Czech Technical University in Prague
Faculty of Mechanical Engineering

Department of Automotive, Combustion Engine and Railway Engineering
Study program: Master of Automotive Engineering
Field of study: Advanced Powertrains

Simulation of AEB system testing

DIPLOMA THESIS

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Year: 2017

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date Bc. Patrik Zíta

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Abstract: This master thesis describes a simulation tool which was created to analyze ADAS functions and vehicle dynamics. The tool was created in CarMaker and Microsoft Excel. The software can be used as SIL testing to analyze sensor output data before proving ground test.

Key words: CarMaker, ADAS, autonomous vehicle, AEB, simulation, testing

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Abbreviations

ABS	Anti-Lock Braking System
ACC	Adaptive Cruise Control
ADAS	Advanced Driver Assistance Systems
BSD	Blind Spot Detection
CMS	Collision Mitigation System
EBA	Emergency Brake Assist
ESC	Electronic Stability Control
ESP	Electronic Stability Program
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
LCDAS	Lane Change Decision Aid Systems
LDW	Lane Departure Warning
LKS	Lane Keeping System
SCT	Soft Crash Target
TSR	Traffic Sign Recognition

Introduction

During 20th-century vehicles improved people ´s lives in a way of faster transport for longer distances. Now, vehicles have become an essential part of everyday life. On one hand, they enhance people's comfort but at the same time can endanger their lives. With the increase in traffic density, the number of interactions between all elements of the transport system increases too and that means a higher probability of crisis situations or even traffic accidents. There is an effort to reduce the number of these situations or at least limit its effects.

Automotive companies are continuously improving vehicle safety for past few decades. The safety systems developed in vehicles can be divided into two categories: passive safety and active safety. Passive safety reduces the injuries sustained by passengers when an accident occurs. For example, airbags and seatbelts. Active safety systems are systems that try to avoid accidents in general. For example, ABS can prevent wheels from locking up when driver brakes and he can continue to steer. Advanced Driving Assistance System (ADAS) can alert the driver to potential problems or avoid collisions by implementing safeguards and taking over the control of the vehicle [7].

It is expected that active safety systems will play a key role in collision avoidance in the future. Each application supported by ADAS requires its private sensor(s), so adding new applications will require more sensors. Different sensors have different observation capabilities and various detection properties. These systems are tested during development but it is also necessary to evaluate their proper function and activation during a real drive.

This master thesis describes the development of real-time simulations which were created to evaluate vehicle behavior under different conditions with regards to ADAS systems and vehicle dynamics. Those systems are continuously developing and to save time and money it is very useful to simulate as much as we can. Some of the testing scenarios are not possible to realize because of its danger or its complexity.

Proper testing of safety systems is necessary to avoid unwanted activation e.g. AEB during rapid changing lane on the highway. The main motivation was to create simulations with same scenario but different conditions and evaluate the effect of each variable. These simulations can be used to improve sensors and software in vehicles to increase reliability.

The goal of diploma thesis is to realize simulation testing loop to test ADAS/AEB systems primarily with software simulation tools and optimized output for hardware-in-the-loop validation. Another part is research of state-of-the-art in the field of ADAS system software testing with regards to sensor physics modeling and sensor description in general. In the end output of this simulation should be geodetic coordinates and speeds for final test procedure validation in proving ground tests.

Autonomous systems are not easy to develop and implement in real life, as there are many interactions with surroundings which must be correctly understood by sensors and software to provide the correct response.

Chapter 1

1. Advanced Driver Assistance Systems

1.1. General description

Common systems like ABS, ACC, ESP and much more are used in nowadays cars. Car producers and its suppliers want to increase safety, so inevitably it has led to the production more sophisticated vehicles. Cars also became a part of our everyday life, that means it is usual to have more than one car per family. This has led to an increasing number of inexperienced drivers who can easily cause an accident. The second class of dangerous drivers are those who drive thousands of kilometers per month and are distracted by their work or other activities whilst driving, and therefore do not fully focus on the road while driving. For these and other reasons, many automotive companies are developing Advanced Driver Assistance Systems (ADAS).

Advanced Driver Assistance Systems are electronic systems that are designed to support the driver in his driving. This support is ranging from simple information presentation through advanced assisting and even taking over the driver's tasks in a critical situation. The common characteristic of these ADAS is that they (compared to passive safety systems) directly intervene with the driving task leaving it a delicate task for the automotive industry to integrate these systems in their vehicles, get the drivers to accept them and most importantly, having them improve traffic safety in the way they are intended to.

On the other hand, for many experienced drivers, some of those systems are unnecessary and they perceive them as an irritation, especially when those systems cannot be switched off.

For many automotive companies, ADAS is a tool to reduce accidents to zero and ultimately to achieve produce fully autonomous vehicles. Nevertheless, there is still a long way to go and many problems must be solved before such cars can go on roads autonomously.

1.2. Systems and its principles

Many companies across the world are developing ADAS systems in the automotive industry. The main players are Bosch Group, Delphi Automotive Company, Valeo SA, Continental AG, Panasonic Corporation, TRW Automotive, Denso Corporation etc. [3]. Those companies are developing similar systems, but sometimes with different names.

In general, the ADAS systems can be divided into several various categories: lateral control, longitudinal control & avoidance, parking aids and so on [36].

Examples of systems which are considered as ADAS are:

- Adaptive Cruise Control
- Automatic Emergency Brake
- Blind Spot Detection
- Emergency Brake Assist
- Lane Change Assistant
- Lane Departure Warning
- Traffic Sign Recognition

1.2.1. Adaptive Cruise Control

Adaptive Cruise Control (ACC) is a system which automatically adjusts the vehicle speed to maintain a safe distance from vehicles ahead without using the throttle or brake pedals. It helps to decrease fuel consumption and keep traffic flowing.

The first kind of this system was introduced in 1995, but the functionality was limited to use only throttle control or down-shifting to adjust the speed. In 1999 Mercedes introduced ACC Distronic which was the first RaDAR-assisted ACC and it could apply brakes [16]. The first manufacturer to offer ACC capable of a complete stop and go was BMW with their 7 series. Not only premium brands like BMW and Mercedes were developing these systems also Volkswagen Group, GM or PSA Group did.

Very first version of ACC was based on laser, but due to the environmental conditions like weather reliability was affected. Nowadays system using long-range RaDARs (full range). Typical long-range RaDAR specification is that it sees up to 200 m which are equivalent to about six seconds of lead time at highway speeds but in a small range around 15 – 20°. This system also uses short range RaDAR for closer distances about 30 m or one second of lead time and the range is around 80° [37]. This type of RaDAR works in a wider range of environmental conditions and does not have a problem with recognizing non-reflective cars.

Figure 1.1 - Adaptive Cruise Control [17]

1.2.2. Automatic Emergency Brake

Automatic Emergency Brake (AEB) systems improve safety in two ways: firstly, they help to avoid accidents by identifying critical situations early and warning the driver; and secondly, they reduce the severity of crashes which cannot be avoided by lowering the speed of collision and, in some cases, by preparing the vehicle and restraint systems for impact [1][14].

This system can apply braking power automatically without driver intervention. AEB continuously monitors the area in front of the car and when the systems recognize a serious possibility of a collision occurring then the driver is alerted to start braking and brakes are pre-activated. Sometimes small braking power is applied to save as much braking distance as possible. If the driver, at the critical distance, does not start braking, the system automatically applies as much braking power as possible to stop the vehicle or to reduce speed and the possibility of a fatal accident. An example of an AEB system at work is shown in figure 1.2.

Rear-end collisions mostly occur in inter-urban areas and at speeds of up to 25 km/h. To monitor the rear-end of a car, manufacturers use RaDAR, (stereo) camera and/or LiDAR-based technology to identify potential collision partners ahead of the car. Short Range LiDAR is cheaper, works at speeds of up to 50 km/h and is used in the compact car segment because it became an active safety standard, along with ABS and ESC.

Long Range RaDAR Sensor is necessary for adaptive cruise control as it can also recognize critical situations and work at speeds of up to 200 km/h [8].

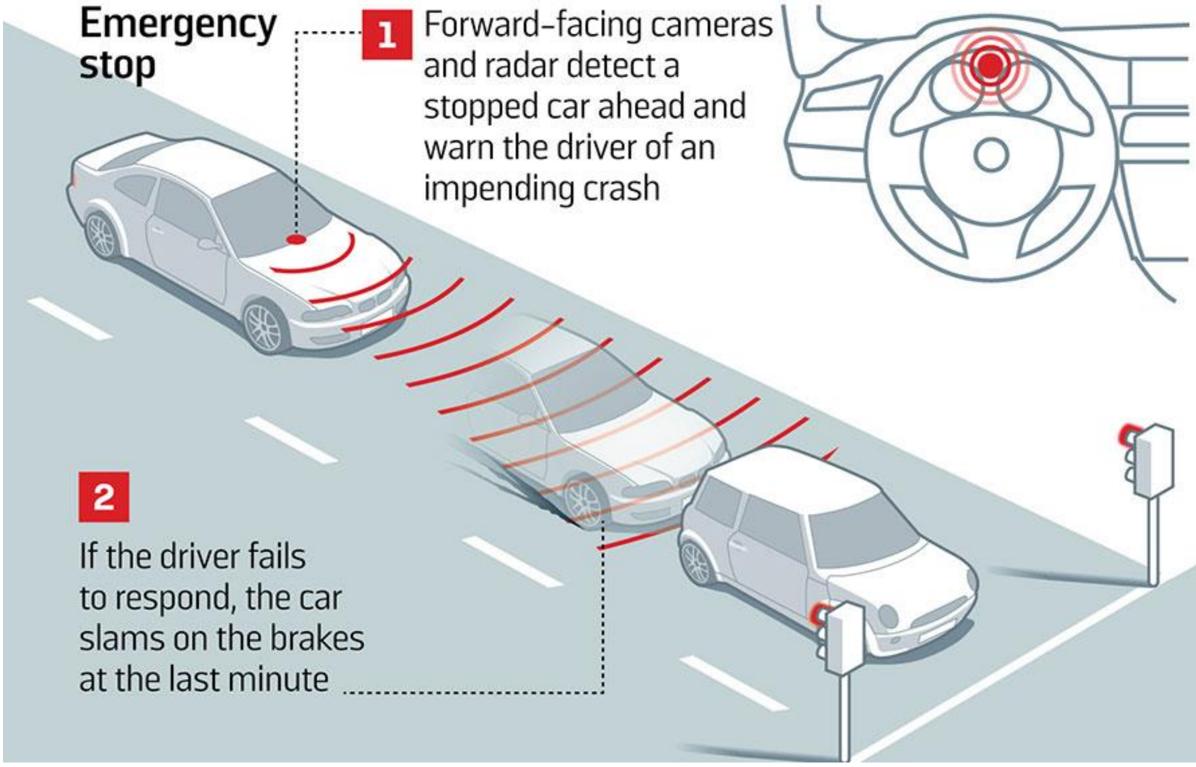

Figure 1.2 - AEB functionality [22]

1.2.3. Blind Spot Detection System (BSD)

The blind spot is a space where the driver is unable to see. In urban traffic, critical situations may arise if vehicles in the so called blind spots are overlooked. Blind spots can be either on the side or behind the vehicle and through a camera integrated into the lateral rear window, the blind spot detection system provides the driver with information on whether there are any vehicles, cyclists or pedestrians in the area not visible to him.

These spots are dangerous because pedestrians or even vehicles can be missed. The blind spot is also defined by ISO 17387:2008. This norm describes Lane Change Decision Aid Systems (LCDAS) — Performance requirements and test procedures and the location and size of the spots.

BSD systems use a combination of sensors/cameras to recognize objects and provide information about an object to the driver. This information is often provided through an orange lamp in the mirror and is generated depending on the difference in speed between the driver's own vehicle and others but some automotive companies also prefer vibration of the steering wheel or a combination of these with sound.

The latest versions of BSD systems can recognize the difference between large or small objects and warn the driver that a car, pedestrian or motorcycle is in a blind spot [4] [10]. Figure 1.3 shows an example of warning on the right side of the figure and monitoring area on the left side.

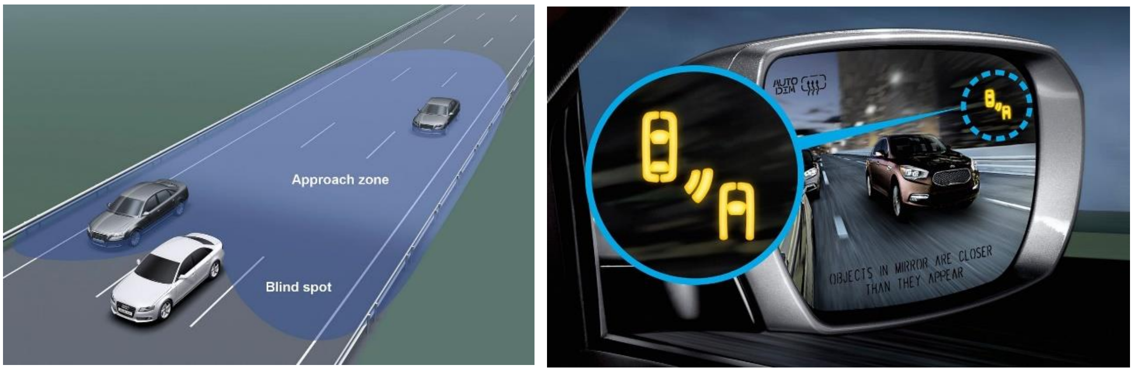

Figure 1.3 - Blind spot detection [41][42]

1.2.4. Emergency Brake Assist

Emergency Brake Assist (EBA) detects danger and distributes optimum braking pressure to each wheel to ensure as short a braking distance as possible. Research conducted in 1992 at the Mercedes-Benz driving simulator in Berlin revealed that more than 90% of drivers fail to brake with enough force when faced with an emergency. By interpreting the speed and force with which the brake pedal is pushed, the system detects if the driver is trying to execute an emergency stop, and if the brake pedal is not fully applied, the system overrides and fully applies the brakes until the Anti-Lock Braking System (ABS) takes over to stop the wheels locking up. Each car manufacturer has its own emergency braking system technology, but they all rely on some type of sensor input. Mostly speed with which a brake pedal is depressed.

EBA system is often combined with other brake systems like AEB, ESP and ABS. AEB systems use lasers, RaDARs or even video data [1]. This sensor input is then used to determine if there are any objects present in the path of the vehicle. If an object is detected, the system can then determine if the speed of the vehicle is greater than the speed of the object in front of it. A significant speed differential may indicate that a collision is likely to occur, in which case the system is capable of automatically activating the brakes. If driver does not act EBA pump up brake system and apply full brakes. Slippery road can cause sideways sliding, so ESP is activated and if wheels are block ABS prevent it. Entire process is described in figure 1.4.

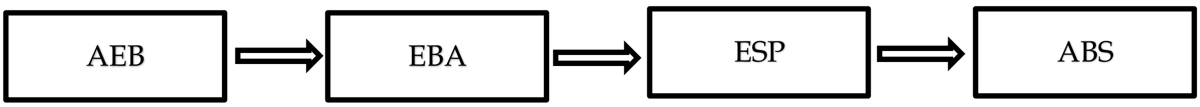

Figure 1.4 - Sequence of used system for critical braking

1.2.5. Lane Departure Warning, Lane Keeping Assistant

These kinds of systems are designed to reduce collisions especially on highways and to eliminate run-off-lane accidents. Lane Departure Warning (LDW) and Lane Keeping Assistant (LKAS) are systems which use optical recognition of markers on roads, usually white lines. They rely mainly on optical recognition, so those systems are sensitive to the quality of roads markings and the effects of the weather. That means that there is a high possibility of a mistake in heavy rain, snow or if there is excessive glare from the sun.

LDW is a simple system which will only warn the driver when to start moving out of the lane. This system cannot steer the wheels [5].

LKAS is more proactive. This system also monitors lane markings, but it can take corrective action and return vehicle between lanes. If the driver doesn't respond to an initial warning, a Lane Keeping Assistant can typically act to keep the vehicle from leaving its lane.

Early Lane Departure Warning systems used single video camera to monitor lane markings, but modern systems use multiple cameras placed on bumper or wind shield. Citroën became the first in Europe to offer LDW system on its 2005 C4 and C5 models, and its C6 [31]. It works with six cameras altogether mounted at the bottom of the front bumper. This system is presented in figure 1.5.

Figure 1.5 - Citroën LDW system

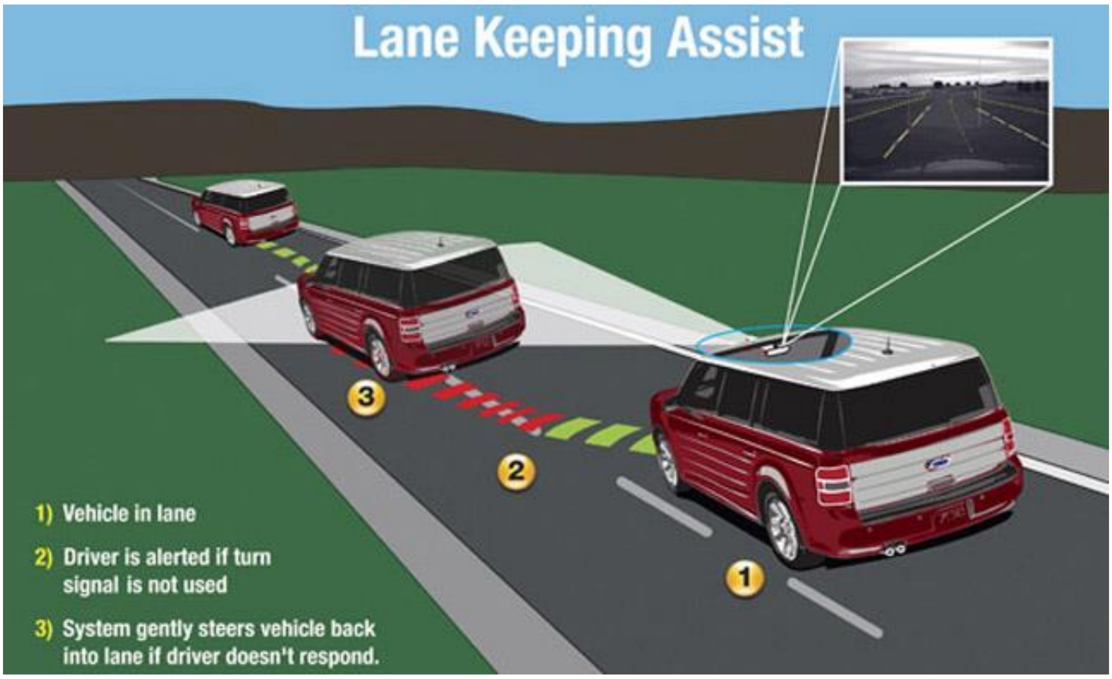

Figure 1.6 - Lane Keeping Assistant

1.2.6. Traffic Sign Recognition

Traffic Signs Recognition (TSR) is a system which helps drivers to watch traffic signs. The vehicle can recognize the traffic signs and display an icon on the dashboard or a head-up display. An example is shown in figure 1.7. This system uses video cameras and video analysis to recognize signs and compare it with the digital maps data which it receives from GNSS navigation or traffic services.

The process of sign recognition is divided into two phases. The first step is the traffic signs detection in a video or image by using image processing. The second part is the identification of the detected signs. This system has one disadvantage. When traffic signs valid only for limited distance and they do not have end signs to which could be recognized by the system. E.g. reduction of a speed limit before crossroads is made by signs. In most cases, the end of speed restriction is done by end of crossroads, not by end sign. In such case, the system cannot recognize change and if there is no connection to digitalize maps data or data are old, then the system will show wrong signs [2].

TSR not only reduces the prosecution risk but encourages maintaining a legal speed, obeying traffic instructions and safe driving as well. Using vision information only, a TSR systems can recognize and interpret both fixed traffic signs and variable LED signs. However, the signs covered by trees, vehicles or any other obstacle might not be detected by the system.

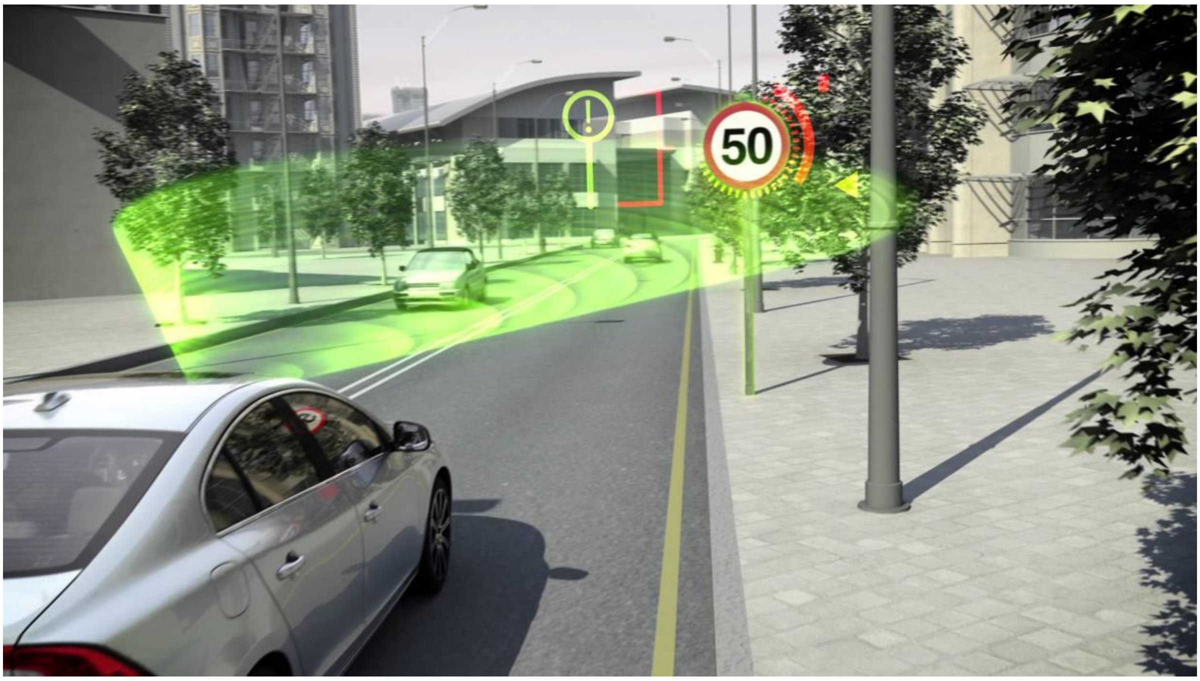

Figure 1.7 - Traffic sign recognition [2]

1.3. Vehicle sensors [6]

Current vehicles are equipped with many sensors for different purposes. ADAS systems need sensors to provide all necessary data from surroundings. These can monitor driver, car, and environment. Figure 1.8 shows typical sensors used in a modern vehicle.

