Czech Technical University in Prague

Faculty of Mechanical Engineering

Department of Automotive, Combustion Engine and Railway Engineering

Development of a virtual car model and subsequent physical validation

DIPLOMA THESIS

Study program: Master of Automotive Engineering

Field of Study: Advanced Powertrains

Supervisor: Ing. Václav Jirovský, Ph.D.

Jakub Záhorský

Prague 2018

Volba jistoty.
Více hodnoty.

!!!!! Na toto místo před svázáním VLOŽIT ORIGINÁLNÍ ZADÁNÍ PRÁCE

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I hereby declare that this thesis is my own work and that, to the best of my knowledge and belief, it contains no material which has been accepted or submitted for the award of any other degree or diploma. I also declare that all the software used to solve this thesis is legal.

I also declare that, to the best of my knowledge and belief, this thesis contains no material previously published or written by any other person except where due reference is made in the text of the thesis.

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Date: August 2018

Abstract

The goal of this master thesis is to optimize approaches to the universal methodology for the creation of virtual car models based on physical testing of real cars. Nowadays, the rapid development of ADAS technology forces us to find new ways of car testing. Since the complexity and amount of possible scenarios which have to be considered to ensure the right functionality of the systems is too high, it makes complex physical testing impossible. This leads to a necessity for software simulation testing, which will help us to test the systems in more efficient, quicker and less expensive way. It is, however, necessary to have an appropriate virtual environment to run these tests correctly. This means that the virtual car model has to behave as close to the real car as possible. The thesis shall cover the following topics:

- A literature review of current approaches in dynamic model development
- Building up a test list which will prove the accuracy of the virtual model
- Running these tests both in real and virtual world
- Compare the results and suggest the approach which will ensure reasonable accuracy in general use

Key words

Virtual testing, IPG CarMaker, ADAS, vehicle dynamics, test driving, model calibration, simulation, validation

Acknowledgements

I was very lucky to be able to write my thesis about the topic I am very familiar with. For the last 18 months, I have been working as an intern in TÜV SÜD Czech, where I was a member of a small team, which is aimed at Highly Autonomous Driving (HAD). Thanks to this opportunity I knew what this topic is about even before starting the thesis because as an intern I attended a lot of international conferences concerning autonomous vehicles. I am also very glad that my work will have a practical use for the company and its employees. Thank you for all the experience you gave me, TÜV SÜD.

I would like to thank to my colleagues, who were always kind to help me with my problems and questions. Namely *Patrik Zíta* and *Vojtěch Hujňák*. Not only you two have been the best colleagues one can have, but you helped me a lot many times.

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Last, but definitely not the least thank you goes to my beloved family, who has always supported me during my studies not only mentally, but also financially. Without them, it would be much harder, if not impossible to finish my studies. Dear Marcela, Petr, and Honza, thank you very much for all your support and patience!

J.Z.

I also would like to exploit the opportunity to add one greatly personal remark. This thesis, as a final outcome of my master studies, will always remind me that really nothing is impossible, no matter which obstacles the life surprises us with, it only requires time, patience and strong will to overcome them. I am truly glad to be able to write those lines with both my hands, because that's what was my greatest wish I had almost exactly 3 years ago, when, instead of starting the first semester of master studies with my friends and schoolmates, I was in the hospital fighting for my life. I am so grateful for my second chance and will never forget to appreciate how precious the life is.

Nomenclature

Symbol list

a	$[m/s^2]$	Acceleration
f	$[Hz]$	Frequency
m	$[kg]$	Mass
P	$[W]$	Power
v	$[km/h]$	Velocity

Abbreviations

ABS	Anti-lock Braking System
ACC	Adaptive Cruise Control
AD	Automated Driving
ADAS	Advanced Driver Assistance Systems
AEB	Automatic Emergency Brake
BSD	Blind Spot Detection
COG	Centre of Gravity
EBA	Emergency Brake Assist
ECE	Economic Commission for Europe
ECU	Electronic Control Unit
ESC	Electronic Stability Control
ESP	Electronic Stability Program
EU	European Union
Euro NCAP	European New Car Assessment Programme
EV	Electric vehicle
FA	Front Axle
FL	Front Left Wheel
FMVSS	Federal Motor Vehicle Safety Standards
FR	Front Right Wheel
GUI	Graphical User Interface
HiL	Hardware-in-the-Loop
ISO	International Organization for Standardization
KPI	Key Performance Index
LDW	Lane Departure Warning
LiDAR	Light Detection and Ranging
LKA	Lane Keeping Assist
NHTSA	National Highway Traffic Safety Administration
OEM	Original Equipment Manufacturer

RA	Rear Axle
RaDAR	Radio Detection and Ranging
RL	Rear Left Wheel
rpm	Revolutions per Minute
RR	Rear Right Wheel
SAE	Society of Automotive Engineers
SiL	Software-in-the-Loop
VDSG	Vehicle Data Set Generator

Contents

1. Introduction

This very first chapter shall present a brief synopsis of this thesis as well as an introduction to the topics covered in this thesis. Section 1.1 explains the motivation for this thesis and the main goals. Section 1.2 describes the background to better understand the topic. Section 1.3 is about ADAS technology since the ADAS is one of the main reasons to test the vehicles virtually. The succeeding section 1.4 describes the ways how to test ADAS. Section 1.5 is about the regulatory. Section 1.6 presents the review of the current state in vehicle modelling. And finally, in section 1.7 some of the necessary remarks concerning the topics covered by this thesis are covered.

1.1. Objectives and main goals of the thesis

The assignment of this thesis came during my internship in TÜV SÜD Czech because the company needed to have a clearly defined process to follow when building up a virtual model of a vehicle. TÜV SÜD is a company with more than 150 years of history and experience, providing technical service for its customers and having automotive industry as one of its main scopes, being an innovative development partner for the automotive industry manufacturers. The company provides testing, certification, homologation and inspection services and naturally wants to do so even in the nearby future in the field of advanced driver assistant systems and autonomous vehicles. Having its own proving ground and high end measuring and testing equipment, TÜV SÜD Czech is very strong in the field of physical testing. With the current changes in the world of automotive industry towards the autonomous driving, the logical step is to support physical testing with the virtual simulation and provide a complex solution for future type approvals, testing and eventually for cooperation and projects within the automotive industry.

As an independent company, we have a very limited access to the parameters and technical specifications of the vehicles. This kind of information is an internal secret of each manufacturer or supplier and we only get access to a commonly available data, which makes the model development very challenging. Also, only a limited number of parameters is possible for us to measure. This means that e.g. tyre characteristics, chassis stiffness, damper characteristics or suspension kinematics, remains unknown to us, as specifically discussed in chapter 5. Lack of knowledge about these parameters means we have to either estimate it or neglect it, depending on its importance and complexity. These issues got us to the need of some kind of procedure, which when followed, will make the future work somewhat easier, reliable and will speed up the process of modelling.

I tried my best to find the way how to build an accurate model of the vehicle while having only a limited amount of knowledge and financial resources. Physical testing is very expensive to do, so it was my job to define the list of necessary tests to perform in order to measure relevant data and to obtain the information about the vehicle's behaviour while keeping the costs reasonable.

Very important is to remember the purpose of the models we create, because that defines the desired accuracy which is reasonable for us. As long as our scope is not the development of the suspension nor finding the right setup for a sports car, we don't need the virtual car to drive and behave exactly like the real one, which is not even possible after all. For our purposes, the accuracy does not have to be somewhat high, because the car should get to its physical limits very rarely (i.e. during emergency braking), if ever. Also, every parameter measured during the physical testing is of different importance for each case, some of them being even not even relevant for us, so the KPIs had to be defined, based on the experience and knowledge about ADAS and for each case individually. Different applications of ADAS have different vehicle dynamics parameters critical for them. Generally speaking, the most important vehicle dynamics parameters for the use of ADAS are roll and pitch of the vehicle, because it directly influences the field of view of the sensors. The importance of concrete parameters is further described in the chapter concerning the simulation results.

To sum all the things above up, this thesis should be a clear framework or even kind of a "cookbook" describing a process of a virtual vehicle model build for everyone in our company, who will be working with IPG CarMaker, to make his work more effective or to help new employees to learn and make their first projects easier to cope with. However, elementary knowledge of CarMaker is required. The table below clearly presents goals of this thesis.

Table 1 - Assignment of the Thesis

Given name for the Thesis	*Development of a virtual car model and subsequent physical validation*
Requirements defined	• A literature review of current approaches in dynamic model development
	• Building up a test list which will prove the accuracy of the virtual model
	• Running these tests both in real and virtual world
	• Compare the results and suggest the approach which will ensure reasonable accuracy in general use

1.2. Background

Modern society is absolutely dependent on cars and other means of transportation. As for the cars alone, millions of people commute to work and back home on a daily basis, and the car is clearly an essential part of their life. Speaking of the importance of cars, it also has to be considered that faster and easier transportation has led to an acceleration of economic growth during the 20th century. And for Europe, the automotive industry itself is one of its key economic fields, having more than 12 million European citizens employed in automotive business [1]. Therefore, the role of cars is absolutely crucial in our everyday lives and now, the whole automotive industry is on the eve of major technological changes, which are already happening now and will continue to happen even more rapidly in the very close future, so it’s really important to be ahead and be prepared for them. The change I’m talking about is that in the upcoming years the cars will slowly take over the control from the driver, who will no longer be considered as a driver, but as a passenger. This will necessarily lead to new approaches in development and testing, which exactly is what this thesis shall contribute to.

Ever since its first introduction in the 19th century, cars have always been continuously developed and improved towards increasing comfort, performance, efficiency and safety. In modern, first world countries, safety is the market’s demand number one, and manufacturers are naturally trying to meet the expectations of their customers. And not only needs of the customers, but the cars also have to perform safely according to the legislation, that defines approval regulations and criteria, which have to be fulfilled in defined tests. These regulations are defined e.g. by ECE and EU for Europe or NHTSA and FMVSS for United States Of America. Hand in hand with the growing importance of personal transportation comes the increasing density of traffic. It is estimated that in 2010, there were more than 1 billion cars worldwide [2]. The higher number of cars on roads ultimately leads to higher risk of collision, setting the importance of safety even higher than ever before.

When it comes to safety, the main scope for car manufacturers has almost always been a passive safety, however in recent years, thanks to the massive technological leap, car manufacturers started to focus more and more on the active safety aspects. The difference between passive and active safety is that the target of the passive safety is to mitigate the consequences of the collision in cases when collision avoidance no more possible, whilst the target of the active safety systems is to avoid the collision itself. Passive safety involves mainly the restraint systems, first of which were introduced approximately in the 1950s, when manufacturers started to equip their cars with seatbelts and later with airbags, both of which are designed to prevent the occupants from having a secondary impact with the interior parts of the car. The most critical part of passive safety, however, is the construction of the vehicle alone. Its crumple zones help to absorb the impact energy, whilst the body has to be rigid enough to provide enough space for the crew even when deformed after the impact. As for the active safety, it involves such things as a mechanical condition of the car (brakes, tyres), view from the car, seating position or even ride comfort to keep the driver fresh and focused, and therefore able to avoid a collision. From the technological point of view, active safety involves, for instance, ABS to prevent wheels from locking up when braking or ESP to keep the vehicle stable at the limit of its handling capabilities. These systems help the driver to control the car even in critical situations and contribute to prevent the collision, but the driver has to act all by himself. Systems, which can literally take over the control and avoid the collisions are called ADAS, further described in section 1.4. ADAS contribute both to the safety itself (by avoiding the collision) and to the comfort of the driver, who has to operate less controls (i.e. when driving a car equipped with an ACC, driver does not have to operate a gas pedal nor brake, only thing to operate is the steering wheel) and therefore gets tired later, which makes the drive safer. [3]

However, these active systems can only be beneficial if they are working in the manner they are supposed to. Manufacturers and suppliers have to secure that the system will work correctly in every possible situation, which is a quite challenging task. Regarding the malfunctions of the systems, it is considered that the better case of improper function is when the system does not take any action when it is supposed to (because the collision would happen anyway), than when the system activates when not expected and needed, i.e. unexpected activation of AEB – sudden hard braking during the overtaking manoeuvre in high speed can cause critical situation, which would otherwise never happen if the system would not unexpectedly intervene [4]. Technology is only as flawless as the people who create it. And people always tend to make mistakes, especially when designing such complex systems, which consist of some very complicated algorithms with thousands of code lines. Hence the ADAS have to be thoroughly tested, which is a very challenging issue, as described more in detail in section 1.5.

This master thesis presents the way how to develop a sufficiently accurate (for the use of ADAS testing) model of a real car and how to verify its compliance with the real one by running several essential test cases to compare the driving behaviour of both. This virtual vehicle model could then be used for virtual testing of ADAS. The virtual simulation will soon be a very powerful tool during the development and testing of such systems, as well as for their approval.

1.3. ADAS

Acronym ADAS stands for Advanced Driver Assistance Systems, a collective term for a set of electronic systems, which are designed to help the driver, increase his comfort and safety by correcting his errors. These systems can be generally characterized by their direct intervention to the driving [7]. ADAS also involves the field of vehicle dynamics, smart infrastructure and interconnected traffic. Generally, ADAS can be divided into the following categories: lateral control, longitudinal control and parking aids [5]. Also, it is important to know the difference between assisted, automated and autonomous driving. Following overview makes the difference clear [6]:

- **Assisted driving**
  The driver has to activate the function consciously and may exceed it at any time. The driver also permanently monitors the ambient environment and in critical situations, his response is required.

- **Automated driving**
  The driver has to activate the function consciously and may exceed it at any time. The system monitors its function limits and when it reaches the limits, the control is handed over back to the driver. The driver is allowed to do his own activities but is obliged to keep himself ready to take over at any time.

- **Autonomous driving**
  The system controls the driving task all the time and in all situations. The driver still might take over the driving if he wishes as far as the vehicle concept allows it.

Having all the terms above clearly defined, it is also important to mention universally accepted levels of automation among cars, defined by SAE [8]. This ranking describes 6 different levels, defined in figure 1:

Level	Name	Narrative definition	Execution of steering and acceleration/ deceleration	Monitoring of driving environment	Fallback performance of *dynamic driving task*	System capability (*driving modes*)	BASt level	NHTSA level
Human driver monitors the driving environment								
0	No Automation	the full-time performance by the *human driver* of all aspects of the *dynamic driving task*, even when enhanced by warning or intervention systems	Human driver	Human driver	Human driver	n/a	Driver only	0
1	Driver Assistance	the *driving mode*-specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	Human driver and system	Human driver	Human driver	Some driving modes	Assisted	1
2	Partial Automation	the *driving mode*-specific execution by one or more driver assistance systems of both steering and acceleration/deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	**System**	Human driver	Human driver	Some driving modes	Partially automated	2
Automated driving system ("system") monitors the driving environment								
3	Conditional Automation	the *driving mode*-specific performance by an *automated driving system* of all aspects of the *dynamic driving task* with the expectation that the *human driver* will respond appropriately to a *request to intervene*	System	**System**	Human driver	Some driving modes	Highly automated	3
4	High Automation	the *driving mode*-specific performance by an *automated driving system* of all aspects of the *dynamic driving task*, even if a *human driver* does not respond appropriately to a *request to intervene*	System	System	**System**	Some driving modes	Fully automated	3/4
5	Full Automation	the full-time performance by an *automated driving system* of all aspects of the *dynamic driving task* under all roadway and environmental conditions that can be managed by a *human driver*	System	System	System	**All driving modes**	-	

Figure 1 - Levels of automation defined by SAE [9]

1.3.1. Systems and sensors [7]

ADAS need many sensors to operate. Those sensors are of several different kinds and physical principles, further described below. Figure 2 clearly shows the application of each kind of sensor used nowadays.

All of the image acquiring systems, including RaDAR, LiDAR or camera, has to be able to analyse obtained data. This is done by two different methods, which can also be used simultaneously.

The first method of data analysing is called *pattern recognition* and works with a database of well-known shapes and patterns, which are used to compare the obtained image with.

The second method compares two or more sequentially taken images and finds changes of individual points in them. From these changes, the positions and movement direction are determined.

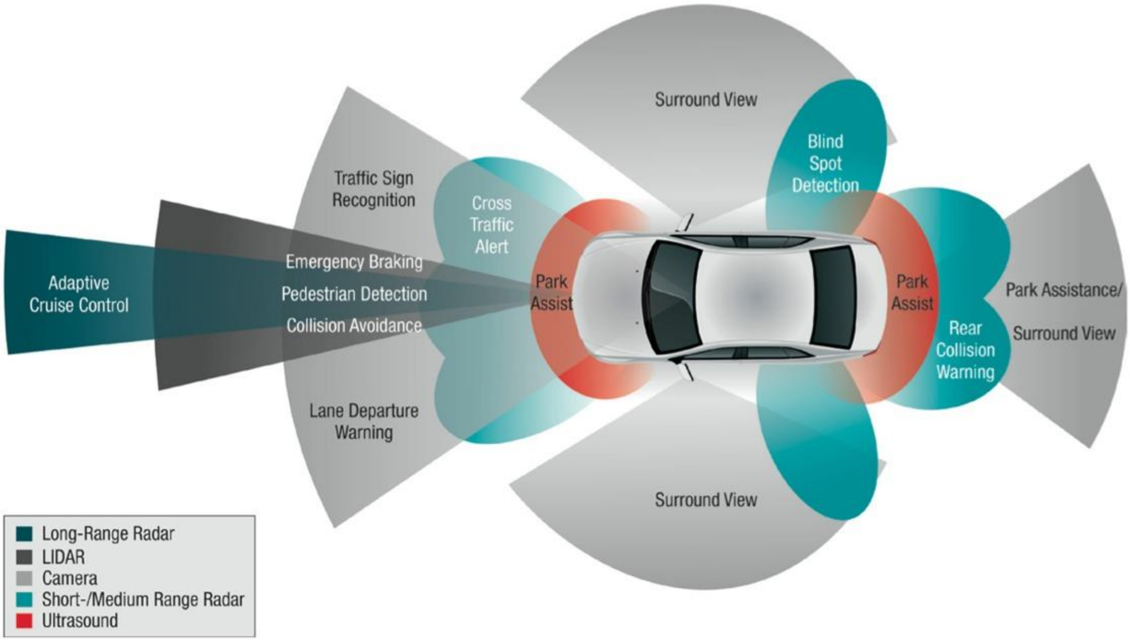


Figure 2 - Sensors in Vehicles [12]

RaDAR (Radio Detection and Ranging)

Transmitter creates and emits high-frequency electromagnetic pulses, which are spreading through free space and are reflected by objects within the RaDAR range. Reflected waves, called echo, are then detected by the receiver. The RaDAR processor calculates the direction and the distance of the reflecting object from the delay and angle of the received echo waves [13].

LiDAR (Light Detection and Ranging)

The principle of LiDAR is very close to the principle of RaDAR. The main difference is that LiDAR emits laser light with a wavelength of around 900 nm, which is reflected from the objects in the same manner as RaDAR waves are. Use of the LiDAR is mainly for low-speed interurban driving since the range of such device is only 10 – 20 m. LiDARs can also be used for lane keep assist systems.

Camera systems

Cameras used in modern cars are of two types, first type working in the visible spectrum of the light in wavelengths of 380 – 780 nm and the second type in spectrum close to the infrared light (780 – 1400 nm). Cameras are used for imaging both the surrounding environment and the interior and their range depends on their parameters - mainly on the frame frequency and resolution.

Images are captured in black and white colour scheme and the resolution of the cameras is kept as low as possible to keep the computing demands reasonable [4]. Camera systems are sensitive to weather conditions and therefore used mainly as a supplement device to the radar sensors.

Ultrasonic sensors

This type of sensors is used for low-speed applications only, due to its very limited range and difficulties with directing the wide signal cone, which leads to the inaccurate determination of objects. Mainly used for parking assistant systems, having a range of 3-10 m with an accuracy of around 5 cm.

A brief overview of the most important and most frequently used systems follows [11]:

Adaptive Cruise Control

Adaptive Cruise Control (ACC) is a system for automated speed management which automatically adjusts the speed of the vehicle in a way to match the speed of the car ahead while maintaining the safe distance between the cars. The system operates both the throttle and brakes. This leads to fluent driving with rapid acceleration/deceleration only if it is really needed and thus improves both the fuel economy and the traffic flow.

Cars equipped with ACC mainly rely on long-range RaDARs with a range up to 200 m, which is equivalent of around 6 s gap between the vehicles at highway speeds.

