Developing a Solution to Utilize Vehicle Dynamics Simulation Tools with a Motion Driving Simulator

Developing tools and methods to use vehicle dynamics simulation software with a driver-in-loop motion simulator to evaluate its use in the concept engineering phase

Final report in Automotive Engineering Project course

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CHALMERS UNIVERSITY OF TECHNOLOGY
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Automotive Engineering Project Report 2021:01

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Abstract

The project develops a method to integrate a CAE software (IPG CarMaker) vehicle model into the CASTER driving simulator. The vehicle dynamics performance is assessed by comparing CarMaker (CM) simulation data against the driving simulator data. First, a baseline generic passenger SUV was modeled on CM with K&C parameters that resemble a real-world vehicle. Then, the driving scenarios and maneuvers such as steady state cornering [6] and double lane change [5] were modeled on CM. Alongside this, IPG Movie and CM for Simulink were used to create real driving scenarios with accurate driving views. Next, the baseline vehicle was simulated in CM and driven on the simulator for both maneuvers. Driver input signals from the driving simulator were fed into CM through CM for Simulink to run the physics of the vehicle model. The output signals computed by CM were fed to the driving simulator to provide motion, audio and visual cues. The integration tool was developed to introduce it in the early phase of vehicle development. The software simulation provides good objective data but no subjective assessment. The use of DIL-simulator is a good method to add subjective assessment in vehicle dynamics development. After every maneuver run, driver's subjective assessment and rating was recorded. A statistical and graphical comparison of objective data between CM simulation and driving simulator drivers. Analysis of this data showed there is good correlation between results from CM simulations and the driving simulator. Then, vehicle parameter variations were made to understand the vehicle dynamics performance objectively and subjectively. For each model variation, a CM simulation and driving simulator test was carried out by multiple drivers. The vehicle specification variations were designed to produce changes in the steering feel and controllability. This indicates that the driving simulator is a viable supplement to prototype testing, however, further studies must be made to validate the preliminary conclusion. In reality, vehicle evaluations are performed by highly skilled test drivers with accurate subjective assessments. The project yields a tool to develop and evaluate the vehicle dynamics performance. In the hands of a professional driver, this will produce good subjective assessment that ties in with the objective metrics, thus validating it's use as a cost effective and time efficient tool to develop vehicles.

Keywords: Vehicle Dynamics, CarMaker, Simulink, Simulator, DIL, vehicle testing, subjective assessment, objective metrics, steady state cornering, double lane change, motion platform,

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Ajit Kumar Madhava Prakash, Anup Garje Mohankumar, Clive Rahul Misquith, Diler Paresh Ganatra, Irfan Ahmed Khan Soudagar, Jonas Johnsson, Gothenburg, Month 2020

Abbreviations

Abbreviation	Description
ARB	Anti Roll Bar
CAE	Computer Aided Engineering
CASTER	Chalmers Automotive Simulator Technology Education Research
CM	CarMaker
CoG	Center of gravity
DIL	Driver in-Loop
DLC	Double Lane Change
DOF	Degree Of Freedom
DS	Driving Simulator
GUI	Graphical User Interface
OM	Objective Metrics
SA	Subjective Assessment
SSC	Steady State Cornering
SUV	Sports Utility Vehicle
SWA	Steering Wheel Angle

Contents

1

Introduction

1.1 Background

In the last couple of decades, CAE simulation tools have been highly effective in the vehicle development process. These tools have proved to be cost-effective and give shorter lead time by providing robust system solutions. However, these tools have a limited capacity to understand the interaction between human driver and the vehicle. The perceived behavior of the vehicle through the driver feedback is also absent. A computer-controlled driver cannot give feedback on the driving feel of the development vehicle in the CAE simulation. So, simulating the scenarios and maneuvers with a driver in the loop enables the engineers to subjectively assess the characteristics of the vehicle and also it enables simulations for higher risk scenarios and maneuvers. Meanwhile, the integration of CAE and driver in loop tools for the early phase of chassis development in the automotive industry have proved as a good fit over the years. It eliminates the cost and time involved in building a prototype and implement changes into the prototype during the vehicle development phase.

1.2 Problem description

Simulation tools enable engineers to make better conceptual designs as well as engineering solutions. However, it hasn't been possible to replace actual prototype testing in the early stages of vehicle development. This is due to a lack of physical and tangible feedback, since the simulation is only virtual. This project intends to integrate vehicle dynamics simulation tools and a Driver-in-Loop simulators to improve the vehicle development process. An accurate integration will allow engineers to make major changes in vehicle models quickly unlike in real prototypes. Problems arising due to the unpredictability of weather, road surface during outdoor testing can also be easily eliminated. Safety issues when testing unreliable and prototypes in early stages of vehicle development are also eliminated since the tests can be stopped immediately and the wayward parameters can be tweaked instantly. This will considerably reduce lead times and cost of manufacturing the prototype while allowing engineers to objectively quantify and then subjectively verify the vehicle model during development.

1.3 Goal statement

To develop a method that will investigate to what extent can virtual simulation and Driver-in-loop simulator be used for passenger vehicle development for cost and time reduction.

1.4 Objective

The primary goal of this project is to develop a method of utilizing IPG CarMaker's and Cruden's Ephyse Simulink libraries and integrating it into CASTER's DIL motion simulator. Additionally, this project will help us in finding out the extent to which IPG CarMaker software can be used in model optimization and thereby understanding the changes in driving experience on the motion platform. A set of different maneuvers and statistical tests will be carried out in order to understand the relation in results between virtual simulations and Driver in Loop tests. The segment of vehicle in focus will be a generic vehicle model based on a Sports Utility Vehicle since the vehicle dynamics characteristics are profoundly perceived with modifications made to specifications. The objectives are extended to obtain a subjective assessment from the driving simulator tests and compare them with the changes made in vehicle specifications.

1.5 Deliverables

- A vehicle model in the selected vehicle segment, used in all significant offline and online simulations
- Specify maneuvers that will be used in the simulations
- Transfer and integration methods of simulation model to the driving simulator
- Simulation results of vehicle dynamics performance to be used for the assessment of integration into the simulator
- Quantitative comparison of vehicle dynamics performance between simulation model and driving simulator
- A set of parameter variations that will change the dynamics of the vehicle which can be perceived by the driver. These will be used for the development of vehicle dynamics performance in the on the driving simulator
- Develop chassis engineering solutions in the driving simulator through driver feedback
- A set of tests that will verify if the drivers will experience a change with varying the parameters and a statistical analysis of the feedback
- Description of the tools and the methods

1.6 Limitations

- One vehicle model, a generic SUV model
- No commercial vehicles (trucks and buses) will be considered

- Limited access to real world test data for vehicle virtual model verification
- Standardized maneuvers that are used in the industry
- Repeatability of the maneuvers by the drivers may vary
- CASTER DIL simulator with existing motion queuing
- Maneuvers suitable for this type of simulator
- No clinic will be held, drivers only include project members
- Performance evaluations based on the chosen tire model

1.7 Social and ethical aspects

Vehicle occupant safety is a vital part of the development of a new vehicle. Vehicle dynamics aspects are a key part in keeping a vehicle safe and on the road. Maneuvers such as collision avoidance for eg. double lane change and the moose test can upset the car in dangerous ways. Testing these maneuvers in a driving simulator removes the risk to the test driver.

Making the development process less costly for the manufactures can allow the car to be sold at a lower price point, and therefore make modern and safer car accessible to a larger demography. Safer vehicles will safeguard the lives of many and reduce the cost to governments associated with road accidents.

2
Theory

2.1 Vehicle dynamics development

Vehicle Dynamics Engineering plays a vital role in the development process at automotive companies. Vehicle dynamics is mainly concerned with handling, steering and ride comfort. The vehicle dynamics department in most automotive companies tend to follow the 'V-cycle' development approach, right from concept development followed by design to system integration and validation of the desired concept. The performance requirements for the vehicle, classified by sub-systems, are initially bench-marked and the concepts are developed thereafter. Over the years, the development process has been overhauled with the help of computers and software tools. These generally simplify the work by providing a simulation model of subsystems that reduce the dependency on fabricating physical systems for tests. Hence, a lot of time and thereby cost, in order to develop the system solutions can be saved. Control modules like Drive-line Control, Anti-lock Braking System, Electronics Stability Control, etc., needs to be tested for its robustness before integrating into vehicles. These modules are integrated in a hardware and tested in loops to arrive at the desired outputs. This iterative process allows the engineers to develop and implement the subsystems in the control modules.

2.1.1 Maneuvers

The maneuver is a driving input that results in a vehicle's motion in a certain situation or scenario. The interaction between the vehicle and the road during the motion is influenced by the driver maneuver inputs. Maneuvers are generally classified into open-loop control and closed-loop control, based on test requirements, nature of desired vehicle motion and state. An open-loop maneuver can be seen as an input signal or driver control such as steering wheel angle, accelerator pedal position, and brake pedal position to be operated as per the maneuver guidelines in sequence as a function of time. During an open-loop maneuver, the driver input signal is independent of the factors like driver skills, so driving robots and thus driver input are controlled and programmed to the maneuvers. Open-loop maneuvers does not represent most of real-life driving but still allows for recording of relevant data to develop the vehicle. A closed-loop maneuver can be seen as driving, where vehicle input signals are controlled by the driver. They better represent real-world driving situations. This type of maneuver helps to obtain a subjective assessment of the development vehicle. A closed-loop maneuver is affected by the driver's response to vehicle dynamic characteristics such as steering wheel torque, lateral acceleration, and other factors that affect the drivers perception of vehicle control and stability. The maneuvers used in this project according to ISO standards are:

- Steady State Cornering (SS-ISO 4138:2012)[6]
- Double Lane Change (SS-ISO 3888-2:2011)[5]

ISO standard maneuvers gives the technical specification for testing the vehicle performance on a test track. The technical aspects of the testing are reviewed and improved to support the vehicle performance and handling quality. ISO maneuvers are used because they specify the scope for vehicle variables to be measured, desired route or path to be followed and test parameters which are defined by the vehicle test team. This gives the project several testing scenarios to develop the vehicle model and obtain a desired handling characteristic.

2.1.1.1 Steady-state cornering (SS-ISO 4138:2012)

Steady-state cornering is a standard testing procedure followed to evaluate vehicle handling performance and understand its lateral dynamic behavior. The steady-state cornering test has three different test methods: constant radius, constant steering wheel angle, and constant speed tests with discrete turn radii and discrete steering wheel angles. The driver must follow the standard driving guidelines of ISO 4138 [6] to obtain quality data during the maneuver. A constant radius test method helps to understand the directional-control response characteristics when the vehicle is driven on the desired circular path at the given test speeds, starting from lower test speed and then to attain steady-state at each test speed. The vehicle's longitudinal velocity is increased until the vehicle cannot attain steady-state or stay on a constant radius. The steady-state cornering test radii (Rp) are 100m and 40m; the vehicle is tested in both turning direction to evaluate complete lateral dynamic behavior. The vehicle deviation from the desired path should be within ± 0.5m to complete a constant radius test. The driver should have a constant steering wheel angle and fixed throttle position for at least 3 seconds to demonstrate a steady-state cornering maneuver. The baseline spec vehicle characteristics are used as the reference to evaluate the modifications made on the vehicle. The data collected in the maneuver are used to quantify the change in vehicle performance. It consists of measured vehicle quantities that are affected by the changes made in the vehicle specification. The measured vehicle signals during a steady-state cornering maneuver are in table 2.1.

Table 2.1: Measured signals in steady-state cornering maneuver.

	Measured Signals
1	Longitudinal velocity
2	Lateral acceleration
3	Yaw angle
4	Yaw rate
5	Vehicle roll angle
6	Steering-wheel angle
7	Steering-wheel torque
8	Side-slip angle

2.1.1.2 Double lane change (SS-ISO 3888-2:2011)

The double lane change is a transient dynamic maneuver that involves quick steering wheel input. Here, the vehicle moves from the initial lane to another lane parallel to it. Then after clearing the parallel section the vehicle is steered back to the initial lane. This is done in order to measure the vehicle's lateral handling characteristics. The test is limited to passenger cars and commercial vehicles up to a gross vehicle mass of 3.5 tons. The test is done on a test track marked with pylon cones kept parallel to make lane sections.

The track dimensions are as shown in Figure 2.1. The total track length as well as individual section lengths are fixed whereas the track width 'b' is function of vehicle width. These dimensions are as shown in Table 2.2. The section 7 is referred to as the Lane offset in said table. The number 6 defines the driving direction.

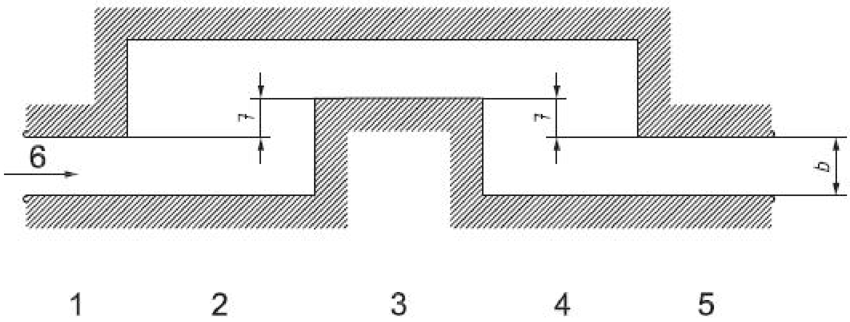


Figure 2.1: DLC track layout

Table 2.2: DLC track dimensions

Section	Length (m)	Lane Offset(m)	Width, b (m)
1	12	-	1.1 × vehicle width + 0.25
2	13.5	-	-
3	11	1	vehicle width + 1
4	12.5	-	-
5	12	-	1.3 × vehicle width + 0.25, min 3

In order to carry out the test procedure by ISO standard, the driver was to drive the vehicle by entering Section 1 with the highest gear position that guarantees a minimum engine speed of 2000 rpm. At 2 m into Section 1, the throttle and brake pedals are released and the remaining distance is driven in this state. For reproducible results, the initial velocity of the vehicle at the start of the maneuver was maintained at 50 and 60 km/h. The signals of interest are as shown in Table 2.3.

Table 2.3: Measured signals in double lane change

S.No	Measured Signals
1	Steering wheel angle
2	Steering wheel torque
3	Yaw rate
4	Roll Angle

The test run is considered complete when none of the cones have been displaced during the maneuver. ISO 3888-2:2011 guidelines do not recommend objective metrics for testing a closed-loop maneuvers. However, for the purpose of correlating the results from the simulations with the results from the driving simulator, some objective data were reviewed (Note that subjective data are not directly comparable with objective data). The subjective assessment were used merely as indicators of the change in vehicle behavior. This would prove helpful in determining the effect of changes in suspension parameters, whether these changes are as expected, and thus validating whether or not the simulator could produce desired motion in the real world so that a vehicle design engineer could sense these while tuning the virtual model.

2.1.2 Objective and subjective measures

In the vehicle development process, the characteristics and performance of the vehicles are designed to meet market and regulatory requirements. Engineers require good evaluation tools i.e. objective metrics and subjective assessment to guide the development using vehicle sensor data and driving feel feedback. An objective metric is a maneuver specific physical measurement, that is collected and calculated from each test. This provides a measure of physical quantity to evaluate the performance of the vehicle. Meanwhile, a subjective assessment is data that is provided by the test driver to understand the driving feel and characteristics. Subjective assessment consists of test drive experience which is rated on a 1 to 10 scale and a questionnaire that is focused on understanding effect and change in the driving feel for the changes made during the vehicle development [7].
The objective metrics and the subjective assessment correlation allows an engineer to understand the desirable vehicle dynamics performance for the vehicle development. This helps to define the vehicle characteristics through objective metrics instead of chasing a specific level of subjective assessment [3].

2.2 Virtual tools for vehicle development

2.2.1 Offline simulation

Offline simulations utilizes a driver model which gives the vehicle inputs instead of a human driver. This type of simulation is best suited for well defined objective metrics that are open loop in it's nature. However, closed loop maneuvers such as double lane change can be run here as well. The main benefit of offline simulations are that they can be utilized for mass testing of different parameters where the engineer specifies a range of parameters, conditions of failure or success and receives a test report back.

2.2.2 Driving simulator testing

There are many different types of driving simulators and ways to run a simulation, each with their characteristic benefits and drawbacks. Deciding on what type of simulation to use is crucial to produce good results. Driver In the Loop simulators are in nature more expensive and can only run one test at once. But, they can be used to derive/tune driver models by recording driver input and vehicle response. The recorded data can be used to train a neural network driver model with machine learning. Driving simulators main benefit is the realistic driving input, possibility for subjective assessment and all types of testing where the human needs to respond to an event.

2.2.2.1 Desktop simulator

Desktop simulators are useful when a human driver is needed to provide inputs to the simulation, but the level of feedback that the driver needs is low. Characteristic use cases are fuel consumption testing, reaction time testing, driver awareness testing (eye gaze).

2.2.2.2 Fixed-base motion platform

This category of simulator encompasses up to 6-DOF simulators where the driver sits on a platform that has a limited range of motion. For example, CASTER has an E2M 640 mm stroke platform. The limited stroke of the platform limits the platform to short events of G-forces such as bumps and rotations such as roll, side slip yaw, heave, squat. Sustained G-forces such as braking, accelerating and cornering cannot be readily produced with the small range of motion. However, by tilting the platform and using gravity to fake lateral/longitudinal g-forces is possible to some extent. This creates a dilemma for the motion queuing engineer that must decide if staying true to the outputs from the vehicle model is more important than imposing fake movements to use gravity as a G-force. The discrepancy between these comes from that the rotation angles created by the vehicle model are much smaller than those created by the motion queuing algorithm to simulate G-forces.

2.2.2.3 Moving-base motion platform

When the purpose of the simulator is to allow the driver to experience sustained G-forces and reduce the amount of damping the G-forces, a full room scale simulator is needed. This type of simulator is the most expensive and technically advanced since it has the most moving parts of all four categories. It takes the moving platform with 6-DOF and puts that on a platform that can move in the X-Y plane. The upper 6-DOF platform can usually rotate along the Z-axis of the lower platform.

2.2.3 Creating a realistic experience

2.2.3.1 Sensory input

Sensory input to the driver in a driving simulator can be categorized into three main categories, haptic, visual and auditory. Visual feedback is what a driver sees on a screen or through HMI devices in the cockpit, auditory feedback is sound ques such as tire screech or warnings, haptic feedback encompasses the steering torque and movement of a motion platform.

2.2.3.2 Timing/syncing

The synchronization and delay of sensory feedback to the driver is critical to create a good simulation that is realistic. It would be a jarring experience if the delay between a slide starting on the screen and the yaw movement of the platform is to large, and might induce motion sickness and difficulty to control the vehicle since the driver receives erroneous feedback.

2.2.3.3 Motion queuing

Motion queuing is the process of translating the movement and accelerations of vehicle model to movement and accelerations of a motion platform. Since the motion platform is constrained in it's range of motion while the vehicle model is not, there must be some decision on what excitation that are relevant for the simulation at hand. There must also be some filter that returns the motion platform to its center position.

3

Methods

3.1 Vehicle specifications - generic SUV

Choosing a good baseline vehicle specification is the first step in making an accurate and high fidelity model for simulations. A generic SUV vehicle model was chosen as the simulation model to be run on IPG CarMaker. The model's sensitivity to parametric changes was observed in a basic handling test on IPG CarMaker. It is necessary to chose parameters that can be changed quickly that give a notable difference in the metric we observe. The model's fidelity was tested on 42 m steady state cornering scenario from the CarMaker product examples and as well as highway driving test. It was observed that the variation in observed metrics were in accordance theoretically defined outputs. The tire data and a kinematic geometry file is already provided by CarMaker for use in this project. However, other parameters were identified and tested on a handling test. The parameters that the model is sensitive to were listed in table 3.1 and were used for tuning the different models as well as to check for correlations. Other kinematic parameters and vehicle dimensions are listed from the CarMaker model in Appendix A

Table 3.1: Tuning parameters - baseline vehicle specification

Parameter	**Static**	**Units**
Front Spring Stiffness	40000	N/m
Rear Spring Stiffness	35000	N/m
Front Damper Stiffness	2500 Compression - 5000 Rebound	Ns/m
Rear Damper Stiffness	3000 Compression - 6000 Rebound	Ns/m
Front ARB Stiffness	17687	N/m
Rear ARB Stiffness	15508	N/m
COGz	0.73	m
Weight Distribution	50F-50R	-

The parameters listed above were expected to show tangible and observable changes in vehicle behavior on the simulator as well as on CarMaker simulations, helping to create a correlation between objective metrics and subjective assessment. Here, the weight distribution was kept ideally at 50-50 to minimize the effect of static weight distribution on the baseline model. This is done to create a strong baseline for subjective assessment and objective metrics against other vehicle specifications (one of the parameters for baseline vehicle specification ref 3.5. Changing one of the tuning parameters will result in a change of the vehicle's behaviour for the maneuver from the initial baseline vehicle. There will be observable and tangible change in driving feel, steering response, under-steer or over steer characteristics, lateral and longitudinal acceleration and body roll. The measured signals to study a vehicle characteristic for a steady-state cornering test is mentioned in table 2.1.

how and where to input these parameters, sub-systems (2-DOF model for suspension systems, Gen angle model for steering)

3.2 IPG CarMaker- simulation setup

3.2.1 IPG scenario editor

After choosing the vehicle specification for evaluation, the driving scenarios or test track for SSC and DLC are created. The scenario editor interface in CarMaker provide necessary tools to create the test track with ease. The SSC test track is created using multiple lane with radius 100m and the inner lanes with a width of 10m as shown in figure 3.1. The DLC test track is created to the required dimensions as given in 2.1 using pylon markers and provide the driver visual input of the DLC section boundaries as shown in the figure 3.2. The driver route is then selected based on the direction of turn, testing radius for SSC and entry speed limits for in DLC. Additional features such as road paintings, road markings and pylon markers were used to create lanes and radius info, trees and geographic elevations are added to provide the DIL-Simulator a near realistic experience to get the driver involved in the driving environment. But, the additional features are added to give realistic driving experience on driving simulator as shown in 3.6a, while this has no effect on CarMaker driver model or simulation.

