České vysoké učení technické v Praze
Fakulta dopravní
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Problematika inovativních uživatelských rozhraní pro vozidla s alternativními pohony

DISERTAČNÍ PRÁCE

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Rok: **2019**

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Jméno a Příjmení

Poděkování

First of all, I want to thank my family for supporting me during my work on this thesis. I will always be grateful to my relatives: my mother and father who managed to help me even when we were separated by more than 1000 km. I want to thank my supervisor Petr Bouchner and co-supervisor Stanislav Novotny for the help and guidance they have given me during this work and time they devoted to me. This thesis would not be possible without the opportunities they gave me during the study. They have become not only my guides but also colleagues and good friends. I also want to express my gratitude to Ing. Jiří First, for his intellectual investment in this work.

Special thanks go to all my students working side by side on a common goal. And Ricardo s.r.o. company for providing software and guidelines needed for accomplishing my goals. Finally, I would like to thank my colleagues Ing Josef Mik PhD., Ing Alina Mashko, Ing Adam Orlicky and Honza Valek for providing support and keeping me company during these amazing years..

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Jméno a Příjmení

Název práce: Problematika inovativních uživatelských rozhraní pro vozidla s alternativními pohony

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Druh práce: Disertační práce

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Abstrakt: Tato disertační práce se zabývá návrhem a ověřováním rozhraní vozidel s alternativními pohony, protože tato vozidla budou v příštích desetiletích tvořit většinu v provozu. Přitom se budou od současných lišit nejen pohonným ústrojím, ale také jinou rolí individuálního vozidla v komplexních systémech typu smart cities. Práce navrhuje výzkumnou a vývojovou platformu pro ověření HMI vozidla pomocí detailní fyzikální simulace pohonného systému integrovaného do interaktivního vozidlového simulátoru. K tomu je využit Function Mockup Interface (v překladu nejblíže "fuknční model rozhraní"), včetně speciálních softwarových modulů pro sbírání dat z eye trackeru a synchronizaci dalších měřících přístrojů. Tato platforma je validována na dvou experimentech, které detailně představují celý proces vývoje.

Klíčová slova: Elektrická vozidla, hybridni vozidla, HMI, interaktivní simulace

Title: *Problematics of human-machine interface for vehicles with alternative propulsion systems*

Author: Rozhdestvenskiy Dmitry

Abstract: .This thesis deals with the new emerging vehicles with the alternative propulsion system and new challenges related to their HMI It provides the evidence that these vehicles will substitute the majority of conventional vehicles in upcoming decade and emphasize the need for proper HMI design specially oriented on these vehicles and special tools for their evaluation. Not only due to the technological differences but also because of fast development of smart cities concepts and shift in user mental models. It proposes a platform for evaluation of HMI through detailed physical simulation of powertrain architecture with integration to the interactive vehicle simulator through Function Mockup Interface, including special software modules for complex HMI simulation eye-tracker data acquisition and synchronization, and measures of evaluation. This platform is further validated on two experiments where the whole development lifecycle was described in details

Key words: Electric vehicles; Hybrid vehicles; HMI; Interactive vehicle simulators

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1. Introduction

This thesis is dedicated to the topic of Electric Vehicles (EV) and Hybrid Electric Vehicles (HEV) and problems associated with these technologies in terms of user acceptance, driving performance, and energy efficiency. These aspects, as will be shown, are closely related to the problematics of the design of Human-Machine interface, which affects the interaction of a driver and a vehicle. Additionally, it proves the importance of the simulation for the development and validation of such interface. This leads to the necessity for the design and implementation of a set of tools or a platform for the purpose of EV and HEV evaluation, especially in the time when Smart cities and Industry 4.0 becoming a reality and can influence the interaction model of a user and a vehicle, these changes can have dramatic effect on this interaction. A symbiosis of all modern technologies and concepts rice set of questions and risks, which must be addressed from different perspectives such as:

- From the perspective of the user and the user interface:
    - What information is important (or interesting) for users.
        - How this information is displayed/transferred to the user.
        - When, under what circumstances, in what order this information should be presented to the user.
        - How to deal with input from the driver to the vehicle system.
- From the perspective of the vehicle:
    - What data can / should be obtained from vehicles.
    - What data can / should be obtained from ITS.
    - How to process the data from the vehicle and ITS so that:
        - User needs were fulfilled.
        - Vehicle efficiency is maximized.
        - Driver safety is increased.
        - The vehicle system is not vulnerable to external penetration.
- From the perspective of Information Transparency.
    - What interfaces are needed for P2P and I2P communication.
    - How to present this information to the user so that:
        - Increase the efficiency of infrastructure usage.
        - Not to irritate the user.
        - Make the user not to ignore this information.
        - Ensure data safety.

Combination of these questions creates a complex multidisciplinary task which requires a unique approach and set of tools, which can cover a relatively wide range of research activities. The goal of the thesis is to develop and validate these measures and tools. The main task is to treat and address the whole system, including users, mobile devices, infrastructure interfaces, problems associated with data sharing and transferring, and different means of data acquisition and control. Which means that the developed methods and tools should be designed as a modular system, giving a possibility to swap different interfaces, equipment and controls and measuring devices in a short period. We can sum up a set of tasks to be achieved at the end; these include:

- Electric vehicle technology explanation
    - Historical contests.
    - Physical principal.
    - Problems and advantages.
- Upgrade an existed interactive vehicle simulator, especially in the area of SW
    - System modulization.
    - Creation of a universal test platform for HMI.
    - Creation of a simulation module of the EV and HEV powertrain.
    - Validation of the simulation module.
    - Create a modular HMI architecture.
- Develop a methodology for evaluation of HMI.
    - Experiment design guidelines.
    - Objective assessment guidelines.
    - Result evaluation methodology guidelines.
    - Create a modular measuring architecture.
- Perform a set of experiments for the verification of the methodology.
    - Design experiments.
    - Develop scenarios.
    - Run experiments.
    - Analyze results.

This thesis contains four main chapters. The first chapter provides an introduction to the topic of EV and HEV technology, vehicle simulators, and Human-machine interface. It explains the essence why the new approach to the design and validation is needed, starting from an explanation of how EV and HEV differ from ICE vehicles, going further into the details of how and why new HMI interfaces are emerging and need to be tested. And explains the possibility to use vehicle simulators for such a purpose.

The second chapter describes the development and evaluation of the simulation platform for HEV and EV vehicles. It contains the detailed description of the physical model for the modern battery, electric machine, and controllers and set of equations for their simulation. These equations are then further used to develop a simulation element in Modelica programming language and integrated into existed vehicle simulator. Additionally, it contains description and implementation of a modular HMI interface which is further integrated with the powertrain module. It also describes the modulization of existed simulation software, and integration of the eye tracker measuring devices for gaze analysis into existed simulation platform.

The third chapter deals with the description of methods and measures for testing and validation of the EV and HEV HMI and components in the vehicle simulation. It describes developed guidelines for experiment design and evaluation and provides a set of metrics to measure and calculate during the simulation for objective analysis, and a possible approach to the subjective analysis through the questionnaires.

Forth chapter is dedicated to platform evaluation. It contains a description and evaluation of two experiments on the developed platform. The first experiment is focused on the user acceptance of the EV and its interface. The second experiment is focused on the evaluation of an ADASIS system specially developed for EV.

1.1 Electric and Hybrid Vehicle Technology Today

This chapter provides the description of the EV and HEV technology starting from the history of the development, describing principals and differences between different types of EV and HEV, moving further, explaining the environmental and social impact of the technology on the modern society and environment, and why introduction of these technologies is crucial for today. Additionally, the description of the benefits and drawbacks of chosen technologies are described.

1.1.1 History

History of Electric vehicle (EV) started in the middle of 19 century when the first demonstrative vehicle was made in 1830. This electric vehicle used a non-rechargeable battery. The question of who the first inventor was, is not clear, but several candidates are considered. Hungarian Ányos Jedlik or Scotland Robert Anderson can be accounted as first inventors of small-scale electric vehicles. The first rechargeable battery, however, was invented by William Grove only in 1840 and It took another 50 years to developed battery technology to the level, when EV started to be used as commercial vehicles, when in 1891 A. L. Ryker and William Morrison built a six-passenger wagon. Many innovations followed, and interest in motor vehicles increased greatly in the late 1890s and early 1900, but the first real and practical EV was designed by William Morrison's with a capacity for a passenger in 1981. (Figure 1). However, despite the promising start of EV technology, internal combustion (IC) vehicles (invented in 1911) concur the leadership once cheap oil was widely available

Figure 1 William Morrison EV

Several factors played a major role in IC success, first of all, as it was mention, the oil became cheaper and widely available, secondly, the “specific energy” (Energy stored per kilogram of fuel) for IC is around 9000Wh/kg and for a lead-acid battery it’s just 30Wh/kg which is 300 times less. In more practical terms, it means that same amount of fuel in the IC vehicle can give you the range 50 times longer than EV with the same weight of the battery. The third reason is the time to recharge EV batteries. It is incomparable with the time it takes fully refuel IC vehicle. Moreover, the final reason was the price of batters for EV. All these factors contributed to the fact that there are around 1.1 billion[1] IC vehicles around the world today and amount of EV are not even a six-digit number (rough estimation is 750 000 -capable plug-in electric passenger cars and utility vans have been sold worldwide in year 2014). [1]

But increased concern about the environment in the late 20th century and technical development and improved design of battery technology an overall vehicle design gave EV another chance to become widely used transportation technology.

1.1.2 EV and HEV technology

This subchapter explains the basic difference between an internal combustion engine (ICE) vehicles and EV, including different types of HEV, their basic components, and physical principals. This explanation is needed to understand how dramatically can differ the behavior of the vehicle when, the well-known, gasoline engine is substituted or assisted with an electric machine (EM).

Battery electric vehicles also called fully electric vehicle, where the internal combustion engine is substituted with one or more electric motors which are using energy stored in batteries. They have no internal combustion engine and must be plugged into the electric power grid for recharging. Among EVs, the most common types of electric motors are permanent magnet motors and Alternate Current (AC) induction motors. Battery electric vehicles are also called Zero Emissions vehicles because they do not burn fossil oils during the operation. However, one should not forget about pollutions associated with electricity production, which will be described in chapter 1.1.4 or particle pollutions produced by mechanical braking and tire-road contact, these, however, are also lower than from ICE vehicles, due to the regenerative braking (RB), the concept of RB is described further in chapter.1.1.3.1

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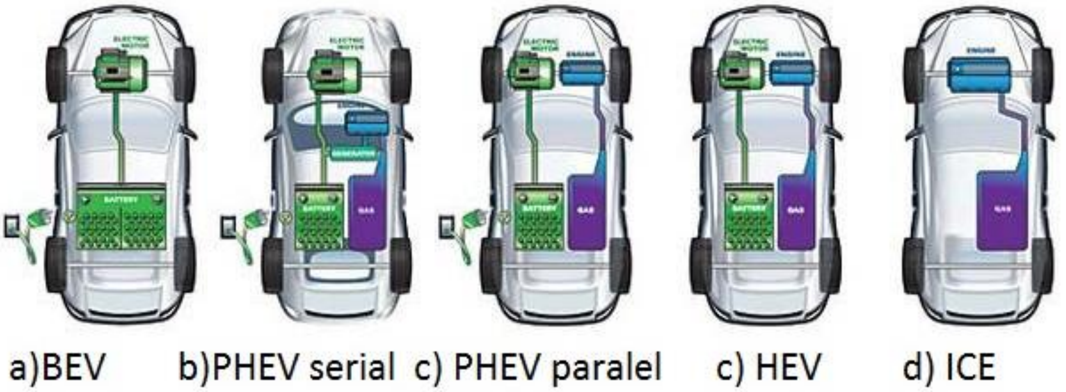
[1] Estimated in year 2012 by http://rfidtires.com/



a)BEV b)PHEV serial c) PHEV paralel c) HEV d) ICE

Figure 2 Types of Electric Vehicles [3]

Hybrid Electric Vehicles, relate to dual-fuel cars and have one or more EM to assists an ICE as an additional driving power to increase its efficiency and decrease environmental impact There are three main categories of HEV, structural schemas of which are represented in Figure 2 (b to c). Several factors can categorize HEV

First, the power train interaction:

- Parallel HEV where ICE an EV can work simultaneously. Both EM and ICE can drive a vehicle. This type of HEV is popular among vehicle manufacturers.
- Serial HEV, where ICE is used only as a power source to generate electrical power through generator and voltage convertor, for EM, and cannot provide power to wheels directly. Serial hybrids are tending to be used in a special application, such as powered rail engines and ships.

And secondly by battery charging opportunities:

- HEV has a battery with a relatively small capacity and recharged by a gasoline engine and regenerative braking.
- PHEV has a bigger battery than HEV and can be charged directly, either from the power grid or from generators driven by ICE and regenerative braking.

One probable scenario of PHEV is when electric motors are responsible for acceleration and movement of the vehicle at low speed (less than 30 -40 km/h) and only in case of enough battery charge. In case of higher speed or insufficient battery charge, a combustion engine is used. Such a strategy gives an advantage when the vehicle moves inside a city center or during rush hours. Additionally, modern control technics applied to IC can be used to minimize exhaust emissions of ICE and maximize fuel economy. This is explained in the next chapter where characteristics of ICE and EM are compared

1.1.2.1 Other hybrid propulsion technologies

In this section, major alternative propulsion systems will be shortly described. The basic gasp of principals behind the technology is needed to understand how one or another implementation can influence driver experience and consequently, interaction with a vehicle.

Fuel Cells Vehicles

Fuel-cells vehicle is an electric vehicle where the battery is substituted with a fuel cell (FC). FC technology itself is dated back to 1801 when Humphry Davy demonstrated the principles behind the technology, and it was firstly used in 1950 as a propulsion system for the Electrovan by General Motors.

The basic principle behind is that it uses hydrogen fuel to produce electricity in battery-like devices. The product of the reaction $2H_2+O_2 \rightarrow 2H_2O$ is thus water and energy. As it uses the same powertrain as battery vehicles, all the advantages are inherited. Additionally, it overcomes some disadvantages of BEV in terms of range which is now limited to the volume of the hydrogen tank, which for a modern vehicle is around 500-700 km. [20] And recharging time and process is similar to ICE.

Disadvantages of the technology include:

- Cost - even higher than for batteries.
- Hydrogen supply and refilling infrastructure.
- Hydrogen storage.

However, these are engineering challenges which can be overcome in future for instance to avoid the difficulties of hydrogen storage and infrastructure, a fuel processor using methanol or gasoline as a fuel can be incorporated to produce a hydrogen-rich gas stream on board.

Flywheel

A flywheel is mechanical storage of kinetic energy; they are usually used in combination of other propulsion systems to absorb energy during the braking and release when needed (rapid acceleration or high-power demands). During the braking or re-energizing a disk is accelerated either by hydrostatic transmission or by a motor-generator. The high inertia of the wheel allows storing this energy and release it later through a special transmission. In recent years a lot of companies have studied a possibility to use flywheels in modern hybrids systems, which is less expensive then HEV and potentially can provide up to 40% fuel economy [21]

There were some attempts to use a flywheel as an only propulsion system for public transport [22] when the flywheels re-energized at each stop with an amount of energy sufficient to cover the distance to the next stop. However, these projects remained in the research stage.

One disadvantage is the potential safety risks that arise if a flywheel is loaded up with more energy than its components can handle, and behavior of the system in case of an accident. This scenario could result in an almost explosion-like event, which requires security walls, thus increasing the weight of the unit.

There are also continuing challenges to minimize energy losses due to friction. Classic ball bearings have proved relatively ineffective, while magnetic bearings in a vacuum have been shown to meet the challenge better.

Hydraulic hybrids

Hydraulic hybrids use an ICE as the main propulsion system and either electrical pumps or mechanical pumps to pressurize a special fluid into the accumulators, by the energy recovered during the braking and release this energy when needed via Hydraulic Motor. Usually, the pump and the motor are combined in one device Hydraulic Pump Motor (HPM) It is mostly used in SUV, trucks, and buses, but can also be used for personal vehicles. HHV can improve fuel efficiency by up to 50%[21]. There exist two possible architecture for HHV Parallel and Serial Figure 3

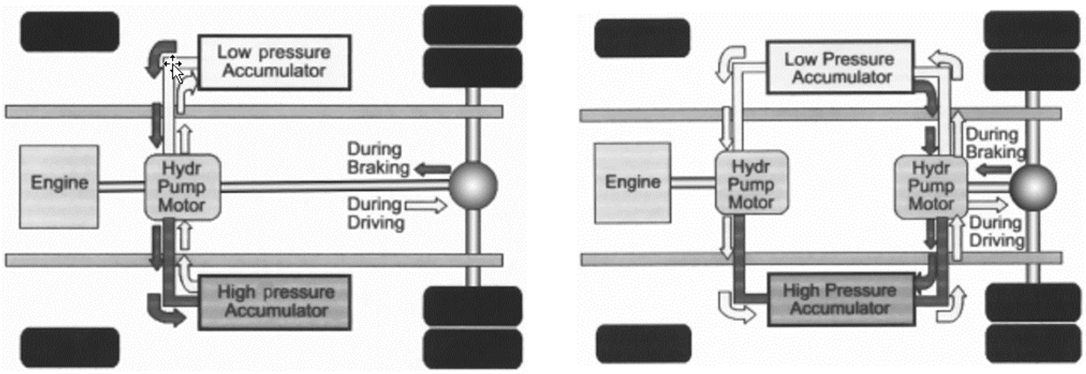


Figure 3 HHV parallel (right) and serial (Left) architecture[21].

These systems have a lot of potential in the future, but there are some challenges to overcome these includes:

- Increasing the storage capacity.
- Increasing the reliability of the components of the vehicle.
- Optimizing the control systems for the vehicle to improve fuel economy.
- Reducing noise.

1.1.3 Difference between ICE and Electric machine

The question of energy efficiency of EM over ICE was slightly touched in the introduction chapter, and in the next chapter, it will be expanded by the introduction of a notion of "well to wheel." Well to wheel is a method to compare the environmental performance of energy production, transportation, and delivering, or in case of the transportation, conversion to the kinematic energy, which moves the vehicle. But, when the fuel production and transaction efficiency are neglected, and the overall efficiency of the machine is considered, then there is a clear and comprehensive advantage of the EM over the ICE, a gasoline engine typically has less than 30% overall efficiency[5] When even a standard EM is expected to have an efficiency over 90% [5]

Motor characteristic (torque versus revolution speed) shown in Figure 4 can be used to understand the difference between the behavior of IC and EM in terms of efficiency and power,

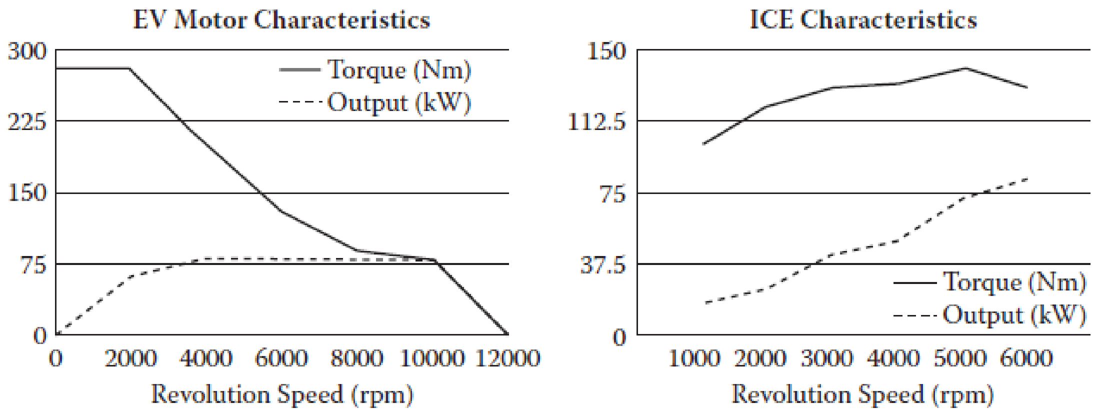


Figure 4 EM and ICE power characteristic [4]

As it can be seen from the (Figure 4) electric motor starts with 0 revolutions with maximum torque, and its power increase linearly till the peak point and remains more or less constant till the end of revolution rang. The torque, in reality, is limited during first ~2000 revs to limit the current, to prevent destruction of the EM and batteries by the heating produced by such big current. The ICE, however, has its lowest torque and power during idling (usually 700–1,000 RPM), power keeps increasing even after torque reaches its maximum and starts declining. Usually, the maximum power of ICE is delivered close to the maximal engine speed. EV torque appears to drop dramatically starting from 2000 RPM, but still, it is higher than the torque produced by ICE until around 6000 RPM. After this speed, the torque of EV falls below the typical torque of ICE.

This difference has an obvious human factors implication both to the engineering of the vehicle as well as to how a driver experiences the vehicle. First of all, acceleration characteristic of the EV and ICE are dramatically different, the EV has a higher acceleration rate at a lower speed, secondly during a higher vehicle speed, the acceleration characteristic of the EV can be lower than ICE and thus can lead to different behavior on the highways or during the overtaking maneuvers. Of course, modern controllers and control strategies can eliminate these differences to some extent.

Comparing the efficiency maps of EV and IC represented in Figure 5. It is visible that IC engine efficiency dramatically drops on higher speed. The basic reason for that is the pumping losses, and thermal losses which become greater as the speed of the engine goes up. The second reason is that at higher speed, the brake specific fuel consumption is higher due to the increased injection rates at high speed. There are also less torque production effects occurring at high speed for gasoline engines as well as less horsepower produced at high speeds. EM loses efficiency with increased speed as well due to the winding losses and backpropagation EMC. However, the overall efficiency of EM is still much higher, around 80%. These values, of course, can differ for both engines for different modifications.

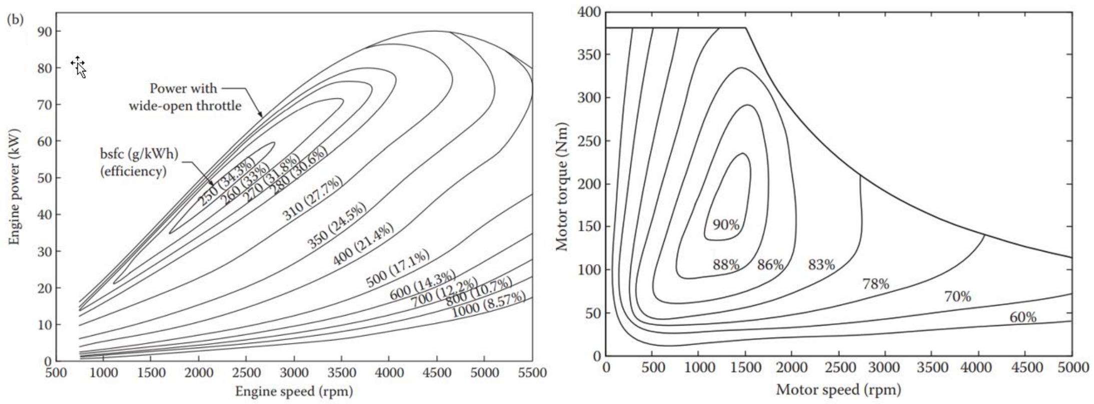


Figure 5 Example of EM and ICE Efficiency map [28]

Additionally, when EM is used as a generator, (in this case the characteristic of the motor is mirrored over horizontal axis), it is providing a negative torque which can slow down the vehicle and producing the current to recuperate some kinetic energy back to the battery, this effect is called regenerative braking.

1.1.3.1 Regenerative braking.

In an EV, and HEV regenerative braking is the conversion of the vehicle's kinetic energy into chemical energy stored in the battery, during the deceleration. Obtained power can be used later to drive the vehicle. The conversion process goes through generation of the charging current by the EM, and charging the batteries, EM working as a generator produces a slowing down torque, which slows down the vehicle and eliminates, at some extent, the use of mechanical brakes, experienced driver can stop the vehicle using only regenerative braking, thus increase power efficiency of the EV.

The kinetic energy stored in a moving vehicle is related to the mass and speed of the vehicle by the well-known *Equation 1*

$$E = \frac{1}{2} m \cdot v^2. \qquad \textit{Equation 1}$$

Where:

m - Vehicle mass.

v - Vehicle velocity.

E – Energy.

According to the Law of Conservation of Energy which states*:*

„Energy cannot be created or destroyed, but it can be transferred or transformed from one form to another (including transformation into or from mass, as matter).“

The total amount of energy in a closed system never changes. Thus, whenever an HEV or EV slows down, the kinetic energy stored in the vehicle must go somewhere. Of course, there is always some kinetic energy consumed by the rolling resistance, mechanical friction, and aerodynamics of a HEV (they act to slow down the car, but the energy dissipated, cannot be recovered, and goes into heating the road, the surrounding air, and various spinning parts of the vehicle). However, in conventional vehicles without regenerative braking, most of the kinetic energy is converted into heat brake. Consequently, the main idea of RB of HEV is to recover some energy that would otherwise have been wasted in the brakes. Around 60% of remained energy can be recovered. Energy makes a full circle back into the battery, and it is converted twice for a net efficiency of at most 80% * 80% = 64%. (Battery-to-wheel conversion efficiency can be up to 80%) Figure 6 shows an outline of a car and steps that indicate the regenerative braking process:

- As the car brakes, the energy of motion from the wheels is transferred to the electric motor.
- The electric motor acts as a generator, producing energy.
- This electricity is sent to the battery where it is stored.
- In case if more braking force is needed hydraulic, mechanical brakes are activated.

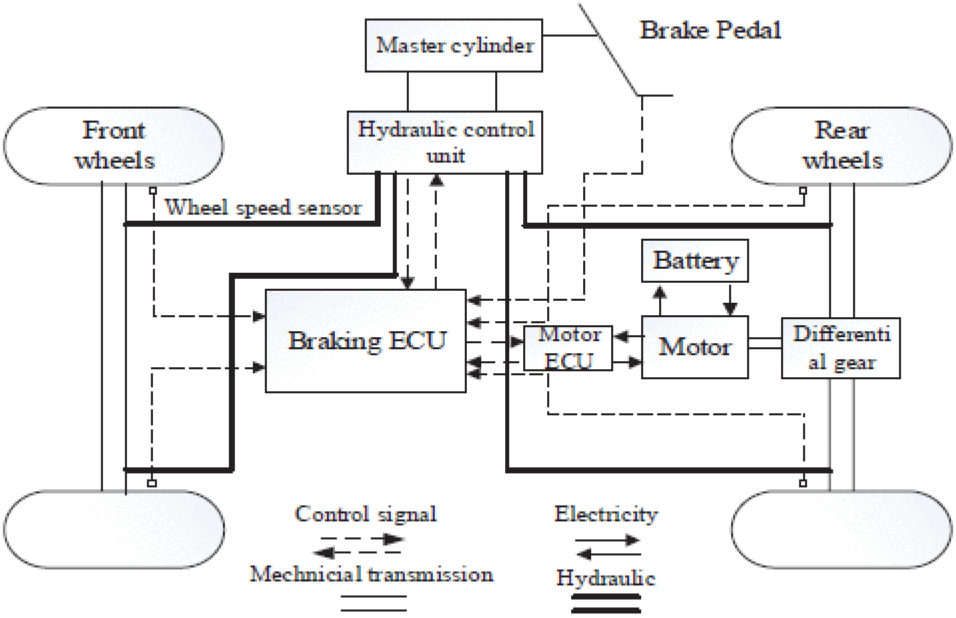


Figure 6 Regenerative braking [2]

To be able to use EM as a brake and to charge the battery during the slowdown, it has to be connected as it is shown in Figure 7.

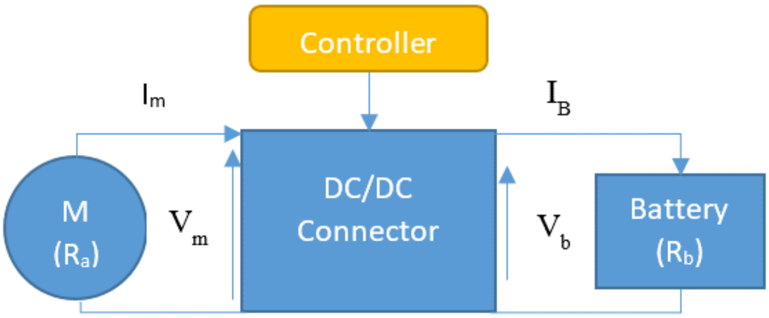


Figure 7 EM connection diagram

Where:

V_m and I_m - Voltage and current generated by the motor.

V_b and I_b - Voltage and Current generated by the battery.

K_m – Motor Constant depended on a number of turns in each coil.

Φ – Total flux passing through the EM coils.

R_a and R_b– Internal Resistance of the EM and Battery.

ω – EM rotational speed.

T – Slowing down torque.

I – Generated current.

$$I = \frac{V}{R} = \frac{K_m \Phi \omega - V_b}{R_a + R_b}$$ *Equation 2*

$$T = -\frac{(K_m \Phi)^2 \omega}{R_a + R_b}$$ *Equation 3*

From *Equation 2* and *Equation 3* we can see that I (generated current) is proportional to slowing down torque T

When ω reaches the value where the voltage generated by the motor reaches the voltage of the battery $Vb = K_m \Phi$ the braking effect vanishes, and from the other hand, when the ω is too high, the braking torque T will increase dramatically.

A controller which controls produced voltage (DC/DC convertor) helps to overcome these issues by controlling I_m and consequently controlling braking torque. At the same time, DC/DC is charging the battery by the use of transformed power obtained from motor $P=V_m * I_m$ (reducing the current and increasing the voltage) The topic of DC/DC controller and its simulation discussed further in Chapter 2.

1.1.4 Environmental impact

This chapter considers the ecological benefits of EV and HEV over the ICE. In general, the transportation sector has known negative effect. Noise and air pollutions in the form of nitrous oxides (NOx), carbon monoxides (CO) and dioxides (CO2), particle matters (PM) and volatile organic compounds (VOCs) of vehicles are the main impact transportation has on the environment. A while ago, the problem of running out of irreplaceable fuels was pointed out as one of the main issues as well, but based on recent discoveries regarding deep oil production this issue is not so crucial anymore, as it turns out there is more cruel oil than we expected [6].[7]

There is a whole list of accepted health problems directly associated with air pollutions caused by transportation [8] List of negative effects of pollutions related to pollutants produced by IC engines includes but not limited to:

- NOx exacerbate asthma, affect the lungs, and increase the risk of respiratory infections among young children and elderly people.
- CO can cause a permanent damage t nervous system and inhibits the ability of the blood to carry oxygen.
- PM cause lung problems such as breath shortage, worsen the cardiovascular disease, damage of lung tissues, and considered to be one of the causes of lung cancer.

Additionally, the greenhouse effect of CO2 is one of the major reasons contributing to global warming. According to Europe Environment Agency, transportation is responsible for 19.7% of greenhouse emissions (GHG) in Europe see Figure 8 and only passenger cars are responsible for 12% of this share. Moreover, CO2 emissions from transport have risen rapidly in recent years, from 21% of the total emissions in 1990 to 28% in 2004 [9]

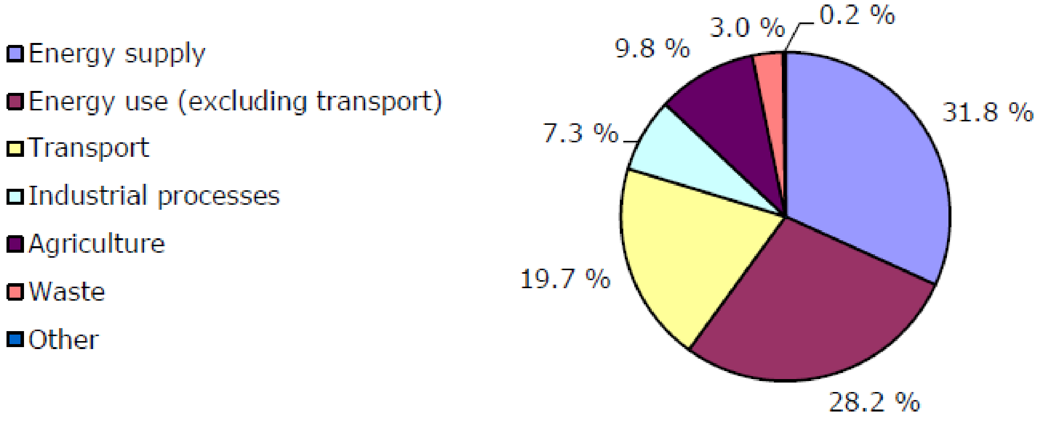


Figure 8 Share of GHG emissions 2010 [9]

As it was pointed in the previous chapter ICE engines are very inefficient especially in slow traffic, the fuel consumption and consequently pollutions of conventional IC

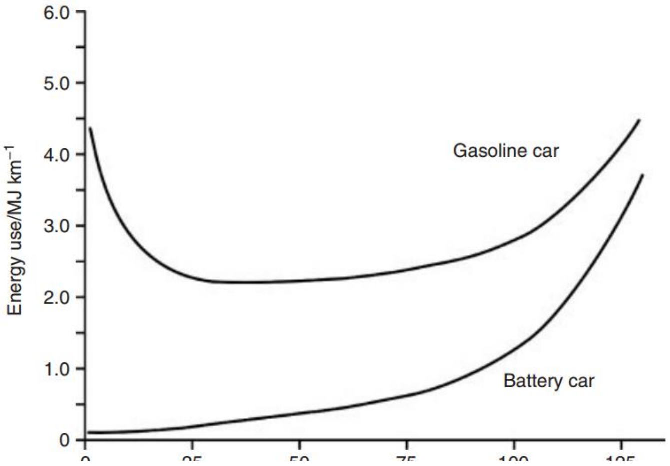


Figure 9 Indicative energy use 116[4]

engine increases dramatically in speed lower than 20 km/h [10]. It makes rush hours in such cities as London, Moscow, Tokyo, etc. even a bigger problem. EV and HEV can potentially improve this situation, the comparison of energy used by IC vehicles and EV vehicles are represented in Figure 7, and, as it can be seen, the energy consumption of EV at lower speed is four times lower.

Under these conditions, EV produces considerably less CO2, which makes a strong environmental case for their use, especially in towns and cities.

However, one should not forget about the fact that EV uses electricity, which has to be somehow produced and delivered to the end-user. The term “well to wheel” is the key part of the consideration for the environmental impact of EV vehicles. And to be fair, in terms of energy efficiency, ICE and EV are almost the same. Energy efficiency for EV is about 20% and 12 -18% for IC (based on driving conditions)[11]. It comes from the fact that the efficiency of fuel production has to be considered, additionally to the efficiency of EM or IC motor. When speaking about EV, it includes:

- Electricity production (around 45% efficiency for modern fossil fuel power plant).
- Electricity transition efficiency (90%).
- Charging efficiency (50-60%).
- Motor Efficiency (90%).