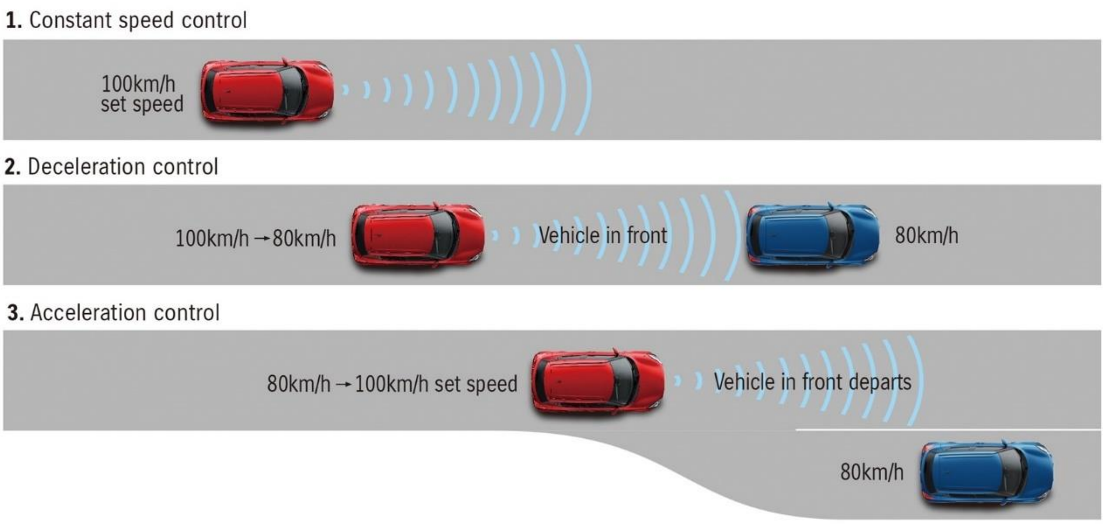


Figure 3 - Adaptive Cruise Control [15]

Automatic Emergency Brake

Automatic Emergency Brake (AEB) is designed to prevent the collisions from being fatal. The most advanced systems are able to avoid the collision altogether, while most of the systems on the market reduce the speed of the car before the crash down to the speed where the accident should no longer be severe.

The working principle is that the vehicle constantly monitors the area in front of it, using a laser, RaDAR or video data. If the system detects an object in the trajectory of the car, it compares its current speed with the speed of the object in front. If the speed of the car is significantly greater, the collision may likely occur, and the system starts to act. The first step is to warn the driver in case the greater speed is just because of a lapse of his attention. At the same time, the car prepares its braking system by increasing the pressure in the brake circuit, so the full brake force can be applied immediately. If the driver does not react up until critical distance is reached and the crash is inevitable, the system automatically applies as much braking power as possible to stop the vehicle completely or to slow it down to the speed which is not likely to be fatal.

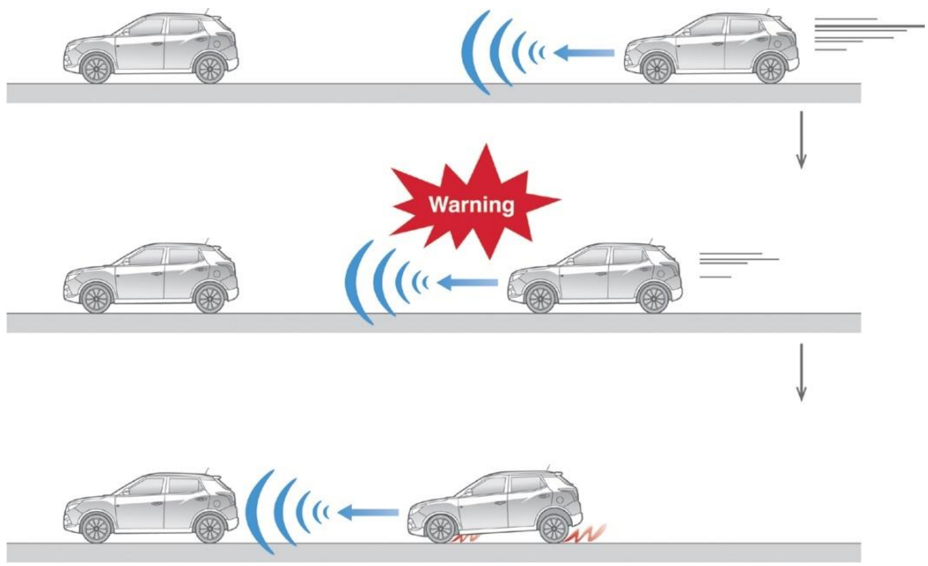


Figure 4 - Automatic Emergency Brake [16]

Blind Spot Detection

The blind spot is an area outside of the car, where the driver does not see, caused by the window pillars, other passengers or other things in the interior of the car. There is also a blind spot big enough to hide an entire car, located in the space between the peripheral vision of the driver and the area, which is reflected in the outside rear-view mirrors.

Combination of sensors and cameras monitor those blind spots and when the object appears in those areas, the BSD system informs the driver. Usually, the orange light lights up in the mirror to warn the driver against a possibly overlooked object. Some of the manufacturers also implement sound alert or soft vibrations of the steering wheel to alert the driver even more sharply.

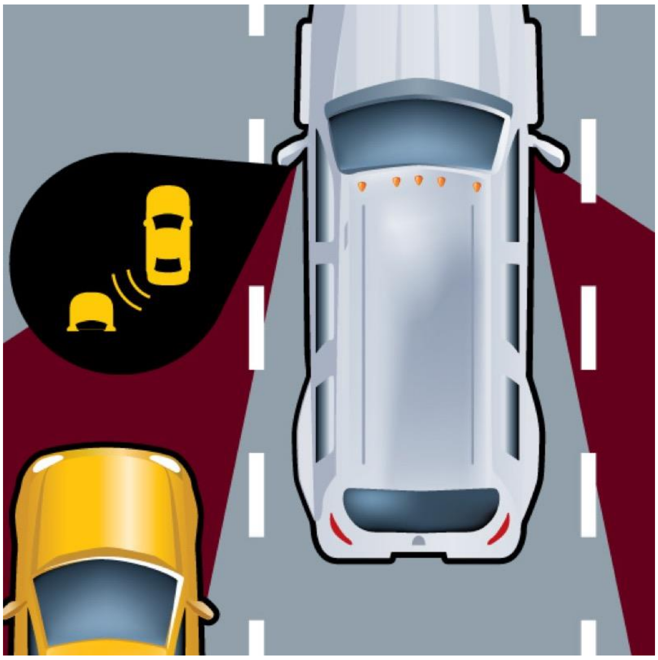


Figure 5 - Blind Spot Detection System [17]

Driver Drowsiness Detection

Another considerable cause of the accidents is driver's poor reaction times caused by his fatigue. Sensitive sensors in the steering wheel can recognize jerky steering, typical for the fatigued driver. The cameras monitor the driver's eye movement, typically the drooping eyelids. If the system recognizes that the driver's attention starts to wander, graphical alert along on the instrument cluster appears, usually along with some kind of sound alarm. Some of the systems don't allow to turn the alarm off until the vehicle is stopped, and the engine is shut off.

Emergency Brake Assist

Emergency Brake Assist (EBA) is the system to support the driver during emergency braking. This system was developed because the study done in the 1990s by Mercedes–Benz has shown that the majority of the drivers does not apply the full braking force when facing the danger of collision. When EBA detects that the driver is trying to perform an emergency stop, it overrides the braking and applies the maximum possible braking force up until the wheels start to lock up and ABS activates. EBA is usually coupled with AEB and thus the detection of the critical situation is based on the data from the RaDAR and from the speed with which the driver activates the brake pedal.

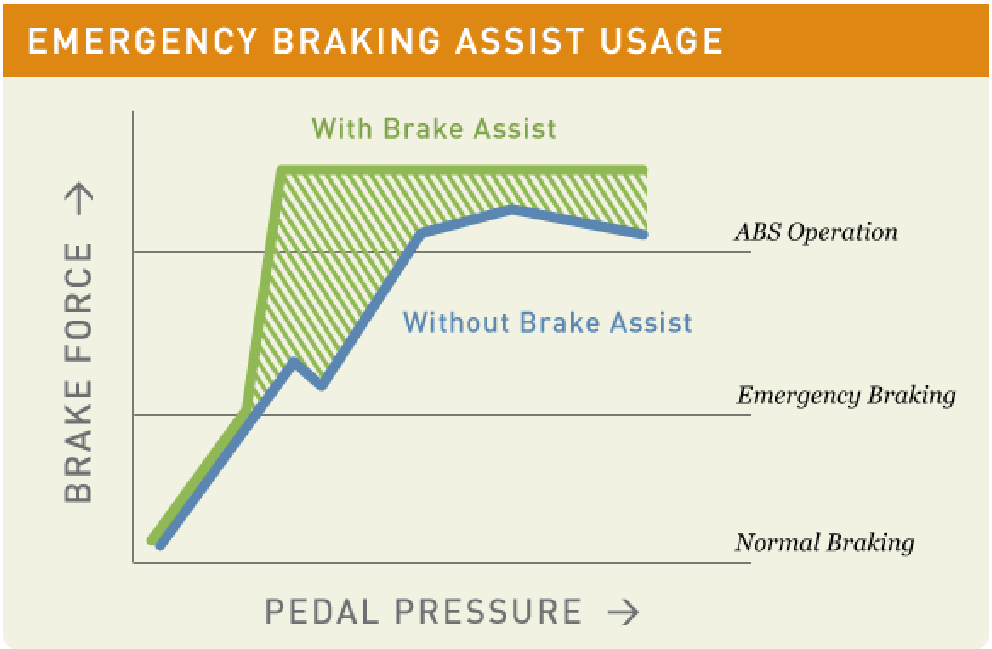


Figure 6 - Emergency Braking Assist Usage [18]

Lane Departure Warning & Lane Keeping Assistant

Both Lane Departure Warning system and Lane Keeping Assistant are designed to prevent the vehicle from leaving its own lane. These systems are designed mainly for highway purposes and work on the same principle based on optical recognition of road markings, making it sensitive to harsh weather conditions.

Lane Departure Warning can only provide a warning to the driver that he is about to leave the lane but cannot take an action by itself.

Lane Keeping Assistant can take the steering over and perform small corrective actions to keep the vehicle within the lane if the driver ignores the initial warning and makes no steering corrections by himself.

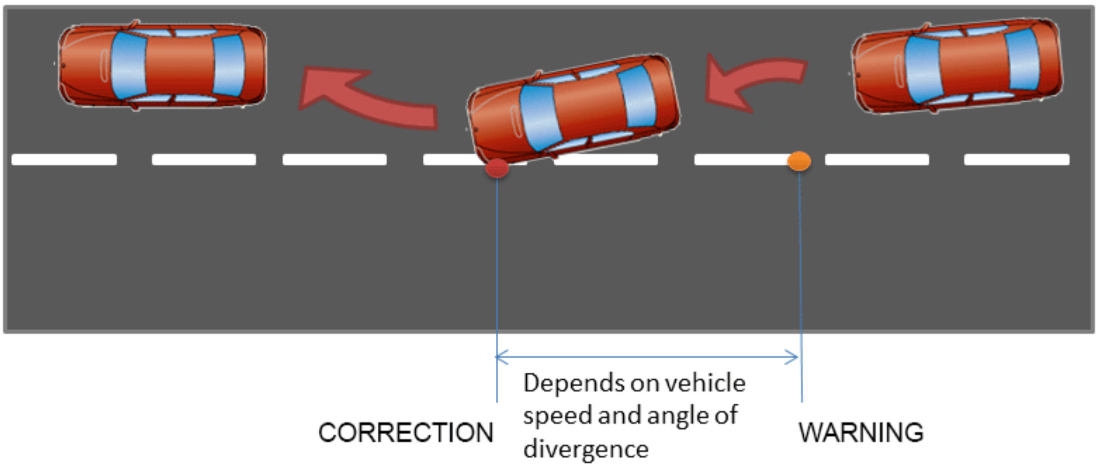


Figure 7 - Lane Keeping Assist [19]

Parking Assist

Parking assist is designed to help the driver to park his vehicle. While the vehicle is moving slowly through the parking lot, the system scans (using ultrasonic sensors) for space free enough to fit the vehicle in. When such space is found, the car performs the parking manoeuvre itself (considering the cutting-edge systems). The only action required from the driver is to change between forward and reverse gears.

Traffic sign recognition

More or less just a comfort system, which uses video cameras to recognize and read the traffic signs along the road. When the traffic sign is detected and identified, the little icon of the particular sign pops up on the dashboard, clearly visible for the driver. This system is used mainly for the speed signs to inform the driver about the maximum allowed speed and most advanced systems can work with ACC and adjust the speed accordingly to the signs. The disadvantage of the system is that it does not recognize the signs which are valid only for a limited distance, and does not recognise the junctions, which usually mean the end of the speed limit. Therefore, the modern systems are coupled with GPS and map data to avoid showing signs, which are no more valid.

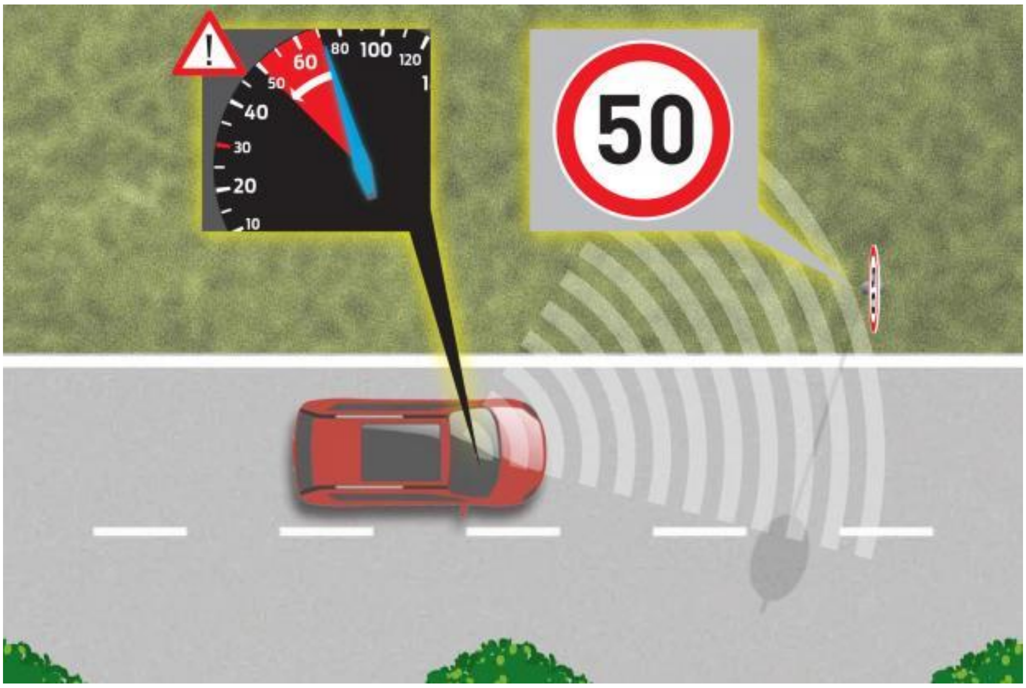


Figure 8 - Traffic Sign Recognition [20]

1.4. ADAS testing

In the field of ADAS, the main development focus lies on the everyday reliable functionality and performance, as well as on the safety aspects. To ensure both mentioned objectives are fulfilled, extensive testing, along with the subsequent verification and validation needs to be performed, mainly due to the continuously increasing complexity of traffic scenarios [22]. The tests have to ensure that the vehicle will operate reliably to be perceived as safe and thus to be accepted by the public. The tests also should assess the benefits and identify the potential weaknesses of the systems, which can be very expensive to fix when detected too late. Fixing a bug during the development phase costs $ 25 on average, whereas average $ 16 000 when fixed after the release of the product [22]. Figure 9 should clearly present the current approach to testing according to the V model.

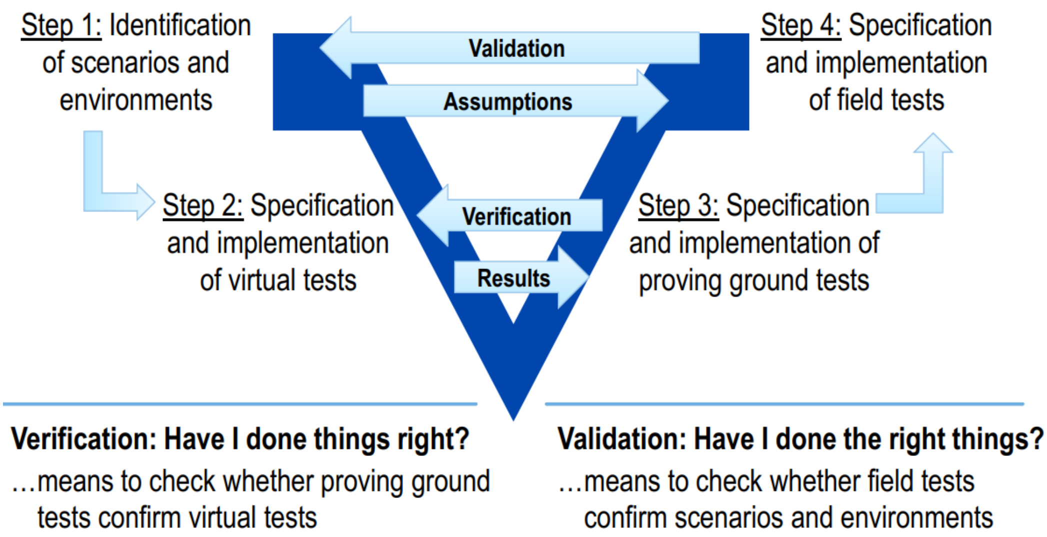


Figure 9 - V diagram for ADAS testing [24]

There are, however, many challenges to overcome when it comes to testing the autonomous vehicles. Firstly, ADAS are very complex systems (current cars have more than 100 million code lines on average, compared to 7 million in a Boeing 747 airplane [22]) with intensive interaction both with the driver and with the environment, hence there is an infinitely large number of potential scenarios which might possibly occur. Most of the test situations in the real life happen randomly, making the reproducibility of such scenarios close to impossible. Definition of test scenarios and pass/fail criteria is therefore currently the biggest challenge for the automotive test engineers. Creating a good scenario requires the skill and vast experience of engineers and should be able to test safety goals and ways in which the system may fail or reach its limits [22]. Also, no standards for testing exists yet, being still under development [21]. The only requirements that have to be fulfilled are defined by a functional safety standard ISO 26262, which provides some basic guidance for testing methods, but it’s far from sufficient for ADAS. Besides the missing standards and regulatory, the issue frequently discussed at the conferences is the strive to set up a catalogue of test scenarios, which will precisely define the essential tests to verify the correct functionality of autonomous systems. Lack of the standardisation of test methods and scenarios has led to a subjective interpretation of safety [22]. Nobody actually does know how safe if safe enough, how much more testing might be required and how can one know that the vehicles are sufficiently safe to deploy. In fact, the testing probably will never be enough to ensure absolute safety, since it is infeasible to test the systems thoroughly enough to make sure they will operate flawlessly [25]. It also has to be remembered that road traffic regulations, road signs and markings differ from country to county, making the development and testing even more challenging, since the ADAS have to operate ubiquitously across the borders and in all roadway, traffic and weather scenarios. The issue of traffic is that is totally random and mixed, including not only the other cars but motorcyclists, pedestrians, cyclists or even the animals. Autonomous vehicles must also have strong protection against the evolving cyber-attacks [10].

In general, there are 4 levels of testing: virtual tests, driving simulator tests (hardware-in-the-loop) proving ground tests and the field tests. Difference between them is clearly depicted in figure 10.

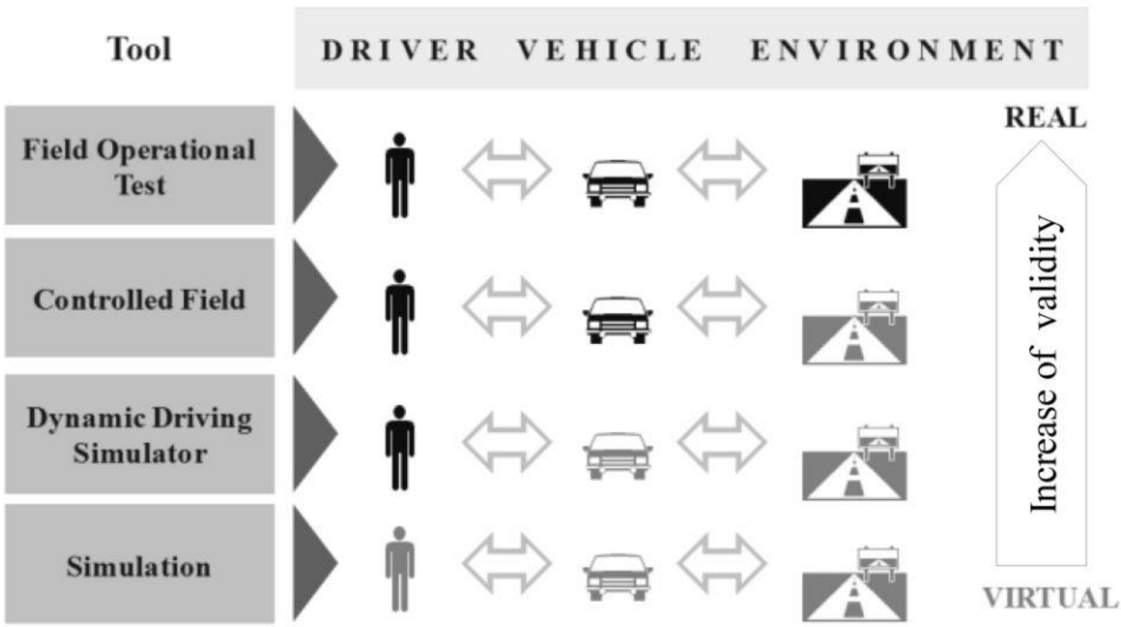


Figure 10 - Levels of testing (grey: virtual elements, black: real elements) [26]

1.4.1. Real world testing

Field and proving ground tests are very expensive and time demanding, with limited reproducibility and a lot of influential factors, which cannot really be influenced, such as weather or light conditions. Even so, such testing is very important, because it actually shows how the car copes with the real-world obstacles. Currently, when no standardized scenario database exists, each of the manufacturers or system suppliers has its own list of scenarios and know-how. In general, the scenarios consist mainly of simple interurban and highway situations, which happen on a daily basis in ordinary traffic. Such scenarios might be for instance *approaching a traffic queue, approaching obstacles, veer into/out of the lane, passing the slower vehicle, stop & go,* etc. Each of the scenarios has many variations and modifications with different amount of traffic objects, different speeds, distances or trigger points. For the highest possible precision and reproducibility, steering and braking are not operated by humans, but by the robots. To ensure the test driver's safety in case the system works incorrectly, special soft crash targets are used to imitate the traffic vehicles, as shown in figure 11. These targets are either inflatable or build up from several pieces made out of special soft foam, so when the vehicle under test collides with them, they just pop or fall apart and the driver in the vehicle under test stays perfectly safe. These soft crash targets can be used to substitute not only the static traffic objects but also the dynamic objects. This is done by putting them on a special self-driving platform with a very low profile and high rigidity, so when the collision happens, the vehicle under test just runs over it, without any damage. The final evaluation of physical tests, thanks to the presence of a test driver in the car during the manoeuvres, might involve both objective and subjective evaluation, which allows the comprehensive assessment of the system features, including the evaluation of human-machine interface, which is very important to fine-tune the system behaviour in a way to be comfortable for its users [21].