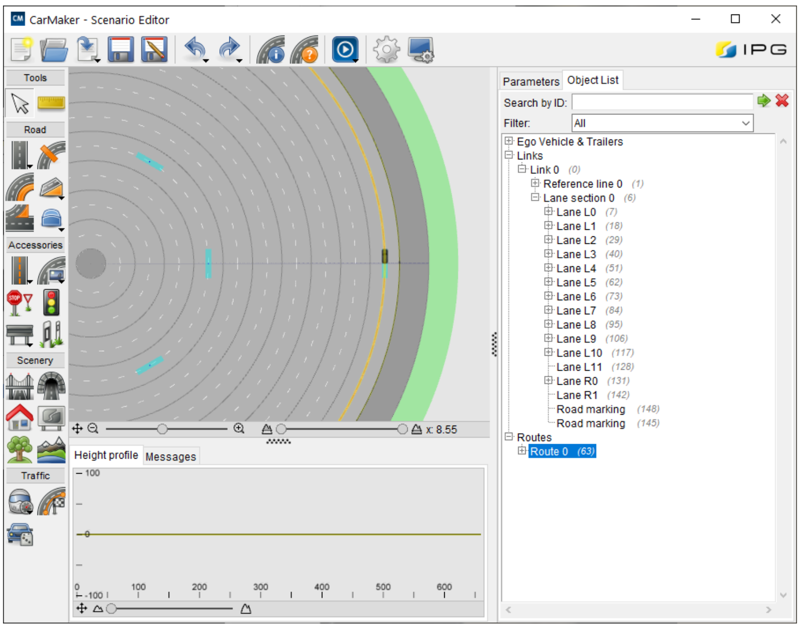


Figure 3.1: Steady-state cornering test track development

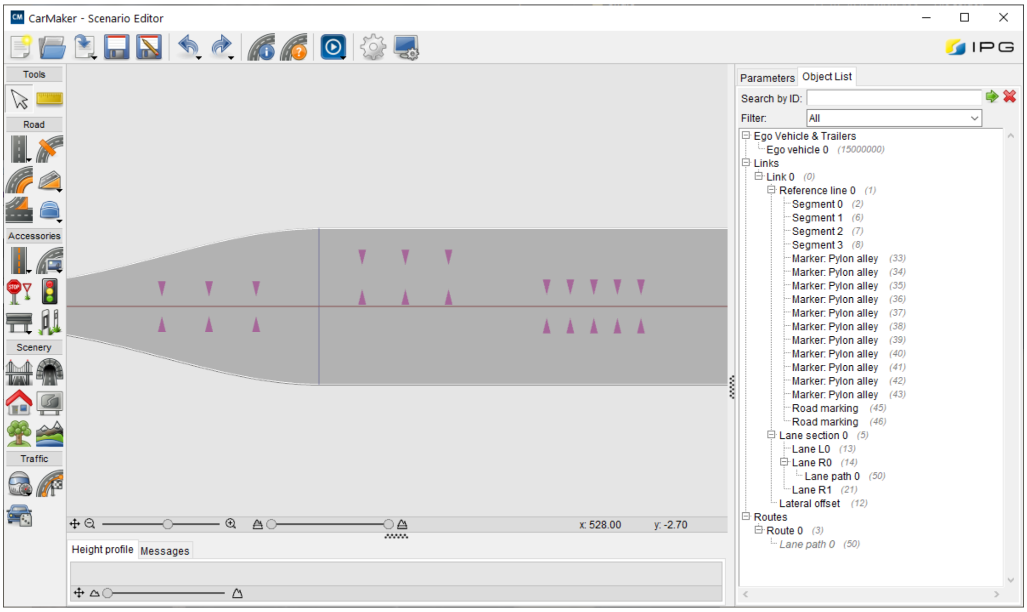


Figure 3.2: Double lane change test track development

3.2.2 Maneuver and driver parameter setup

The maneuver is defined on the maneuver GUI, the maneuver definition is similar to driving guidelines and can be used to set certain driving conditions for the CarMaker driver such as speed, maximum allowable route deviation, gear selection, end conditions to follow next driving guidelines and also the open loop control commands controlling the driver steering angle input and accelerator pedal position. The driver parameters are set according to the test requirements like allowable longitudinal acceleration and deceleration, lateral acceleration. Also, driver knowledge from CarMaker product examples have been used in the maneuver definition and setting driver inputs as per ISO driving guidelines. The maneuver and driver parameter GUI enable easy open loop control input for SSC and closed loop control for DLC with existing driver knowledge and parameters.

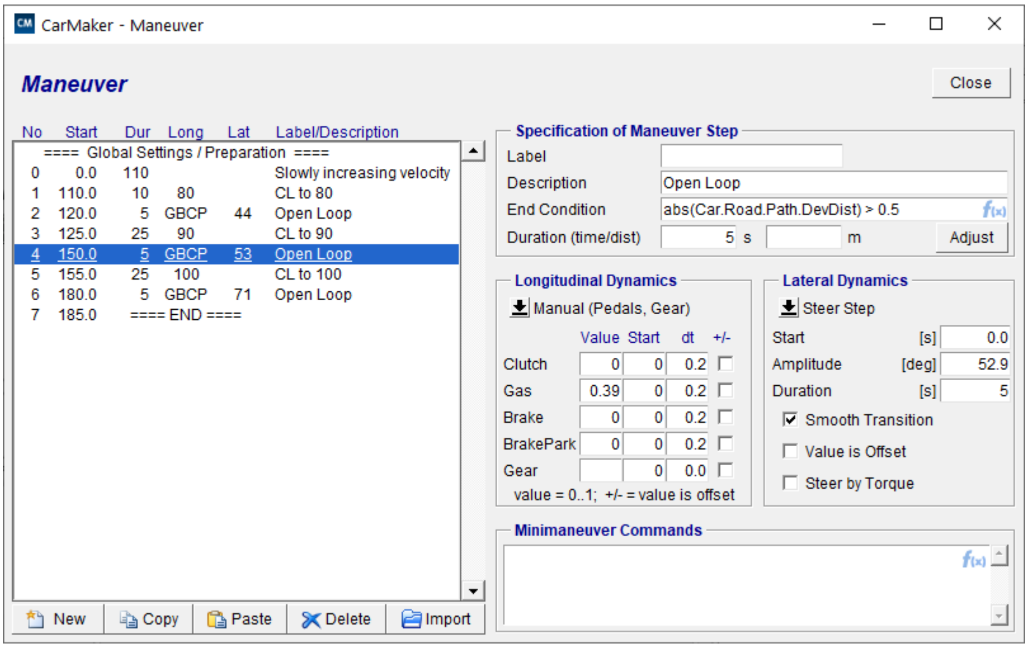


Figure 3.3: Steady-state cornering maneuver definition

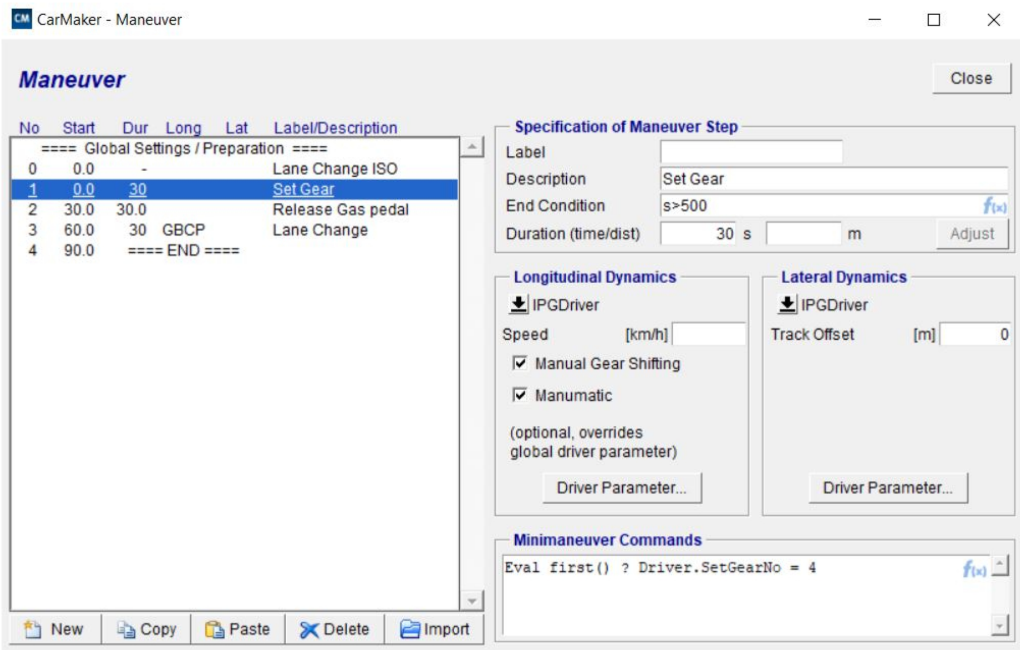


Figure 3.4: Double lane change maneuver definition

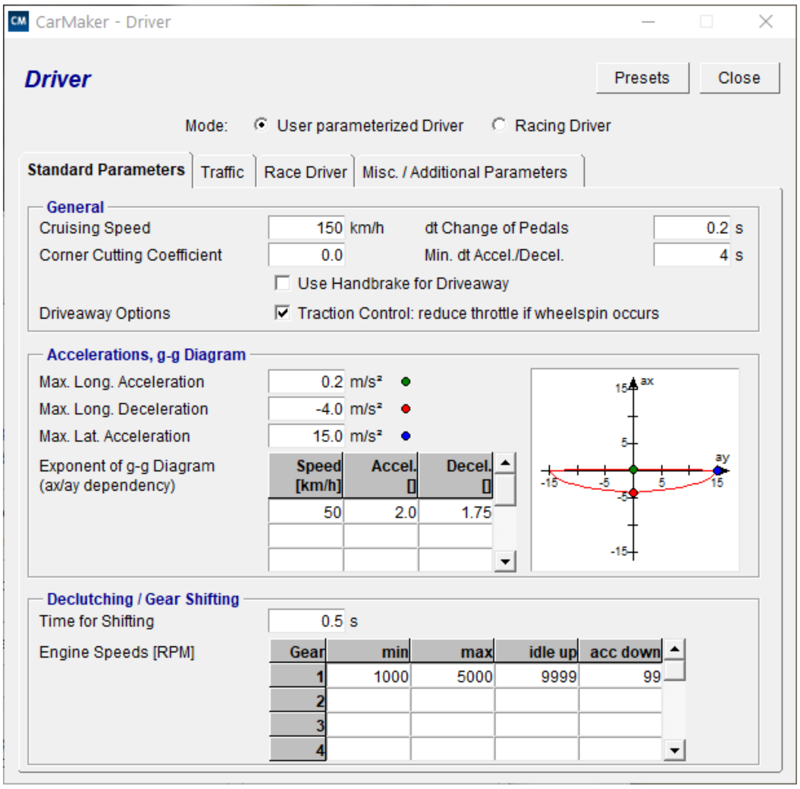


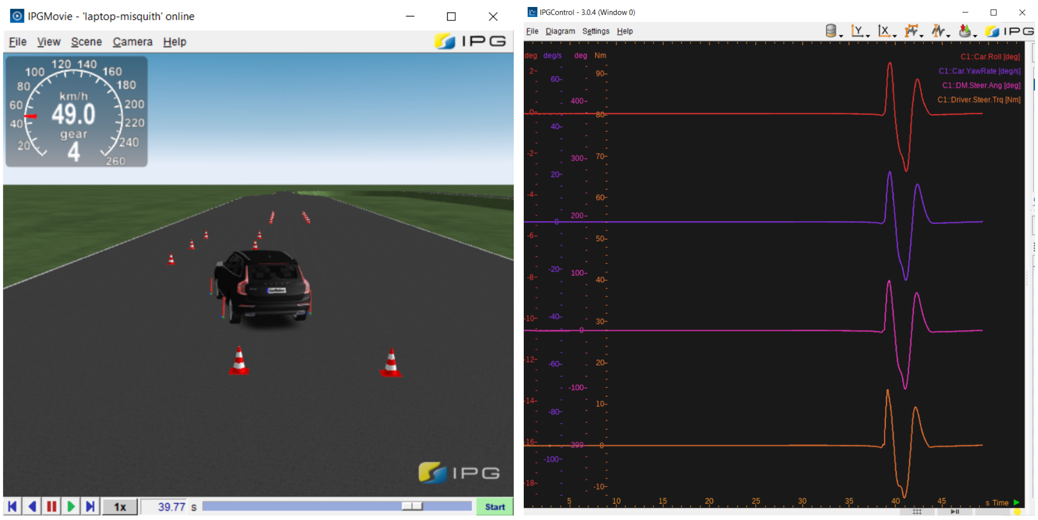
Figure 3.5: Steady-state cornering driver parameter

3.3 IPG CarMaker simulation

The CarMaker simulation setup is complete with vehicle model as discussed in section 3.1, scenario or testing track in section 3.2.1, maneuver definition and driver parameter in 3.2.2. The simulation is now ready to run and is observed on IPG Movie. The vehicle data or measured signals from maneuver simulation is shown on the IPG Control interface and this interface provides the required signals and variables live during the simulation. These signals are then extracted in .xls format for data processing.

(a) IPG Movie SSC simulation (b) IPG Control SSC signals

Figure 3.6: IPG Movie and IPG Control, SSC scenario



(a) IPG Movie DLC simulation (b) IPG Control DLC signals

Figure 3.7: IPG Movie and IPG Control, DLC scenario

3.4 Driving simulator integration

Chalmers have had a motion DIL simulator since 2015 and uses it in various courses and projects. The motion simulator is maintained by the student organization CASTER [1], CASTER gives students and Chalmers the opportunity to develop and explore new areas of vehicle dynamics and racing. This allows all Chalmers students to interact with a industry grade Cruden simulator used by other respectable organizations [2]. An overview of the data and information flow is pictured in figure 3.8.

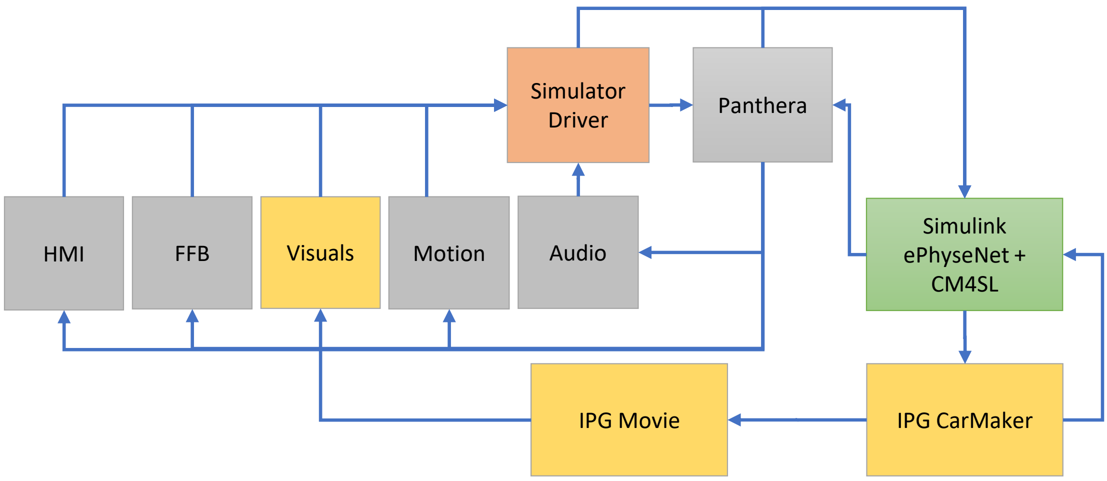


Figure 3.8: DIL simulator data flow

3.4.1 Cruden simulator

The Cruden simulator uses ePhyseNet Toolbox to communicate the CarMaker vehicle model in a Simulink interface. The Simulink blocks on the ePhyseNet Toolbox are as follows:

- Simulator – Platform Input: This block contains signals from the simulator steering, accelerator, brakes, clutch, gears and motion of the simulator platform in 3-dimensions
- Simulator – Panthera Input: Processes the signals from the Simulator – Platform input block and converts them into measurable physical quantities
- Simulator – Panthera Output: Takes simulated data quantities from the vehicle model and converts it into visible signals driver can see and hear
- Simulator – Platform Output: Takes vehicle dynamics metrics from the vehicle model and sends it to the motion platform for conversion to movement in the platform – Panthera output block into quantities that are comprehensible by the driver

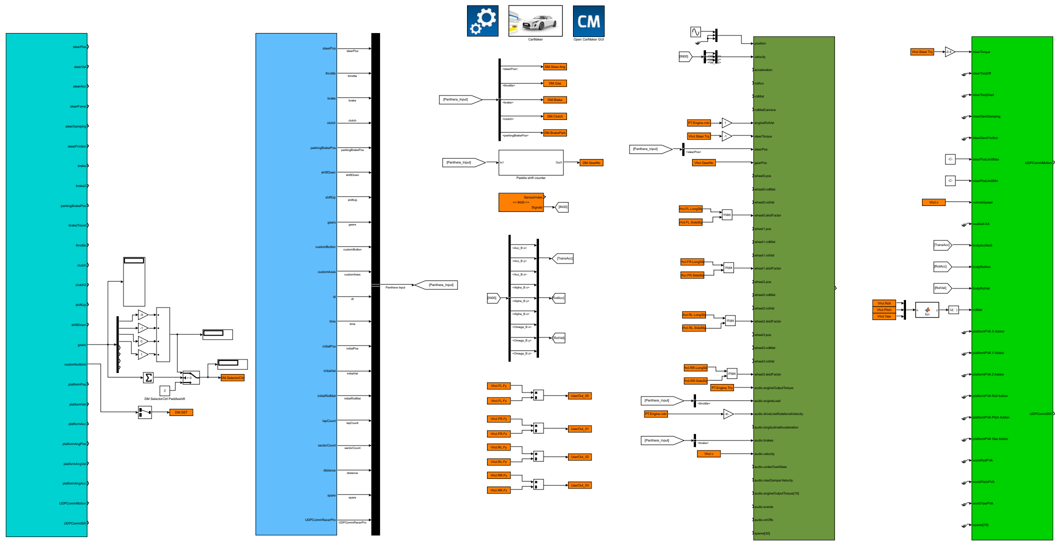


Figure 3.9: Simulink model integrating CM and ePhyseNet (vector image)

A larger version of figure 3.9 can be found in appendix C.

3.4.2 CarMaker for Simulink (CM4SL)

The vehicle model on IPG CarMaker can be accessed through CarMaker for Simulink (CM4SL). This provides us the opportunity to interact with the signals within the vehicle model. The various sub-systems in the CM4SL are as follows:

- CM First: External periphery input – output signals, environment signals
- DrivMan: Signals from the driver which are inputs to the vehicle control
- VehicleControl: Control inputs to the vehicle model, ADAS, ESC, ABS
- Vehicle: Vehicular sub-systems models (Steering, Suspension, Powertrain, Brakes. . .)
- CM Last: Outputs from the simulation

Connecting the correct signals to the correct variables is crucial to provide good simulation integration. Driver inputs from the motion platform is input to CarMaker through the DrivMan interface per the programmers guide [4]

3.4.3 Audio integration

The Panthera simulator software is used for sound since IPG-movie does not have an audio engine to create auditory ques. The table 3.2 consists of the signals that were synchronized in order to have the desired audio output.

Table 3.2: Audio integration signals

Input Signals		Output Signal	Description
Panthera	CM4SL	Panthera	
-	PT.Engine.Trq	audio.engineOutputTorque	Engine audio based on engine torque
throttle	-	audio.engineLoad	Engine audio based on engine load
-	PT.Engine.rotv	audio.driveLineRotationalVelocity	Driveline audio
brake	-	audio.brakes	Audio under braking
-	Vhcl.v	audio.velocity	Wind noise based on vehicle speed
max(latslip,longslip)	-	wheel[x].slip	Tire skidding/squeal

Table 3.3: Visual integration signals

Input Signals		Output Signal	Description
Panthera	CM4SL	Panthera	
-	PT.Engine.rotv	engineRotVel	Engine speed (rpm) on the screen
-	Vhcl.v	vehicleSpeed	Vehicle speed display on the instrument panel
-	Vhcl.GearNo	gearPos	Gear position display on the instrument panel

3.4.4 Graphics integration

We have decided to use IPG Movie for our visualization of the driving environment, this allows us to use the IPG scenario builder to create our test runs. A drawback to this approach is that IPG Movie is not intended for this type of use case and lacks some convenient features that could be expected if this was its intended use case.
We have found that the supplied 3D-model is quite low detail with low resolution textures and low polygon models on the interior. The steering wheel model cannot be removed, neither does it turn with the steering wheel angle input. There is no seating position frame of reference defined for the vehicle models, therefore all camera settings must be defined to the car main reference, where a drivers head would be in relation to that changes depending on the car. This might be something that could be addressed by defining the drivers head position for every vehicle model that would run in the driving simulator and then reference all camera settings to that reference frame
We found that having reflections is not feasible with our computer hardware since IPG Movie seems to be doing all reflection calculations on the CPU, which in turn reduces the frame rate to unfeasible levels.
Apart from the IPG movie visuals on the screen, the instrument cluster on the driving simulator was also used to give visual cues to the test driver. Details of the signal origin and destination is illustrated in the table 3.3.

3.4.5 Motion platform integration

The motion platform applies supplied inputs as if they are in the drivers head. Where you then place your inertial sensor in the vehicle model is then up to us. Placing it in COG or approximately in the drivers seat creates slightly different experiences, especially in non steady state motion.
The motion platform provides steering wheel angle as an output to the vehicle model and uses steering wheel torque as an input to the platform, this means that the CarMaker vehicle model must use the GenTorque steering subsystem.
Since the CASTER motion platform is configured for use with a paddle or H-pattern shifting and not with an drive mode selector we opted to use the H-pattern shift to act as our drive mode selector. 1st is park, 2nd reverse, 3rd neutral and 4th is drive. An alternative strategy could be using the paddle shift in the following configuration; reverse, park, neutral, drive. There is no parking brake switch neither, therefore we chose to leave the h-pattern shifter in park when changing scenario.

3.5 Modification of vehicle parameters

In early chassis development phase, the dimensions of the vehicle are already chosen and locked. However, the tuning parameters such as spring stiffness, roll stiffness, suspension geometry are in the development phase. Here, different suspension tuning specifications are assessed objectively and subjectively to improve the vehicle performance to meet the targets. Six variations in vehicle specification were created for testing objective metrics, subjective assessment and correlation between them. For each vehicle specification, only one parameter was changed, keeping everything else the same as baseline vehicle specification in table 3.1. As a starting point, the change of each parameter was approximately 20%, relative to the baseline specification, to check for sensitivity of the motion platform and thus the driver.

Table 3.4: Vehicle specification variation over modified general parameters

Specification	**Parameter**	**Direction**	**Value**	Unit
Spec1/ M1	Spring Stiffness	Front	32000	N/m
		Rear	45000	N/m
Spec2/ M2	Spring Stiffness	Front	45000	N/m
		Rear	32000	N/m
Spec3/ M3	Anti Roll Bar	Front	12687	N/m
		Rear	15508	N/m
Spec4/ M4	Anti Roll Bar	Front	15687	N/m
		Rear	12508	N/m
Spec5/ M5	Damper Stiffness	Front	3000 Compression 6000 Rebound	Ns/m
		Rear	3600 Compression 7200 Rebound	Ns/m
Spec6/ M6	Damper Stiffness	Front	2000 Compression 4000 Rebound	Ns/m
		Rear	2400 Compression 4800 Rebound	Ns/m

3.6 Simulator testing

3.6.1 Steady-state cornering - 100m and 40m

The ISO:4138 recommends the standard radius of path of 100m and 40m. This maneuver is tested to understand the directional response characteristics at different speeds on the constant radius test paths at steady states. The 100m radius test evaluates the steady state behavior of the vehicle at 80, 90 and 100 km/h, while 40m radius path evaluates the vehicle behavior at lower speeds such as 55, 60 and 65 km/h.
The steady state cornering maneuver for the CarMaker simulation and simulator test are done on a flat track with a friction of 0.8. Initially, the steady state cornering is run with the baseline vehicle on the simulator. After the driver gets to feel and

understand the performance of the baseline vehicle, the four specification variations are driven twice for each driver and the output signals are recorded. Then after the driving session, the vehicle specifications are subjectively assessed as shown in fig 3.10.