The producing of electricity itself on a power plant is not harmless, and it is obvious that pollutions of the plant strongly depends on the resources which were used to produce the energy itself. Electricity generation based on resources, such as hydro, sun or wind, have nearly zero GHG emissions, while production based on fossil sources, such as coal or fuel oil, have the highest GHG emissions. Pollutions g/kW for the main type of resources can be found in Table 1

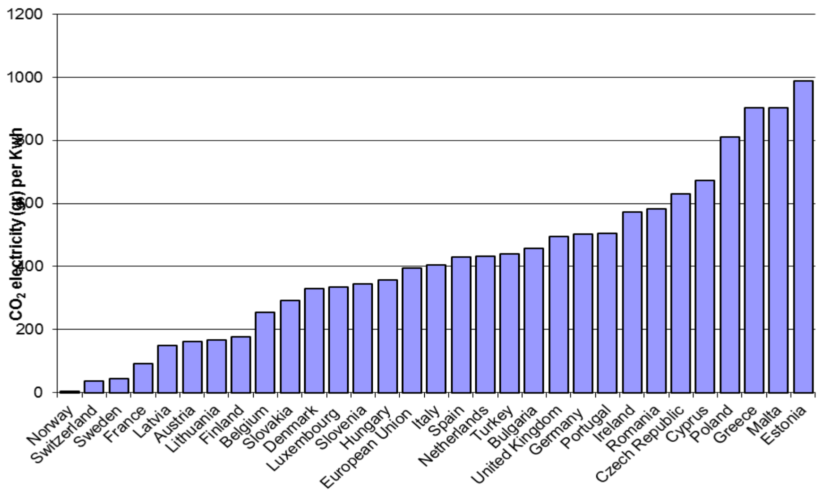


Figure 10 CO2(g) electricity per kW [13]

Table 1 Pollution per kW [12]

		Pollutions g/kW		
Fuel type	Plant efficiency %	CO2	SO2	NOx
Coal	(36-43)	916	9.3	3
Fuel Oil	(23-43)	777	3.1	2.1
Natural Gas	(55-60)	354	0	0.9
Hydro	(85-90)	12	0.04	0.04
Wind	(35-40)	10	0.02	0.02
PV	(12-18)	90	0.28	0.03

Thus, the final value of pollutions per kW differs from country to country, even within the European Union. Figure 10 shows the CO2 generated electricity per kilowatt-hour per member country. The first place with almost zero GHG belongs to Norway that is followed by Switzerland and France, and this is obvious when one visits these countries, forests of wind turbines and solar plane fields can be met almost every tenth of kilometers.

The reason why the Czech Republic is fifth from the end is simple and represented in Figure 11, where we can see that nuclear plants and coal are the main sources for the production of electricity in the Czech Republic. However, future development of “Near-zero emission” power plants, can significantly reduce these showings.

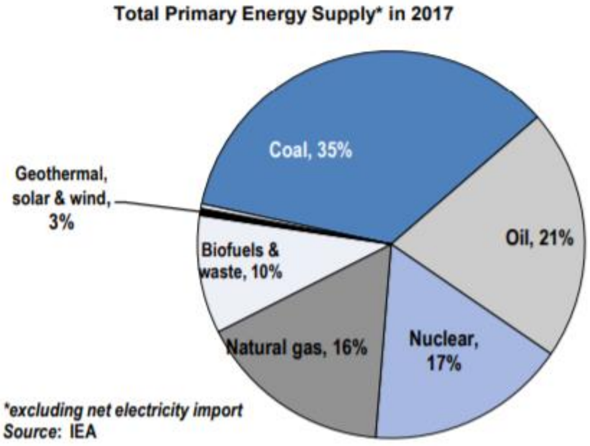


Figure 11 Czech republic energy sources [14]

That’s the reasons why more and more countries all over the world have adopted a guideline published in EU Directive Regulation CE/443, which is focused on limiting pollution caused by road vehicles. For instance, the government of the United Kingdom published “The Carbon Plan” in December 2011 and set their plans for achieving the emissions reductions up to 80% by 2050.

Germany aims to cut greenhouse gas emissions by 40 percent by 2020 and up to 95 percent in 2050. To increase the share of renewables in final energy consumption up to 60 percent (from 12.6 percent in 2015) by 2050. And to make renewables up a minimum of 80 percent of the country’s gross power consumption by the middle of the century. [15]

Averaged Europe Union targets among all members for 2020 are the following:

- 20% cut in greenhouse gas emissions (from 1990 levels).
- 20% of EU energy from renewables.
- 20% improvement in energy efficiency.

EU leaders set the targets in 2007 and enacted them in legislation in 2009. They are also headline targets of the Europe 2020 strategy for smart, sustainable, and inclusive growth. And as for 2050, the goal is to reduce transport CO2 emissions by 60% [15]

The EU is acting in several areas to meet the targets, and the transportation sector is one of them. It is enough to take a look at the reinforcing of the legislation for new vehicles in the US and EU Figure 12 to see how government targeting emission from this sector

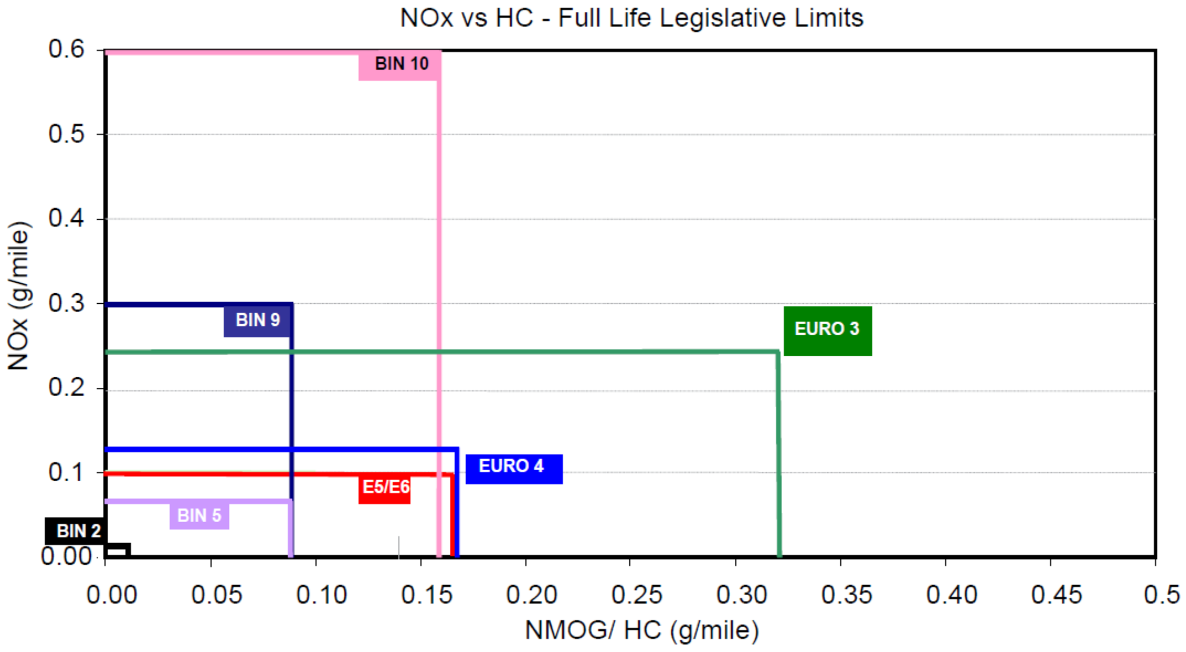


Figure 12 Europe and American Legislation [16]

1.1.4.1 Prediction and trends

So, the question on how to reduce emissions of transportation is of a high priority not only for automakers because they have to fit in tapering frames of legislation, but also among engineers and researchers. To stay in the legislation limits a lot of effort is put into improving vehicle efficiency and reduction of carbon in fuels. Car manufacturers and engineering companies address this by research and development it these fields:

- Weight and friction (air and rolling) reduction.
- Energy recovery systems (flywheels supercapacitors).
- Reduction of thermal losses.
- Greener technology for energy productions.
- Use of biofuel.
- Renewable H2/CH2.
- Hybridization.

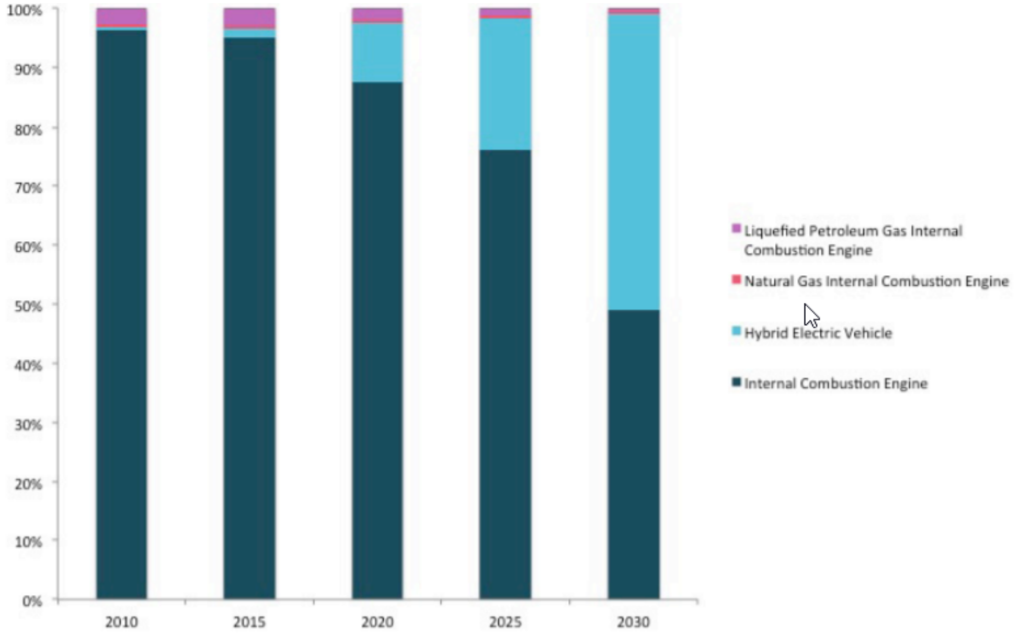


Figure 13Technology deployment rate [16]

A lot of engineering and analytical companies performed studies to construct a technological road map of vehicle technology for future decades one of them was performed by Ricardo (Figure 13) where it is expected that nearly 50% of the vehicle on the market will be hybrids. Another example is a BLUE map scenario in a Roadmap study published by International Energy Agency where in the year 2050 only 13% of the sales belongs to conventional gasoline engines

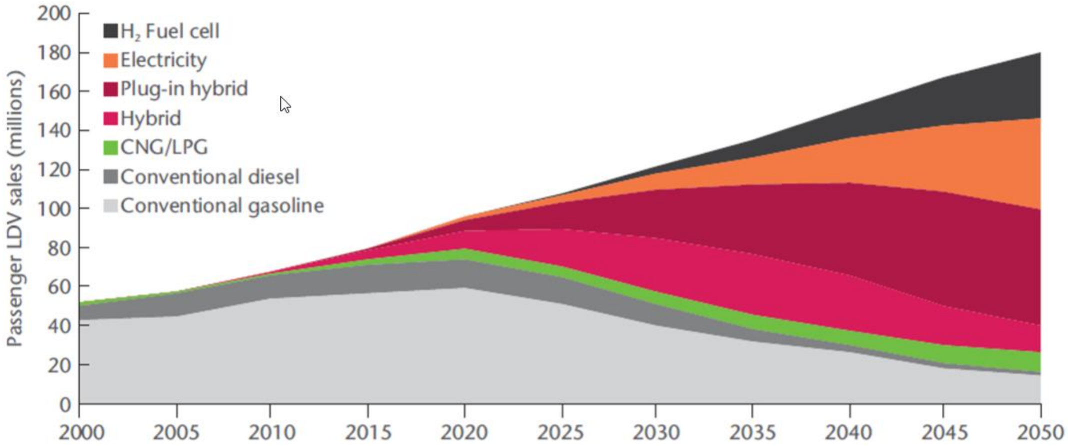


Figure 14 Vehicle Sales by technology type IEA prediction[15]

Predictions are different in their exact numbers, but they have one ground point: it is expected that the majority vehicles (light and heavy duty) will use alternative fuels either as the only source of energy or as a part of a hybrid system

1.1.4.2 Electric cars benefits and disadvantages

Electric vehicles have not only ecological benefits but also can provide energy independence for a country and bring financial benefits to an owner. To summarize the advantages of EV and HEW vehicles:

- When compared with internal combustion engines, the use of electrical motors leads to increased efficiency. Depending on the type of an electric motor the efficiency can go from 85% up to 95%.
- Electricity is cheaper than gas and can come from zero-emission resources such as solar and wind power.
- EV pollutes less than gas-powered cars (especially when renewable energy sources are used to generate electricity).
- EV is much more reliable and require less maintenance than gas-powered cars.
- By using domestically-generated electricity rather than relying on foreign oil, the Czech Republic can achieve energy independence.
- Electric cars can utilize the existing electric grid rather than require the development of new, expensive energy infrastructure (as would be the case with hydrogen).
- Reduce pick load on network grid.

EV and HEV technology has its drawbacks as well such as

- The range on one charge.
- Time to recharge.
- Battery price and lifetime.
- Pollution in terms of well-to-wheel.

Nevertheless, for the average inhabitant of modern city EV range and charging time should be enough. Based on the survey performed by the Joint Research Centre. The average distance that is daily driven by drivers ranges from an average of 40 km (UK) to an average of 80 km [18] for EU member states. This distance can be covered within one charge of modern EV. However, base on a survey [19], several factors are slowing down the penetration of EV to the market. The most important of them are:

- Distance with one recharge (Range anxiety Phenomena) – 32%.
- Car purchase price – 32%.
- Re-charge at home without private garage -25%.
- Re-charged time -9%.
- Max speed -2%.

Range anxiety phenomena”- is a fear of potential driver that he or she will not be able to reach a destination point without a recharge. The properly designed HMI for EV or HEV can address 2 out of five issues listed above. In chapter 1.2 the topic of proper HMI design specially for vehicles with alternative propulsion systems will be explained

1.2 HMI

The previous chapter was focused on the difference between ICE and EV in terms of technology, efficiency, and environmental impact this chapter will touch a different aspect of the vehicle – human-machine interaction. Previously it was already slightly mentioned that EV and HEV needs a different approach to the human-machine interface. In this chapter, this topic is covered with much greater details.

The human-machine interface is an interaction point between an operator, (in case of the vehicle a driver), and a machine (under the term machine falls the variety of technical, mechanical computational systems, which are needed to be externally controlled or monitored). Design of the HMI must focus on the reduction of the complexity in information flow between the operator and the machine, but at the same time providing as much information as needed for the operator (driver) to understand and react on the current situation, with as little delay as possible. In terms of HMI for heavy machines, or machines that can potentially harm the operator or surrounding, in the event of the operator error, it is important to make interaction as clear as possible, to avoid such mistake, properly design HMI becomes a crucial point of the control system which cannot be ignored.

It has been almost 120 years since the development of, what is known as the first accepted automobile developed by Karl Benz [24] around 20 years later a steering wheel appeared as a part of the vehicle control mechanism. Design of a body, powertrain components and even architecture of cars have changed dramatically during last 100 years and looking at today vehicle it is almost impossible to recognize first motorized tricycle, which was considered to be the first automobile. However, what has happened with control elements and HMI as a whole? If the early stage of development (until 1950) is neglected, it can presumably conclude that these elements stayed unchanged until now. One can argue that emerging touchscreen and LCD technologies had influenced modern HMI. It is true from the technological point of view but not true from actual usability. LCD and touchscreen just substituted well-known HMI mechanical elements like buttons, pointers, and gauges with digital replicas. So, such questions as, why automotive manufacturers often ignore the critical interaction point between car hardware and a user, and what must be done to apply cutting-edge technology and the basic theories underlying cognition and human-machine interaction to the novel UI for the vehicle remains opened. This part of the work will deal with these questions with the emphasize on why it is not acceptable to use conventional approach any longer, especially for the VAP.

1.2.1 The systems currently in use

A set of functions and processes distinguishing VAP vehicle from the ICE explain why the issue of HMI design must be addressed separately includes:

- Limited “refiling” infrastructure.
- Different recharge / refill time.
- Limited or reduced range.
- Different Starting procedure.
- HVAC system (pure EV related issued).
- Different longitudinal behavior.

First attempt to introduce different HMI specially designed for vehicles with different propulsion system was made in the 1990s when Honda EV Plus introduced the digital monitor substituting dashboard with 3 x 7-segment display integrated with battery SoC (state of charge) and distance to empty indicators. As it was mention, since the 2000s, when LCD and touch screen display development, automakers started rapidly implement, so-called, digital instrument clusters based on this technology. The SoC, Range information, charging mode gauges have not changed conceptually except that they appear more attractively, but some new features such as power flow display and ‘green’ ADAS interfaces, aimed at encouraging environmentally-friendly driving were added [28][68][69]

Vehicle-to-driver (driver to vehicle) communication can be subdivided into display systems (the information displays and gauges), starting system, pedaling and charging system. Further, each of these systems is studied in detail.

1.2.1.1 Design of display system for EV

There are two approaches to the design of EV or HEVdisplay gauges. The first one tries to make the appearance of the system maximally similar to ordinary ICE vehicles Analog gauges with pointers are used to display additional information related to EV systems operation. Familiar appearance makes the interaction intuitive for a user familiar with ICE vehicles and makes the transition from ICE to EV more comfortable.

Location of gauges and manner of information is carried out on the assumption of the general knowledge and standards.

Thus, instead of tank fuel level, there is SoC (State of Charge) indicator, and energy consumption and energy flow status are usually associated with the revolutions counter. Smart for Two or Tata Vista are good examples of such design, where power in/out gauges and SoC represented similar to fuel tank capacity gauges of ICE (Figure 15). Gauges usually located similarly to ICE vehicle. Nevertheless, information representation can be different, for instance, SoC indicator can show battery charge level in percent, in km or in scale value.

The second approach is quite innovative. It differs not only in localization of interface components but also uses external, and portable devices such as in-vehicle display latest Tesla models is a good example of such an approach.

Figure 15 Analog gauges dashboard with SoC and Power in/out gauge

Nevertheless, both approaches need some additional functionalities, such as extended navigation features. Information about the closest available charging station is crucial in case of the limited travel distance of EV. A good example of such a system is a ProtosCar HMI where elevation profile is used to estimate vehicle range more precisely. (Figure 16), or BMW ActiveE system were all charging stations, positions of which are known to the system, are displayed on the navigation screen

Figure 16 BMW ActiveE concept system navigation features (left). ProtosCar HMI extended navigation features. (right)

To function properly, such systems need reliable, continuous, and, in the ideal case, centrally distributed source of information, where information about all available charging station and their occupancy are stored and distributed among vehicles. In this case, one authority, who is responsible for gathering and updating information about CS location and their availability, provides information to end-users. And a user does not have to check several providers to find the closest CS on his route. Additionally, centrally distributed information canter can ensure information integrity and standardize information distribution schema among different types of vehicle or navigation devices. A reliable source of such information can significantly improve a user's confidence that he can always find a CS on his route if needed. Secondary displays are usually used to provide this information to a driver

1.2.1.2 Starting and longitudinal control systems

Longitudinal controlling elements and starting system of EV and HEV are parts of HMI interface, and they deserve additional attention. One important issue occurs because EV does not need a starter (electric motor which is used to start an ICE vehicle), and there is no feedback users used to. Consequently, they are not able to tell if the vehicle is "Ready to Go" or in "Turn off" mode. Additionally, EV in motionless mode are silent and do not vibrate. Car manufacturers address this problem differently, some of them uses READY message on a dashboard or uses speedometer pointer to point on Ready position (0 km/h speed), or uses audio feedback (Figure 17)

Figure 17 Ready state indication on Audi A8 hybrid, Mercedes S400, Chrysler Aspen Hybrid

In case of pedals, feedback from pressing the pedals in EV is different from ICE vehicles. Due to the regenerative braking EV decelerates with the bigger rate when acceleration pedal is released in comparison to ICE vehicles, and it is possible to stop EV by using only acceleration pedal, thus, it makes it possible to drive with one pedal only.

Power Flow displays of different kinds were introduced as a part of EV and HEV HMI to educate users on the concept of regenerative braking and encourage them to use it as much as possible. A majority of users report that the usefulness of the information presented by Power Flow displays reduces the longer they own the vehicle. [40] This information becomes redundant for them because they got familiar with the behavior of the vehicle and can anticipate what kind of energy is used in a particular moment by their HEV without additional information displayed on the dashboard.

Another attempt to educate a user to drive more efficiently is called Eco-feedback or EcoGuide® interfaces. A system used in new Ford Focus Electric is a good example of such a system represented in Figure 18

Figure 18 Ford Focus Electric Smart Gauge®

Efficiency Leaves gauge introduced by Ford is aimed to encourage the user to drive more efficiently, it displays a green tree with leaves, where the amount of leaves depends on how efficiently driver is manipulation with his car. This gauge is real-time feedback on driving style to encourage the driver to drive in a more environmentally friendly way incorporates additionally historical data. These types of displays were introduced first time on Toyota Prius an Lexus hybrids but less artistically (histograms and bar plots). Nevertheless, new users warmly welcomed these gauges.

1.2.1.3 Charging system

Regarding charging EV and PHEV differs from ICE vehicles dramatically, recharging of EV can take hours and should be done in specially equipped (CS) charging stations. That is why the development of infrastructure and V2I communication is an important issue for EV integration. HMI can help a user in a transaction from ICE to EV in terms of “refueling/recharging.” Numbers of ready-to-use solution already exist on the market proposed by energy companies (General Electric, Eaton, Siemens, etc.) as well as by electric cars manufacturers (Tesla Motors, BMW, etc.). These CS can be available on the market as a public CS, corporate stations for companies supporting the development of green technologies, or for private use at home. Specially designed mobile application or WEB application provides a user with a possibility to monitor CS occupancy and location, unfortunately, there is still no centralized data canter, and user have to visit/open more than one sources to find closest available CS.

A possibility to delay a charging process at home and start charging during “low rate” hours, when the demand on power network grid is low, can improve energy distribution efficiency, and even reduce pick load on network grid in case if smart schemas and V2G (Vehicle to Grid) is applied. Roughly speaking Smart Grid is a set of CS connected to a central data canter, and subsequently connecting this server to either a utility network or a third-party hosted platform, a geographically fragmented charger network can be managed by one network operator. This gives a possibility to the network operator to monitor and control the charger network through a demand response load reduction mechanism, while the grid operator is able to maintain an overall view of charger-specific demand across its operating region. [40] A set of issues arise from such a charging process, first of all, for some users it can prolong a charging process, and vice versa, so a strong and reliable schema is needed to provide customers with information about charging status. Different manufacturers approach this issue differently, via either web or mobile application and simultaneously installing charge indicator directly into the vehicle to give a user the possibility to monitor the state of the battery directly. Examples of these interfaces are shown in Figure 19.

Figure 19 Top left Nissan leaf Charging indicator/ lower left MINI indicator/ right VOLT mobile application

1.2.2 Current State of the art HMI

So, with all these problems stated above it is clear that simple touchscreen technology is not an option any longer, so a lot of effort was put by researches all over the world to address these issues. Here is the list of modern technologies which can potentially be implemented in the near future:

- Haptic control (steering wheel, pedals).
- Embedded touch control.
- Gesture control with and without aural feedback.
- Soft interaction aid by computer vision (drowsiness detection, attention reduction).
- Touchscreens with possible haptic feedback.
- Voice control and feedback.
- Contextual information on secondary displays.

Each of this technology can bring additional advantages in terms of reduction of driver’s cognitive load, and better control of the in-vehicle environment. A lot of studies have been performed in laboratories of DSRG to study these technologies separately in recent years but it worse to mention that technology at that time was not mature enough to unlock the full potential of the solution. Additionally, there was no experiment to study the combination of more than two of these technologies as an integrated system. The need to provide facilities and measures to perform such experiments on a complex system with a random combination of these interfaces becoming undeniable.

1.2.3 Why changes are needed to vehicle HMI as a whole

The fact that the interface roughly remains the same for the generation of vehicles brought one positive advantage:” A *user needed to learn to drive only one car to be able to drive any.”* And it was true till the beginning of 21 century, where the composition of physical buttons and mechanical gauche were more or less the same for any brand of the vehicle manufacturer.

But this statement does not hold any longer with the development of electronic and telematics systems available for modern vehicles and does not particularly hold when we consider VAP vehicles (as we described the major difference between ICE and EV). Such systems as GPS, ADAS (Advanced driver assistant system) and infotainment systems added a new layer of complexity and interactivity and dramatically changed cognitive models and expectations.

Over the last 40 years, a subsequent three layers control model proposed by Allen. Lunenfeld and Alexander was used to analyses the driver-vehicle interaction and description of driver tasks. These levels are:

- Maneuvering level – basic control task, including longitudinal and latitudinal movement control and control over vehicle accessories such as wipers and HVAC.
- Tactical control – consists of tasks that require decision making in response to a changing environment.
- Strategic level – includes highly demanding cognitive tasks, learning behavior, risk tacking and vehicle performance, driving style, and preferences.

Let us tackle how modern technology and lifestyle affects changes in UI in each of these levels.

Maneuvering level is probably the easiest to analyze. First of all, it is affected by modern ADAS systems which are designed to assist the driver in challenging situations such as slippery road, limited visibility, or rapid stops and consequently reduce cognitive load. Such systems as ABS ESP and adaptive cruise control designed to minimize the effect of human errors and improve vehicle handling. Concerning the VAP as it was described above an electrical machine changes the longitudinal performance of the vehicle dramatically. The principle of modern hybrids or electric vehicles is based on the regenerative braking strategy, which is not to waste any energy during braking but regenerate it and store in storage in some form. In case of batteries and supercapacitors, it is to transfer kinetic energy, using electric motors working as a generator, into the electrical current, and in case of a flywheel, it is to absorb and store pure kinetic energy. From an ergonomics point of view, the obvious effect is that the accelerator pedal effectively becomes a reversed brake pedal, which is applied when released and makes it difficult for a novice driver to adjust.

Tactical control level is mainly affected by IVIS (In-vehicle information system) and telematics systems. GPS, weather forecast, traffic information, and other services are designed to help the driver in tactical tasks so he can anticipate and react to the environmental changes in advance, but with a positive benefit, additionally, they introduced new layers of complexity to interactivity, completely changing cognitive models and expectations. Additional information provided by these systems has to be communicated to the driver somehow, and currently, automakers solve this by adding an extra “menu” folder to LCD touch screens. This approach seems to be reasonable form the first glance but let us dig a little further.

“Old” interface was the spatial arrangement of the dials, knobs, and sliders for both control and direct mechanical feedback. This allowed drivers to develop a mental map of the HMI elements over time and let a muscle memory to perform needed actions and thus reduce cognitive load. The modern approach of automakers is “*simply use screens to replicate what has been before*” [25]rather than to use an opportunity provided by modern IO technologies. So, the complexity of modern IVIS system illuminates this advantage completely. The layout and combination of available IVIS systems and, consequently HMI interface and control, differs from automaker to automaker, so simple “swap” of a vehicle demands a learning period of adjustment, and makes a transaction hard, especially for inexperienced drivers. It even worse in case of switching from one propulsion system to another where a conciliation of main control elements can be different. This makes another reason to review the approach to HMI design today

Another reason is that today concept of a “personal car” has significantly shifted. Today’s young urban inhabitant is moving away from car ownership towards “pay as you go” paradigm, which means that automakers cannot any longer rely on the user to be familiar with the system in advance to operate the vehicle. Changing from one vehicle brand to another should be smooth and straightforward. Leaving a sharing vehicle “as simple as possible” is not an option too, as people become ever more dependent on their smart devices; they begin to expect more of embedded technology elsewhere in their lives. Thus, when sitting in a vehicle, they expect it to be as intelligent as their phone meaning providing basic telematics and navigation features.

Considering the third level (Strategic level), we can see that it is, affected the most by the VAP systems and by the psychology of modern costumers. To begin with, alternative propulsion will bring some limitation as either a limited range or limited availability of “recharge/refill” stations, thus brings a user to the point where he must plan his trip in advance. This becomes an issue for users inexperienced with VAP technology and even stops them from switching from conventional ICE to VAP. The notion of a connected car (CC) can potentially illuminate or at least help to overcome these issues. We can distinguish at least three models used today:

- The radically connected car - hardware, software, and HMI is all custom-built; integrated from the ground up. This model allows the deep integration of not only the multimedia systems but also diagnostics and control systems inside the car with the driver. The brightest example of this model is a Tesla Model X or S.
- Custom HMI modules that use software platforms like ‘Microsoft Embedded Automotive 7 or Blackberry’s QNX to manage and integrate different devices and sensors in a car into one platform.
- Integration of same platform devices to onboard HMI as done by Apple, Microsoft, or Google, examples of these systems are Apple car and Android car.

Each of these approaches has its advantages and disadvantages, but a third model is preferable by today’s automakers for the reason of cost reduction. They redirect the development of the HMI to the third parties and thus save money during the development stage but is it a right way to give a design of vehicle interfaces to software companies unfamiliar with the specific problems of the vehicle. Even more is it a safe way to let third parties get access to the internal network of the vehicle. Modern telematics and IVIS requires at least limited access to CAN (Controller Area Network) bus network to obtain such information as speed, engine state, etc. and more advanced systems such as Adaptive cruise control, lane assist, eco-driving will get access to a crucial control element such as acceleration, braking, and steering signals. It has been already proven by the latest hacks of Chrysler and Tesla that there are already enough loopholes, and the development of HMI and entertainment system should be handled with extra caution in terms of security.

Returning to the charging problem stated above, simply knowing the location of the CS in advance is not enough. An essential chunk of information is missing: does this particular CS, which is on the limit of the range of the vehicle, has the fuel needed and in needed amount, is it opened, is there a free space available (in case of pure EV it needs a considerable amount of time to charge the vehicle). Without this information, a simple location of CS is useless. So, it brings the notion of Connected Cars, but now with an emphasis to the importance of V2I (Vehicle to infrastructure) I2I (Infrastructure to infrastructure) V2P (Vehicle to person) or I2P (Infrastructure to person) communication. Let’s consider a hypothetical situation concerning pure electric vehicle for better understanding, but the explained scenario is applicable for all VAP vehicles.

Two EV is heading in one direction, there is a charging station (CS) at the end of their route (this CS is the furthest one they can reach and has been chosen by both drivers, for whatever reason), there are some additional CS along the path. All chargers at the CS are occupied, but there is one vehicle which will be charged in the time of arrival of the EV, but the driver of this vehicle left it unattended (to take a coffee, or he is working in the vicinity). It brings us to the situation, when EVs arrive at the CS where there is no charger available, and no information if it will be available soon, forcing them to look for another CS (if they have another charge left, and the situation can repeat itself) or wait there for undefined amount of time, bringing frustration for drivers and inefficient usage of CS infrastructure. The notions of I2V, V2V, and V2P can resolve this one hypothetical situation presented above and was nicely summarized in the project INDUSTRY 4.0 when applied to the real world instead of the plant. It is addressed by WG2 (The real environment) by applying a principal Information Transparency and Cyber-physical system.

"*Cyber-physical systems (CPS) are enabling technologies which bring the virtual and physical worlds together to create a truly networked world in which intelligent objects communicate and interact with each other*" [33]

So, let's study how this principle can resolve the hypothetical example. If the approach above is applied and virtual representation of all actors and a measure to communicate information between all of them are available. So the driver of the charged vehicle will be notified that the charging process is complete and it is demanded by another vehicle at time *t* (estimated time of arrival of the EV needed to be charged),. He is asked if he can remove his EV and in case of a positive answer, one of our driving EV will get the information that there is an available charger in time of his arrival, and it can be reserved. The third vehicle will get the information that there are no available chargers and the IVIS will offer the driver to choose any other CS within vehicle range where the charger is available. Of course, there are different possible development of the scenario presented above (driver of charging vehicle will not response, or another vehicle reserve space faster) but the vision of Information Transparency can resolve all of them. These concepts have been already tested in several pilot projects such as Ha:mo [34]

1.3 Vehicle simulators

Development of the new HMI interface usually consists of several stages, starting from the research stage where the task is to find any already existed interfaces and their evaluation and following by constructing a set of clearly defined user requirements, then a loop of concept creation and validation is repeated until the concept satisfies all user requirements. This process is displayed in Figure 20. To evaluate an HMI system for a vehicle, a user should try this system during driving. In case of concept definition, it is feasible to create a "virtual" prototype of the system, where a system functionality is simulated by means of computer graphics and perform several sets of experiments on a driving simulator to give a user a chance to test system functionality.

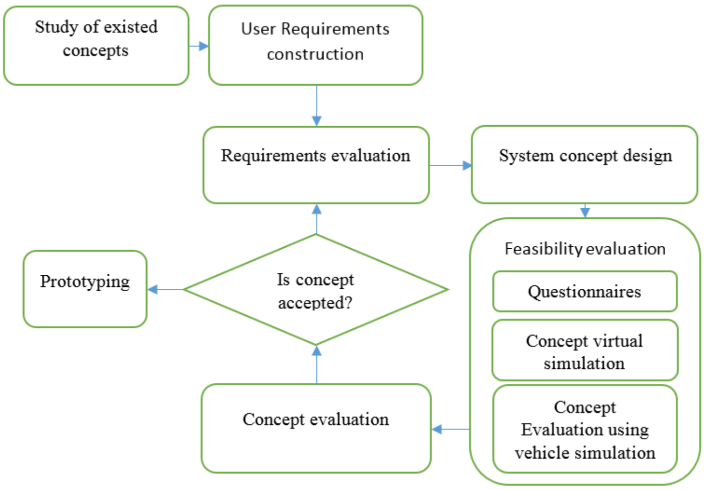


Figure 20 HMI prototyping

This chapter presents a notion of vehicle simulator and how it can assert in the area of VAP and HMI design and engineering.

"Simulation is an approximate imitation of the operation of a process or system; the act of simulating first requires a model of a set of problems or events that can be used to teach someone how to do something "[2]

A driving simulator is a model of a vehicle moving in a virtual environment. The model and the virtual environment are a simplified and/or virtualized version of the real-world objects. These types of simulators were used since early 1950 by such companies as BMW and Ford. Of course, these simulators were considerably simpler and less "real" then the modern one, (where even the forces acting on the driver can be simulated), but the main idea remains the same, a human driver drives a model of the vehicle in the virtual environment, preforming and completing tasks.

Figure 21 50s driving school simulator on the left and modern vehicle simulator on the right [35]

Modern simulators usually consist of parts of real vehicles with which a driver interacts through actual vehicle control components such as steering wheel pedals, and

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[2] Cambridge Dictionary

other vehicle HMI interface, and the complex system of computer-generated virtual reality (Figure 21 on the right). Virtual reality should cover the widest possible range of driver's sensor input so that it can induce a sense of realistic environment. These simulators allow researchers to monitor driver performance during a different predefined situation which is not possible or too dangerous or too expensive to perform in real life. An additional advantage of simulators against a real-life test is an ability to put different measuring devices in a controlled environment, which means the effect of "simulated" environment on measured data can be calibrated and minimize. The validity of results obtained from driving simulator has been studied multiple times. [36][37][38][39] and proven to be a reliable method of testing and validation of HMI interfaces and ADAS systems. Development of simulators and experiments from scratch is a complicated multidisciplinary task[36]. Which need professionals from different areas such as software engineers, 3D artists, sociologist, psychologists, electrical and mechanical engineers. Thankfully the simulator laboratory in the Faculty of Transportation Science department of vehicle technology has a long history and experience in creating not only simulators but also the design of experiments, and data analysis. This provides a solid foundation for developing and build VAP vehicle simulation platform.