Figure 11 - Soft Crash Targets [23]

1.4.2. Virtual testing

A very promising, rapidly evolving and more and more employed, but still very challenging method of testing, mainly due to the complexity of a real-world physics modelling. The simulations are basically mathematical representations of the physical systems in vehicles. Nonlinear components such as tyres, dampers, bushings and engine mounts are very hard to model, thus we have to use non-perfect models, or sometimes estimate or even neglect the effect of these components, making the accuracy of virtual testing significantly varying. Hence it will never be possible to represent the real world identically, the virtual representation only can get somewhere close to the real one. Simulation might become a very powerful tool to contribute to the physical tests and help to identify the critical cases and scenarios, but it will actually never fully substitute the real world testing, since the fully realistic tests in pure simulation are often not possible and testing the product in the real world is mandatory to make sure everything works like its supposed to. The way the simulations will eventually contribute to the framework of testing is that they will be used as a kind of filtering tool to rapidly reduce the amount of the scenarios, which have to be tested physically. The simulation will be the first step, which should identify the critical scenarios among the hundreds of millions of other scenarios, as shown in figure 12.

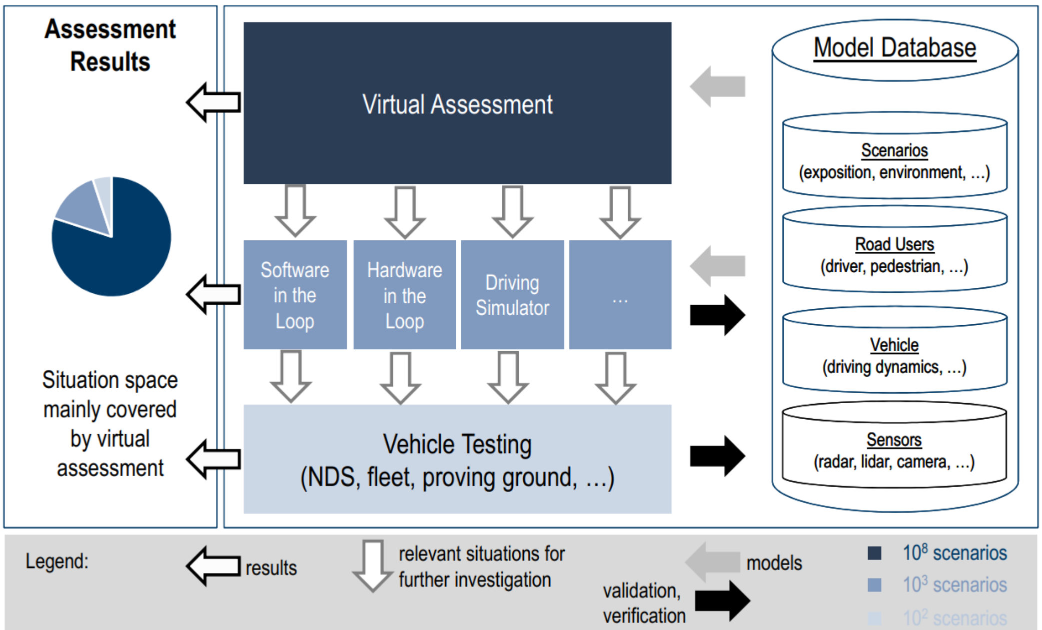


Figure 12 - Contribution of virtual assessment in the toolchain of testing [24]

Despite all the disadvantages and challenges mentioned above, testing the ADAS systems with the use of simulation has many benefits. It might be used right from the start of development in its very early phases when no prototypes yet exist and enables the opportunity of rapid development and early bug fixing. After the validation against experimental data, virtual models could be used for fine tuning of the prototype and thus improve its performance. This shows that the simulation can also be applied even during the later testing phases when the prototypes are already available [27]. This method becomes truly indispensable when we realize that in order to prove AVs are safer than human drivers, they need to be driven more than 11 billion miles, which is impossible to perform in the real world [22]. That is a value, which is very time demanding to even simulate, let alone to be driven physically. Compared to the traditional physical tests, the simulations are much more cost effective, can easily cover all weather and environmental conditions, can be automated and can simulate every possible traffic scenario and objects. Thanks to the simulation, we can also perform testing of very exotic cases, where the real world testing would be too dangerous or even impossible to perform. To sum all the benefits of the virtual testing up – simulations are cheaper, faster and more versatile solution, which, however, will never fully substitute the real world testing.

A very popular method of testing, which also can be classified as a virtual method, is the hardware-in-the-loop testing. It is the state of the art technology for testing ECUs and sensors in the automotive field. The principle is that the scenario simulation is running on the test bench in the real-time and the connected hardware is stimulated by the data from the simulation. The data are processed by the connected hardware and then sent back to the simulation loop as an input. The hardware part connected in the loop might be ECU, a sensor (commonly camera or RaDAR) or the vehicle alone. HIL is used very useful for an end to end testing of the entire signal chain, from the first sensor in the chain all the way up to the last actuator that executes an action. This is a unique way to test compulsory time delays reliably and repeatably. Acoustic and visual feedback and warnings can be automatically checked by monitoring systems and thus no real person has to be subjected to continuous sounds and alerts of ADAS during testing [29]. Also, the entire driving simulators are being built to investigate the human – vehicle interaction and to observe the drivers acceptance of the systems, which is very important to assess when bringing the new technology to the market. The scheme of the hardware-in-the-loop test bench is shown in figure 13 for better understanding.

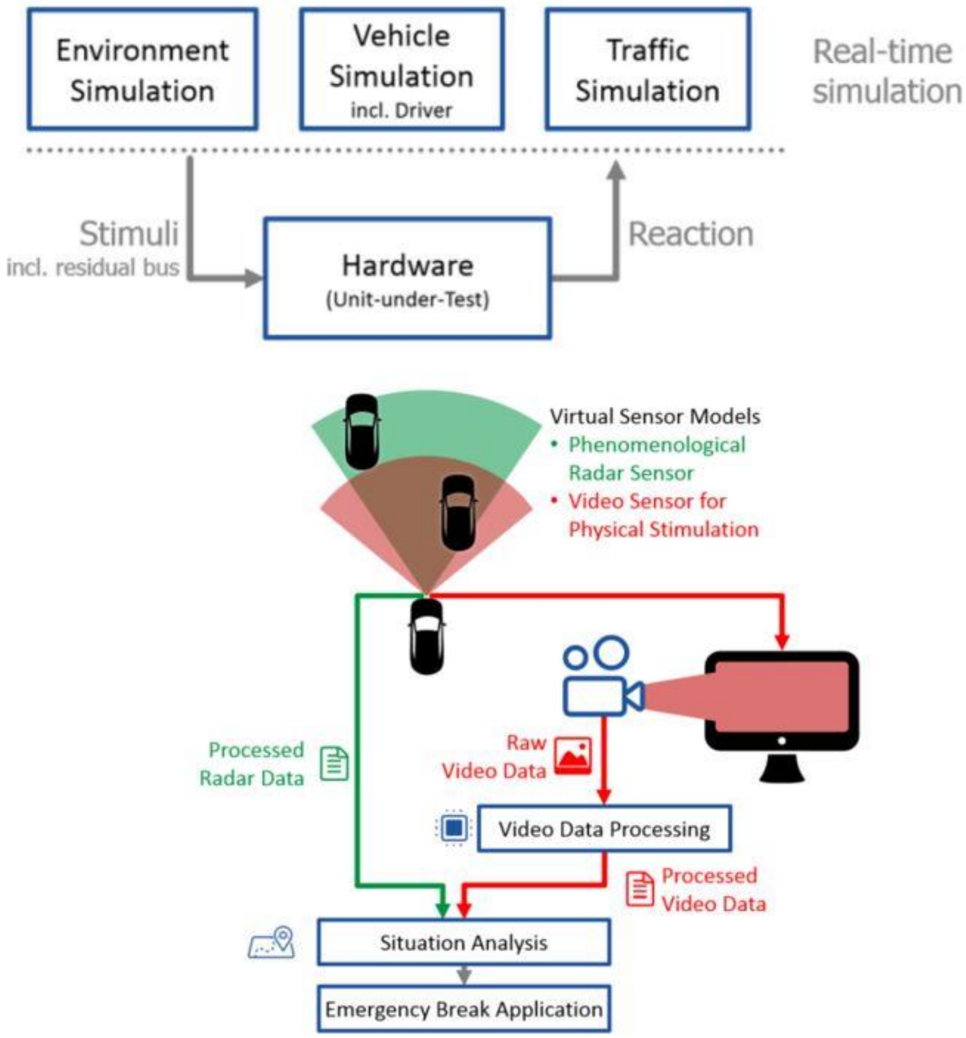


Figure 13 - Scheme of HiL test bench [28]

1.5. ADAS and regulatory

For every car sold within EU, it is obligatory to fulfil the requirements in defined approval tests. The approval regulations are defined by two bureaus - Economic Commission for Europe (ECE) or European Union (EU). Right now, there is no general legislation or specified requirements concerning ADAS globally, since the technology is ahead of regulatory, but it is currently being worked on it. Most of the norms concerning ADAS and their testing was defined by International Organization for Standardization (ISO). These norms are however not mandatory, they are only recommended to follow.

Some of the existing ISO norms concerning ADAS and simulation are mentioned. The norms won't be further discussed, as this list should only be an overview for easier orientation in case of some future work. To keep the list clear, it contains the regulation number and the concerning topic, not the entire title of the norm.

ISO 11270: Lane keeping assistance systems (LKAS)

ISO 15622: Adaptive Cruise Control systems

ISO 15623: Forward vehicle collision warning systems

ISO 17361: Lane departure warning systems

ISO 17387: Lane change decision aid systems (LCDAS)

ISO 19364: Vehicle dynamic simulation and validation

ISO 22178: Low speed following (LSF) systems

ISO 22179: Full speed range adaptive cruise control (FSRA) systems

Among the obligatory regulations, there are the first cases touching the ADAS and AV systems, some of which are:

UN/ECE-Regulation 79: Uniform provisions concerning the approval of vehicles with regard to steering equipment. It comes with the definition of so-called "hands-on" respectively "hands off" functions. By means of this regulation, it is defined for how long the LKA system is allowed to provide lateral support (steering) while the driver has his hands off the steering wheel.

UN/ECE-Regulation R130 LDWS and UN/ECE-Regulation **R131** AEBS, which are concerning Lane Departure Warning System and Autonomous Emergency Braking System respectively. These regulations made a significant footprint in the field of ADAS regulatory because they specify the mandatory installation of LDWS and AEBS in all new truck models from 2013.

UN/ECE-Regulation 140: Homologation of ESC Systems directly enables to verify and approve the Electronic Stability Control System by simulation, as quoted: „Where a vehicle has been physically tested in accordance with […], the compliance of versions or variants of that same vehicle type may be demonstrated by a computer simulation […]."

1.5.1. Euro NCAP concerning ADAS

Euro NCAP is an independent agency supported by several European governments and automobile clubs, which provides an independent vehicle safety rating system. The cars are rated with stars, which are awarded based on the total score the car reaches during the series of tests. The maximum number of stars awarded is 5, making it very clear for the customer to objectively compare the safety of different cars from different manufacturers. These tests are not mandatory to pass and are only of informative importance, but the result of NCAP tests might be a very strong marketing tool, being well known among the laic public, thus is quite important for manufacturers to perform well.

Being very famous for passive safety assessment, since 2014 Euro NCAP also assess the active safety systems. As these systems contribute to overall score gained, it is no more possible to have a good overall score and star rating based only on excellent passive safety. Active systems assessed by NCAP are ESC, Seatbelt Reminders, Speed Assistance, AEB and Lane Support. Since this thesis is focused on ADAS problematics, ESC and Seatbelt reminder will not be discussed further.

„For AEB Interurban systems, Euro NCAP evaluates the automatic brake function and the forward collision warning function in 3 different driving scenarios: driving towards a stationary vehicle (30-80 km/h), closing in at a slower vehicle in front (30-80 km/h) and following a car in front which suddenly starts braking (50 km/h, gentle and harsh braking). Two scenarios – stationary target vehicle and slower-moving target vehicle – are repeated for left and right offsets, where the centreline of the test vehicle is not in line with the centre of the target. A high score is awarded to systems that are able to avoid a collision in all test conditions or are able to significantly reduce the severity of the crash." [34]

„LKA and ELK systems are evaluated using a standard set of tests performed on a test track. Both types of system are tested against various types of road-markings, including solid lines and dashed lines, and in situations where the road edge is not marked by a line. The performance is evaluated by considering the proximity of the vehicle to the edge of a lane marking or road edge at the time of intervention. Additional points are awarded to cars equipped with a Lane Departure Warning system and a Blind Spot Monitoring system.“ [35]

Speed assist systems are considered as functional when the system can be used without undue distraction to the driver. For systems that actively control the speed, tests are performed to ensure the system does this accurately.

Euro NCAP recently presented its Roadmap 2025, where the goals on the use of advanced technologies are presented. Their goal is to deliver improved passenger car safety, ultimately leading to the dramatic fall in road fatalities, called VISION ZERO. By 2020, NCAP wants to start the assessment of driver monitoring systems, later followed by testing of AEB in respect to pedestrian and cyclist detection.

1.6. Current state in vehicle modelling

One of the assigned tasks of this thesis was to make a literature review of current approaches in dynamic model development. This turned out to be a very tricky part of this work since this topic is very specific and very rarely presented to the public. Vehicle dynamic simulations are used internally by car manufacturers or suppliers mainly during the development of new cars. The development phase is naturally a very confidential matter and the companies make a big effort not to leak any of their know-how so the competition could not make any advantage from it. Thus, no essential literature concerning this topic is available, only some technical papers are presented, mainly by universities or students.

The practical use of virtual vehicle models could be as follows:

Use of fully parametrized vehicle model during raw development of a new car from scratch. Having several different parameters defined by project management, which however contradict each other. With a help of optimization toolchain and design space evaluation methods, the overall best trade-off solution is being found and the combination of individual parameters is then used for the development [41].

Dynamic vehicle model could also be used for race car suspension settings parametric optimisation in order to achieve a better lap time, as presented by Formula SAE team from the University of Leeds [27].

Interestingly, simulations are used even in the field of agricultural vehicles. In this case, the simulation was used during the development of an active suspension system for tractors [42].

However, one of the most significant practical use of simulations worth to mention is the currently running project of highway chauffeur system, supported by the German government and a syndicate of automotive companies (Audi, BMW, Daimler), called Pegasus. Simulations in this project are used for broad purposes, involving identification of critical scenarios, sensor simulation, and plausibility check of scenarios subsequently performed during field test runs. For all of these purposes, the dynamic models of cars are extensively used [40].

1.7. Remarks

As a last part of the introduction chapter, I would like to make a brief remark on some of the topics, which are covered by this thesis, namely reverse engineering, optimisation and validation.

1.7.1. Reverse engineering

The approach used within this thesis is based on reverse engineering principles. Reverse engineering is commonly used approach in engineering, when the already existing product is taken and decomposed or deconstructed, extensively measured or throughout tested in order to obtain the parameters, specifications and to gain knowledge about this product. This was the way to obtain the data used as an input for the simulation. The real car was tested on a test track with the aim to measure the parameters needed as an input for simulation and validation.

1.7.2. Optimisation

In order to make the framework proposed in this thesis more effective and the results more precise, my supervisor and I were discussing the possibility to involve some kind of automated optimisation method or algorithm, which will automatically set the several selected physical parameters of the car in a way that that the right combination of them will be reached.

I directly addressed IPG as a software provider with a question concerning the optimisation opportunities, but it turned out that nothing like it is yet possible to implement in the simulation chain. The process proposed by IPG was to use TestManager by IPG to define the values and their range and then use a "brute force method", which means varying the critical parameters and iterate step-by-step up to the desired result.

1.7.3. Validation

Validation is an essential process in the simulation-based development and research. It is the process of ensuring whether the model properties correspond to the properties of a real object. It is of exceptional importance when it comes to virtual testing and virtual vehicle model development because it directly influences the quality of the representation of the real car.

There are many different approaches and theories of validation. In my work, I followed the validation framework recommended directly by IPG, which describes the vehicle prototype validation in 6 consecutive steps, which are as follows:

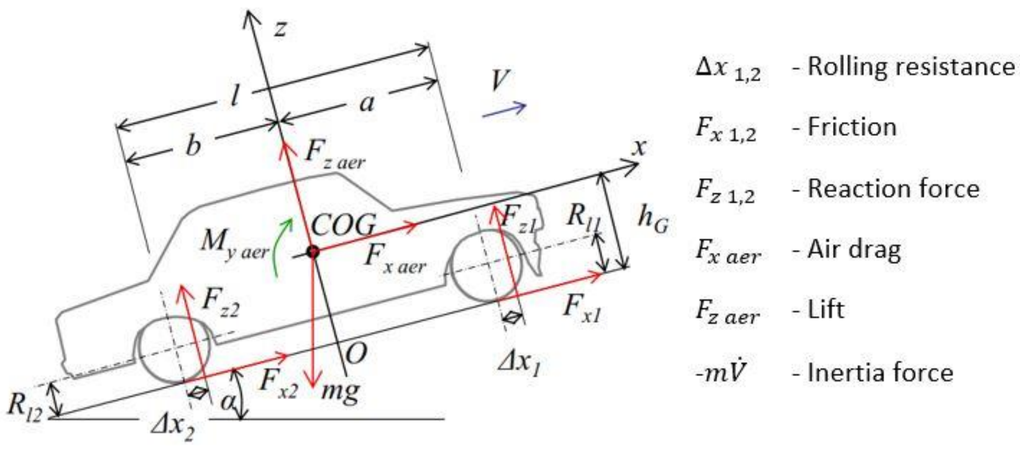
- *Validation of kinematics and compliance data* – verification of suspension kinematics and steering
- *Equilibrium configuration* – verification of weight distribution and COG position
- *Longitudinal dynamics* – verification of acceleration and brake performance
- *Steady-state lateral behaviour* – verification of steering and vehicle behaviour
- *Dynamic lateral behaviour* – verification of vehicle reactions during step steer and sinus steer manoeuvres
- *Closed-loop manoeuvres* – verification of vehicle behaviour during ISO lane change and slalom

2. Vehicle dynamics essentials

Vehicle dynamics is a part of engineering primarily based on physics and classical mechanics, which describes the behaviour of the vehicle. Indeed, there are many influential aspects and variables that directly affect the way the car drives, some of them having linear characteristics, whereas other having nonlinear characteristics, making the field of vehicle dynamics a very complex discipline. These aspects influence mainly the tyre-road interaction and are of an environmental kind, for instance, the air and road temperature, parameters influencing the road friction (varying surface roughness, wet/dry) or road disturbances [36].

During the ride, the vehicle body is subjected to vertical, longitudinal and lateral motions accomplished in acceleration, braking or cornering. These motions are a response to forces developed by tyres, inertia, gravity or atmosphere. The sum of forces acting upon the moving vehicle in the longitudinal direction is clearly depicted in figure 14, along with the equilibrium equations. These forces may be divided into 2 subgroups – aerodynamic forces acting on the body and tyre forces. Considering the physical tests described in chapter 4 were performed at low speeds around 100 km/h maximally, aerodynamics plays a secondary role. Thus, the group of interest are the tyre forces. The factors influencing the tyre forces are following [27]:

- Tyre itself
- Suspension design and kinematics
- Suspension stiffness and damping
- Rigidity of the chassis
- Mass and its distribution throughout the vehicle
- Torque at the wheel from the engine and the brakes



Dynamic equilibrium equations:

$$x: F_{x1} + F_{x2} + F_{x\_aer} - mg\sin(\alpha) = m\dot{V} \tag{1}$$

$$y: F_{z1} + F_{z2} + F_{z\_aer} - mg\cos(\alpha) = 0 \tag{2}$$

$$M_O: F_{z1}(a + \Delta x_1) - F_{z2}(b - \Delta x_2) + mgh_G\sin(\alpha) - M_{y\_aer} + \left|F_{x\_aer}\right| h_G = -mh_G\dot{V} \tag{3}$$

Figure 14 - Forces acting on a vehicle in motion [37]

In general, the purpose of all the mechanical parts mentioned above and further described below is to maintain the contact between the tyre and road in a way to exploit maximum from tyre friction capabilities and hence generate the most grip and to keep the vehicle stable, yet to have smooth driving behaviour and to be comfortable to drive. In other words, to make the vehicle handle well. Vehicle handling is an important part of vehicle dynamics. It is used to describe the effectiveness of a vehicle to change direction and negotiate corners. However, handling can also be defined as driver's perception of the vehicle's cornering behaviour and thus handling has both an objective and subjective aspect to it [27]. Good handling of the vehicle also very strongly depends on the driver's experience in driving and handling the car, in his ability to feel the slip of the tyres or the weight transfer during braking and cornering and also on the way how the driver reacts to the vehicle's behaviour under varying circumstances, for instance on the limit of grip [36]. An inexperienced driver can exploit the handling potential of the car much less than the experienced one.