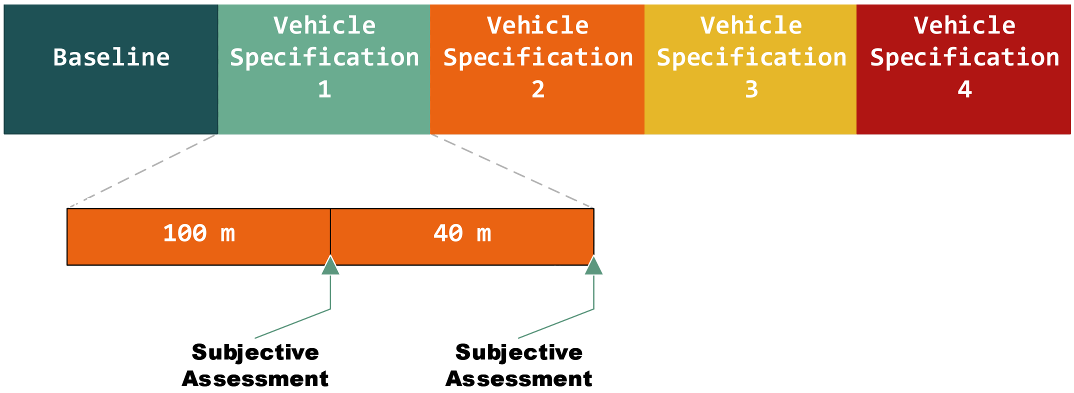


Figure 3.10: Testing procedure for SSC

Table 3.5: Vehicle signals extracted during SSC simulator testing

Vehicle Signals	**Unit**	**Usage**
Gas	-	Steady state/validity check
Body roll	rad	Correlation & steady state
Side Slip angle	rad	Correlation
Steering Wheel Angle	rad	Correlation & steady state
Steering Torque	Nm	Correlation
Yaw	rad	validity
Yaw Rate	rad/s	Steady state
Lateral Acceleration	m/s^2	Steady state
Longitudinal Velocity	m/s	Steady state/validity check

The test data from the simulation is saved for every test run with timestamps for 3 seconds where the driver steering angle input, longitudinal velocity and accelerator pedal position is kept constant for steady state maneuver as recommended by the ISO standards.The measured vehicle signals are listed in the above table 3.5.

Table 3.6: Objective metrics for steady state cornering maneuver evaluation

Objective Metrics
Side slip angle
Vehicle roll angle
Steering wheel angle
Steering wheel torque

The objective metrics is evaluated at the points mentioned in the above table 3.6 at the steady state cornering test of constant radius 100m at speeds of 80, 90 and

$100km/h$ resulting in steady state lateral acceleration of 0.5g, 0.63g and 0.78g respectively. Similarly, at 40m constant radius test at 55, 60 and 65 km/h resulting in steady state lateral acceleration of 0.59g, 0.7g and 0.81g respectively. The correlation between CarMaker simulation data and simulator data are compared at these points to evaluate the fitness of the simulator integration.

3.6.2 Double lane change - 50 km/h and 60 km/h

The ISO standard for a double lane change specifies the track dimensions to be used based on the vehicle dimensions. Specifically, the length of the track sections are fixed, while the widths are modeled based on the vehicle width. The total length of the track is 61m. The following dimensions were used to model the double lane change track on CarMaker.

Table 3.7: DLC track dimensions (in metres)

Section	Length (m)	Lane Offset	Width, b (m))
1	12	-	2.5
2	13.5	-	-
3	11	1	3.0
4	12.5	-	-
5	12	-	2.9

The DLC was carried out at two speeds - 50 & 60 km/h. After the driver gets to feel and understand the performance of the baseline vehicle, the two specification variations are driven twice for each driver and the output signals are recorded. Also, after the driving session the vehicle specifications are subjectively assessed in fig 3.11.

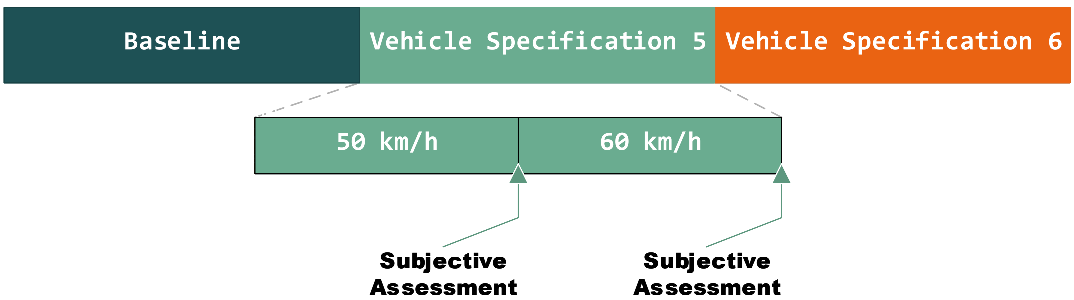


Figure 3.11: Testing procedure for DLC

The measured vehicle signals are listed in table 3.8. The correlation between CarMaker simulation data and simulator data for the baseline vehicle was done. This data would provide insight as to how close the real world driver was able to replicate the IPG Driver model.

Table 3.8: Variables measured during DLC testing

Variable	**Unit**
Gas	-
Body roll	rad
Side slip angle	rad
SWA	rad
Steering torque	Nm
Yaw	rad
Yaw rate	rad/s
Lateral Acceleration	m/s^2
Longitudinal velocity	m/s

3.6.3 Driving simulator testing

The baseline vehicle is first driven in city, highways and windy roads with the purpose to find the vehicle specification quirks that are hard to identify by looking at vehicle parameters and simulation results. Driving the vehicle allows the driver to quickly identify issues using intrinsic knowledge. Driving in the simulator is done using the tools developed in this project, with the same scenario and road definitions used for offline simulations with a driver model. This means that the difference is the driver in loop, 3 drivers are used to obtain the average values and to study the spread of the results, having more than 2 drivers enable unbiased statistical evaluation and to reduce the eventuality of erroneous results.
The maneuver specifications to be followed as per the offline simulations to provide results that can be compared and correlated to show that changes made to the vehicle specification can both be objectively measured and subjectively assessed.

3.7 Correlation coefficient

The vehicle signals measured during the offline CM simulation and driving simulator tests are compared to each other to find the correlation between them. One approach is to evaluate the correlation between the IPG driver and the 3 simulator drivers over the complete maneuver test to see that both the driver inputs result in expected output signals. The other method is to compare the data sets at each steady state cornering accelerations to find correlation relationships in non linear behavior characteristics region in the measured signals. This is quantified with a correlation coefficient values that range from +1 to -1. Positive coefficient means that both the data set increase or decrease together and a negative coefficient means that one data set is increasing and the other data set is decreasing or visa versa, where $\pm$ 1 denotes the strongest possible relation and 0 denotes no relation between the two data sets.

3.8 Subjective assessment questionnaire

The subjective assessment is critical to understand the behavior of test vehicle. The vehicle handling performance is evaluated at the end of the simulator driving sessions. A set of question that is focused to quantify and rate the change in the behavior are answered at the end of each driving session.

The drivers used in the maneuver tests are not professional drivers and the rating of the vehicle behavior was challenging due to the lack of experience in using a traditional absolute rating scale. So, the subjective assessment had to be approached with a different method. A relative rating scale is therefore used instead of the absolute one, where the baseline vehicle is given a fixed rating of 5. Vehicle specifications that have more desirable behavior than baseline specification are rated above 5 and the undesirable behaviors are rated below 5. The cumulative rating of the vehicle specifications are also done.

The drivers were asked subjective questions that is concerned with the difference in the test vehicle's behavior with respect to the baseline vehicle. The larger the behavior difference felt in the test vehicle when compared to the baseline vehicle, a higher number is graded on specification difference scale. To summarize, the rating scale is concerned with desirable/undesirable behavior, while the specification difference is concerned with how large of a difference was perceived.

Table 3.9: Subjective assessment rating and specification difference scale

Rating	Scale	Specification Difference
Excellent	10	
	9	Strong
Good	8	
	7	Moderate
Fair	6	
	5	Some
Poor	4	
	3	Trace
Very Poor	2	
	1	Imperceptible

3.8.1 Steady-state cornering

The drivers were briefed on the vehicle characteristics that are to be evaluated during the test. The steady state maneuver gives some time to feel the changes made on the vehicle parameters during the maneuver and the difference in the vehicle handling behavior. Also, at the end of driving sessions the vehicle specifications are observed against driving experience from the baseline vehicle tested earlier in the steady state cornering maneuver.

Table 3.10: SA questionnaire for steady state cornering maneuver

Questions for rating and evaluating the vehicle specification difference
Does the steering torque feedback give the feeling of available grip?
Is the vehicle roll angle different when compared to baseline vehicle at the steady states?
Is the steering angle demand different when compared to baseline vehicle at the steady states?
Is the steering torque demand different when compared to baseline vehicle at the steady states?

3.8.2 Double lane change

The subjective assessments in the DLC maneuver dealt with roll, steer torque and vehicle response. The driver would be asked to drive the baseline specification vehicle, following which they would be asked to drive the M5 and M6 specification vehicle. Further, the subjective assessment questionnaire would be filled in by the drivers to provide their assessment on the specification - this would be compared to the physical variation of the parameters of the model. During the SA questionnaire the driver gives feedback within 1 to 10. The baseline is rated 5 as mentioned in the section 3.8 above. The higher numbers are awarded if the vehicle characteristics being rated is felt greater than that in the baseline model and lower numbers if the vehicle characteristics being rated is felt lesser than that in the baseline model.

Table 3.11: SA questionnaire for double lane change maneuver

Questions for rating and evaluating the vehicle specification difference
Was there more roll compared to the baseline model? (10- high roll, 1- less roll)
Was the vehicle steer torque required higher or lower compared to the baseline model? (10- Greater Steer Torque, 1- lesser Steer Torque)
How responsive was the steering of the vehicle compared to the baseline model? Were there any delay? (10 – very responsive, 1 – too much delay)

4

Results

4.1 IPG CarMaker and driving simulator correlation

The figures 4.1, 4.2 and tables 4.1, 4.2 are used to show the measured OM signal (vehicle roll angles and steering wheel torques respectively) correlation between the IPG driver and simulator drivers. Figures 4.1 and 4.2 are called box plots. In these plots, the points represented by red "*" represents the measured signals from the offline CM simulation where maneuvers are performed by the IPG Driver. The blue box denotes the 75^{th} and 25^{th} percentiles of the results from the driving simulator tests, the solid red "-" line denotes their median and the black "-" line denotes the extremes of the driving simulator tests signals. The red "+" are outliers of the driving simulator tests. The driving simulator tests were done with 3 drivers, each performing the tests twice (accounting for 6 sample points for the box plots).

The tables 4.1 and 4.2 shows two types of data sets, IPG driver CM simulation signals and individual driver DS signals for steady state cornering 100m test. The correlation coefficient is obtained between the drivers to show the possible relation in terms of their inputs i.e steering torque demand and vehicle output signals i.e resulting vehicle roll angle. Correlation coefficient values range from +1 to -1 where positive coefficient means that both the data set increase or decrease together, a negative coefficient means that one data set is increasing and the other data set is decreasing or visa versa. The $\pm$ 1 denotes the strongest possible relation and 0 denotes no relation between the two data sets.

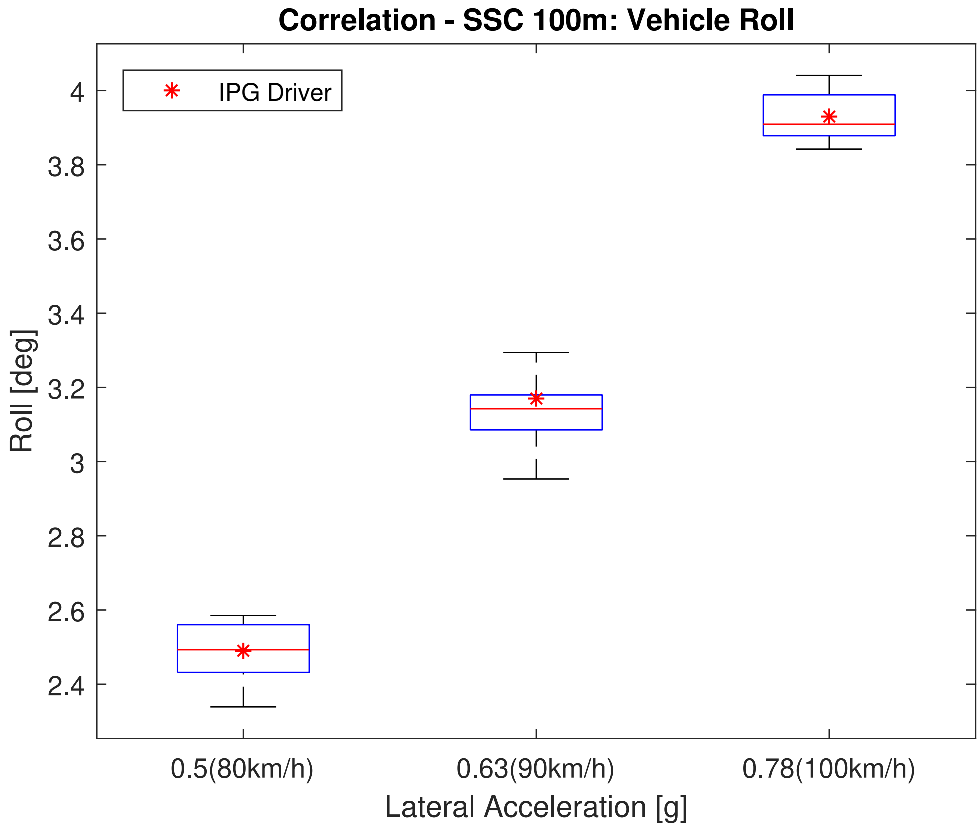


Figure 4.1: CM simulations and DS test correlation - vehicle roll angles

Table 4.1: Baseline specification vehicle roll angle signal OM correlation between IPG Driver and simulator driver in SSC 100m

Objective Metrics SSC 100m Roll angle (deg)	0.5g	0.63g	0.78g	Correlation Coefficient
IPG Driver	2.49	3.17	3.93	-
Driver 1	2.5	3.08	3.84	0.9990
Driver 2	2.48	3.17	3.88	0.9997
Driver 3	2.58	3.1	3.98	0.9934

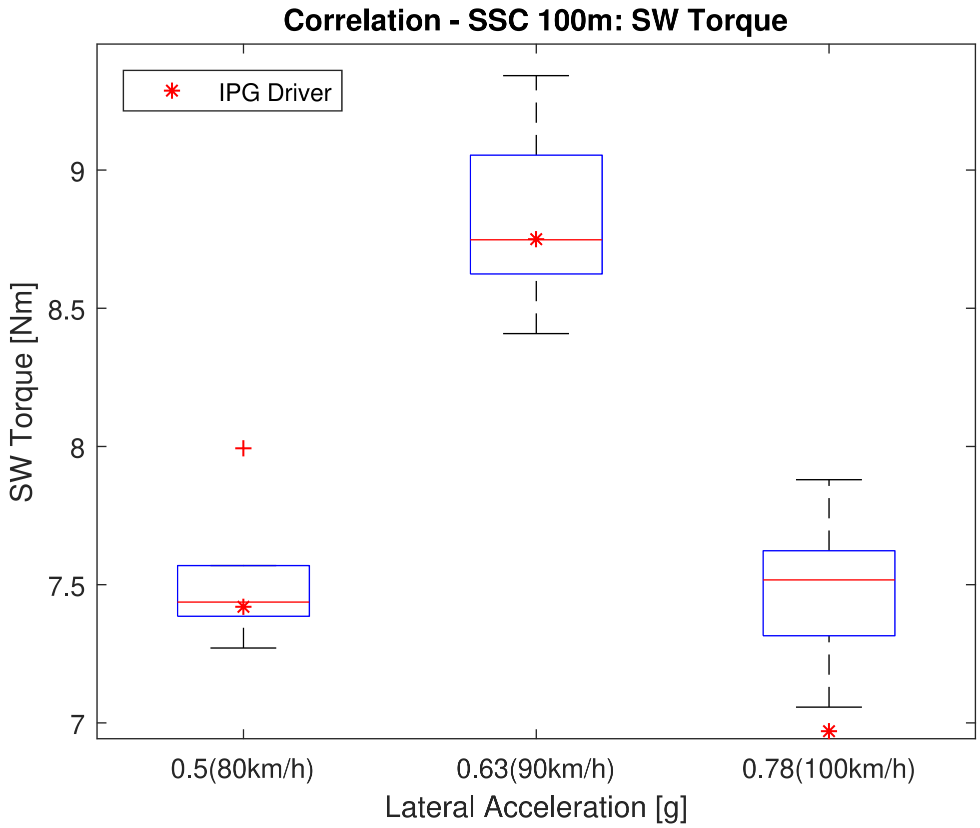


Figure 4.2: CM simulations and DS test correlation - steering wheel torque

Table 4.2: Baseline specification steering wheel torque demand signal OM correlation between IPG Driver and simulator driver in SSC 100m

Objective Metrics SSC 100m Steering Wheel Torque (Nm)	0.5g	0.63g	0.78g	Correlation Coefficient
IPG Driver	7.42	8.75	6.97	-
Driver 1	7.45	8.62	7.8	0.8570
Driver 2	7.42	8.73	7.3	0.9856
Driver 3	7.99	9.05	7.6	0.9998

4.2 Vehicle dynamics characteristic plots

4.2.1 Steady-state cornering

The figures 4.3, 4.5, 4.7 and 4.9 shows the characteristic plots of the side slip angle, vehicle roll angle, steering wheel angle and steering wheel torque respectively, the data are collected at 0.5g, 0.63g and 0.78g (driving at 80, 90 and 100 km/h) for the 100m constant radius test. In these plots, the solid red line denotes the results from offline simulations from IPG CarMaker. The dashed lines corresponds to the results from online Simulator testing.The points represented by "*" and "^{o}" represents the measured signals from the offline IPG simulation and the online Simulator signals (output signals averaged over 6 test runs by 3 drivers on the simulator) respectively. Similar plots for Steady state cornering on 40m radius for speeds of 55, 60 and 65 km/h can be found in the appendix B.
The figures 4.4, 4.6, 4.8 and 4.10 shows the statistical plots, i.e the IPG simulation vehicle signals and the mean of driving simulation test vehicle signals; the distribution of the signals recorded during the driving sessions for different objective metrics data such as side slip angle, vehicle roll angle, steering wheel angle and steering wheel torque respectively, the data are collected at 0.5g, 0.63g and 0.78g (driving at 80, 90 and 100 km/h) for the 100m constant radius test. In these plots, the points represented by red "*" represents the measured signals from the offline CM simulation where maneuvers are performed by the IPG Driver. The blue box denotes the 75^{th} and 25^{th} percentiles of the results from the driving simulator tests, the solid red "-" line denotes their median and the black "-" line denotes the extremes of the driving simulator tests signals. The red "+" are outliers of the driving simulator tests. The driving simulator tests were done with 3 drivers, each performing the tests twice (accounting for 6 sample points for the box plots). These figures shows 3 set of boxes one below another corresponds to 3 different data sets from steady state lateral accelerations (0.5g, 0.63g and 0.78g) across different test vehicle specifications. There exists 4 such sets that illustrate the characteristic values for each objective metrics evaluated in the steady state cornering maneuver tests.
The tables 4.3, 4.4, 4.5 and 4.6 shows the two types of data sets dealt in the project, CM is objective metric data collected from the CarMaker simulation, whereas the DS is the data recorded from the driving simulator. The data are compared to show the correlation between the offline (CM- CarMaker simulation) and online (DS-driving simulator) simulation. The correlation coefficient observed between the two data sets are also displayed.

4.2.1.1 Side slip angle characteristics

The fig 4.3 shows the characteristic plot of the side slip angle behavior with respect to lateral acceleration. The x-axis represents the lateral acceleration and the data points 0.5g, 0.63g and 0.78g are at the steady state test speeds 80, 90 and 100 km/h respectively. The y- axis represents the magnitude of side slip angle recorded from the vehicle. In the plots, the solid red line denotes the results form offline simulations on CarMaker. The dashed lines corresponds to the results from online Simulator testing. The points represented by "*" and "^{o}" represents the measured signals from the offline IPG simulation and the online Simulator signals (output signals averaged over 6 test runs by 3 drivers on the simulator) respectively.

The figures 4.4, the points represented by red "*" represents the measured signals from the offline CM simulation where maneuvers are performed by the IPG Driver. The blue box denotes the 75^{th} and 25^{th} percentiles of the results from the driving simulator tests, the solid red "-" line denotes their median and the black "-" line denotes the extremes of the driving simulator tests signals. The red "+" are outliers of the driving simulator tests. The driving simulator tests were done with 3 drivers, each performing the tests twice (accounting for 6 sample points for the box plots).