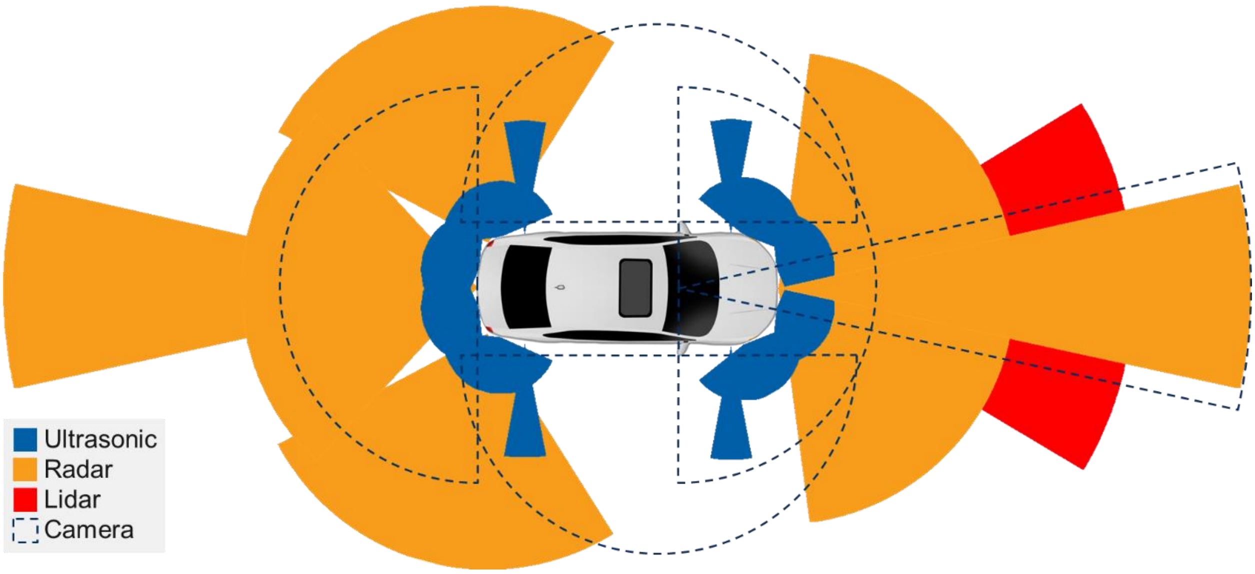

Figure 1.8 - Sensors in vehicles [7]

1.3.1. RaDAR (Radio Detection and Ranging)

RaDAR sensors usually work on frequencies 24 or 76-81 GHz. The 24GHz systems are being used for short- and mid-range smart-driving features such as blind-spot detection and collision avoidance in a wider area. Ranges of those sensors are around 50 – 60 m with a beam angle of 90 degrees. The 24GHz frequency band has a few limitations. These include the potential for interference with radio astronomy and satellite services and, as a result, these RaDARs will be phased out of new vehicles by 2022 in Europe [24]. Types of RaDARs are shown in figure 1.10.

RaDARs with frequencies around 77 GHz are used to detect obstacles in a long range around 100 - 200 m and a beam angle of 15 - 20 degrees as it is shown in figure 1.9. The technical advantages of the 77GHz band include that the higher frequency pairs effectively with a smaller antenna. The relationship between the antenna size and the frequency is linear, so 77GHz systems will need antenna sizes a third of the size of the current 24 GHz ones. The most important thing is that the wider bandwidth available in the 77 GHz band enables greater accuracy and, as a result, provide drivers with better object resolution [32].

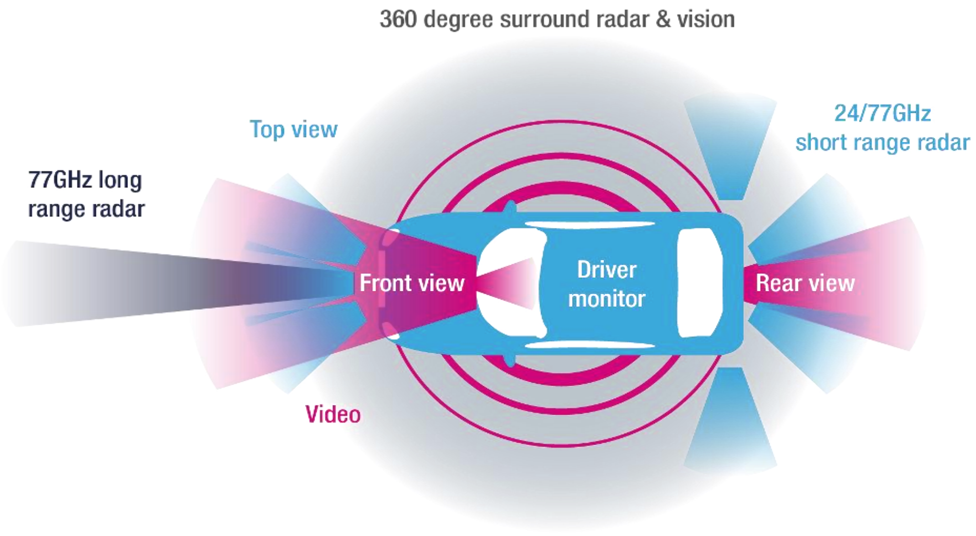

Figure 1.9 - RaDAR sensors application [23]

All automotive RaDARs are Doppler type [37]. The signal from the RaDAR is transmitted and received continuously and modulated to recognize stationary obstacles. RaDAR sensors for ACC or AEB usually contain two transmitters and four receivers or one transmitter and two receivers as a cheaper option which is used for detection of rear vehicles [11].

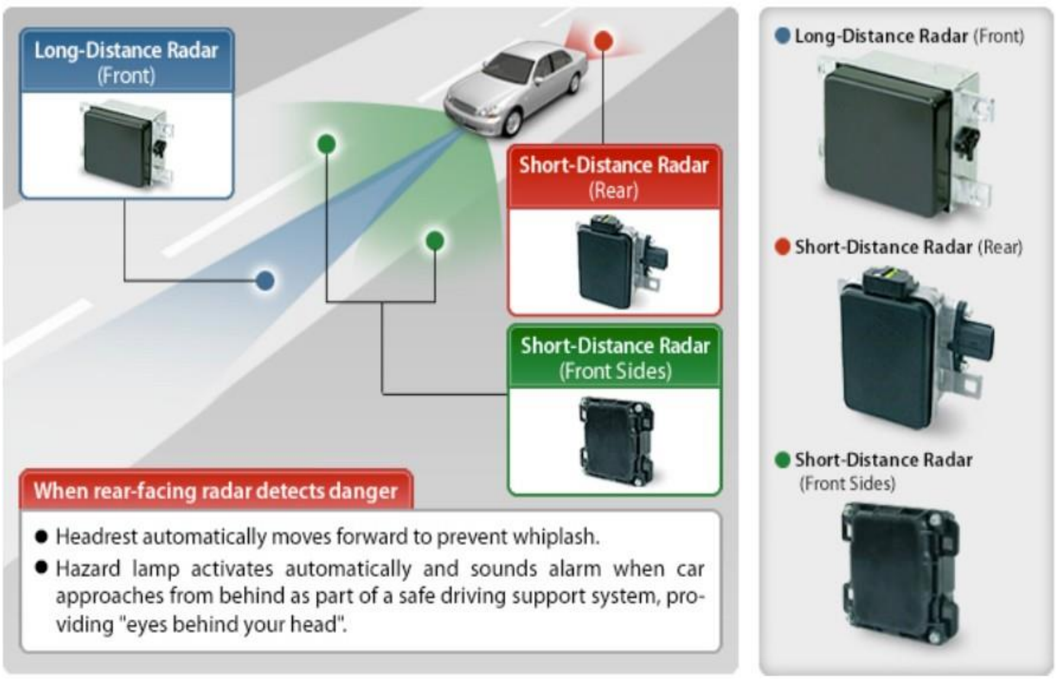

Figure 1.10 - Type of RaDAR on vehicles [11]

1.3.2. LiDAR (Light Detection and Ranging)

LiDAR is a RaDAR which uses ultraviolet or near infrared light to image objects. Typical automotive LiDARs have wavelengths around 850 or 900 nm. Usually, they are pulsed with power around tens of milliwatts with peak power of pulse up to 80 W. The range of common LiDARs is from 10 to 20 m and they are used to detect obstacles in low speed during urban driving. LiDARs were first applied as sensors for ACC because they were smaller. Nowadays they are often replaced by RaDARs or cameras due to excessive cost and low-resolution capabilities [6], [18]. Typical LiDAR is shown in figure 1.11.

Figure 1.11 - LiDAR produced by Continental [12]

1.3.3. Optical cameras

Cameras such as mono, surround view, rear view or stereoscopic presented in figure 1.12 are also used in vehicles. Car manufacturers use two types of cameras, one which works in a visible spectrum of the light (380 - 780 nm) or the other that works near the infra-red spectrum of the light (760 - 1400 nm) [37]. The range of those cameras depends on their resolutions and frame frequencies. They focus on using black and white images with low resolution to decrease computing time as much as possible. Hence cameras for pedestrian recognition need resolution around 360 x 240 pixels and frame rate of 10 Hz. The best parameters have cameras which are used for traffic sign recognition and LKAS as they have resolution 752 x 480 pixels and frame rate of 15 Hz. The newest stereoscopic cameras can have a resolution up to 1280 x 980 pixels. Cameras are sensitive to harsh weather conditions so they are often used as support for RaDAR systems.

Another usage of cameras is for driver monitoring. These cameras monitor the speed of eyes winking and head movements. From such information system can recognize that driver does not pay full attention and should take a rest.

Figure 1.12 - Stereo Camera [19]

1.3.4. PMD (Photonic Mixer Device) sensors

They are sensors with short and middle range. The principle is that they shoot infra-red spectrum of light (740 - 870 nm) from reflected object in the range of sensors and measure duration of light beam flight. It is very like LiDARs but PMD sensors use CCD or CMOS to shoot a whole picture. The advantage of those sensors is a detection of the scene in 3D directly and a precise image compares to stereoscopic cameras. These sensors are used by Lexus in their luxurious models.

1.3.5. Ultrasonic sensors

Ultrasonic sensors are used for low speed, especially for parking and maneuvering like in figure 1.13. The range of such sensors is from 3 to 10 m and their precision is around 5 cm. Sensors units which are also transmitters and receivers send cone signal 40 times per second with frequency from 30 to 40 kHz and beam angle 30 - 45 degrees. Although ultrasonic sensors are mainly used for parking, some car manufacturers manage to extend their usage by integrating them into safety systems. The problems are that wide signal cone is difficult to direct and it leads to the discrediting of the result, so it is not feasible to create a correct analysis of the surrounding in brief time. One of the application is blind spot detection to recognize other cars around the vehicle.

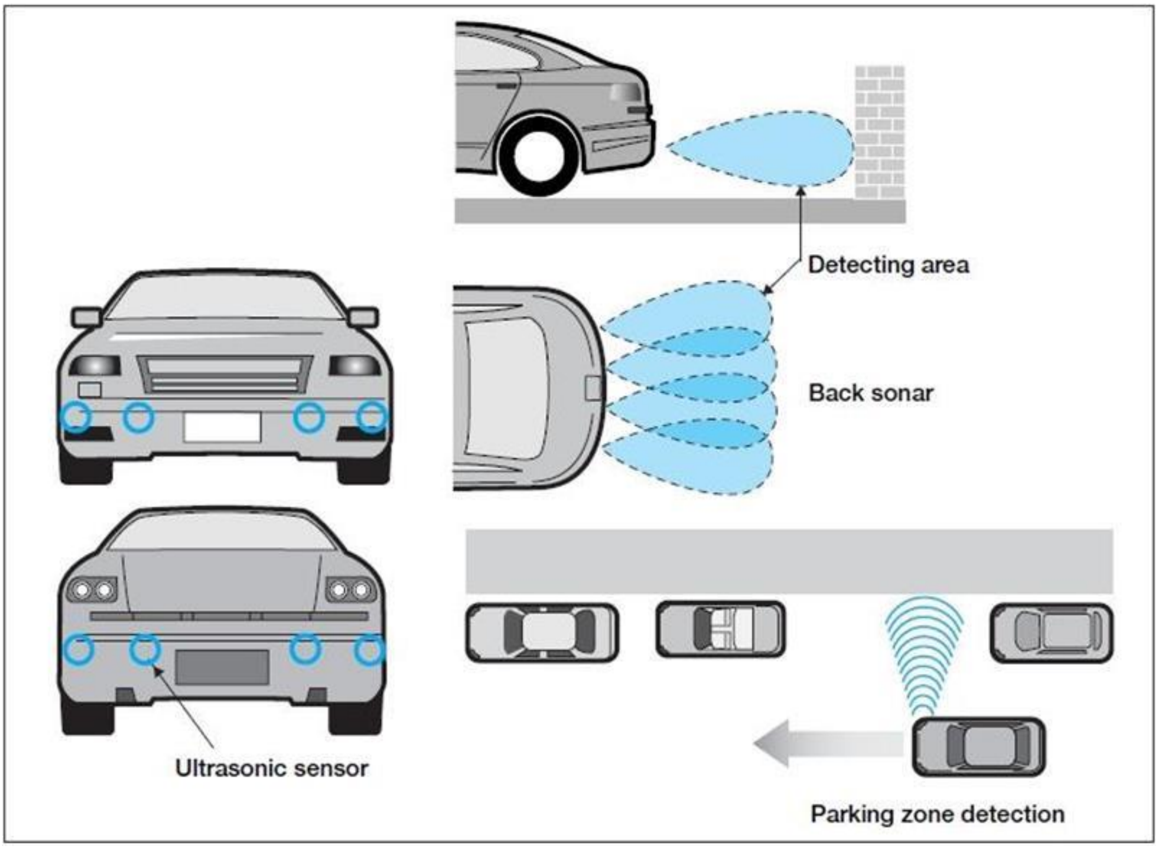

Figure 1.13 - Ultrasonic sensor for parking [20]

1.3.6. Information evaluation

Camera, LiDAR or RaDAR, just each system which acquires images, must be able to acquire and analyze this image correctly. For those analyses, there are used two methods which can be used simultaneously.

The first method is known as pattern recognition which means that it is based on recognition of known shapes or patterns, these patterns are saved in the database.

The second method works on the principle of comparing two or more consecutive images and finding changes of points and for these points determine their positions and direction of movement.

The first method does evaluate object which is not in a library as unknown, the second one does not have to know any object and it evaluates only the possibility of occurrence of moving points in a trajectory of the car, so it can detect some points as dangerous but, it would be only some inappropriate group of points which are not dangerous. Static objects are analyzed as objects with speed of the car and can be also detected by this method.

These sensors often cooperate or use data from other basic sensors inside vehicles to ensure safety and proper run. Nowadays a lot of effort is put into Vehicle2Vehicle (V2V), Vehicle2Infrastructure(V2I) or generally Vehicle2Everything (V2X) communication.

1.4. Sensor physics modeling

The degree of automation in the car in the form of advanced driver assistance systems is steadily on the rise. This means the development of more complex systems and requirements for quick feedback on viability and robustness [25]. A significant help with these problematics can be provided by a virtual environment. Virtualization alleviates the dependency on hardware availability and provides a controlled environment with reproducible conditions. To fulfill this role, a sensor model must generate the sensor data that constitutes the input of the function algorithms in such a way as to be virtually indistinguishable from a comparable real-world scenario.

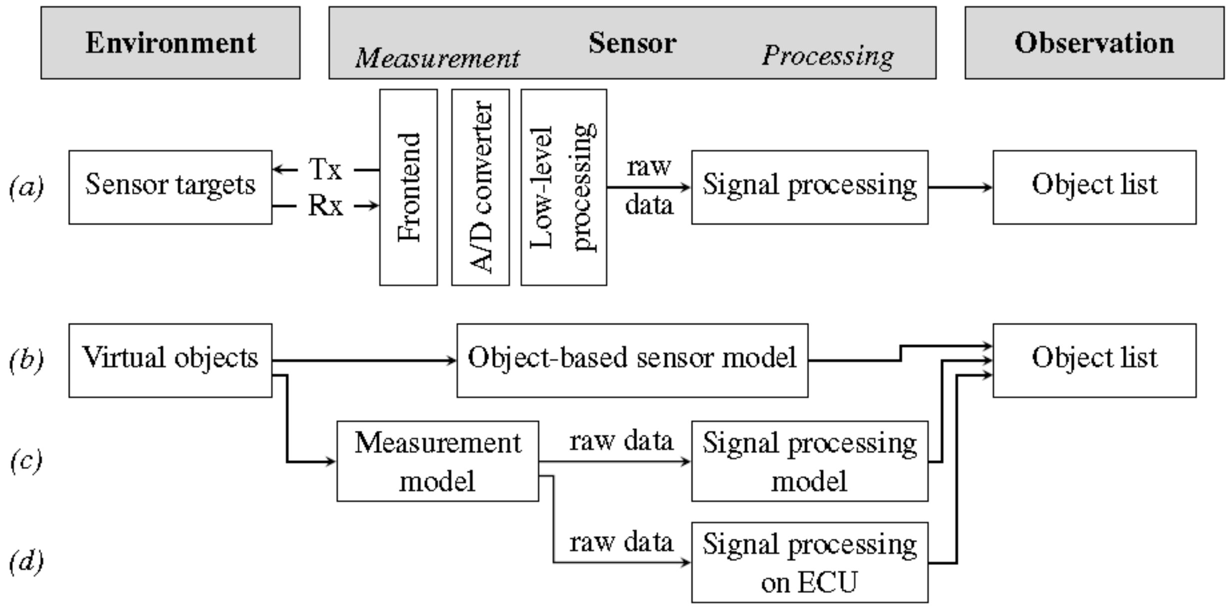

Figure 1.14 - Overview of the sensing process [25]

(a) Detection and processing chain of a real sensor.
(b) Direct mapping of virtual objects in the simulated environment onto an output object list.
(c) Separate models for the measurement and processing steps connected by a raw data interface.
(d) Sensor raw data generated by a measurement model used as stimulation for the signal processing on the sensor ECU in a hardware-in-the-loop setup.

In a real environment, sensor maps its targets (e.g. other cars, static obstacles) onto a digital representation. Then compare it with object list (pattern recognition) or comparing two or more consecutive images and finding changes of points. The sensing process consists of two subsequent steps: measurement and processing. Measurement is the detection of sensor targets by means of an electromagnetic (RaDAR, LiDAR, camera) or acoustic (ultrasound) interaction. From the resulting raw data, a signal processing unit extracts objects and object properties. An example is in Figure 1.14 – (a).

In a virtual environment, the input consists of virtual objects provided by a simulation framework. Direct mapping encompassing both the measurement and processing steps is usually achieved by means of a stochastic model – Figure 1.14 – (b).

An independent treatment of effects occurring during the two steps comes at the cost of increased complexity and requires a raw data interface – Figure 1.14 – (c).

This opens the possibility of a hardware-in-the-loop setup with the electronic control unit (ECU) of the sensor stimulated by simulated raw data – Figure 1.14 – (d).

properties of sensor targets	**properties of detected objects**
unique object ID	tracking ID
	existence probability
object type (e.g. vehicle, pedestrian) object class (e.g. sedan, child)	classification vector
position, velocity, acceleration vectors	position, velocity, acceleration vectors with measurement uncertainties
	point of reference for the position measurement (usually a corner of the
orientation and rotational rate (yaw, pitch, roll angles and rates)	orientation and rotational rate with measurement uncertainties
length, width, height of bounding box	bounding box with size uncertainties
(surface) material properties	reflectivity measurement
additional state data (e.g. head lights	sensor specific additional data

Table 1 - List of properties provided by simulation framework [25]

Also, environmental conditions can be considered as a further input for the sensor model and need to be provided by the virtual environment. Required information depends on the complexity of the model and may include information about weather, the day-night cycle, road conditions, and structures that could cause stray reflections. Sometimes these environmental conditions are shown only as a graphical representation without any real effect on simulation results.

Reasons for advanced sensor models for ADAS simulation:

- Access simulated data at any level of the processing chain for multiple usages
    - Raw sensor data
    - Tracks/Objects data after signal processing
    - Fused objects data
- Consider effects of the sensor technology
    - Signal losses
    - Detection noises
    - Sensitivity
    - Resolution
- Consider environment and targets interaction
    - Material properties
    - Multi-reflections
    - Weather conditions
- Allow multi-sensor configuration
    - Interferences
    - Sensor fusion

Typical example of sensor output for AEB scenario is in the figure 1.15. In the part 1 vehicle is constantly decelerating with a = - 4 m/s^2 for t = 2.6 s. In the part 2 significant acceleration peak occurs with top value a = 8,9 m/s^2 for t = 0.6 s. This acceleration is caused by sensor blindness. For limited amount of time sensor cannot see obstacle in front due to the pitch during braking. In part 3 full brakes are applied, because sensor can see the obstacle again.

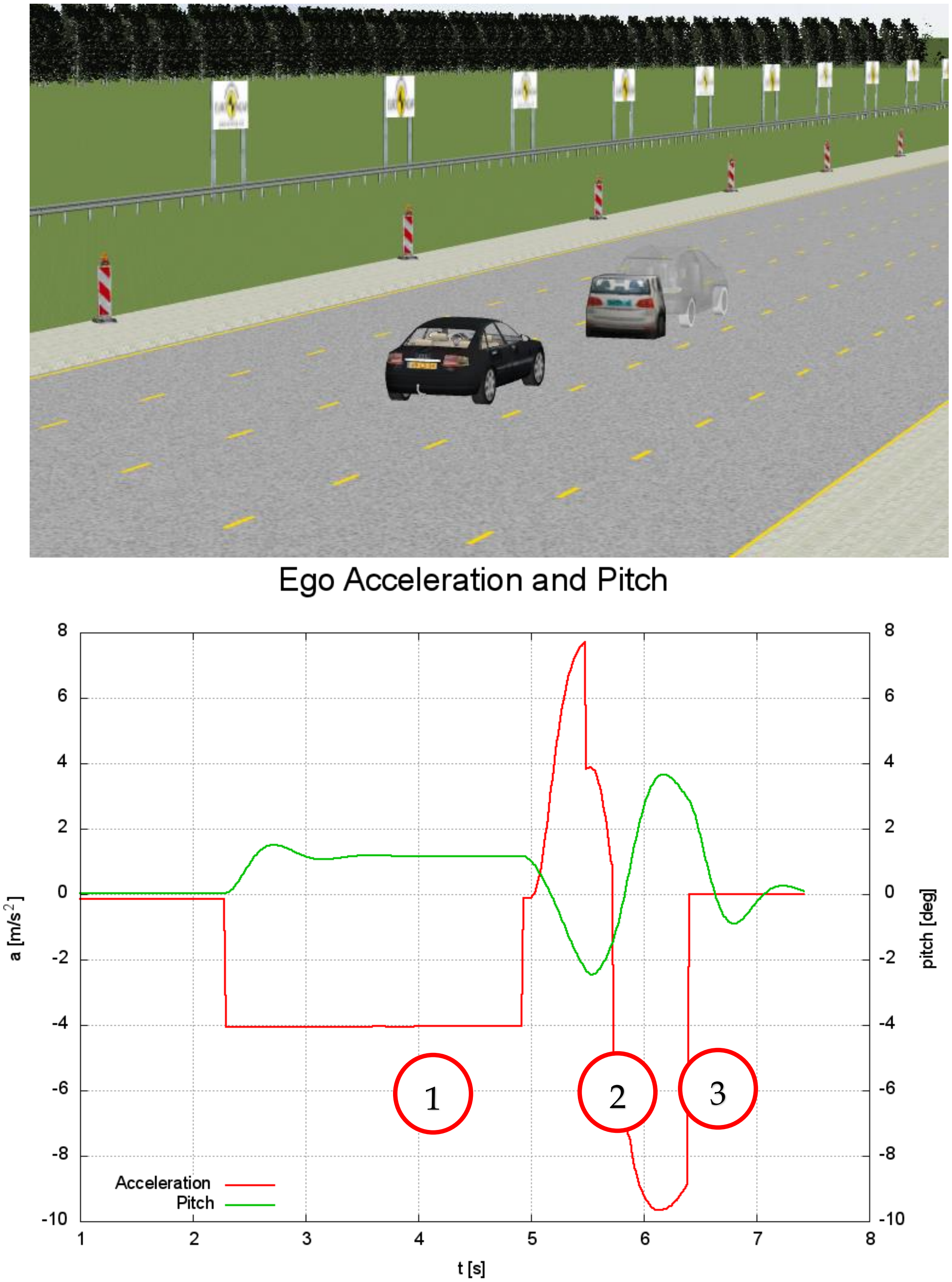

Figure 1.15 - AEB braking and graph representing acceleration and pitch [27]

1.4.1. Sensor modeling complexity

Each virtual simulation software has its own library of the sensor with different level of realism. This mostly depends on the application of sensor and on requirements. Figure 1.16 shows an example of sensors used in CarMaker and how detailly modeled they are [30].