To create a comprehensive vehicle model, a good understanding of the topic of vehicle dynamics is required. A complete overview and an overall understanding of this topic are very important, due to the complexity of the entire vehicle system. Assuming that the person reading this document will have at least some basic knowledge of mechanics, physics and other fields of engineering, this section therefore should be just a very brief introduction to the topic of vehicle dynamics, summarizing just the basic principles and function of main mechanical parts of the vehicle and their effects on overall vehicle dynamics.

After all, the aim of this thesis is not to be a coursebook of vehicle dynamics as it would significantly extend the scope of this work. For the eventual need of deeper understanding, I would recommend the literature found under reference numbers [34], [35] and [36]. Throughout study of these publications should provide all the necessary knowledge to understand the topic correctly.

2.1. Tyre

Tyre is the only component of the entire car, which interferes with the road, making it the only connecting link between the car and the ground. It transmits all longitudinal, lateral and vertical forces, that are generated between the vehicle and the road and thus significantly affects the handling of the vehicle.

Tyre has three basic functions:

- To support the vertical load and cushion against road shocks
- To develop longitudinal forces for acceleration and braking
- To develop lateral forces for cornering

The most important parameter of the tyre is a so-called slip. Tyre slip describes proportionality between local tyre deformation and the longitudinal position in the tyre contact area [36]. The slip is important because it generates the tractive and cornering forces. Slip is both lateral and longitudinal.

Longitudinal slip is defined as the ratio of the speed with which contact zone moves on the ground and the forward speed of the wheel. Longitudinal tyre characteristics are shown in figure 15.

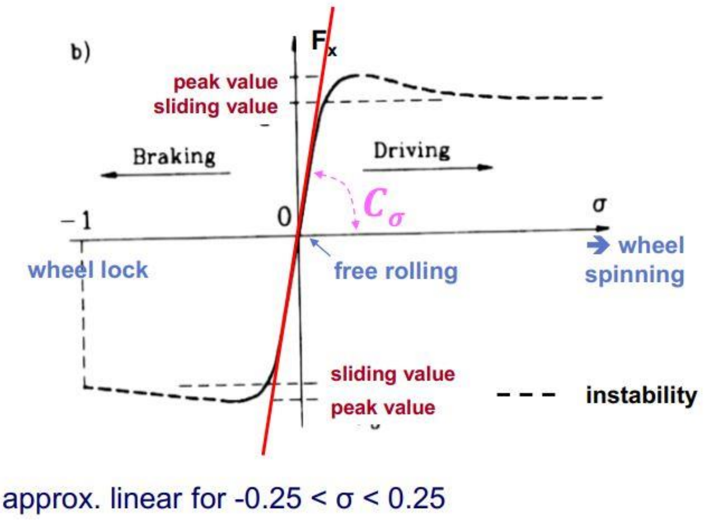


Figure 15 - Longitudinal tyre characteristics [38]

Lateral slip is defined as the angle between the direction the tyre is actually moving and the direction it is pointing. This angle comes from the ability of the tyre to deform, as shown in figure 16.

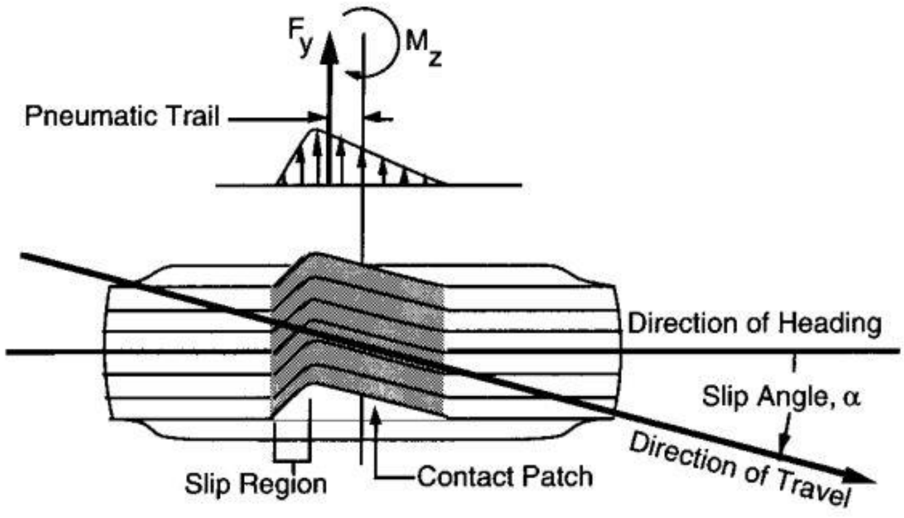


Figure 16 - Tyre deformation under a lateral force [34]

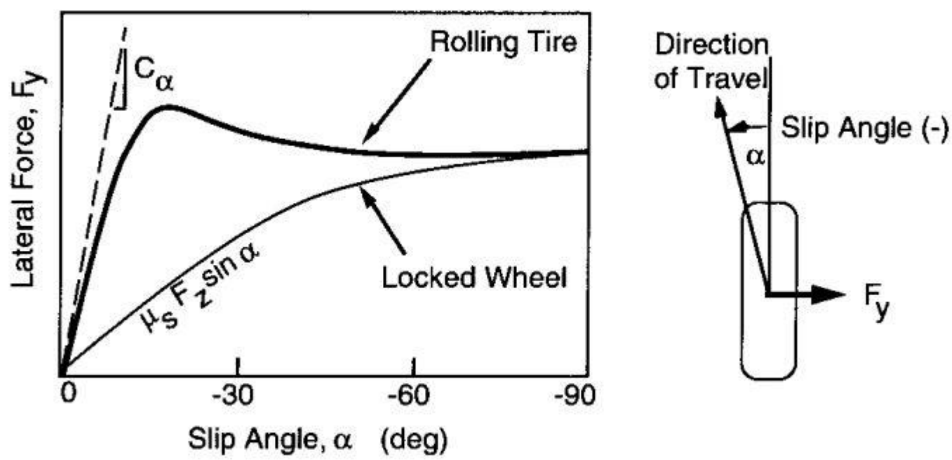


Figure 17 - Lateral tyre characteristics [34]

2.2. Chassis

Chassis is the fundamental structure of the entire car and hence it plays a substantial role in overall vehicle dynamics. It is the anchorage base not only for suspension and wheels, but also for the engine and the drivetrain, thus the mechanical properties of the chassis directly influence the behaviour of these components. The critical property of the chassis is its stiffness, which can be described as the resistivity against torsion or bending. No chassis is 100% stiff, but the manufacturers strive to make it as rigid as possible while keeping its weight reasonably low. The issue is that when the chassis is way too flexible, it does not provide sufficient support to the suspension. Having the poor support, the suspension geometry will be affected, and the kinematics will differ from its optimal trajectories, making the handling worse. Also, when there is flex, the chassis itself works as an additional spring in the car, making the behaviour of the car less linear and predictable for the driver.

Next general parameter of the car, which affects its behaviour, is the static weight distribution. In fact, during the simulations realized by the University of Leeds, the weight distribution was found to be one of the most influencing parameters [27]. By the weight distribution, both the centre of gravity position and the distribution of weight between the axles is meant. The desired state is to have the COG as close to the ground as possible so that the body roll is small. The ideal weight balance between the front and rear axle is 50:50 to ensure the neutral behaviour. While tackling the corner, the car is subjected to the laws of physics, and the weight directly influences the strength of the resulting centrifugal force and thus when the weight load of one of the axles is significantly higher than of the second one, the car gets unbalanced and tends to understeer or oversteer, depending on which axle is more loaded.

Also, the heavier the car is in total, the more inertia it has, making it harder to stop, accelerate or corner. On the other hand, more weight means a higher load of the tyre, which will generate higher friction force.

2.3. Suspension

The suspension carries the weight of the car, keeps the tyres in contact with the road, controls the position and forces of the wheels relative to the vehicle body and ensures the ride comfort, and therefore it has a significant influence on the overall behaviour and vehicle handling. Majority of the critical parameters is related to suspension geometry as it directly defines the kinematics of the suspension movement [27]. Well-designed suspension kinematics for can, for example, affect the progression of wheel camber related to the vehicle roll, ultimately giving better grip with increasing body roll during aggressive cornering.

Vehicle suspension consists of guiding and force elements. Guiding elements are control arms, links or struts and define the kinematics of the suspension. Force elements maintain the contact between the tyre and the road and ensure comfort and stability. Force elements are damper, spring, anti-roll bar or bushing.

Suspensions are generally of two kinds:

- Solid axles, when both wheels on one axle are connected and thus the movement of one affects the second one. This is the cheaper and simpler solution used in cases, when the good handling is not the main design target, e.g. for pickups, vans, etc.

- Independent suspension – no physical connection (except for the anti-roll bar) allows each wheel to move independently. More expensive and complicated solution. Many different designs, each of which has different kinematics, behaviour, pros and cons. Involves e.g. trailing arm, swing axle, double wishbone, MacPherson, Multi-Link.

Two major characteristics of suspension setup are toe and camber, each of them is described below.

Toe is defined as an angle between the longitudinal axis of the vehicle and the centre line of the wheel. When the extensions of the centre lines of the vehicle meet in front of the vehicle, it is called toe-in. In the opposite case, when the lines meet behind the car, it is called toe out. Toe settings affect straight-line stability, tyre wear and corner entry handling characteristics [35].

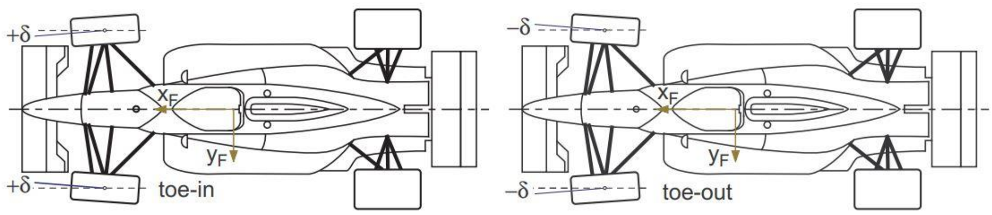


Figure 18 - Toe-in and Toe-out [35]

Camber – the tyre can generate the maximum lateral force during cornering if it is operated with a slightly negative camber angle. The suspension must be designed that the camber changes as the chassis rolls in the corner. An ideal suspension will generate higher negative wheel camber as the suspension moves up (compresses) [35].

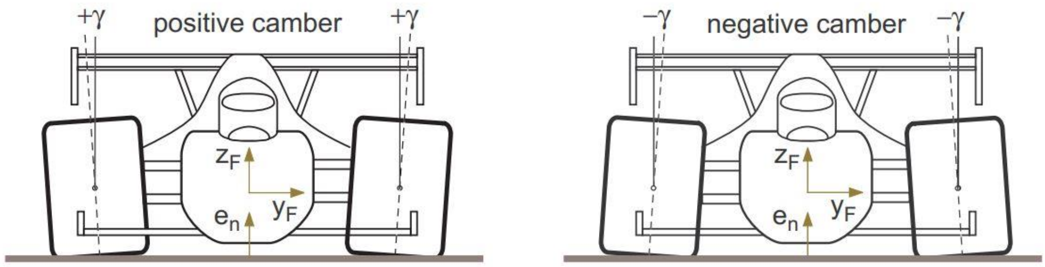


Figure 19 - Positive and negative camber angle [35]

Suspension geometry layout has a big influence on handling, but apart from it, the behaviour of the car can also be influenced by different parameters of its force elements, further discussed below.

2.3.1. Damper

The purpose of the damper is to absorb the vertical shocks from the uneven road surface and thus to reduce the chassis vibration and subsequently increase the ride comfort. The principle of cushioning is based on dissipation of the energy mostly via heat, which is produced by the internal friction of the fluids inside the damper. Its behaviour is nonlinear as it depends on the velocity of compression, hence this makes the modelling quite challenging.

Dampers are of two kinds - pneumatic or hydraulic and their principle is that the piston is sliding inside a cylinder filled with hydraulic fluid or the air, making resistance to the movement of the piston. The parameters, which define the behaviour of the damper, are *rebound* and *compression*, defining the progression of the dampers movement up or down.

2.3.2. Spring

The purpose of the spring is the same as of the damper, to support the weight of the car and to absorb the shocks from the road by self-compressing. The parameter, which defines the spring characteristics is called spring rate and is given by the amount of force you need to apply to deform the spring by one millimetre of distance. Suspension springs can have either linear or nonlinear spring rate.

There are several kinds of springs used in the cars: coil springs, air springs, leaf springs or torsion bars.

2.3.3. Anti-roll bar

Anti-roll bar, called also sway bar or stabilizer, is the connecting link between the opposite wheels on one axle and its purpose is to reduce the body roll during cornering and to provide additional stability. It usually is a simple U-shaped metal rod connected to both lower control arms, either directly or via links [35]. Varying the stiffness of front or rear anti-roll bar has a significant effect on vehicle understeer or oversteer behaviour, but this won't be discussed further as the change of the cornering behaviour depends on many variables and factors, such as the type of drive or weight distribution and thus is impossible to generalize.

3. Simulation software

The software used for all the virtual tests presented within this thesis is CarMaker (in its 7.0 release), developed by German company IPG Automotive. The reason for use of this particular software was pragmatic – it is the main tool for ADAS simulations used in TÜV SÜD. CarMaker is capable of real-time virtual testing of passenger cars and light-duty vehicles. Real-world test scenarios, including every important part of the environment, can be accurately modelled and reproduced in the virtual world using this software. A huge benefit of CarMaker is that it is an open integration and test platform and can be applied throughout the entire development process – from the pure simulation up to the hardware in the loop testing thanks to its real-time capabilities.

CarMaker includes a complete model environment comprising a driver model, a detailed vehicle model and models for roads and traffic. Within this model environment, a complete and realistic test scenario can be built with ease, taking the test run off the road and directly to the computer. The event and manoeuvre-based testing method ensure that the necessary flexibility and realistic execution of real-world test driving are also features of virtual test driving. CarMaker also offers the full test automation with a use of Test Manager [39].

A test scenario editor, which collects all the information required to parameterize the virtual vehicle environment and to start a simulation is called a TestRun. Depending on the complexity of the simulated test case, the TestRun composes a different number of modules. As a minimum requirement to be able to simulate, the following modules must be parameterized within the TestRun:

• Vehicle: Parametrization of the vehicle.

• Road: Parameterization of the road.

• Manoeuvre: Definition of the driver's task.

• Driver: Driver behaviour (reactions, driving style..)

Additionally, the following modules can be defined:

• Traffic: Configuration of static or moving traffic objects.

• Environment: Configuration of ambient conditions.

• Trailer: To simulate a test car with a trailer configuration.

• Tyres: Overwrite the default tyre data set referred to the vehicle model.

3.1. Alternative tools on the market

In the field of automotive simulation, a lot of other companies is active, making a strong competition. Their products differ in a lot of aspects but provide mainly the similar outputs. I made a research on companies that provide software concerning vehicle dynamics simulation, so the very brief overview of some of the main competitors to IPG is presented below:

ProSIVIC is a simulation software specialized in the advanced rendering of ADAS, which also allows integrating vehicle dynamics models, setup complex driving situations in complete environments, objects animation (such as pedestrians for example). ProSIVIC can operate in real time or virtual time which allows addressing tests and validation use cases of ADAS functions with or without a human in the loop.

dSpace ASM is a tool suite for simulating combustion engines, vehicle dynamics, electric components, and the traffic environment. The open Simulink models are used for model-based function development and in ECU tests on a hardware-in-the-loop (HIL) simulator.

CarSim is a commercial software package that predicts the dynamic behaviour of vehicles in response to driver controls (steering, throttle, brakes, clutch, and shifting) in a given environment (road geometry, coefficients of friction, wind).

VTD is a complete tool-chain for driving simulation applications. VTD is our toolkit for the creation, configuration, presentation and evaluation of virtual environments in the scope of road-based simulations. It is used for the development of ADAS and automated driving systems as well as the core for training simulators.

4. Conducted tests

This chapter describes all of the proving ground tests that were physically realized with a car on the proving ground and then subsequently reproduced in simulations in order to validate the virtual vehicle prototype. The list of tests was defined with a help of experienced test engineers. The tests are mainly based on the testing standards defined by ISO or ECE. Performed tests were both of static and dynamic kind and the list is divided in the same way to provide a clear overview. Not all of the tests are necessary for every measurement, and some data may be duplicate, this depends on a future specific application. These tests were made as the first project in this field to learn new approaches and thus some redundancy is not really an issue. All of the measured data could be found on the attached CD.

4.1. Subject of testing

Table 2 - Weight distribution between individual wheels and axles

Curb weight						
	FL	505	kg	**RL**	425	kg
	FR	503	kg	**RR**	441	kg
	FA	1008	kg	**RA**	866	kg
Weight in total:	1 874		kg			
Partial load for handling tests						
	FL	545	kg	**RL**	465	kg
	FR	529	kg	**RR**	456	kg
	FA	1074	kg	**RA**	921	kg
Weight in total:	1 995		kg			
Partial load for tests executed with the use of driving robot						
	FL	550	kg	**RL**	477	kg
	FR	532	kg	**RR**	482	kg
	FA	1082	kg	**RA**	959	kg
Weight in total:	2 041		kg			

Table 3 - Parameters of the vehicle

Make		
	Audi	
Model		
	Q5 2.0 TDI quattro 120 kW	
Engine		
Engine type	Diesel, I4, turbocharged	
Displacement	1968	cm3
Power / at rpm	120 / 3800-4200	kW
Torque / at rpm	400 / 1750 - 2750	Nm
Max rpm	4500	rpm
Drivetrain		
Drive type	All wheel drive (4x4)	
Transmission type	Automatic	
Number of gears	7	
Gear ratios (1/2/3/4/5/6/7)	3.188/2.190/1.517/1.057/0.738/0.508/0.386	
Final drive ratio	5.302	
Dimensions		
Length	4663	mm
Width	1893	mm
Height	1659	mm
Wheelbase	2819	mm
Wheeltrack Front	1616	mm
Wheeltrak Rear	1609	mm
Overhang Front	899	mm
Overhang Rear	845	mm
Steering ratio		
	15.8	m
Turning circle		
	11.7	m
Tyres		
Model	Michelin Latitude Sport 3 103W	
Width	235	mm
Aspect ratio	60	
Wheel diameter	R18	inch
Wheels		
	8.0J x 18H2 ET39	
Tyre pressure for all variations of load		
	230	kPa

4.2. Measuring and testing equipment

For the execution of the tests the following measuring equipment was used:

- Steering robot SR60 by AB Dynamics for defined turning of the steering wheel and measurement of steering wheel angle. Features: Steering torque 60 Nm; Steering rate 1300 deg/s.
- Stabilized internal navigation system device RT4102 by OxTS for measurement of lateral acceleration of the vehicle, vehicle roll angle, vehicle yaw angle, vehicle pitch angle, roll rate, yaw rate, pitch rate, slip angle of the vehicle and the speed of the vehicle. Features: ax, ay, az $100\ m/s^2$; Angle rate 100 deg/s; Velocity 200 km/h.
- Measuring steering wheel Corrsys MSW/S for measurement of the steering wheel angle and the steering torque. Features: Steering torque 50 Nm; Steering angle 1250 deg; Steering rate 1000 deg/s; Output voltage ±10 V.
- Pressure sensors Kulite HEM-375M-140 BAR SG for measurement of brake pressure for each wheel individually. Features: Maximal pressure of 17 MPa.
- Displacement sensor ILD 1402-600SC by Micro-Epsilon for measurement of lift for each wheel individually. Measurement range: 600 mm (200 ÷ 800 mm).
- Photoelectric sensor for activation of the system for manoeuvre speed measurement.
- Digital pressure gauge XP2I by Crystal Engineering for precise tyre pressure check during the tests. Measurement range: -0,8 ÷ 7 bar.
- Weather station Vantage Pro2 by Davis Instruments for air temperature, air humidity and wind speed measurement. Measurement range: 880 ÷ 1080 hPa.
- Notebook DELL with NI 9862 a NI 9206, NI 9234 converters used for recording.