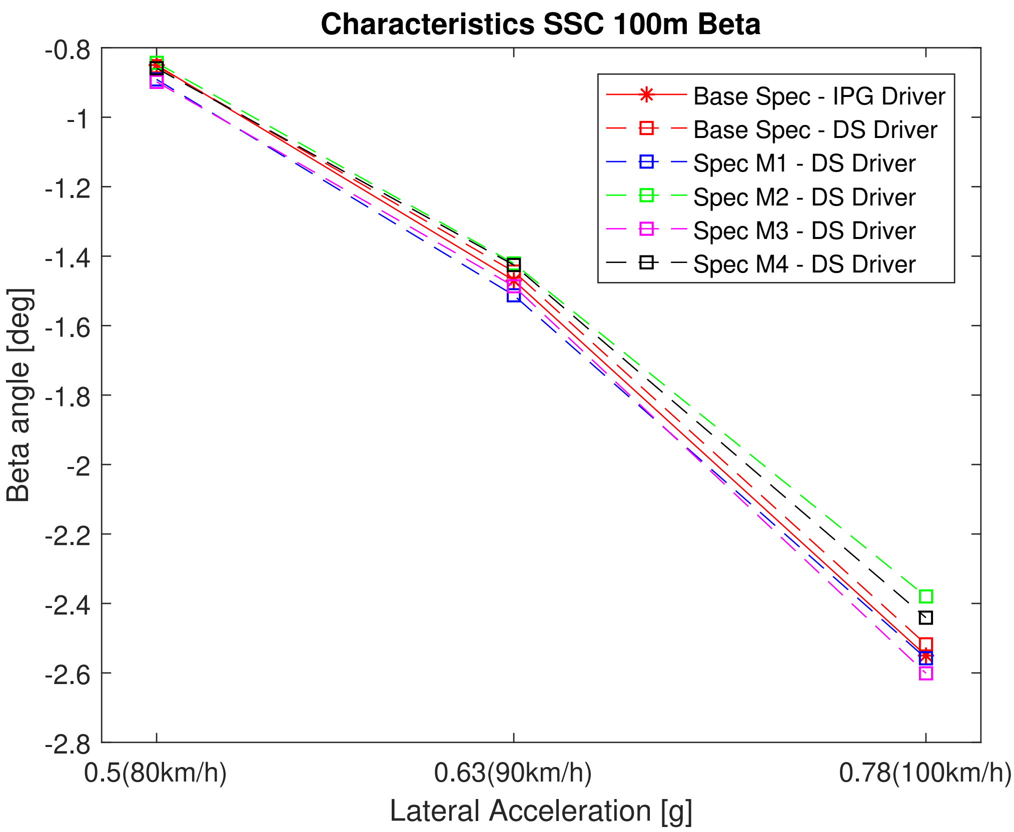


Figure 4.3: Steady-state cornering 100m - side slip characteristic plot

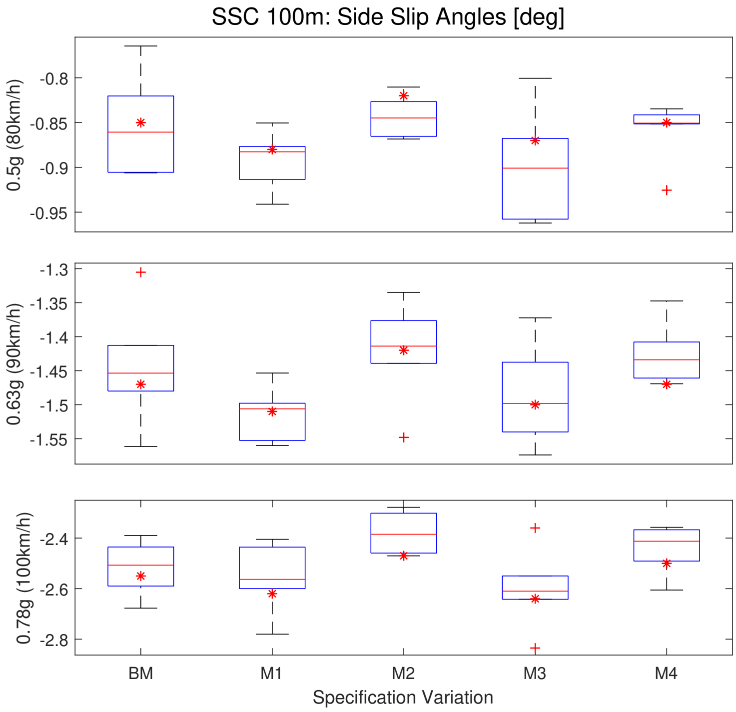


Figure 4.4: Steady-state cornering 100m - side slip angles and data distribution

The table 4.3 shows the correlation between the IPG driver CM simulation signals and DS signals of side slip angle at each steady state cornering lateral accelerations (resultant of radius 100m and test speeds 80, 90 and 100 km/h) across different vehicle specifications.

Table 4.3: Side slip angle correlation coefficient analysis between IPG and driving simulator test

Objective Metrics SSC 100m	**0.5g**		**0.63g**		**0.78g**	
Side slip angle (deg)	**CM**	**DS**	**CM**	**DS**	**CM**	**DS**
Baseline	-0.85	-0.85	-1.47	-1.44	-2.55	-2.52
Spec 1/ M1	-0.88	-0.89	-1.51	-1.51	-2.62	-2.56
Spec 2/ M2	-0.82	-0.84	-1.42	-1.42	-2.45	-2.38
Spec 3/ M3	-0.87	-0.89	-1.5	-1.49	-2.64	-2.6
Spec 4/ M4	-0.85	-0.86	-1.47	-1.43	-2.5	-2.44
Correlation co-efficient	0.93		0.89		0.99	

4.2.1.2 Vehicle roll angle characteristics

The fig 4.5 shows the characteristic plot of the vehicle roll angle behavior with respect to lateral acceleration. The x-axis represents the lateral acceleration and the data points 0.5g, 0.63g and 0.78g are at the steady state test speeds 80, 90 and 100 km/h respectively. The y- axis represents the magnitude of the roll angle recorded from the vehicle. In the plots, the solid red line denotes the results form offline simulations on CarMaker. The dashed lines corresponds to the results from online Simulator testing. The points represented by "*" and "^{o}" represents the measured signals from the offline IPG simulation and the online Simulator signals (output signals averaged over 6 test runs by 3 drivers on the simulator) respectively.

The figures 4.6, the points represented by red "*" represents the measured signals from the offline CM simulation where maneuvers are performed by the IPG Driver. The blue box denotes the 75^{th} and 25^{th} percentiles of the results from the driving simulator tests, the solid red "-" line denotes their median and the black "-" line denotes the extremes of the driving simulator tests signals. The red "+" are outliers of the driving simulator tests. The driving simulator tests were done with 3 drivers, each performing the tests twice (accounting for 6 sample points for the box plots).

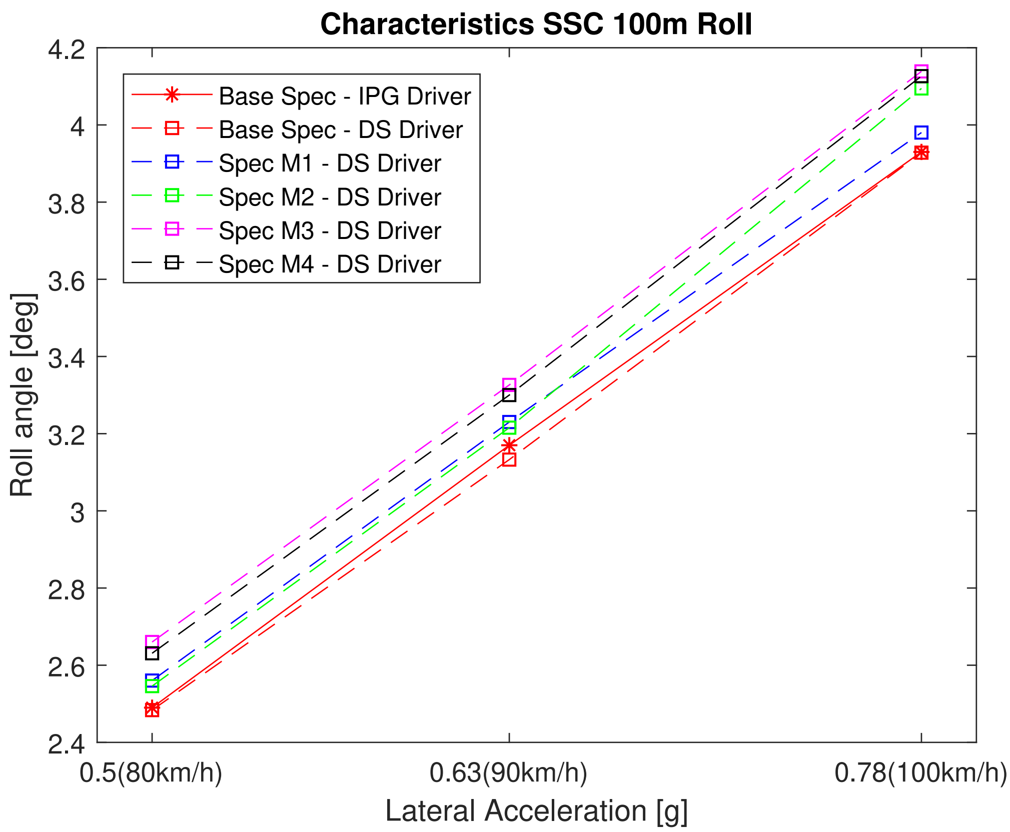


Figure 4.5: Steady-state cornering 100m - vehicle roll angle characteristic plot

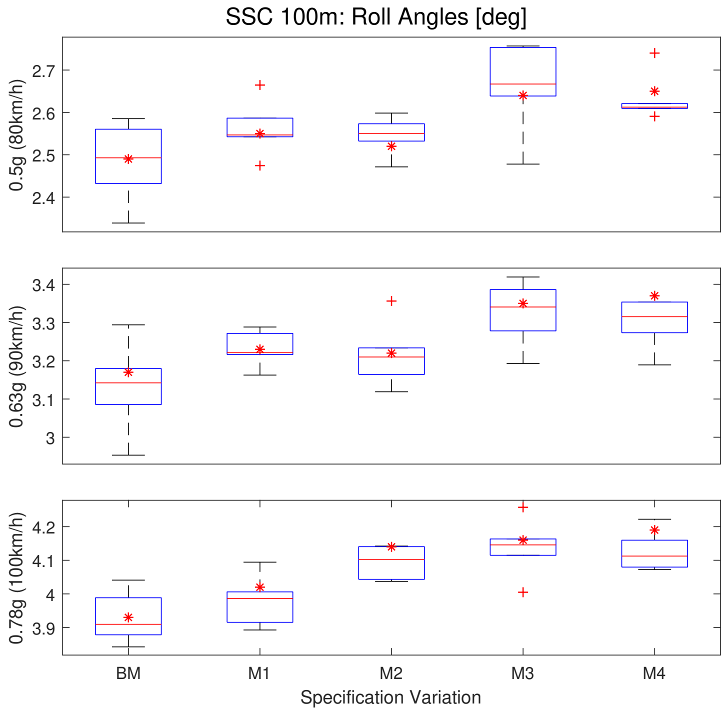


Figure 4.6: Steady-state cornering 100m - vehicle roll angles and data distribution

The table 4.4 shows the correlation between the IPG driver CM simulation signals and DS signals of vehicle roll angle at each steady state cornering lateral accelerations (resultant of radius 100m and test speeds 80, 90 and 100 km/h) across different vehicle specifications.

Table 4.4: Vehicle roll angle correlation coefficient analysis between IPG and driving simulator tests

Objective Metrics SSC 100m	**0.5g**		**0.63g**		**0.78g**	
Roll Angle (deg)	**CM**	**DS**	**CM**	**DS**	**CM**	**DS**
Baseline	2.49	2.48	3.17	3.13	3.93	3.93
Spec 1/ M1	2.55	2.56	3.23	3.23	4.02	3.98
Spec 2/ M2	2.52	2.55	3.22	3.22	4.14	4.1
Spec 3/ M3	2.64	2.66	3.35	3.33	4.16	4.14
Spec 4/ M4	2.65	2.63	3.37	3.3	4.19	4.13
Correlation co-efficient	0.96		0.94		0.98	

4.2.1.3 Steering wheel angle characteristics

The fig 4.7 shows the characteristic plot of the steering wheel angle behavior with respect to lateral acceleration. The x-axis represents the lateral acceleration and the data points 0.5g, 0.63g and 0.78g are at the steady state test speeds 80, 90 and 100 km/h respectively. The y- axis represents the magnitude of the steering wheel angle input by the driver. In the plots, the solid red line denotes the results form offline simulations on CarMaker. The dashed lines corresponds to the results from online Simulator testing. The points represented by "*" and "^{o}" represents the measured signals from the offline IPG simulation and the online Simulator signals (output signals averaged over 6 test runs by 3 drivers on the simulator) respectively.

The figures 4.8, the points represented by red "*" represents the measured signals from the offline CM simulation where maneuvers are performed by the IPG Driver. The blue box denotes the 75^{th} and 25^{th} percentiles of the results from the driving simulator tests, the solid red "-" line denotes their median and the black "-" line denotes the extremes of the driving simulator tests signals. The red "+" are outliers of the driving simulator tests. The driving simulator tests were done with 3 drivers, each performing the tests twice (accounting for 6 sample points for the box plots).

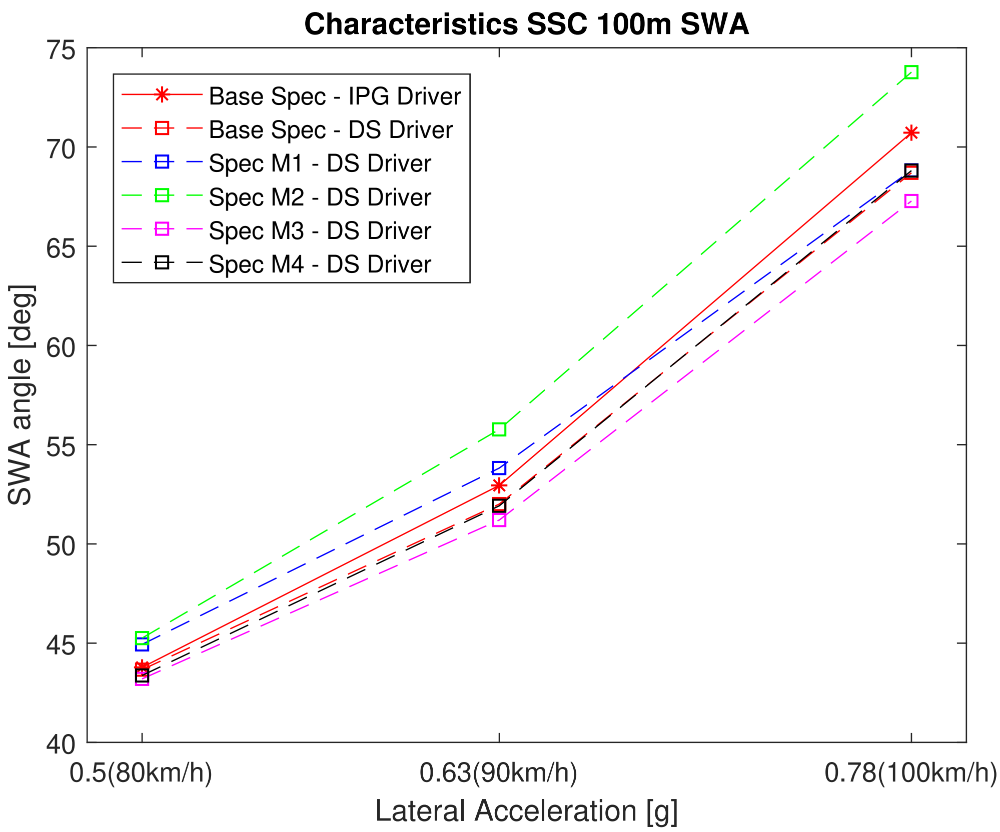


Figure 4.7: Steady-state cornering 100m - steering wheel angle characteristic plot

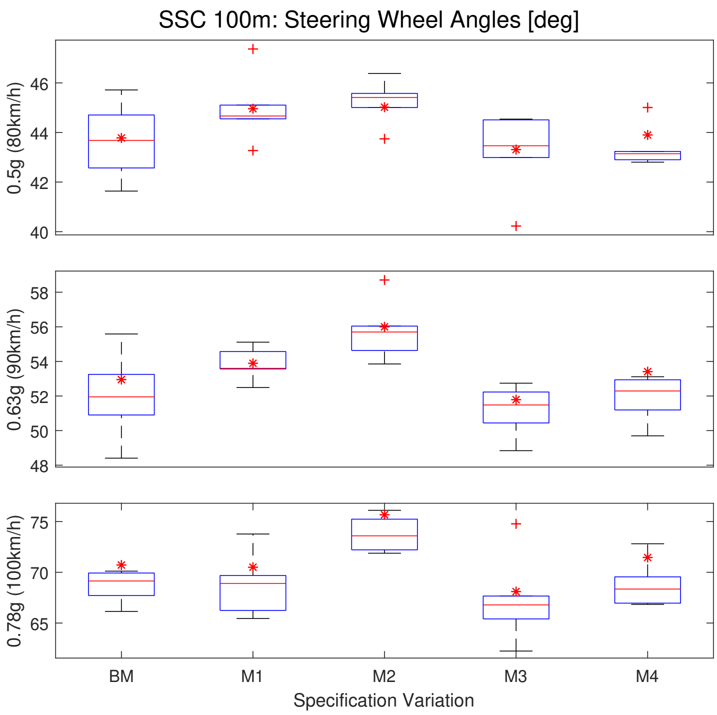


Figure 4.8: Steady-state cornering 100m - steering wheel angles and data distribution

The table 4.5 shows the correlation between the IPG driver CM simulation signals and DS signals of steering wheel angle at each steady state cornering lateral accelerations (resultant of radius 100m and test speeds 80, 90 and 100 km/h) across different vehicle specifications.

Table 4.5: Steering wheel angle correlation coefficient analysis between IPG and driving simulator test

Objective Metrics SSC 100m	**0.5g**		**0.63g**		**0.78g**	
Steering Wheel Angle (deg)	**CM**	**DS**	**CM**	**DS**	**CM**	**DS**
Baseline	43.78	43.66	52.95	52	70.72	68.7
Spec 1/ M1	44.96	44.94	53.89	53.82	70.5	68.3
Spec 2/ M2	45.02	45.26	56	55.77	75.67	73.77
Spec 3/ M3	43.31	43.2	51.79	51.2	68.1	67.28
Spec 4/ M4	43.9	43.37	53.41	51.92	71.46	68.81
Correlation co-efficient	0.97		0.96		0.97	

4.2.1.4 Steering wheel torque characteristics

The fig 4.9 shows the characteristic plot of the steering wheel torque behavior with respect to lateral acceleration. The x-axis represents the lateral acceleration and the data points 0.5g, 0.63g and 0.78g are at the steady state test speeds 80, 90 and 100 km/h respectively. The y- axis represents the magnitude of the steering wheel torque demand to the driver. In the plots, the solid red line denotes the results form offline simulations on CarMaker. The dashed lines corresponds to the results from online Simulator testing. The points represented by "*" and "^{o}" represents the measured signals from the offline IPG simulation and the online Simulator signals (output signals averaged over 6 test runs by 3 drivers on the simulator) respectively.

The figures 4.10, the points represented by red "*" represents the measured signals from the offline CM simulation where maneuvers are performed by the IPG Driver. The blue box denotes the 75^{th} and 25^{th} percentiles of the results from the driving simulator tests, the solid red "-" line denotes their median and the black "-" line denotes the extremes of the driving simulator tests signals. The red "+" are outliers of the driving simulator tests. The driving simulator tests were done with 3 drivers, each performing the tests twice (accounting for 6 sample points for the box plots).

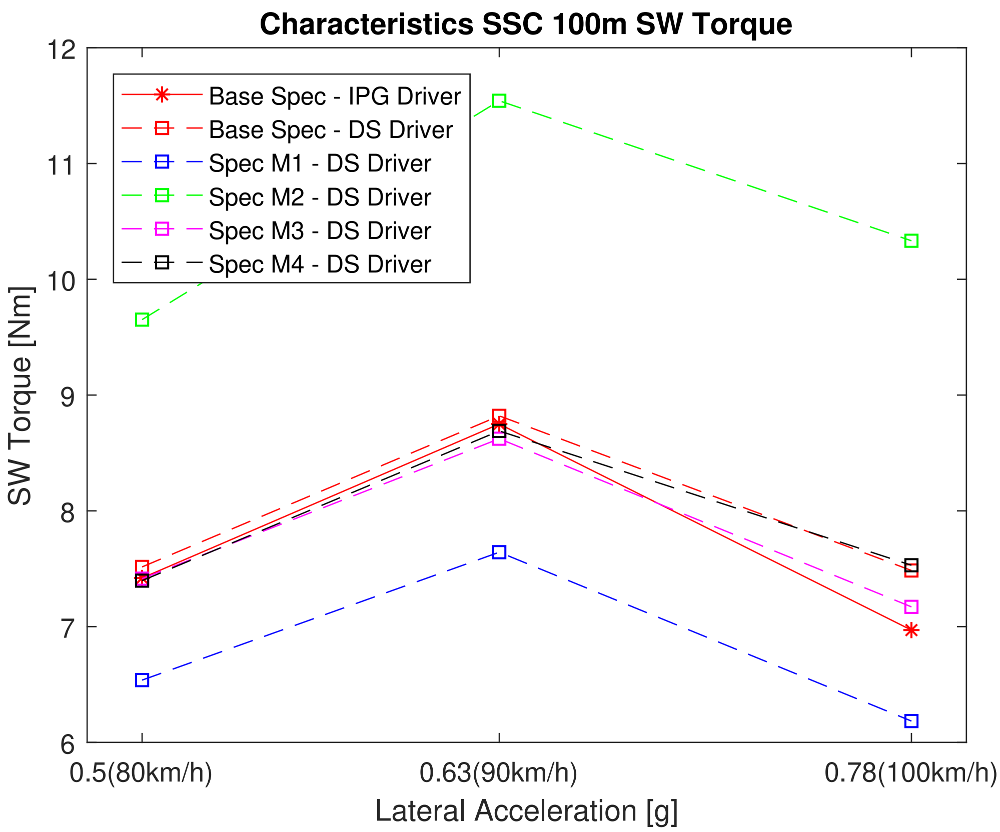


Figure 4.9: Steady-state cornering 100m - steering wheel torque characteristic plot

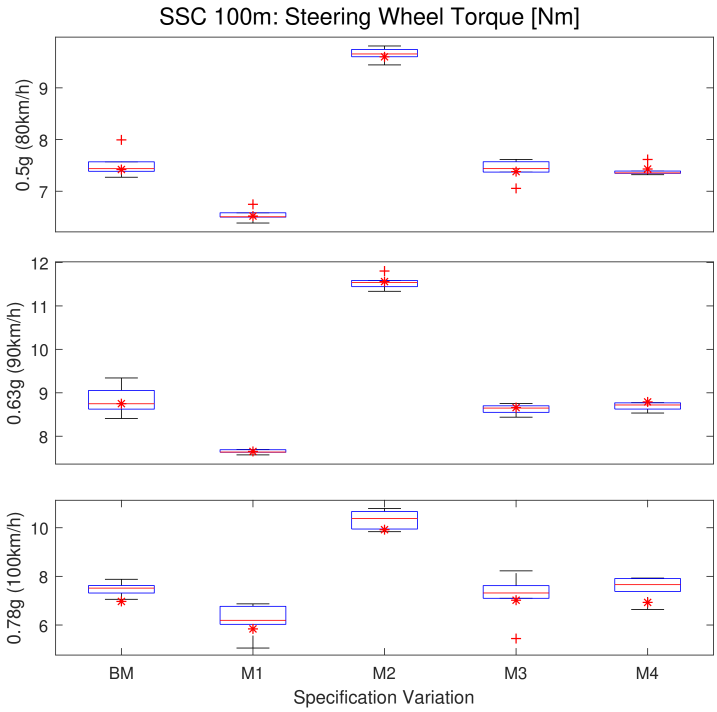


Figure 4.10: Steady-state cornering 100m - steering wheel torque and data distribution

The table 4.6 shows the correlation between the IPG driver CM simulation signals and DS signals of steering wheel torque at each steady state cornering lateral accelerations (resultant of radius 100m and test speeds 80, 90 and 100 km/h) across different vehicle specifications.