Ideal sensors are for rapid prototyping, proof of concept or verification. High Fidelity (HiFi) Sensors for general function development and testing sensors are more complex. Raw Signal Interfaces are for component/signal processing development and testing. With increasing realism computational costs and parametrization effort are increasing rapidly.

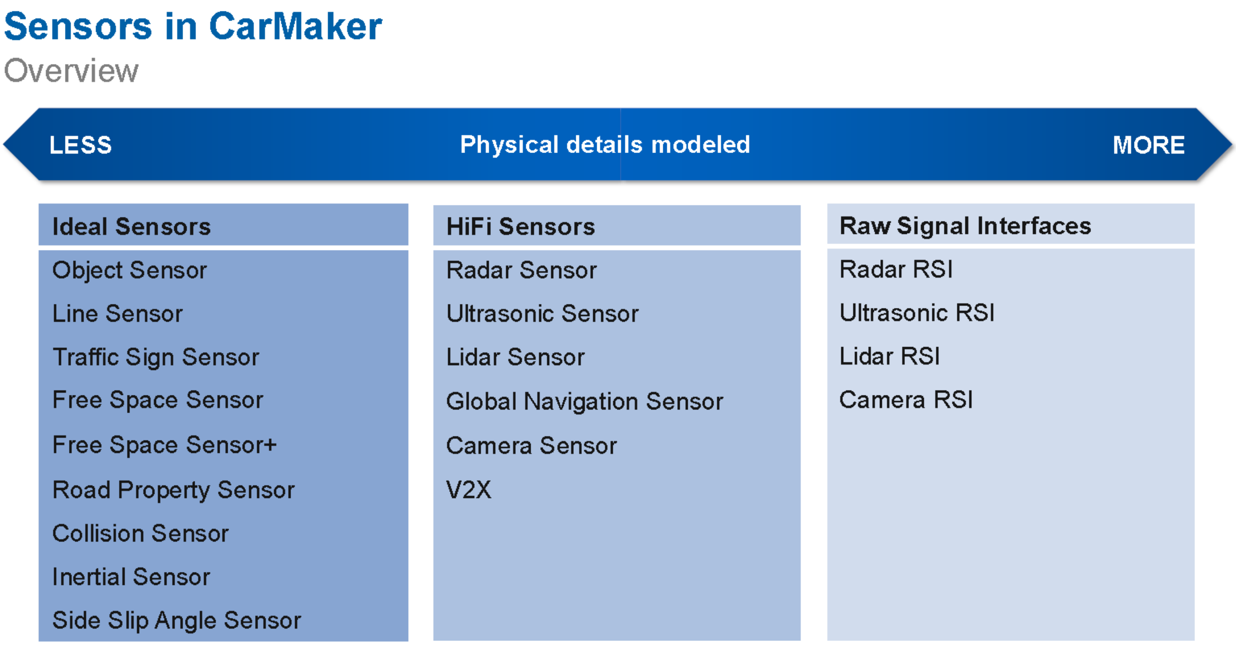

Figure 1.16 - Sensors in CarMaker [26]

1.4.2. Advanced RaDAR sensor modeling

The simulation of electromagnetic sensors can be achieved through dedicated rendering process tuned to detect RaDAR targets or using ray tracing techniques combined with the modeling of the RaDAR antenna. The strategy proposed here is relying on a preliminary 3D characterization of the RaDAR devices obtained using the CEM Solutions [28].

RaDAR sensors and devices are embedded in a simulation chain featuring three various stages, (1) the modeling of the emitting/receiving antenna itself, (2) the targets to be identified in the nearby environment and finally (3) the so-called propagation channel allowing both to interact.

The propagation of electromagnetic waves is usually handled through ray tracing or other SBR techniques (Shooting and Bouncing Rays). Instead of using an ideal (isotropic) radiating source, the propagation of electromagnetic waves is weighted according to the direction being considered using the antenna directivity. This chaining is quite loose but allows reaching quite easily a much more realistic modeling of the sensor performance. The electromagnetic radiation can be assumed in free space or with the RaDAR sensor located behind the plastic bumper and interacting with near-by metallic parts or metallized paint coatings.

1.4.3. Modeling of a new generic virtual optical sensor for ADAS prototyping

To achieve a physically realistic simulation of an optical camera, lighting computation is a key challenge, since a biased input to the camera will unavoidably lead to erroneous camera output. Ray Tracing, Radiosity and

Monte Carlo Analysis algorithms are identified approaches that focus on different goals. To model the full optical chain, these methods are often combined with adaptations or improvements yet are too computationally heavy [29].

To compute a physical-driven camera simulation, realistic information must be applied to the camera model. It must be kept in mind that the optical information to be provided to a camera may be different to human vision. Thus, the rendering stage should compute realistic spectral luminance data based on the geometrical description of the scene, lighting conditions, and material properties.

To model a broad range of optical sensors with various levels of accuracy, a mechanism of adapted rendering has been implemented in a simulation engine, called multi-rendering. It then becomes possible to define and use different rendering plug-ins adapted to specific requirements. For instance, a basic graphical rendering for an optical sensor, or a more realistic optical sensor with HDR (High Dynamic Range) textures, shadows, filters and tone mapping.

Currently, three optical rendering techniques are available. The first one provides a classical 3D graphical engine rendering, the second one provides a better shadow and light management, and the last one developed in the framework of the eMotive project improves the physical realism of light interaction with objects [29]. The engine allows applying various post-processing effects to complete the rendering.

There are mechanisms for efficient environment modeling:

1) Lighting and interaction with object
2) Several types of filters for rain, fog, lights, blur and glow effects, color management, lens distortion or depth of field.

Chapter 2

2. Software

Within this diploma thesis is mainly used software CarMaker by company IPG Automotive. CarMaker is real-time simulation software for virtual testing of automobiles and light-duty vehicles. Using this software, we can accurately model real-world test scenarios, including the entire surrounding environment, in the virtual world. CarMaker is an open integration and test platform and can be applied throughout the entire development process – from the model- to software- to hardware- to vehicle-in-the-loop.

Figure 2.1 - CarMaker - virtual testing software [21]

2.1. CarMaker

CarMaker includes a complete model environment comprising an intelligent driver model, a detailed vehicle model and highly flexible models for roads and traffic. With the aid of this model environment, one can build complete and realistic test scenarios with ease, taking the test run off the road and directly to the computer. The event and maneuver-based testing method ensure that the necessary flexibility and realistic execution of real-world test driving are also features of virtual test driving.

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

- Vehicle: Definition of the vehicle data set used.
- Road: Parameterization of the test track.
- Maneuver: Mainly to specify the driver's task.
- Driver: Set driver behavior (defensive, normal, aggressive, ...)

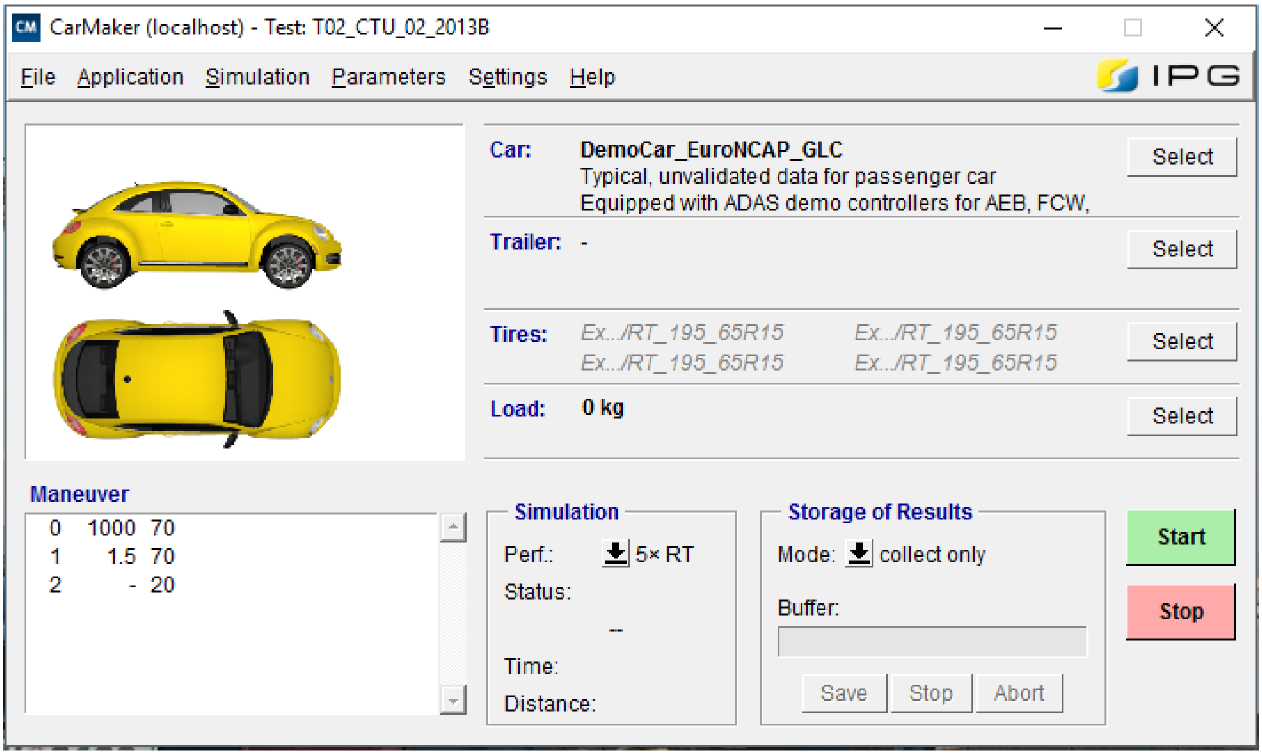

Figure 2.2 - CarMaker

Additionally, the following modules can be defined in the TestRun, depending on the field of application:

• Trailer: To simulate a test car with trailer configuration.
• Tires: Overwrite the default tire data set referred to the vehicle model.
• Traffic: Add other static or moving traffic objects.
• Environment: Configuration of the test environment with date, time and ambient conditions.

In figure 2.3 is shown a list of available sensors. The majority of them are for ADAS application, so we can test almost any setup of nowadays vehicles. This approach can be used also for rest of car parts such as suspensions, steering, powertrain etc.

A similar setup is in road definition like in figure 2.4. We can create any kind of road including bridges, crossroads, traffic lights, sign and so on.

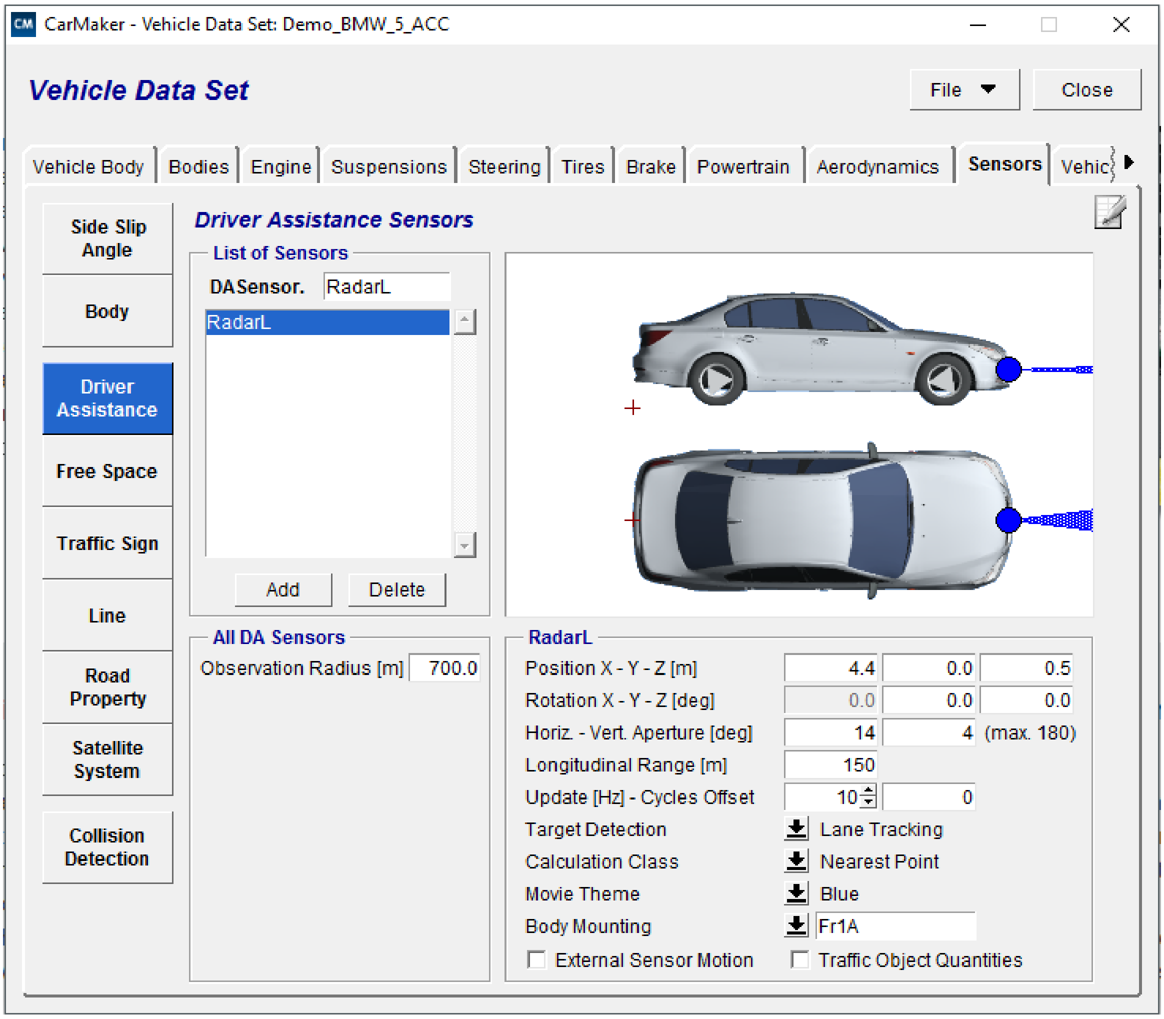

Figure 2.3 - CarMaker - car setup

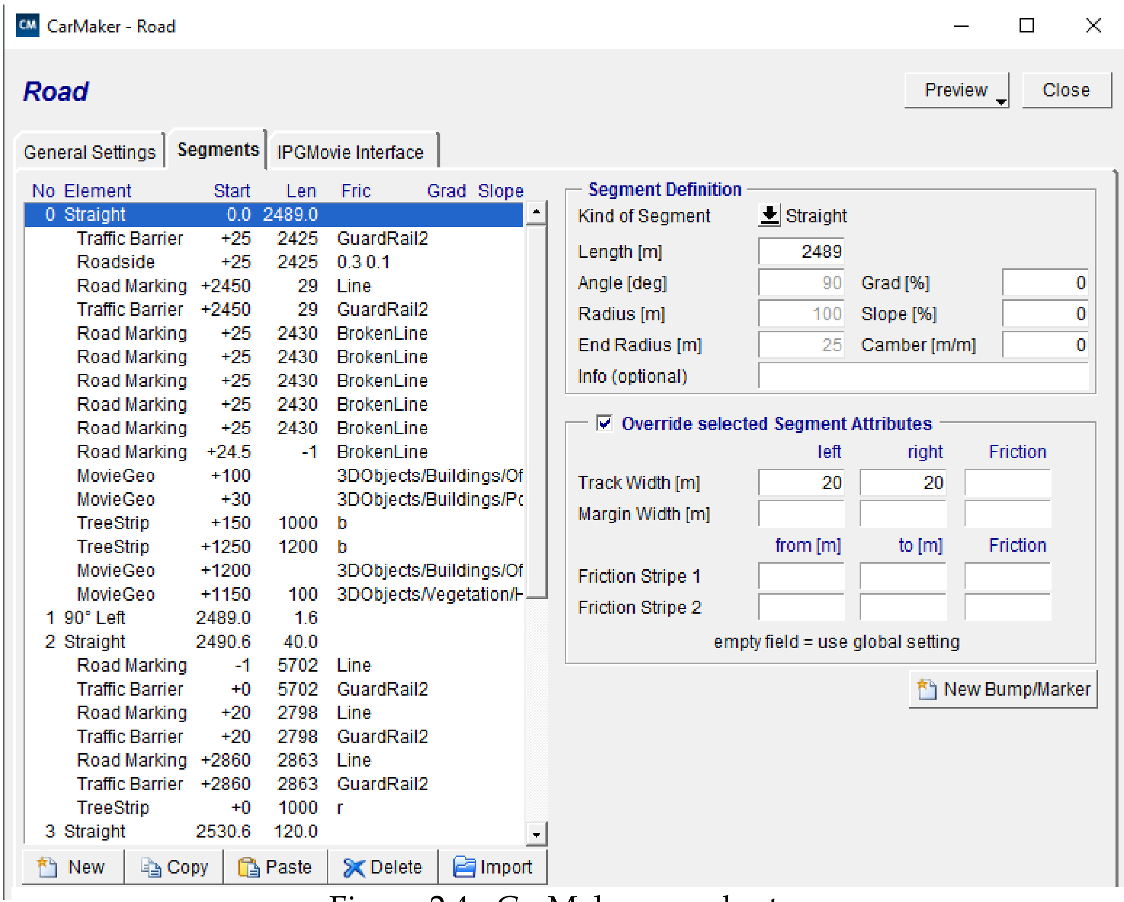

Figure 2.4 - CarMaker - road setup

2.2. CarMaker and other software tool

According the assignment CarMaker should be coupled with other software tool. As the file interface was used Microsoft Excel. This tool will be used to export data from CarMaker. These data will be GNSS coordinates and speed for final test procedure validation in proving ground test.

Figure 2.5 - Export of GNSS data from CarMaker to Microsoft Excel

2.3. Research of other automotive simulation tools

IPG Automotive is not only company developing vehicle simulation software. For reference, other companies are introduced in following part.

2.3.1. dSpace - Automotive Simulation Models (ASM)

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.

The ASM concept consists of coordinated, combinable models of automotive components. There is a vehicle model with a trailer, plus other ASMs for gasoline, diesel and hybrid engines, exhaust systems, turbochargers, brake hydraulics, electrical systems, electric motors, environment sensors, roads and traffic. The ASMs support an entire range of simulations from individual components to complex virtual traffic scenarios [33].

Figure 2.6 - dSpace - Automotive Simulation Models [33]

2.3.2. CarSim

Mechanical Simulation produces and distributes software tools for simulating and analyzing the dynamic behavior of motor vehicles in response to steering, braking, and acceleration control inputs. CarSim is a commercial software package that predicts the performance of vehicles in response to driver controls (steering, throttle, brakes, clutch, and shifting) in a given environment (road geometry, coefficients of friction, wind). CarSim is produced and distributed by an American company, Mechanical Simulation Corporation, using technology that originated at the University of Michigan Transportation Research Institute (UMTRI) in Ann Arbor, Michigan [34].

Figure 2.7 – CarSim [35]

Chapter 3

3. Simulation of predefined driving scenarios

All simulated driving scenarios are based on dissertation [6]. There are 11 scenarios altogether which were simulated, parametrized and evaluated. Most of them are designed to test ADAS systems in general – mainly AEB, ACC or CMS systems. Parametrization is done with respect to vehicle dynamics. The result of every simulation is in the form of geodetic coordinates and speed for final test procedure validation in proving ground test.

3.1. Test track description

Test track used in these simulations were inspired by the airport Hradčany u Mimoně. This airport is often used as the proving ground test track for many vehicle systems.

Test track is designed with the same dimensions. All scenarios were done at the main runway with a length of 2700 m and with 90 m. Optional features are lanes and surrounding done by myself. Lane has width of 4 m. The whole track is presented in figure 3.1.

The advantage of modeling this track is, that we can set it into the real map by GPS coordinates – figure 3.2. This means we can export these coordinates directly or show them through Google Earth and see the longitudinal or lateral movement of eGo vehicle and its speed – figure 3.3.