Figure 20 - Steering robot SR60 in the vehicle

Figure 21 - Displacement sensor mounted on the vehicle

4.3. Static tests

4.3.1. Measurement of the centre of gravity (COG)

The goal of this test is to find the exact position of the COG. The X-position is measured as a distance from the front axle centre line in longitudinal direction having positive sense pointing to the back of the vehicle, the Y-position as a transverse distance from the vertical symmetry plane having positive sense on the right side, given perspective of the driving direction and Z-position as a distance from the ground in vertical direction when the tyres are inflated as specified for the vehicle.

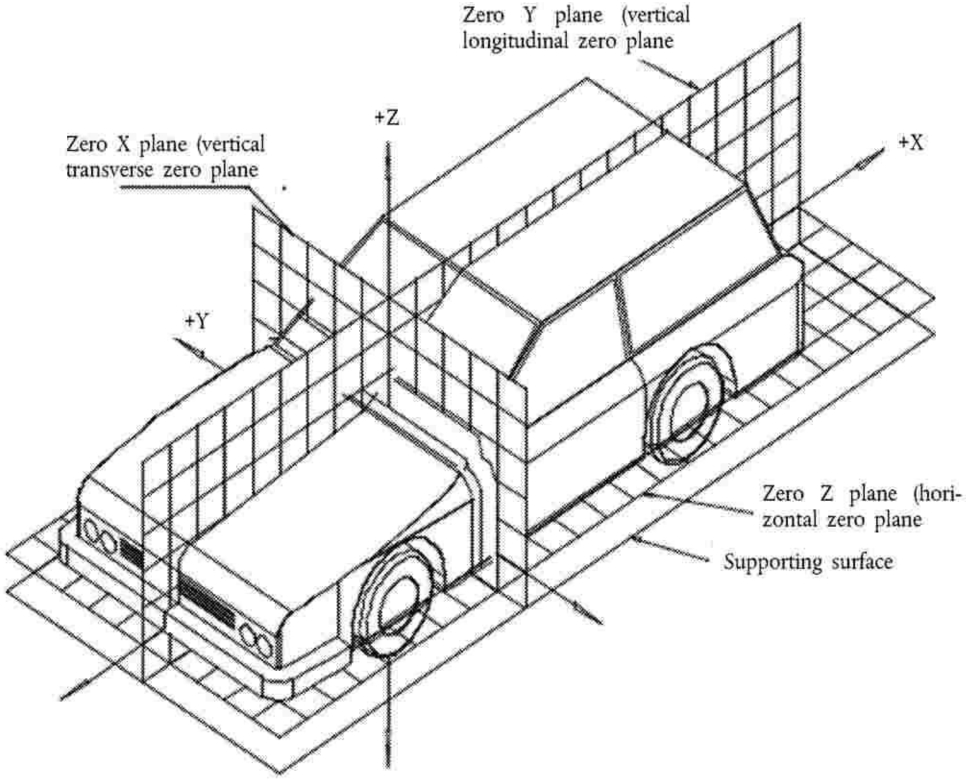


Figure 22 - Coordinate system of the vehicle [30]

A special equipment was used to prevent the suspension springs from moving. The measurement itself was performed with use of a digital weighing scales. The rear axle of the vehicle was lifted up by a pillar crane so the vehicle was tilted at the angle of approximately 15 - 24 degrees. Value of the tilt angle was limited mainly by the overhang of the car, which must not touch the ground. The same procedure was performed also with the front axle. Each of the lifts was carried out in at least 3 steps, starting with the lifting of the wheel axis by approximately 1350 mm, and then up to the height of 1450 mm.

For each of the steps - including the first one (static position in the initial state) - vertical positions of all wheels were measured, as well as the weight displayed by both scales under the wheels. The position of the COG in the direction of X-axis and Y-axis was calculated with the vehicle standing still (with no tilt) on the weighing scales. The height of the COG in the Z-axis direction was calculated for each step of the measurement individually. As mentioned above, each measurement was realized both for the rear and front axle and was repeated 2 times. The final value of the COG height is the mean value from all measurements.

The test was done with curb weight.

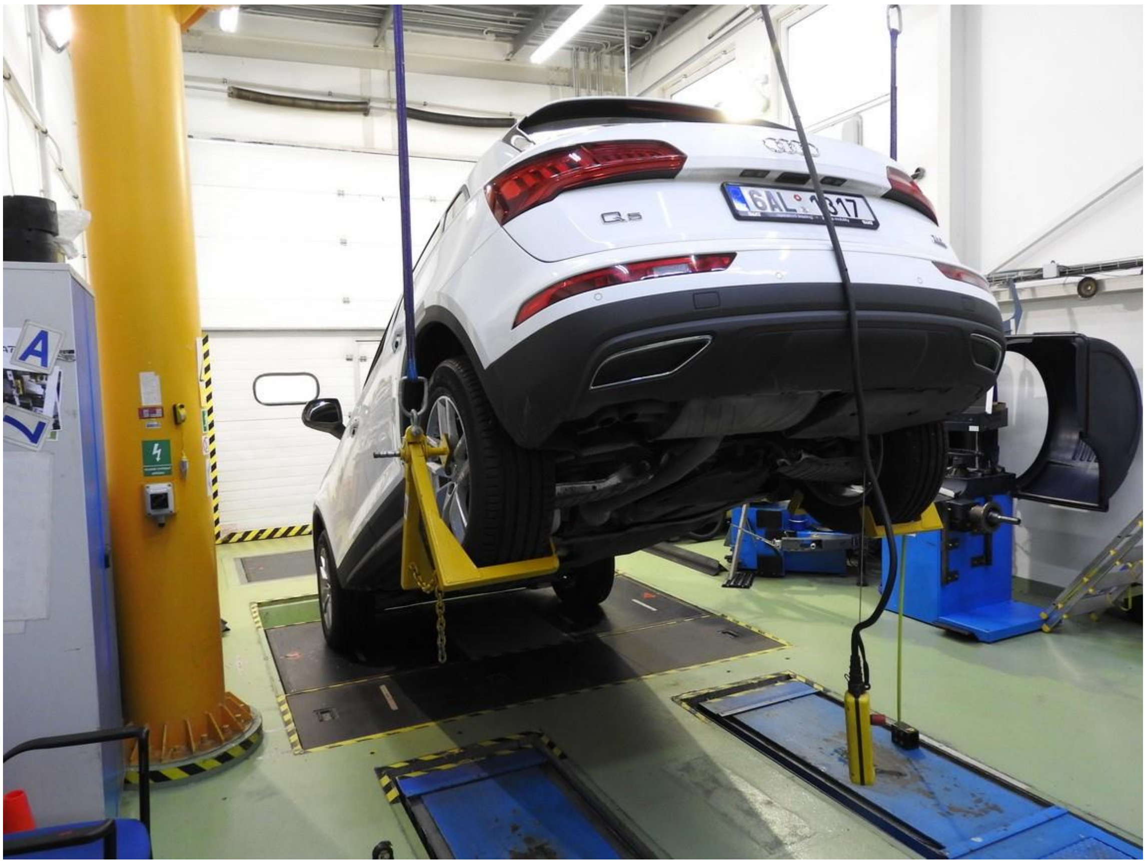


Figure 23 - COG measurement

4.3.2. Relation between the steer and wheel angle

The relation between the angles was measured while having the car lifted on the scissor jack. The angle of the front wheels was measured with the use of calibrated turntables, which were put under the front wheels.

As for the steering wheel, the calibrated protractor was used for measuring the angle of rotation.

Value of the wheel angle was measured simultaneously with the steering wheel angle for every 60 degrees of steering wheel rotation, starting from the full left lockup (-480 degrees) up to the full right lock up (+480 degrees). 18 positions in total were measured and plotted, giving the relation between steering and actual wheel turning.

The test was done with curb weight.

4.3.3. Measuring the spring deformation in relation to loading

The principle of this measurement is that the vehicle is being gradually loaded with weights while standing still on the digital weighing scales with it's all 4 wheels. Additional weight is put in the vehicle in consecutive steps, adding 60 kg each time. Weight is distributed evenly between front and rear axle. For every of the overall 10 steps, a load of each wheel is measured on the digital scales. The deformation of the springs is measured as a distance between two defined points, one of them being on a chassis and the second one on a rim.

4.4. Dynamic tests

4.4.1. Acceleration test

The test was performed by accelerating the vehicle from standstill up to the speed of 100 km/h. The test runs were repeated 3 times for both opposite directions.

The measured values were: distance needed to accelerate the vehicle up to the speed of 100 km/h, longitudinal acceleration, time elapsed during the acceleration, the speed of the vehicle, acceleration of the vehicle, pitch and pitch rate.

Vehicles with automatic transmission are changing gears without driver action.

The test was done with a partially loaded car.

4.4.2. Brake test

The vehicle under test brakes from the speed of 100 km/h to standstill. The tests were performed with various braking intensity:

- 2 m/s2
- 4 m/s2
- 6 m/s2
- 8 m/s2
- Maximal possible intensity with the actuation of ABS

All braking variations were performed exactly 3 times. From these tests, the standard outcomes for the deceleration, braking distance and braking time were measured.

Furthermore, the time dependencies of longitudinal acceleration, pitch angle, pitch rate and a brake pressure of each wheel were measured.

The test was done with a partially loaded car.

4.4.3. Coast down test

This test is performed to evaluate the resistances which a running vehicle is exposed to. The vehicle under test coasts down to standstill from the initial speed of 100 km/h. In order to mitigate vehicle's sensitivity to external effects of wind, air density and slope, the test has to be executed on a perfectly levelled and flat road without any bumps, with zero wind speed and with minimal temperature alternations during the test, in both opposite directions. Before the execution of the test, the vehicle has to be properly warmed up and fitted with brand new and correctly inflated tyres.

The principle of this test is that the driver accelerates the vehicle up to the speed of approximately 105 km/h, then the driver shifts to neutral and lets the vehicle to drive itself propelled only by its inertia up until it completely stops standstill. This procedure is repeated in the same manner 3 times in one direction and 3 times in the opposite direction, immediately one after another. The test has to be performed in a way that no interventions to the steering need to be done. In case of necessary correction of the direction, the steering has to be done very slowly and gently, without rapid interventions and on relatively large distance to prevent the lateral acceleration values higher than 1 m/s2 from having effects on the car and its parts, ultimately leading to increasing the further internal resistances of the vehicle.

Following the described procedure, the data files of measured values were obtained. The coasting distance of the vehicle evaluated is based on the longitudinal speed of the vehicle, specifically from the area of speed from 100 km/h down to 0,5 km/h, i.e. almost to standstill.

Rolling resistance of the vehicle was evaluated from the characteristics of longitudinal speed – longitudinal deceleration for the speed close to standstill, thus for the case when we can neglect the aerodynamical resistance, due to its close-to-zero value.

From this test, the driving distance of the car coasting from the speed of 100 km/h to standstill and rolling resistance of the vehicle driving at a speed close to zero were evaluated. Furthermore, pitch, longitudinal deceleration and speed of the vehicle have also been measured.

The test is done with a partially loaded car.

4.4.4. Slalom

This test is mainly used by journalists to compare the behaviour of different types of cars and tyres.

The layout of this manoeuvre is following: The course is defined by a set of 11 cones placed in a straight line with a gap of 18 m between each, thus there are 10 pitches through which the driver passes.

The starting point to the manoeuvre is a 3 m wide cone gate so that the driver is not too "wide" while entering the manoeuvre. The end of the course is built in the same way.

The test itself is realized in such a way, that the driver tries to pass through the cones as fast as possible. The test starts at lower speed around 60 km/h, which is then gradually increased up until the first cones are hit. Following runs are performed at the speed close to this critical one, but without knocking down the cones. Runs are considered as valid only if no cones are hit. The driver has to complete at least 3 successful runs out of 10 attempts. While passing through the manoeuvre, the position of the accelerator is arbitrary, but the driver must not change the style of driving. The manoeuvring speed is measured as the average speed between the first and the last cone, thus on a distance of 180 m. The result is the average speed of the 3 valid passes.

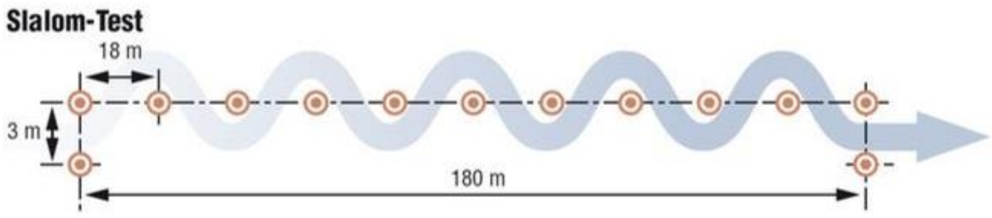


Figure 24 - Slalom layout [31]

The test was realized with a partially loaded car.

From this test, the following values in dependence on time were evaluated:

Steering wheel angle [deg]

Steering wheel rotation rate [deg/s]

Roll angle of the vehicle [deg]

Roll rate of the vehicle [deg/s]

Yaw angle of the vehicle [deg]

Yaw rate of the vehicle [deg/s]

Slip angle of the vehicle [deg]

Lateral acceleration of the vehicle [m/s2]

Lift of individual wheels (change of the distance between the wheel centre and the ground over time, which shows vertical deformation of the tyre) [mm]

4.4.5. ISO 4138 – Steady-state circular driving behaviour

The purpose of this test procedure is to measure the steering wheel angle as a function of lateral acceleration and to describe vehicle steering behaviour for left-hand and right-hand turns.

The procedure of this test is based both on ISO4138:2012 and the methodology of TÜV SÜD Czech. For this case, the variant with continuous speed increase was used. The diameter of the circle was 60 m.

Recording of the measured values began while the vehicle was yet stationary, and right after the start of recording it slowly started to accelerate. In the beginning, approximately one half of the circle was completed with the constant speed while generating the minimal possible lateral acceleration. Steering wheel angle used for this half circle was considered as an initial angle. After running through the first half of the circle, the driver started to steadily increase the speed of the car while making corrections of steering angle sufficient to maintain the circular path of the vehicle as precisely as possible. The test was carried out up to the vehicle's limit.

The test was performed both for clockwise and anticlockwise direction. The test is done with a partially loaded car.

From the test, the following values in dependence on lateral acceleration were evaluated:

*Steering wheel angl*e [deg]

Roll angle [deg]

Slip angle of the vehicle [deg]

Slip angle of the front wheel [deg]

4.4.6. ISO 3888-2 – Severe lane change manoeuvre

The severe double lane-change is a dynamic process consisting of rapidly driving a vehicle from its initial lane to another parallel lane and returning to the initial lane, without exceeding lane boundaries.

The procedure of this test is based both on ISO3888-2:2002 and the methodology of TÜV SÜD Czech. The scheme of the test is depicted in the picture below.

Total measured distance is 61 m. Orange squares are cones, dimensions of cones are defined in ISO 3888-2:2011 document. Dash line is a vehicle path. Width of the section 1 is A = 1,1 x width of the vehicle + 0,25 m. Width of the section 3 is B = vehicle width + 1 m. Section 5 is the same for all vehicles and it is 3 m wide. The driver tries to pass through the manoeuvre at maximal possible speed. It is prescribed that the driver enters the manoeuvre at the constant speed with the highest possible gear to keep the engine running above 2000 rpm. Driver releases the throttle 2 m after the first cone and drives the whole manoeuvre with a foot off the gas pedal, but with the gear still engaged, so the vehicle is slightly decelerated by its engine. The speed of the run is measured at the last cone of the entry. The target of this test is to drive through the cones in maximal possible speed. The speed at the beginning of the test is set lower and then gradually increased up until first cones are hit. At this moment the test begins.

Next runs are performed at the speed close to this critical one, but without knocking down the cones. Runs are considered as valid only if no cones are hit. The driver has to complete at least 3 successful runs out of 10 attempts, whilst there has to be at least one invalid run in the series. Furthermore, the speed of the valid runs can’t show significant increasing nor decreasing trend.

Result speed is the average from 3 valid runs. The exit speed is measured for informative purpose.

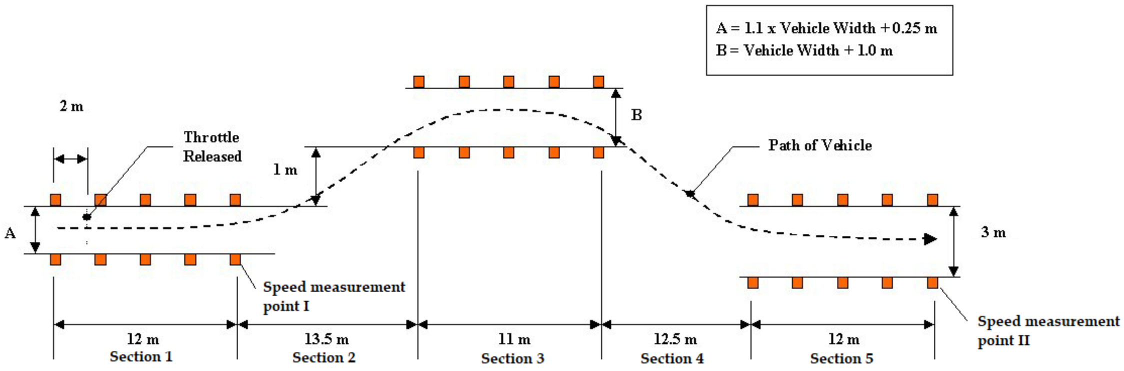


Figure 25 - ISO 3888 Layout

The test was realized with a partially loaded car.

From this test, the following values in dependence on time were measured:

Steering wheel angle [deg]

Steering wheel rotation rate [deg/s]

Roll angle of the vehicle [deg]

Roll rate of the vehicle [deg/s]

Yaw angle of the vehicle [deg]

Yaw rate of the vehicle [deg/s]

Slip angle of the vehicle [deg]

Lateral acceleration of the vehicle [m/s2]

Lift of individual wheels (change of the distance between the wheel centre and the ground over time, which shows vertical deformation of the tyre) [mm]

4.4.7. ISO 7401 – Lateral transient response test methods

The primary object of these tests is to determine the transient response behaviour of a vehicle. Characteristic values and functions in the time and frequency domains are considered necessary for characterizing vehicle transient response.

This test is based on ISO7401, during which a defined sinewave excitation and a defined step steer are executed.

For the sinewave excitation of the vehicle, the basic input condition is the driving speed of 100 km/h with the accuracy of ± 2 km/h. The frequency of excitation is prescribed to be 0,5 or 1 Hz and the excitation amplitude is corresponding to the angle of the steering wheel when steadily turning with a lateral acceleration of 4 m/s2 at the speed of 100 km/h.

The driving speeds were chosen upon discussion with experienced test engineer as follows:

30 km/h
50 km/h
70 km/h
100 km/h

And the excitation frequencies:

0,2 Hz
0,8 Hz
1,4 Hz
2,0 Hz
2,1 Hz

The amplitude of the excitation is in accordance with ISO norm, as mentioned above.

The step steer was executed according to the prescription at the speed of 100 km/h ± 2 km/h with an excitation amplitude corresponding to the angle of the steering wheel when steadily turning with a lateral acceleration of 4 m/s2 at the speed of 100 km/h. The step steer was performed both in right and left sense and repeated 3 times for each side.

The test is done for tests executed with the use of driving robot.

From this test, the following values in dependence on time were measured:

Steering wheel angle [deg]

Steering wheel rotation rate [deg/s]

Roll angle of the vehicle [deg]

Roll rate of the vehicle [deg/s]

Yaw angle of the vehicle [deg]

Yaw rate of the vehicle [deg/s]

Slip angle of the vehicle [deg]

Lateral acceleration of the vehicle [m/s2]

Lift of individual wheels (change of the distance between the wheel centre and the ground over time, which shows vertical deformation of the tyre) [mm]

5. Vehicle model building process and subsequent simulation

In this chapter, the entire process of building up a vehicle model is described step by step. The multibody modelling of the vehicle requires the input data from several aspects of vehicle design. This data was gathered either from the manufacturer or from the physical tests. Building a vehicle model in CarMaker is divided into specific categories, each of them will be described individually.

In order to develop a dynamic model, some of the parameters had to be estimated. This was done through an iterative process with a use of Test Manager. In order to use the Test Manager, the parameters which are going to be variated have to be entered as Named Values, which means the desired value is not entered in the vehicle data set GUI. In the vehicle data set, the dollar sign ($) followed by the name of a parameter is filled into the parameter field to introduce the Named Value. The actual value range of the parameter is then set within the Test Manager GUI.

To start off with the building from scratch, it is highly recommended by IPG to use the Vehicle Data Set Generator (VDSG), which generates the entire vehicle data set based on the several fundamental data. This tool alone is able to generate the model accurate enough for most of the use-cases, thus its ideal starting point for fine-tuning of the model. At this point, all of the known parameters are filled in. Figure 24 shows the VDSG completely filled with all of the parameters, which are to be found in table 3.