Table 4.6: Steering wheel torque correlation coefficient analysis between IPG and driving simulator test. DM - Driving Simulator, CM - CarMaker

Objective Metrics SSC 100m	**0.5g**		**0.63g**		**0.78g**	
Steering Wheel Torque (Nm)	**CM**	**DS**	**CM**	**DS**	**CM**	**DS**
Baseline	7.42	7.52	8.72	8.82	6.97	7.49
Spec 1/ M1	6.52	6.54	7.65	7.64	5.84	6.18
Spec 2/ M2	9.6	9.65	11.56	11.54	9.92	10.33
Spec 3/ M3	7.38	7.41	8.66	8.62	7.02	7.17
Spec 4/ M4	7.43	7.4	8.79	8.69	6.93	7.53
Correlation co-efficient	0.99		0.99		0.99	

4.2.2 Double lane change

4.2.2.1 Baseline vehicle data comparison at 50 & 60 km/h

A comparison between CM simulation data with that from the CASTER signals of yaw rate, steering wheel angle, vehicle roll and steering torque from the steering wheel was made. The graphs show the IPG driver signals plotted against the real drivers' signals for each driving speed.

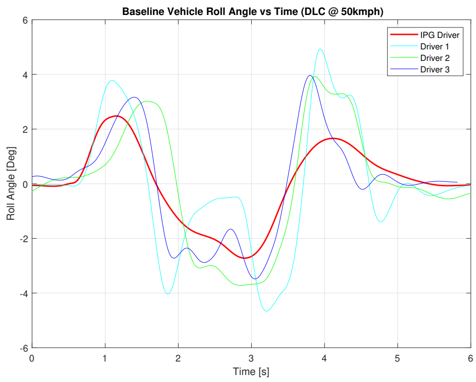


Figure 4.11: Roll angle for baseline vehicle DLC at 50 kmph

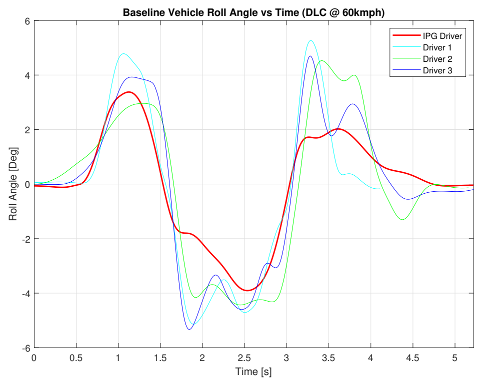


Figure 4.12: Roll angle for baseline vehicle DLC at 60 kmph

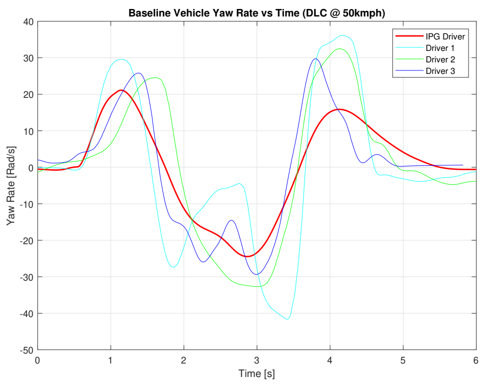


Figure 4.13: Yaw rate for baseline vehicle DLC at 50 kmph

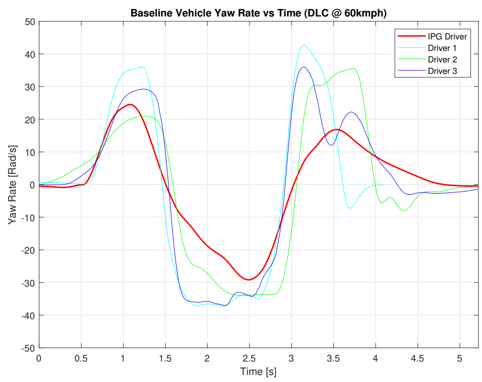


Figure 4.14: Yaw rate for baseline vehicle DLC at 60 kmph

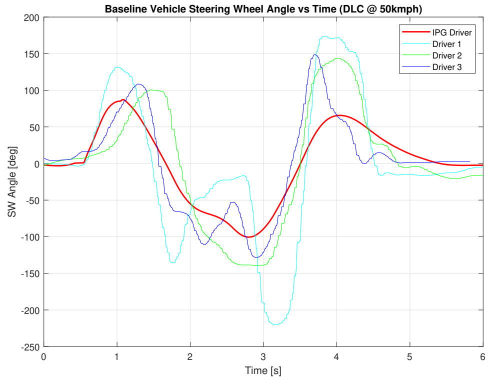


Figure 4.15: Steering wheel angle for baseline vehicle DLC at 50 kmph

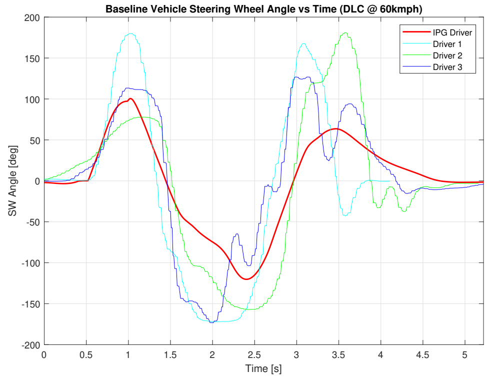


Figure 4.16: Steering wheel angle for baseline vehicle DLC at 60 kmph

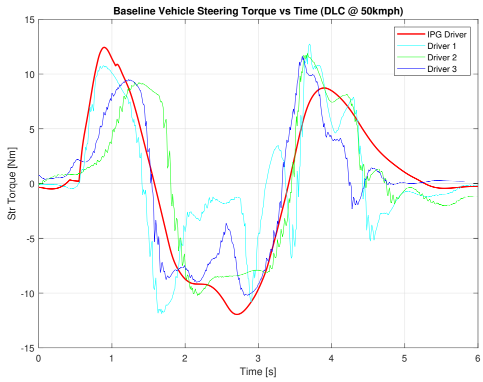


Figure 4.17: Steering torque for baseline vehicle DLC at 50 kmph

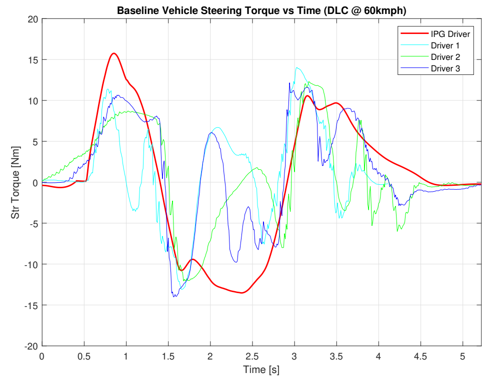


Figure 4.18: Steering torque for baseline vehicle DLC at 60 kmph

4.2.2.2 Vehicle telemetry for DLC at 50 km/h

For further analysis, data was recorded for drivers driving on the simulator with M5 and M6 models as seen in table 3.4 - M5 has a stiffer suspension whereas M6 has a softer suspension. The DLC maneuver was first performed at 50km/h. The plots below show the variation of Roll Angle, Yaw Rate, Steering Wheel Angle and Steering Torque between the 3 drivers.

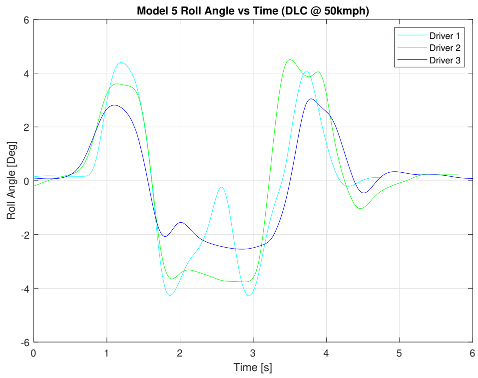


Figure 4.19: M5-roll angle

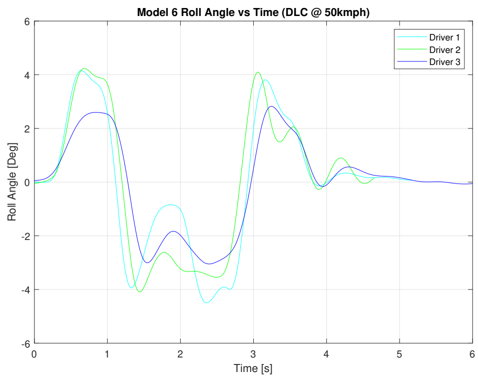


Figure 4.20: M6-roll angle

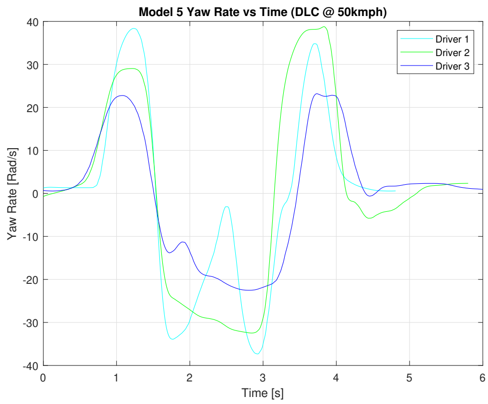


Figure 4.21: M5-yaw rate

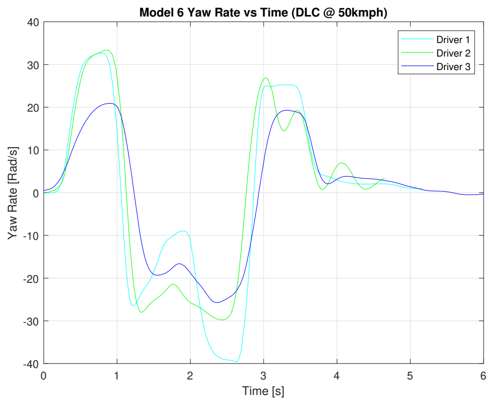


Figure 4.22: M6-yaw rate

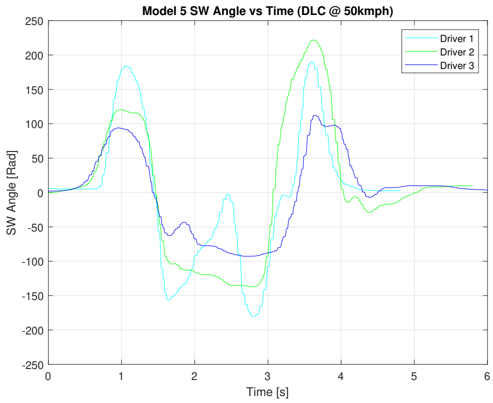


Figure 4.23: M5-steering wheel angle

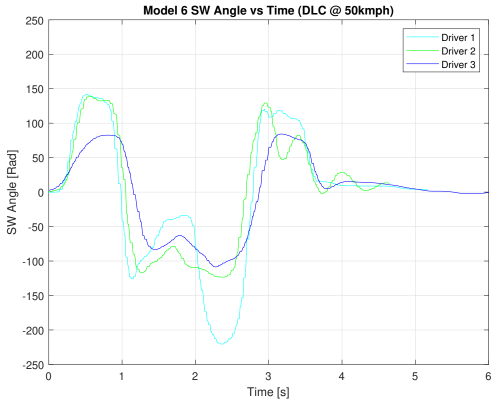


Figure 4.24: M6-steering wheel angle

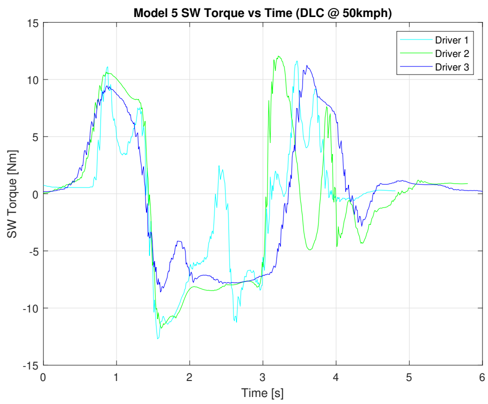


Figure 4.25: M5-steering torque

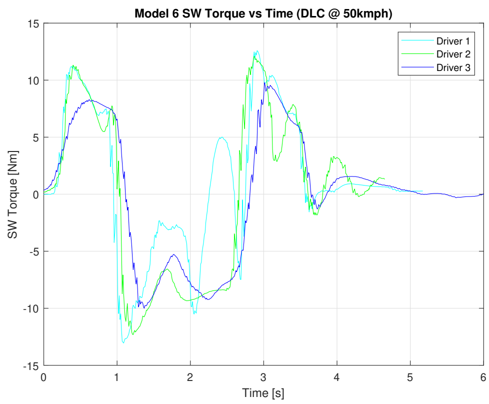


Figure 4.26: M6-steering torque

4.2.2.3 Vehicle telemetry for DLC at 60 km/h

The DLC maneuver was first performed at 60km/h. Data was recorded for drivers driving on the simulator with M5 and M6 models as seen in table 3.4 - M5 has a stiffer suspension whereas M6 has a softer suspension. The plots below show the variation of Roll Angle, Yaw Rate, Steering Wheel Angle and Steering Torque between the 3 drivers.

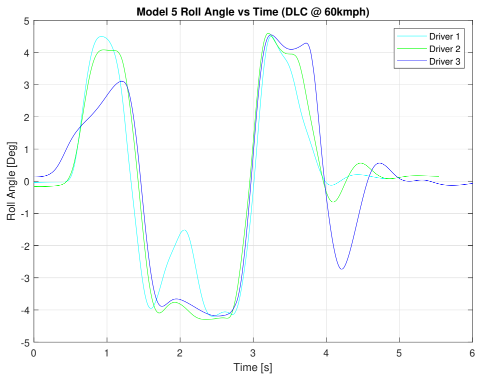


Figure 4.27: M5-roll angle

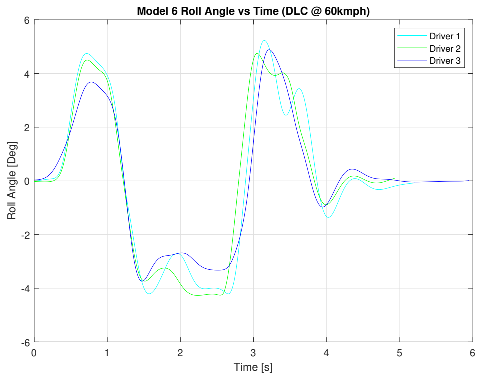


Figure 4.28: M6-roll angle

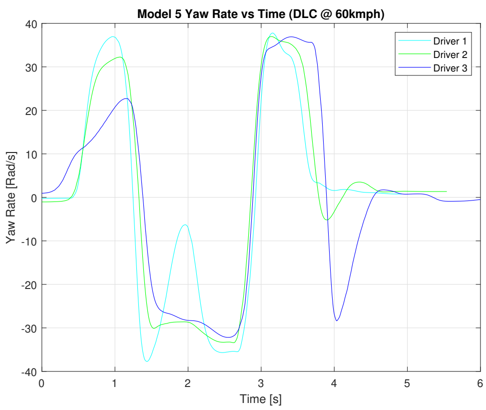


Figure 4.29: M5-yaw rate

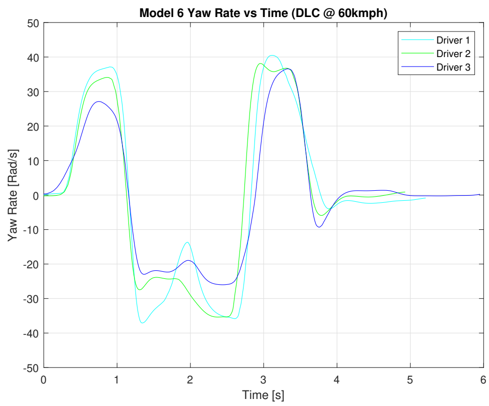


Figure 4.30: M6-yaw rate

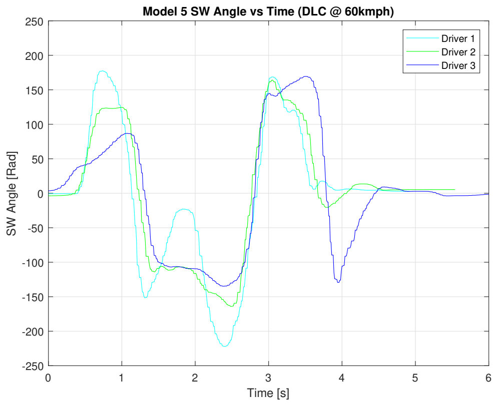


Figure 4.31: M5-steering wheel angle

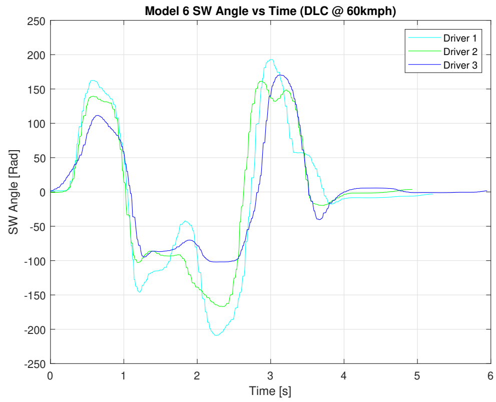


Figure 4.32: M6-steering wheel angle

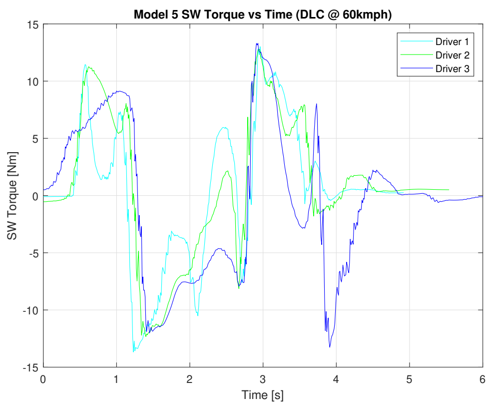


Figure 4.33: M5-steering torque

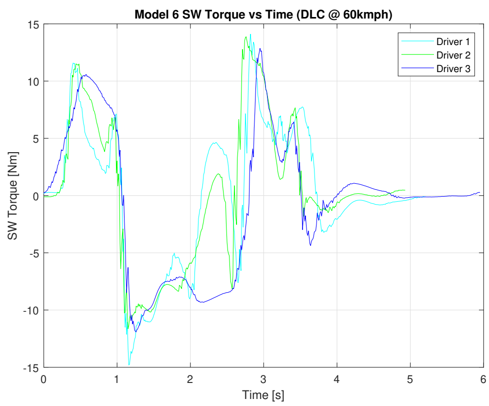


Figure 4.34: M6-steering torque

4.3 Subjective assessment

4.3.1 Steady state cornering 100m- vehicle specification difference

The figure 4.35 shows the average vehicle specification difference felt during driving sessions by the drivers. The specification difference felt explains the perceived availability of grip when compared to baseline vehicle while driving the other vehicle specifications in steady state cornering maneuver test.

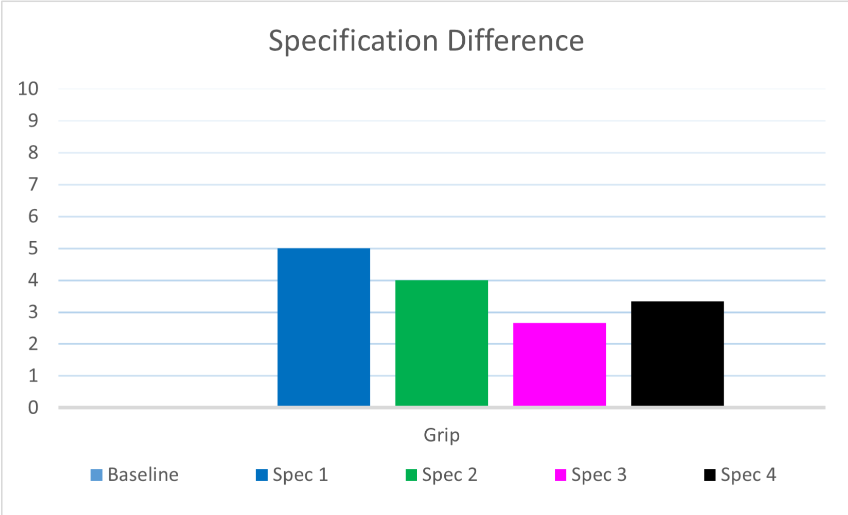


Figure 4.35: Vehicle specification difference felt in grip for SSC 100m

The figure 4.36 shows the average vehicle specification difference felt during driving sessions by the drivers. The specification difference felt explains the perceived vehicle when compared to baseline vehicle while driving the other vehicle specifications in steady state cornering maneuver test.

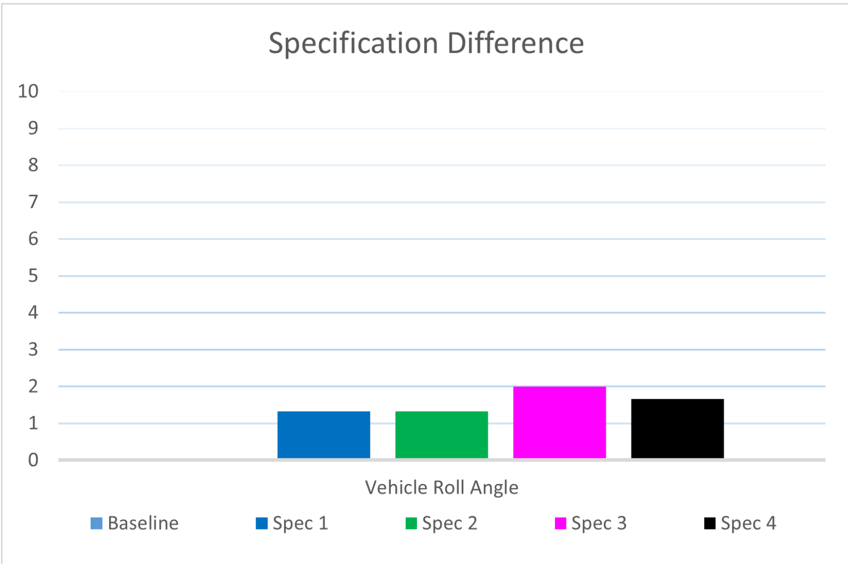


Figure 4.36: Vehicle specification difference felt in vehicle roll angle for SSC 100m

The figure 4.37 shows the average vehicle specification difference felt during driving sessions by the drivers. The specification difference felt explains the perceived input of steering wheel angle when compared to baseline vehicle while driving the other vehicle specifications in steady state cornering maneuver test.