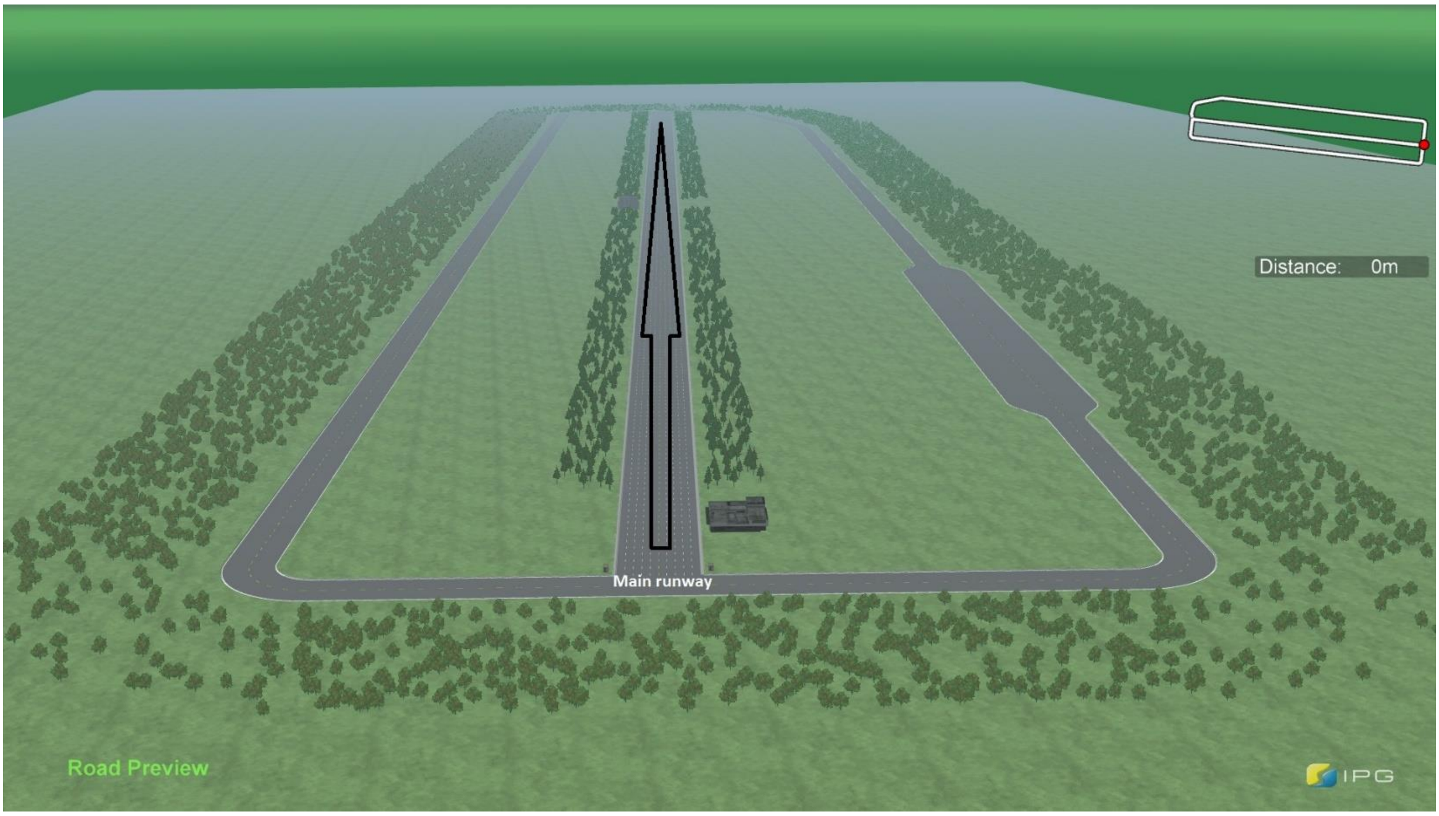

Figure 3.2 – Test track Hradčany u Mimoně in CarMaker

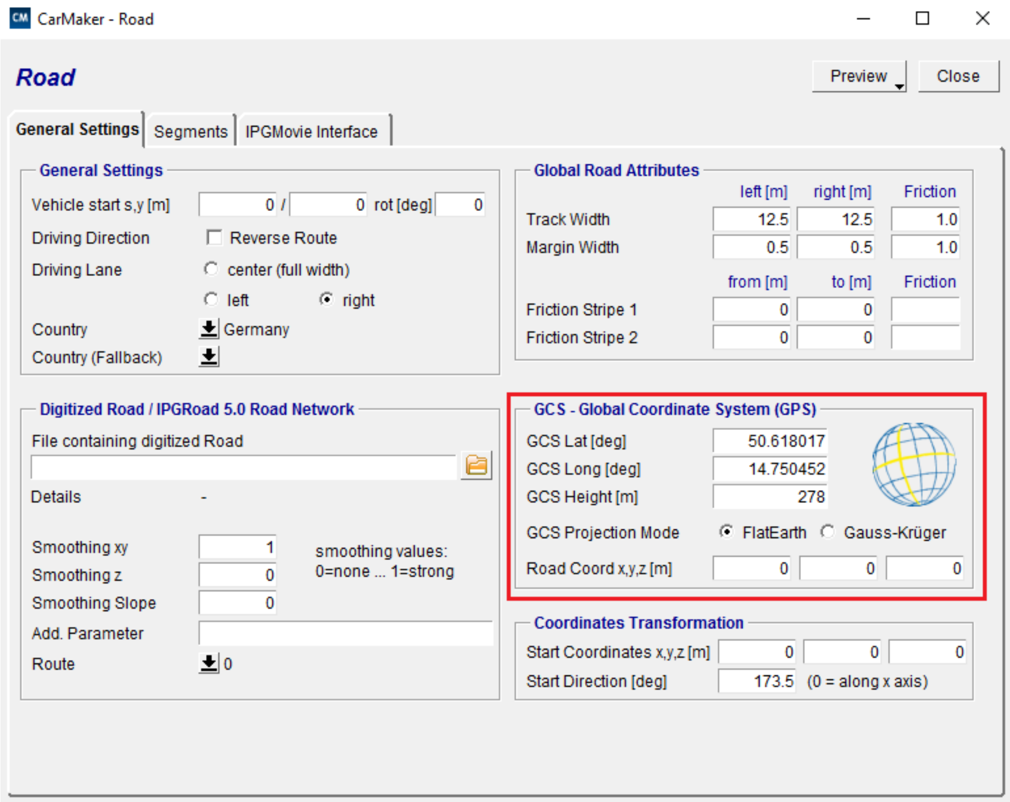

Figure 3.1 - CarMaker and GPS

Figure 3.3 - Google Earth view from CarMaker

3.2. Maneuver description

The concept of CarMaker for the driving scenario is the following:
There is one maneuver definition, which is split into several maneuver steps (e.g.: acceleration, braking, ...). These maneuver steps are called minimaneuvers. Each minimaneuver is composed of:

- longitudinal dynamic actions: accelerating, braking, gear shifting
- lateral dynamic actions: steering
- additional actions, defined by a list of special minimaneuver commands of a very easy script language.

In figure 3.4, we can see maneuver definition. To build a driving scenario, we must add and parameterize successively the various maneuver steps necessary to control the vehicle as we want. The list of the maneuver steps is displayed and can be built in box 1 of Figure 3.4 at the left side of the Maneuver dialog. After creating a maneuver step, the actions need to be defined. Each minimaneuver consists of a duration (box 2 in Figure 3.4) and a description of the driver's task, separated in longitudinal and lateral dynamics (box 3+4 in Figure 3.4).

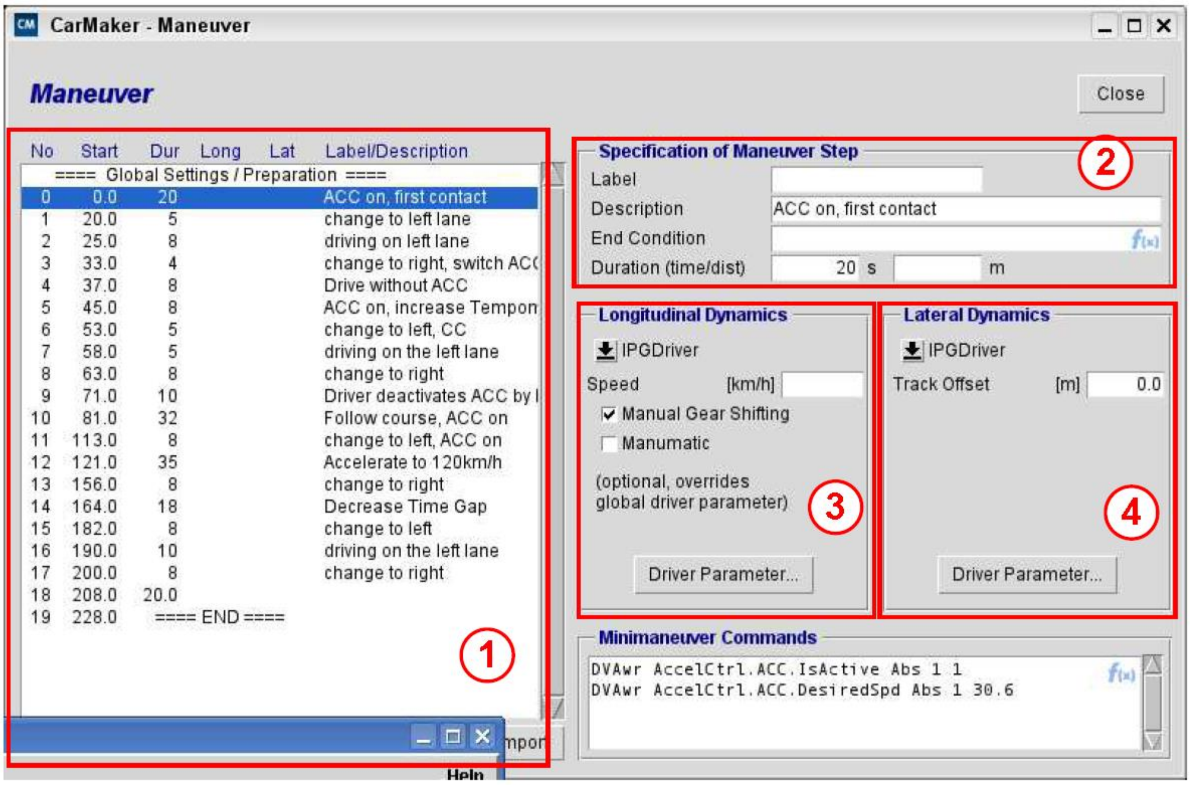

Figure 3.4 - Maneuver dialog

3.3. Vehicle description

Each vehicle is a dynamic model of existing car. These models are not validated, so there can be differences in vehicle behavior despite reality.

For our purposes, we use 2 vehicles:

- DemoCar VW Beetle
- Demo BMW 5-series

Volkswagen Beetle has setup for AEB testing and BMW 5-series for ACC testing. Vehicle data set has many possibilities of tuning of the vehicle starting with body, engine, suspension, steering, tires, brakes, powertrain, aerodynamics and sensors along with vehicle control. Last two are most important for our applications.

Volkswagen Beetle uses General Longitudinal Control for controlling the vehicle. The simple Generic Longitudinal Control model contains two functionalities: Autonomous Emergency Braking and Forward Collision Warning, which are explained below.

- **Autonomous emergency braking (AEB)**
  The Autonomous Emergency Braking system has the task to decelerate safely the vehicle to the velocity of the target object ahead. For this, the system compares the time-to-collision t_{tc} with a time-threshold-brake t_{tb} to decide if a braking intervention is required.

- **Forward Collision Warning (FCW)**
  The Forward Collision Warning system has the task to warn the driver by different degrees of warning level if time-to-collision falls below the defined time threshold. The simple generic model supports two different warning levels, which are activated before the AEB reaction.

To ensure correct behavior camera is used as a sensor for scanning area in front of the vehicle. The camera has its own place on the vehicle as well as its working parameters like range and horizontal and vertical aperture – see the figure 3.5 and 3.6.

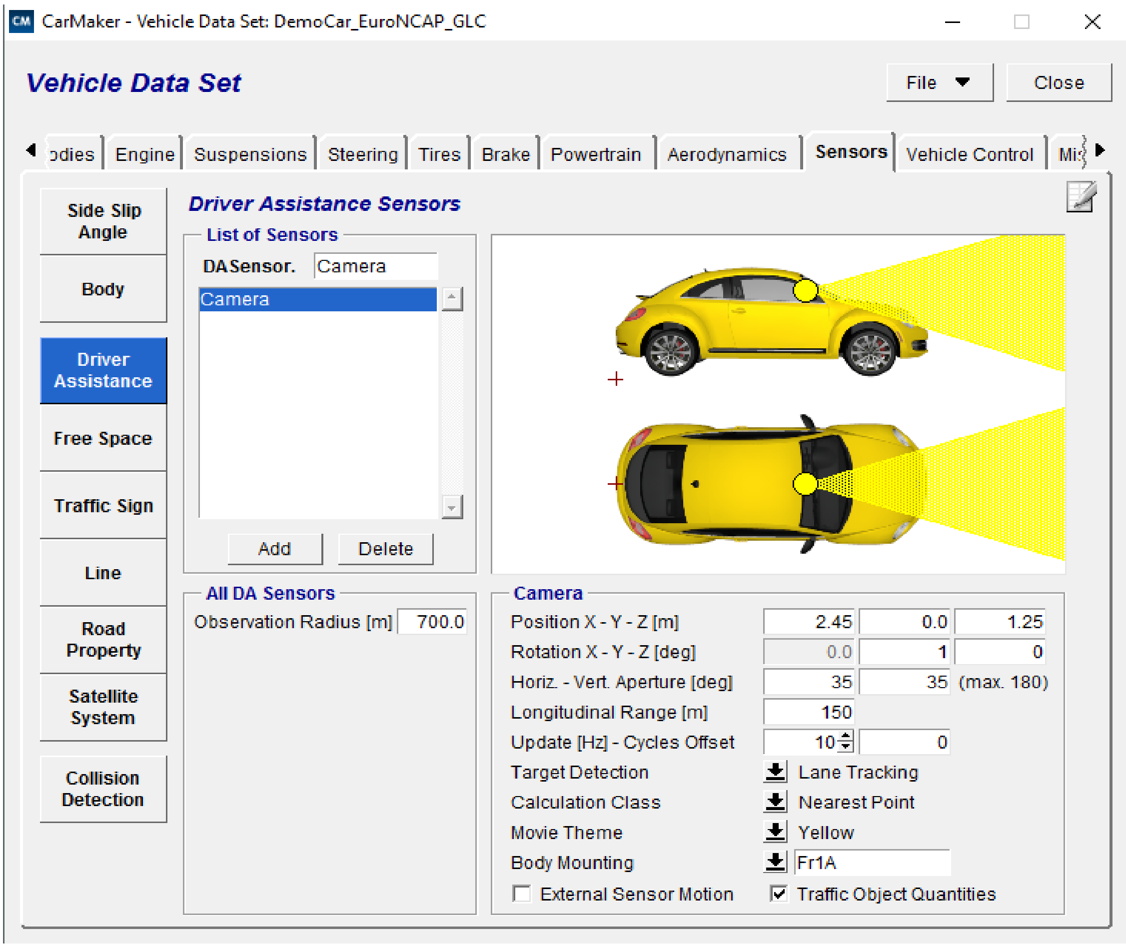

Figure 3.5 - VW Beetle sensor setup

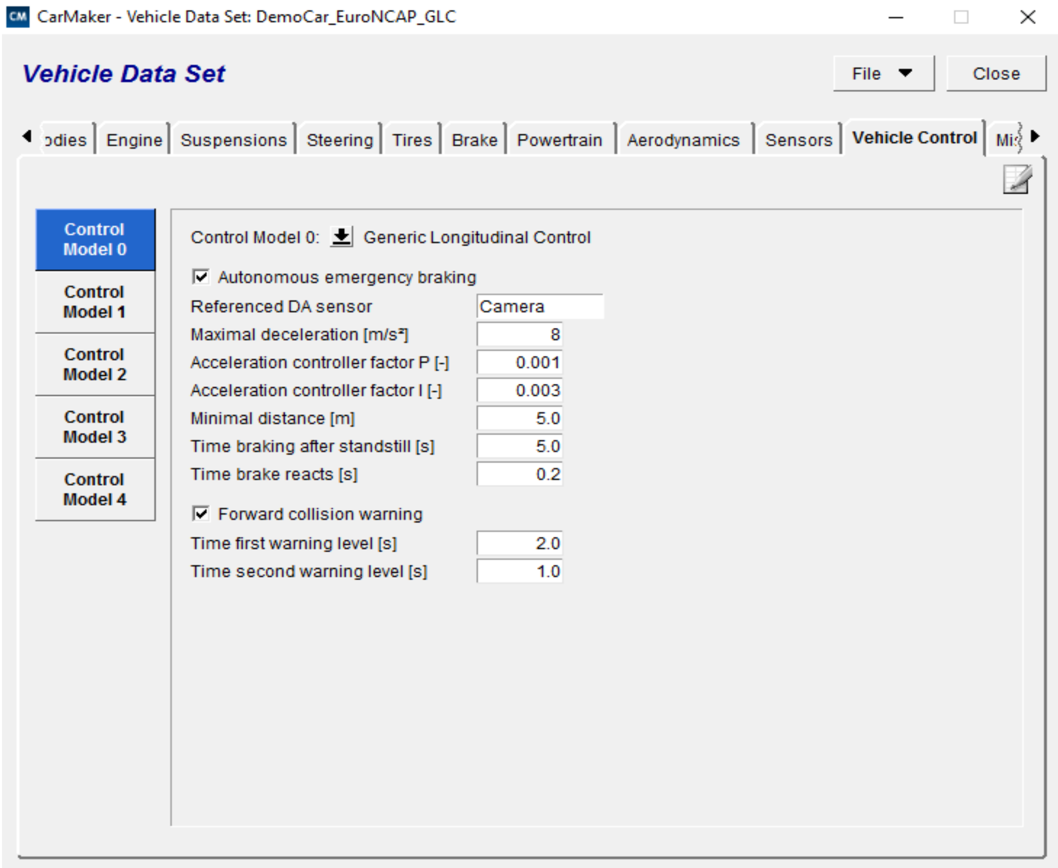

Figure 3.6 - VW Beetle vehicle control

BMW 5-series uses Acceleration control + ACC for controlling the vehicle. ACC controls the longitudinal acceleration of the vehicle by changing the position of the brake and gas pedal. If ACC is deactivated there is no manipulation of the pedal position by the controller – figure 3.7. The controller distinguishes two cases:

- If there is no target detected, the velocity will be controlled.
- If there is a relevant target detected, the distance will be controlled.

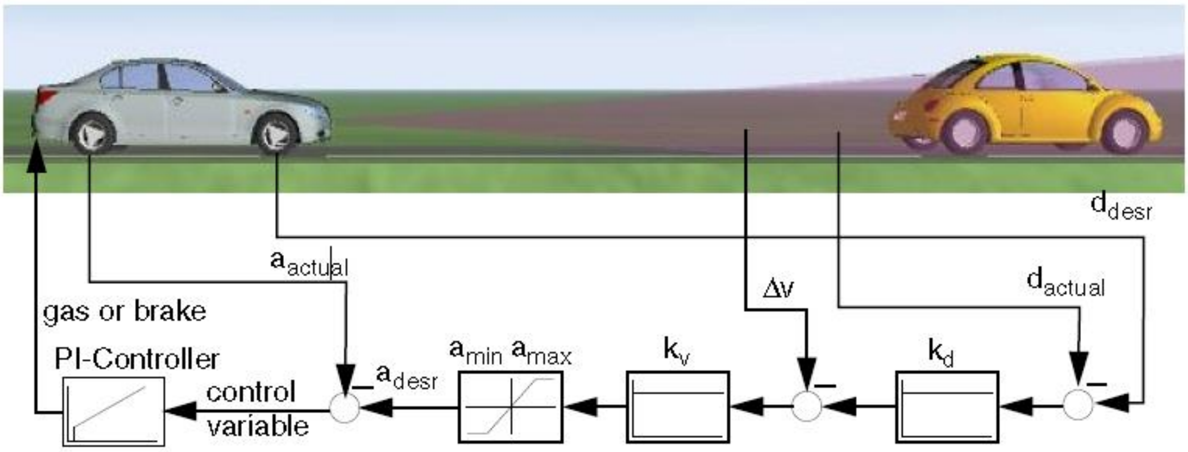

Figure 3.7 - Closed loop of the ACC-Controller

This controller uses a PI-Controller. The desired longitudinal acceleration can be calculated in different manners: using CarMakers built-in ACC-Controller, via Direct Variable Access or using a user implemented function.

To ensure correct behavior of the RaDAR is used as a sensor for scanning area in front of the vehicle. RaDAR has its own place on the vehicle as well as its working parameters like range and horizontal and vertical aperture – see the figure 3.8 and 3.9.

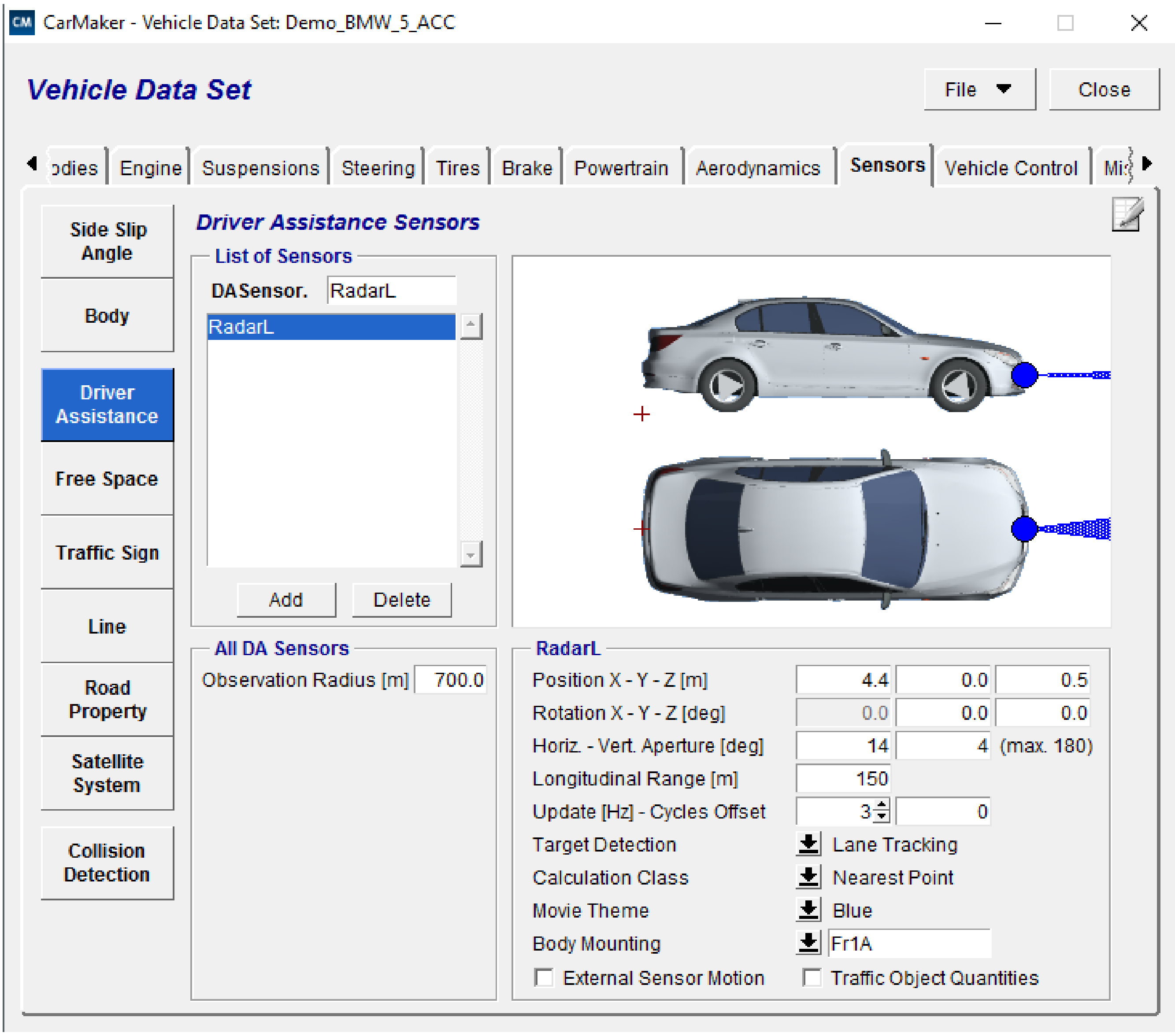

Figure 3.8 - BMW 5-series sensor setup

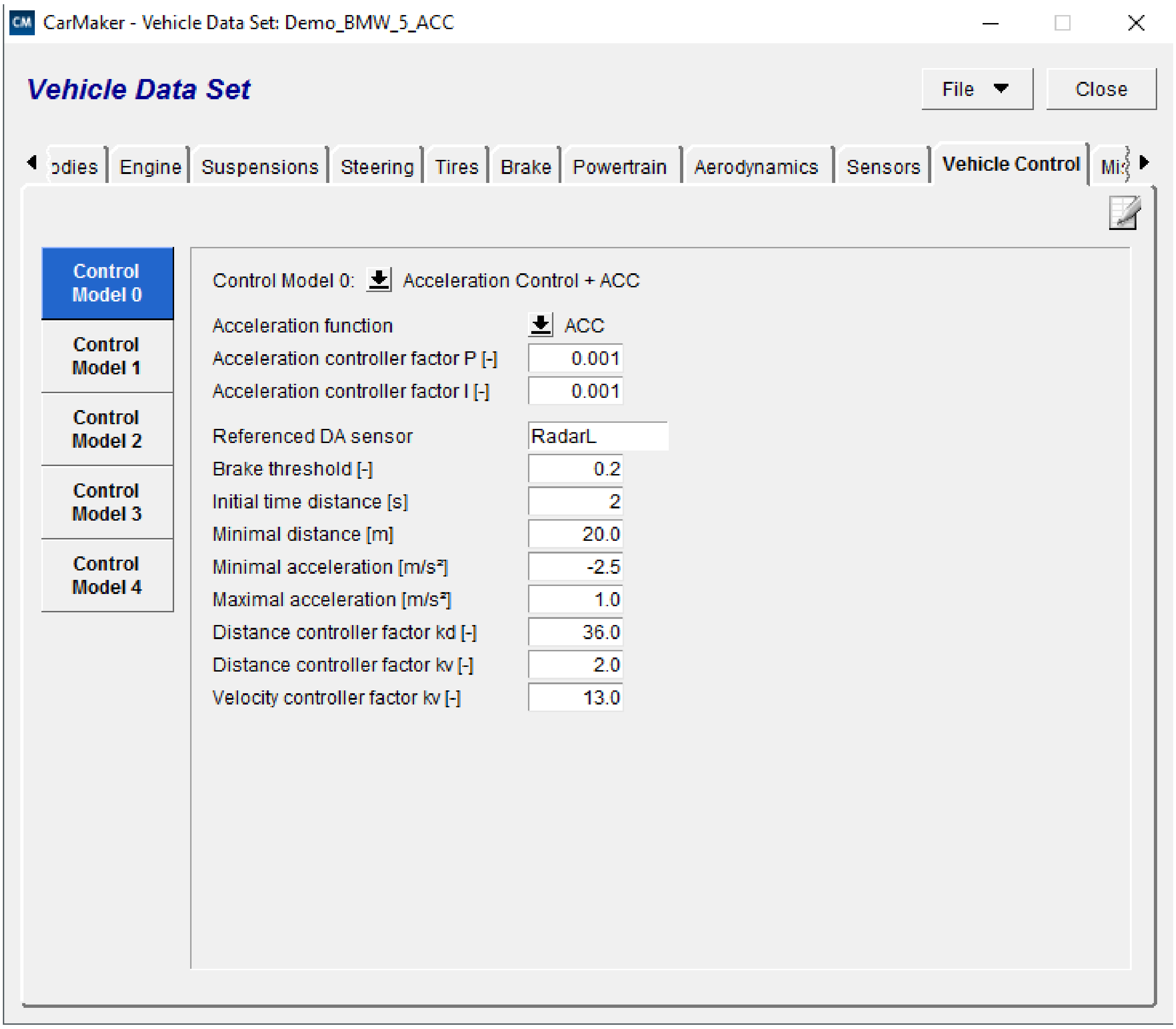

Figure 3.9 - BMW 5-series vehicle control

3.4. Description of driving scenarios

Every driving scenario has been simulated individually. A detailed description of each is below. All these scenarios are based on dissertation [11] from my supervisor.