1.3.1 Description of existed simulators

The architecture of the existed simulation software is presented in Figure 22. It is based on a modular architecture, where each module can be treated separately. However, the inputs of some modules require output from the previous. The intercommunication of the modules is realized through the communication bus, thus allows access to the needed information for any module. The system can be decomposed into the subsystems such as:

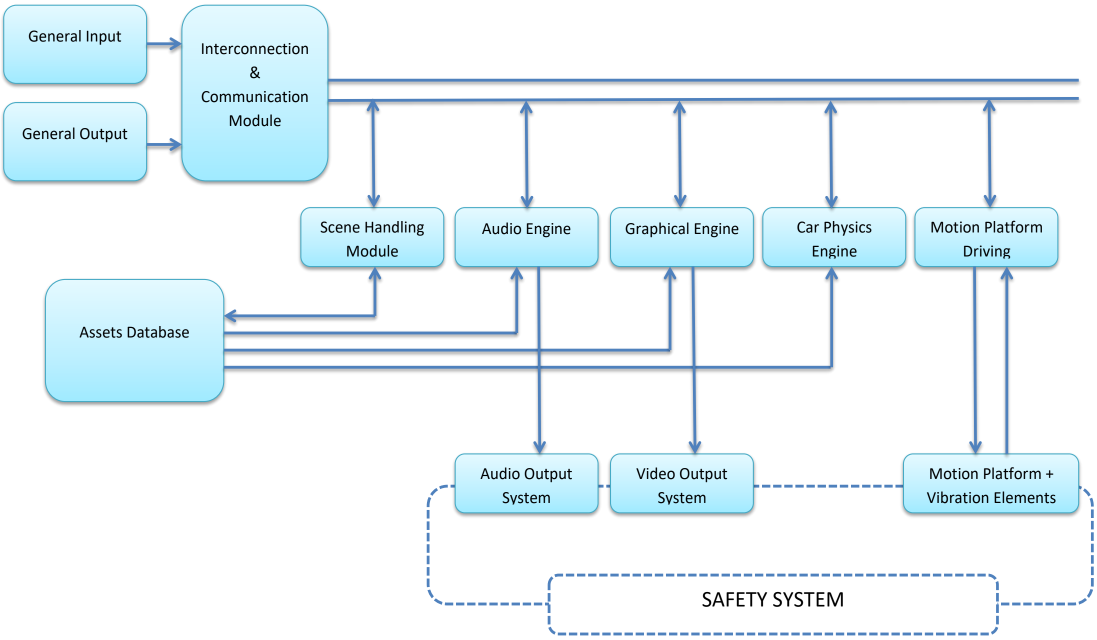


Figure 22 Advanced driving simulation system block diagram [23]

- Graphical engine – responsible for rendering virtual reality elements.
- Graphical output system responsible for mapping different viewports of virtual reality (front view, rear view, side view, mirrors).
- Spatial Audio System – generation of the sound of the vehicle and virtual environment.
- Motion Platform and vibration system module for communication with a moving platform for simulation of force feedbacks.
- Scene handling and generation – a module responsible for positioning other virtual actors (traffic, pedestrians, etc.) and events in the simulation (traffic lights, designed events).
- Car physics Engine - Module responsible for calculation and simulation of physical systems such as vehicle powertrain and suspension, contacts of road and tire, and with other actors.
- General input system – module to obtain user input (steering, acceleration, braking.).
- General-purpose output system.
- Communication module - responsible for internal module intercommunication.
- Safety and emergency system (system to prevent unsafe events if the moving platform is used, and for emergency stop of the simulation).

1.3.2 Car physical engine

The implementation of the car physics engine is based on the open-source engine ODE, which is a high-performance library for simulating rigid body dynamics. Capable of simulation of the interaction between body primitives such as spheres, cylinders, boxes, surfaces, and planes. Interaction is based on the physical laws, meaning that includes concepts of applying forces, tongues, for objects acting on each other.

The model of the basic vehicle is represented in Figure 23 this is a simplified model of a vehicle (with suspension and tire-road contact simulation) constructed from the primitive ODE objects.

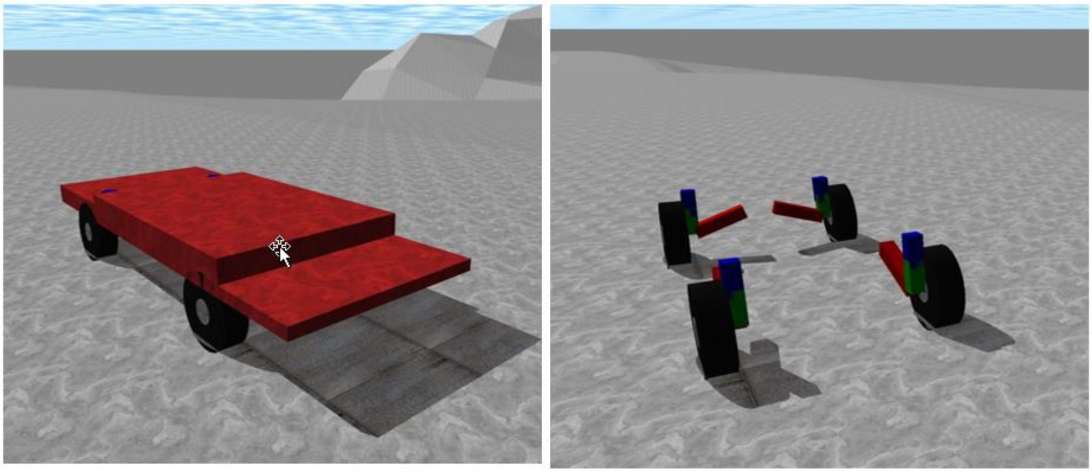


Figure 23 ODE vehicle [88]

The models of an engine, transmission, and clutch are self-developed mathematical models implemented in C+ programming language which calculates torque applied to wheels based on current system state (speed, position, user input). Calculated torque then applied on the vehicle wheels.

The ODE engine calculates and updates the position of the actors in the virtual world such as a vehicle, traffic, and environment objects. This information is then passed to the Graphical engine which is responsible for rendering an appearance of the virtual objects.

Such implementation provides an opportunity to substitute simulation of the conventional powertrain system with a developed module for simulation of VAP vehicle powertrain. The implementation is further discussed in chapter 2.1

1.4 Conclusion to the first chapter

This chapter provided an introduction and study of problems associated with the EV and HEV vehicles, their HMI and ADAS systems, starting from history and description of the current state, moving further to describe their technological and environmental advantages. It proves that this technology becomes a reality and, in few decades, EV and HEV will substitute the majority of ICE vehicles, because of environmental and technological problems and limitation of the ICE, and progress in the development of alternative propulsion systems. This substitution comes with new challenges and tasks, design of HMI for VAP vehicles need a conceptually new approach, not only because of their different architecture and behavior but also because of the conceptual shift of user models, such as a shift from owning a vehicle to sharing a vehicle.

Additionally, these new HMI and ADAS systems need to be designed keeping emerging Smart Cities and Industry 4.0 standards and ideas in mind, to ensure the efficient usage not only of the vehicle but also infrastructure and information shared among all actors. Design and prototypes of these systems need to be validated to ensure safety and user satisfaction. This brings the need for new tools and measures, at the same time keeping the cost and complexity of these validations to the minimum. As it was stated at the end of the chapter, an interactive vehicle simulator can be updated to cover the testing of such complex multi-dimensional systems Simulation of the VAP vehicle powertrain itself forms a complex multidomain (mechanical, electrical, chemical) task, the next chapter will describe details and approach for such simulation.

2. Virtual Testing Platform

The demand to develop a new set of tools and methods for the development and validation of HEV and EV systems and HMI interface was proven in chapter one. One of the challenges is to create a modular simulation platform for different types of HEV and EV powertrains. This is a multidomain task includes simulation of mechanical, electrical, chemical and thermal behavior of components such as a battery, motor controller, fuel cell storage, and convertors. Additionally, the simulation platform should be able to adjust for any powertrain architecture. This chapter deals with the description of developed modular simulation platform. It starts with the definition of changes and tasks needed to be performed to integrate the powertrain simulation model into the existed simulator, followed by the development of mathematical models for main components and then integration of the module to existed simulator. Another task is to create tools to simulate and validate HMI of EV and HEV vehicles. This tool also must follow the principle of modularity, since the rapid development in the area of the HMI. Testing and validation of the HMI concept require additional equipment and synchronization mechanism for data provided by different measurement equipment. One important tool for HMI evaluation is an Eye tracker device, which allows monitoring the behavior of driver gaze. This chapter covers following topics:

- Enhancement of the Physical Engine.
    - Mathematical background for simulation of main components (Battery, EM, Generator, DC/DC converters).
    - Modulization of the powertrain elements.
    - Integration and validation of the module.
- Introduction of Communication Module.
    - HMI element communication.
    - V2X communication for the purpose of ADAS simulation.
- Development of the Virtual HMI module.
    - Virtual Dashboard.
- Integration of eye-tracking module.

2.1 Power train simulation architecture

This chapter deals with the development and implementation of the modular EV and HEV powertrain module. It starts with a description of the powertrain simulation module architecture and moves to the selection of appropriate integration technics and an explanation of the implementation.

2.1.1 Powertrain model architecture

As it was described at the beginning of the chapter 1.3.2, existed simulator is using a modular architecture, this allows only to modify existed Car Physical Engine (CPE) to simulate a VAP powertrain. The architecture of the proposed solution is shown in Figure 24 where simulation of car physics is split into the simulation of the powertrain and ODE simulation of vehicle suspension and world interaction.

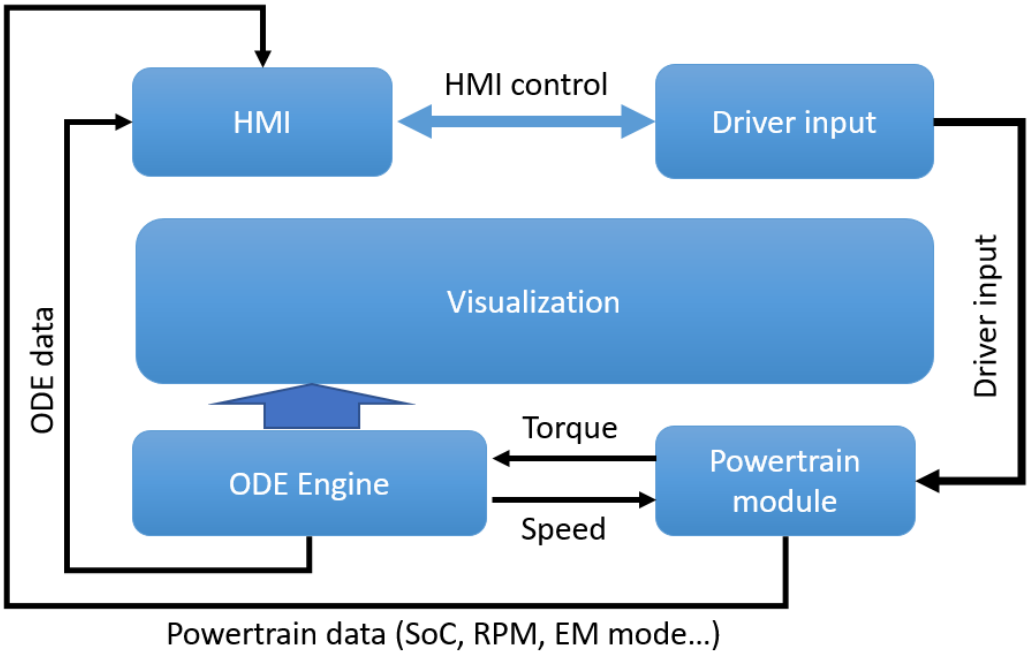


Figure 24 EV HEV powertrain module integration

For each simulation step, based on the user inputs (acceleration pedal signal, braking pedal, selected gear, clutch and additional signals from the HMI), and current state of the system (speed, battery state, temperature etc.) powertrain module calculates a toque, which should be applied to wheels. Then provides this information to ODE which calculates the movement of the vehicle and providing information (actual seed and traveled distance) back to the powertrain module. A flow diagram for the simulation of BEV is represented in Figure 25

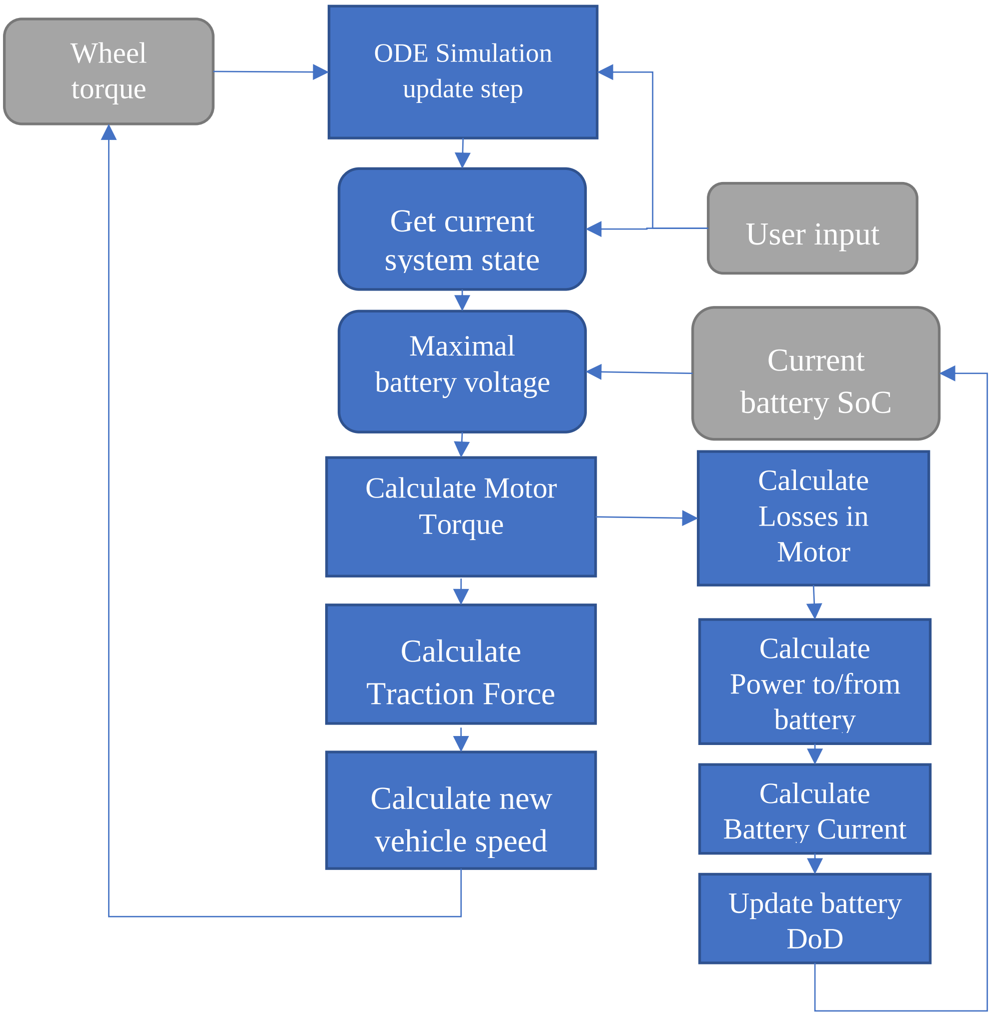


Figure 25 EV simulation algorithm

This approach allows fast replacement of the powertrain module for different types of VAP vehicles.

2.2 Development of the models for VAP powertrain

This subchapter deals with the simulation of the main components of EV and HEV vehicle and describes the process and equations needed for the simulation. These equations are later used to develop main components.

2.2.1 Driving resistence

ODE physical engine calculates the position of the vehicle from the provided torque. However, it does not consider traction effort, it must be calculated separately and applied on the vehicle as an external force acting in the opposite direction of the movement. Forces acting on the vehicle are shown in Figure 26 and can be found based on *Equation 4* This equation represents all losses during the driving, including losses for aerodynamics, drive-train, tires, and axillary systems

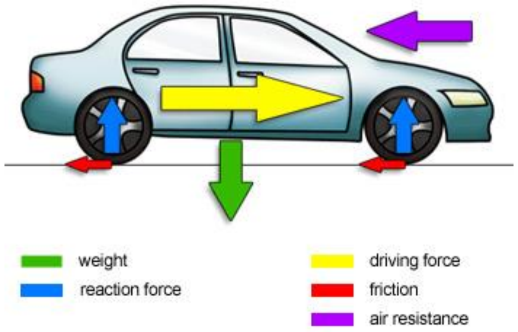


Figure 26 Forces acting on a vehicle

$$O_{total} = \frac{O_F + O_V + O_S + O_Z}{\eta} \qquad \textit{Equation 4}$$

Where

- O_{total}- is a power which we need to overcome the forces acting over the vehicle
- O_V - Drag resistance.
- O_F - Friction Resistance.
- O_Z - Acceleration resistance (This resistance is calculated by the ODE automatically).
- O_S - Resistance to overcome a slope (This resistance is calculated by the ODE automatically).

Following subchapters will explain in detail how to simulate these losses and their physical meaning.

2.2.1.1 Friction (rolling) resistance

This resistance appears mainly because of the friction between road and vehicle tires, but additionally, such components as bearings and gear system also contribute to this value and can be found based on *Equation 5*

$$\mathrm{O_f} = \mathrm{m} \cdot \mathrm{g} \cdot \mathrm{f_k} \cdot cos\,\alpha \qquad \textit{Equation 5}$$

Where:

- m – Mass of the vehicle
- f_k- Drag coefficient (rolling resistance coefficient)

- g – Gravity acceleration.
- α– Angle of movement.

The magnitude of the drag coefficient (f_k) is influenced by several factors, such as road type and road condition. Sample data for different road type is represented in Table 2.

Table 2 Drag coefficient base on surface type [41]

Surface	f_k	**Surface**	f_k
Asphalt	0.01-0.02	Dry dirt road	0.04-0.15
Mikroporit	0.015-0.025	Wet dirt road	0.08-0.20
Paving	0.02-0.03	Road covered with snow	0.20-0.30
Macadam	0.03-0.04	Frazil road	0.01-0.025

Additionally, rolling resistance coefficient depends on the velocity, suspension type, and tire pressure, these dependencies represented in Figure 27 This dependency can be represented through the second-order polynomial regression or quadratic interpolation of tabular data

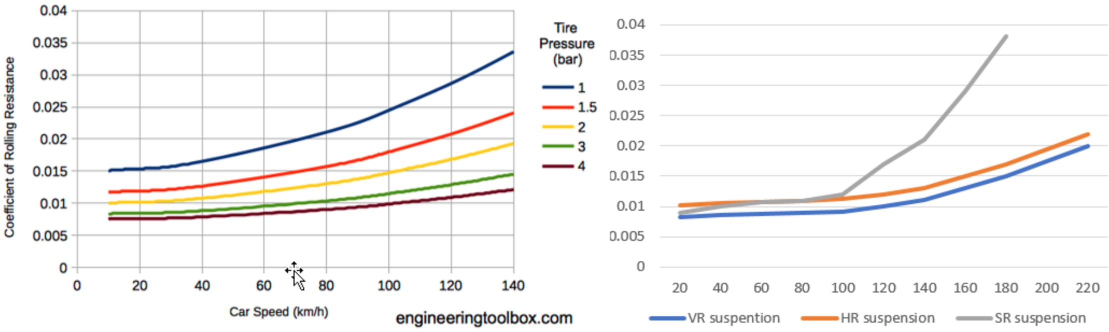


Figure 27 Friction coefficient dependence from velocity [41]

2.2.1.2 Air resistance

Air resistance or aerodynamic resistance appears mainly due to the friction of the vehicle body and the air itself and plays a major role in higher velocities. It mainly depends on the vehicle body design and frontal area. It can be calculated using *Equation 6*

$$O_v = \frac{1}{2}\,\rho \cdot c_x \cdot S_x \cdot (v - v_{wind})^2 \qquad \text{Equation 6}$$

Where

- c_x - drag coefficient,

- ρ- Air density.
- S_x - Vehicle frontal area.
- v – Current velocity of the vehicle.
- v_{wind}– the current speed of the wind (actin upon the direction of movement).

Drag coefficient and frontal vehicle area depend on vehicle type and its design. Modern personal vehicles usually have c_x coefficient in a range <0.3 … 0.4> and S_x vehicle frontal area in a range <1.6…2.0> This information can be obtained in advance from the vehicle manufacturer or estimated using special computer aid engineering CAE and Computational Fluid Dynamics (CFD) software.

2.2.1.3 Accessories power consumption

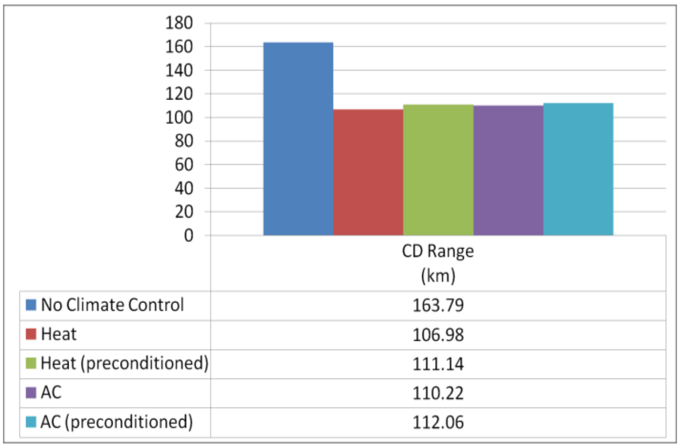
Energy consumed by vehicle accessories such as lighting, entertainment or energy for battery management and additional accessories are combined via *Equation 7*

$$O_{aux} = O_{climat} + O_{batmngm} + O_{light} + O_{audio} \qquad \textit{Equation 7}$$

Where:

- O_{aux}- Losses from 'all other' electrical loads in the vehicle from user-related systems. Such us climate control, external lights, and audio.
- O_{climat}– Consumption of power by a climate control system (ACC and Heating).
- $O_{batmngm}$– Consumption of battery system management - systems necessary to regulate battery temperature, not all EV has this function.
- O_{light}– Consumption of lighting assumed that the maximum power consumption of internal & external lights is equal to 80 Watts. Due to the fact, that LED lights are used in new vehicles and due to Czech legislation (lower beams should be turned on always) it's not a temporal function.
- O_{audio}– Consumption of Audio, navigation system, and communication system assumed to be 180 Watts.

Both $O_{climat}$and $O_{batmngm}$ are functions of external temperature and can reduce EV range up to 34.7% when heating is turned on, and up 32.7% when ACC is turned on.



	CD Range (km)
🟦 No Climate Control	163.79
🟥 Heat	106.98
🟩 Heat (preconditioned)	111.14
🟪 AC	110.22
🟦 AC (preconditioned)	112.06

Figure 28 EV CD range

Figure 28 represents the results of a test performed in [42]. Mean values of Climate Control system consumption is represented in Table 3

Table 3 Climate control Load Profile [42]

Mode	**Peak Load (kW)**	**Average Transient load(kW)**	**Steady-state load (kW)**
A/C	3.89	2.99	2.1
Heater	6	4	2

Based on this information, *Paux* (Power consumed by accessory systems) profile as a function of ambient temperature can be constructed and can be found in Figure 29.

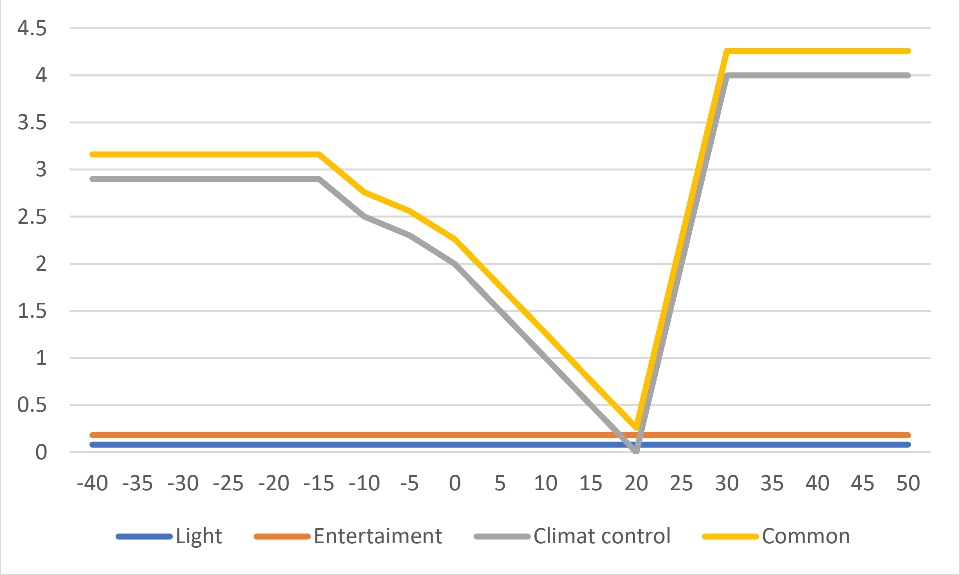


Figure 29 Axillary consumption as a function of ambient weather

2.2.2 Simulation of Battery charge Discharge behavior

Simulation of the battery can be done for different reasons:

- Chemical and physical changes of the battery active elements
- Predict the behavior of the battery type

For the purpose of integration, we will focus on the second type of simulation. However, selected implementation allows further enhancement to support the first type as well.

Predict the behavior of the battery type includes several steps:

1. Construct an equivalent battery circuit Figure 30. This circuit simulates not only static behavior but also introduces a dynamic effect when a new load connected to the battery.

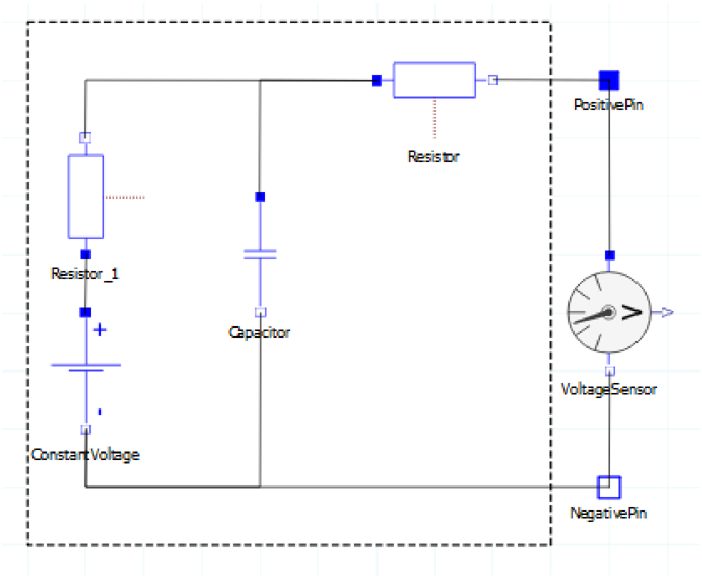


Figure 30 Battery equivalent circuit

2. Calculate an open circuit battery voltage *Equation 8* for lead-acid This characteristic depending on SoC , and internal resistance (different for different battery types). For nickel-based batteries, the characteristic is not linear, and some algorithms are needed to construct the polynomial equation to fit the battery characteristic in the form of *Equation 9* where coefficients A,B,C…Y needed to be obtained from polynomial fitting algorithms for each battery type.

$$E \;=\; n\,(2.15 - SoC\;(2.15 - 2.0))) \qquad \textit{Equation 8}$$

$$E = n\,(A * SoC * n + B * SoC * n\text{-}1 + \ldots C * SoC + Y)) \qquad \textit{Equation 9}$$

3. Calculate battery current from *Equation 10*

$$P_{bat} > 0 : I = \frac{E - \sqrt{E^2 - 4RP_{bat}}}{2R}$$
$$P_{bat} < 0 : I = \frac{-E + \sqrt{E^2 + 4R_cP_{bat}}}{2R_c} \qquad \textit{Equation 10}$$

4. Make a correction to the charging/discharging current with Peukert[3] coefficient (k) and update battery SoC based on *Equation 11*

$$C_n = C_{n-1} \pm \frac{\Delta t * I^k}{3600} \qquad \textit{Equation 11}$$

Where

- C removed or supplied charge [Ah].
- Δt -time interval[s].

---

[3] Peukert's law expresses mathematically that as the rate of discharge increases, the available capacity of that battery decreases

5. Calculate the depth of discharge- ratio of charged removed from the battery to the original capacity

$$\text{SoC} = \frac{C_n}{C_p} = \frac{C_n}{I^k T} \qquad \textit{Equation 12}$$

This algorithm allows precise calculation of battery discharged rate for known battery types.

2.2.3 Simulation of the Motor and motor control

The maximum torque of the brushed or brushless DC motor in most cases is a linear function where the controller voltage limits torque at low speed, the characteristic of the motor can be written as follow:

$$T = \begin{cases} T_{max} & \omega < \omega_c \\ \dfrac{K_m \Phi E_s}{R_a} - \dfrac{(K_m \Phi)^2}{R_a}\omega & \omega > \omega_c \end{cases} \qquad \textit{Equation 13}$$

Where

- E_s –supply voltage.
- $K_m -$ the motor constant.
- $\Phi -$ total flux passing through the coil.

$K_m\Phi, R_a$, are either known from a manufacturer or obtained from experiments. Usually, characteristics of the motor provided by the manufacturer contain:

- Motor speed Ms $\frac{rpm}{V}$.
- Armature resistance Ω.

Then using *Equation 14* and the value of maximal current (in the region <250 350>) finding the maximal torque T

$$T = K_m \Phi I \qquad \textit{Equation 14}$$

Obtained characteristic is shown in Figure 31. From these equations and from the Figure it is clear that the output torque and consequently force applied to move the EV can be controlled by the value of supply voltage, obtained from the battery, this supply voltage is a function of the position of acceleration pedal.

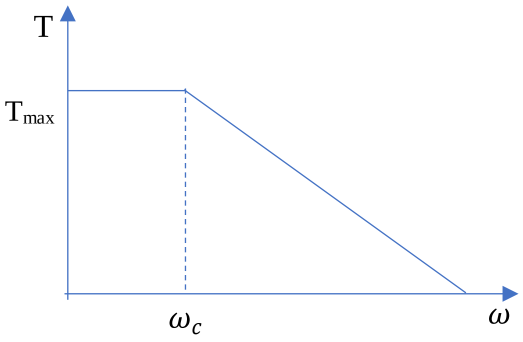


Figure 31 Brushed motor characteristic

Another possible approach to control the output torque is to control magnetic flux Φ it can be done if coils rather than permanent magnets provide the magnetic field and the voltage is applied to the coil in parallel, and the variable voltage is applied to the coil itself Figure 32

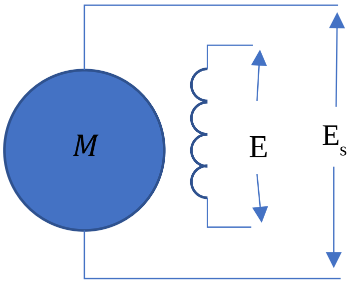


Figure 32 Control of the motor with Magnetic Flux

An electric motor is not an ideal system and has some losses during the operation there are 4 main types of losses which then are combined to calculate motor efficiency (not all power provided to the motor itself is transferred to the kinetic energy

Equation 15 represents the total loss of the motor as a function of rotational speed ω where k_v, k_i, k_w, C - are obtained from the manufacturer or estimated for different motor types

$$T\omega + k_c T^2 + k_i\omega + k_{iw}\omega^3 + C \qquad \textit{Equation 15}$$

Where

- Copper Losses ($k_c T^2$)– electrical resistance of wires and brushes (heat instead of actual work).
    - k_c – can be estimated to be 0.1.
- Iron Losses ($k_i\omega$) – magnetic effect in the iron including Hysteresis losses- the energy required to magnetize and demagnetize the iron.
    - Eddy current - heating of the iron because of the electromagnetic induction.
    - k_i – can be approximated to be 0.01 [4].
- Friction Losses ($T\omega$)- friction in rotor bearings.
    - k_i can be estimated to be $5*10^{-6}$ [4].

- Windage losses ($k_{iw}\omega^3$) aerodynamic losses because of the rotor rotation and cooling.
- Constant losses - power ECU or coils itself. Can be estimated to be 600.

The overall efficiency of the motor is calculated by *Equation 16*:

$$\eta = \frac{T\omega}{T\omega \ + \ k_c T^2 \ \ + \ k_i \omega \ + \ k_{iw}\omega^3 \ + \ C} \qquad \textit{Equation 16}$$

2.2.4 Simulation of the invertor

Invertors or Voltage regulators are used to control output voltage provided by a source (battery or Fuel cells) because it can vary with time, temperature, soc, and current (as it was shown in chapter 2.2.2). For instance, during the regenerative braking. DCDC regulator has to take an electric power generated by a motor and apply it to charge a battery at an increased voltage and reduced current. The equivalent circuit is shown in Figure 33

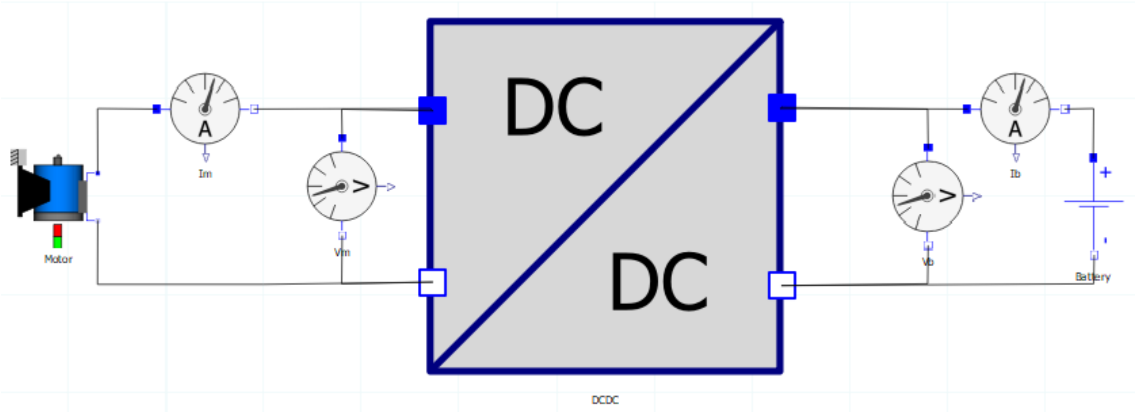


Figure 33 RB of a DC motor

There are two approaches to simulate a DCDC invertor:

1. Detailed simulation based on the schematic and characteristic of particular components (Example of a step-down converter is shown in Figure 34).
2. Simulate only losses in the inverter unit.

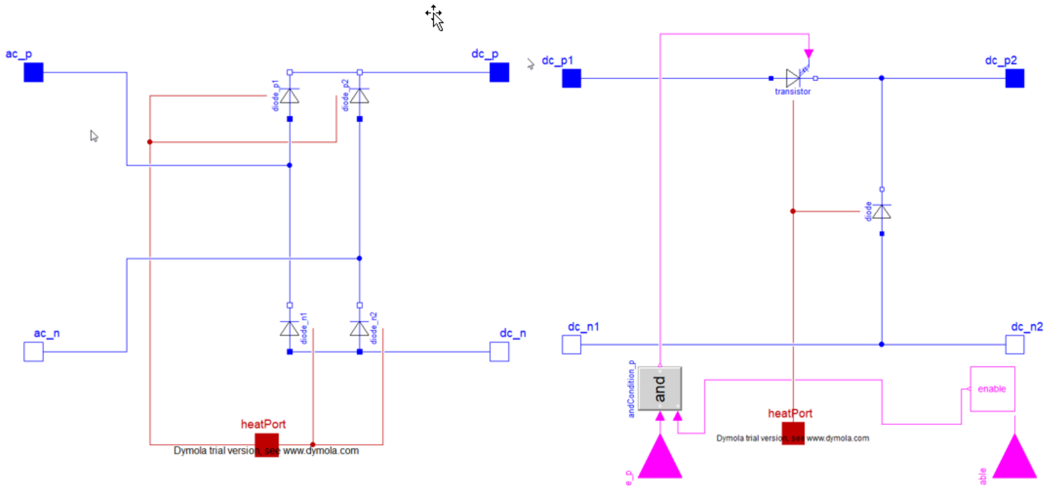


Figure 34 ACDC inverter (right) / Stepdown DCDC convertor (left)

For our purposes, we can use a simpler version and calculate losses in the inverter and efficiency of the whole system including a controller.