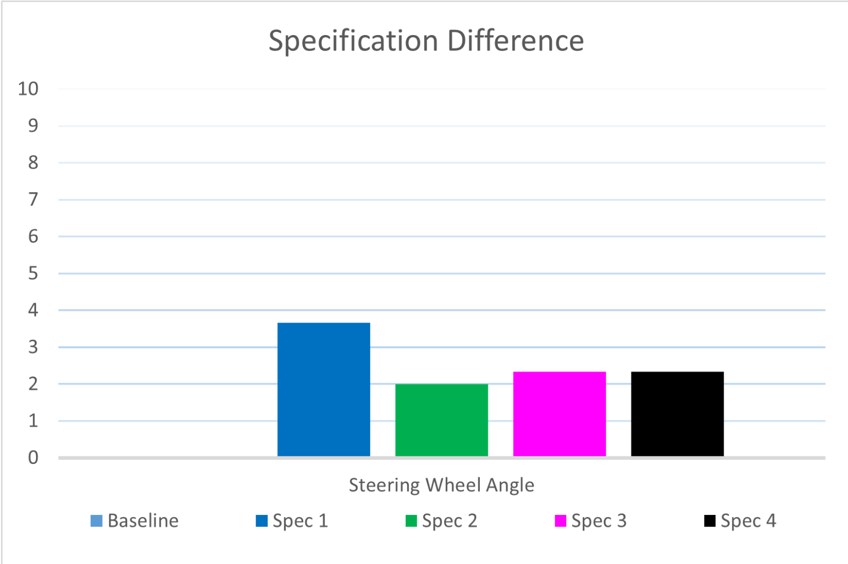


Figure 4.37: Vehicle specification difference felt in steering wheel angle for SSC 100m

The figure 4.38 shows the average vehicle specification difference felt during driving sessions by the drivers. The specification difference felt explains the demanded steering wheel torque when compared to baseline vehicle while driving the other vehicle specifications in steady state cornering maneuver test.

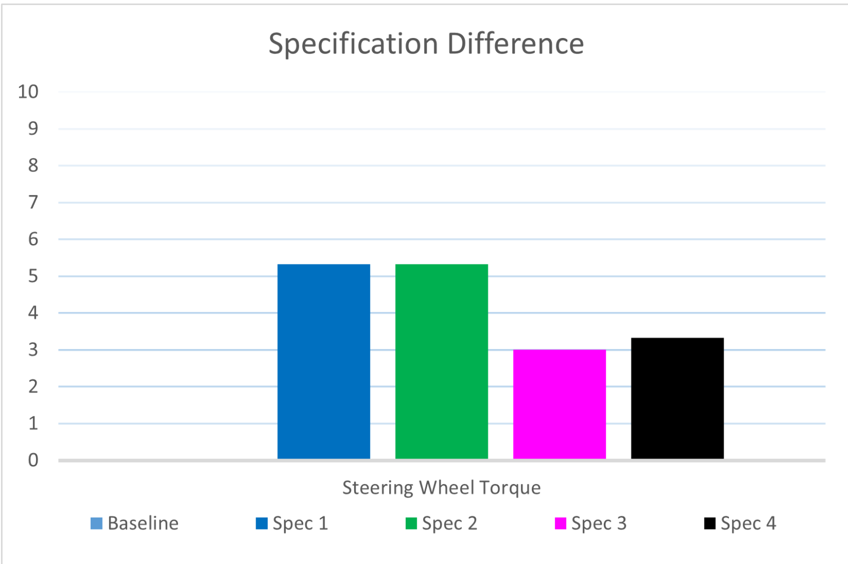


Figure 4.38: Vehicle specification difference felt in steering wheel torque for SSC 100m

4.3.1.1 Steady-state cornering 100m- vehicle specification rating

The figure 4.39 shows the driver rating the vehicle specification assessing the availability of grip in steady state cornering maneuver across different vehicle specifications.

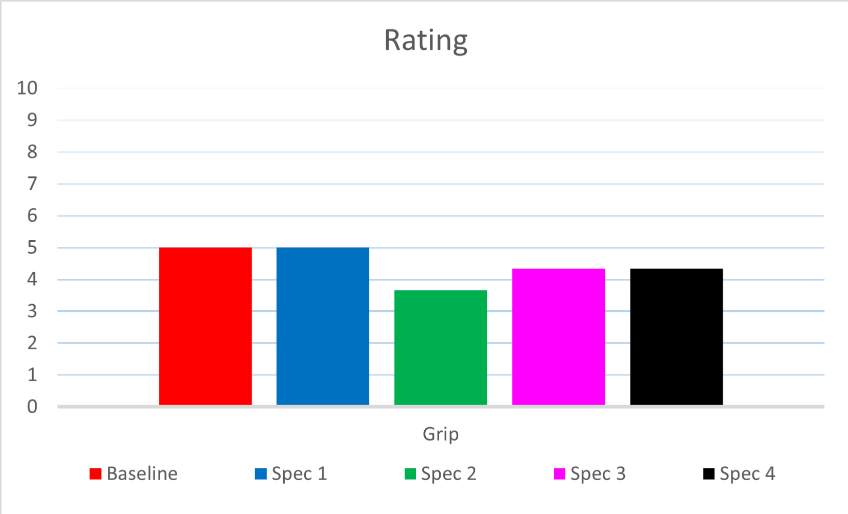


Figure 4.39: Vehicle specification rating for grip for SSC 100m

The figure 4.40 shows the driver rating the vehicle specification assessing the availability of grip in steady state cornering maneuver across different vehicle specifications.

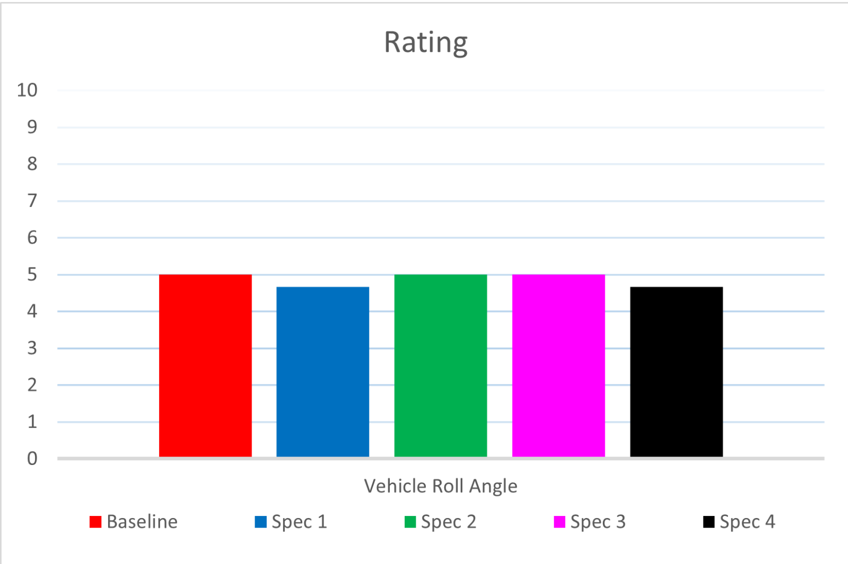


Figure 4.40: Vehicle specification rating for vehicle roll angle for SSC 100m

The figure 4.41 shows the driver rating the vehicle specification assessing the availability of grip in steady state cornering maneuver across different vehicle specifications.

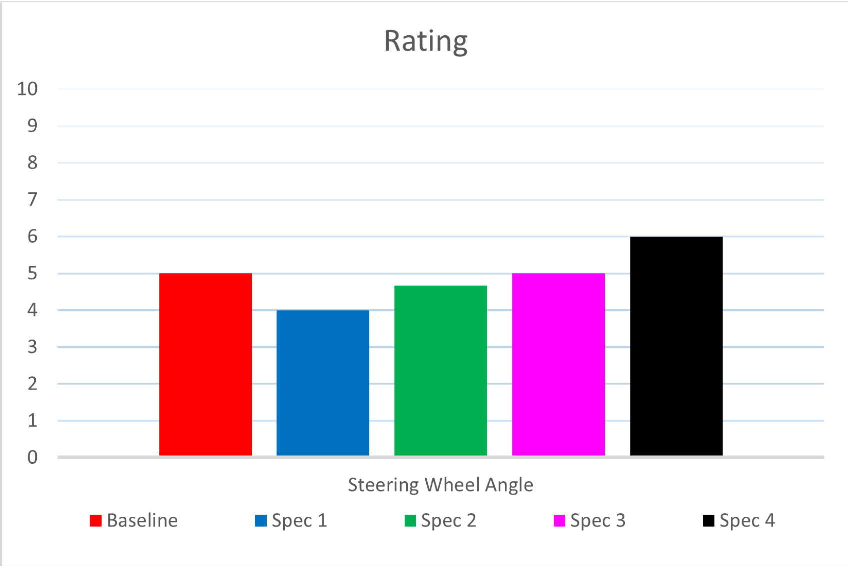


Figure 4.41: Vehicle specification rating for steering wheel angle for SSC 100m

The figure 4.42 shows the driver rating the vehicle specification assessing the availability of grip in steady state cornering maneuver across different vehicle specifications.

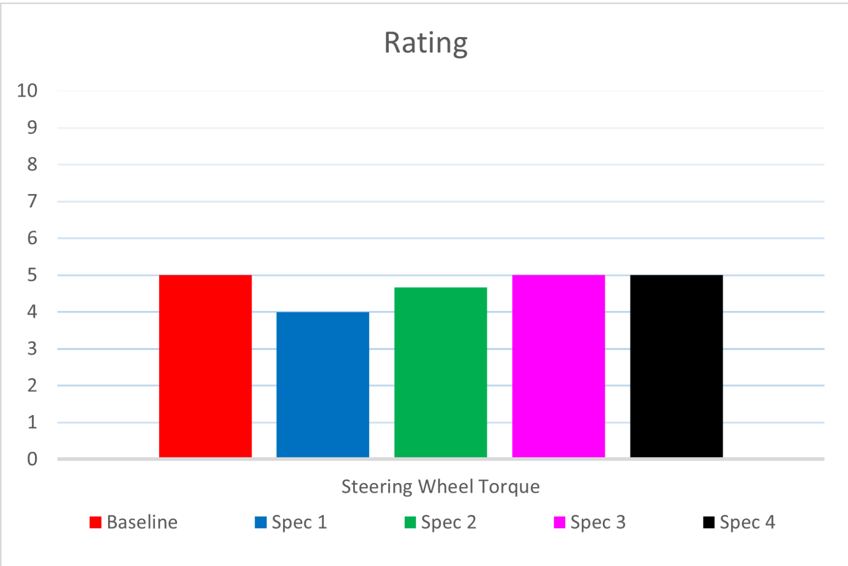


Figure 4.42: Vehicle specification rating for steering wheel torque for SSC 100m

Similarly, the subjective assessment regarding vehicle specification difference felt and the rating for steady state cornering 40m maneuver test are in Appendix B.1.

4.3.1.2 Steady-state cornering 100m- cumulative rating

The summation of the average subjective rating per vehicle specification. This shows how well each specification (refer table 3.4) fairs against the baseline specification in the driver's perspective.

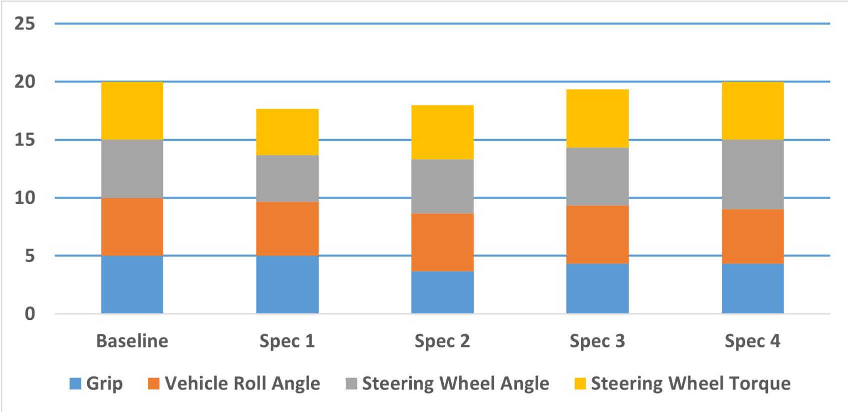


Figure 4.43: Cumulative rating for SSC 100m

4.3.2 Double lane change- vehicle specification rating

The subjective assessment of the drivers was carried out to compare their driving experiences of the baseline, M5 and M6 vehicles. The ratings provided by the drivers can be graphically visualized in the bar graphs below. The average rating of the 3 drivers for the baseline, M5 & M6 model at two driving speeds - 50 and 60km/h - is shown.

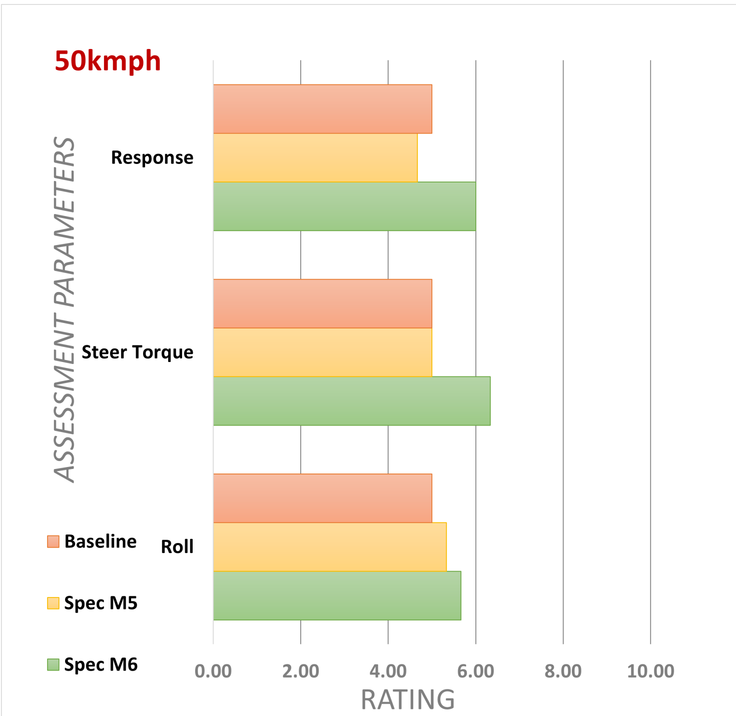


Figure 4.44: DLC subjective assessment for 50kmph

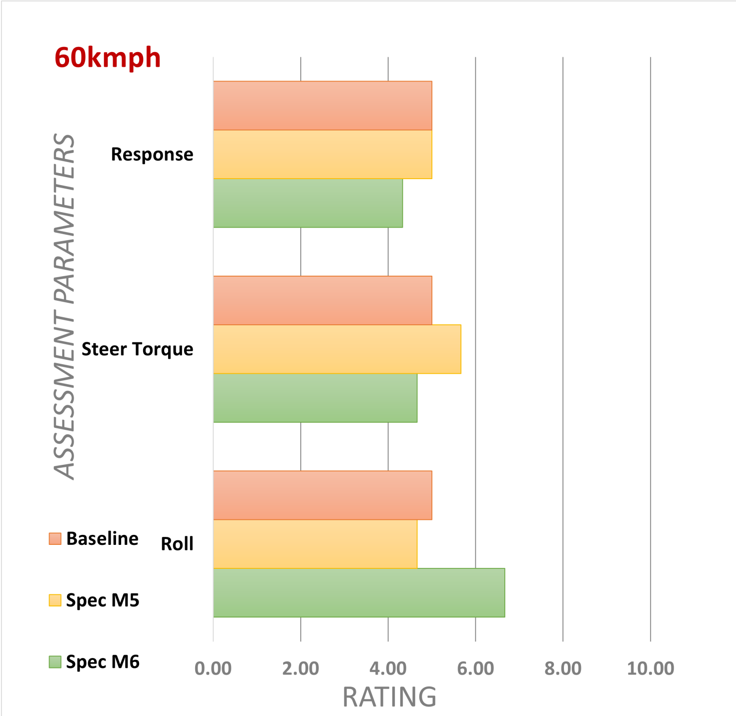


Figure 4.45: DLC subjective assessment for 60kmph

4.4 Time log

An approximate time requirement per test driver is presented below for each category of maneuver and normalized for differing number of vehicle specifications run. This includes baseline vehicle run and the subjective assessment after 100m and 40m test runs for every vehicle specification. The details of the procedure is explained with the help of figures 3.10 and 3.11, accounting for the total time requirement to conduct each test.

Table 4.7: Approximate time requirement for different maneuvers

Maneuver	Time requirement	Per vehicle spec
Steady State Cornering	60 min	12 min
Double Lane Change	40 min	15 min

5

Discussion and Conclusion

This chapter discusses the inferences from the results obtained in chapter 4 in comparison with the objectives of the test runs. A correlation between offline CM simulations and online Simulator testing results will also be made. A conclusion on vehicle dynamics performance due to changes in parameters will also be provided. As seen in table 4.7, the process of testing a vehicle configuration is fairly time consuming. The parameters that can be tuned in conjunction with the variety of maneuvers that a vehicle can be subjected to are numerous. Experienced test drivers with clear driving guidelines and with instant OM calculation, could help in improving the tuning process in a time frame that fits into the existing vehicle development timelines.

5.1 Project milestones

This section highlights the achievements of the projects against the intended deliverable as mentioned in section 1.5. The following points support the accomplishments made:

- **Vehicle model**: A representative vehicle model a generic SUV was built on the CarMaker tool (sections 3.1 and A). This model was used for both offline CM simulations and driving simulator tests
- **Maneuver selection**: Out of the 3 maneuvers studies in section 2.1.1, steady state cornering and double lane change maneuvers were selected. The said maneuvers were created on CM tool (refer section 3.2)
- **Integration into driving simulator**: The vehicle model and driving environment built on CM tool was integrated into the driving simulator (refer section 3.4). The simulations run on CM tool can therefore be directly compared with the test runs on the driving simulator since they use the same vehicle model and the driving environment
- **Simulation results**: The results thus obtained from CM simulations are highlighted in section 4.1. These results were quantified and compared with that from the driving simulator test runs, thereby confirming a good correlation
- **Parameter variations**: Suspension spring, Anti-roll bar and Suspension damper stiffness were modified in the baseline vehicle model (refer section 3.5). A comprehensive understanding of the vehicle dynamics performance as a consequence of these modifications was observed and the results were documented in section 4.2
- **Chassis development through driver feedback**: The different vehicle

specifications were tested on the driving simulator and subjectively assess through driver feedback (refer sections 3.8 and 4.3). Conclusions on the direction of chassis development are made by analyzing the driver feedback in the sections below (sections 5.3, 5.4 and 5.5)

- **Tools and methods**: The tools used and the methods followed in completion of this project are discussed in chapter 3 of this report

5.2 Baseline correlation verification

The integration of the vehicle model from the offline CM simulations into the DIL simulator has to be verified by comparing the simulation outputs between the offline simulations and driving simulator tests. The baseline specification vehicle is used in this process. The offline simulation (CM) and online simulation (DS) should give OM measured signals that are close and should follow similar trend at different test speeds when compared. It is observed from figures 4.1, 4.2 and tables 4.1, 4.2 that a good correlation between offline CM simulation with IPG driver and online driving simulator tests is achieved for the baseline model. This shows that for similar vehicle behavior in the maneuver, the simulator drivers inputs and the IPG driver inputs are very similar to perform the same maneuvers and this yielded very close vehicle signals. Similar correlation in slide slip angles, steering wheel angles and steer wheel torques were observed.

For DLC, a comparison between the physical driver on the offline simulator and the driver on the online simulation (figures 4.11,4.12, 4.13, 4.14, 4.15,4.16, 4.17, and 4.18) shows good correlation. The general trajectory of the curves and close peaks for each driver shows that the baseline model dynamics on the simulation and simulator align well.
Another observation that can be made are the increase in values when driving the vehicle at 60km/h compared to when it is driven at 50km/h.

5.3 Vehicle dynamics evaluation

This section discusses the inferences from the results obtained in sections 4.2 and 4.3 in comparison with the objectives of the test runs. The subjective assessments done for each test runs is also discussed.

5.3.1 Steady-state cornering

The steady state cornering 100m maneuver tests across vehicle specification variation (refer table 3.4) in both CM simulations and driving simulator yielded the results displayed in section 4.2.1. The evaluation of vehicle specification variations from 3.4 can be observed in the table 5.1.

Table 5.1: Specification difference evaluation for SSC

Specification Variant	**Parameter Evaluation**
Spec1/ M1	Softer Front Spring
Spec2/ M2	Stiffer Front Spring
Spec3/ M3	Softer Front ARB
Spec4/ M4	Stiffer Front ARB

Figure 4.3 compares side slip angles for the different specifications at 100 km/h. It can be observed that the side slip angles show non-linear behavior at higher lateral accelerations. The side slip angles for vehicles with specifications M1 and M3 and vehicles with specifications M2 and M4 are clustered in either directions from that of the baseline vehicle specification. This shows that the changes made in M1 and M3 results in a higher magnitude of side slip for the same lateral acceleration, whereas that of M2 and M4 had lower side slip angle than baseline specification. The softer front Anti Roll Bar in M3 causes the vehicle to roll more and thereby reduces the extent of understeer. The same happens in the case softer front suspension than that in the rear in specification M1. It reduces understeer due to roll stiffness distribution between the front and rear. Therefore, specifications M1 and M3 have more aggressive attitude in a corner as compared to the rest, with M3 understeering the least at highest lateral acceleration. Specification M2 has the least side slip for given lateral acceleration and thus would be an appropriate direction of modification to the vehicle parameter because specification M2 is the most understeered when compared to the others.

From the comparison of roll angles at 100 km/h from figure 4.5, it can be observed that the roll angles increase linearly with increasing lateral accelerations across all specifications. The roll angles for the baseline specification is the least amongst all specifications inferring that the modifications made to the specifications of the vehicle results in a higher body roll as compared to that of the baseline vehicle. This can be intuitively concluded as well given the changes made to ARB stiffness as mentioned in table 3.4. Specification M3 has the highest roll magnitude, thereby the difference in roll angles as compared to the baseline vehicle can be perceived better with increasing lateral acceleration, when compared to other specifications.

It observed in figure 4.7 for steering wheel angle, specifications M1 and M2 have similar steering wheel angle at lower lateral accelerations, whereas they diverge at higher lateral accelerations. This can be attributed to the fact of M2 being more understeered than M1. This argument can be extended to specifications M3 and M4, where M4 is more understeered than M3.
Steering Torque characteristics can be observed in figure 4.9 where on comparison, modifications in spring stiffness has a significant influence on the steering torque demand as compared to modifications in ARB stiffness. It is observed that the steering torque is greater than the baseline for specification M2 at all lateral accelerations.

This is due the fact that a stiffer front suspension causes higher load transfer in the front than in the rear, causing the inside front tire to lose grip through the corner. This happens as the increased load goes beyond a point where the cornering stiffness of the tires at that speed reduces. The understeering effect can be felt by the driver as steering torque i.e. the heaviness in feel of the steering. The heaviness indicates the that the tire is trying to pull the car through the turn, dragging it almost in the process. As for specification M1, the steering torque is much lower than the baseline, which indicates less understeer or some oversteer as compared to the baseline vehicle specification. The loss of steering torque can be attributed to a softer front suspension than the rear. This causes more load transfer in the rear than the front, causing the rear to lose grip, making it oversteer. This can be felt by the driver as the steering wheel feel lighter and sensitive. Finally, the drop in steering wheel torque beyond 0.63g is because the car exceeds it's critical speed (about 92 km/h).