3.4.1. T02 - CTU 02/2013 B, C - Limitations to another maneuver

This test run is focused on the analysis of the behavior of the automatic emergency brake system and the adaptive cruise control reaction. Reactions of the eGo vehicle being tested always behind the target vehicle – case B. Distance of about 15 m behind the target vehicle is maintained and no automatic braking response is expected.

In the Adaptive Cruise Control, however, the reaction to the newly discovered obstacle is desirable - the test vehicle should start to brake. The cruise speed is set at 5 km/h higher than the speed of the target vehicle and its distance from the adaptive cruise control system is set to the shortest possible. These tests are marked T02 - CTU 02/2013 B for the Integrated Safety System Test and T02 - CTU 02/2013 C for Adaptive Cruise Control.

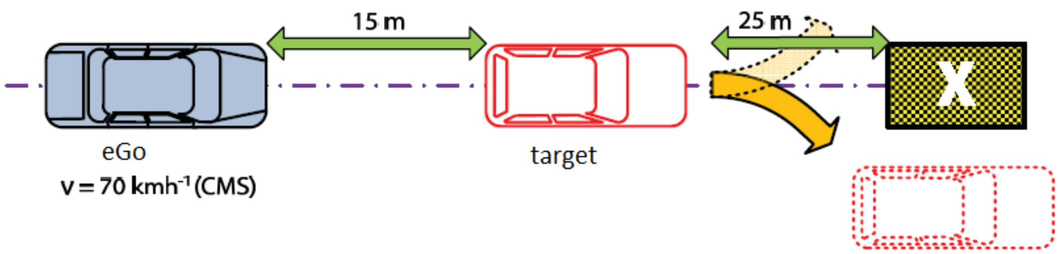

Figure 3.11 - T02 - CTU 02/2013 B

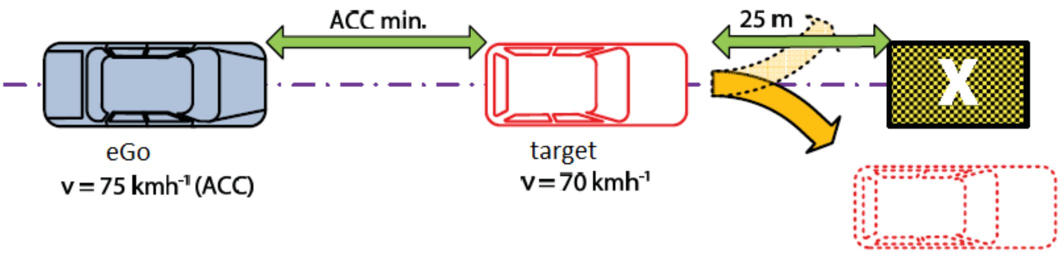

Figure 3.10 - T02 - CTU 02/2013 C

3.4.2. T05 - CTU 02/2013 E - Adaptive cruise control adaptation

The test is focused on adaptive cruise control adaptation when driving multiple vehicles with this system in a row. For all vehicles, the speed at the beginning is set to 70 km/h, then the first vehicle will slow down to 50 km/h and the response of other cars is monitored. After stabilization of the speed, the first vehicle accelerates in the same way to 70 km/h and the response of other vehicles is re-analysed. All vehicles in the row traveling behind the first vehicle, have a cruise control always set to a speed of 10 km/h higher than the vehicle ahead. This test is labeled as T05 - CTU 02/2013 E.

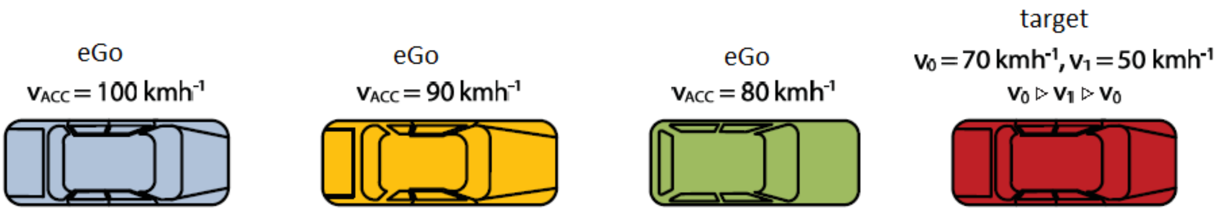

Figure 3.12 - T05 - CTU 02/2013 E

3.4.3. T06 - CTU 02/2013 F - Secure and predictable vehicle interaction

The test is focused on the analysis of the behavior of the ADAS system in the context of other traffic. The behavior of the interactive technology interface of the autonomous system and other vehicles is evaluated. The eGo vehicle maintains a constant speed of 80 km/h through adaptive cruise control which is set at a maximum distance from the vehicle in front. Outside the axis of the eGo vehicle, the target vehicle moves at the same constant speed. After the distance between vehicles is between 15 and 20 m, the eGo vehicle moves to the target lane. Vehicle and the alignment of the distance are monitored to match the set distance. This should be smooth without using the car's brakes. The test is designated as T06 - CTU 02/2013 F.

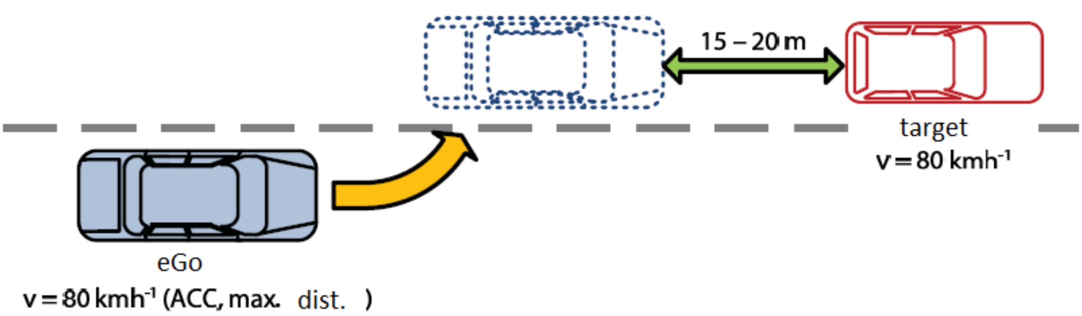

Figure 3.13 - T06 - CTU 02/2013 F

3.4.4. T07 - CTU 02/2013 G - Consistency of system behavior

The purpose of the test is to verify the behavior of the automatic emergency brake system according to the manufacturer's specification. The tested vehicle again moves outside the obstacle axis with a speed of 20 km/h, maintained by the driver, and approximately 100 m before the obstacle enters its axis. The manufacturer's prescribed reaction response is expected, for example, automatic braking before the obstacle, while the driver does not change the driving speed.

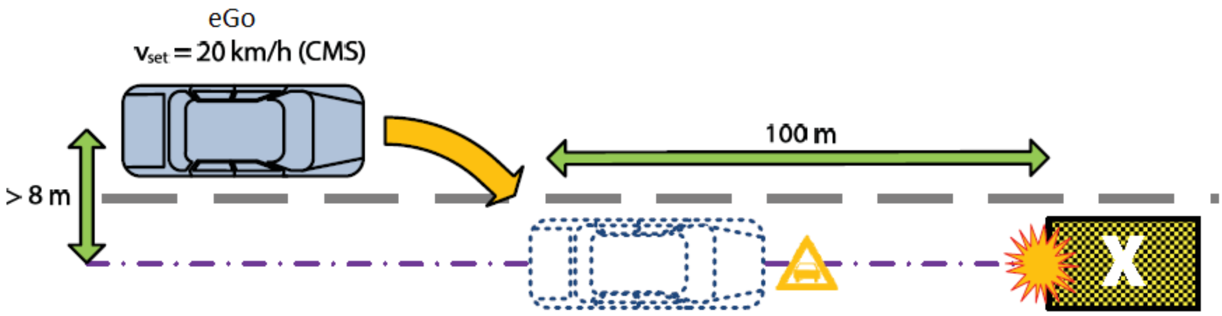

Figure 3.14 - T07 - CTU 02/2013 G

3.4.5. T08 – ES 347/2012 A - Recognizing the trajectory between standing vehicles

The first standardized test is part of European Union Regulation No. 347/2012, prescribing the characteristics of the automatic braking system for trucks and buses. The test verifies whether the detection system can recognize the space between two side-by-side standing vehicles whose rear parts are aligned in one plane.

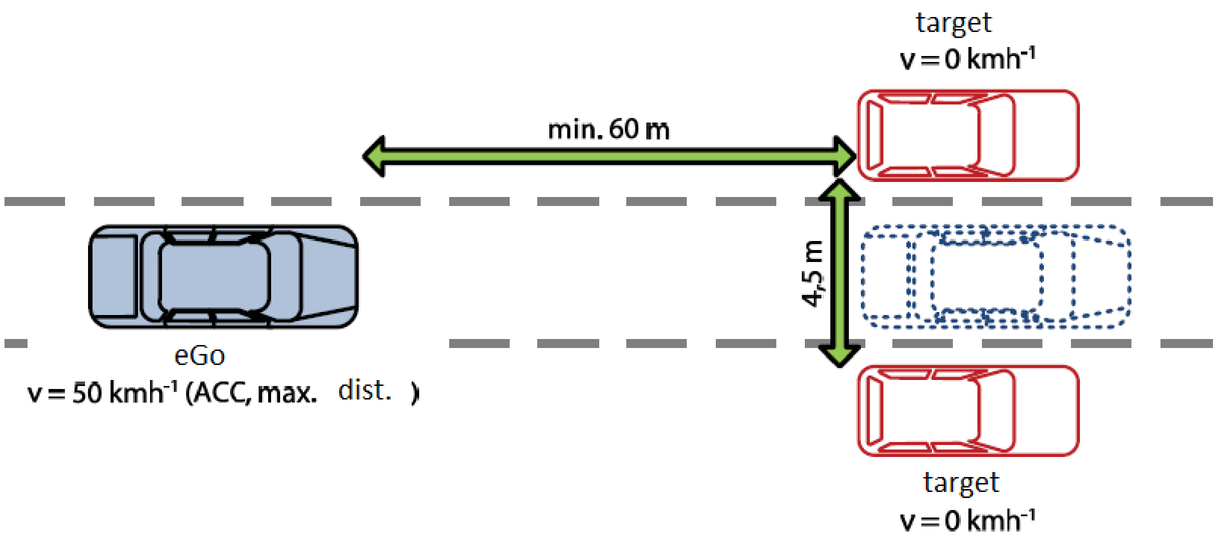

Figure 3.15 - T08 - ES 347/2012 A

The prescription defines the passage without the adaptive cruise control only for automatic braking systems. For greater clarity and the possibility of merging similar tests, the adaptive cruise control is on and set to maintain the 50km/h with maximum distance.

3.4.6. T12 - ISO 15623 B - Recognition of the target vehicle from two consecutive targets

The test is one of the tests defined by ISO 15623. The test determines whether the eGo vehicle recognizes two near-running vehicles that do not overlap completely. During the test, the main target vehicle (center) is driven at a constant speed outside of the eGo driving axis (however, it is necessary to reach at least 0.5 m of its width in the test vehicle strip). The eGo vehicle accelerates until the warning system alerts and then decelerates until the warning system disappears. Then begins to decelerate the middle target vehicle and decelerates until the warning system of the eGo vehicle again responds.

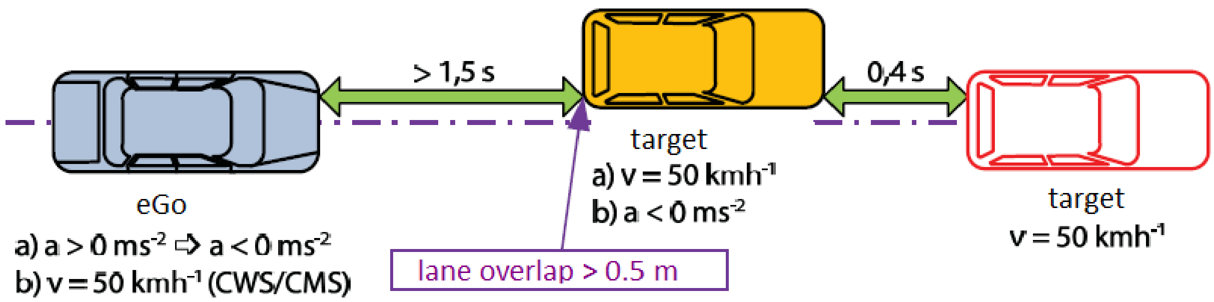

Figure 3.16 - T 12 - ISO 15623 B

3.4.7. T15 - ISO 22178 B: Column slow ride: Target vehicle recognition from overtaking car

The experiment is defined by ISO 22178 and focuses on the ability of the detection subsystem to distinguish between parallel driving vehicles. The column

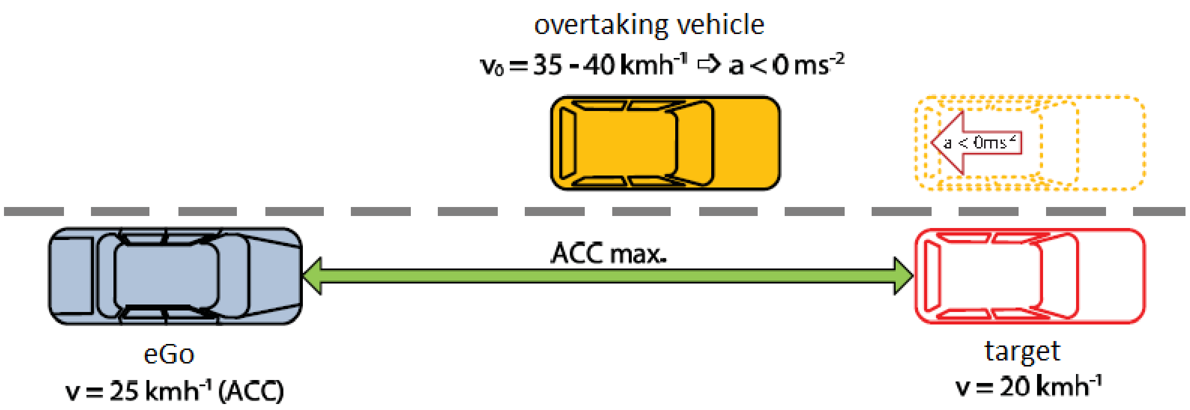

Figure 3.17 - T15 - ISO 22178 B

overtakes a faster vehicle that slows down at the target vehicle's speed and slows down further. The eGo vehicle maintaining speed through the adaptive cruise control and does not have respond to the overtaking vehicle.

3.4.8. T16 - ISO 22178 C: Slow drive in the column: the target vehicle leaves the column

The test is again defined by ISO 22178 and is aimed at detecting the new target vehicle. In a column of three vehicles traveling with minimum intervals between them, the middle target vehicle decides to leave the column. The eGo vehicle is set to maintain a minimum distance and the cruise control has a set speed corresponding to the minimum possible, but at least 5 km/h more than the speed of the column. The eGo vehicle must continuously link to the new target vehicle.

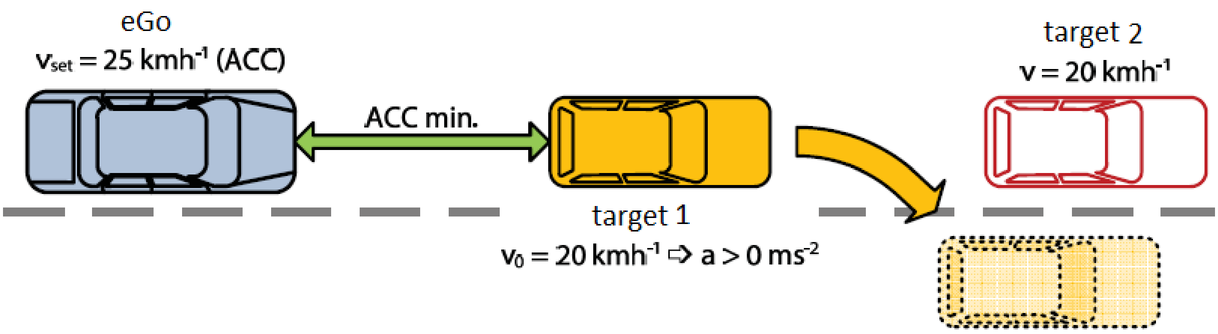

Figure 3.18 - T16 - ISO 22178 C

3.4.9. T18 - ISO 22179 A: Tracking the target vehicle to stop

The test is based on ISO 22179 and is focused on tracking the target vehicle via adaptive cruise control until it stops if the manufacturer specifies this function. The test combines a column test with an adaptive cruise control running from zero speed. The faster eGo vehicle arrives at the slower target vehicle, which then continuously decelerates until it stops.

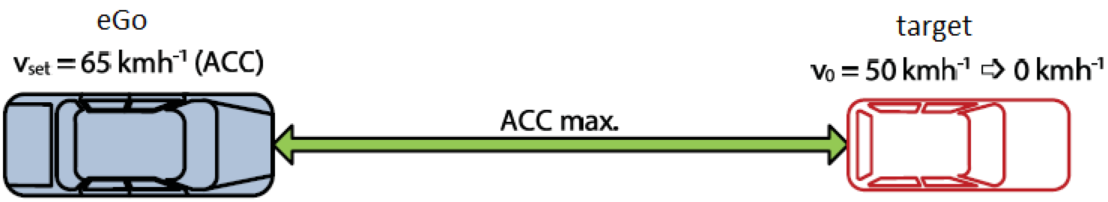

Figure 3.19 - T18 - ISO 22179 A

3.4.10. T19 - ISO 22179 B: Resolution of the target vehicle from the overtaking car

The test is based on the ISO 22179 standard. It is focused on the analysis of the ability to discretize two parallel-running vehicles without stabilizing the relative position of the target and the parallel vehicle. The objective is to verify the capabilities of the detection subsystem. The test was performed according to the specification in the standard. The eGo vehicle, with the adaptive cruise control on, set at a higher speed than the target vehicle, moves behind the target vehicle. The target and eGo vehicles are gradually overtaking a parallel slower car. The eGo vehicle does not have responded to the overtaken vehicle.

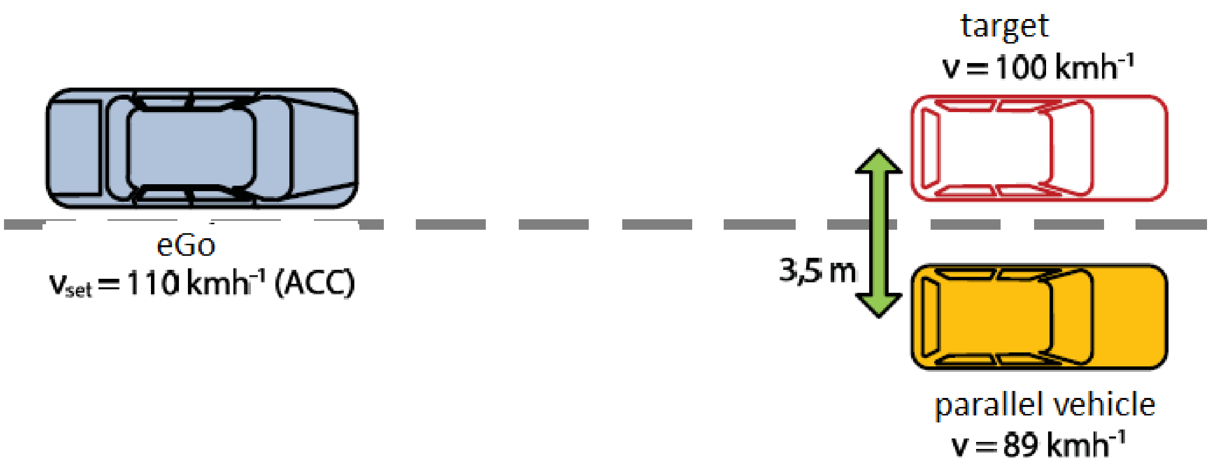

Figure 3.20 - T19 - ISO 22179 B

3.5. Parametrization of driving scenarios

CarMaker offers different possibilities to make simulation work a lot easier, for example, the test automation. Using it, we perform simulations with varying parameters completely autonomously. This parametrization was done by CarMaker Test Manager.

A test series in the Test Manager basically consists of TestRuns that are executed automatically one after another. However, the Test Manager offers a lot of functionalities to optimize the preparation, execution, and analysis of TestRuns: We can use variations to modify parameters of a TestRun instead of creating a TestRun for each scenario. We can add script files to define certain actions which should be executed at the beginning or at the end of each simulation. The definition of criteria can be used to judge the results of a simulation at one glance or even to abort the execution of the test series once a user defined condition is met.

All the TestRuns, variations and scripts that make up a test series in the Test Manager are executed consecutively starting from top to bottom. An overview of the execution order is given in the figure 3.21, marked as box A in the picture below. In box B, we can find a description of the current test series (if activated under View) or we can place settings such as select a TestRun or enter a value for a variation.