- Step Down chopper efficiency 0.9 ~ 0.98 [4].
- Step-Up or 'Boost' Switching Regulator.
  - 0.8 when regulated voltage V <100V [4].
  - 0.95 when regulated voltage V >100V [4].

The resulting equation is presented bellow

$$V_bI_b = \eta_c V_m I_m$$ *Equation 17*

Where V_bI_b – Battery Voltage and current and V_mI_m motor Voltage and current and η_c – the efficiency of the invertor

However, in the proposed platform, if desired, a full circuit can be developed to simulate inverter electrical and thermal behavior. Example of such ACDC and DCDC circuits presented in Figure 34 These models are capable of simulation of both domains, electrical and thermal, giving a wide range of possible application, starting from cooling design and Over/Under voltage tests, finishing with tests for failed elements in the circuits.

2.2.5 Full cells

There are three different types of FC simulation such as:

- Chemical – simulation of complex chemical and thermodynamics phenomena.
- Experimental -simulation based on lookup tables and empirical equations from data available from experiments.
- Electrical – representation of the fuel cell by the electrical circuit elements example of such circuit is shown in Figure 35.
  - Larminie Model.

    - Dicks-Larminie Model.
    - Yu-Yuvarajan Model.
    - Choi Model.
- Simulation from the data obtained from fuel cells datasheets, this is the model suitable for electrical stimulation programs and can represent the effect of operating parameters on the fuel cell.[31]

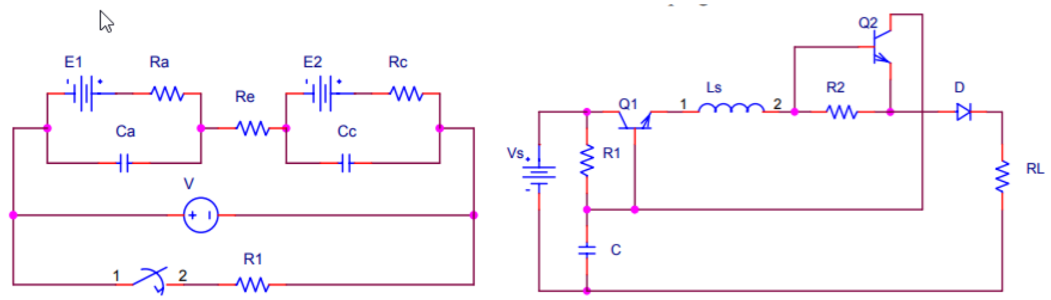


Figure 35 Equivalent electric circuit Larminie model on the right Pae model on the left [29]

For the purpose of EV and HEV simulation, the fourth method is used. However, implementation of the electrical and experimental model is straightforward and explained in details in [29] [30] and can be easily imprinted using the approach described in the next chapter

Choose method described in details in. [31] and is based on *Equation 18* and *Equation 19*

$$E = E_{oc} - N\,A\ln\left(\frac{i_{fc}}{i_0}\right)\cdot\frac{1}{sT_d/3+1} \qquad \textit{Equation 18}$$

$$V_{fc} = E - R_{ohm}\cdot i_{fc} \qquad \textit{Equation 19}$$

Where is obtained from FC datasheets:

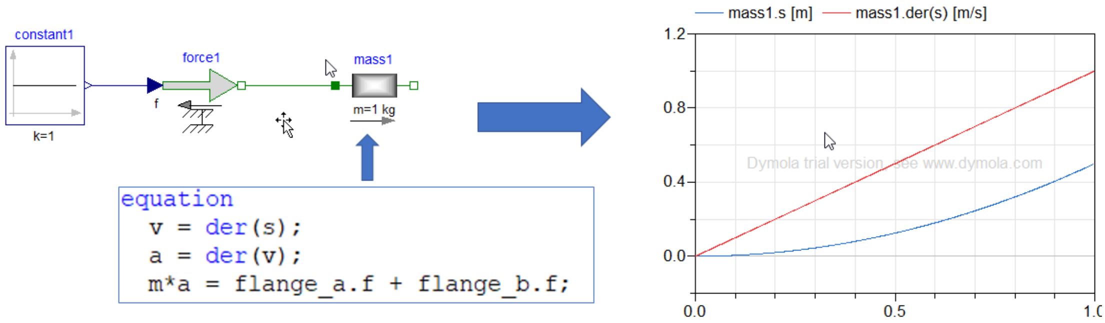
E_{oc}	Circuit voltage (V).
N	Number of cells.
A	Tafel slope (V).
i_0	Exchange current (A).
T_d	The response time (at 95% of the final value) (sec).
R_{ohm}	Internal resistance (Ω).
i_{fc}	Fuel cell current (A).
V_{fc}	Fuel cell voltage (V).

2.2.6 Implementation

Modelica programming language and its compilation to the Function Mock-up Interface (FMI) and further Co-simulation with the ODE engine in existed vehicle simulator was chosen for simulation of EV and HEV and VAP. This was done due to the complexity of the simulation process described in the previous chapter. To perform the simulation a set of differential and algebraic equation (DAE) must be constructed and solved for multiple components such as Motor Battery Inverter and e.t.c. in real-time. Modelica programming language was selected as a tool to construct and solve sets of differential equations (DAE) because of a more natural and efficient way of writing DEA down. Next chapter will explain the choice in deeper details.

2.2.6.1 Modelica programming language

Modelica is an open-source, object-oriented language for modeling of massively complex systems. It is suited for multi-domain modeling (including electrical, physical, thermal, mechanical and other domains). Additionally, it can be used for hardware-in-the-loop simulations and embedded control systems. [43] Models in Modelica are described by differential, algebraic and discrete equations. Which can be later represented as a schematic object diagram. Figure 36, where a component can be defined as a combination and interaction of multiple subcomponents.



```
equation
  v = der(s);
  a = der(v);
  m*a = flange_a.f + flange_b.f;
```

Figure 36. Modelica Model architecture

Subcomponents relationship is defined by drawing connection lines between “connectors”. Connectors describe the interaction possibilities (electrical pin, mechanical flange, or an input signal

Regarding development time for complex models, Modelica language is on average, twice faster than any technics in proprietary code or any other block modeling languages. This is explained by several factors:

- A developer does not have to manually derive relationships between inputs and outputs between subsystems models. No particular variable needs to be solved for manually.
- Modelica code has been developed since 1996 so a lot of subsystem components have been already developed and available for public.
- Implementation time and complexity is the same as for any Block modeling language.

All these points are summarized in Figure 37

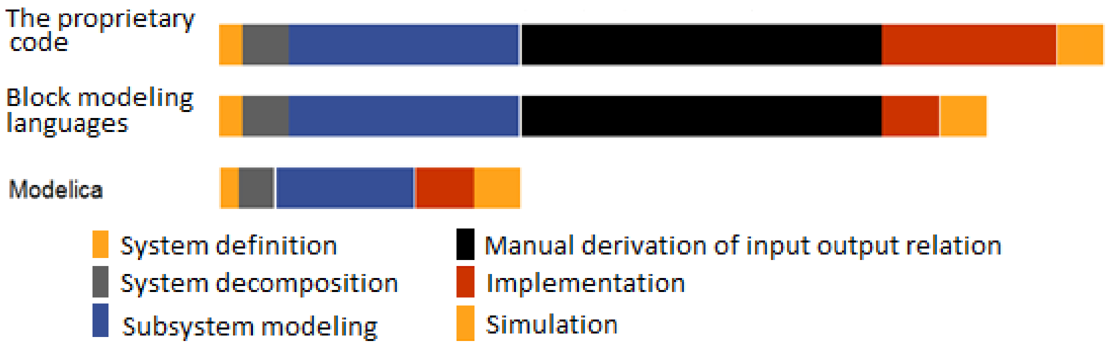


Figure 37 Development time chart [43]

All mentioned above puts Modelica language ahead of other languages, especially when dealing with simulation of such a complex and multidisciplinary system as hybrid and electric vehicle powertrain.

However, integration of the model in the virtual world creates a new engineering task which can be solved with an application of the FMI (functional mock-up interface standard).

2.2.6.2 Function Mock-up interface

Functional Mock-up Interface (FMI) is a standard to support both model exchange (ME) and co-simulation (CS) of dynamic models developed in different independent tools, its primary goal is to support the exchange of simulation models between suppliers and OEMs, providing a possibility to protect product knowledge, which could be recovered from these models. The difference between ME and CE is that ME FMUs do not include the DEA solver, but provides only a set of equations to be solved for each integration point, meaning that the main process has to provide means of DE solving. Where, on the other hand CS FMU has integrated DAE solver and the master process has to deal only with the synchronization of inputs and outputs between FMU and other proceses or models. Since the ODE engine is used in the vehicle simulator does not provide a DAE solver a CS FMU type was selected for the purpose of the project.

An FMU (Function Mock-up Unit) essentially is a zip (.zip extension is changed to .fmu for the clearness of the file usage) file containing several files:

- Definition of the variables used in the module in the form of the XML file.
- A compiled C code containing interface and all equation for simulation of each integration step.

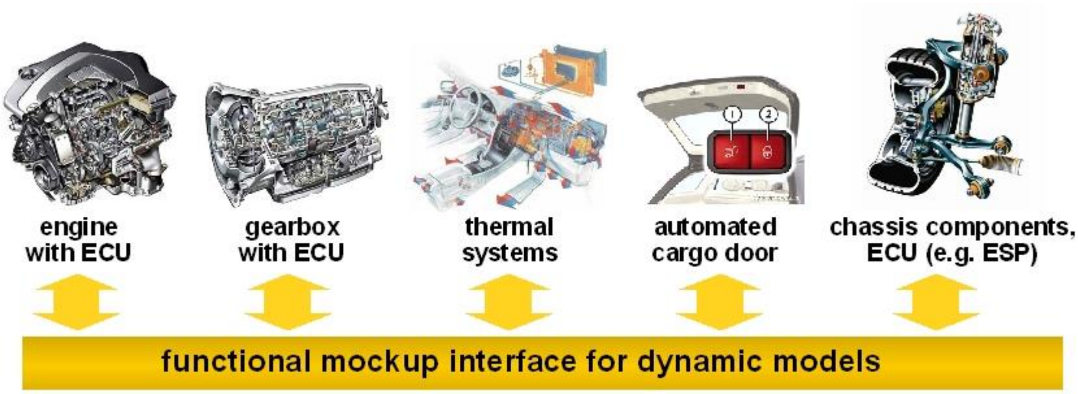


Figure 38 FMI integration concept [44]

Additional files needed for the simulation runtime (external data files, tables, and resources dynamic link library (DLL))

A schematic view of an FMU is shown in Figure 39:

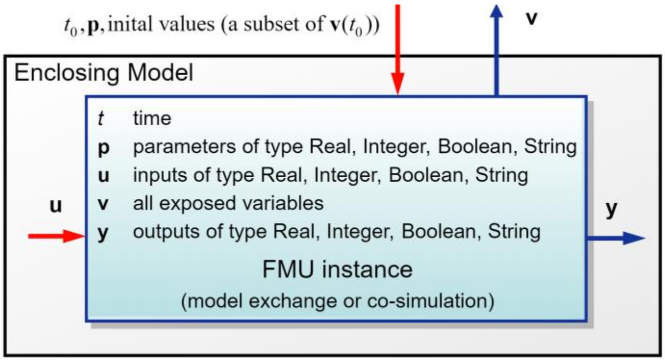


Figure 39 FMU schematic view [45]

The most common way of co-simulation is to simulate separated models sequentially and allow data exchange between one simulation model and another, as it is shown in Figure 43.

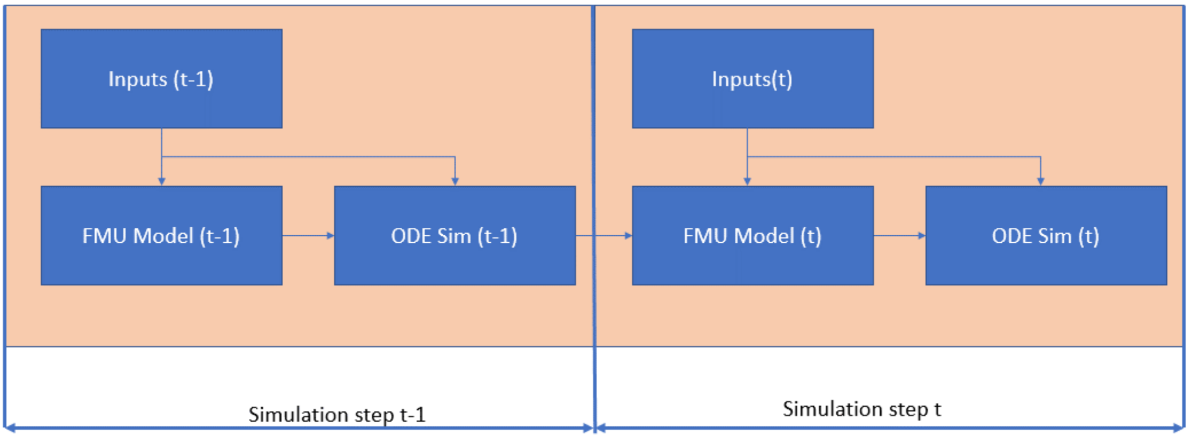


Figure 40 FMU ODE co-simulation

From the mathematical viewpoint, co-simulation results in a class of time integration methods for coupled systems which are described by time-dependent ordinary differential equations or algebraic differential equations.[46]:

$$\mathrm{i} = 1, \ldots\ldots \mathrm{r}, \mathrm{t} \in [t_{start}, t_{stop}] \begin{cases} \dot{x}_i = f_1(t, x_i, u_i) \\ \dot{y}_i = g_1(t, y_i, u_i) \end{cases} \qquad \textit{Equation 20}$$

And as it was described in [46] co-simulation accuracy strong depends on the simulation step size but the with proper model tuning the error can be minimized to magnitude of 10^{-3}

2.2.7 Development of VAP Powertrain integration API

Modelica association provides an opensource FMI library for interfacing and manipulation of the FMU.[47]This library contains main functions for interaction with the FMU of different types CS1.0, ME1.0, CS2.0,ME2.0.Such as read and initialize the FMU, set outputs and inputs, preform integration step, reading outputs or values of public variables.

This Library, however, is ambitious for our purposes, and hard to use and understand for the end-user, to make the simulation configuration user-friendly and more understandable standalone powertrain simulation library (PSL) was created. It is using FMI API as a foundation and provides a simplified interface for the integration of the FMU into any vehicle simulator. This library is released under MIT license.

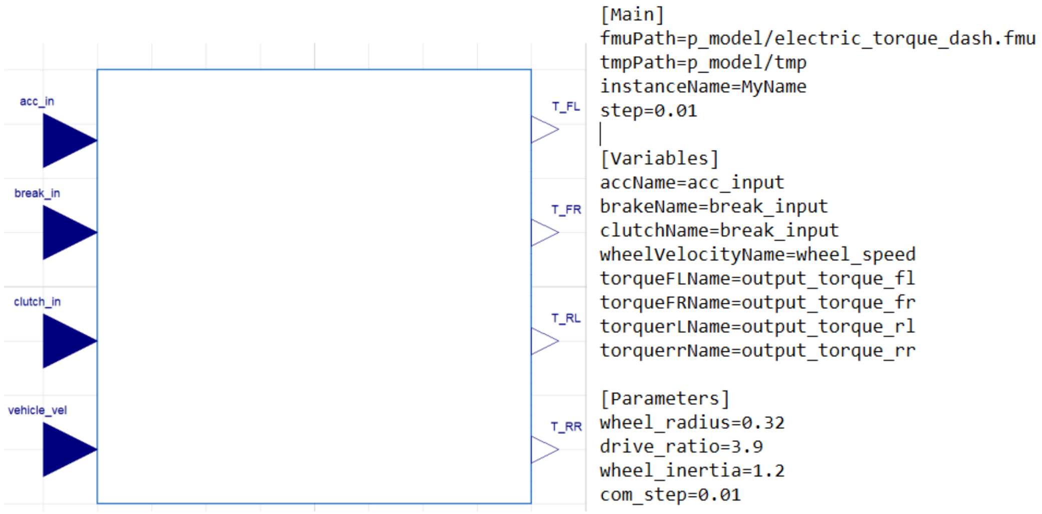
For the VAP model to work the FMU model should contain five inputs:

- Acceleration pedal.
- Braking Pedal.
- Vehicle Velocity.
- Clutch pedal (Can be set to 1 for automatic transmissions).
- Gear input (Can be set to 0 for automatic transmission).

And four outputs:

- Torque on the front left wheel.
- Torque on the front right wheel.
- Torque on the rear left wheel (can be set to 0 for 2D drive).
- Torque on the rear right wheel (can be set to 0 for 2D drive).

Additionally, it is required to create a simple setting file which defines name mapping of the inputs mentioned above and outputs channels, simulation step, FMU model location, and allows changing public model parameters. The FMU architecture and example setting file presented in Figure 41



```
[Main]
fmuPath=p_model/electric_torque_dash.fmu
tmpPath=p_model/tmp
instanceName=MyName
step=0.01

[Variables]
accName=acc_input
brakeName=break_input
clutchName=break_input
wheelVelocityName=wheel_speed
torqueFLName=output_torque_fl
torqueFRName=output_torque_fr
torquerLName=output_torque_rl
torquerrName=output_torque_rr

[Parameters]
wheel_radius=0.32
drive_ratio=3.9
wheel_inertia=1.2
com_step=0.01
```

Figure 41 VAP PSL layout and settings file

The API interface consists of several functions

- FMU load and initialization.
- FMU deinitialization.
- Setting inputs.
- Getting outputs.
- Start/Stop/Reset the simulation.
- Setting Model parameters.
- Registering Extra inputs and outputs.

Every integration point master simulation interface set up input signals to the FMU model such as acceleration, brake, clutch, gear and velocity (velocity input provides a feedback of an actual speed of the vehicle from the ODE simulation environment, which is derived for each simulation step with respect to the elevation grade, tire/road contact friction, collisions, bumps, etc.) After inputs are set, PSL performs a simulation step for the powertrain model and calculates output wheel torque for each wheel then the master applies this torque to the physical model of the vehicle in the ODE physical engine. Traction effort (Aerodynamic, acceleration, internal and rolling losses), battery, motor, and convertor behavior are calculated in the FMU model directly. After this the ODE performs its simulation step and update vehicle position (torque applied to the virtual vehicle) concerning another actors’ position. The architecture of the final solution is represented in Figure 24.

Traction effort is calculated by a Modelica component created based on equations described in chapter **Error! Reference source not found.** Additionally to the traction effort component, these elements were created:

- HMI communication interface provides a means to send and receive signals from any external devices/software via UPD communication to control the powertrain model and send desired output to the HMI interfaces. This is achieved through the extendable connector and dynamic data structure.

- Data visualization interface and software module to display simulation data for control and validation purposes.
- Data logging module – module to record the defined set of data during the simulation.
- Vehicle and Driver co-simulation interfaces provide above defines inputs and outputs for co-simulation, vehicle interface includes a traction model for resistance calculation.

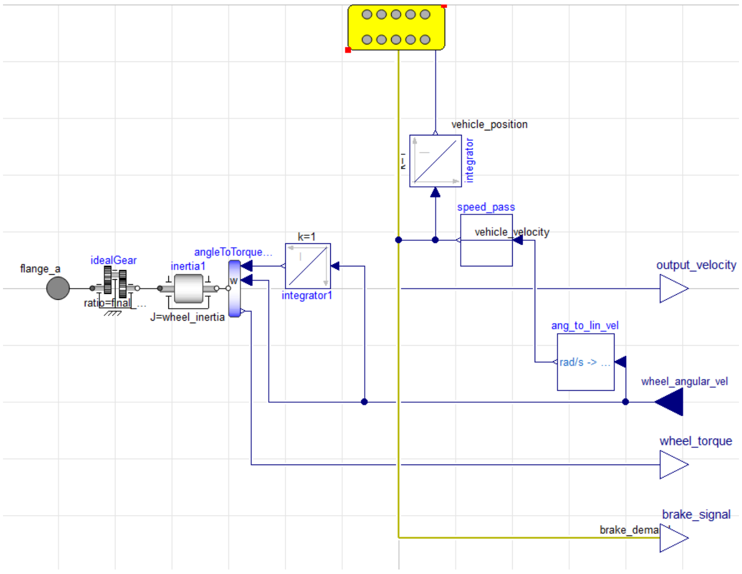


Figure 42 Vehicle co-simulation model

During the validation, it was observed that the calculation of the powertrain could take longer than real-time. This is happening due to the features of Modelica programming language (event-based calculation).In Modelica step calculation time is not determined and can vary based on the current system state rather than the complexity of calculation To overcome this limitation the PSL model simulation was moved to the parallel calculation thread, and the data exchange between the FMU Powertrain Model and ODE engine, is performed with the frequency of 100 HZ. As it is shown in Figure 43.

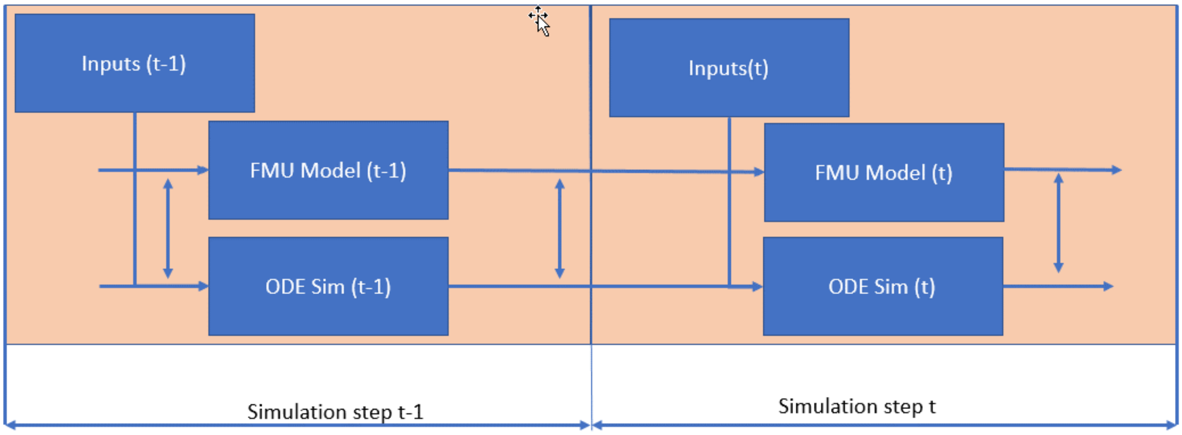


Figure 43 Parallel co-simulation technics

This approach, however, increases the co-simulation error magnitude. In [48] where developed PSL library was used to integrated combustion-engine powertrain model FMU for simulation in the Unreal Engine this error was approximately 5% for cumulative fuel consumption of the vehicle compared to the direct simulation of the powertrain model for the NEDC drive-cycle Figure 44, This error, however, can be minimized by the extrapolation of the inputs and/or outputs, and providing .[49]

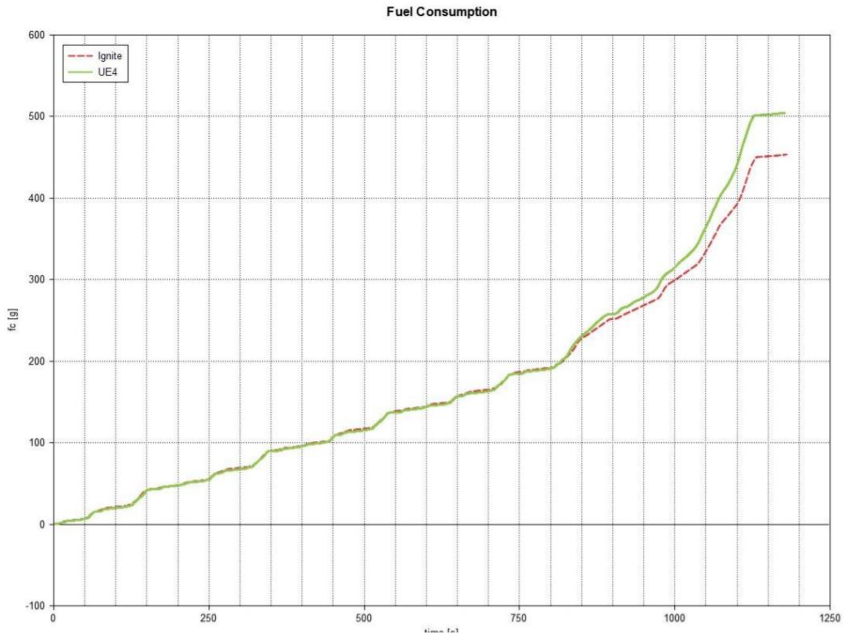


Figure 44 Fuel consumption co-simulation cumulative error [48]

2.2.7.1 Powertrain Model Creation and Hybridization

A lot of commercial software available on the market are using Modelica as a simulation language, and either already has, or are planning to implement FMU import/export routine. One of such software is IGNITE, developed by RICARDO Software. IGNITE is a physics-based system simulation package focused at complete vehicle system modeling and simulation. It consists of a set of libraries containing vehicle and thermal system components such as an engine, transmission, controllers, motors, and e.t.c.

These components allow fast and easy modeling and parametrization of a powertrain system for any vehicle, and simulation of temperature-dependent systems, this will allow further possibility to simulate heating ventilation and air condition systems (HVAC) and battery management of HEV and EV. As a part of SGS grand the negotiation with Ricardo s.r.o was arranged to provide IGNITE software free of charge for research and educational purposes for the CTU in Prague, for an unlimited period. Giving mentioned above the FMU models were created using Ricardo Ignite software.

Creation of a model of HEV in IGNITE is a straightforward process that consists of several steps :

1. Collect all necessary vehicle information (tires, aerodynamics, mass, etc.). Vehicle manufacturer usually provides this data in technical documentation.

2. Collect powertrain information (gear efficiencies, shifting maps, engine, and electric machine maps and battery characteristics). This data can either be obtained from automaker directly on request or derived from an experimental data mathematically.

3a. Build a conventional vehicle model using IGNITE libraries.

    a. Parametrize the model with collected data.
    b. Run test cases to validate the model.
    c. Turn the conventional model into a hybrid – add hybrid components (Electric motor, battery, controller).
    d. Run test cases to validate the model.

3b. Build an EV model using IGNITE libraries.

    a. Parametrize the model with collected data.
    b. Run test cases to validate the model.

4. Substitute driver and vehicle models with developed co-simulation interfaces.

For HMI simulation, we must add communication interfaces and obtain additional outputs from the model to simulate gauges and control element of HEV. Usually, these outputs include:

- State of Battery charge SoC.
- Engine speed.
- Electric machine engine speed.
- Battery temperature.
- Powertrain energy flow.
- ICE state.

These outputs can then be further processed to be displayed on a virtual gauge or in any other graphical form. The process of the HEV model creation is represented in Figure 45.

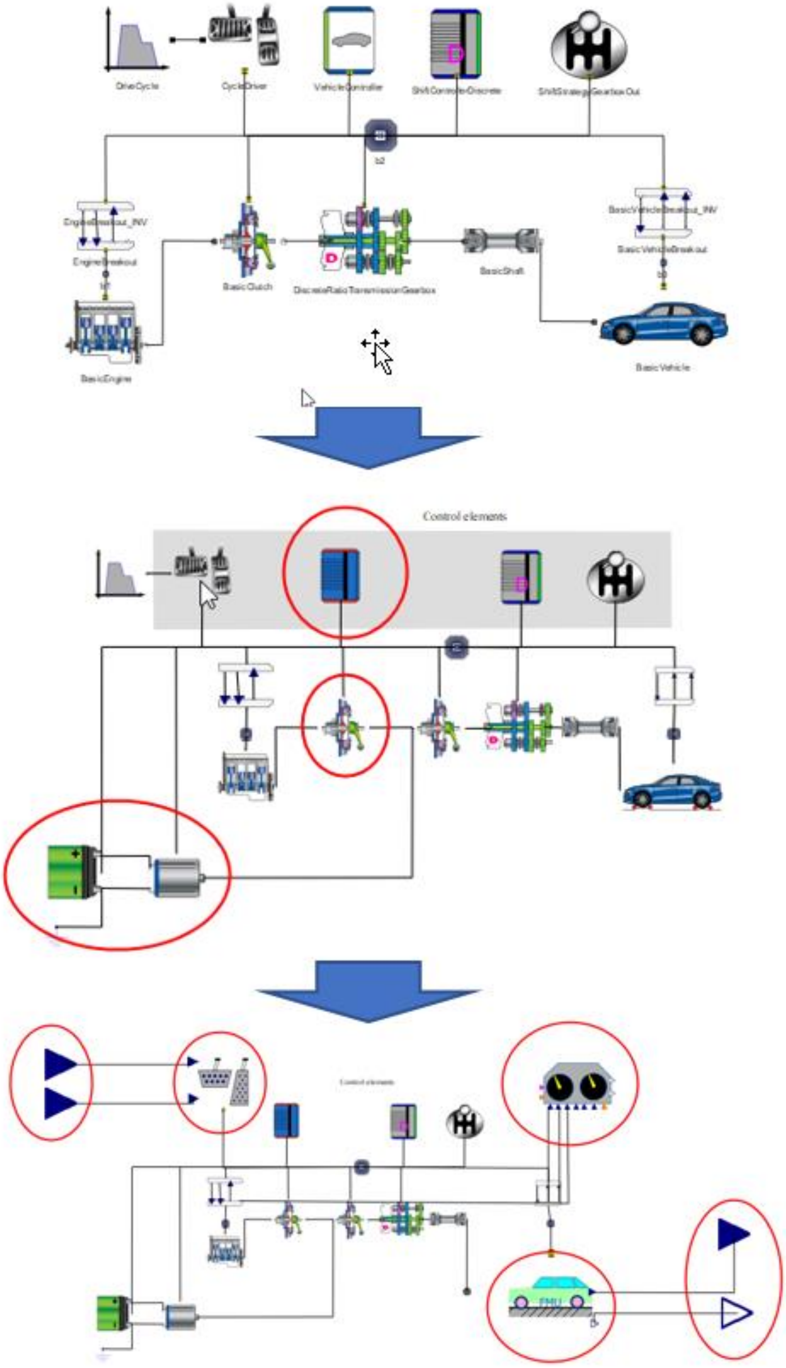


Figure 45 Model creation and hybridization

In chapter 4.1.1, this algorithm will be used to create and validate the Volkswagen E-Golf BEV vehicle. Because E-Golf is the pure BEV step 3B in the algorithm defined above is used.

2.2.7.2 Model Validation

Car manufacturers provide information about vehicle performance testing them against standard drive-cycle (DC). Drive- cycle is a set of data points of vehicle speed versus time. DC produced and standardized by different countries, either obtained theoretically or based on real measurements. New Europe Drive Cycle (NEDC)

(Figure 46 left) was used till the 1st September 2019 to estimate the levels of pollutants, CO2 emissions and fuel consumption of traditional and hybrid cars, as well as the range of fully electric vehicles. Since then, a new Worldwide Harmonised Light Vehicles Test Procedure (WLTP) (Figure 46 right) is used. The test is performed on a cold vehicle at 20–30 °C on a flat road, in the absence of wind. However, to improve repeatability, they are generally performed on a roller test bench.

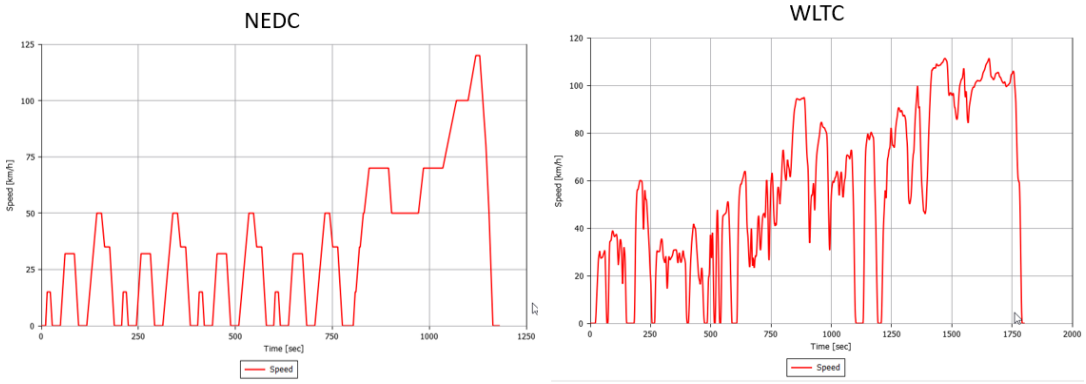


Figure 46 WLTC and NEDC drive cycles

The results from these tests are usually provided by the vehicle manufacturers, and results obtained from the simulation on the same drive cycle can be compared with provided data or analyzed. Results of the simulation contain comprehensive data for every model component and manufacturer the possibility to perform this analysis. Such measures can be used to validate the model:

- Maximal speed comparison
- Acceleration rate comparison (time to accelerate to 100 km)
- Fuel consumption comparison (for hybrid and conventional vehicle) or Distance on one charge comparison (for BEV)
    - Using NEDC or WLTC drive-cycles
- Engine working region comparison
- Braking distance

These validation metrics can be used to validate the model; against publicly available information for any vehicle. If the more reliable comparison is needed, and there is an access to experiment results or real vehicles, then comparison of internal vehicle parameters (Current, Voltage, RPM, Gear) can be performed, by simulating the model through the cycle mimicking the experiment data, and perform much more detailed comparison, or controller tuning.

2.3 Simulation of HMI interface

As it was described in the first part of the dissertation a means of simulation of HMI elements of modern EV and HEV vehicles are needed for the developed modular platform, this chapter describes the Virtual Gauge Module (VGM) developed as a part of the platform. The VGM is a software module capable to receive the data from the simulation environment and display it in different forms such as analog gauges, displays, map position, etc. on the virtual dashboard interface and additionally providing means of inputs (sliders, knobs buttons) to control the powertrain model (such as mode switching, turning different ADAS functions on/off).

2.3.1 Virtual dashboard

HMI communication component, developed in Modelica language, is used to send dynamic data via bidirectional UDP communication channel to the VGM, Input from the driver is achieved either from the touch actions (areas, virtual buttons, and switches) or through physical switches through the designed analog IO interface.

The data VDM send via the UDP channel is a vectorized structure containing information about signals such as signal type (analog/ digital), signal index, and description. This information is decoded and displayed on the VGM or redirected to the analog IO interface, or in case of reverse communication, output signals are produced by the VGM software are provided as inputs to the FMU model. The architecture of the system is represented in Figure 47

IO interface is a wiring board containing DC/DC converters to acquire inputs from analog knobs, switches, and buttons, and providing 5V outputs which can be used as external indicators such as light (diodes), servos, vibration interfaces. The board is based on the open-source Arduino platform and easily expandable to support additional IO devices. Communication with VGM is realized through RS232 communication interface.