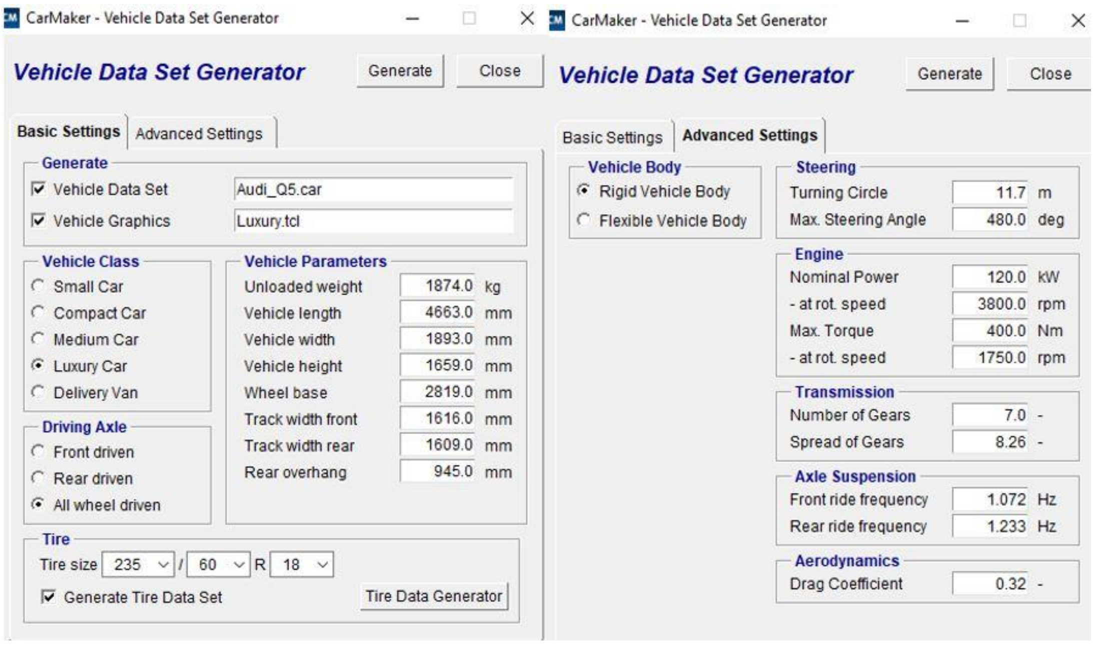


Figure 26 - Vehicle Data Set Generator

In this thesis, only some of the main screens from the Vehicle Data Set GUI are shown. The entire model of the car is enclosed in the appendix, named as *Audi_Q5.car.*

5.1. Vehicle body

The first option within this category is to choose between rigid or flexible vehicle body model. Since we have absolutely no data concerning the rigidity of the chassis as there is no way to measure it, it is better (according to IPG) to consider the body as rigid.

It is important to not forget to make sure if the overall weight corresponds with the real weight (1874 kg in our case) and that the position of the COG corresponds to the measured values. The position of the COG can be found under the INFO button and for the Audi Q5 should be following: $x_{COG} = 2475\,mm$, $y_{COG} = 11\,mm$, $z_{COG} = 626\,mm$. Adjustments of position are done through vehicle body input field. In Y-axis, CarMaker uses opposite sense of direction, so the input from the measurement should be put in with – sign. The coordinate system of CarMaker is shown in figure 27.

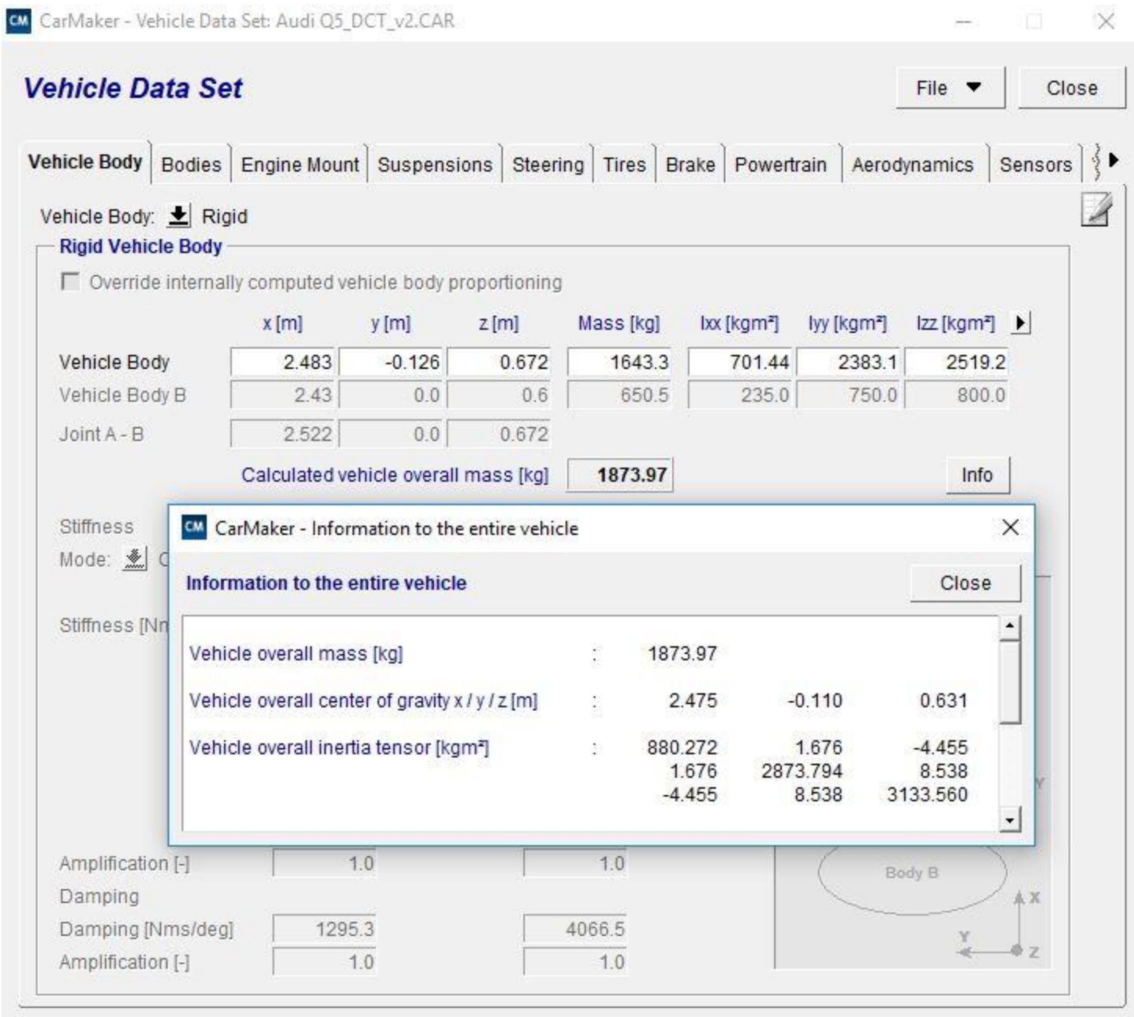


Figure 27 - Vehicle Body GUI

5.2. Bodies

This category has a lot of input fields, but the majority of them does not to be adjusted. The wheel centre positions are calculated from the VDSG input data, only the Z direction might sometimes be calculated incorrectly (reason unknown), so make sure it corresponds the reality, being 0,3695 m in our case.

Masses and inertias of the wheels and wheel carriers are approximately calculated by CarMaker based on the data input from the VDSG and since there is no measured data available on that, no further adjustments are done here.

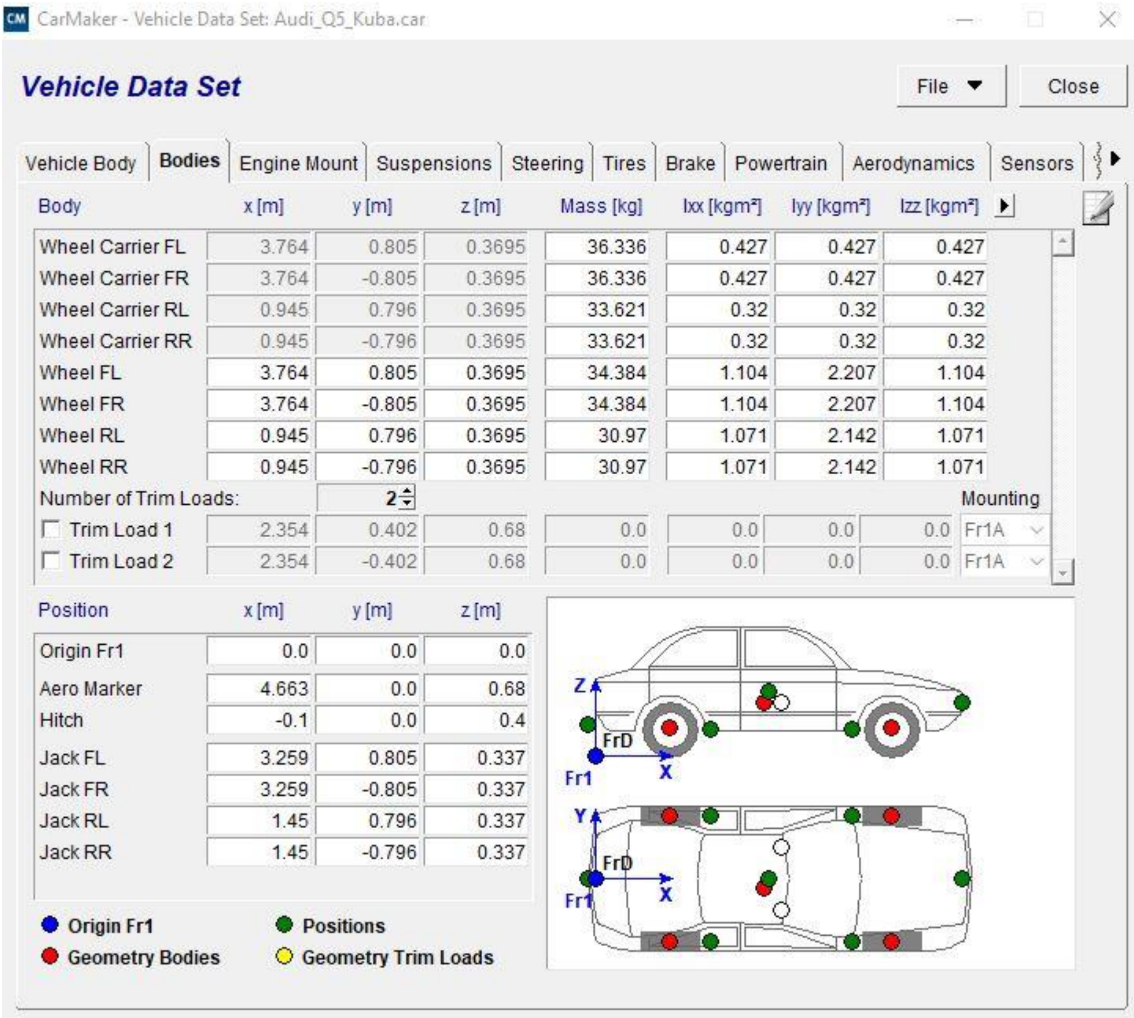


Figure 28 - Bodies GUI

5.3. Engine mount

We have no data about the properties of the engine mount and so the engine is considered as rigidly mounted. Therefore, this block is skipped completely.

5.4. Suspensions

A category, which has an extensive effect on overall vehicle dynamics. However, only a few parameters might be measured or estimated in the simulations, while the rest has to be left as default or neglected.

- **Spring**

Stiffness mode can be defined both as a characteristic value or as a 1D lookup table. Having the data obtained from the measurement of the static spring deformation in relation to loading, the 1D table is the best choice to define the spring characteristics accordingly. Measured data is shown in table 4. As shown in figure 29 the CarMaker needs the input in form of compression and force values, so the values have to be recalculated using the simple equation of $F = k * \Delta l$. Force is calculated from the weight of load by multiplying it by gravitational constant.

Table 4 - Spring deformation in relation to loading

	Wheel load [kg]				Spring deformation [mm]			
	FL	FR	RL	RR	FL	FR	RL	RR
1	502	496	412,5	432,5	275	279	289	281
2	512	505,5	432,4	452	274	277	285	277,5
3	519,5	512,5	454,6	475,9	273	276,5	281	273
4	527	520	476	498,8	271	275,5	277,5	269
5	535	527	497,5	519,5	269,5	274,5	273	264,5
6	544	535,5	518,8	545,5	268	272,5	269	260
7	552	544	539,8	564,4	267	271,5	265	257
8	562	556,5	558,9	588,3	262	267,5	261	252
9	568	564	583,6	610	261	266,5	256	246,5
10	574	571	607,9	639,4	259	265	250	241

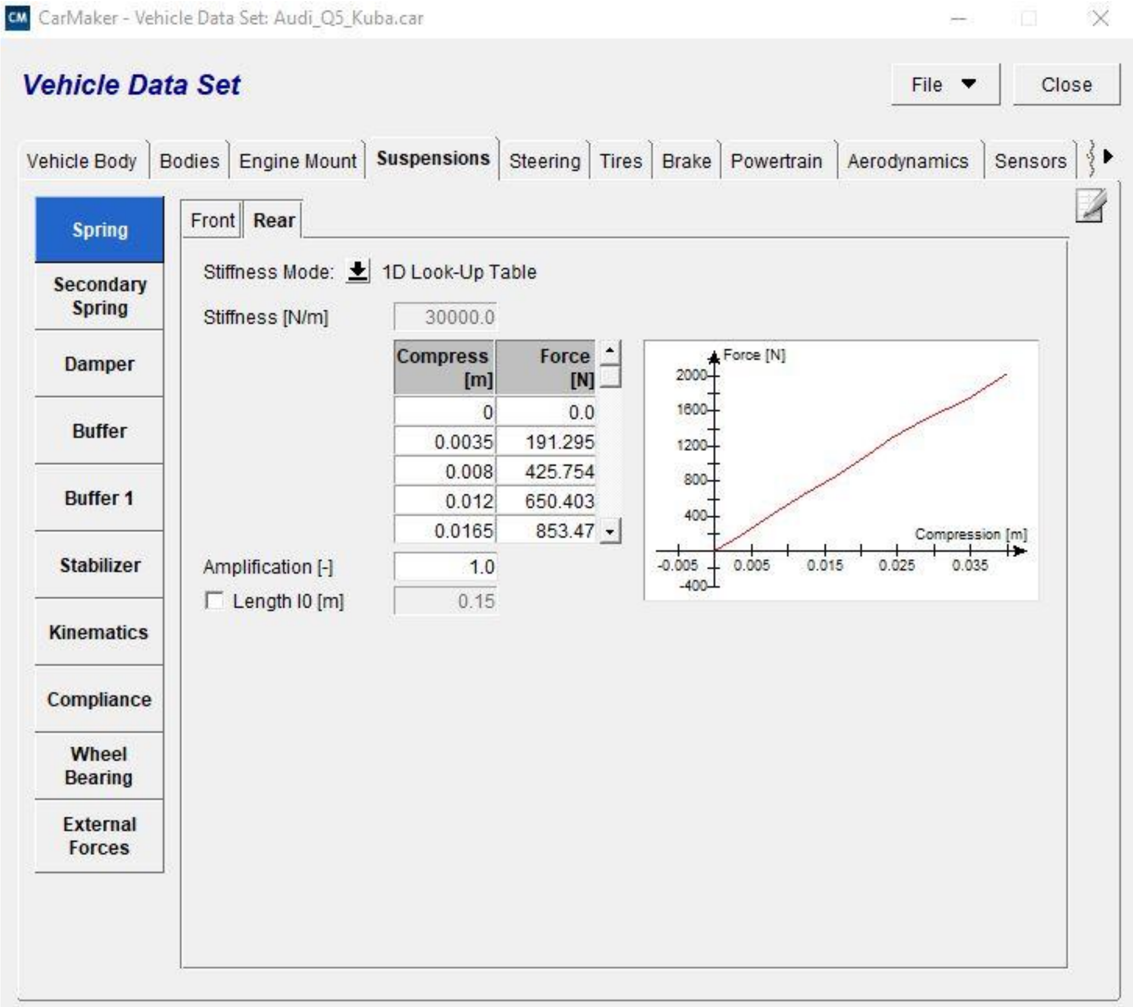


Figure 29 - Input of spring characteristics

- **Secondary Spring**

  Left in default settings as neglected, has a minor influence on overall dynamics and no relevant data is available on that.

- **Damper**

  From the roll-up menu, the characteristic value option is selected, and Named Values are filled in for both front and rear axle to parametrize it in Test Manager.

- **Buffer**

  Left in default settings as the car will not experience the situation when the suspension hits the buffer and thus it has no significant effect and is of no such importance to be the subject of tuning, therefore the default characteristics computed by VDSG is sufficient.

- **Buffer 1**

  Same as for the buffer.

- **Stabilizer**

  From the roll-up menu, the characteristic value option is selected, and Named Values are filled in for both front and rear axle to parametrize it in Test Manager.

- **Kinematics**

  As the Audi Q5 uses the 5-link suspension for both front and rear axle, modelling the kinematics alone would be a topic for diploma thesis. Having a lot of variables, it is not possible to parametrize with the limited software capabilities, so no adjustments are done here.

- **Compliance**

  Left in default settings as neglected, no data on that.

- **Wheel Bearing**

  Left in default settings as neglected, since it has minor effects. In case the coasting tests are not corresponding to the real ones, the wheel bearing friction could be parametrized, but in my case, there was no need to do that.

- **External Forces**

  Left in default settings as neglected, the vehicle does not experience any external forces.

5.5. Steering

Left in default settings because the CarMaker calculates the values automatically based on the VDSG inputs, namely the turning circle, steering angle and wheel track and wheel base. The measurement of the relation between the steer and wheel angle was used to verify the linearity of steering.

5.6. Tyres

One of the most critical components of them all, but at this point, I had to completely rely on IPG. Firstly, measuring of tyre characteristics requires a special test rig, which is very expensive and not available to us. Secondly, the development of a tyre model is a scientific task, which requires vast knowledge and experience. Thus, the tyre model provided by IPG is selected.

5.7. Brake

Selected brake model is hydraulic, as the car uses the hydraulic brake system. Brake amplification left default with the value of 1.0.

When the hydraulic brake model is selected, also the hydraulic basic controller has to be selected in the Control section.

In the system section, the pressure to Brake Torque can be filled in with Named Value (as shown in figure 30) to parametrize the braking force of the system. But it is not necessary, while the default value defined by CarMaker is quite appropriate as it turned out during the braking simulations.

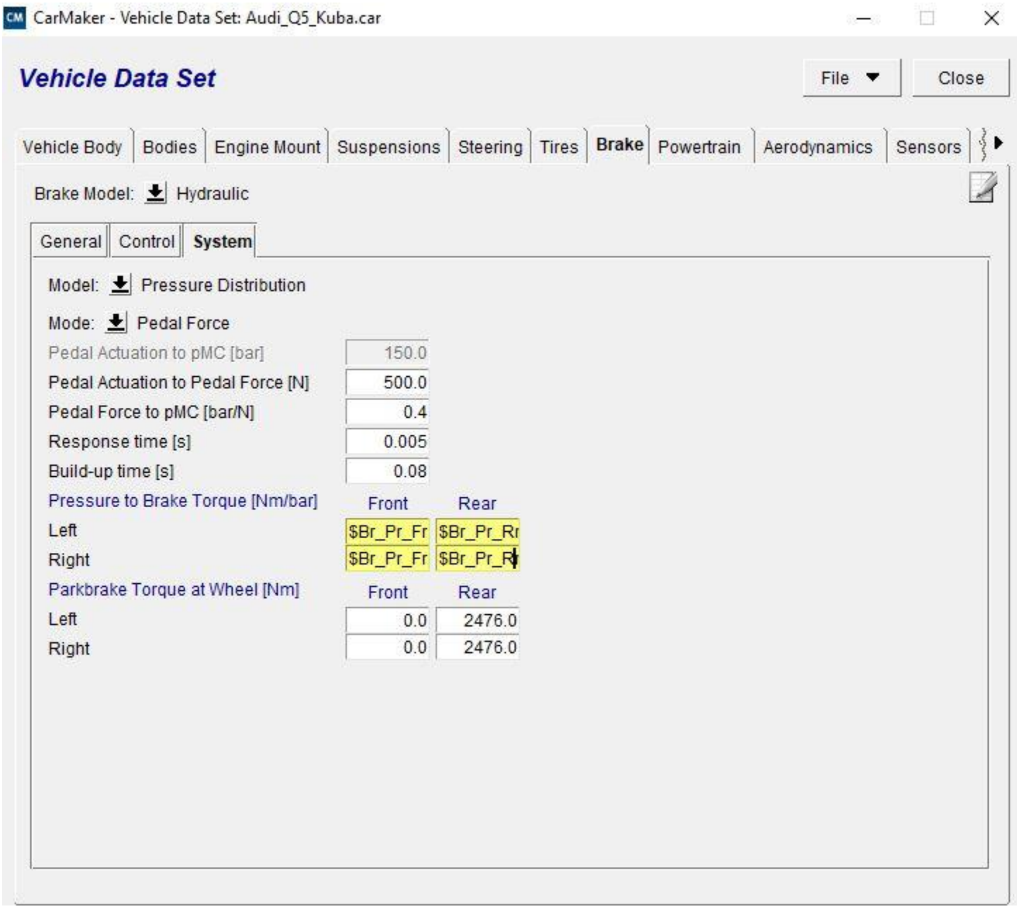


Figure 30 - Brake system parametrization

5.8. Powertrain

Proper powertrain definition is mandatory to obtain accurate results from dynamic tests.

First off, it is necessary to choose the right powertrain mode by clicking on the black arrow in the top-left corner. In the case of Audi Q5, the conventional mode has to be chosen. In the case of different power source is used to propel the car, the appropriate mode has to be chosen, e.g. hybrid or electric. Further settings are divided into 5 subcategories, each of them being described separately below.