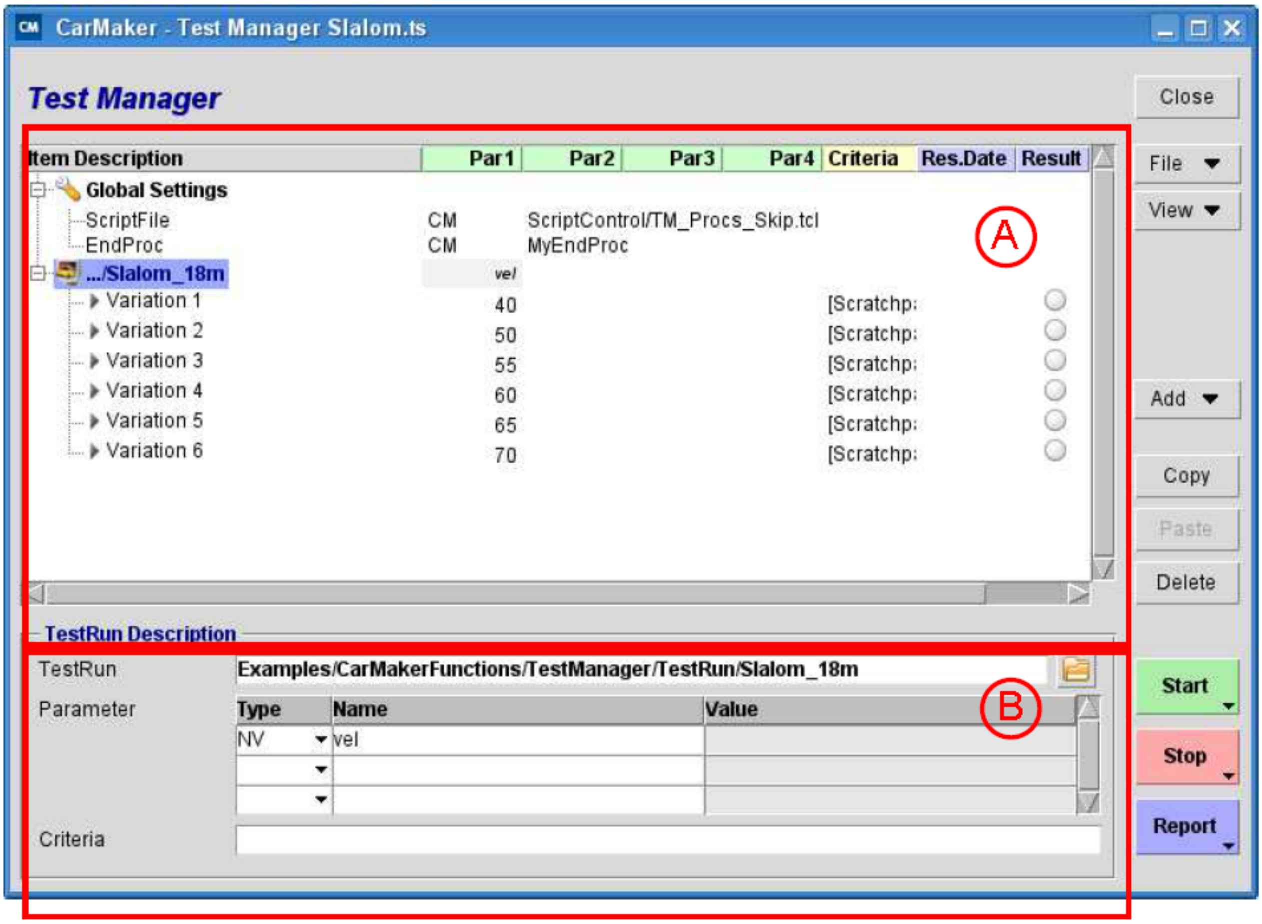

Figure 3.21 - Clear view (A) and description window (B) of the Test Manager GUI

Every driving scenario has been parametrized to three cases from A to C. These cases have different values for every variable. These values were chosen with regards to vehicle dynamics and driving scenario definition.

Every TestRun will be described by following parameters:

- **TestRun**: name of the test run in CarMaker
- **Car**: name of the car in CarMaker
- **Test manager**: name of the test manager in CarMaker
- Parametrized variables and its values

Explanatory notes for variables with units:

Variable	Unit	Description
Deceleration	[m/s2]	deceleration of target vehicle
Distance_eGo_Target	[m, s]	longitudinal distance between eGo and target vehicle in meters or seconds
Distance_eGo_SCT	[m]	longitudinal distance between eGo vehicle and soft crash target
Distance_Target_SCT	[m]	longitudinal distance between target vehicle and soft crash target
Distance_target_target	[m]	lateral distance between two targets driving axis
Distance_target_target1	[m]	lateral distance between two targets driving axis in negative values
Friction_coef	[1]	friction coefficient of road surface
Sensor_range	[m]	longitudinal sensor range
Sensor_view_angle_horizontal	[deg]	horizontal sensor view angle
Sensor_view_angle_vertical	[deg]	vertical sensor view angle
Speed	[km/h]	speed of eGo vehicle
Speed_parallel	[km/h]	speed of parallel driving vehicle
Speed_target	[km/h]	speed of target vehicle
Speed_traffic	[km/h]	speed of traffic object
Target_overlap	[m]	lateral distance between target driving axis and lane axis

3.5.1. T02 - CTU 02/2013 B, C - Limitations to another maneuver

TestRun: T02_CTU_02_2013B_testrun
Car: DemoCar_EuroNCAP_GLC_T02_CTU_02_2013B
Test manager: Parametrization_ T02_CTU_02_2013B.ts

	Name of parameters	Case A	Case B	Case C
Input	Distance_eGo_Target [m]	20	15	10
	Distance_Target_SCT	30	25	20
	Friction_coef	0.5	0.8	1
	Sensor_range	20	40	80
	Sensor_view_angle_horizontal	25	35	45
	Sensor_view_angle_vertical	25	35	45
	Speed	65	70	75
Output	Distance_eGo_SCT	29	35	28

TestRun: T02_CTU_02_2013C_testrun
Car: Demo_BMW_5_ACC_T02_CTU_02_2013C
Test manager: Parametrization_ T02_CTU_02_2013C.ts

	Name of parameters	Case A	Case B	Case C
Input	Distance_eGo_Target [s]	3	2	1
	Distance_Target_SCT	30	25	20
	Friction_coef	0.5	0.8	1
	Sensor_range	100	150	200
	Sensor_view_angle_horizontal	2	4	6
	Sensor_view_angle_vertical	10	13	16
	Speed	65	70	75
	Speed_traffic	60	65	70
Output	Distance_eGo_SCT	25	25	25

3.5.2. T05 - CTU 02/2013 E - Adaptive cruise control adaptation

TestRun: T05_CTU_02_2013E_testrun
Car: Demo_BMW_5_ACC_T05_CTU_02_2013E
Test manager: Parametrization_T05_CTU_02_2013E.ts

	Name of parameters	Case A	Case B	Case C
Input	Friction_coef	0.5	0.8	1
	Sensor_range	100	150	200
	Sensor_view_angle_horizontal	2	4	6
	Sensor_view_angle_vertical	10	13	16

3.5.3. T06 - CTU 02/2013 F - Secure and predictable vehicle interaction

TestRun: T06_CTU_02_2013F_testrun
Car: Demo_BMW_5_ACC_T06_CTU_02_2013F
Test manager: Parametrization_T06_CTU_02_2013E.ts

	Name of parameters	Case A	Case B	Case C
Input	Friction_coef	0.5	0.8	1
	Sensor_range	100	150	200
	Sensor_view_angle_horizontal	2	4	6
	Sensor_view_angle_vertical	10	13	16
	Speed	75	80	85
Output	Distance_eGo_Target	44	32	19

3.5.4. T07 - CTU 02/2013 G - Consistency of system behavior

TestRun: T07_CTU_02_2013G_testrun
Car: DemoCar_EuroNCAP_GLC_T07_CTU_02_2013G
Test manager: Parametrization_T07_CTU_02_2013G.ts

	Name of parameters	Case A	Case B	Case C
Input	Friction_coef	0.5	0.8	1
	Sensor_range	20	40	80
	Sensor_view_angle_horizontal	25	35	45
	Sensor_view_angle_vertical	25	35	45
	Speed	15	20	25

3.5.5. T08 – ES 347/2012 A - Recognizing the trajectory between standing vehicles

TestRun: T08_ES_347_2012A_testrun
Car: Demo_BMW_5_ACC_T08_ES_347_2012A
Test manager: Parametrization_T08_ES_347_2012A.ts

	Name of parameters	Case A	Case B	Case C
Input	Distance_target_target	2.2	3	4
	Distance_target_target1	-2.2	-3	-4
	Friction_coef	0.5	0.8	1
	Sensor_range	100	150	200
	Sensor_view_angle_horizontal	2	4	6
	Sensor_view_angle_vertical	10	13	16
	Speed	45	50	55
Output	Actual gap [m]	2.65	4.5	6.3

3.5.6. T12 - ISO 15623 B - Recognition of the target vehicle from two consecutive targets

TestRun: T12_ISO_15623B_testrun
Car: Demo_BMW_5_ACC_T12_ISO_15623B
Test manager: Parametrization_T12_ISO_15623B.ts

	Name of parameters	Case A	Case B	Case C
Input	Distance_eGo_Target [s]	1	2	3
	Friction_coef	0.5	0.8	1
	Sensor_range	100	150	200
	Sensor_view_angle_horizontal	2	4	6
	Sensor_view_angle_vertical	10	13	16
	Speed	45	50	55
	Target_overlap	-2	-1.5	-1
Output	Actual overlap [m]	0.85	1.35	1.85

3.5.7. T15 - ISO 22178 B: Column slow ride: Target vehicle recognition from overtaking car

TestRun: T15_ISO_22178B_testrun
Car: Demo_BMW_5_ACC_ T15_ISO_22178B
Test manager: Parametrization_ T15_ISO_22178B.ts

	Name of parameters	Case A	Case B	Case C
Input	Deceleration	-1	-3	-5
	Friction_coef	0.5	0.8	1
	Sensor_range	100	150	200
	Sensor_view_angle_horizontal	2	4	6
	Sensor_view_angle_vertical	10	13	16
	Speed	20	25	30
	Speed_target	30	35	40

3.5.8. T16 - ISO 22178 C: Slow drive in the column: the target vehicle leaves the column

TestRun: T16_ISO_22178C_testrun
Car: Demo_BMW_5_ACC_ T16_ISO_22178C
Test manager: Parametrization_ T16_ISO_22178C.ts

	Name of parameters	Case A	Case B	Case C
Input	Distance_eGo_Target [s]	1	1.5	2
	Friction_coef	0.5	0.8	1
	Sensor_range	100	150	200
	Sensor_view_angle_horizontal	2	4	6
	Sensor_view_angle_vertical	10	13	16
	Speed	20	25	30

3.5.9. T18 - ISO 22179 A: Tracking the target vehicle to stop

TestRun: T18_ISO_22179A_testrun
Car: Demo_BMW_5_ACC_ T18_ISO_22179A
Test manager: Parametrization_ T18_ISO_22179A.ts

	Name of parameters	Case A	Case B	Case C
Input	Deceleration	-1	-3	-5
	Distance_eGo_Target [s]	2	3	4
	Friction_coef	0.5	0.8	1
	Sensor_range	100	150	200
	Sensor_view_angle_horizontal	2	4	6
	Sensor_view_angle_vertical	10	13	16
	Speed	60	65	70

3.5.10. T19 - ISO 22179 B: Resolution of the target vehicle from the overtaking car

TestRun: T19_ISO_22179B_testrun
Car: Demo_BMW_5_ACC_ T19_ISO_22179B
Test manager: Parametrization_ T19_ISO_22179B.ts

	Name of parameters	Case A	Case B	Case C
Input	Distance_target_target	3	3,5	4
	Friction_coef	0.5	0.8	1
	Sensor_range	100	150	200
	Sensor_view_angle_horizontal	2	4	6
	Sensor_view_angle_vertical	10	13	16
	Speed_parallel	69	79	89
	Speed_target	80	90	100

3.6. Evaluation of driving scenarios

The evaluation was done with help of IPGMovie tool, which graphically represents all the simulations and IPGControl. IPGControl offers the functionality of an online result management. This means that the current simulation data is provided without delay, which enables us to display diagrams directly during the simulation.

3.6.1. T02 - CTU 02/2013 B, C - Limitations to another maneuver

The goal of this test for T02 – CTU 02/2013 B was to test reactions of AEB system. eGo vehicle should not start braking when target vehicle exits its lane and new static target (SCT) appears because eGo vehicle exits this lane also.

Limit distances (eGo does not brake) between SCT and eGo vehicle are:

Name of parameter	Case A	Case B	Case C
LongCtrl.AEB.dDist [m]	18.4	25	9

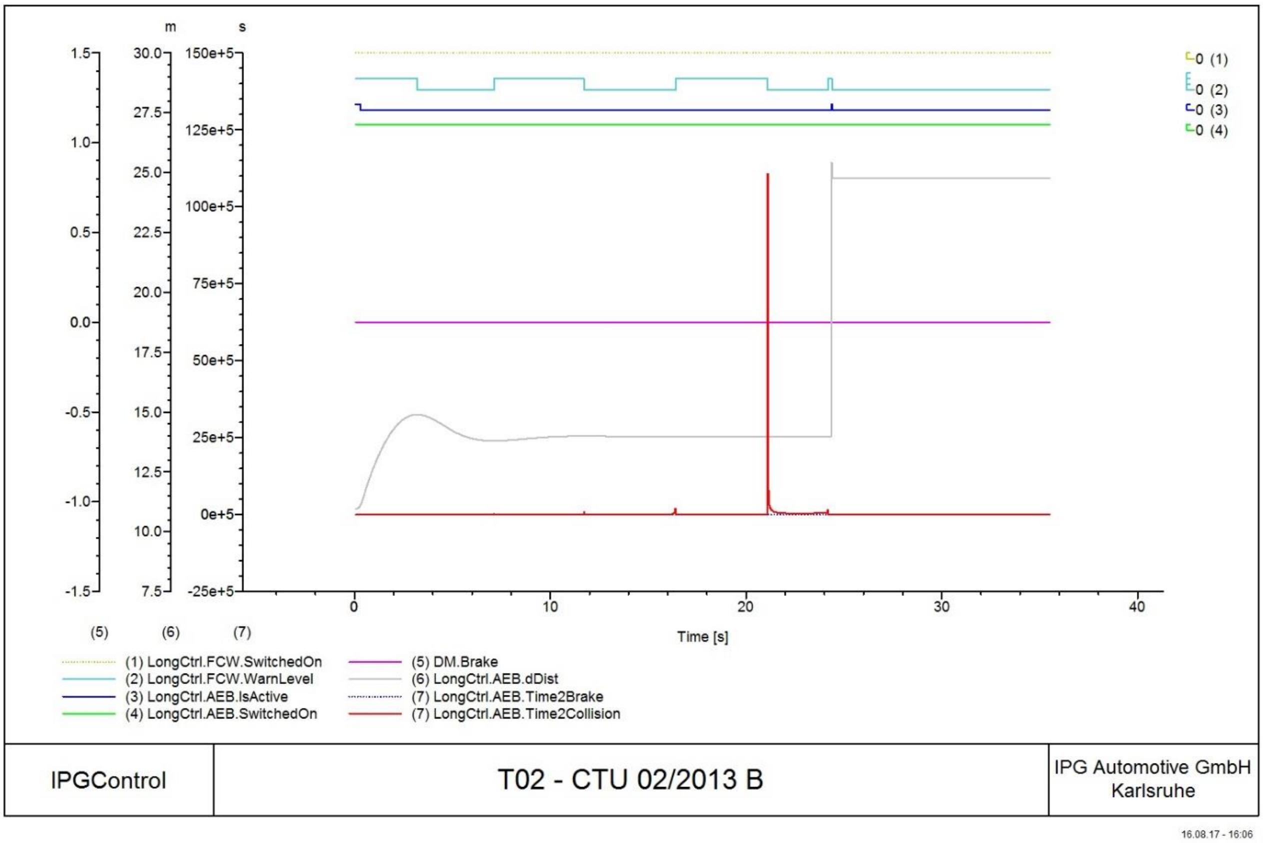

Figure 3.22 – eGo and SCT driving parameters – Case B

(1) LongCtrl.FCW.SwitchedOn: Flat if FCW system is switched on
(2) LongCtrl.FCW.WarnLevel: Warning level of FCW system: 0=no warning, 1-2=warning level 1-2
(3) LongCtrl.AEB.IsActive: Flat if AEB system is active (=braking)
(4) LongCtrl.AEB.SwitchedOn: Flat if AEB system is switched on
(5) DM.Brake: Brake/decelerator activity, relative pedal force (0..1)
(6) LongCtrl.AEB.dDist [m]: Relative distance to relevant target object
(7) LongCtrl.AEB.Time2Collision [s]: Time to collision with the target vehicle
(7) LongCtrl.AEB.Time2Brake [s]: Time threshold to brake to equal velocity of the target object

This test has a limit of 25 m and it has been reached in all of these cases. In Case C, the relative distance was shortest - 9 meters to the target vehicle. In Case B, the relative distance was 25 m, so on the limit, but still acceptable. Variable DM.Brake represent inactivity of braking pedal during whole simulation.

For version T02 – CTU 02/2013 C limit of 25 m was met. The required behavior of the vehicle was braking when it recognizes a new target. This behavior was met in every test case. DM.Brake shows that vehicle was braking for 1.5 s

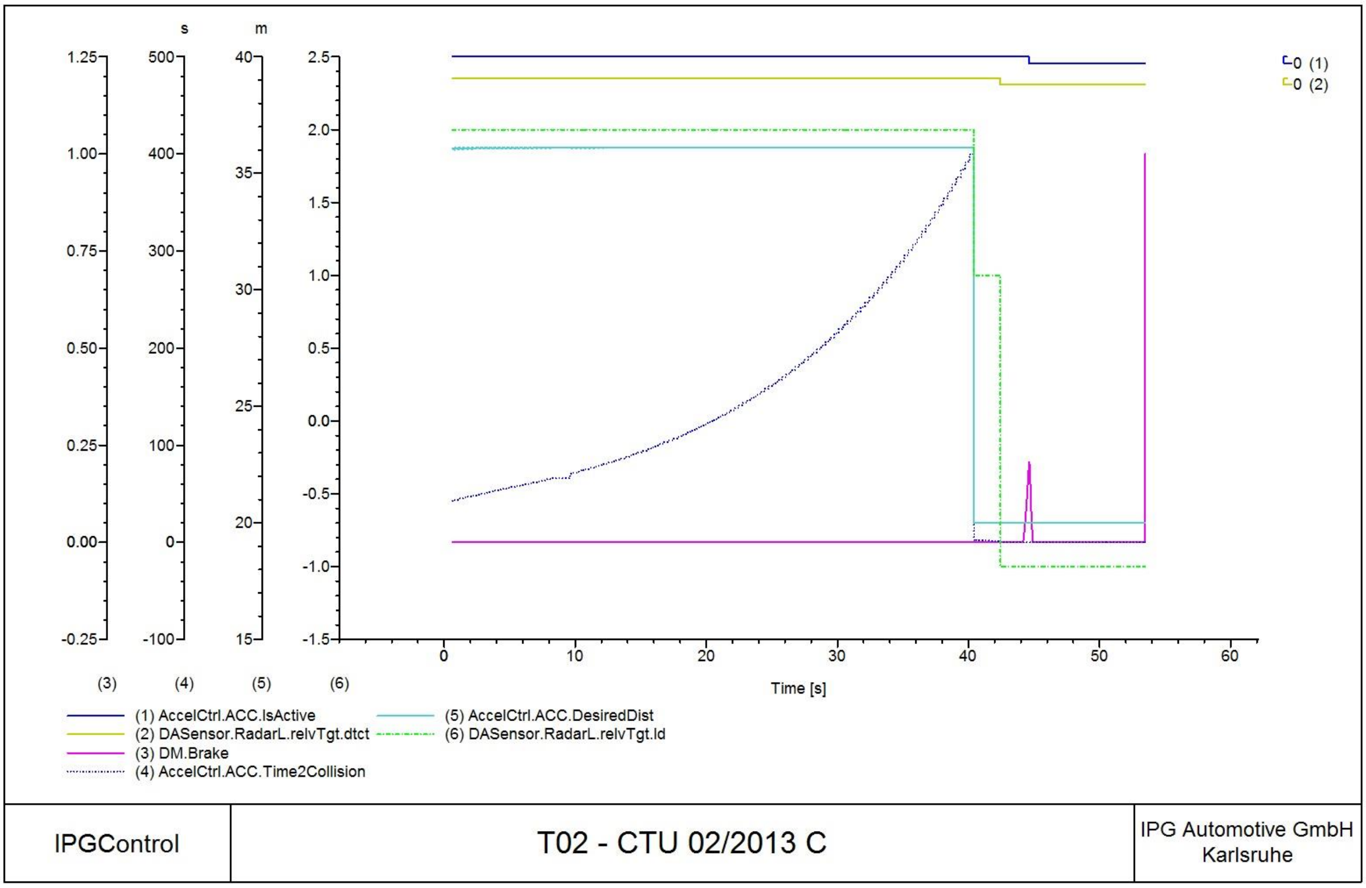

Figure 3.23 - eGo driving parameters for ACC - Case B

(1) AccelCtrl.ACC.IsActive: Flat if the ACC controller is activated
(2) DASensor.RadarL.relvTgt.dtct: Flat if a relevant target is detected (boolean)
(3) DM.Brake: Brake/decelerator activity, relative pedal force (0..1)
(4) AccelCtrl.ACC.Time2Collision [s]: Time to collision with the target vehicle
(5) AccelCtrl.ACC.DesiredDist [m]: Desired distance to the target vehicle
(6) DASensor.RadarL.relvTgt.dtct: Flat if a relevant target is detected (boolean)

3.6.2. T05 - CTU 02/2013 E - Adaptive cruise control adaptation

The goal of this test was to verify adaptation of ACC. The response of other cars was monitored. In every case, ACC of every car adapts to the new situation. ACC of target vehicles has default setup, which cannot be tuned, but eGo vehicle has the possibility to improve the response of ACC. In the figure 3.25 is described the list of parameters. For Case B graph with speeds is plotted in figure 3.24. In the first part vehicles have default starting positions and must create 1.5 s gaps between each other. Traffic object T04 is leading the column and rest is setting up right distance. In part two all speeds are same and vehicles travel simultaneously. In part three it is clearly visible, that target T04 starts braking first and every following object copies its behavior until steady state in part four. In the last fifth part vehicles start to accelerate again.