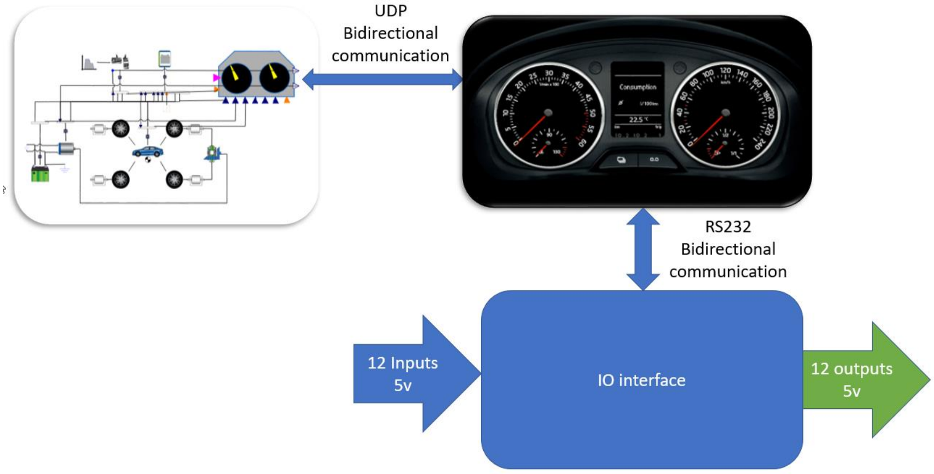


Figure 47 VDM Architecture

Adjusting of the interface layout and functionality is achieved through the setting file where for each element in the data vector should exist a description containing information such as:

- Input / Output.
- Signal index.

- Type (Gauge, Digital, Slider, Button, switch).
- Value range (minimal maximal).
- Position.
- Background.
- Dynamic background (needle, slider, switch).
- Size.
- Physical range (needle angle min, max, slider position min, max).

Example of the interface for different vehicles (electric, conventional, SUV) are represented in Figure 48.

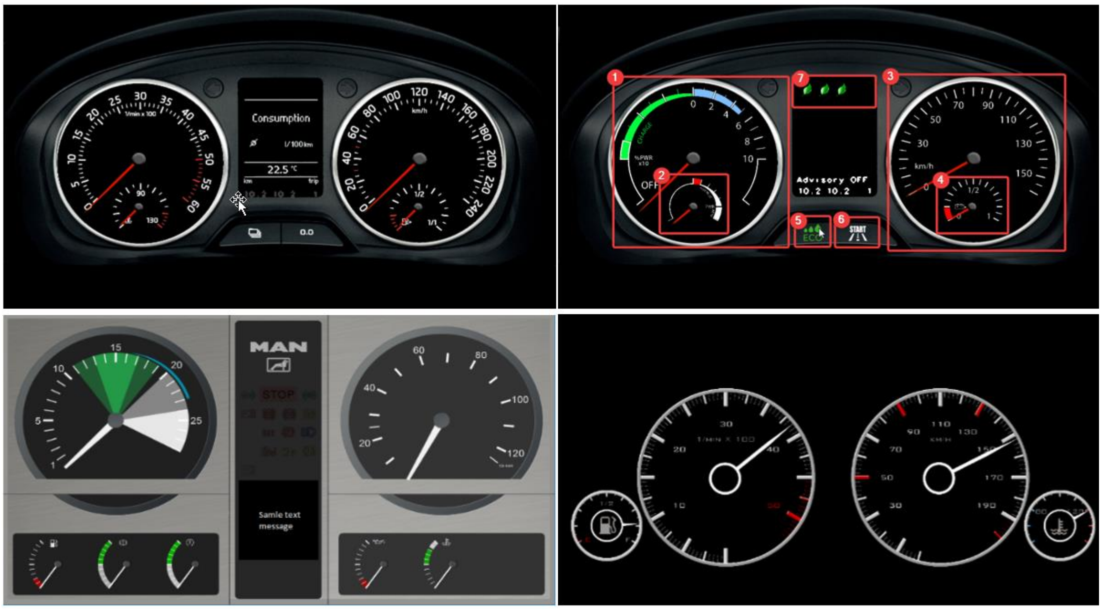


Figure 48 Example of Virtual dashboard interface

This approach allows fast and easy modification of the interface for different vehicle types and models, for different kind of experiments, one of such experiments to test an ADAS system is described in the last chapter.

2.4 Eye-tracking system integration

During the ride, a driver performs a whole set of secondary tasks such as controlling the HVAC system of the vehicle, controlling the navigation system, checking and adjusting vehicle settings. As it was described in chapter 1.2.1 HEV vehicles and Connected cars introduces a new level of complexity of provided information, demanding driver attention switching from primary driving tasks to the secondary more frequently. A situation such as a driver looking for an available charging station described in chapter 1.2.1.3 is a good example of such effect. Development of the HMI to provide such means of communication put a high demand on testing procedures and methodologies. One of the measures to estimate driver load by introducing new HMI functionality is an analysis of driver gaze, to perform these tests special equipment is needed. These devices are called Eye tracker. Where term eye-tracking (ET) means a technique, where eye movements of an individual are recorded in a way, that the researcher knows, at any given time, where the person is looking. And allows for the collection of information to infer user activity and his/her cognitive workload Moreover, nowadays, ET is also used as an input device, providing a new way to point or interact with a vehicle or monitor driver state[50], these putting the need to create the means to evaluate these systems. However, ET integration within existing systems remains a challenging task for several reasons:

- ET equipment is produced by the third-party companies as a standalone device with a non-standardized data output format and interface.
- ET system usually produced a large amount of data which is demanding to store and proceed.
- Data needs to be synchronized with the master system to allow reliable and time-oriented means for analysis.

We can separate two different categories of ET systems which can be used in the vehicle or simulator.

- Head-Mounted ET. Forward-looking camera and an infrared camera located on a helmet. An infrared camera tracks the position of a pupil through a transparent plastic mirror.
- Distant Stereo Head and ET systems. Consist of several cameras and additionally track position and rotation of a head relatively to a position of cameras.

Advantage of the second system is that the tested subject does not need to wear any additional equipment on his/her head, and results, provided by the software, has fixed coordinate origin (usually assigned during the calibration relatively to cameras position). This means that a gaze direction vector is calculated in respect to a static point of origin, in comparison to a head-mounted ES where a direction of gaze is calculated relative to a position of the head. This using a distant ET system can give an advantage during the data analysis stage.

Figure 49 Eyetracking system, distant on the left, wearable on the right [51][52]

However, regardless of the technology, the proper implementation of the analysis algorithms and software is needed to analyze produced data. This creates a challenging task on how to seamlessly integrate the ET into the developed system. This chapter is dedicated to the method of integration, providing easy means of experiment design, data synchronization, and evaluation algorithm into the developed platform.

2.4.1 Coordinate transformation

All ET systems produce similar data set which usually includes

- Blinking flag 0 when eyes are closed and 1 when eyes are opened.
- Eye-opening in % value from 0 -1 based on how wide proband eyes are opened.
- Gaze vector or gaze coordinate with respect to watching object/plane.

For the purpose of the developed platform, a special software module integrated to the vehicle simulator and dashboard system was developed to analyze the point or object of interest (special gauge, object on the road in the virtual environment or the virtual mirror).

To do this, a transformation of coordinates provided by the ET system is needed into a 3D projection, by tracing rays from the viewpoint (driver head in the real environment) into the viewing volume either of vehicle simulator itself or virtual gauges. This process is called ray-casting and involves these steps:

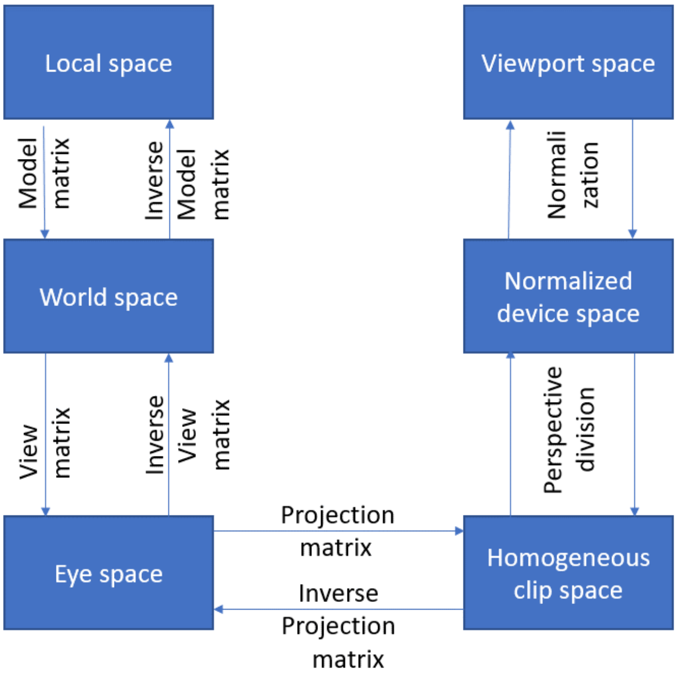


Figure 50 Diagram of ray casting algorithm:

- Map a gaze coordinate to the screen/projection coordinate system.
- Finding the ray origin and direction.
    - Origin is always situated in virtual camera location.
    - Direction can be found from a coordinate of the point on the screen from ET software and map it to Screen coordinate through inverse transformation.

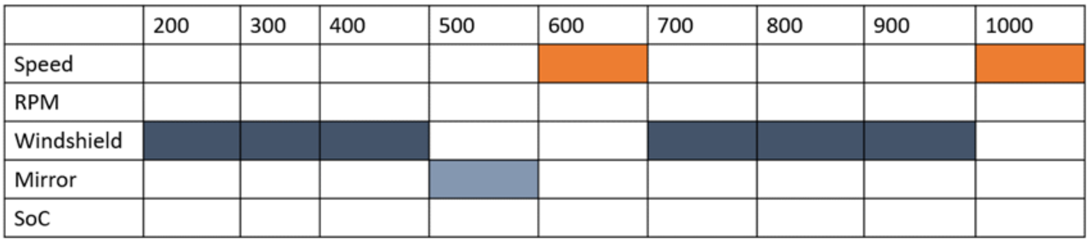
- Cast the ray through the scene and determine the closest object.

It is as well possible to perform an inverse transformation to map the position of the virtual object in the real environment. The algorithm is represented in Figure 50.

2.4.2 ET data analysis and visualization

There exist several methods to analyses data collected by the ET system. These can be divided into the following categories:

- Statistical methods.
  - Saccades -the process of visual research when the focus of attention is shifted from one object to another.
  - Number of fixations, which is often an indicator of the importance attached to a specific object.
  - Determine an object of interest (OOA).
  - Mean fixation duration or total dwell time can be correlated to the visual demand induces by the design of an object or the associated task engagement.
  - Scan path (gaze switch matrix) usually used to arrange HMI elements in a way to minimize the time to interact with HMI.
- Visualization technics.
  - Heat map or attention map - The heat maps represent the spatial distribution of eye movement throughout the HMI and can often be used for quantitative analysis. The most common method of visualizing heat maps is using a Gaussian based solution see Figure 49 left [53].
  - Timeline visualizations - A point-based timeline visualization represents time on one axis of a coordinate system and OOA name on the other axis. Such plots are usually represented in 2D space (seeFigure 51)



	200	300	400	500	600	700	800	900	1000
Speed					🟧				🟧
RPM									
Windshield	■	■	■			■	■	■	
Mirror				▨					
SoC									

Figure 51 Timeline visualization

A set of metrics used to evaluate gaze data are further described in chapter 3.2.2

2.4.3 System integration

As it was described in the beginning, it is needed to provide means of integration and synchronization of data provided by the ET and vehicle simulator. There exist two kinds of data collection methods which are:

- Usage of the original software provided by the ET manufacturer.
- Integration of the data acquisition algorithm and integrated data analysis software using a System Development Kit provided by the ET manufacturer.

For the purpose of the data synchronization, the second approach was chosen. The implementation was done by introducing a replaceable dynamic interface to the simulation architecture. This interface consists of several parts:

- ET synchronization interface – receives data from the ET system and synchronize it in the time domain with the data obtained from the simulator .
- Preforms the ray casting algorithm to determine the OOA.
- Collect and recorded synchronized data.

Result architecture is represented in Figure 52.

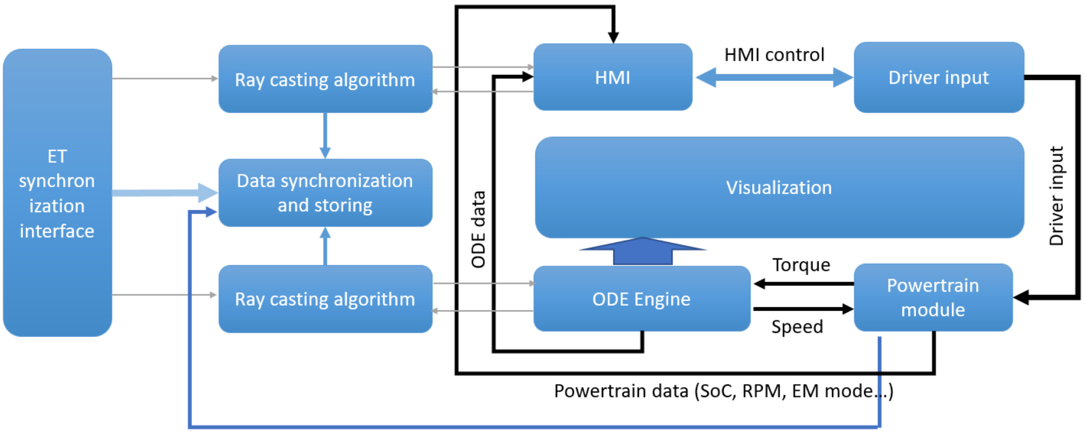


Figure 52 Eyetracking integration

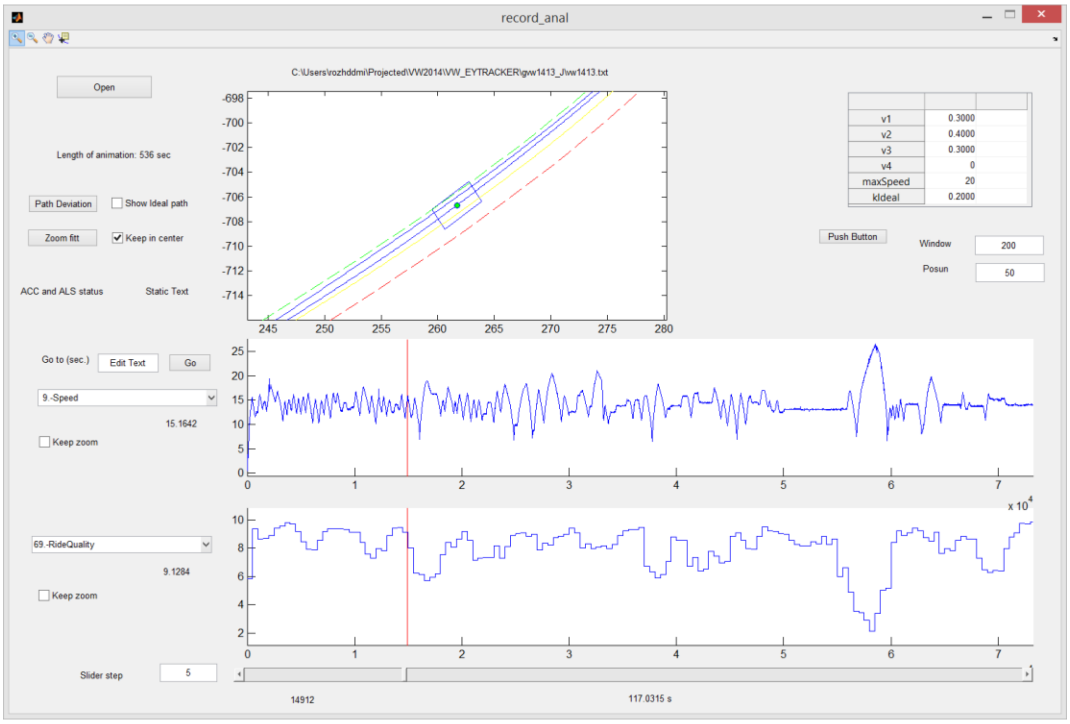
2.5 Data Analysis

A methodology developed at the faculty by DSRG members and students forms a solid background for evaluation of the experiment, driver behavior, and driver quality evaluation [55][56][57] This experience helped to create a data analysis software module written in Matlab. This module is capable of reading the data obtained from the simulator, including synchronized eye tracker data, and data from the FMU simulation module, and perform basic analysis for metrics described in chapter 3. Screenshot of the software is shown in (Figure 53).

This Modular software allows to incorporate different evaluation methods for different tasks, and perform an automatic evaluation of:

- Evaluation of Driving quality.
- Evaluation of proband workload.
- Acceptability.
- Occlusion workload.

- Driver energy efficiency.



C:\Users\rozhddmi\Projected\VW2014\VW_EYTRACKER\gw1413_J\ww1413.txt

Length of animation: 536 sec

9.-Speed 15.1642

69.-RideQuality 9.1284

v1	0.3000	
v2	0.4000	
v3	0.3000	
v4	0	
maxSpeed	20	
kIdeal	0.2000	

Window 200

Posun 50

Slider step 5

14912

117.0315 s

Figure 53 Data Analysis software

This software again follows the principles of modularity and allows in the future to integrate additional modules for data evaluation.

2.6 Conclusion to the second chapter

This chapter described developed set of new tools and measures to simulate and evaluate EV and HEV systems and HMI interface. This set of tools consists of:

- Modular module for EV and HEV powertrain simulation integrated to the vehicle simulator.
    - Basic EV and HEV components developed form mathematical equations and implemented in Modelica programming language.
    - Communication interface element for the purpose of data exchange between the powertrain module and HMI simulation software.
    - Model creation and validation guidelines.
- Modular HMI software capable of simulation of different HMI elements of modern vehicles.
    - Virtual dashboard software.
    - Analog IO device for simulation physical components such as buttons knobs, haptic and vibration modules and signalization elements.
- Eye tracker integration module, for data acquisition and synchronization
- Data analysis software.

This set of tools creates a universal testing platform allowing simulation and validation of a variety of different systems. Validations of capability and acceptability of these tools based on the guidelines for experiment design and evaluation measures explained in chapter 3, is presented further in chapter 4. The approach used to create the platform was to make easily adjustable and upgradable system for further implementation of different powertrain components such as battery management, HVAC systems, thermal simulation, or more detailed simulation of separate components such as fuel cells, or different types of batteries. Developed integration technics allow fast and efficient integration of additional HMI elements such as mobile devices, secondary and heads-up screens. And synchronization and evaluation of different measurement equipment. Thus, creating a solid background for further research in the area of EV and HEV.

3. Experiment design Methodology

This chapter deals with the development and description of the experiment design guidelines. It categorizes experiments related to the EV and HEV vehicles and their HMI and provides guidelines for the design of the virtual environment, experiment timelines, and metrics used in the evaluation phase.

We can divide possible experiments related to the EV and HEV vehicles into several categories, such as:

- Experiments aimed to determine general user acceptance of HMI and its efficiency.
- Experiments aimed to determine the effect of HMI on
    - Driver energy efficiency.
    - Range anxiety phenomena.
- Experiments aimed to compare different HMI against each other.
- Experiments aimed to study acceptance and effect of HMI element.
- Experiments aimed to determine preferred feedbacks on different event types.

Even though any of these experiments should be adapted to a specific requirement, we can distinguish ten high-level steps essential for any type of experiment

- Determine the aims of evaluation in terms of usability, safety, workload, acceptability, time frame.
- Describe a system (systems) which will be tested during the experiment.
- Define a high-level scenario (scenarios) In terms of road type, and conditions, visibility, traffic type and actors, tasks and goals.
- Define the subject sample in terms of amount, age and experience group.
- Define subjective and objective parameters and instruments to collect and evaluate them.
- Develop experimental instruction for both participants and experimenters.
- Perform a pilot experiment test and data evaluation..
- Carry out the experiment.
- Analyze the data.
- Produce the summary report and conclusion.

3.1 User acceptance and preferred feedbacks

This chapter describes a best practice to performing experiments aimed to evaluate user acceptance and preferred feedbacks of the HMI interface or a particular HMI element, at the chapter 4.1 this methodology would be applied to evaluate the interface of the VW E-Golf vehicle

We can distinguish between user and social acceptance of the proposed solution, the first one is more directed towards evaluation of ergonomics, so such aspect as effectiveness, usability, and intuitiveness of the system are evaluated and the second one focused on system usefulness equity affordability and overall user satisfaction.

Moreover, these kinds of experiments are aimed to evaluate a new concept of the HMI in the early stage of development or analyses and improve existed version and to obtain user feedback on HMI look and feel experience and propose appropriate design changes if needed.

Usability, from the other hand, has a too wide meaning to understand if a system satisfies all the user needs. In [58] it was proposed to subdivide usability metric into five subcategories:

- Learning difficulty - How easy is it for users to accomplish basic tasks the first time they encounter the design.
- The efficiency of the usage- Once users have learned the design, how quickly can they perform tasks?
- Difficulty to remember – When a user returns to the system evaluation after a period of not using it, how easily can they recall the functionality of the system?
- Error persistence - How many errors do users make, how severe are these errors, and how easily can they recover from the errors?
- Subjective feeling - How pleasant is it to use the design?

Objective measures of primary task interference, such as lateral and longitudinal control and visual behavior, are affected by the driver’s workload, which can be influenced by the interaction of the driver with tested system, Metrics to evaluate these measures are discussed further in chapter 3.2.1 At the same time to measures secondary driver task these metrics can be used:

- Time to perform a related task – measured in seconds after proband was asked to perform desirable action, this time is measured by the operator or automatically.
- Error during task performance – the amount of false actions or misjudgments during the task execution, this parameter also is measured by the operator or based on analysis of the experiment video or data.

Subjective measures, which involve the assessment of people’s attitudes and opinions towards a system, primarily yield qualitative data. This data usually obtained through pre and post-experiment questionnaires and direct verbal interaction with a proband during the experiment.

Usually, experiments focused on the usability evaluation should follow the following rules:

- Should contain static test of HMI (without vehicle movement) when user familiarize himself with a system.
- Should cover all evaluated state of HMI.
- Should contain dynamic test of HMI (Interaction with HMI while driving) in different areas (rural areas, city area, highway, mixed drive).
- Pre experiment questionnaires.
- On-going experiment questionnaires.

- Post-experiment questionnaires.

The good practice is to make a recording of the experiment for future analysis, especially during the on-going experiment questionnaire.

During this experiment, we need to measure and evaluate

- Proband Workload using NASA-TLX[4] methodology.
- Occlusion workload.
- Driving quality and efficiency.

Evaluation of subjective data is a multidimensional task, and as it was correctly stated in [68], there is no standard way of doing it. However, a Van der Laan scale methodology proved to be a reliable way to validate user acceptance[68]. This is a two-dimensional scale to evaluate usefulness and satisfaction from a system or separate system function/mode. A user is asked to fill the table with a question “How do you evaluate a system/function/mode” and asked to fill up a form presented in Table 4. Afterward, the tables are evaluated as following

Usefulness scale is the sum of item 1 + 3 + 5 + 7 + 9 divided by 5 (so it has a range from -2 to +2), the Satisfying scale is the sum of items 2, 4, 6, and 8, divided by 4.

Table 4Van der Laan Scale[68]

		Scale					
		-2	-1	0	1	2	
1	Useful						Useless
2	Pleasant						Unpleasant
3	Bad						Good
4	Nice						Annoying
5	Effective						Superfluous
6	Irritating						Likeable
7	Assisting						Worthless
8	Undesirable						Desirable
9	Raising Alertness						Sleep-inducing

---

[4] Subjective, multidimensional assessment tool that rates perceived workload in order to assess a task, system, or team's effectiveness or other aspects of performance. [Wikipedia]

This scale can be used to evaluate HMI interfaces after the experiment through post-experiment questionnaires. However it does not take into account user category and his familiarity with tested technology, so-called pre-experiment questionnaires are usually used to categorize user. These can be divided into four sets:

- General categorization: age, gender, education level, marital status, number of children and job title.
- Driving group categorization this set is aimed to categorize the driver experience based on his age at which participants started driving, driving frequency, kilometers that participants drove per year, type of road where they usually drove, number of fines that they had received for offenses and if they had participated in any special driving course.
- Health condition and current medical state aimed to understand if anything could influence their performance This set includes such questions as if a driver uses contact lenses, if they had taken any medication int he last 48 hours or whether they tended to feel sick when traveling by car.
- Technology familiarization questions such as if the driver is familiar what is EV or HEV, if he had any previous experience, what is his attitude to the technology, was he considering this as a possible purchase and why.

During the data analysis, this data can be used to better understand the distribution of the results according to the specific proband group and to analyze user needs and requirements better.

3.2 Experiments determine the effect of HMI on user behavior

These types of experiments are aimed to measure the effect of the HMI or ADAS system on user behavior or performance. The methodology defined in the previous chapter can still be used to evaluate the user acceptance of new technology, but additionally, a more specific objective metrics should be used to evaluate the effect of the system on user behavior.

To perform these types of experiments, a base data set (the data measured in the same virtual environment without the system) should be compared with the data sets obtained from the experiments where the system is activated.

We can distinguish three metrics groups to evaluate driver performance; these include:

- Drive quality metrics used to evaluate driving performance.
- Gaze related metrics usually used to evaluate driver workload.
- Energy metrics used to evaluate driver efficiency in terms of fuel consumption.

3.2.1 Driving quality metrics

In this subchapter metrics to evaluate driver quality are described in some extend. The energy efficiency metrics were developed here to use them to evaluate the effect of EV and HEV vehicle systems and HMI on the driver performance in terms of fuel efficiency. The metrics are sorted under the following main categories

- Longitudinal control metrics.
- Lateral control metrics.
- Gaze metrics.
- Energy efficiency metrics.

3.2.1.1 longitudinal metrics

The longitudinal metrics can be grouped into three major categories:

- Speed.
- Vehicle following.
- Pedal movement metrics.

Speed metrics

Speed metrics are commonly used in studies of driving behavior. For instance, it can be used for evaluation of speed-reducing effects of, for example, Intelligent Speed Adaptor, also in the assessment of autonomous driving systems like Cruise Control and Adaptive Cruise Control and Stop&Go system or speed advisory system and GPS navigation.

Studies show that visual distraction (visual task) causes a decrease in travel speed [69][70] and[71]. We can use four different types of speed metrics to determine the driving quality and driver workload:

- Mean speed -The average of the speed calculated as the total distance traveled by the vehicle divided by the elapsed time to cover that distance. This metrics can be used to evaluate the effect of the secondary task activities. It was shown in [70] that a driver tends to decrease his speed during the secondary task due to the reduction of primary task demand.
- Speed variation (standard deviation of speed) tends to increase with the increased secondary task [60][59]for the driver. A high pass filter with application of 0.1 Hz cut-off frequency, the minimal valid data length of 10 seconds can be used to obtain this data .[59].
- Maximum speed the single maximum speed value. The maximum value of the velocity in the interval where the driver interacts with the system.

- Speed change - the purpose of this metric is to filter out other variance in the speed signal and to calculate the speed change during interaction with ADAS/IVIS A linear function is fitted to the speed signal in a certain interval (corresponding, e.g., to the operation of an IVIS) by means of least squares. The speed change value is then computed as the difference between the start and end value of the fitted line.

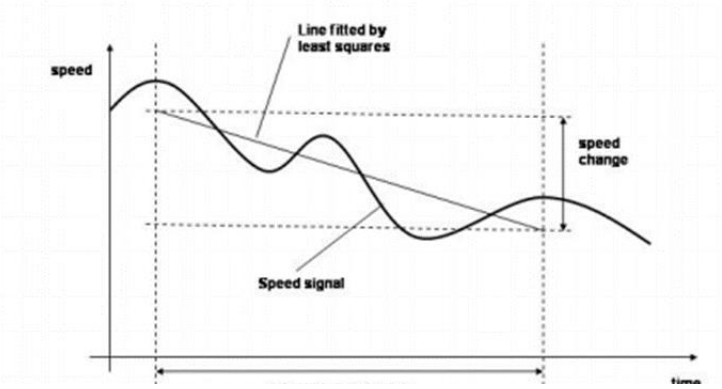


Figure 54 Speed change algorythm exampel

Vehicle following

The distance from the leading vehicle can serve as an indicator of a safety margin accepted by the driver, Reduction in this distance can be interpreted as degradation in driver performance with a negative effect of the studied system on the safety.

1. Headway metric Headway stands for a gap to a preceding vehicle. There are two types of headway – time and distance (space) headway. Given the mean headway, driver's car following strategy could be estimated. The increase of mean headway means increased mental and visual distraction, and changing headway may be evidence of failing to control own speed or traffic surroundings. Time headway is time difference for two vehicles (one followed by another) at a moment of passing the same point.
2. Time to collision (TTC) -This is time to collision with the preceding vehicle, which is close to time headway metrics and is determined as speed difference of two vehicles divided by distance between the following and leading vehicle.
3. Brake metrics is useful for estimation of reaction time. The measure is widely applied in the assessment of IVIS while performing some task. The brake reaction time usually needs to be triggered by some event. The precision of measured reaction time depends on the quality of calibration of this event, that's why this measure is somewhat complicated. It is mostly used in driver simulator experiments [72].

3.2.1.2 Lateral metrics

One of the primary driving tasks is to control a vehicle to stay inside selected lane boundaries except for the situation when a driver decided to change the lane or merge to another lane. Therefore, increased lane waving or lane boundary trespassing during interaction with the HMI interface can indicate a degradation of directional control and consequently decrease safety and increase the chance of an accident. However, this metrics is also influence by road curvature and traffic density, therefore, uniform experimental conditions (timing of interaction) are necessary for fair comparisons.

The lateral control metrics are grouped into three main categories:

- Lane-keeping metrics.
- Steering wheel metrics.
- Heading metrics.

Lane-keeping metrics

1 Lateral position variation is usually calculated as lateral position standard deviation (SDLP). The lateral position depends on data duration, therefore the SDLP shall be analyzed using time window[72] Lateral position spectral representation for the HASTE project [61] experiment results are shown in Figure 55. Lateral positions deviation has been increasing with respect to different complexity levels of the visual task (Figure 56).

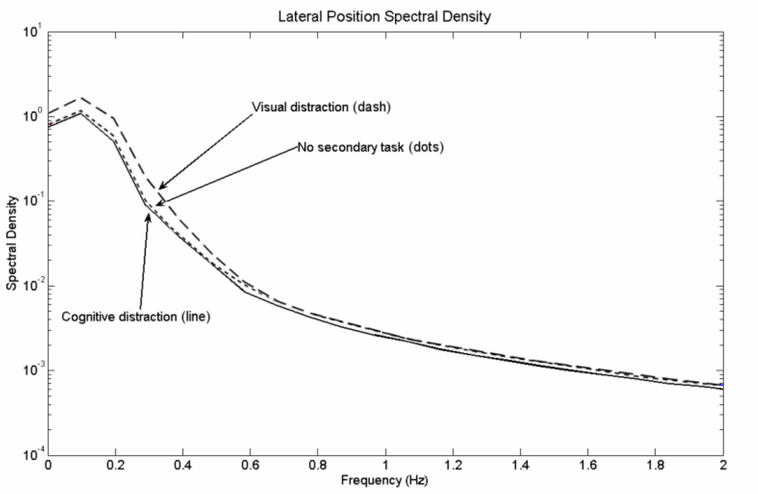


Figure 55: Lateral position spectral density based on data from an experiment within [61]

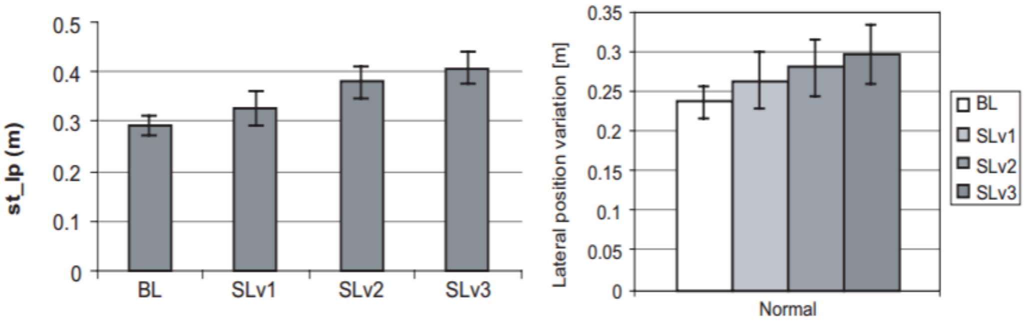


Figure 56: Lateral position deviation change task in experiments of three complexity levels as compared to baseline on two different simulators[70]

2 Vehicle position with respect to the lane - this metric is used to evaluate the area of the vehicle outside the desired lane, this can be calculated by simplification of the environment to the 2D bird view. The vehicle body is represented as a rectangle and the desired lane as a simple polygon object (see Figure 57), a lot of mathematical software algorithms and packages can be used to calculate inverse intersecting area. After this value is calculated a floating window can be used to compare these values with baseline data.

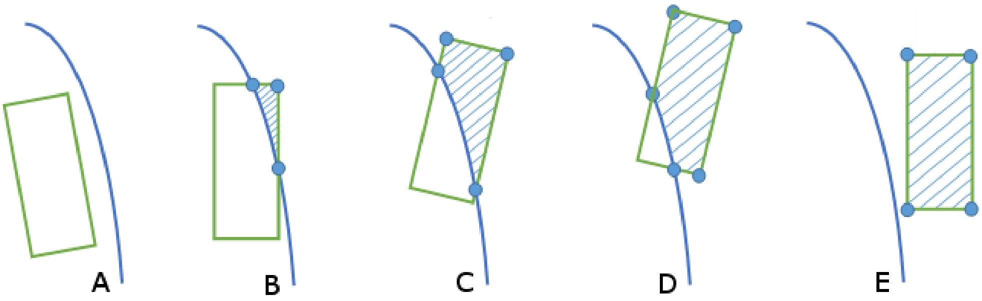


Figure 57 In-lane metrics

3 Time to line-crossing metrics (TLC) This type of metrics was developed by Godthelp and Konings in 1981. This measure stands for the estimated time needed to reach lane border mark when heading angle assumed as fixed and speed is constant. In practice, approximate TLC is estimated based on lateral position of vehicle under condition that the lateral acceleration is either negative (acceleration to the left, TLC to the left lane marking), or positive (acceleration to the right – TLC to the right lane marking). TLC cannot be estimated when lateral acceleration is equal to zero. See Figure 58 for reference. For assessment of IVIS mean TLC and number of marking line crossings can be used [72] .