Similar arguments can be placed for the results at 40m steady state cornering (refer appendix B for results) to predict and correlate vehicle dynamics behavior from theory and practice.

5.3.2 Double lane change

The specifications and it's evaluation used for the DLC test is shown in the table 5.2.

Table 5.2: Specification difference evaluation for DLC

Variant	Parameter Evaluation
Spec5/ M5	Stiff Damper
Spec6/ M6	Soft Damper

Comparing the yaw rate peaks observed in figure 4.21 for M5 and 4.22 for M6 at 50 km/h, it is observed that the yaw rate has a higher peak average for M5 than M6. However, M6 reaches peak yaw rate faster than M5. Comparing the steering wheel torque for specification M5 in figure 4.25 and for specification M6 in figure 4.26 at 50 km/h shows that M5 and M6 produce similar steering torques.

Comparing roll angle observed in figure 4.19 for specification M5 and in figure 4.20 for specification M6 at 50 km/h, it is observed that the average peak for roll angle is higher for M6. This can be attributed to the softer damper introduced in the vehicle.

5.4 Subjective assessment

5.4.1 Steady-state cornering

The subjective assessment made for the vehicle specifications tested for SSC 100m maneuver are recorded as per the rating scale discussed in section 3.8. The characteristics observed while driving the baseline vehicle specification were considered as a starting point for subjective assessment and therefore given a rating of 5. The vehicle specification M1 when compared to baseline specification vehicle showed similar performance in terms of available grip, but the other characteristics such as roll angle, steering wheel angle and steering wheel torque were not desirable and had lower rating in these aspects. The specification difference felt in terms of availability of grip and steering wheel torque demand had largest difference from the baseline vehicle.

The vehicle specification M2 when compared to baseline vehicle, was given a lower rating in the availability of grip and had similar rating in the other observed characteristics as baseline vehicle. The specification difference felt in steering wheel torque demand and the availability of the grip were the largest difference from the baseline vehicle. Similarly, vehicle specification M3 had lower rating in all the characteristics similar to M2. But, the specification difference felt in vehicle roll was largest compared to other vehicle specifications. The steering torque demand and side slip angle difference are given lower specification difference felt.

The vehicle specification M4 has the best rating when compared to the other varied vehicle specifications. The drivers perceived the modification to be similar to baseline specification such as steering wheel torque, a small lower roll angle and low availability of the grip rating, but the steering wheel angle characteristics was found desirable more than the baseline specification. The vehicle specification difference was low in terms of steering wheel torque demand and steering wheel angle.

The SA rating of the vehicle characteristics were not entirely reflective of the parameter changes made on the vehicle and felt by the driver. The reason for adapting a different SA scale i.e specification difference explained in 3.8 allows driver to show the magnitude of change felt with changing the parameter. Thus, to avoid misinterpretation from SA rating from the drivers in the project, the SA specification difference has proved to be a good indicator to understand the vehicle parameter variation made in steady state cornering maneuver test.

An average of the specification ratings from the test drivers was computed for each metric. These averages were summed for each vehicle specification to get an overall understanding of the vehicle behavior in the driver's perception (refer figure 4.43). It can be observed that the modifications made to the vehicle specifications (M1, M2 and M3) in the test runs did not meet the driver's expectations when compared to the baseline vehicle specification. Specification M4 however could be considered to have imparted a similar sense of overall vehicle dynamics behavior.

5.4.2 Double lane change

An observation from figures 4.44 and 4.45 of the average assessment of the drivers for yaw rate or response, steer torque and roll at 50 km/h and 60 km/h is made.

At 50 km/h, the drivers on average felt a decrease in response for vehicle specification M5 as compared to the baseline model. As for M6, the drivers felt a higher or faster response as compared to the baseline model. At 60 km/h, the drivers felt similar response characteristic for M5 as they did for the baseline. Then for M6, they felt a slower response than the base.

Comparing the assessment on steer torque, the drivers felt the same steer torque for M5 as compared to the base model while they found a little increase for M6 at 50 km/h. At 60 km/h, the drivers felt very slight changes in steer torque for both M5 and M6 with M5 getting a rating of 5.67 suggesting a small increase in steer torque while M6 being rated at 4.8 suggesting a small decrease in steer torque.

The roll angle subjective assessment shows that the drivers felt a very small increment in roll angle at 50 km/h for both M5 and M6 versus the baseline. However at 60 km/h, specification M6 was felt to roll much more than the baseline model with a rating of 6.3 as compared to 5 of the baseline, as result of lesser damping.

5.5 Objective metrics and subjective assessment

5.5.1 Steady-state cornering

The correlation between the objective metrics and the subjective assessment are found to be good in vehicle roll angle characteristics (figures 4.5 and 4.36) and steering wheel torque demand (figures 4.9 and 4.38) characteristics. The SA recorded to show the 'specification difference' in figure 4.36 and 4.38 were felt in driving different vehicle specifications were reflective of the objective metric changes. The sensitivity to feel the vehicle roll angle and steering wheel torque demand was well perceived by the driver on the simulator through visual, motion cues and steering wheel force feedback.

5.5.2 Double lane change

The SA questions are as shown in table 3.11. The driver ratings as seen in figures 4.44 and 4.45 are compared with the specification difference evaluation in section 5.3.2 to provide an understanding of whether the parametric changes made in the vehicle models (M5 & M6) were physically felt by the simulator drivers.

For the first SA that evaluates vehicle roll, Model 6 is given a higher 'vehicle roll' rating than Model 5. This matches the specification difference evaluation made between the two models. This result is as expected since the damper stiffness of the suspension was reduced for M6.

For the second SA, which questions the driver's experience in terms of steer torque required in the maneuver, the drivers felt a small difference in torque requirement in the M5 and M6 model. This reflects the similar values of steering wheel torque in the specification difference evaluation.

The third SA evaluating steering response is also rated quite close to the baseline model which reflects that the drivers do not feel a high level of change in the steering response when driving the M5 & M6 models.

5.6 Future work

5.6.1 CarMaker integration

The implementation in the Cruden simulator uses Panthera as the audio engine, which works good but has room for improvement. Specifically in terms of the skidding sounds, where there is a mismatch between CarMaker units and Panthera units. This means that the set skidding values set in Panthera provides a bit too much sound. Tuning the levels should be done, for example there is a but too much road and wind noise at low speeds.
Work should be done with making sure the starter button works and is implemented correctly in the Simulink model and hooked up to the correct CarMaker variables.
It was found that it would be good to provide the driver with additional input on the dashboard, for SSC useful data would be longitudinal acceleration as it would aid the driver achieving steady state by seeing it at a glance.
Some performance benefits might be obtained by emptying the Panthera vehicle graphics, i.e. removing all 3d models.
Proposed work items

- Sounds - Tune levels, fade in/out and check variables
- Dashboard - Check the correlation between speed in the Simulink model and shown speed on dash.
- Starter button - Check CarMaker functionality
- Dashboard RPM - Implement driver feedback with the shift-lights
- Panthera track and car - Optimizing the Panthera track and car model for minimum computational impact.

5.6.2 Vehicle specification

The vehicle specification used in this project is a generic SUV model with typical values for an SUV in the large size class. The project has implemented as much data as possible that is correct and relevant for the project. However, there are some limitations with the model that should be addressed to provide more accurate results in relation to the real vehicle.
Proposed work items

- Suspension model - Create an accurate model
- Powertrain - Improve the differential models
- Tire models - The used tire models is a generic and may not be specific to the SUV segment.

Bibliography

[1] Caster. *Engineers in the front seat*. 2020. URL: https://www.casterchalmers.se (visited on 12/01/2020).

[2] Cruden. *Customers*. 2020. URL: https://www.cruden.com/customers/ (visited on 12/21/2020).

[3] G. Gil Gómez et al. "Objective metrics for vehicle handling and steering and their correlations with subjective assessments". In: *International Journal of Automotive Technology* 17.5 (2016), pp. 777–794. URL: https://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-169083.

[4] IPG Automotive Group. *Programmer's Guide CarMaker, Version 8.1.1*. 2019.

[5] *Passenger cars - Test track for a severe lane-change manoeuvre — Part 2: Obstacle avoidance*. Standard. Geneva, CH: International Organization for Standardization, Mar. 2011.

[6] *Passenger cars - Steady-state circular driving behaviour - Open-loop test methods*. Standard. Geneva, CH: International Organization for Standardization, Mar. 2012.

[7] B. Jacobson. *Vehicle Dynamics Compendium*. Vehicle dynamics group, Division Vehicle, Autonomous Systems, Department Mechanics, and Maritime Sciences, Chalmers University of Technology, 2019.