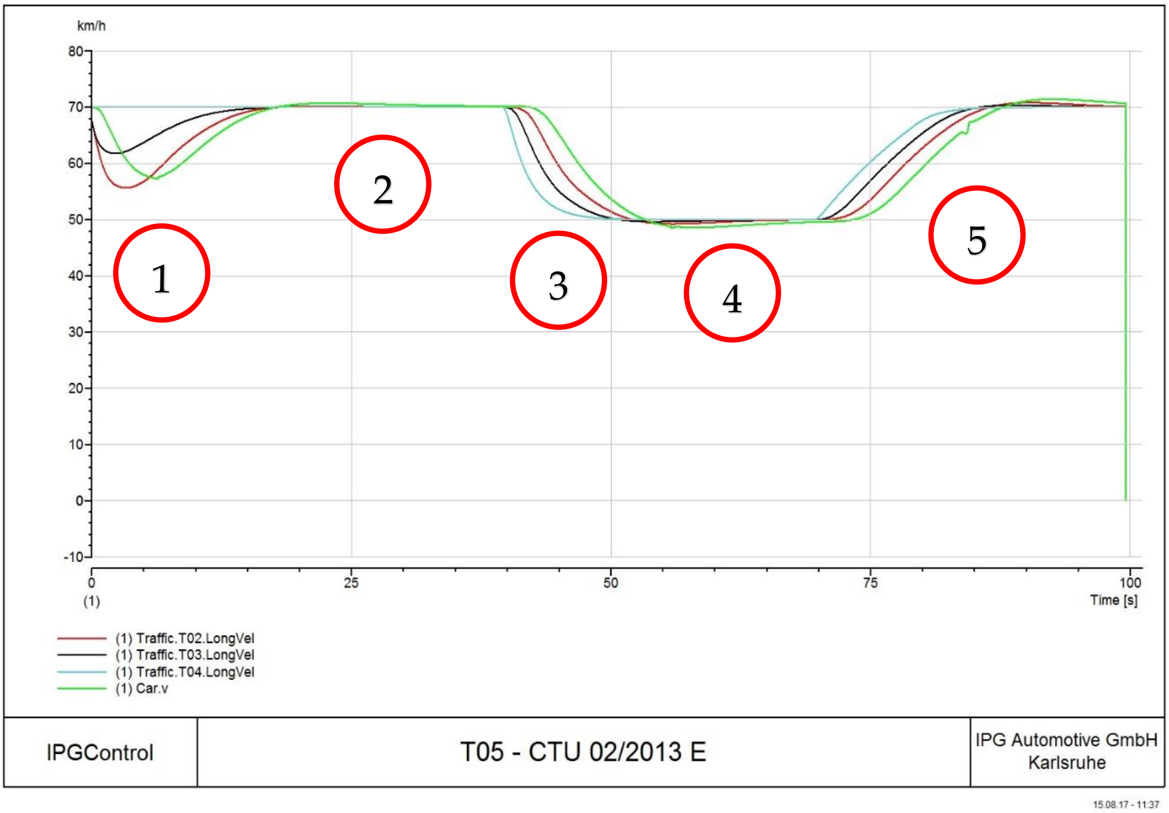

Figure 3.24 - Speeds of each vehicle during simulation - Case B

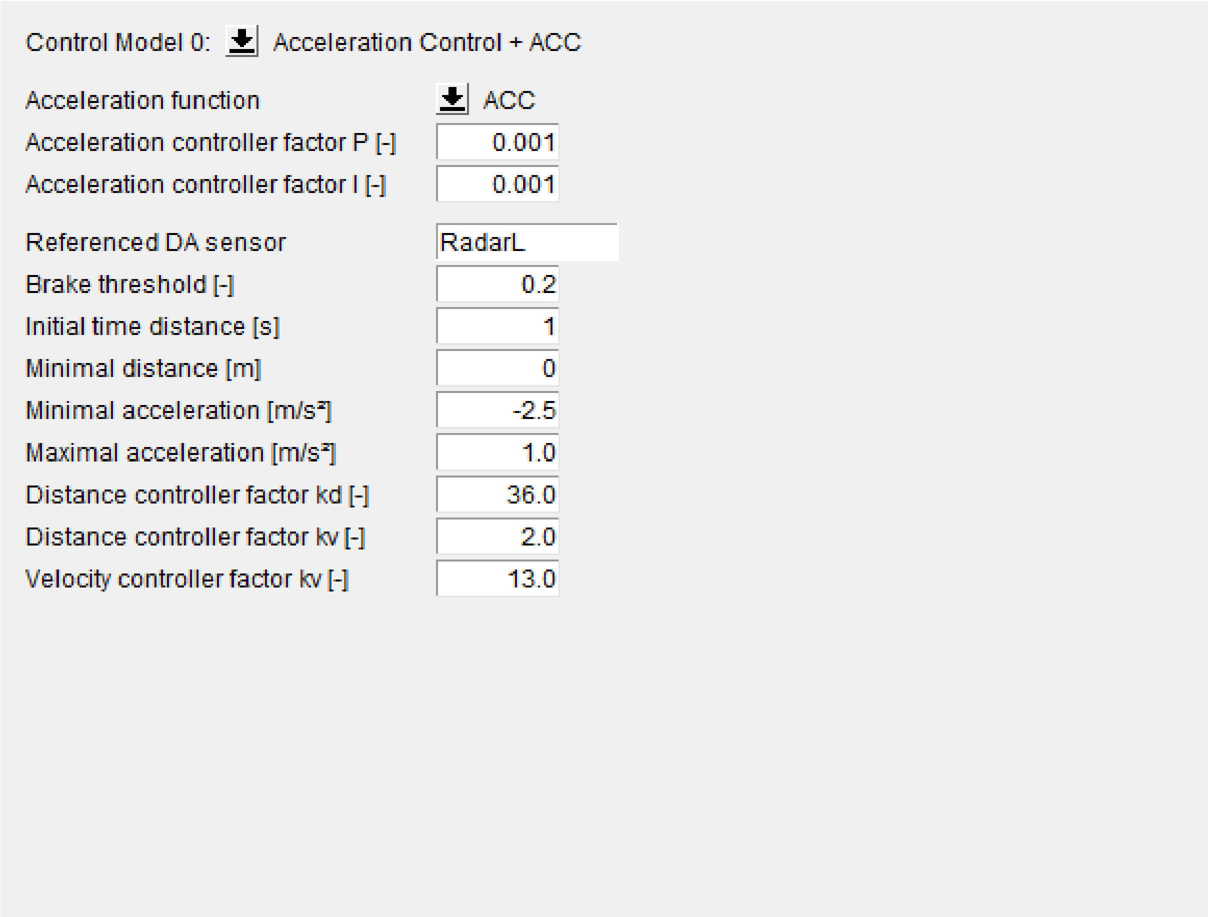

Figure 3.25 – ACC parameters setup

3.6.3. T06 - CTU 02/2013 F - Secure and predictable vehicle interaction

The goal of this test was the analysis of the behavior of the autonomous system in the context of other traffic. eGo vehicle with ACC set to the maximum distance merges into target's lane 15 – 20 m behind it. The reaction of ACC controller is monitored. Setting up of required ACC distance should be done continuously and without using of brakes.

Limit distances (eGo does not brake) between target and eGo vehicle are:

Name of parameter	Case A	Case B	Case C
Distance_eGo_target [m]	44	32	19

ACC maximum distance is set to 3 s gap between eGo and target. For smoother spacing acceleration controller factor, I [-] is changed from 0.001 to 0.0001 and minimal distance is 10 m – figure 3.26. In the default setup merging was always accompanied by braking independently on distance between eGo and target. After tuning controller factor I, values in the table were reached. Only for Case C limit between 15 – 20 m was met. Rest of TestRuns don't suit.

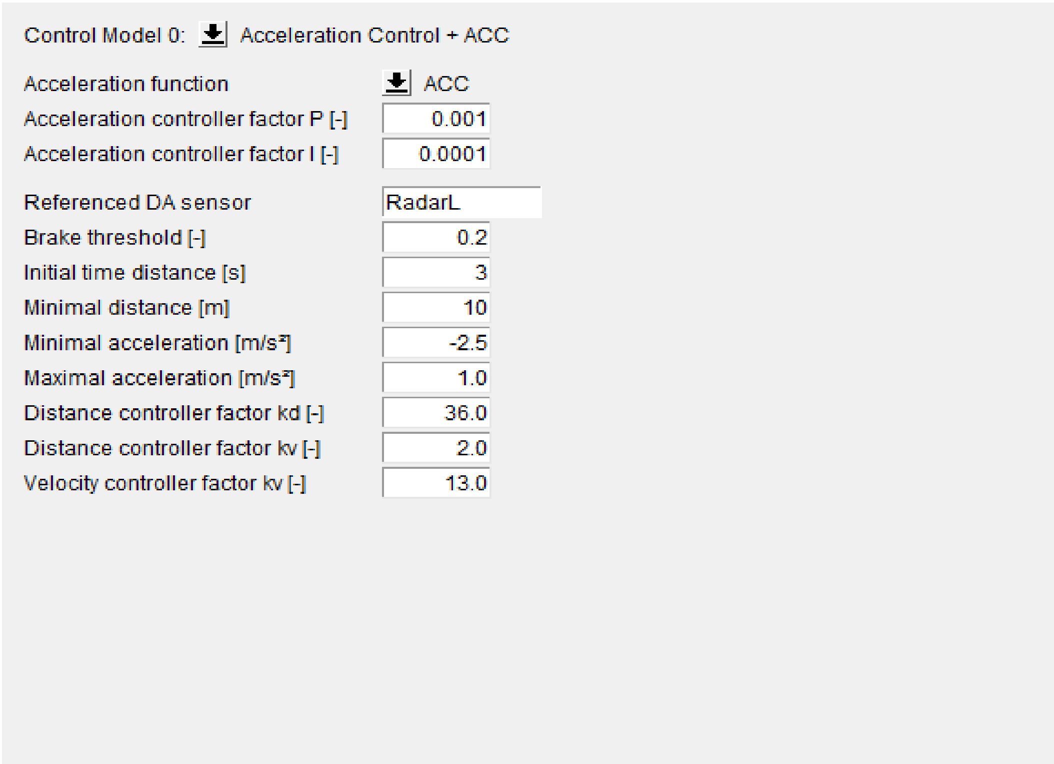

Figure 3.27 – ACC parameters tuning

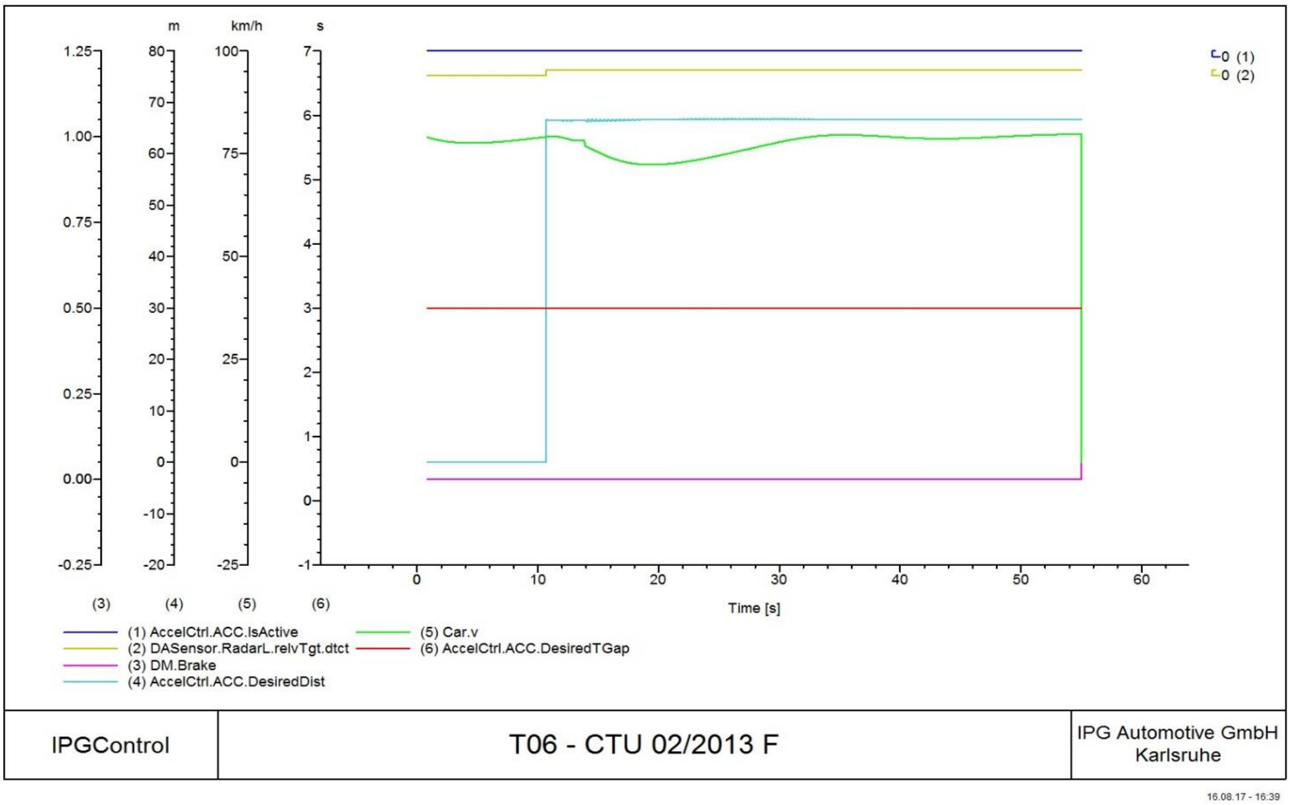

Figure 3.26 – ACC behavior of eGo vehicle – Case B

(1) AccelCtrl.ACC.IsActive: Flat if the ACC controller is activated
(2) DASensor.RadarL.relvTgt.dtct: Flat if a relevant target is detected (boolean)
(3) DM.Brake: Brake/decelerator activity, relative pedal force (0..1)
(4) AccelCtrl.ACC.DesiredDist [m]: Desired distance to the target vehicle
(5) Car.v [km/h]: Absolute velocity of eGo vehicle connected body
(6) AccelCtrl.ACC.DesiredTGap [s]: Desired time distance to the target vehicle

3.6.4. T07 - CTU 02/2013 G - Consistency of system behavior

The goal of the test is to verify the behavior of the automatic emergency brake system according to the manufacturer's specification. In all three cases, AEB system avoided a collision. Figure 3.28 shows moment right before upcoming collision.

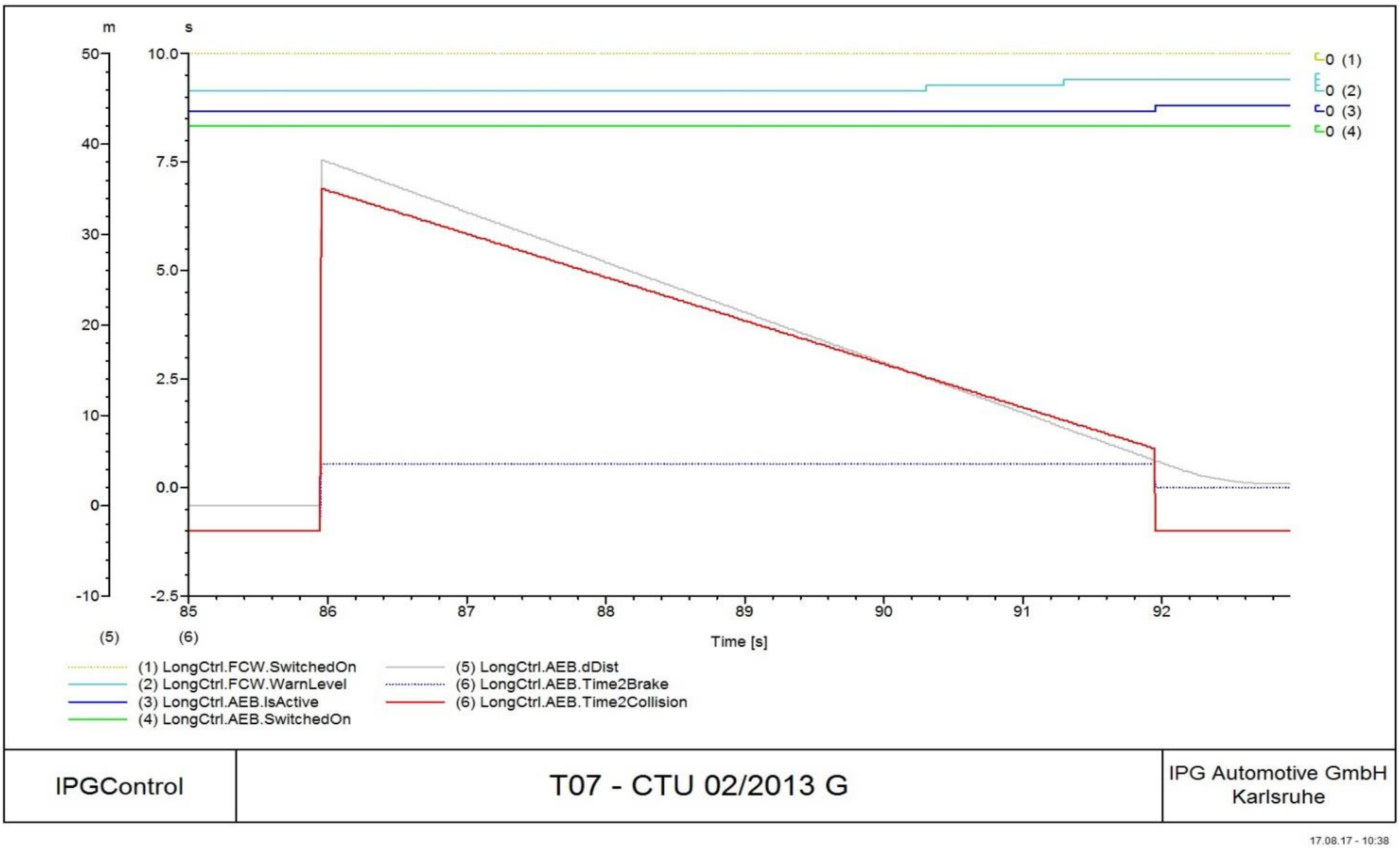

Figure 3.28 -FCW and AEB control factors - Case B

In figure 3.28 is described Case B with time sample of 6 s when collision situation occurs. At the time 86 s variable LongCtrl.AEB.Time2Collision is calculated for about 7 s and it is linearly decreasing along with LongCtrl.AEB.dDist. At the time 90.4 s LongCtrl.FCW.WarnLevel 1 is active and at the time 91.4 s LongCtrl.FCW.WarnLevel 2 is active. When LongCtrl.AEB.Time2Collision and LongCtrl.AEB.Time2Brake are equal LongCtrl.AEB.IsActive is turned on and vehicle starts braking.

(1) LongCtrl.FCW.SwitchedOn: Flat if FCW system is switched on
(2) LongCtrl.FCW.WarnLevel: Warning level of FCW system: 0=no warning, 1-2=warning level 1-2
(3) LongCtrl.AEB.IsActive: Flat if AEB system is active (=braking)
(4) LongCtrl.AEB.SwitchedOn: Flat if AEB system is switched on
(5) LongCtrl.AEB.dDist [m]: Relative distance to relevant target object
(6) LongCtrl.AEB.Time2Collision [s]: Time to collision with the target vehicle
(6) LongCtrl.AEB.Time2Brake [s]: Time threshold to brake to equal velocity of the target object

3.6.5. T08 – ES 347/2012 A - Recognizing the trajectory between standing vehicles

The goal of the test is to verify whether the detection system can recognize the space between two side-by-side vehicles whose rear parts are aligned in one plane.

Values in the table below representing the lateral distance between target driving axis and eGo driving axis. Actual gaps between vehicles are slightly different.

Limit distances between two targets are:

Name of parameter	Case A	Case B	Case C
Actual gap [m]	2.65	4.5	6.3
Distance_target_target [m]	2.2	3.1	4

Smallest gap between two side-by-side standing target vehicle, which eGo vehicle can go through is 2.65 m. Smaller gap is evaluated as an obstacle and vehicle stops. In all three cases, eGo passed.

3.6.6. T12 - ISO 15623 B - Recognition of the target vehicle from two consecutive targets

The goal of the test is to determine whether the eGo vehicle recognizes two near-running vehicles that do not overlap completely.

During Case A eGo vehicle does not manage to break when the target starts to decelerate. This is caused by small eGo and target time gap 1 s and low friction coefficient 0.5 s. Target overlap does not have any effect on this failure.

In rest of cases, everything works fine and eGo reacts correctly and starts braking.

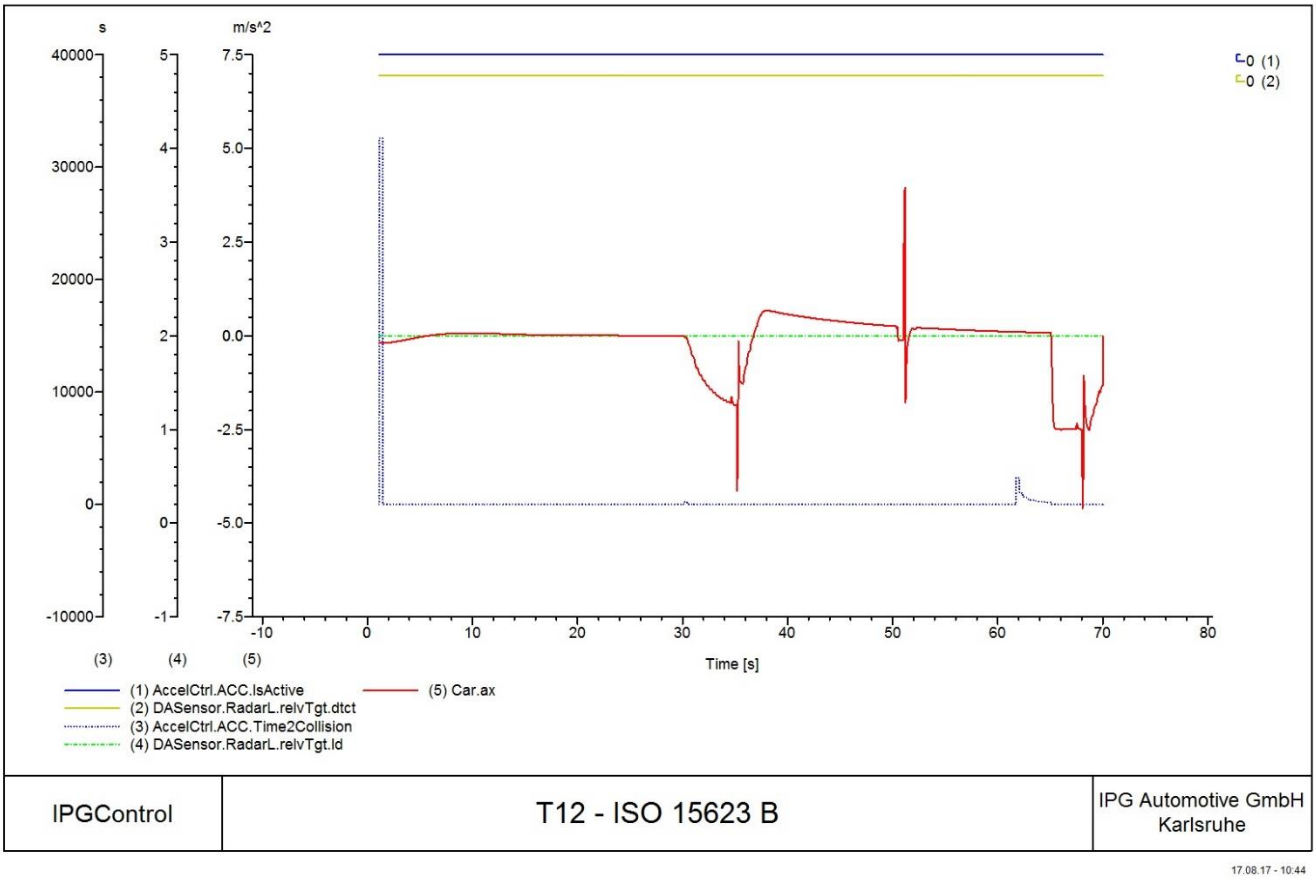

Figure 3.29 – eGo behavior during target' braking – Case B

(1) AccelCtrl.ACC.IsActive: Flat if the ACC controller is activated
(2) DASensor.RadarL.relvTgt.dtct: Flat if a relevant target is detected (boolean)
(3) AccelCtrl.ACC.Time2Collision [s]: Time to collision with the target vehicle
(4) DASensor.RadarL.relvTgt.Id: Traffic object number of the relevant target (integer)
(5) Car.ax [m/s²]: Translational acceleration of eGo vehicle connected body

Figure 3.29 shows whole Case B TestRun. AccelCtrl.ACC.IsActive represents activated ACC control. DASensor.RadarL.relvTgt.dtct show that some relevant target(s) is detected. ACC reacts to target behavior with braking. This braking is represented by Car.ax – red curve. DASensor.RadarL.relvTgt.Id detect for whole period of simulation 2 targets altogether.