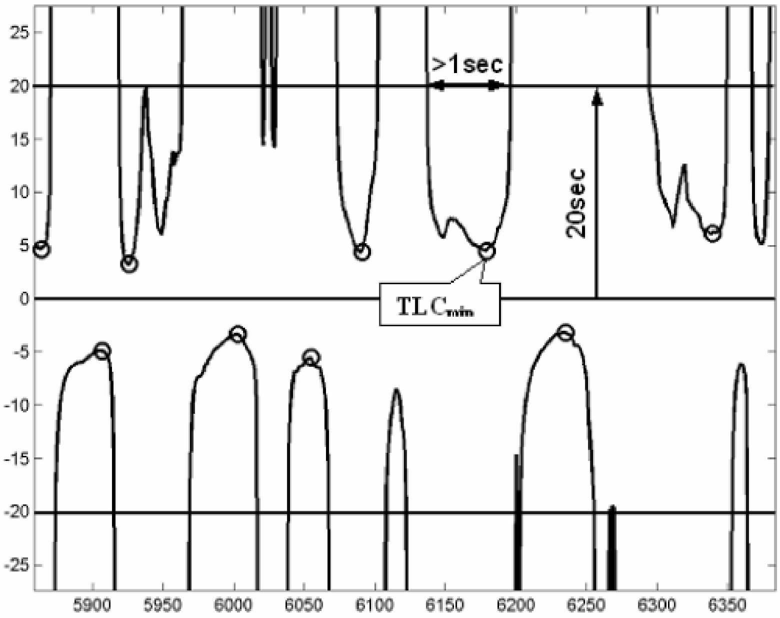


Figure 58: TLC waveforms and identification of TLC min values. [72]

4 Steering grip metrics Steering grip pressure measures the force driver applies to hold the wheel, which gives the possibility to assess driver's effort of vehicle control. With the help of a sensor developed within AWAKE project [62]it is as well possible to determine whether the steering wheel is being held with left, right or both hands, which is an evidence of driver's preparedness to control the vehicle in unexpected situations [72]. It has been shown that variation of steering grip force could be well determined, however, static grip couldn't provide enough measured data [72].

5 Steering angle metrics is a good indicator of the quality of fulfillment of driver task. Many research results show that driver secondary task increases the steering wheel activity along with a variation of lateral position [73][74]. The experimental assessment of steering with drivers being given IVIS system task has shown an increase of steering wheel angle (Figure 59) [72].

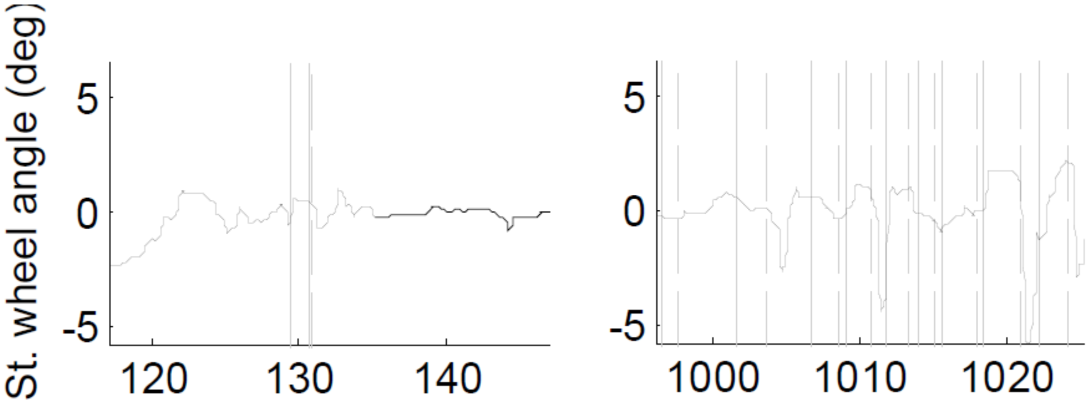


Figure 59: Steering wheel angle; a – baseline, b – visual task[72]

3.2.2 Gaze related measures

Most information required by the driver is obtained through visual observation, the amount of visual resources a driver allocated to the primary driving task can be significantly decreased by the control elements and HMI of IVIS system. This putting the driver into the multitasking phase where his attention is shared among primary driving task and IVIS control or monitoring. This, however, can create a potential problem when a driver chooses to monitor too many secondary stimuli.

Visual behavior measurement is a popular method for assessment of mental load, attention, and concentration, in experiments with IVIS systems. Traditionally the evaluation of gaze metrics was performed manually by observing the recordings of the experiment, however, developed platform includes the integration of Eyetracking software module which simplifies and accelerate the analyses of the experiment result.

The list of glance metrics is provided in Technical Specification ISO Standard ISO/TS 15007-2:2014. These includes:

1 Total Eye off-road - is a valid measure accepted by many researches to measure visual demand associated with the performance of a secondary task [63]This is measured as the amount of time driver spend not looking on the area ahead of the vehicle dividend on the whole time of the experiment task. National Highway Traffic Safety Administration issued a 12-s total eyes-off-road time (TEORT) glance criterion for its visual-manual guidelines simulator test.

2 Number of glances - count of the number of glances at an OOI may indicate the visual intensity of display of tested application/system and thus visual demand and attention required when manipulating with it. Example of glance count measure per area of interest can be seen in Table 5.

3 Glance duration Stands for the duration of glance at a target. Complex HMI layouts require glance durations of 1.25 seconds duration of each until the task is completed [64]. If the value trespasses this margin, the driver might be tempted to increase the average duration of glances, and thus the safety might be compromised.

4 Total glance time, this measure represents glance time at a target (HMI display or particular HMI element). See Table 5 for reference. This measure can help to evaluate problematic HMI elements.

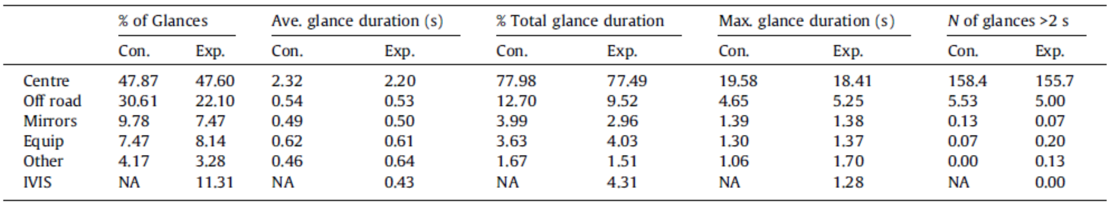
5 Glance rate (or glance frequency) This measure stands for a number of glances per area of interest (AOI). It is of often represented as the mean number of glances.

6 Percent time on AOI The measure of the distribution of time spent on different areas of interest is a measure of visual attention drawn to different areas of interest. The change of visual attention redistribution during the experiment with application of IVIS can be seen in Table 5.

7 Glance location probability. The measure stands for probability of a glance for a location. It is a relative attention demand. The measure is a distribution used for statistical comparison when calculated over a set of mutually exclusive targets or locations.

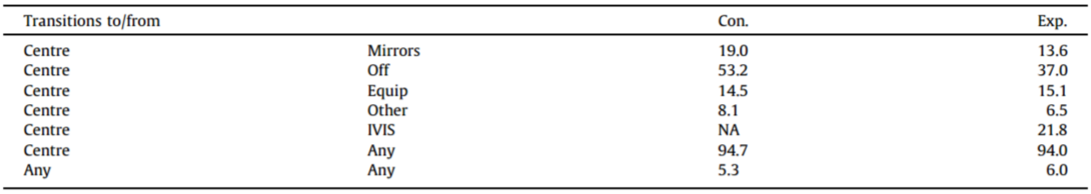
8 Percentage of transition times. The time spent on glance transition to/from a location is usually represented as percentage of total glances time. The measure helps to follow the tendencies of change in glance behavior focus between canter of the road, mirrors, and in-vehicle display concerning using in-vehicle applications. For example, the on-road study [65]has shown that 95 % of all glance transitions are either off or towards the center of the road (see Table 6). During experiment, it has also been observed that 1/5 of glance transitions was towards the tested IVIS, glances towards mirrors reduced by 5,4%. The change of glance transition values with introducing the IVIs can be seen in Figure 60.

Table 5: Example of glance duration measures from an on-road experiment with IVIS [87]



	% of Glances		Ave. glance duration (s)		% Total glance duration		Max. glance duration (s)		*N* of glances >2 s	
	Con.	Exp.	Con.	Exp.	Con.	Exp.	Con.	Exp.	Con.	Exp.
Centre	47.87	47.60	2.32	2.20	77.98	77.49	19.58	18.41	158.4	155.7
Off road	30.61	22.10	0.54	0.53	12.70	9.52	4.65	5.25	5.53	5.00
Mirrors	9.78	7.47	0.49	0.50	3.99	2.96	1.39	1.38	0.13	0.07
Equip	7.47	8.14	0.62	0.61	3.63	4.03	1.30	1.37	0.07	0.20
Other	4.17	3.28	0.46	0.64	1.67	1.51	1.06	1.70	0.00	0.13
IVIS	NA	11.31	NA	0.43	NA	4.31	NA	1.28	NA	0.00

Table 6: Example of glance transitions duration time in control and experimental conditions [65]



Transitions to/from		Con.	Exp.
Centre	Mirrors	19.0	13.6
Centre	Off	53.2	37.0
Centre	Equip	14.5	15.1
Centre	Other	8.1	6.5
Centre	IVIS	NA	21.8
Centre	Any	94.7	94.0
Any	Any	5.3	6.0

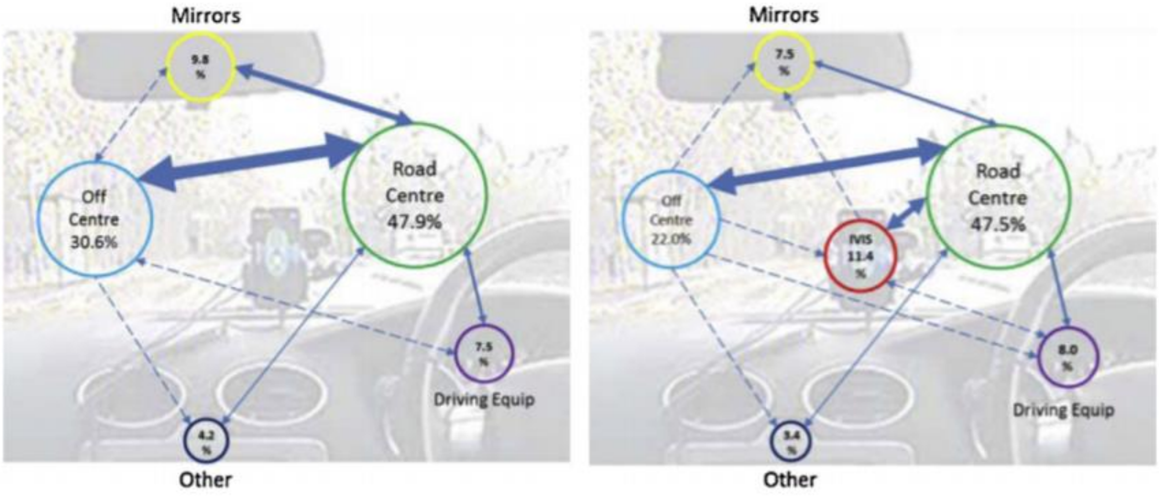


Figure 60: Glance decomposition analysis in the experiment without (left) and with (right) IVIS [7]

3.2.3 Energy efficiency measurement

Set of metrics developed to evaluate the effect of the EV HEV system or HMI are listed in this chapter This measure can be applied to compare the effect of proposed HMI solution on the fuel or energy consumption of the vehicle. And has to be calculated for two cases. At the same road segments. The first case is called baseline $W_b$and it is calculated for the road segment without active HMI system and the second is W_e calculated with an active HMI notification.

3.2.3.1 Cumulative energy consumption measure

This measure is applied to the predefined interval of length L [m] and calculated as cumulative energy consumption in [MJ] using *Equation 21* for ICE and *Equation 22* for EV. For hybrid vehicles, this measure is a summation for all types of fuels used in the vehicle $W_l + W_e$. To convert consumption of liquid fuels into the energy use K_f described in Table 7.

$$W_l = \sum_n (Q_{begining} - Q_{end}) * K_f \qquad \textit{Equation 21}$$

Where:

- $Q_{begining}$ and Q_{end} is the volume of fuel at the beginning of the segment and at the end of the segment consequently and *n* is the amount of fuel sources.
- K_f can be found using Table 7.

Table 7 Fuel Energy Density

Fuel composition	Type	**MJ/liter**	**Litre/Tonne**	**GJ/tonne**
LPG	propane	25.3	1960	49.6
LPG	butane	27.7	1750	49.1
LPG	mixture	25.7	1928	49.6
Gasoline	aviation	33.0	1412	49.6
Gasoline	automotive	34.2	1360	46.4
Kerosene	power	37.5	1230	46.1
Kerosene	turbine fuel	36.8	1261	46.4
Kerosene	lighting	36.6	1270	46.5
Diesel Oil	automotive	38.6	1182	45.6
Diesel Oil	industrial	39.6	1135	44.9
Fuel Oil	low sulphur	39.7	1110	44.1
Fuel Oil	high sulphur	40.8	1050	42.9

For electric energy:

$$W_e = V * \frac{\Delta SoC * C}{100} * 3600 * (1e - 6) \qquad \textit{Equation 22}$$

Where:

- V is a battery voltage.
- C – is an initial battery capacity.
- ΔSoC is a difference of state of the battery at the beginning of the segment and a the end of the segment consequently.

Comparison of two different consumptions on the road interval than can be calculated using *Equation 23*

$$E_c = \frac{(W_{base} + W_{exp})}{W_b} * 100 \qquad \textit{Equation 23}$$

Where:

- W_{base} is cumulative energy consumption for baseline experiment.
- W_{exp} is cumulative energy consumption for experiment with the activated system.

3.2.3.2 Regenerative braking efficiency energy-based

This metrics is calculated as a ration of available kinetic energy divided by the energy supplied to the energy storage. Where available kinetic energy is calculated using *Equation 24.*

$$W_k = \frac{m * v^2}{2} \qquad \textit{Equation 24}$$

Where

- v - is a vehicle velocity before deceleration.
- m – vehicle mass.

And energy supplied to the energy storage

$$W_e = V * \frac{\Delta SoC * C}{100} * 3600 \qquad \textit{Equation 25}$$

Where

- V - is a battery voltage.
- C – is an initial battery capacity.
- ΔSoC –is a difference of state of the battery at the beginning of the deceleration and end of deceleration.

The resulting efficiency is then calculated using *Equation 26*

$$E_r = \frac{W_e}{W_k} * 100 \qquad \textit{Equation 26}$$

3.2.3.3 Regenerative braking efficiency brake engagement

However, in the majority of EV ΔSoC is dependent on a different external variable such as state of ancillary system, temperature, and even an actual SoC, in this case, it is advised to implement a simplified measure where the braking force provided by the braking disks are compared with the overall braking force. The physical measurement of these parameters is a complex engineering task, however in a vehicle simulator with the developed FMU module integration this data is available. The resulting measure is then calculated as follows:

$$E_r = 1 - \frac{\int F_{decel} \; - \; F_{traction}}{\int F_{brake}} \qquad \textit{Equation 27}$$

Where

- F_{decel} Force acting on the vehicle during the slowing down.
- $F_{traction}$Traction force action on vehicle *Equation 4*.
- F_{brake} Force by mechanical brakes .

All these values provided as an output from the FMU module

3.2.3.4 Hybridization efficiency

This is a measure applied only for hybrid vehicles and tends to evaluate the efficiency of hybridization for the whole route and calculated as a ratio of the road distance passed using only alternative propulsion versus overall rout length driven by the driver. And calculated as

$$E_h = \frac{D_e}{D_r} \qquad \textit{Equation 28}$$

Where

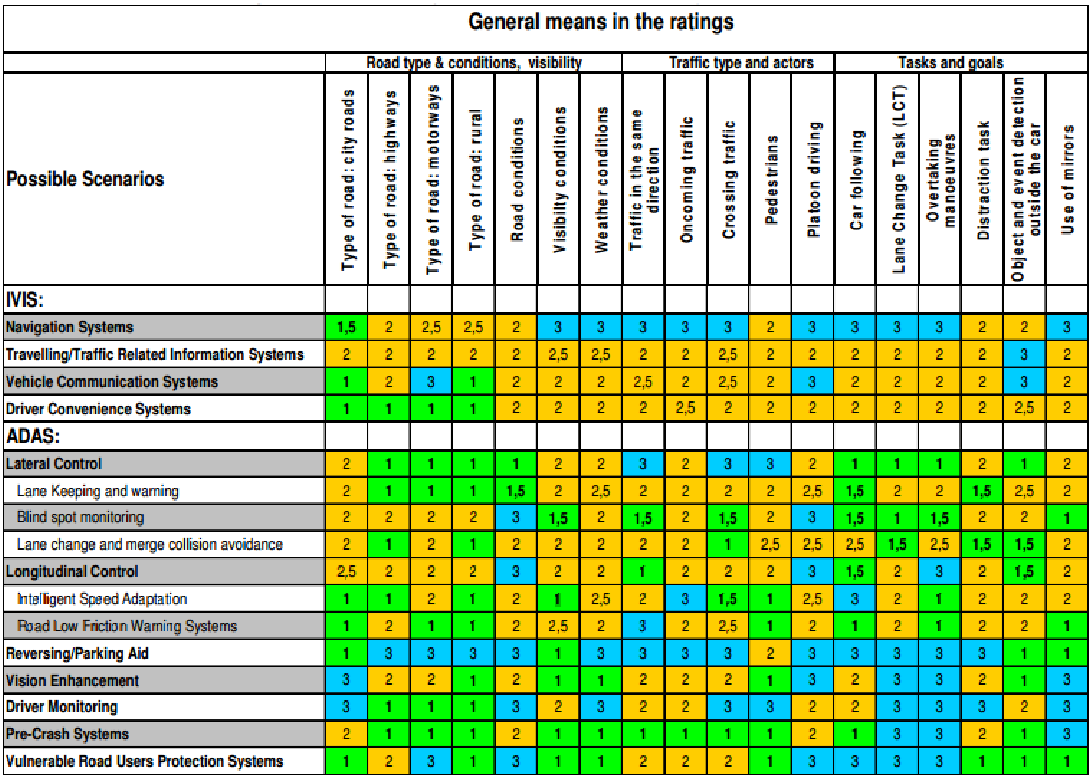
- D_e is a distance passed with ICE engine off.
- D_r is a distance of the whole route.

3.3 Scenario guidelines

This subchapter defines a guideline to create a scenario to test EV and HEV system or HMI.

A scenario is a combination of virtual environment and events happening during the experiment on the vehicle simulator. This environment includes static objects such as road infrastructure, surroundings and buildings and dynamic actors such as traffic lights, information signs, and billboard, traffic and pedestrians. These dynamic actors are playing a crucial role in testing and evaluation of the Connected Cars and Smart city concepts. To create a scenario a proper understanding of the HMI concept, function and purpose are needed. Relevance Table of Scenario Building blocks developed in [59]for validation of HMI interface for ADAS and IVIS can be used to determine static and dynamic composition of the scenario (see Table 8). The first step is to classify HMI for electric and hybrid vehicle in terms of IVIS and ADAS functionality. HMI of EVI can be considered Driver Convenience System with a possibility to effect longitudinal control of the vehicle in terms of regenerative braking and adjustable power.

Table 8 Scenario Building matrix [72]



General means in the ratings																		
	Road type & conditions, visibility							Traffic type and actors					Tasks and goals					
Possible Scenarios	Type of road: city roads	Type of road: highways	Type of road: motorways	Type of road: rural	Road conditions	Visibilty conditions	Weather conditions	Traffic in the same direction	Oncoming traffic	Crossing traffic	Pedestrians	Platoon driving	Car following	Lane Change Task (LCT)	Overtaking manoeuvres	Distraction task	Object and event detection outside the car	Use of mirrors
IVIS:																		
Navigation Systems	1,5	2	2,5	2,5	2	3	3	3	3	3	2	3	3	3	3	2	2	3
Travelling/Traffic Related Information Systems	2	2	2	2	2	2,5	2,5	2	2	2,5	2	2	2	2	2	2	3	2
Vehicle Communication Systems	1	2	3	1	2	2	2	2,5	2	2,5	2	3	2	2	2	2	3	2
Driver Convenience Systems	1	1	1	1	2	2	2	2	2,5	2	2	2	2	2	2	2	2,5	2
ADAS:																		
Lateral Control	2	1	1	1	1	2	2	3	2	3	3	2	1	1	1	2	1	2
Lane Keeping and warning	2	1	1	1	1,5	2	2,5	2	2	2	2	2,5	1,5	2	2	1,5	2,5	2
Blind spot monitoring	2	2	2	2	3	1,5	2	1,5	2	1,5	2	3	1,5	1	1,5	2	2	1
Lane change and merge collision avoidance	2	1	2	1	2	2	2	2	2	1	2,5	2,5	2,5	1,5	2,5	1,5	1,5	2
Longitudinal Control	2,5	2	2	2	3	2	2	1	2	2	2	3	1,5	2	3	2	1,5	2
Intelligent Speed Adaptation	1	1	2	1	2	1	2,5	2	3	1,5	1	2,5	3	2	1	2	2	2
Road Low Friction Warning Systems	1	2	1	1	2	2,5	2	3	2	2,5	1	2	1	2	1	2	2	1
Reversing/Parking Aid	1	3	3	3	3	1	3	3	3	3	2	3	3	3	3	3	1	1
Vision Enhancement	3	2	2	1	2	1	1	2	2	2	1	3	2	3	3	2	1	3
Driver Monitoring	3	1	1	1	3	2	3	2	2	3	3	2	2	3	3	3	2	3
Pre-Crash Systems	2	1	1	1	2	1	1	1	1	1	1	2	1	3	3	2	1	3
Vulnerable Road Users Protection Systems	1	2	3	1	3	1	1	2	2	2	1	3	3	3	3	1	1	1

Based on the evaluation mentioned above, we can summaries requirements for experiments of EV and HEV systems and HMI. In terms of road type and condition scenario must contain all possible road types in different visible condition including:

- City road.
- Highway.
- Rural roads.

In terms of traffic types and actors, the scenario must contain simulation of traffic in both directions

Tasks and goals:

- Lane change and overtaking.
- Object and event detection including detection of HMI events and object in the virtual environment.
- Car following.
- Direction following (finish point of the simulation).

Gravity force acting on the vehicle has a significant effect on fuel consumption (the steeper the slope, the more energy is needed to overcome it $F = M * g * sin\emptyset$) the elevation profile of the road can significantly affect the result of the simulation. It is especially relevant for EV and HEV vehicles where regenerative braking can be used to recuperate the energy during descending parts of the road. Considering specific of EV and HEV, it is required to have elevation changing ground, with ascending and descending parts for all types of road conditions. However it is important to consider synchronization of events for the simulation or to use a zero elevation part of the road, for particular tasks.

3.4 Conclusion to the third chapter

It is impossible to provide a step by step methodology or instructions since each experiment is unique and requires a different approach. However, the basic principles can be used to simplify the process of experiment design.

This chapter described the guidelines and best practices for design of experiments, and evaluation of data and performance of both, driver and possible assistant system or HMI for EV and HEV vehicles. It also described a list of possible metrics for result evaluation. These metrics are specially selected and developed for the platform described in second chapter, since it assumes a synchronized data from measurement equipment and the simulation, including data from the detailed simulation of powertrain model, and eye-tracker equipment. These matrices were incorporated into the data analysis module presented in chapter 2.5

These guidelines and metrics will be further used in the next chapter, where developed technics are applied to perform several experiments on the vehicle simulator.

Finally, it is important to identify the lowest number of methods, tools, and metrics for a particular experiment in order to have a test set valid but still cost-efficient enough to capture the complex task of driving and the different expected effects of the HMI

4. System validation

This chapter is dedicated to the description of experiments performed on the platform to validate its possible application for testing of HMI and ADAS systems for EV and HEV vehicles. Two types of experiments were performed:

1. Experiments aimed to determine general user acceptance of EV and its HMI. It is aimed to understand the current attitude and knowledge of drivers toward the EV and HEV technology in general and evaluation of a particular vehicle in terms of performance and HMI. The powertrain of the Volkswagen e-Golf (2017) is replicated in the FMU module alongside the digital dashboard interface replicated in the VDM software module. This experiment uses only subjective data for the HMI evaluation. Where's the second experiment is more focused on the objective matrices and evaluation technics.
2. Experiments determine the effect of EV ADAS on the energy efficiency of the driver and its acceptance. More precisely its study's an effect of supervised driving mode on energy efficiency of the driving and compared with the baseline data. The system uses an algorithm where range prediction is calculated by "prototype" system based on elevation profile, speed limits and curvaton of the road ahead. The system advice the driver where driver should release the gas pedal and activate controlled regenerative braking deacceleration for the upcoming speed limitation. Then the system controls the motor generator demand to decelerate the vehicle limit precisely before the upcoming speed limit.

These experiments cover all main functionality of the developed platform and describe the process of powertrain model creation, HMI software adaptation, and ADAS system integration. Design guidelines, along with data analysis metrics described in previous chapter, were applied to evaluate the experiment results. At the end of both experiments an evaluation of the developed platform was performed based on the questionaries' related to the platform functionality.

4.1 The experiment focused on HMI evaluation

This chapter describes experiment steps and displays the result of the study aimed to understand current user acceptance of the Electric Vehicle in general and characteristic of one vehicle (Volkswagen E-Golf) in details. Study is performed on the interactive vehicle simulator platform with powertrain model designed and integrated through the process described in chapter 2.2.6 Pre and Post experiment questionaries' were used to understand users preferences and attitude toward Electric and hybrid vehicles and to evaluate simulated vehicle in terms of performance, regenerative braking effect, and usability of particular HMI elements. It includes three main stages:

- Evaluation of HMI.
- Evaluation of Vehicle performance.
- Evaluation of regenerative braking strength.

Only subjective data is analyzed during this experiment, this includes a comparison of the data obtained from the questionaries' before the experiment and after the experiment, during the experiment probands were asked to describe their feelings/thoughts/ concerns.

4.1.1 E -Golf mode creation and validation

In this subchapter, a process of creation and validation of an E-Golf powertrain for the experiment is described. The process starts with information gathering, model parametrization, and followed by validation of the model based on the process described in chapter 2.2.7.2.

4.1.1.1 E-Golf

The driveline of Volkswagen E-Golf consists of synchronous AC motor delivering 100kW and 290 Nm. of torque with maximum revolutions of 12,000 and a single-speed, step-down transmission. The moving power is provided by 264 Samsung lithium-ion cells in a 345kg battery pack providing 35.8kWh (up from 323 volts) the rest of the characteristics are represented in Table 9 This data was obtained from the public resources [75][76][77]. VW E-Golf has an integrated system to limit the available power of the EM-based on the current speed, state of the charge and temperature of the battery module.

Powertrain model of the driveline (presented in Figure 61) consists of the Electric motor Generator (1), Battery (2) and modified EV controller (3).

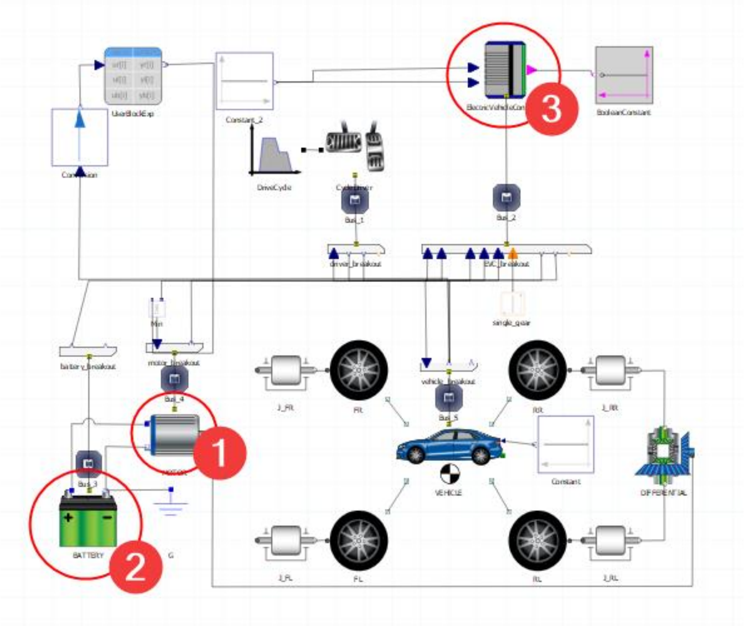


Figure 61 E-Golf powertrain model (RICARDO IGNITE)

Table 9 VW Golf electric parameters

Frontal Area	m^2	1.91
Nominal battery voltage	V	323
Rolling resistance coefficient		0.08
Wheel radius	m	0.32
Motor-generator power	W	100000
The inertia of the wheel	kg.m^2	2
Mass	kg	1600
Battery capacity	A.hr	110
Air drag coefficient		0.35
Power used by an auxiliary system	W	200
Drive ratio		9.73
Maximal Motor-generator torque	N.m	290
Efficiency		0.85

The purpose of the Electric vehicle controller is to control motor-generator (MG) demand based on the acceleration and braking pedal status and calculated available power. A state machine is used to switch between four different states of the system

- Acceleration mode (only acceleration pedal is pressed), the accelerator position is proportionally set to the MG

  $$MG_{demand} = ACC * P_{available} \qquad \text{Equation 29}$$

  Where :

  $P_{avaliable}$ is a table function of the current state of charge and current speed.

  ACC – the status of the acceleration pedal in the region <0…1>

- Coasting mode (Neither acceleration or brake pedal is pushed) depending in the chosen mode of the regenerative braking. MG demand is calculated as follows:
  - 1 – level 20% of maximal generator torque MG_{demand} = -0.2.
  - 2 – level 50% of maximal generator torque MG_{demand} = -0.5.
  - 3 – level 80% of maximal generator torque MG_{demand} = -0.8.

- 4 – level 100% of maximal generator torque MG_{demand} = -1.

The torque characteristics for different RB levels are represented in Figure 62:

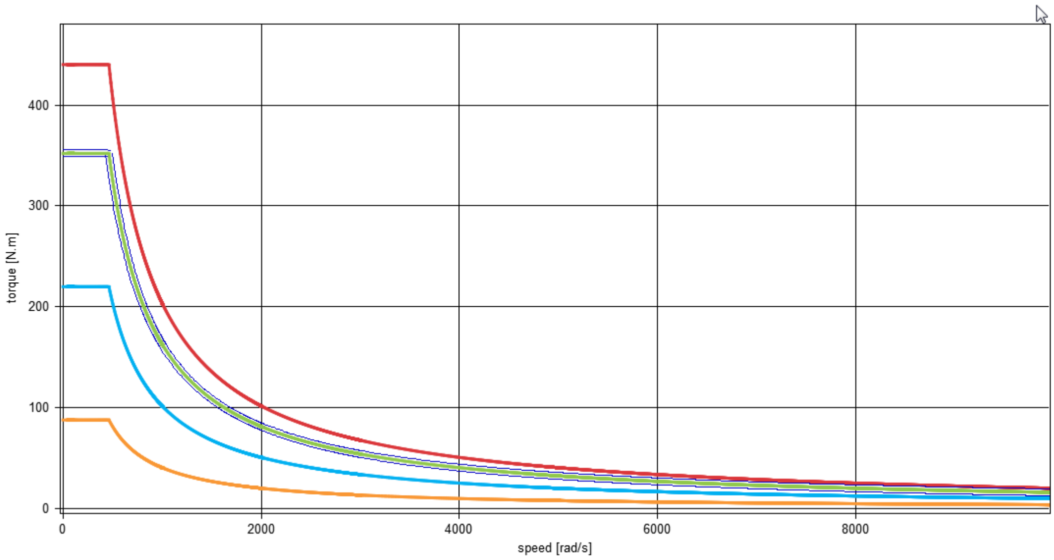


Figure 62 Regenerative torque characteristic

- Braking mode - In this mode, Controller splits the braking demand (brake pedal) between mechanical braking system and Regenerative braking as following:

$$P_r = D_{brake} * F_{brake\_max} * |V| \qquad \text{Equation 30}$$

$$MG_{demand} = P_r * P_{el\_avaliable} \qquad \text{Equation 31}$$

$$MG_{demand} = ACC * P_{available} \qquad \text{Equation 32}$$

$$MB_{demand} = \frac{P_r + MG_{demand} * P_{el\_avalaible}}{F_{brake\_max} * |V|} \qquad \text{Equation 33}$$

$$MG_{demand} = ACC * P_{available} \qquad \text{Equation 34}$$

Where :

- P_r - Requested brake power.
- D_{brake} – Brake demand (brake pedal) in the region <0…1>.
- F_{brake_max} - Maximum friction brake force.
- V – Vehicle velocity.
- MG_{demand} – Generator demand.
- MB_{demand} – Mechanical brake demand.
- $P_{el\_avaliable}$ -Amount of electrical braking available calculated from the motor. characteristic Figure 62 and current motor speed.

4.1.1.2 Internal Validation Model

As it was described in chapter 2.2.7.2 to validate the developed platform against the real vehicle, three experiments were performed:

- Maximal speed.
- WOT (wide open throttle) acceleration time from 0-100 km/h.
- Range of the vehicle on the NEDC drive cycle.

Comparison of the OEM declared figures and figures obtained in the simulation are represented in Table 10 and the output of the simulation is shown in Figure 63 and Figure 64.

Table 10 VW E-Golf model validation results

Name	Actual Value	Simulated Value	Error
Maximal speed	160 [km/h]	158[km/h]	1%
Acceleration from 0 to 100 km/h	9.6 [sec]	9.3[sec]	3%
Range	300[km]	286[km]	4%

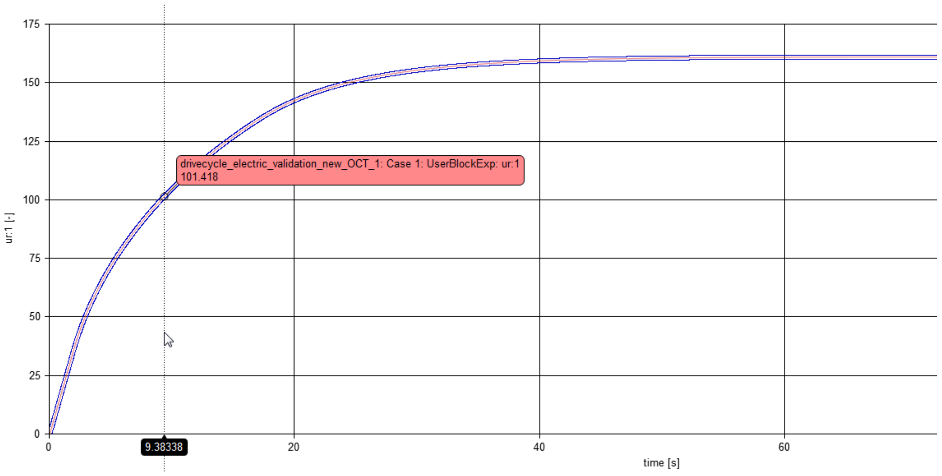


Figure 63 WOT Experiment

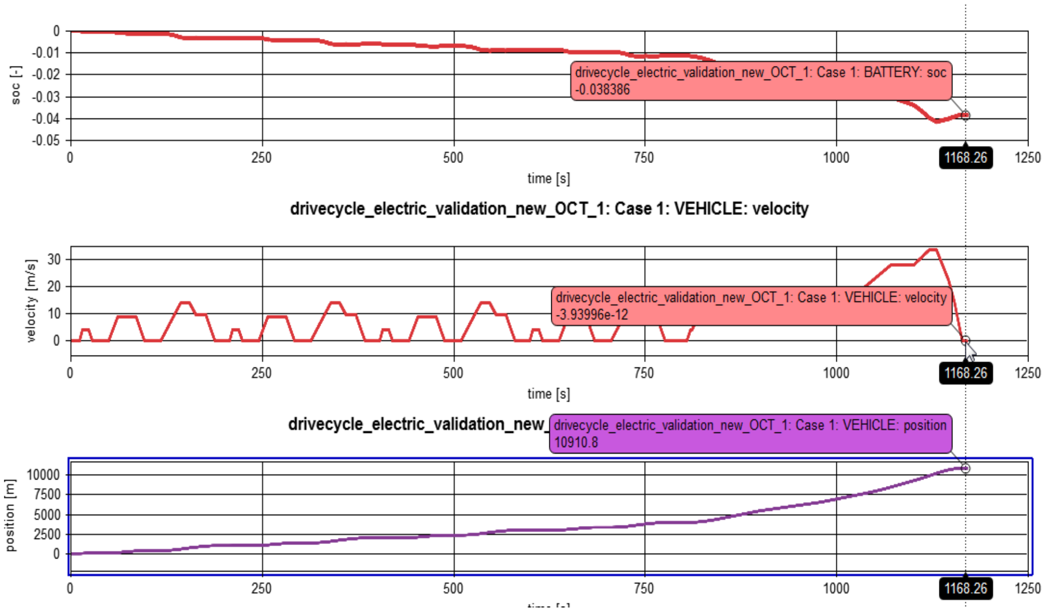


Figure 64 NEDC cycle

These results correlate closely (3% error in acceleration to 100 and 4% error in range estimation) with the data provided by the vehicle manufacturer.