A

Baseline vehicle specification in IPG CarMaker

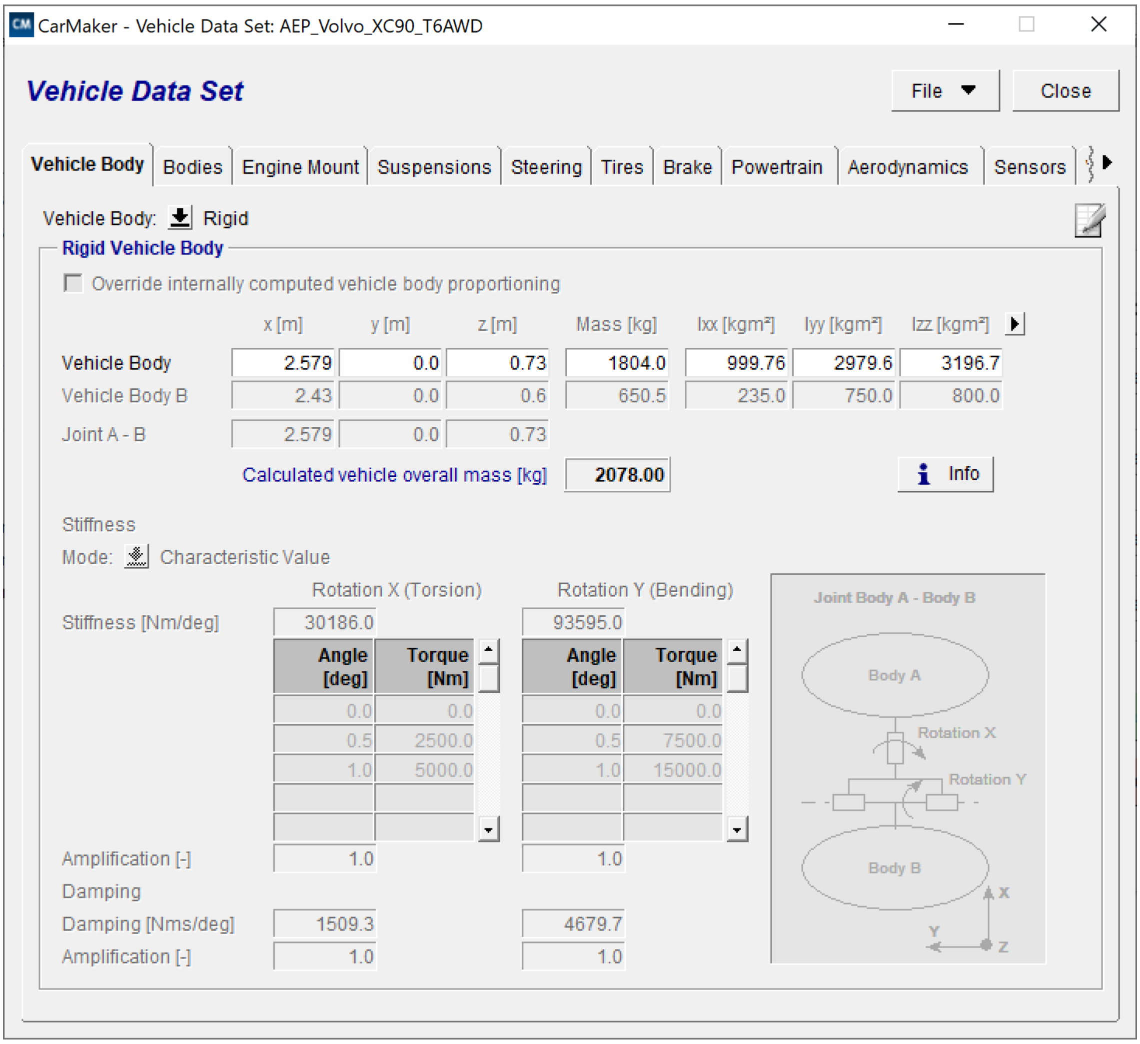


Figure A.1: Base model dimensions

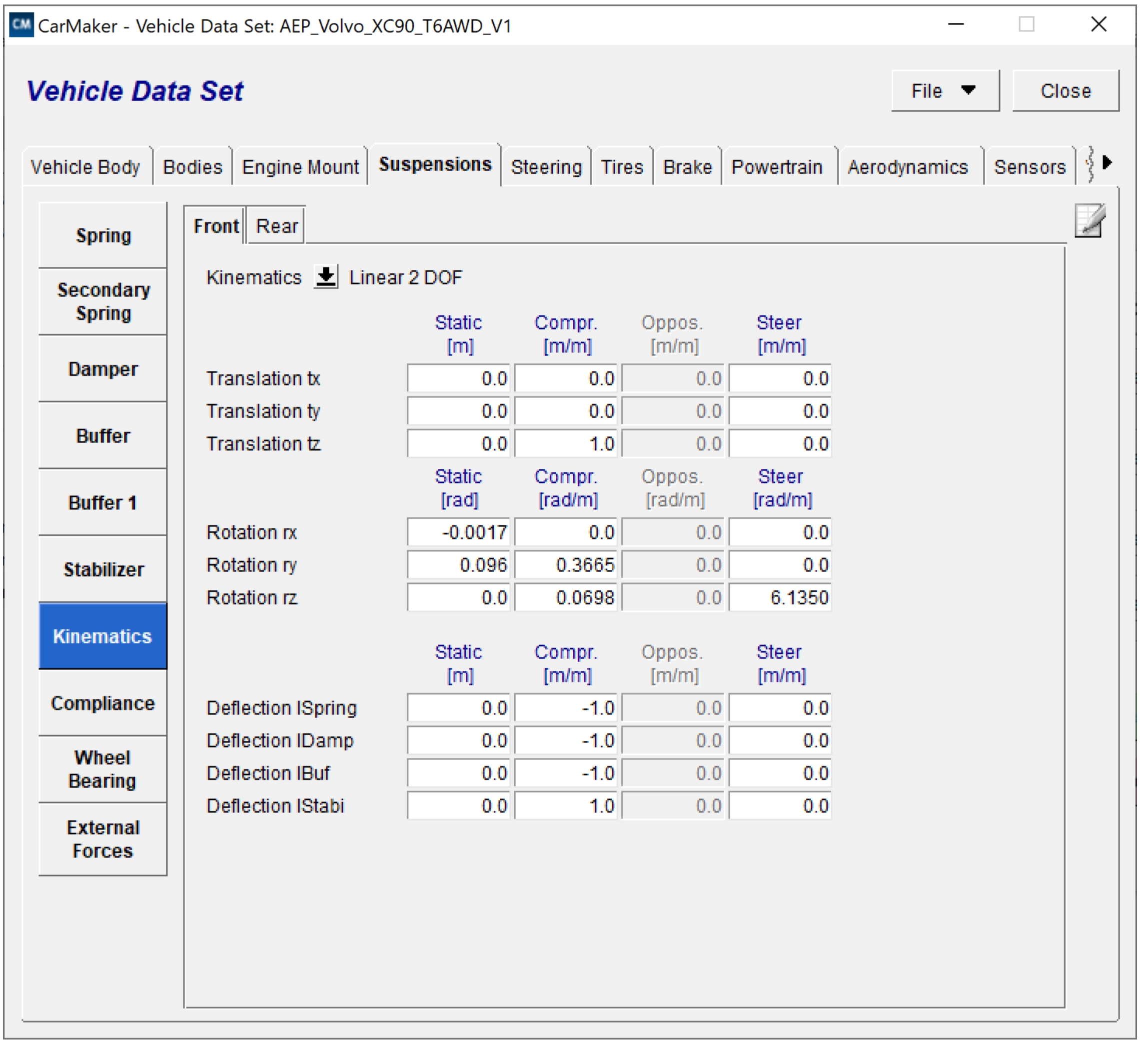


Figure A.2: Front kinematics

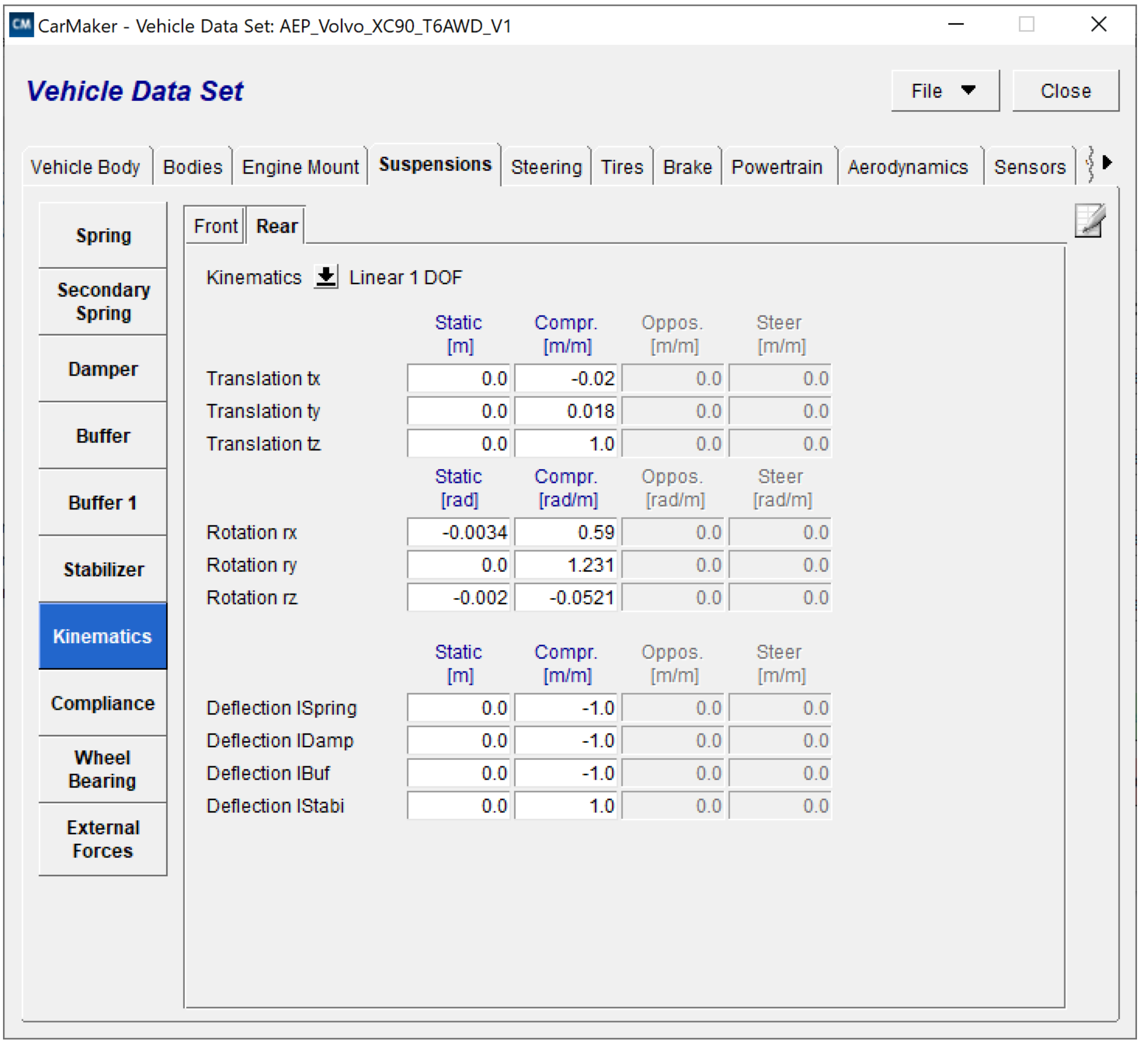


Figure A.3: Rear kinematics

B

Steady-state cornering 40m objective metrics and subjective assessment results

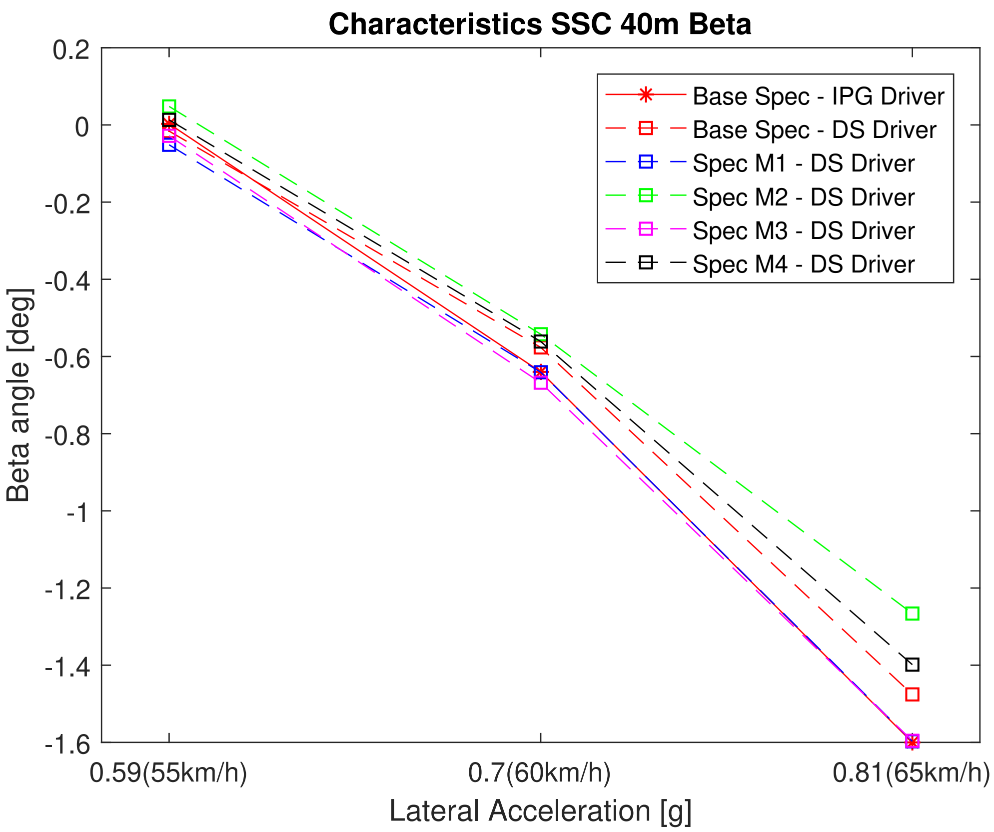


Figure B.1: Steady-state cornering 40m - side slip angle characteristics

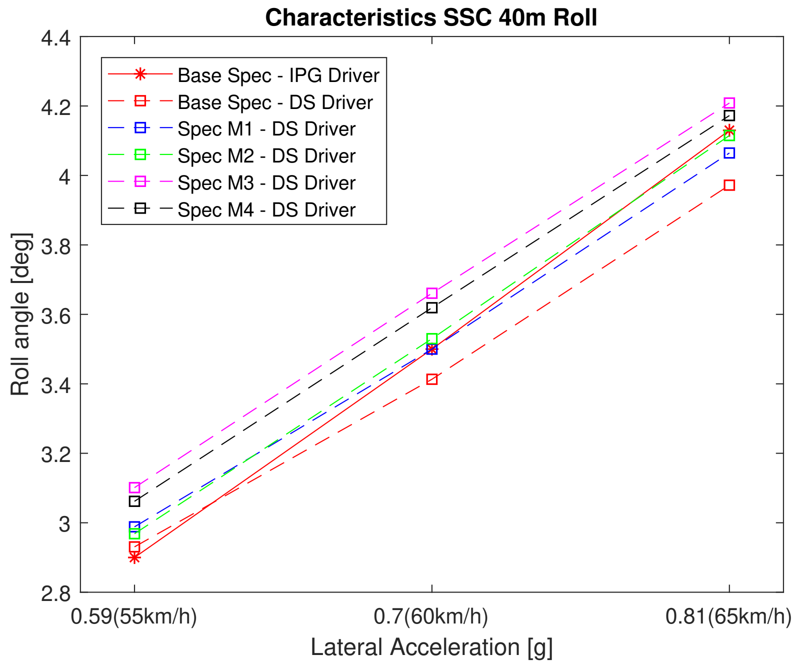


Figure B.2: Steady-state cornering 40m - vehicle roll angle characteristics

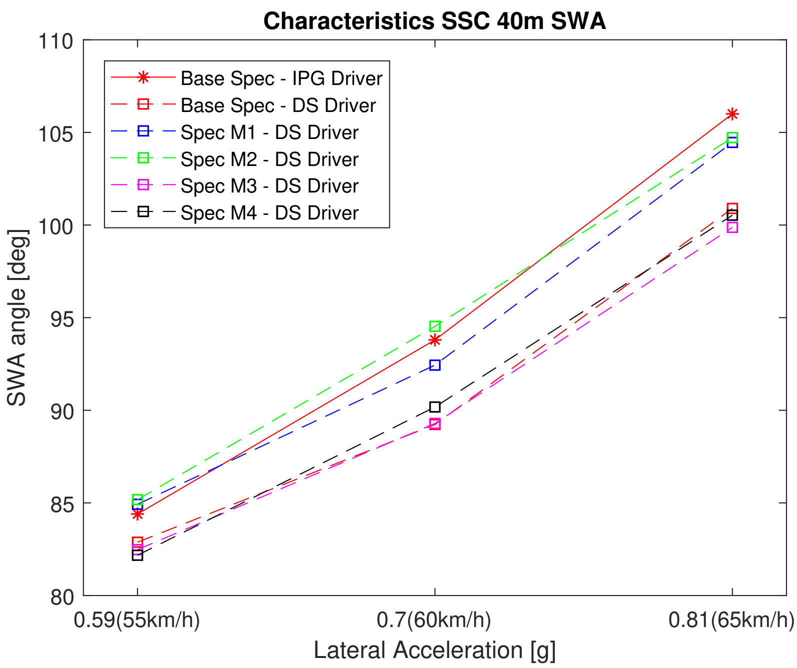


Figure B.3: Steady-state cornering 40m - steering wheel angle characteristics

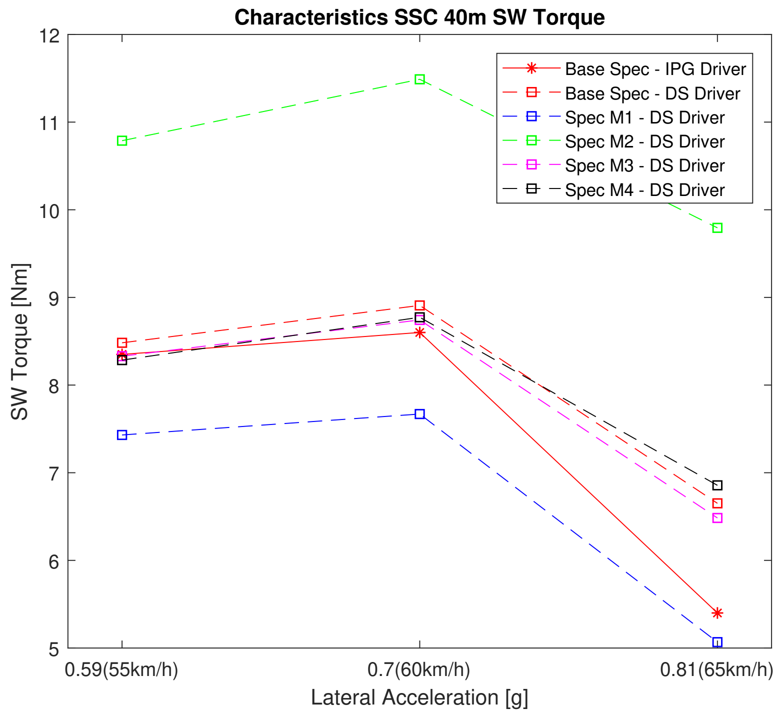


Figure B.4: Steady-state cornering 40m - steering wheel torque characteristics

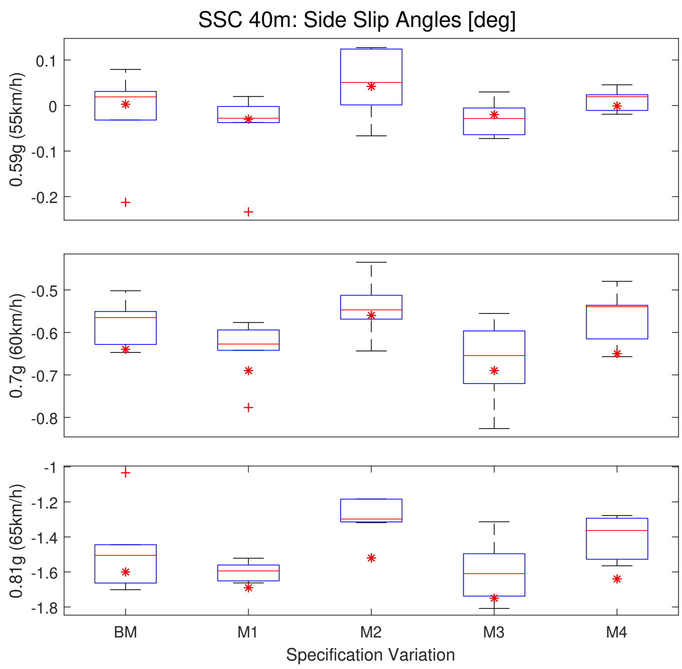


Figure B.5: Steady-state cornering 40m - side slip angles and data distribution

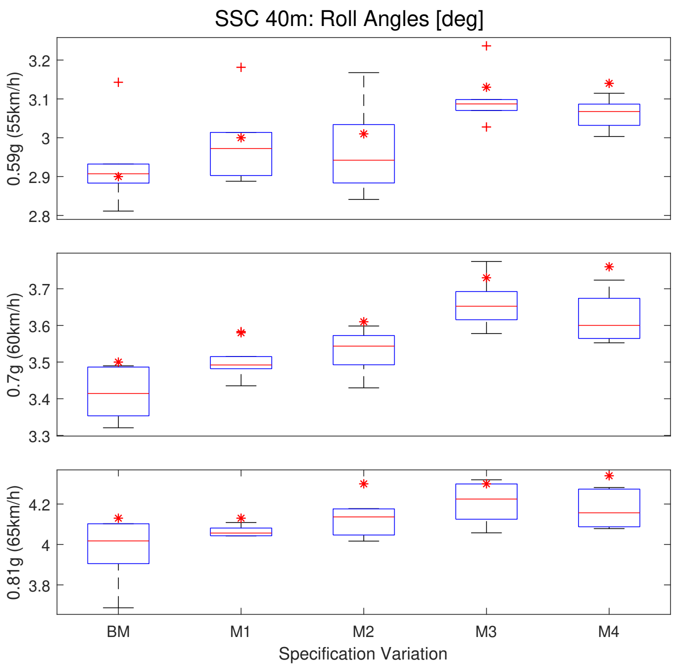


Figure B.6: Steady-state cornering 40m - vehicle roll angles and data distribution

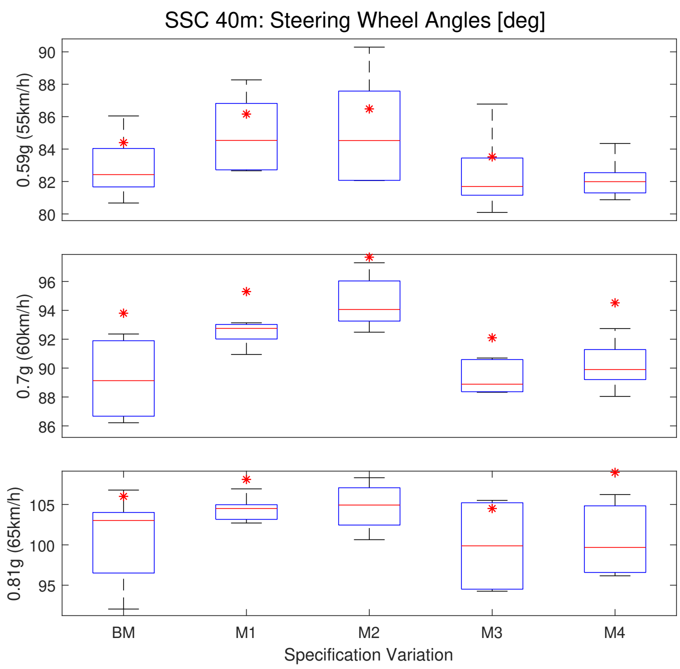


Figure B.7: Steady-state cornering 40m - steering wheel angle and data distribution

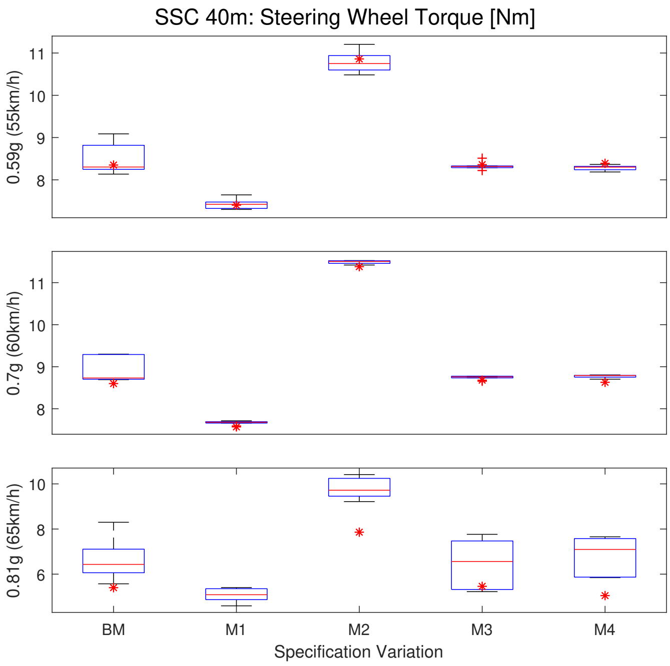


Figure B.8: Steady-state cornering 40m - steering wheel torque demand and data distribution

B.1 Subjective assessment results

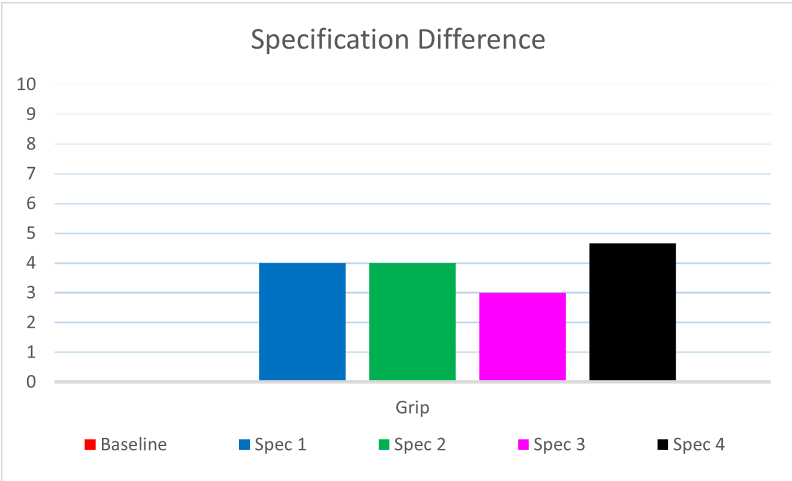


Figure B.9: Vehicle specification difference felt in grip for SSC 40m

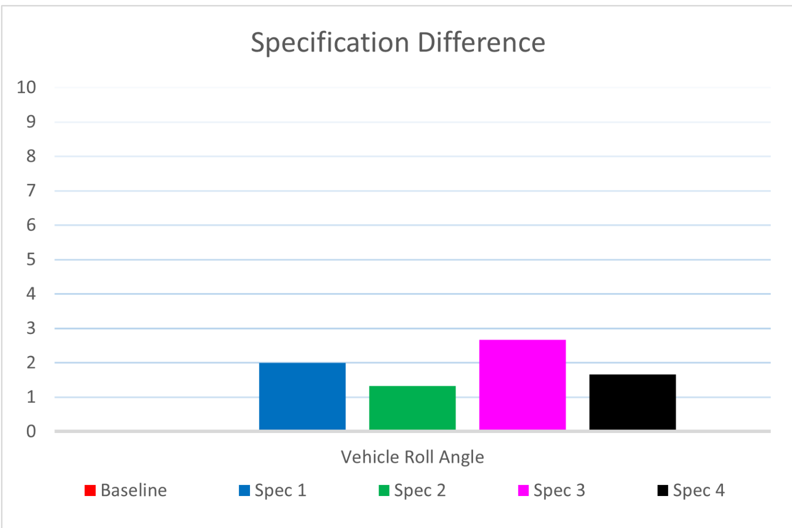


Figure B.10: Vehicle specification difference felt in vehicle roll angle for SSC 40m

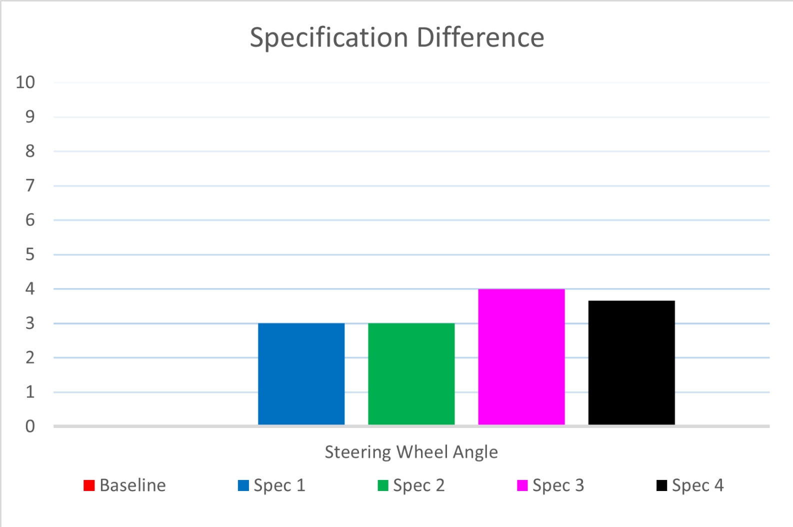


Figure B.11: Vehicle specification difference felt in steering wheel angle for SSC 40m

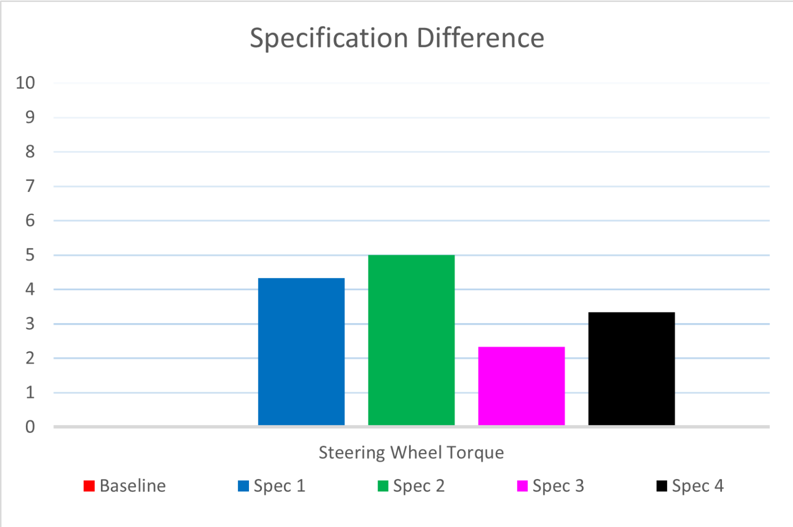


Figure B.12: Vehicle specification difference felt in steering wheel torque demand for SSC 40m

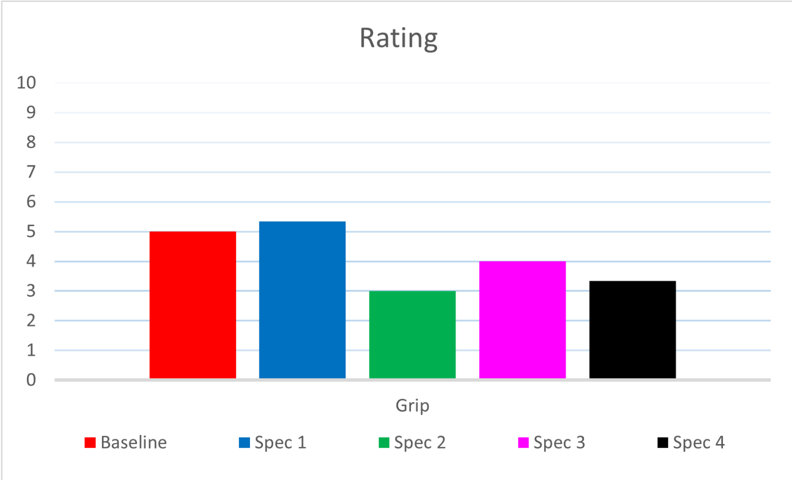


Figure B.13: Vehicle specification rating for grip for SSC 40m

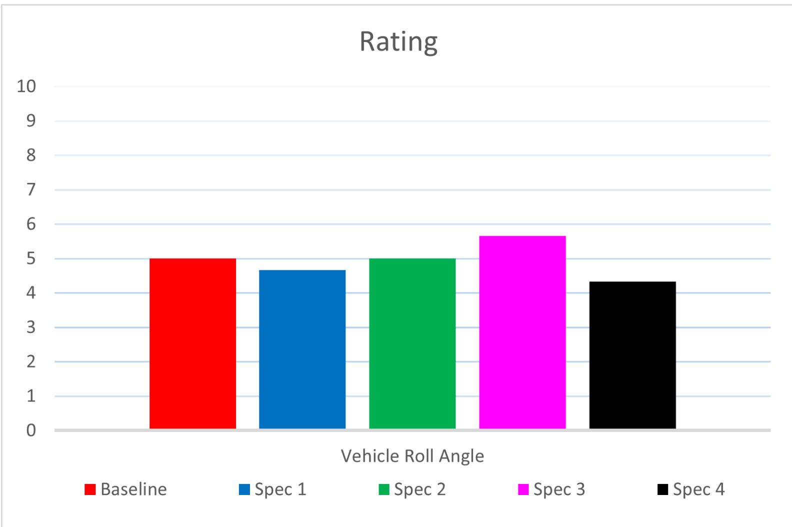


Figure B.14: Vehicle specification rating for vehicle roll angle for SSC 40m

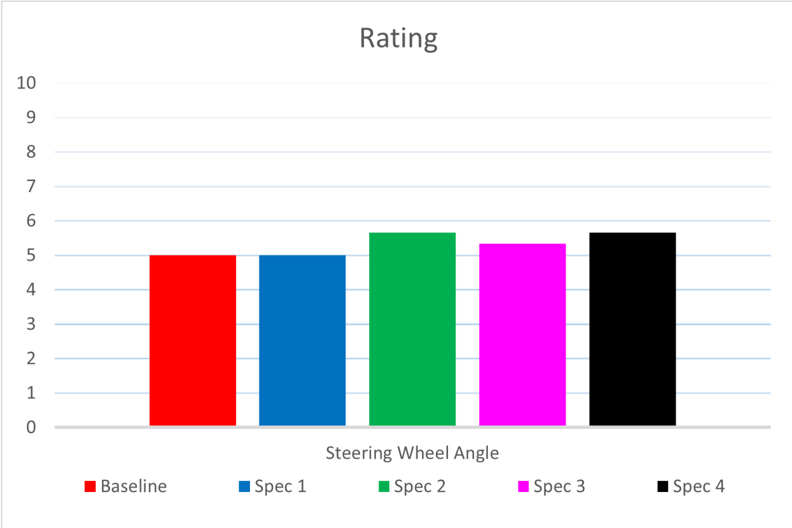


Figure B.15: Vehicle specification rating for steering wheel angle for SSC 40m

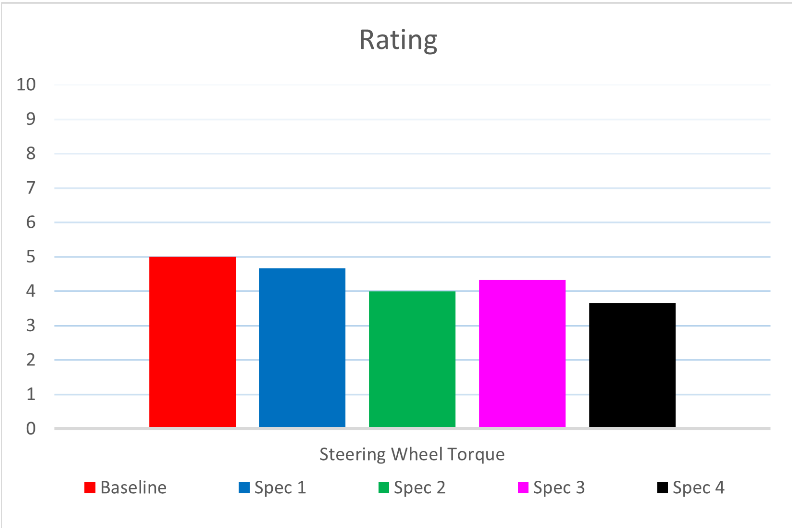


Figure B.16: Vehicle specification rating for steering wheel torque demand for SSC 40m

C

Simulink model

Larger image of the Simulink model used to integrate CarMaker in CASTER