3.6.7. T15 - ISO 22178 B: Column slow ride: Target vehicle recognition from overtaking car

The goal is to test the ability of the detection subsystem to distinguish between parallel driving vehicles. In all three cases, eGo vehicle acts correctly and does not react to parallel driving target.

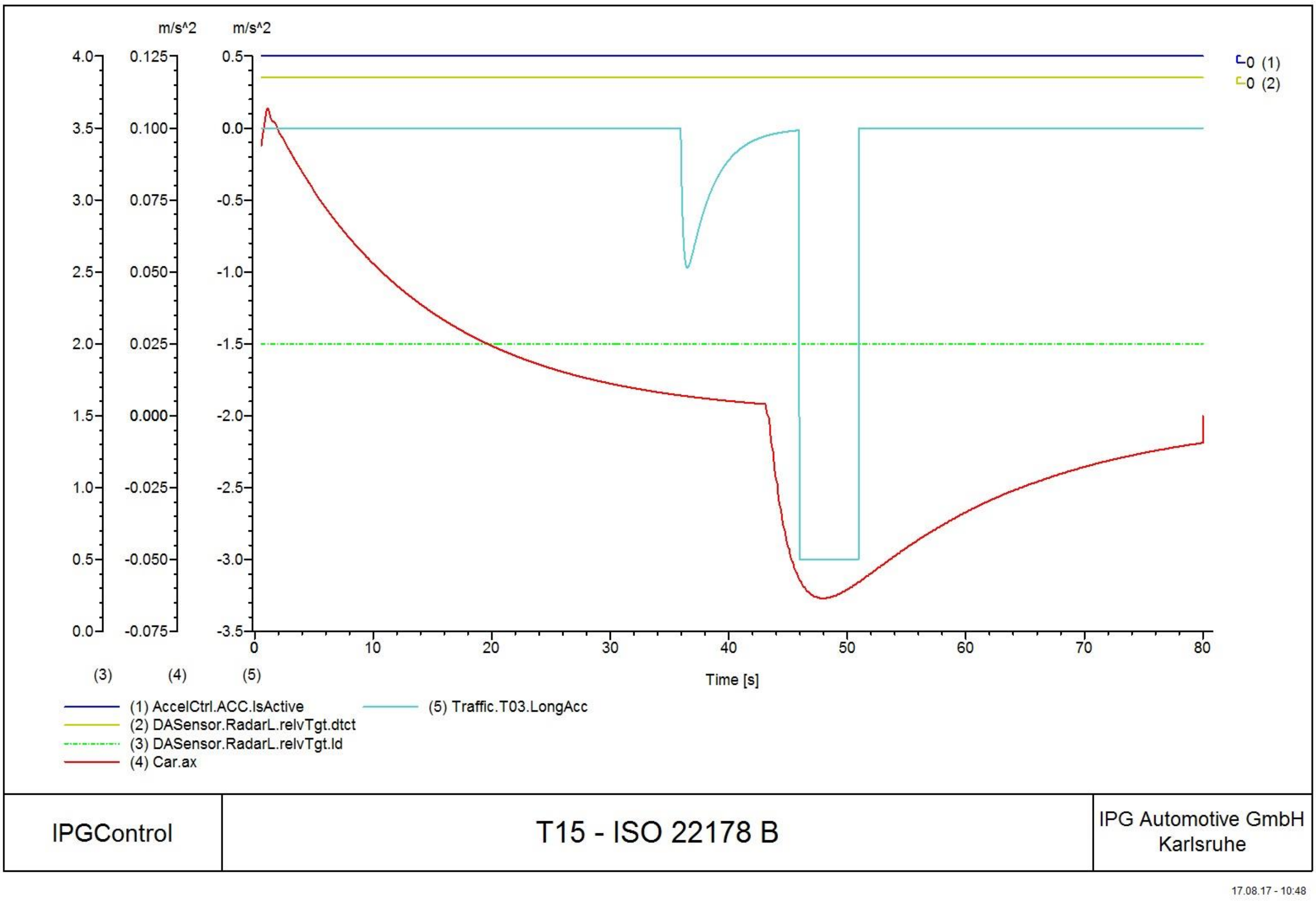

Figure 3.30 - eGo and target behavior during maneuver - Case B

(1) AccelCtrl.ACC.IsActive: Flat if the ACC controller is activated
(2) DASensor.RadarL.relvTgt.dtct: Flat if a relevant target is detected (boolean)
(3) DASensor.RadarL.relvTgt.Id: Traffic object number of the relevant target (integer)
(4) Car.ax [m/s^2]: Translational acceleration of eGo vehicle connected body
(5) Traffic.T03.LongAcc [m/s^2]: Longitudinal acceleration of the traffic object in object frame

Figure 3.30 shows whole simulation time of Case B. AccelCtrl.ACC.IsActive represents activated ACC control. DASensor.RadarL.relvTgt.dtct show that some relevant target(s) is detected. At the time 45 s overtaking vehicle starts braking and eGo vehicle continue its path. There is visible deceleration of eGo vehicle when overtaking vehicle starts braking, but this is not caused by brakes, but because desired distance of ACC is too short and eGo is braking by engine to maintain the gap.

3.6.8. T16 - ISO 22178 C: Slow drive in the column: the target vehicle leaves the column

The test is aimed at detecting the new target vehicle. eGo vehicle always continuously accepts new target.

Figure 3.31 shows whole simulation time of Case B. AccelCtrl.ACC.IsActive represents activated ACC control. DASensor.RadarL.relvTgt.dtct show that some relevant target(s) is detected. DASensor.RadarL.relvTgt.Id detect for 24 s only one target and after that 2 targets altogether. Curve Car.ax representing acceleration of eGo to maintain AccelCtrl.ACC.DesiredTGap 1.5 s.

(1) AccelCtrl.ACC.IsActive: Flat if the ACC controller is activated
(2) DASensor.RadarL.relvTgt.dtct: Flat if a relevant target is detected (boolean)
(3) DASensor.RadarL.relvTgt.Id: Traffic object number of the relevant target (integer)
(4) Car.ax [m/s^2]: Translational acceleration of eGo vehicle connected body
(5) AccelCtrl.ACC.DesiredTGap [s]: Desired time distance to the target vehicle

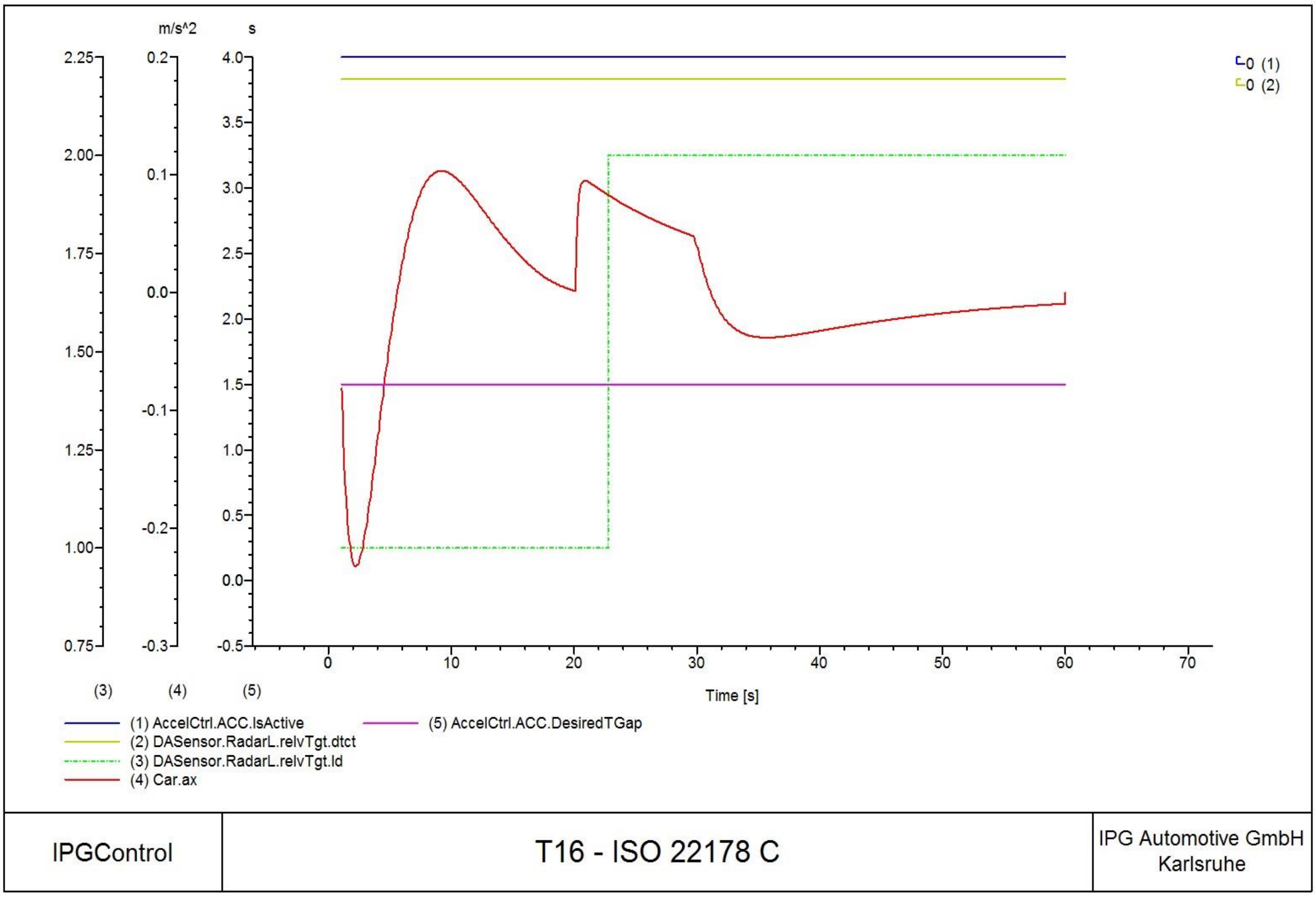

Figure 3.31 – eGo detecting new target and set desired distance – Case B

3.6.9. T18 - ISO 22179 A: Tracking the target vehicle to stop

The goal of the test is focused on tracking the target vehicle via adaptive cruise control until it stops.

Except for Case A eGo vehicle always managed to stop successfully without colliding with the target vehicle. Case A had a crash and the reason is small time gap 2 s and low friction coefficient 0.5.

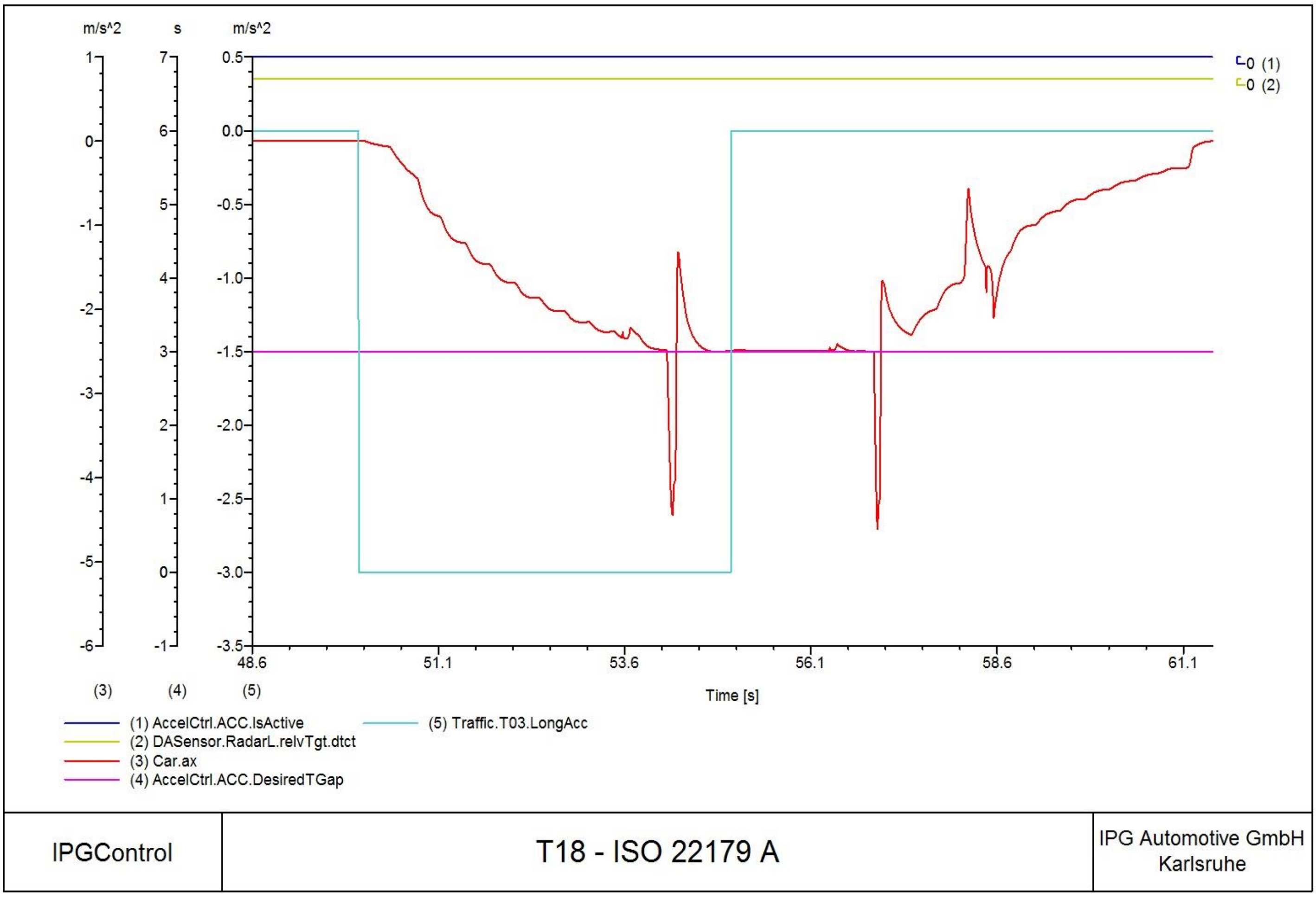

Figure 3.32 – eGo reaction to decelerating target – Case B

(1) AccelCtrl.ACC.IsActive: Flat if the ACC controller is activated
(2) DASensor.RadarL.relvTgt.dtct: Flat if a relevant target is detected (boolean)
(3) Car.ax [m/s^2]: Translational acceleration of eGo vehicle connected body
(4) AccelCtrl.ACC.DesiredTGap [s]: Desired time distance to the target vehicle
(5) Traffic.T03.LongAcc [m/s^2]: Longitudinal acceleration of the traffic object in object frame

Figure 3.32 shows whole simulation time of Case B. AccelCtrl.ACC.IsActive represents activated ACC control. DASensor.RadarL.relvTgt.dtct show that some relevant target(s) is detected. At the time 50 s target vehicle starts braking and eGo reacts with braking as well. Target deceleration reaches value -3 m/s^2 and eGo deceleration peak value is -2.6 m/s^2.

3.6.10. T19 - ISO 22179 B: Resolution of the target vehicle from the overtaking car

The goal of the test is to analyze the ability to discretize two parallel-running vehicles without stabilizing the relative position of the target and the parallel vehicle. eGo vehicle never responds to the overtaken vehicle.

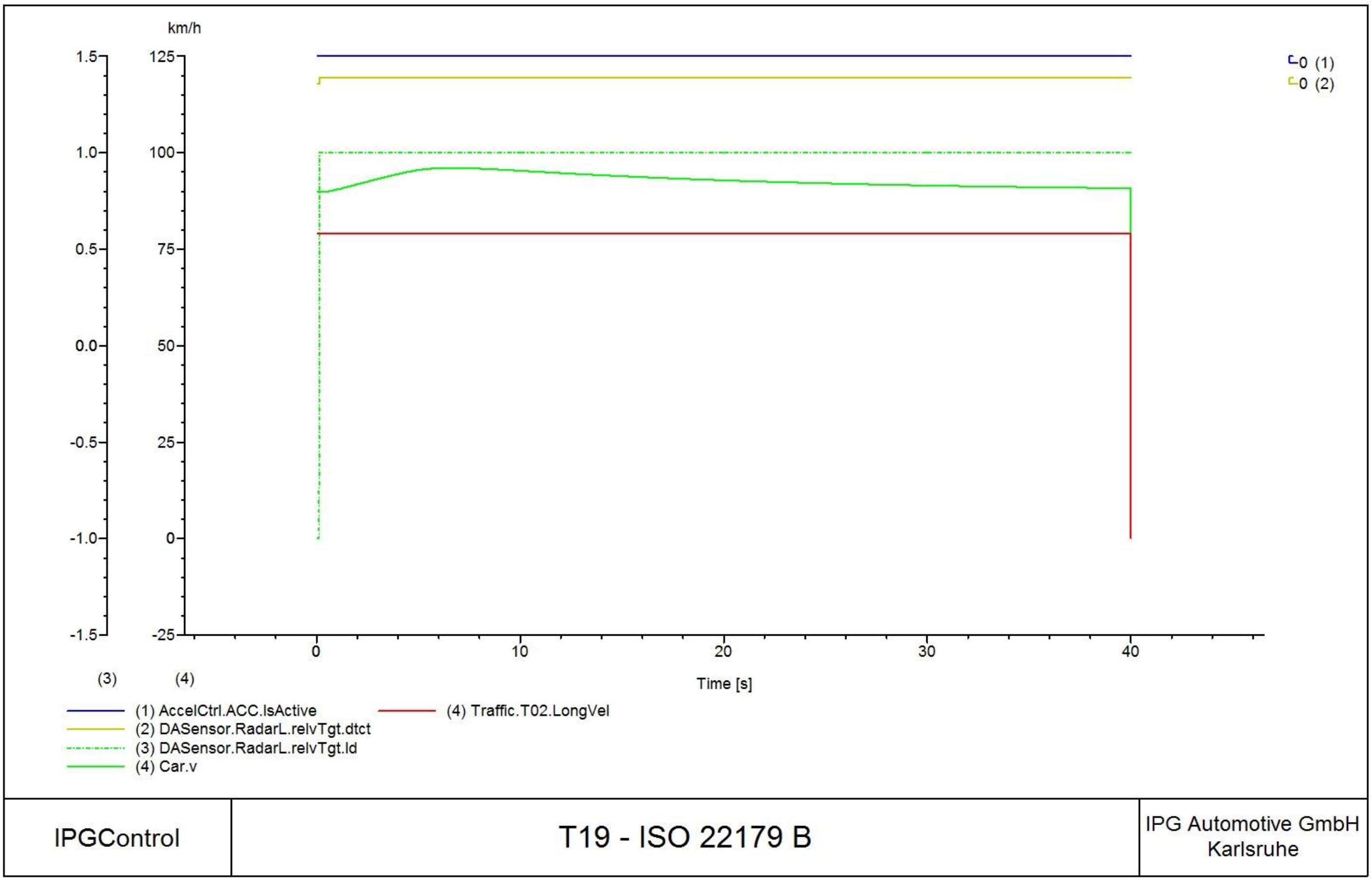

Figure 3.33 -eGo and parallel vehicle speed profile – Case B

(1) AccelCtrl.ACC.IsActive: Flat if the ACC controller is activated
(2) DASensor.RadarL.relvTgt.dtct: Flat if a relevant target is detected (boolean)
(3) DASensor.RadarL.relvTgt.Id: Traffic object number of the relevant target (integer)
(4) Car.v [km/h]: Absolute velocity of eGo vehicle connected body
(5) Traffic.T02.LongVel [km/h]: Longitudinal velocity of the traffic object in object frame

Figure 3.33 shows whole simulation. eGo vehicle does not respond to slower overtaken vehicle by any kind of action and follow target vehicle continuously.

3.7. GPS coordinates as results of simulations

Every single scenario provides us results in form of speed and World Geodetic System - WGS 84 coordinates, which can, for example, be used with Google Earth. These values are exported from CarMaker into Excel sheet.

Due to the small driving ranges (max. 1000 m) these coordinates do not change so much, there are only minor differences.

Example of 0.1 s sample:

Time	Car.Road.GCS.Elev	Car.Road.GCS.Lat	Car.Road.GCS.Long	Car.v
s	m	deg	deg	km/h
62.871	278	50.61844668	14.74577237	19.99999922
62.881	278	50.61844674	14.74577159	19.99999922
62.891	278	50.6184468	14.74577081	19.99999922
62.901	278	50.61844685	14.74577003	19.99999922
62.911	278	50.61844691	14.74576925	19.99999922
62.921	278	50.61844697	14.74576847	19.99999922
62.931	278	50.61844702	14.74576769	19.99999922
62.941	278	50.61844708	14.74576691	19.99999922
62.951	278	50.61844714	14.74576613	19.99999922
62.961	278	50.61844719	14.74576535	19.99999922
62.971	278	50.61844725	14.74576457	19.99999922

Output variables are specified below:

GCS Lat [deg]: Specifies the latitude of the geographic coordinates of the reference point.
GCS Long [deg]: Specifies the longitude of the geographic coordinates of the reference point.
GCS Height [m]: Specifies the elevation of the geographic coordinates of the reference point.
Car Velocity [km/h]: velocity of vehicle

These results can be used for procedure validation in proving ground test. Another option is to use Differential GPS with different output quantities.

Chapter 4

4. Conclusion

4.1. Contributions

This master thesis introduces new simulation possibilities for ADAS system testing with help of IPG CarMaker software tool. We can simulate almost any kind of driving scenario with minimal costs and relevant results. The most crucial things are vehicle models, these should be ideally the same as a real vehicle for getting correct results. We used predefined models.

Road modeling is another very important part of the simulation because we can create any kind road with specific parameters (friction coefficient, elevation, curbs etc.). GPS coordinates can be used in both ways for import and export.

All predefined driving scenarios were successfully simulated and parametrized.

4.2. Assignment

The first part of the assignment was to do research of state-of-the-art in the field of ADAS system software testing with regards to sensor physics modeling. This part was fully accomplished with sensor research in general. This means types of sensor and its usage in vehicles or typical parameters. Sensor physics modeling is pretty much the know-how of companies developing these systems, but few remarks about modeling in general are introduced along with modeling complexity.

The second part of the thesis was to model predefined scenarios in IPG CarMaker and coupling with other software tools. As another software tool was chosen Microsoft Excel. Along with modeling, parameterization with respect to vehicle dynamics was necessary. All scenarios were simulated with success.

The last part was export of geodetic coordinates and speeds for final test procedure validation in proving ground test. These results were exported for every single scenario.

4.3. Future work

The upcoming goal can be set in vehicle model development in CarMaker and validation of ADAS systems. Vehicle models are not properly validated so we cannot judge if these results are good enough or not. Dynamic vehicle model is difficult to develop and depends on requirements or our expectation of reality.

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CD content

- Simulated TestRuns
- Car models
- Parametrization
- GPS output results
- Electronic version of Diploma Thesis