4.1.2 Experiment description

Thirty probands participated in the study. However, 5 experiments were terminated due to the simulation sickness. There was no validation group for this particular experiment since the task was an evaluation of the acceptance.

Based on the guidelines for the experiment design described in section 3.3 a scenario was created It contained three different road type such as: City road, Highway and Rural roads as it can be seen in Figure 65

Before the experiment, a set of questionnaires to determine user group distribution and their familiarity with the EV and HEV technology was performed. Then a training period of 30 minutes was provided, to get probands used to the simulator, drivers were driving a vehicle with an explanation of the vehicle parameters and specifications, principals of electric vehicle and their features including regenerative braking. During this phase drivers adopted themselves to the simulator control and perception of speed and the acceleration. Then followed a task section were users were asked to perform a set of tests such and monitor the dashboard HMI of the vehicles these tests included:

- WOT acceleration and maximal speed test.
    - Highway.
- Overtaking maneuvers from the different initial speed.
    - Rural road and highway.
- Test of different modes of RB.
    - City, rural road, highway.

After followed post-experiment questionaries' to obtain the user feedback on the vehicle performance and HMI acceptance.

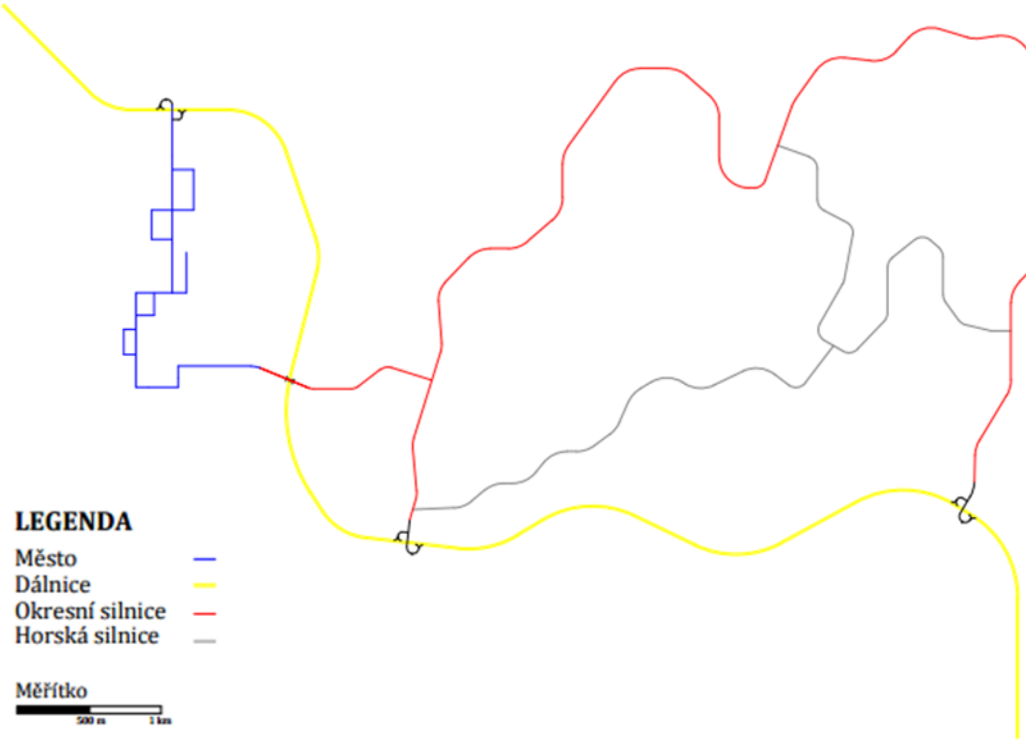


Figure 65 Scenario map

Figure 66 3D Environment of the usability experiment.

4.1.3 Group description

Twenty-five people participated in the study. Eighty percent from them male and 20% female participants, we understand that this distribution does not represent a real-life situation, where now official license distribution is shifting towards female drivers, especially in countries with developed suburban areas [78][79].

Age distribution of the group is the following:

- 58% is the group younger than 24 years.
- 42% between 25 and 40 years old.

Driver experience distribution is the following:

- 47% has less than 5 years of driver experience.
- 32% has from 5 to 10 years of experience.
- 21% are drivers with an experience of more than ten years.

In terms of kilometer per year

- 16% more than 15000.
- 42% drives 5000 to 15000 kilometers.
- 42% drives less than 5000 kilometers.

4.1.4 Groupe familiarity with EV technology

This part of the research is aimed to obtain knowledge about driver familiarities and preferences regarding EV and HEV technology. Only 15% of participated drivers had an experience with either HEV or EV before the experiment, and 80% only heard of them and knew the basic differences from conventional ICE vehicles, and 5% does not know what this term means.

Only 73 % of the participants were familiar with the term of Regenerative Braking. Results of the experiment itself, however, showed confusion or misunderstanding of the principals behind RB. Drivers tended to choose a higher level of RB during coasting (No mechanical brakes applied) with lower level of the battery. More explanation is given in next chapter.

Ninety percent of the group agreed that the range up to 500 km is acceptable for them, and 21 % are ready to by the EV vehicle if their range is less than 250 km. This closely correlates with the statistical data presented in [9] and [79] wherein year 2011 range anxiety phenomena (RAPH)[9] was main reason which stopped protentional customers from buying EV, but the recent development in the field of energy sources and battery technology minimizes the EV range limitation, and RAPH has moved on the third place, in comparison with the year 2011. Additionally, today's inhabitants already started to adapt their preferences to more realistic needs, were, on average, city inhabitant travels no more than 30 km per day. Results of the experiment showed that people now are more concerned with the prices and expect some special privileges, such as reduced taxes, reduced electricity prices, special dedicated low carbon lanes and parking lots.

This correlates with the policies proposed by the International Energy Agency[80] which includes:

- Waivers on regulations that limit the availability of license plates for ICE vehicles.
- Exemptions from access restrictions to urban areas.
- Exemptions from usage fees for specific portions of the road network.
- Dedicated parking and access to publicly available charging infrastructure.
- Allowances to access bus lanes and high-occupancy vehicle (HOV) lanes.

4.1.5 Results

In this chapter results of the experiment are described in detail.

4.1.5.1 Acceptance of the vehicle characteristics

During the experiment, probands were driving the EV on several types of roads, highway for maximal speed and acceleration evaluation, rural road, highway, and city to evaluate regenerative braking.

4.1.5.2 Acceleration performance

Before the experiment 53% of the cohort reported that 5-8 seconds acceleration time from 0-100 km/h is acceptable for electric vehicle and 30% agreed on the value of 8 to 10, this is confirmed with the question after the experiment and the acceleration rate of tested vehicle (acceleration of the tested car is 9.3 sec) was acceptable for them. Detailed results represented in Figure 67.

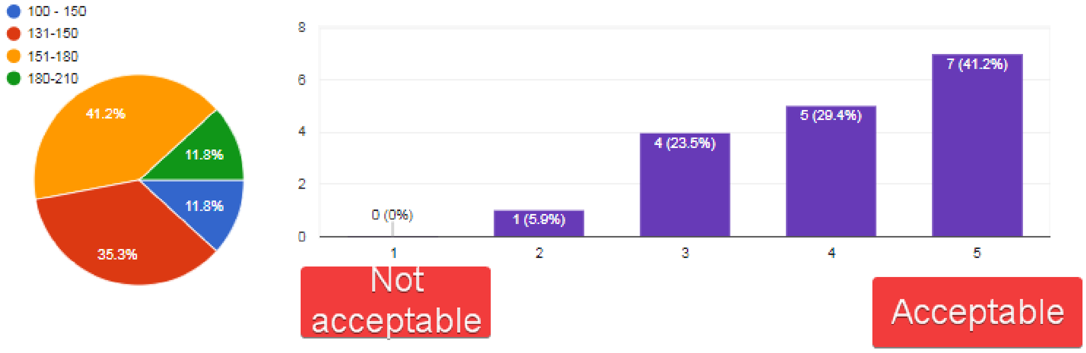


Figure 67 User acceptance of vehicle performance in terms of acceleration

4.1.5.3 Maximal speed performance

In terms of maximal speed before the experiment, 41% reports that maximal vehicle speed should be in the region of 150- 180 km/h and 35% reports even a lower speed 131- 150 km/h would be acceptable. This closely correlates with the data obtained after the experiment, where 41.2% considered the maximal speed of the vehicle (158 km/h) acceptable, and the rest of the responses are shown in Figure 68.

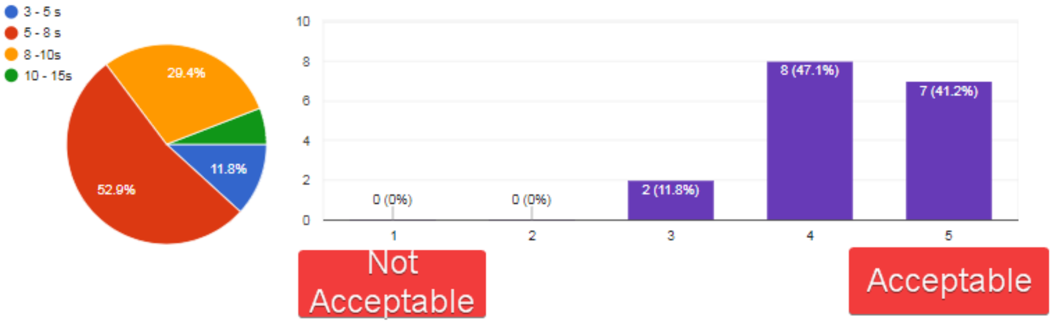


Figure 68 User acceptance of vehicle performance in terms of maximal speed

4.1.5.4 Regenerative braking

As it was already mentioned, drivers were confused with the physical principle behind the RB. The common belief is the following: "Higher deacceleration rate, more energy recuperated" for the same speed interval (deceleration from for example 100 to 80). This was also confirmed by the questionaries' performed after the experiment, where the tendency to use higher RB level was observed when the SoC of the battery was lower even so the was no need to apply mechanical brakes.

Another task of the experiment was to understand what level of regenerative braking is more suitable for a different type of roads from user experience. After driving the simulator for approximately one hour they were asked to fill in the questionnaire, the findings are the following:

Drivers tend to use a higher level of regenerative braking in the city. This can be explained with the fact that start /stop situations in the city are much more frequent and drivers can adopt themselves to use only acceleration pedal for slowing down or even bring vehicle to the full stop.

Whenever the speed goes up (rural and highway) "free" coasting is desired, meaning drivers do not want their vehicle to "lose gained kinetic energy". It worth to mention, that strongest level of RB was considered unacceptable by 44% of drivers on any kind of the road. Detailed results are presented in Table 11 and Figure 69.

Table 11 Preferred RB level

Name	City	Highway	Rural	Nowhere
Level 1	10%	44%	27%	17%
Level 2	16%	28%	48%	8%
Level 3	50%	5%	25%	20%
Level 4	44%	11%	0%	44%

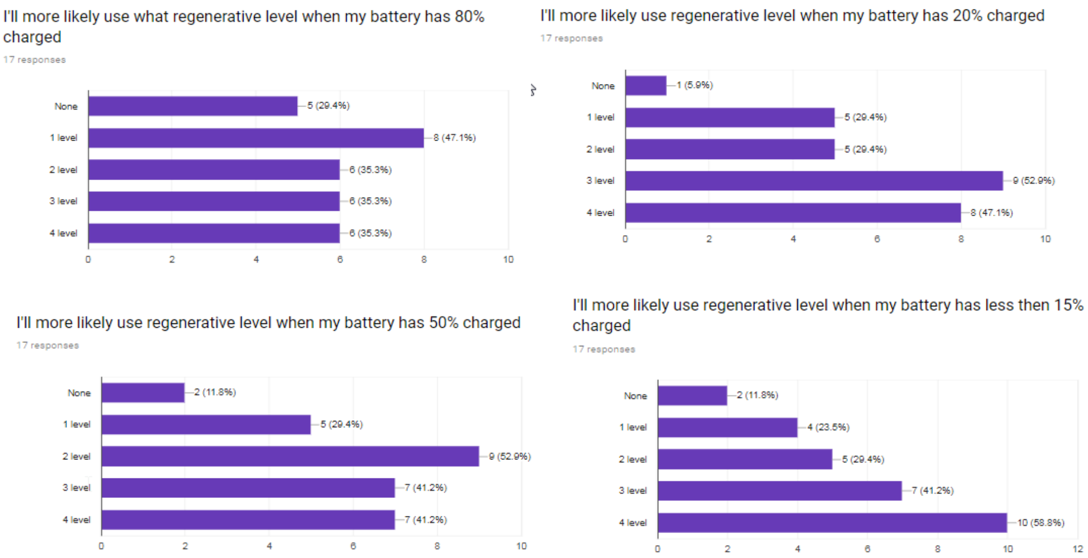


Figure 69 RB level usage preferences based on road type

4.1.5.5 Acceptance of HMI

The exact replica of the digital cluster of the e-Golf was implemented at the vehicle simulator to verify acceptance and usability of different gauges, and evaluate overall HMI. The picture of the simulated gauge is present in Fig 5 System on/off state was simulated and evaluated as well.

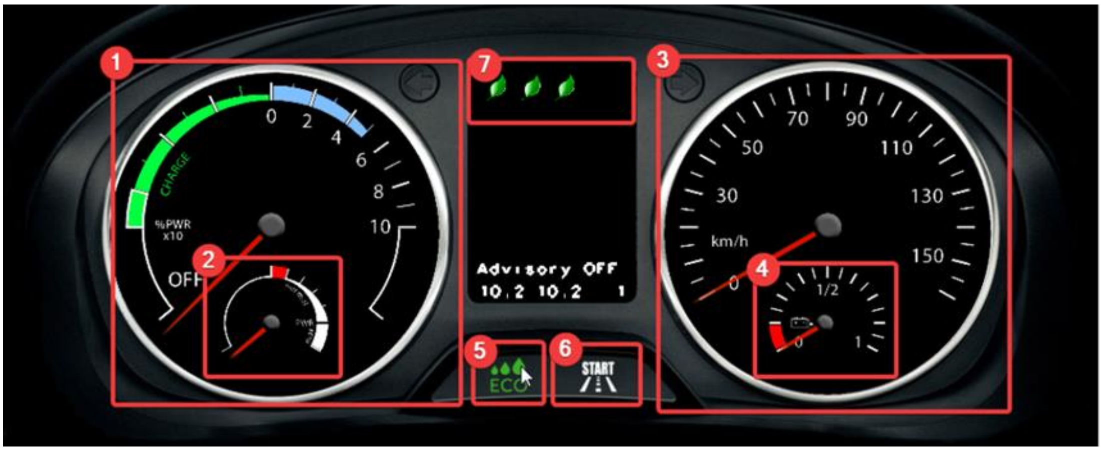


Figure 70 Simulated digital cluster VW e-Golf

The research was mainly focused on the evaluation of the power flow, available power, and state of charge gauges because they usability and effect is still a topic of many research [81][82]:

Power flow gauge (1) – it displays the current power level used, or generated in kilowatts (kW), positive numbers (blue area clockwise) meaning energy is consumed by the vehicle and negative (green are contraclockwise), meaning the energy is generated (recuperation mode). Additionally, it is used to signalize the driver when the electric vehicle is activated (started), by changing display value from OFF to 0. Results of the evaluation are the following: 11.8 % of the provands didn't understand the function of the gauge. And Usability of this gauge is close to a normal distribution with a mean value of "Close to useful" (41.2%).

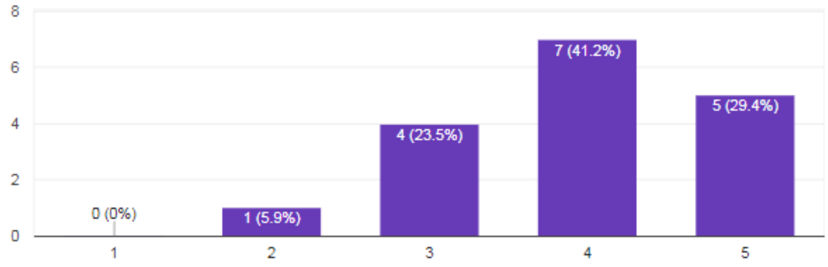


Figure 71 Evaluation of power flow gauge

Available power gauge (2) – displays percentage of maximal power available at that moment based on state of the charge, current speed, selected mode., and battery temperature Results of evaluation are following: 76% of participants did not understand the "Available power gauge", this resulted in the evaluation of the usability, 41.2% of the drivers consider it redundant. On the other hand, for those who understood and used the gauge information during the simulation reported this to be very useful 24.5% and close to useful 11.8% of the test cohort.

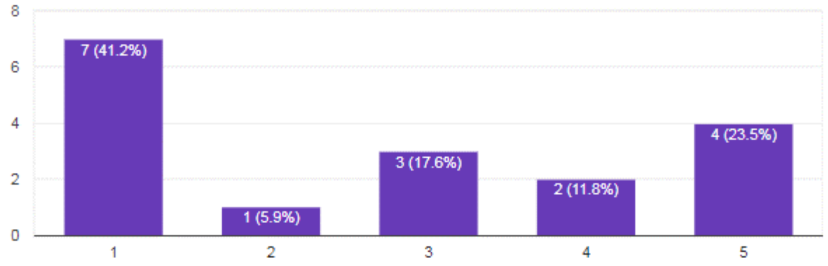


Figure 72Evaluation of the available power gauge

State of charge (4) - displays the charge level of the high-voltage battery. Results of the evaluation are following 11.8 % of drivers did not understand values displayed by this gauge, the reason that they confused this gauge with the "Available power gauge". 76% of drivers reported this to be "really useful" However surprisingly enough 24 % of people said that the "range to full discharge" information is sufficient enough for them and can fully substitute this gauge.

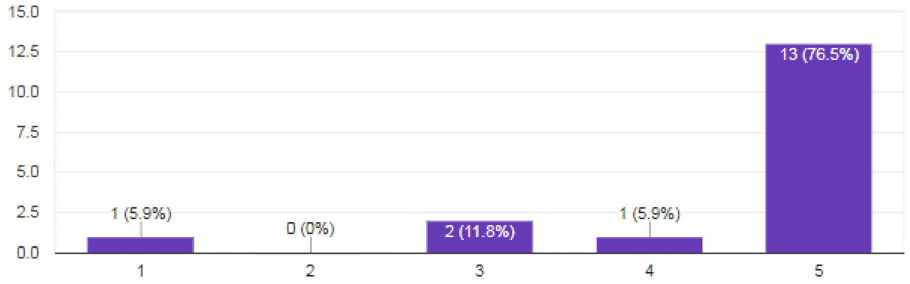


Figure 73 Evaluation of the state of charge gauge

On-off Notification When the vehicle is off all gauges are set to 0 and power flow gauge is set to value OFF. After the vehicle is started power flow gauge moves from position off to position zero, all others display an actual value of the measuring units, and a bell sound is played.

Majority 82.4% reported that this notification was sufficient and 52.9 % said that it was easy to understand that vehicle was switched off at the beginning of the experiment. A list of possible enhancements proposed by users:

- Replace bell sound with motor sound
- Keep motor sound constantly at the low level
- Increased contrast and/or color schema of the dashboard
- Additional icon ON/OFF

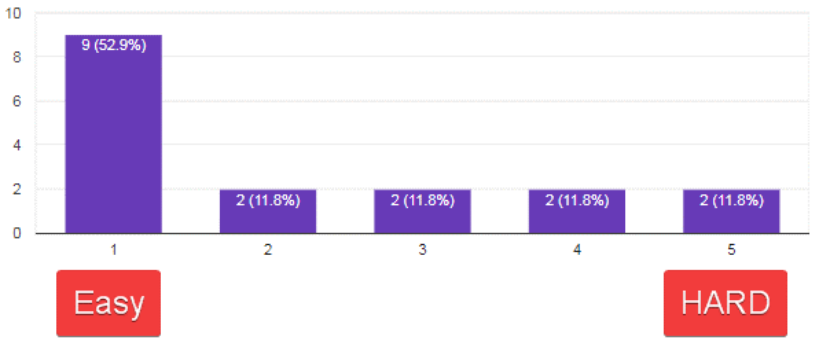


Figure 74 Evaluation of On/Off notification

4.1.6 Experiment Conclusion

The main goal of the study was to understand current user familiarity with the EV and HEV technology and to evaluate developed simulation technology as a possible tool for further research or educational purposes. Platform validation and user feedback showed a potential to use vehicle simulators for these purposes, a detailed physical model based on RICARDO Ignite software package provides a comprehensive set of tools to simulate any vehicle architecture.

Evaluation of the EV performance from the perspective of user acceptance showed that current technological progress, achieved in battery and electric motor area, allows maximal speed and acceleration rate of EV and HEV to be acceptable for future market grows. However, the following actions are needed to support EV and HEV sales, these include:

- Decrees price for EV and HES.
- Develop a wider network for charging station.
- Develop special privileges and bonuses for EV such as:
    - Free parking spaces.
    - Green lanes.
    - Reduced Highway prices.

Inexperienced users of EV tend to misunderstand the concept of regenerative braking and tends to misunderstand some gauges on the instrument cluster of the EV or HES vehicle.

Research and educational projects similar to this can significantly secure growth of the popularity of EV and HES vehicles across society by giving them the possibility to try and evaluate the technology

4.2 The experiment focused on the ADAS / Smart City system evaluation

The task of the experiment was to check user acceptance and practical benefit of the Driver Advisory System which aim is to increase EV range by advising the driver when to release an acceleration pedal to reduce the speed before next limitation, with heavy usage of regenerative braking. This system is based on the data provided by ADASIS protocol version 2.

4.2.1 System description

The RTDAS is designed to improve driving energy efficiency in typical situations when a driver needs to reduce the vehicle speed based on the road conditions. One good example is when the current speed should be adjusted due to upcoming speed limit which is lower than the current vehicle speed, another case is when the vehicle is approaching a curve, and speed adjustment are needed to achieve the desired level of comfort or eventually safety while passing through the curve. Another, typical example that can be considered and incorporated is when a vehicle is approaching an intersection, in this case, if the right of way is not applied to the vehicle, the vehicle must stop (Stop sign) or slow down and prepare to stop if necessary (Yield sign). All these speed limitations on the road segments are considered to be actual speed limits for the vehicle Figure 75. In relevant cases (when the slowdown is necessary), proposed system delivers a message to the driver to release the gas pedal, when the driver releases the pedal, the current speed is adjusted without mechanical brakes usage by regenerative braking and additionally by air, rolling drag and gravity forces. This will increase the utilization of the existing kinetic energy of the vehicle and increase the comfort and safety due to the decrease of deceleration rate.

The advisory system is embedded in the vehicle. The system architecture is represented in Figure 76 It relies on the following data sources:

- GPS sensor for location.
- Speed sensor.
- Map data offered as Electronic Horizon, delivered by Electronic Horizon provider.
- Weather conditions provided by an external provider or estimated from data gathered from vehicle sensors (ABS, Temperature, Wipers).

- Predefined vehicle characteristics (Weight, Frontal area, Drag coefficient, Wheel rolling coefficient, Wheel radius, etc.).

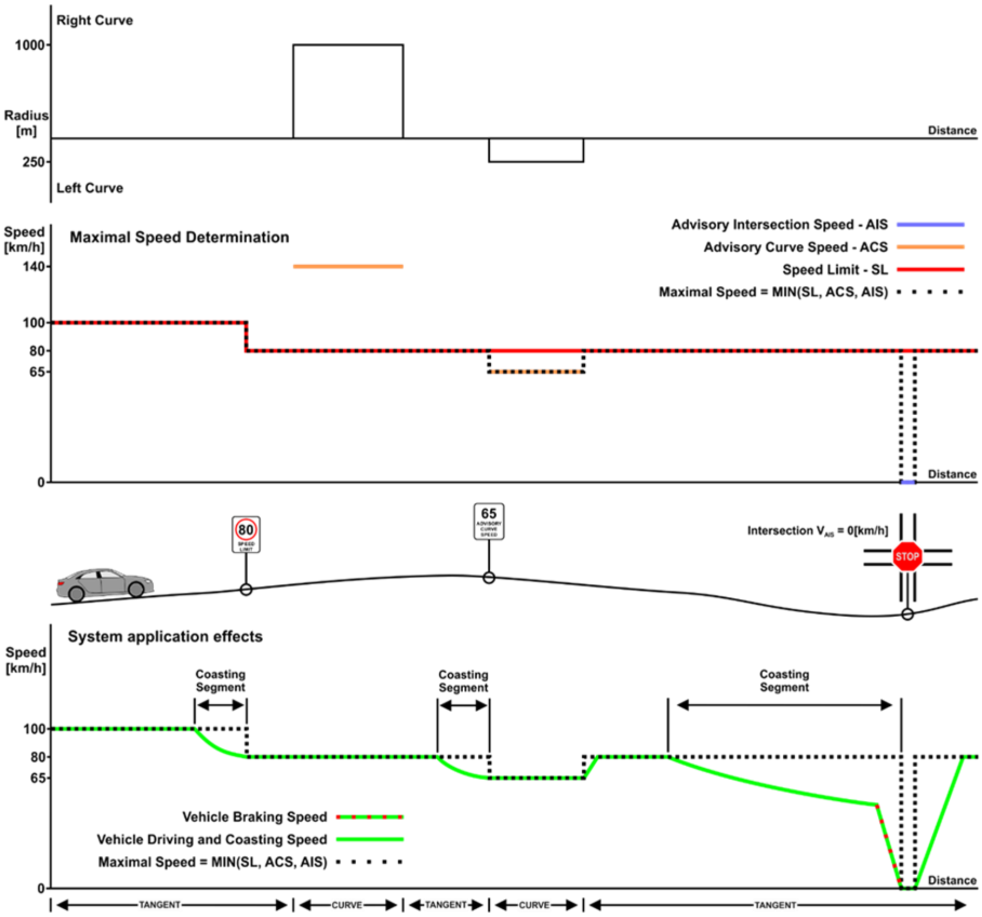


Figure 75 Speed limitation

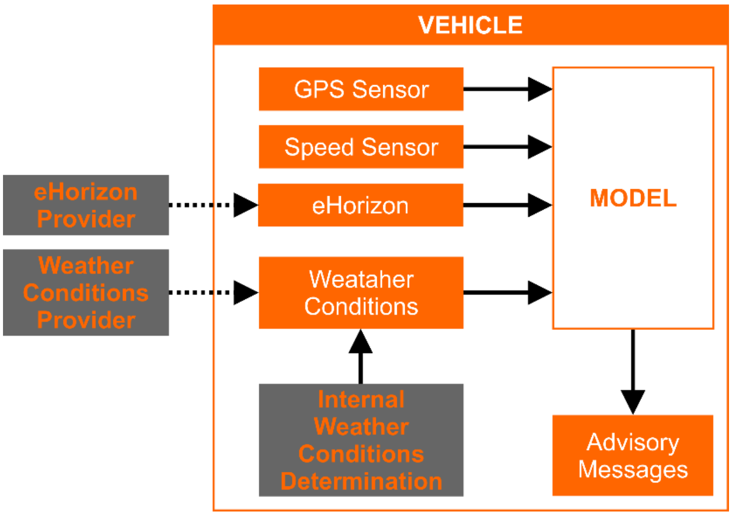


Figure 76 System architecture

The “critical speed” value is calculated for every situation based on available road friction, slope, curvature, superelevation, speed limits, intersections, and road signs position. At the beginning of the trip the system, based on available Electronic Horizon data, identifies the beginnings of segments with a lower speed limit, critical spots inside of curves (maximal curvature / or minimal speed), intersection stop line position, etc. By combining vehicle characteristics and road data, the desired deceleration speed profiles are calculated for all identified segments by using deceleration model. After the deceleration profile is constructed, the system starts monitoring the current speed of the vehicle ($V_{Current}$), and based on the position of the vehicle on the road, it starts looking for a specific event when the vehicle has to start to decelerate to enter a next road segment with a required speed ($V_{Required}$) (Figure 77). Additionally, an offset is added to the initial desired deceleration speed profiles, to compensate for a driver reaction time. For the purpose of our application the offset of 1.5(s) (it is a recommended period for ADAS applications [83]) is transferred to distance offset on the profile. When current vehicle speed profile intercepts the deceleration profile, $V_{Current} >= V_{Deceleration}$, the system sends the message to the driver to release the gas pedal The algorithm of RTDAS is presented in Figure 78.

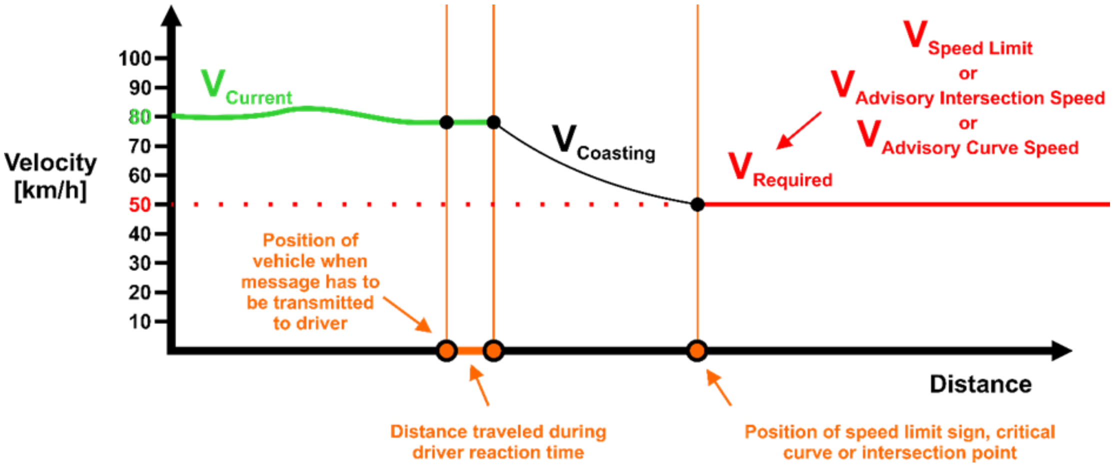


Figure 77 Vehicle controlled deceleration

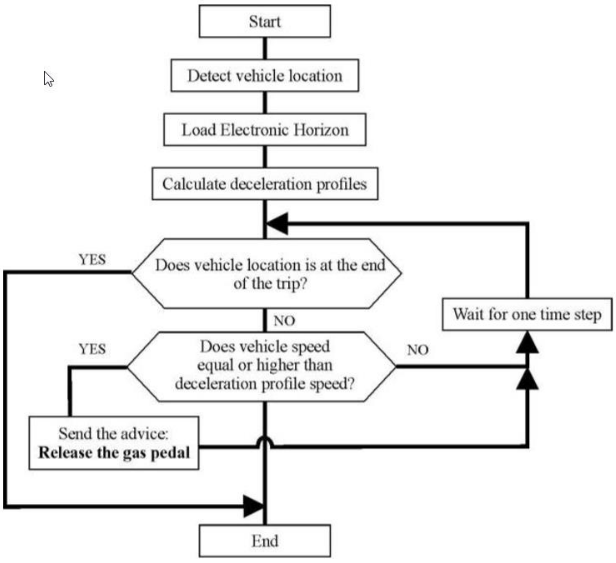


Figure 78 System algorithm

4.2.2 Experiment Description

The experiment was divided into 3 parts. First part is an adaptation period, where drivers spend 30 minutes controlling the vehicle in the simulator on a test track. The second part is the baseline. It is the part where drivers ride the vehicle without activated system and respect the speed limits. After a week, drivers come for the third part where he had to drive the EV with activated system and respect the speed limits. Driver path for the second and the third part consist of a highway part, rural part and city part, track profile speed limits and elevation profile of the track are shown in Figure 79, where artificial speed limits are marked on a map with numbers.

The system signalizes a driver to release the acceleration pedal by a message on a dashboard and a bell sound Figure 80. As soon as driver release the gas pedal system starts to adjust regenerative braking demand to reduce the speed to the desired coasting speed. If a driver pushes a brake pedal or acceleration pedal again system switches back to normal mode.

