.1.

- **How do changes in the antiroll bar configuration affect the outcome of K&C measurements?**
  Changing the configuration of the antiroll bars showed to in some cases have a surprisingly large impact on the outcome of the measurements. This can be explained by the antiroll bar being vulcanised in its bushing ad thus acting as a spring element. The study of this effect is explained further in Section 4.1.2.

- **How well do OMs generated from a VI-CarRealTime model based on K&C measurements correlate with OMs obtained from physical testing?**
  Comparing the results from simulations of the virtual vehicle models with the results from the physical testing yields rather varying results. Some metrics show highly accurate results, others a larger difference. In most

cases, the reason for the differences is however known. This is explained more thoroughly in Section 4.3.

- **To what extent can the performance of vehicles for which a virtual multi-body dynamics vehicle model is not available, be assessed from vehicle models based on K&C measurements?**
  Obtaining the measurements from the kinematics and compliance rig and generating a virtual vehicle model turned out successfully. A vehicle model containing only the data possible to measure in a kinematics and compliance rig is however far from complete. Knowledge and data from systems that are not possible to obtain from the kinematics and compliance rig is required which can cause some potential issues if no virtual multi-body dynamics model is available for the vehicle. The data required to generate a fully functioning model in VI-CarRealTime is described in Appendix A.

- **How well does a SA performed in a MBDS using a vehicle model based on K&C measurements correlate with a SA performed in the same physical vehicle?**
  Of the handling characteristics assessed during the physical and virtual subjective assessments, 94% changes in the same direction, with these showing an average deviation of 6.3 percent points. The steering characteristics assessed during the physical and virtual subjective assessments show a 78% change in the same direction, with these having an average deviation of 18.7 percent points.

5.2 Future work

- Perform the subjective assessments with more drivers participating to allow for a statistically more significant result.

- Perform the virtual subjective assessment before the physical one to study how swapping the order might affect the results.

- Improve the steering model used in the driving simulator to resemble a more realistic behaviour.

- Perform the subjective assessments on more tracks than just Handling track two to allow for a more varied evaluation environment.

- In the kinematics and compliance measurements, measure single compliance with strapped wheels in all three bounce levels to be able to generate more accurate vehicle models.

- Include more steering and handling characteristics in the study for a broader analysis base.

- Include ride characteristics in the study for a broader analysis base.

- Use more vehicles with minor differences during the subjective assessments to study how small changes in the vehicle models are experienced in the driving simulator.

- Generate virtual vehicle models using more physical tools than the kinematics and compliance rig for increased model accuracy.

- Use a vehicle model where all subsystems are carefully generated to be exactly as in the corresponding physical vehicle to ensure the accuracy of the vehicle model.

- Change also the motion cuing used in the driving simulator to study its effect on the outcome of subjective assessments.

- Perform a deeper study in how the amount of experience a driver has of using the driving simulator affects its usability as a digital development tool. A similar study can also be performed of how the level of experience a driver has of subjective vehicle dynamics evaluation in general affects how well that driver can evaluate a vehicle in the driving simulator.

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