- **General**

  In this section, the driveline layout is depicted to clearly see, if the chosen powertrain mode suits the needs of the model. In the input field on the bottom, the number of integration substeps can be selected. This defines the number of calculations of the powertrain model in simulation cycle. Default number, recommended by IPG, is 5 substeps.

- **Drive Source**

  - **Engine**

    - **General**
      Two things have to be defined here. Engine model as a Look-Up table and the Engine Orientation accordingly to the real car. In the case of Audi, the engine is oriented longitudinally, hence the longitudinal orientation has to be selected. The rest of the parameters is left in its default value.

    - **Torque**
      The most important section to define the engine properly. Here, the table has to be filled accordingly with the real engine characteristics. Mapping model selected as 1D table: Drag and Full Load. Drag Power left with default values calculated by CarMaker and Full Load Power table filled in, based on the engine characteristics shown in figure 31 below.

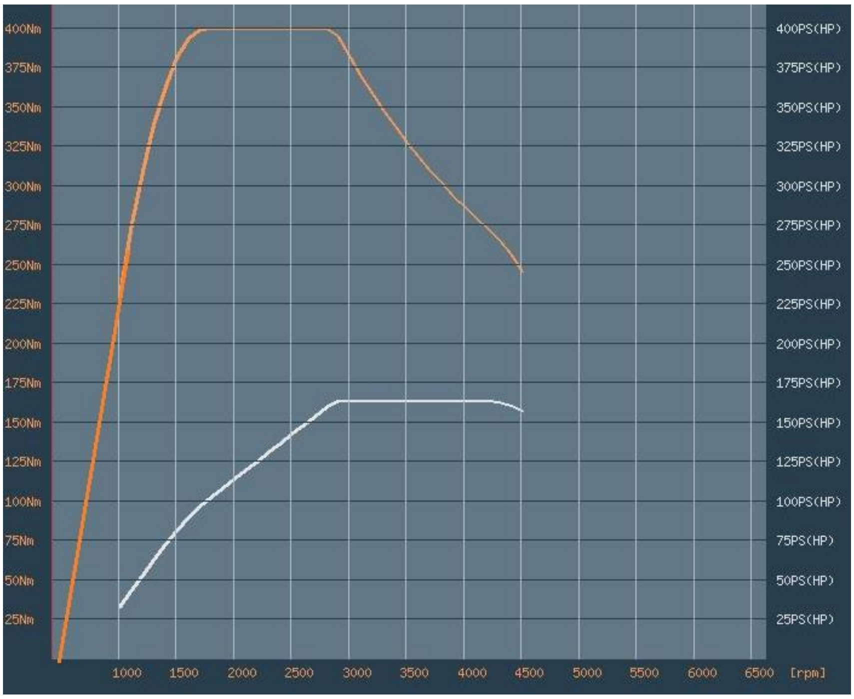


Figure 31 - Engine characteristics [43]

- **Fuel Consumption**
  No data regarding fuel consumption available, thus left unchecked by default.

- **Turbocharger**
  The real engine is equipped with a turbocharger, hence the turbocharger column is checked, however, all of the settings are left in its default values due to the insufficient data on that.

- **Intake Manifold**
  No data regarding the intake manifold available thus left unchecked by default.

- **Starter motor**
  No data regarding the starter motor available, thus left in default settings.

- **Clutch**
  No data regarding the clutch available, thus left in default settings.

- **Gearbox**
  - **General**
    Very important to select the according gearbox model, Dual Clutch Transmission in case of Audi. The rest of the input fields is left in default settings.

  - **Gears**
    Here, the gear ratios for all gears including the reverse gear ale filled in. Gear ratios for Audi are to be found in table 3.

  - **Clutch**
    No data regarding the clutch available, thus left in default settings.

- **Driveline**
  - **General**
    The appropriate type of driveline model has to be selected here. For Audi, it is All wheel drive model, as it has all wheels driven.

  - **Front axle**
    Here, the final drive ratio is specified by filling in the Transmission input field. The value for Audi is 5,302. The rest is left default.

  - **Rear axle**
    Here, the final drive ratio is specified by filling in the Transmission input field. The value for Audi is 5,302. The rest is left default.

  - **Center Differential**
    The appropriate type of coupling model has to be selected here. For Audi, it is Viscoelastic model.

- **Control Unit**

  - **Powertrain control**
    No adjustments required.

  - **ECU**
    No adjustments required.

- **TCU**
  Here, the shifting limits have to be defined by filling up the table. For each gear, there should be specified maximal and minimal rotational speed. Defining the shifting limits correctly is very important for the gearbox to choose the gears reasonably. Audi has its idle speed at 800 rpm and redline is at 4500. Option to fine tune the gearbox behaviour by selecting the 2D lookup table, which also takes the throttle position into account.

- **MCU**
  No adjustments required.

- **BCU**
  No adjustments required.

- **Power Supply**
  No adjustments required.

5.9. Aerodynamics

Except for the frontal area calculated by CarMaker, there is no available data concerning aerodynamics. After all, aerodynamics is of low importance for the purpose of this work, since all of the tests were performed in speeds below 100 km/h. Thus, no adjustments were made here.

5.10. Sensors, Vehicle control, Misc.

These last 3 blocks are irrelevant for the purpose of vehicle dynamic model validation, as neither of them affects dynamic behaviour, so no adjustments are done here.

Now, the vehicle data set is defined completely, and the vehicle model is ready to run the first tests. However, the environment and test course for every individual test run have to be specified. Some of the ISO tests are predefined by IPG in their library of example test runs, however, they all need to be somewhat modified in Scenario/Road editor and the manoeuvres have to be defined within the Manoeuvre editor GUI. This is, for instance, a case for the ISO 3888 test, where the exact layout of the track has to be set accordingly to the vehicle width, as described in section 4.4.6. It is expected that the person using this document as a modelling manual has at least elementary experience with CarMaker and thus, Scenario, Road or Manoeuvre configuration will not be further discussed, hence the scope of this thesis is only a vehicle modelling. When in doubt, all of the test runs are to be found inside the enclosed CarMaker file folder, where all of the settings for all the test runs was kept the same as used by the author, thus the tests can be reproduced in the same way with no additional modifications.

Before the first test runs are performed, two additional steps are recommended. Firstly, the model should be checked via Model Check function, which is a part of CarMaker and can be found under the Simulation tab. This enables to quickly check whether the parameters are somewhat matching the reality. Next tip is to run the Driver Adaption, also found under the Simulation tab. This will enable the IPG Driver to learn the car behaviour and thus get to its limits, which is very useful for subsequent dynamic tests.

6. Evaluation

In this chapter, the results from both physical and virtual tests are presented and directly compared to each other. The evaluation of virtual tests was done with a use of IPG Control and MS Excel, into which the data from CarMaker was exported.

Most of the real tests were run several times to ensure the reproducibility. This is not needed when using the simulation, while the influence of environment is fully controllable and therefore reproducible. For comparison with simulation, only one real test for each scenario was used, always being the average one among the other tests.

Only the main parameters and dependencies are shown plotted directly in this thesis due to the limited extent. The rest of the parameters is to be found in the appendix enclosed on attached CD in form of MS Excel sheets, which are arranged in several folders, each having the same name as tests presented below. In each folder, there is datasheet both for real test and for simulations.

The running order of the simulated tests follows the validation process recommended by IPG and described in section 1.7.3.

The following values were measured, simulated and compared:

Steering wheel angle and steering wheel rotation rate should be as close as possible to physical test. If there are any major differences in specific parts it can be caused by progressive steering ratio dependent on vehicle speed.

Roll angle and *roll rate* is mainly dependent on stabilizer and damper properties. So, by tuning characteristic values or look-up table we can get more reasonable results. For the best results, COG should as close as possible to roll centre. Also, suspension geometry significantly affects body roll. To get precise result suspension should be well designed in CarMaker. Since this is a complicated job, the basic setup is quite satisfactory most of the time. In the end, wheel alignment affects body roll as well.

Yaw angle and *yaw rate* can be affected by the kinematics of vehicle suspension. Setting of correct wheel alignment can lead to better results.

Lateral acceleration of the vehicle is affected by a combination of several influences. Mainly tyres, road friction coefficient and whole suspension setup. There is no general approach to set this variable.

Slip angle is mainly affected by tyre properties, weight on individual wheels and adhesion. A principal means of adjusting slip angles is to alter the relative roll couple (the rate at which weight transfers from the inside to the outside wheel in a turn) front to rear by varying the relative amount of front and rear lateral load transfer. This can be achieved by modifying the height of the roll centre, or by adjusting roll stiffness, either through suspension changes or the addition of an anti-roll bar. Due to its significant dependence on tyre properties, which we are not able to measure is of smaller importance compared to other parameters.

Lift of individual wheels is affected by spring characteristic which ensures correct ride height along with the damper stiffness. There is no way how to define and evaluate this in CarMaker, thus this was characteristics was not compared

Brake pressure of individual wheels is mainly done by design of brake system. Tuning of this parameter is directly possible in CarMaker brake setup.

From all the parameters described above, only a few are important for each test. Their importance depends on the type of test, whether it investigates lateral or longitudinal behaviour, or it is a dynamic or steady state. Because of this, the Key Performance Indexes (KPI) are specified for each test. The reason for choosing the particular KPI is explained for each test separately in the conclusion.

6.1. Acceleration test

The goal of this test is to verify, whether the powertrain is set up accordingly to the real one by comparing the time elapsed during the acceleration or the distance needed to reach 100 km/h.

KPI: *Time of acceleration, Longitudinal acceleration*

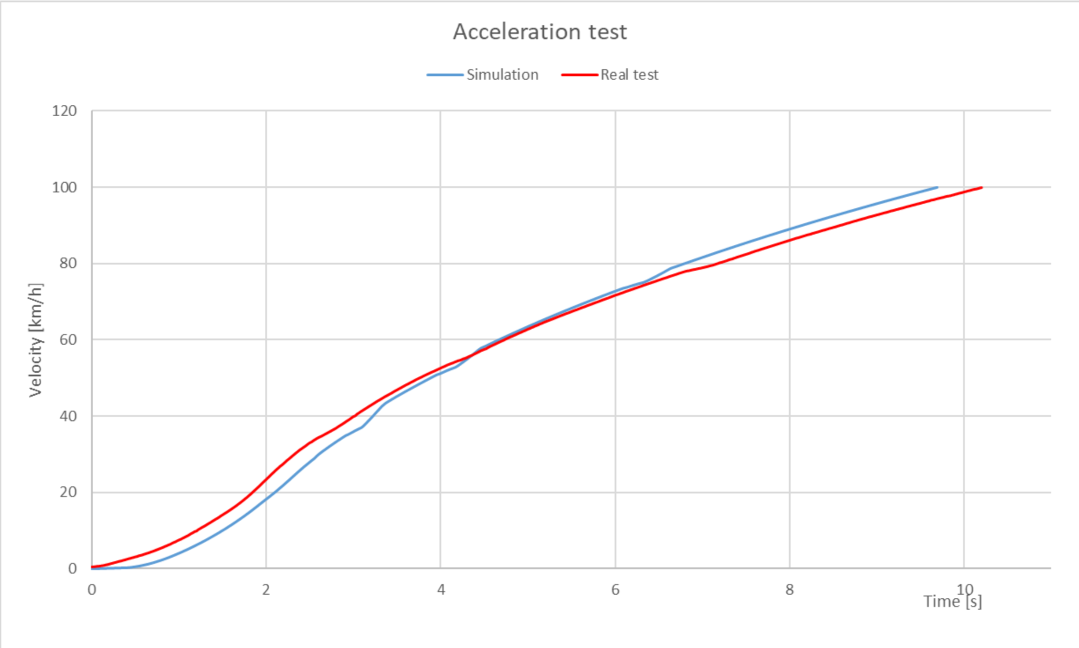


Figure 32 - Acceleration comparison. Velocity vs. Time

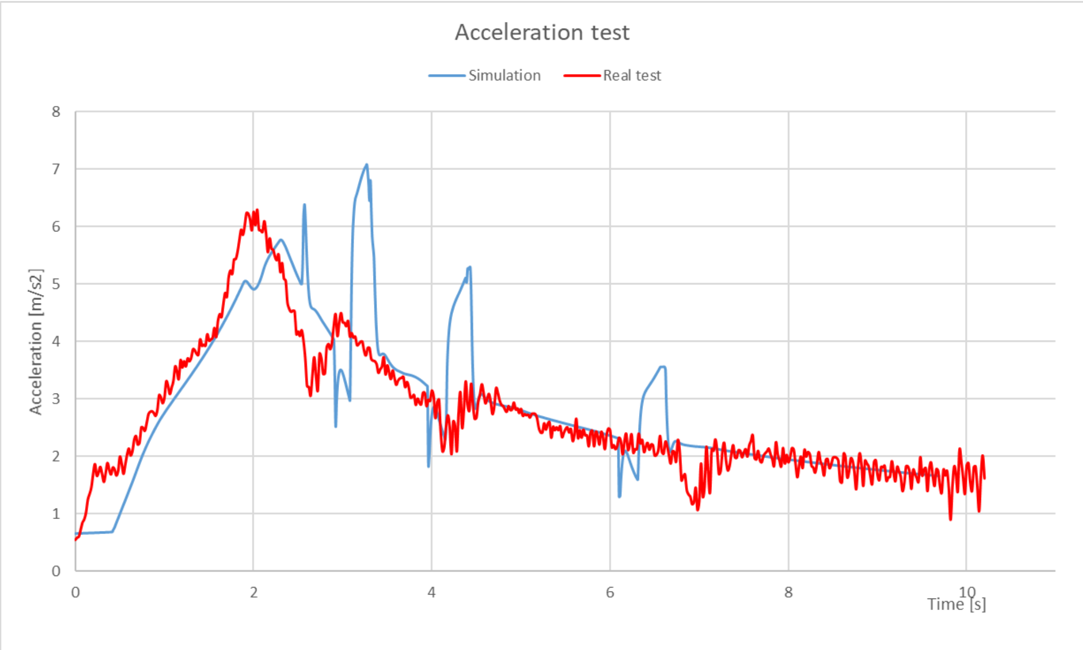


Figure 33 - Acceleration comparison. Longitudinal acceleration vs. Time

Conclusion: This test proved the setup of the virtual model powertrain is matching the real car. Obviously, the main parameter of interest is the time of acceleration. Acceleration of the virtual vehicle to 100 km/h took **9,5 s** in comparison to **10,16 s** measured with the real car. Also, the overall course of the longitudinal acceleration along time corresponds to the real vehicle. However, there are some local differences between the real and the virtual car. In case of simulation, there are 3 peaks of positive acceleration gain, which are caused by very aggressive clutch release during the gear changes. This would be an issue for drive comfort and would require tuning of Gearbox control unit logic, however for purpose of this thesis is not an issue to solve. The harsh shape of the real test curve is caused by the noise of the measurement due to the insufficient sampling frequency.

6.2. Brake test

The goal of this test is to verify, whether the brake system is set up accordingly to the real one by comparing the total braking distance, braking time, longitudinal deceleration or brake system pressure. Additionally, the pitch may be compared to check the suspension behaviour in the longitudinal direction, as it is shown in the graph below. For the validation, the maximum braking intensity test was chosen to compare with, because this test shows the ultimate performance of the system.

KPI: Braking distance, vehicle pitch

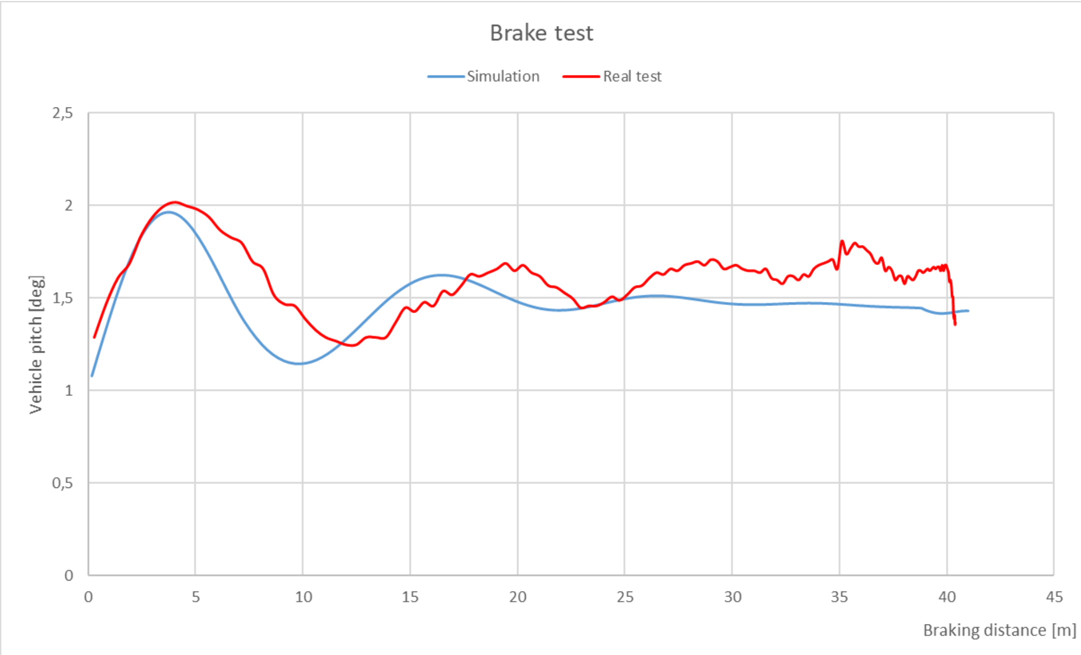


Figure 34 - Brake test comparison. Vehicle pitch vs. Braking distance

Conclusion: Importance of braking distance as a parameter to compare is obvious, while it directly shows the brake system performance as well as the longitudinal adhesion performance of the tyre. Braking distance of the virtual model is **41,58 m** compared to **40,41 m** of the real car. This difference is mainly due to the difference between the longitudinal properties of the real and virtual tyre. Brake system pressure was approximately 8 MPa for both the simulation and the real test, which shows that the system was set up correctly. The maximal value of vehicle pitch angle is important because the tilt of the car during braking directly affects the range of ADAS systems, as they tilt with the whole car. The difference in pitch angle course is caused by slightly different setup of dampers and different properties of the tyre, which in case of a virtual model are able to provide little less grip and thus transmit less force, which affects the tilt.

However, more important than the course is that the maximal values of the pitch are almost matching, thus the virtual car sensors will have similar range as in the real one during emergency braking.

6.3. Coast down test

The goal of this test is to verify, whether the virtual vehicle model resistances correspond to the real one.

KPI: Distance travelled

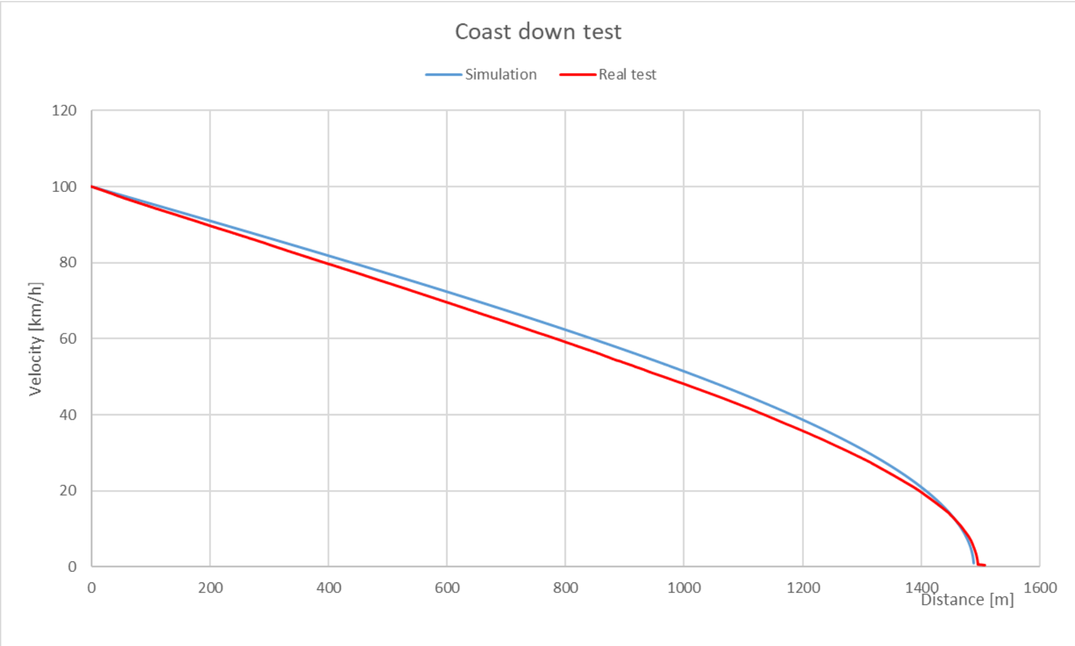


Figure 35 - Coast down test comparison. Velocity vs. Distance

Conclusion: 1488 m of distance travelled for the virtual model proves that it has almost the same resistance as the real car with **1507 m** distance.

6.4. ISO 4138 – Steady-state driving behaviour

This test analyses the vehicle's dynamic behaviour dependent on lateral acceleration. The purpose of this test procedure is to measure steering wheel angle as a function of lateral acceleration. Also, the vehicle roll can be examined. Results are significantly dependent on the quality of the tyre model.

KPI: Steering wheel angle, vehicle speed, roll angle, lateral acceleration

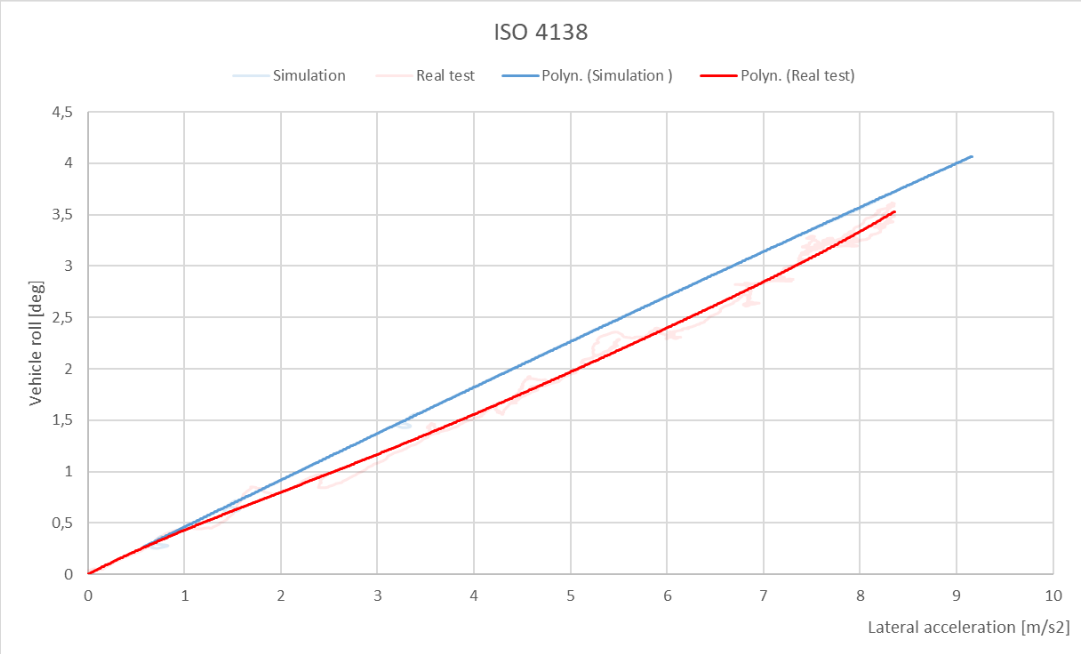


Figure 36 - Steady-state behaviour comparison. Vehicle roll vs. Lateral acceleration

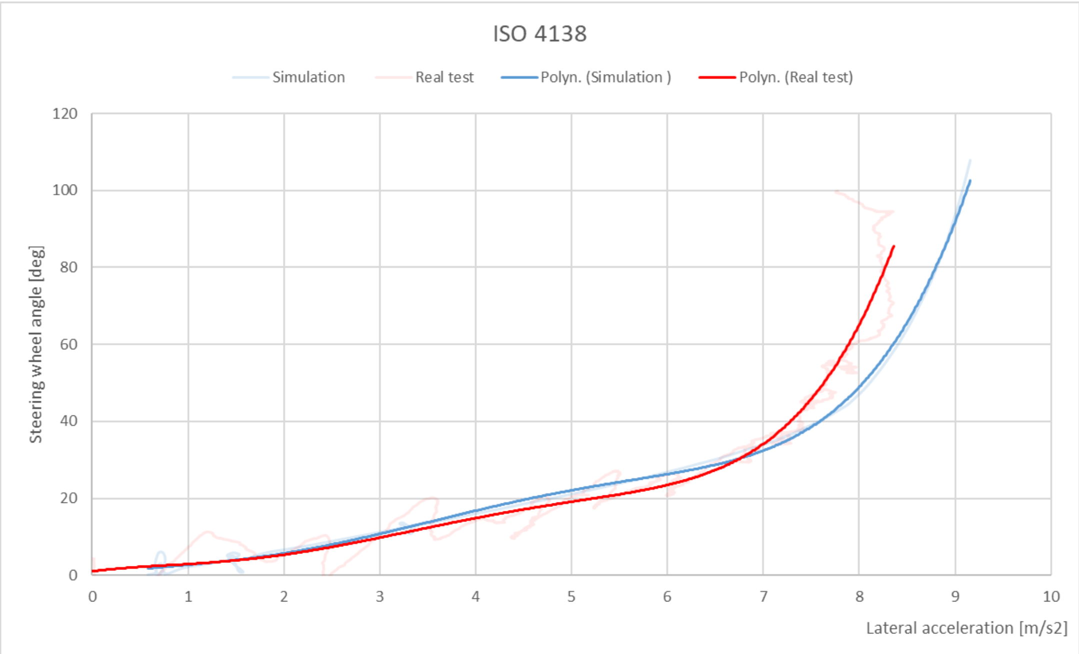


Figure 37 - Steady-state behaviour comparison. Steering angle vs. Lateral acceleration

Conclusion: This test is important to verify the accuracy of the suspension settings, mainly the stiffness of the anti-roll bar and springs. Total vehicle roll of the virtual model approximately corresponds to the real one, so it proves that the suspension of the virtual car was set up right and the steady-state behaviour is similar. The test also clearly shows the tyre behaviour, so the accuracy of the tyre model can be checked. In this case, the virtual tyre is capable to generate a little more lateral grip than the real one.

6.5. ISO 7401 – Lateral transient response test

The primary object of these tests is to determine the transient response behaviour of a vehicle. Characteristic values and functions in the time and frequency domains are considered necessary for characterizing vehicle transient response.

KPI: Lateral acceleration, roll rate, yaw rate

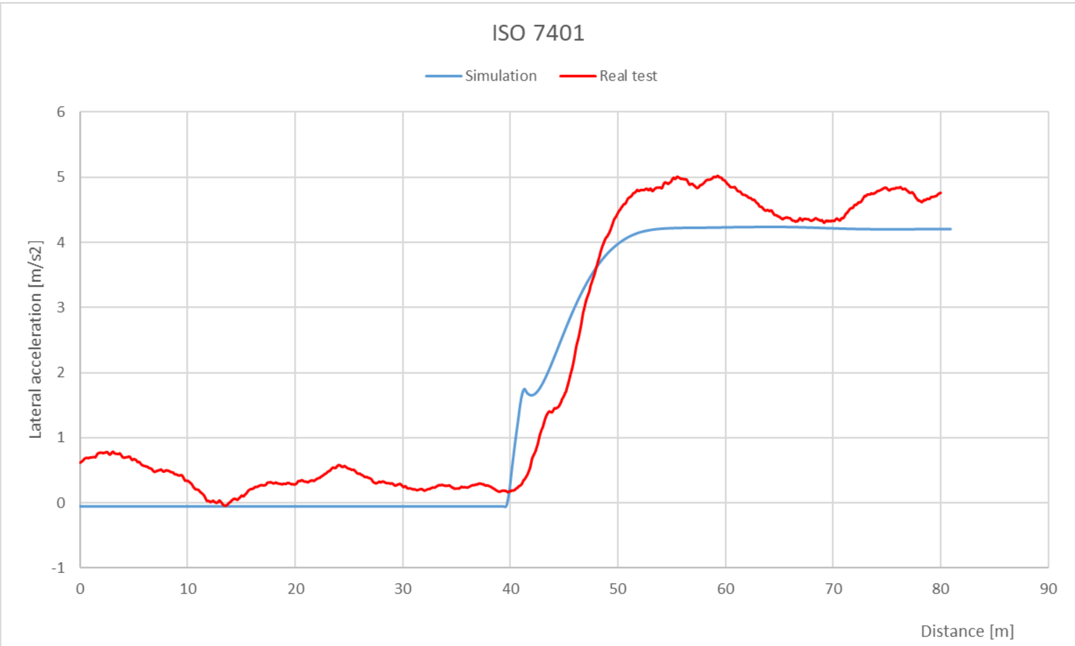


Figure 38 - Lateral transient response comparison. Lateral acceleration vs. Distance

Conclusion: This test should show the vehicle reaction to the change of steering input and thus the lateral acceleration and rates of roll and yaw are examined. The differences between simulation and the real test shown in figure 38 are caused by the precision of IPG Driver, which directly smoothly follows the procedure prescribed by ISO 7401, whereas the steering robot has some reaction time and limited accuracy which makes the course of the real car less smooth.

6.6. ISO 3888 – Severe lane change manoeuvre

The "Lane Change" test is used for evaluating the vehicles safety and handling ability. The primary function is to test the tilt stability of the vehicle.

KPI: Roll angle, lateral acceleration, yaw angle, vehicle speed

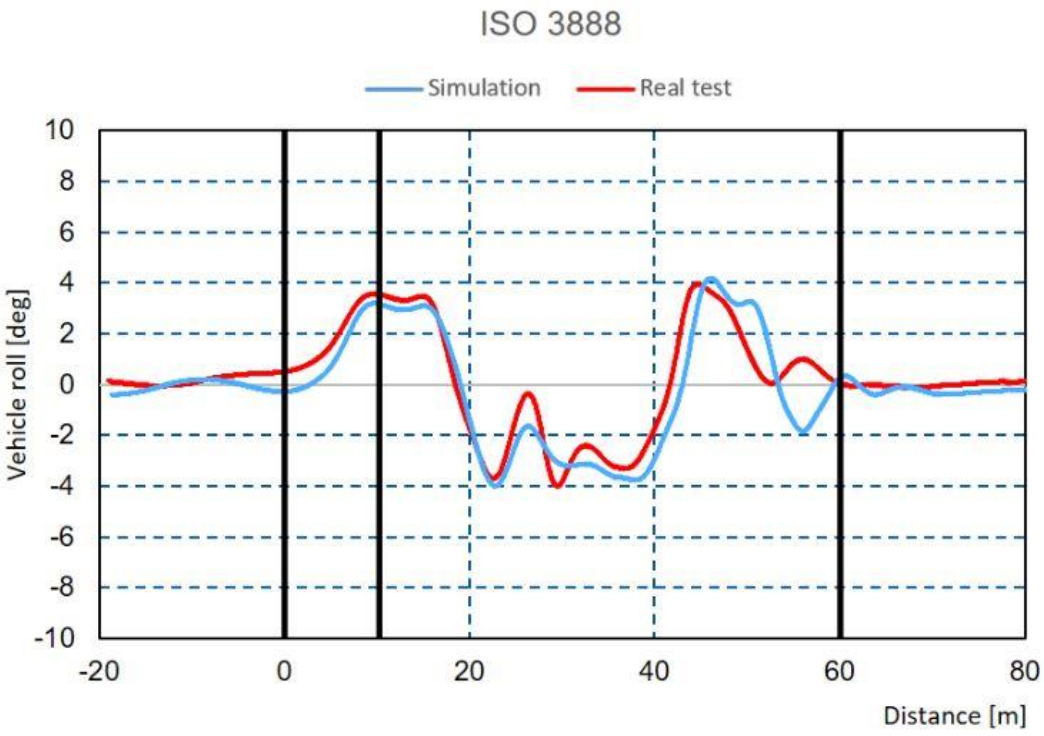


Figure 39 - Lane change behaviour comparison. Vehicle roll vs. Distance

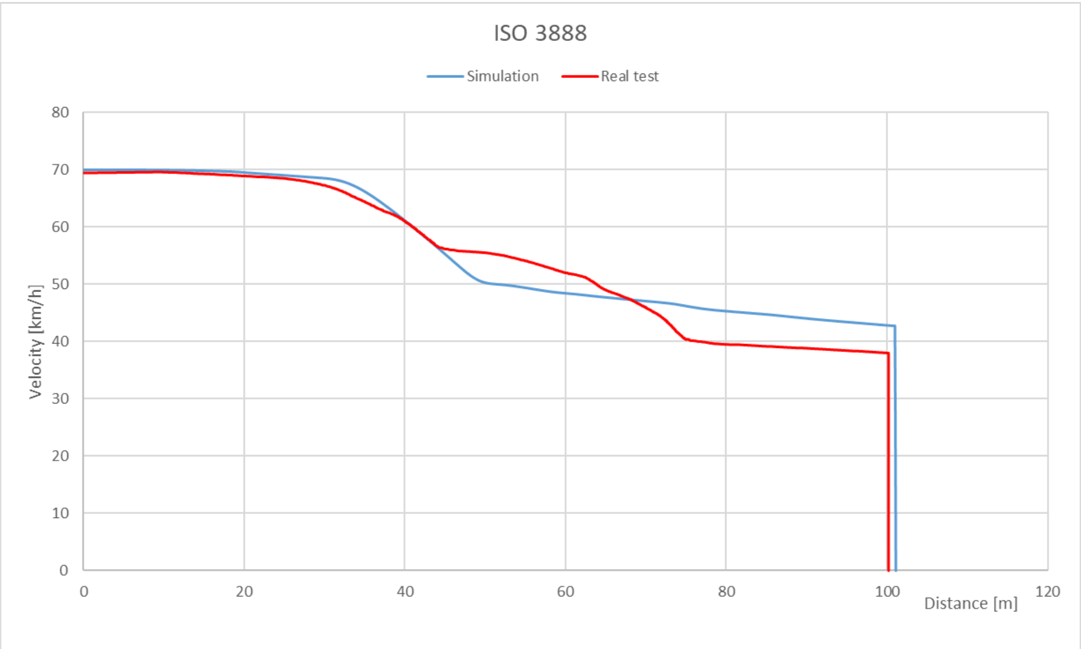


Figure 40 - Lane change behaviour comparison. Velocity vs. Distance

Conclusion: This test shows a vehicle's reaction to the dynamic change of direction and thus proves the accuracy of the suspension setup including the damper characteristics. Because the change of the steering is very rapid, the lateral dynamic characteristics are the main field of scope. Also, the vehicle speed throughout the course is compared, because shows the vehicle overall handling abilities. In the figures above, it can be seen that the virtual vehicle roll more or less corresponds with the real one. The differences between the vehicle roll course may be caused by different suspension kinematics, which was not modelled due to its substantial complexity, by slightly different characteristics of the damper, which was also not measured, or they even can be influenced by different driving style of the real driver and virtual IPG Driver, which has perfect reactions and optimal driving line. The overall behaviour is however very close to the real one, while the peaks of roll angle are getting to almost the same value. Also, the speed comparison shows that the model is quite close to the reality, having just a slightly higher exit speed compared to the real car, which is mainly caused by the driver and his ability to squeeze the car to its physical limits.

6.7. Slalom

These tests are used for the objective and subjective evaluation of the vehicle dynamics. As an objective characteristic of the vehicle's performance, the time needed to complete the slalom course as well as the mean velocity is measured.

KPI: Vehicle speed, lateral acceleration, roll angle, yaw angle

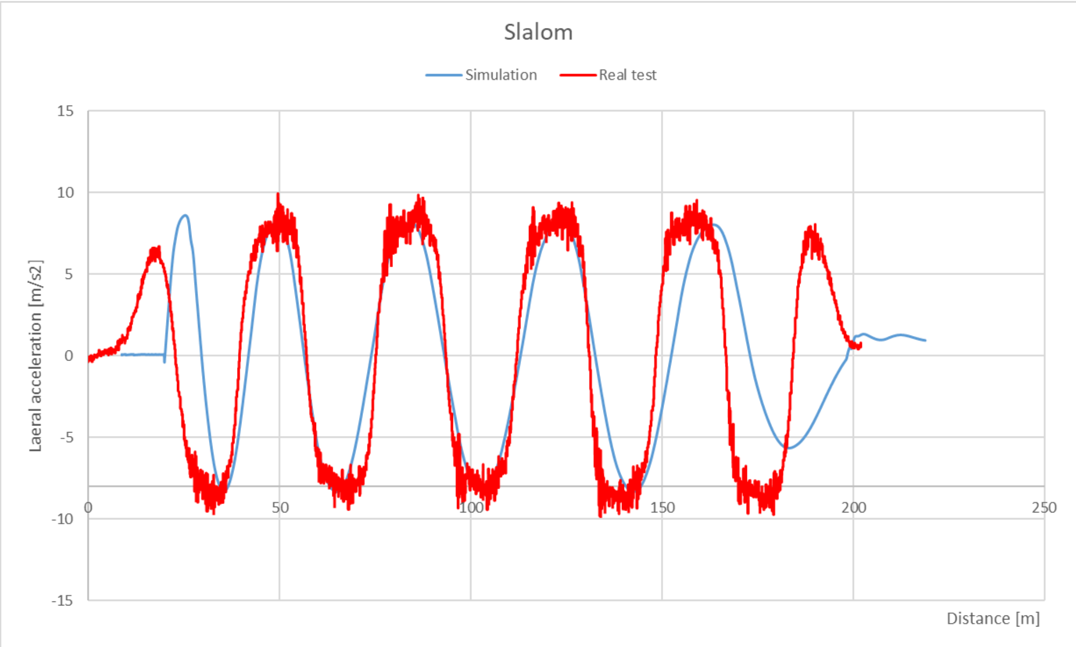


Figure 41 - Slalom behaviour comparison. Lateral acceleration vs. Distance

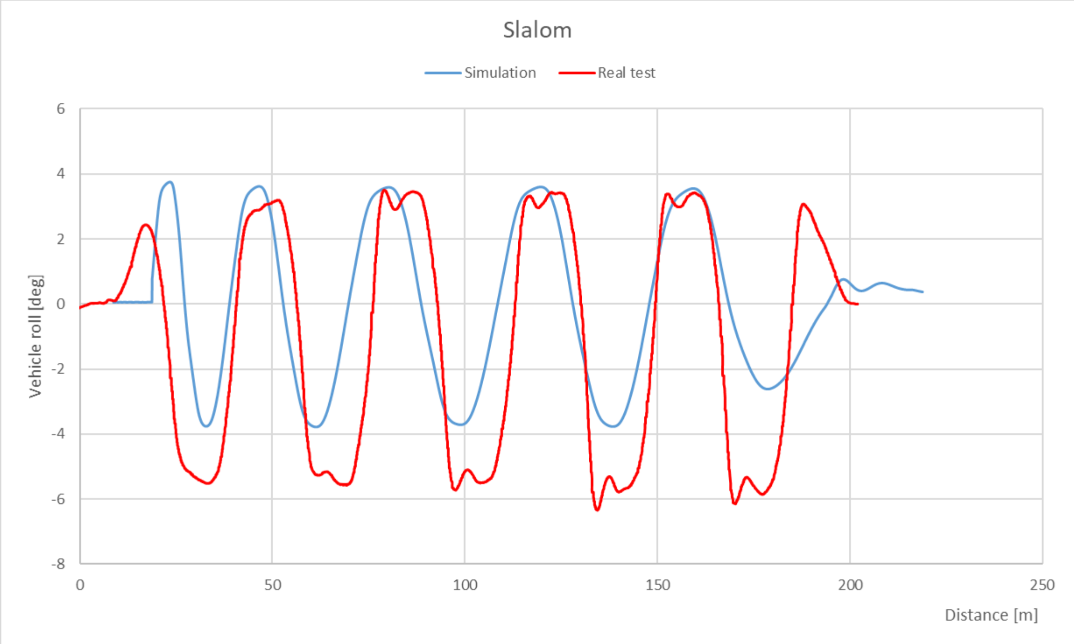


Figure 42 - Slalom behaviour comparison. Vehicle roll vs. Distance

Conclusion: Goal of this test is to compare the ability of rapid direction change and thus reveals the handling properties of the vehicles. The parameters to compare are therefore the lateral acceleration, which the vehicle is able to develop and the roll of the vehicle, both to show the accuracy of suspension setup. Also, the vehicle speed throughout the course or yaw is evaluated, showing also the influence of tyre properties. As shown in the figures above, both maximal lateral acceleration and vehicle roll corresponds to the real car almost exactly, showing that the setup of the car model is right. The difference between the shapes of the graphs at the beginning and the exit of the test is caused by the different driving lane chosen by IPG driver and real driver, while the virtual was more aggressive. Also, the higher negative roll of the real car is visible. This was caused by uneven weight distribution between the left and right side of the car due to the presence of the driver and measurement equipment in the car.

7. Conclusion

Maximum effort was put to build and tune the car to drive and behave as close as possible to its real version. From my experience, the most significant effect on overall vehicle behaviour has the position of COG. At the beginning of the modelling, I have set slightly wrong COG position and I struggled to match the real test results. But when I realized my mistake and corrected it, the results were completely different and way closer to reality.

Final results of the tests are very satisfying, considering the KPIs being mostly less different than 10% from the real values, which is absolutely satisfactory for the purpose of ADAS and AV testing.

7.1. Recommendations for future work

As said above, the achieved results are reasonable enough for the given purposes, however, there is still a plenty of options how to make the model even more precise. This can be mainly done by extending the amount of input parameter knowledge by performing physical measurement of the properties of such components as a damper, antiroll bar or maybe even the tyre, even though this would be extremely challenging and costly.

Another way to make the model more refined is by implementing some kind of automated modelling. A script or algorithm, which will run all the tests and vary the setup of individual components accordingly in a way to find the best combination of their parameters. In this thesis, this was done manually, which is very time demanding and less precise. The solution could be the use of the optimisation algorithm, which will find the best combination of parameters based on the input from the real tests. This could be done for instance by creating a genetic algorithm in Matlab, which will work in the loop within the simulation cycle.

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