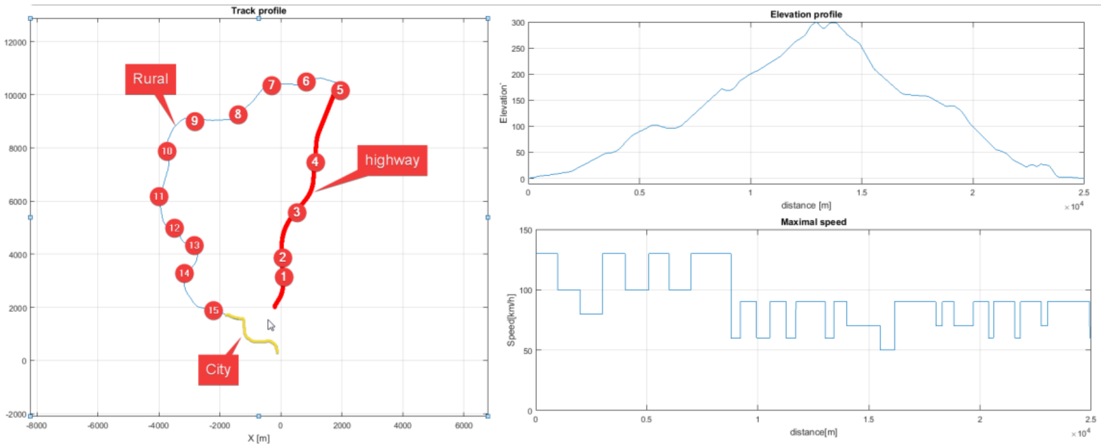


Figure 79 Test track description

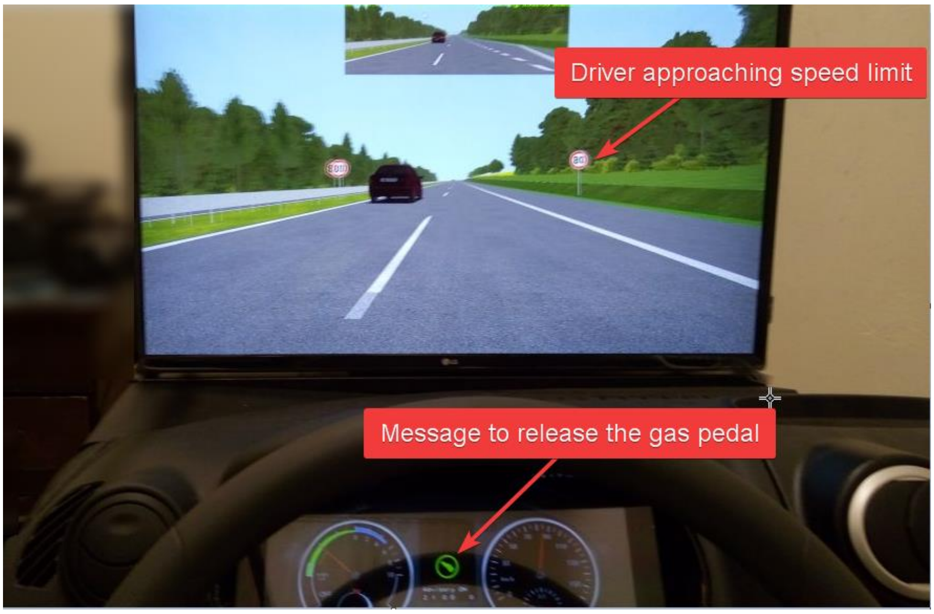


Figure 80 System notification

4.2.3 Model development and integration

Same powertrain model of E-Golf described in 4.1.1.1 was used, however, several new components were implemented to simulate system behavior (Figure 78). These components include:

- Road position and speed limits evaluation module (RPSL)(Figure 81 {2}) this elements contain information about speed limit and road curvature depended on X,Y,Z coordinates of the road. An actual position and speed of the vehicle provided from the ODE engine as an input, the algorithm then calculates the closest point on the polyline determine current speed limit and calculates recommended and costing speed. Calculation of coasting speed is done based on equations and algorithms explained in [85].
- Electric vehicle controller (Figure 81 {1}), this module is based on the controller described in chapter 4.1.1.1 with additional functionality. Two extra inputs were provided coasting status and coasting speed. Coasting status is the Boolean value when system signaled the driver to release the gas pedal and driver followed the suggestion, and coasting speed is the recommended speed calculated based on algorithm explained in [84]. If driver releases the gas pedal after received the message from RTDAS and, neither acceleration nor brake pedal is engaged, MG demand is controlled by internal PID regulator incorporated in the EV controller. The regulator adjusts the demand on the generator to achieve desired constant deceleration and slow down the vehicle. Modelica interface of the element is represented in Figure 82

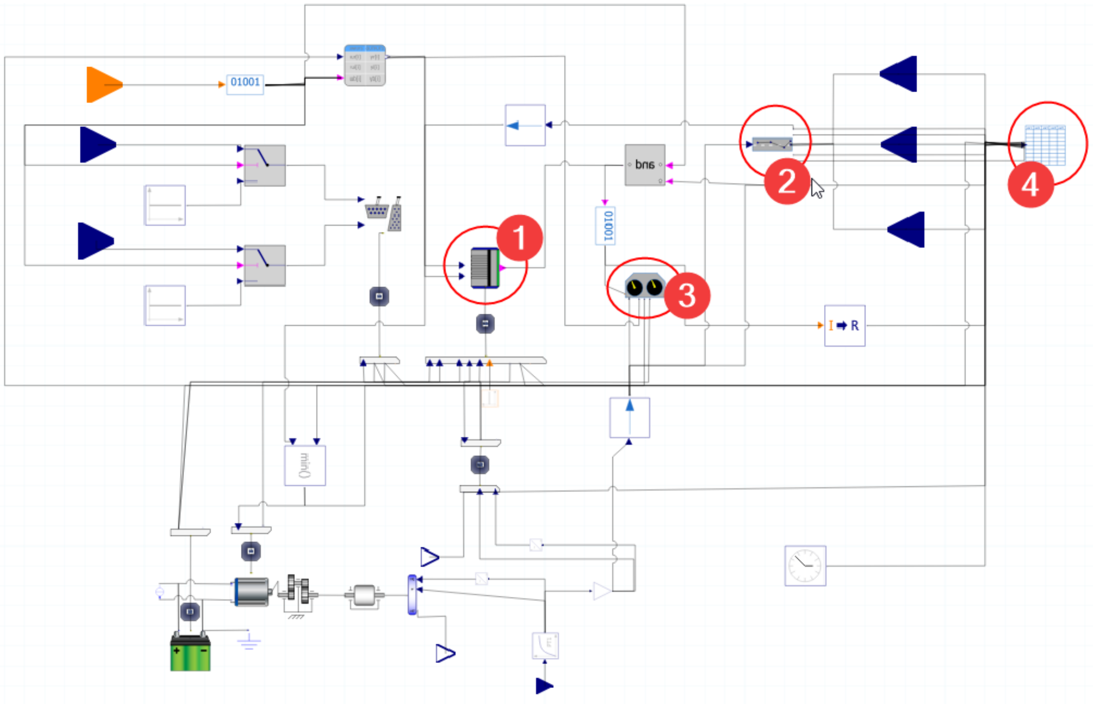


Figure 81 System implementation

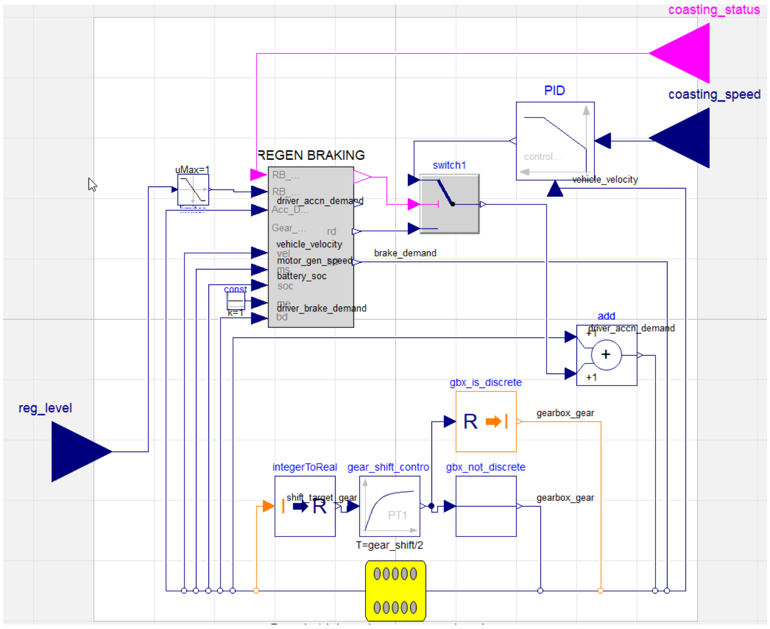


Figure 82 EV RDAS Controller

4.2.4 Results

Metrics introduced in chapter 3 and the software to analyze the simulation output introduced in chapter 2.5 are used in this chapter to evaluate the output of the experiment.

4.2.4.1 Objective data

- **Mechanical brake usage**

Using a modified version of the metrics introduced in 3.2.3.3 we are comparing the ratio of “pseudo” friction energy lost by mechanical brake system, and total consumed energy in percentage between the second and third stage of the experiment. Pseudo here means that it is not possible to calculate (at this setup) actual energy wasted on heat by the mechanical braking system, but we can estimate it based on this equation

$$E_{th} = \int_C F_n(x)dx = 4 * \frac{T_{max}}{R_w} * \int_C C_{brake}(x)dx \qquad \textit{Equation 35}$$

Where:

- F_n – braking force due to the mechanical braking system acting on the vehicle.
- T_{max} - maximal braking torque on one wheel.
- R_w - wheel radius.
- C_{brake} – brake signal (0 - 1).

The actual energy produced during vehicle deceleration

$$E_{dec} = \int_{C(a<0)} F_n(x)dx = m * \int_{C(a<0)} a(x)dx \qquad \textit{Equation 36}$$

Where:

- a – acceleration of the vehicle [m/s^2].
- m – the mass of the vehicle.

Result ratio is then calculated as follow:

$$R = \frac{E_{dec}}{E_{th}} * 100 \qquad \textit{Equation 37}$$

Table 12 Mechanical braking energy ratio

	With the system	Without the system
Mean value	3.7%	34.1%
Max value	13.9%	52.2%
Min value	0.1%	17.7%

From Table 12 it is visible that with the activated system, usage of mechanicals brakes was almost eliminated. One has to keep in mind that the simulation was performed without any interfering traffic, meaning that brakes or decelerations were applied only to adapt the speed for the maximal speed allowed on the road, either by traffic signs or by the physical characteristic of the path.

Energy Consumption metric

Evaluation of the difference in overall energy consumption for the whole track, a mean value of the percentage of the charge used for the whole simulation of baseline drivers is compared with the drivers who were using the system. The distribution of two datasets is shown in Figure 83 and presented in Table 13.

Table 13 SoC consumption comparison

	With the system	Without the system
Mean value	14.5%	14.8%
Max value	16.3%	15.3%
Min value	12.46%	14.06%

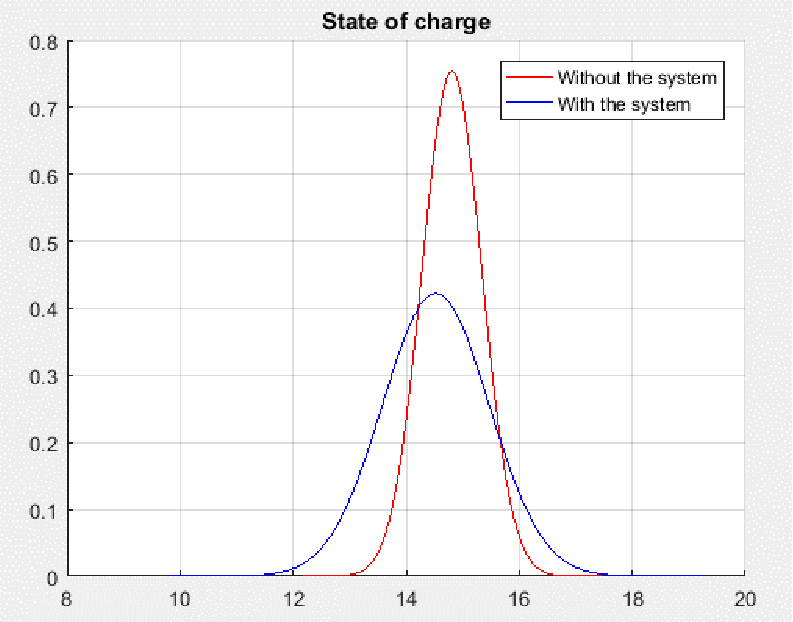


Figure 83 SoC comparison

Overspeed metric

This metric is used to analyze overall driver speed difference in 200 meters just after the speed limit traffic sign. the mean speed difference for each region is calculated and represented as a histogram in Figure 84

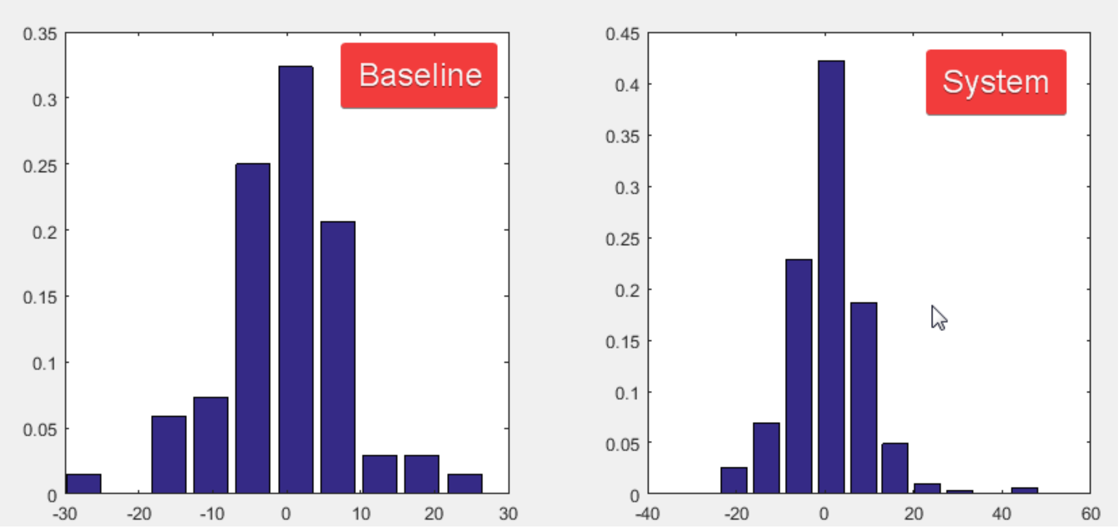


Figure 84 Mean speed difference histogram

From these histograms, it is visible that the system does not have any significant effect on the mean speed difference.

Speed reduction precision

This metric measure the distance in meters before the TS when drivers adjusted the speed to the approaching limit, negative values mean that vehicle speed reached the limit before the TSand positive meaning that vehicle speed reached speed limit after the TS. Based on the histograms shown in Figure 85 it is visible that the system improved the speed adaptation Drivers adopted their speed just before or a little after the TS (70% of the slowing region has the value 0- 30 m in comparison with only 30 % for baseline)

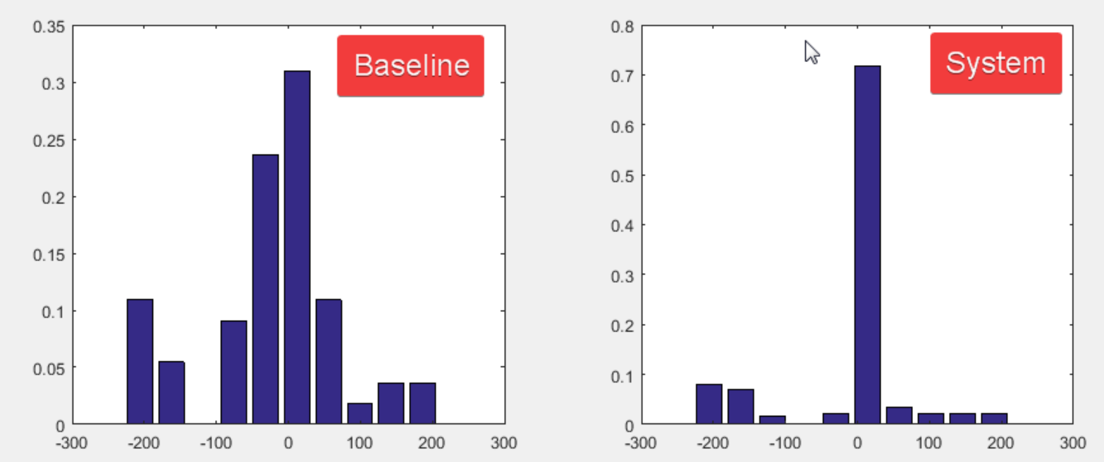


Figure 85 Distance needed to adjust the speed histogram

Speed difference when passing TS

Another metric is a speed difference when drivers passed the speed limiting traffic sign. The data is normally distributed, the distribution and histogram are shown in Figure 86 and Figure 87. Both baseline and system has a speed difference mean value around 0 (2.6520 9702 without the system and -0.1571), however it is visible that without the system the distribution is wider (standard deviation is higher 13.9702 without the system and 7.2423 with the system) this shows a bigger higher precision of speed adaptation to by drivers to the speed regulation.

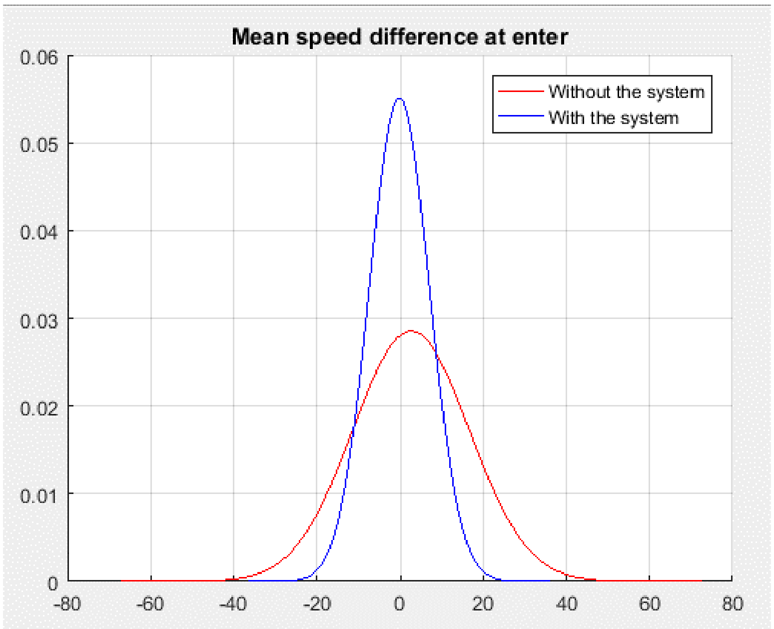


Figure 86 Speed difference at the TS position

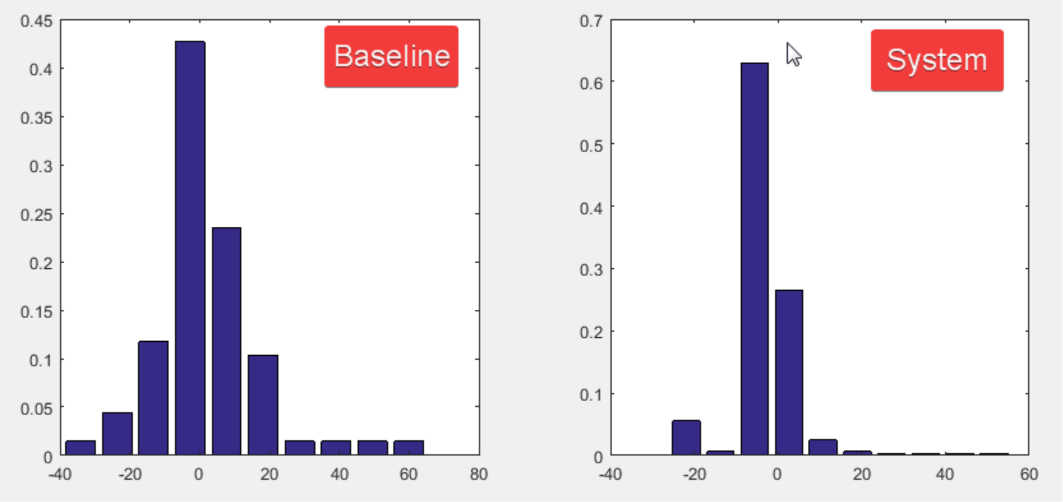


Figure 87 Speed difference at the TS position histogram

4.2.4.2 Subjective data

User acceptance usefulness and satisfaction from the system functionality is analyzed based on post-experiment questionnaires and ongoing experiment interview.

To evaluate the system scale from 1 to 5 was used in questionnaires were 1 meat total disagreement with the statement and 5 means strong agreement.

How helpful was the system?

Majority of drivers (76%) estimated the system to be helpful and really helpful. The histogram of the answer is shown in Figure 88

How much energy did it save?

At the same time drivers already familiar with the concept of regenerative braking were asked to estimate how much SoC this system saved them during the ride, 29.4% guest correct savings provided by the system 1 – 2 % of the SoC, and the rest of the cohort guessed a bigger number

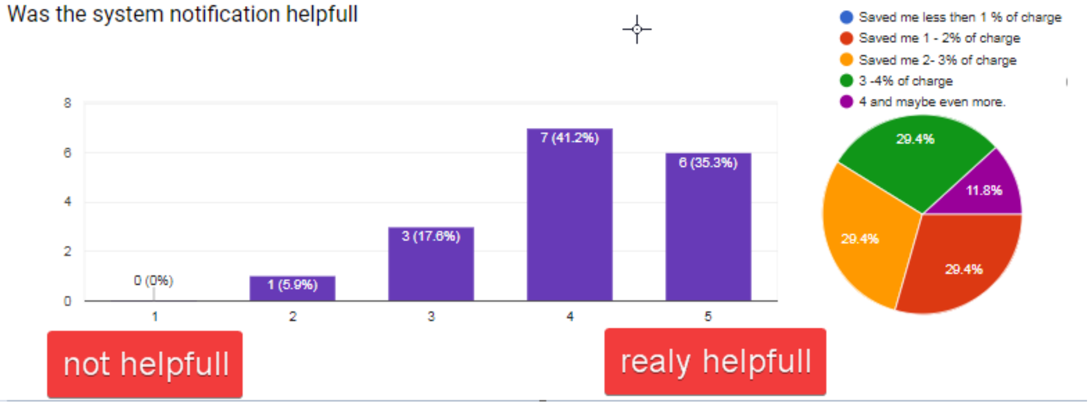


Figure 88 System usability and energy-saving guess

How likely I’ll use the system?

Fifty-nine percent of drivers said they would “very likely” use the system in real life, 11.8% responded to use this system occasionally. Where 11.9% of the cohort said that they would use it only if they have low SoC, and 41.2% reported that they would use it only if they must extend the range of the vehicle (long-distance rides). The rest 47.1% reported using the system all the time.

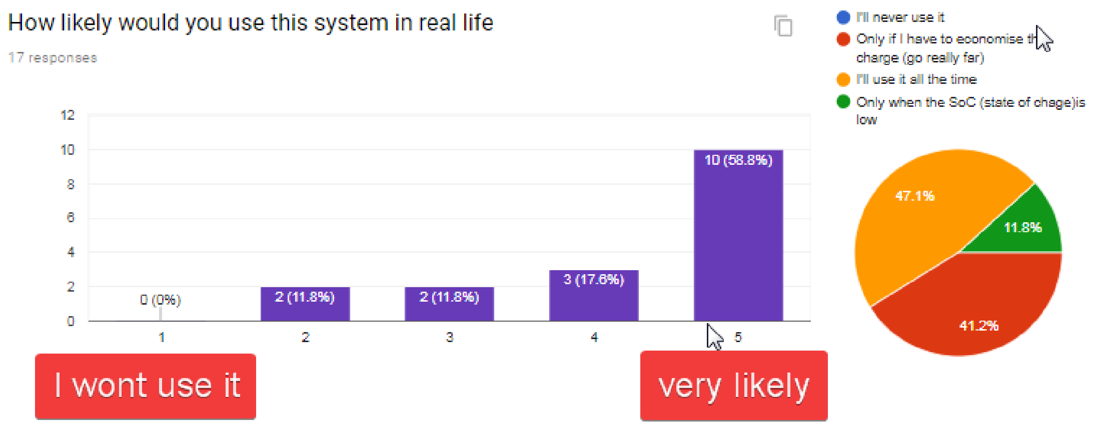


Figure 89 System usage in real life

Analysis of system notification method was done purely on subjective data. Drivers were asked how divertive the system during the ride was and were asked if system notification was enough or any other way of communication is preferred. Results are represented in Figure 90. Majority of the cohort agreed that the system was not divertive 59.8 % and 23% considered a system to be divertive. During the interview, 29% percent of chord mentioned the other way of communication will be better they proposed:

- Tactile, Vibration of ACC pedal.
- Tactile and visual.
- Different icon and color 6%.
- Only sound 6 %.

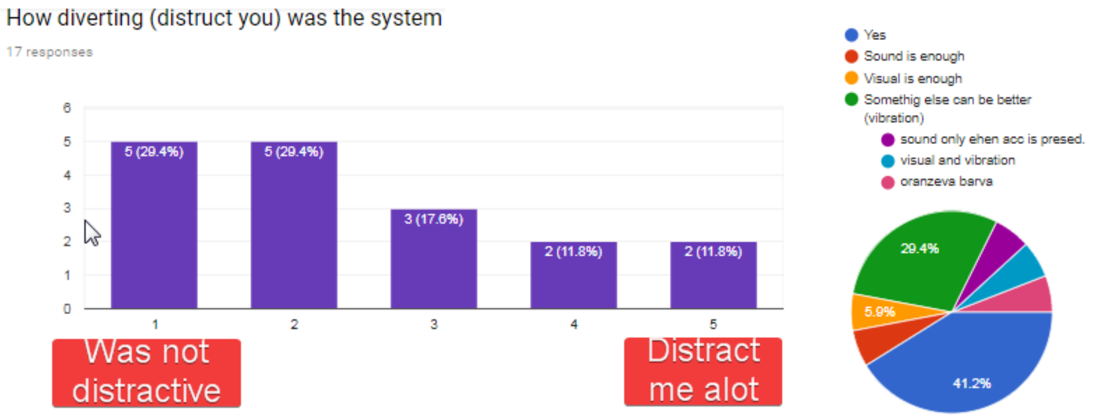


Figure 90 System notification and destruction

4.2.4.3 Conclusion

Overall, the proposed system was positively accepted by the majority of provands and showed a considerable theoretical, and practical improvement not only in energy consumption but also brings safety benefits in terms of overspeed and speed reduction precision

Provands were asked if they would like to see this functionality implemented in the system in real vehicles and 47.1% answered positively, 29.4 % said that this function is helpful, but they would like a possibility to turn it off, and 23% sad that this behavior is undesirable. During the “On-going” interview they reported that:

- The system prevents them from missing speed limits.
- The system helps to keep attention on a primary driving task.
- The system can help novice driver to adopt the speed in the curve.

On average driver without the system consumed 14.8 % of the charge and 14.5% with the system activated and has a mean speed on 1.92 km/h faster for the whole 24 km track, given identical initial conditions. However, in the best-case scenario (an example of the data is shown in Figure 92 and Figure 91) the difference between energy consumption can reach values of 1.86 %.of SoC for 24 km section

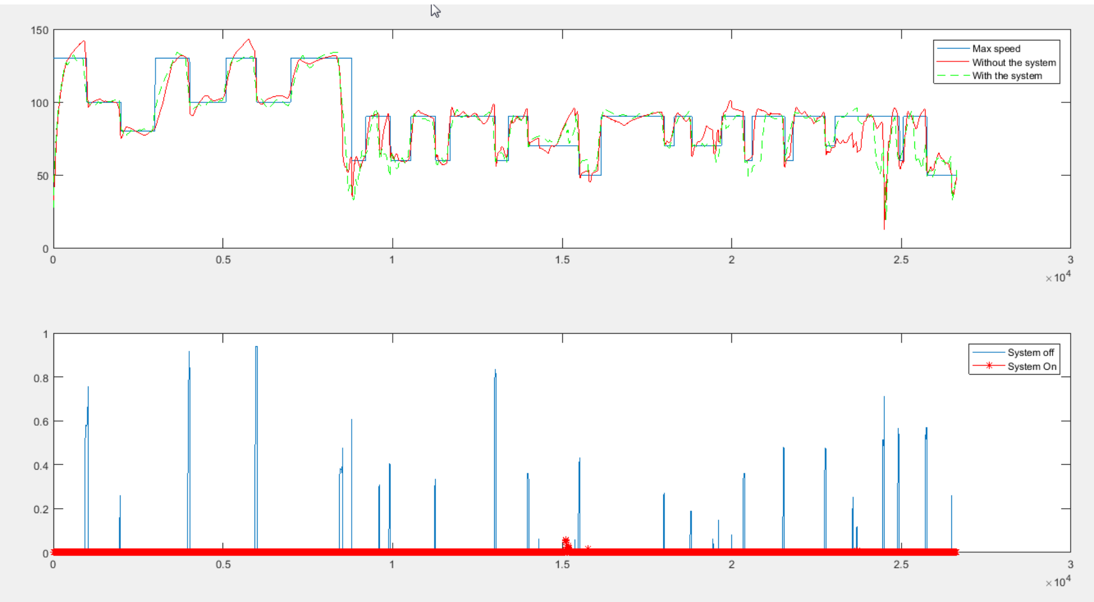


Figure 91 Speed profile and mechanical brake

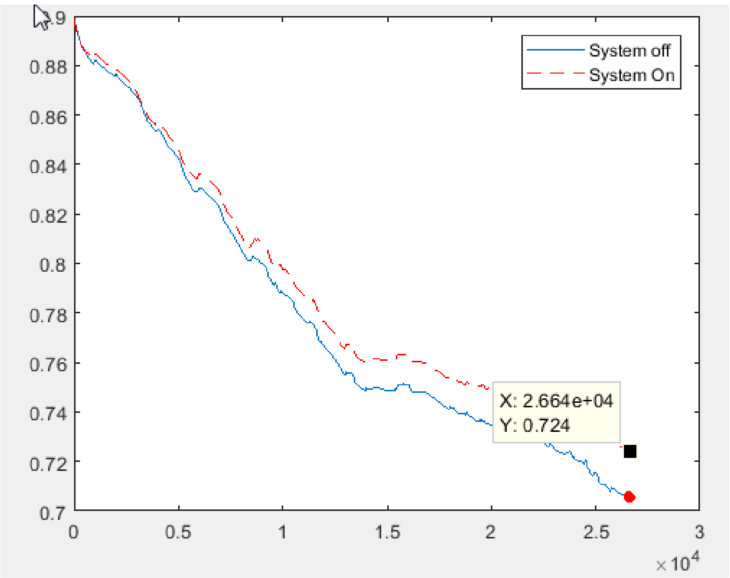


Figure 92 SoC for the route

Another advantage of the system is visible on the bottom plot in Figure 91 where the plot of mechanical brake demand is shown. Without the system driver used mechanical brakes every time before the slowdown, with the engaged system the usage of mechanical brakes was almost illuminated.

Finally, the precision of speed reduction can be considered as a possible advantage, in case if driver reacts on a message within 1.5 seconds the system will reduce the speed to the desired speed exactly at the point of speed limitation location and will switch the EV controller to the normal coasting mode as soon as the limit is reached. This advantage is displayed in Figure 93.

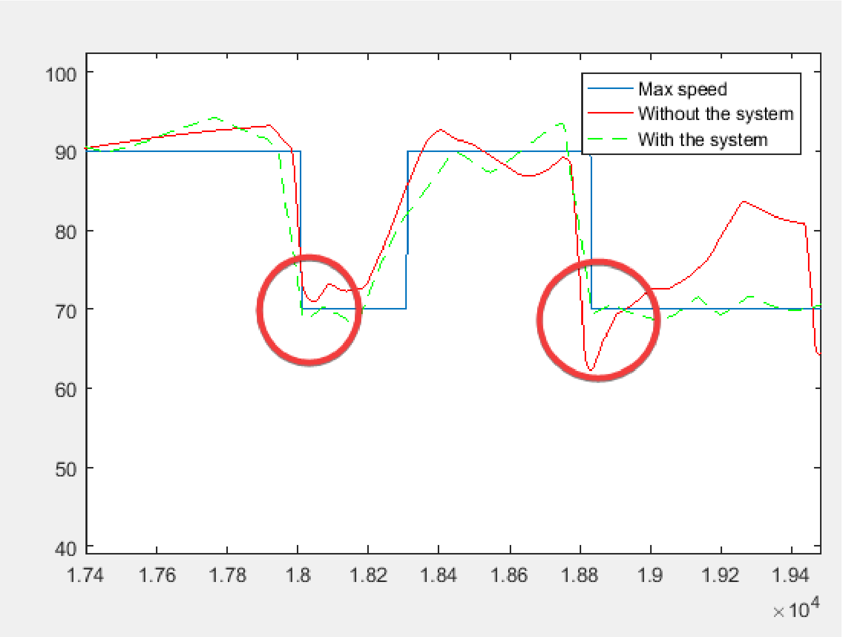


Figure 93 Speed reduction precision

Results acquired by simulations and user acceptance survey confirm the strong potential of utilization of detailed digital map road data in EV and HEV ADAS applications for reaching improved vehicle energy efficiency and driving comfort and safety. The acquired result considering system precision, indicates good performance of purposed approach of vehicle controller logic for EV concept, with an average absolute error of 1.03 km/h. Besides precision, energy flows analyses show improvements in the field of fuel and energy charge savings.

4.3 Conclusion for chapter four

However, described experiments were focused on particular tasks (first was focused on the vehicle performance and HMI evaluation and the second on the evaluation of an ADAS system), the main task of this chapter was to evaluate proposed measures and tools for the purpose of EV and HEV system and HMI evaluation. The platform and methodology of the simulation and development of the EV and HEV powertrain and ADAS systems proved itself to be precise and reliable. The validation results of the simulated powertrain of developed vehicle closely correlate with values provided by manufacturers 4% in range on one charge 3% difference on maximal speed and 1.9 % difference for acceleration characteristics. Additionally, acquired result in the second experiment considering RTDAS precision, indicates good performance of purposed approach of vehicle controller logic for EV and HEV concept, with an average absolute error of 1.03 km/h. Regarding time spend on powertrain creation and usability of the method, students who worked on their master thesis using this methodology reported it to be user-friendly and easy to learn. [48][85], and didn't require any direct knowledge of programming languages.

During both experiments, a few extra questions were asked to get the feedback from probands who participated in experiments. Majority of the provands evaluated the platform positively, 3 and 4 on a 5 points scale,

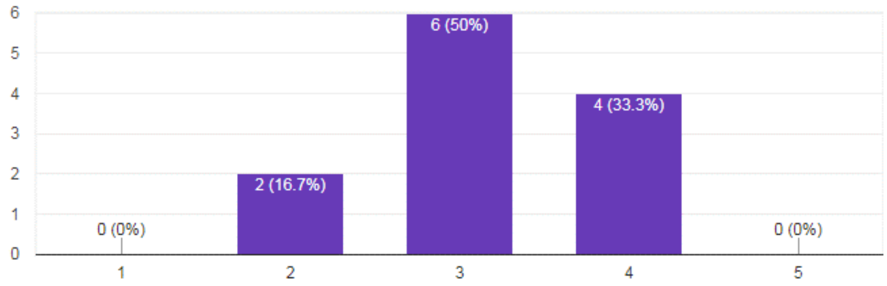


Figure 94 Platform evaluation

The comments provided by probands to be considered for future improvements are:

- Missing lateral forces
- Steering wheel does not feel real
- Brake and acceleration pedal does not feel right

- Distance between pedals is to small

However, even if some of them were complaining about missing feeling of lateral force, the question if the moving platform can improve the simulation experience is answered more negative or neutral, it is clear however that majority of patricians didn’t have any experience with the simulation on the moving platform, and their answer can be ungrounded. Additionally moving platform can significantly increase the number of canceled experiments due to the simulation sickness effect.

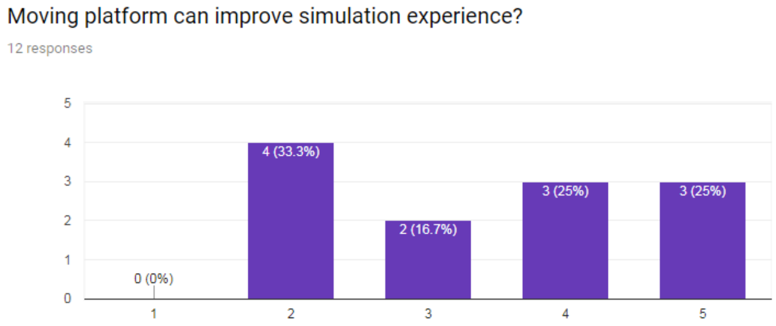


Figure 95 Moving platform effect

5. Conclusions

This thesis is focused on the problematics of EV and HEV vehicles and evaluation and validation of their systems and HMI. And had tme main goals definedas:

- Electric vehicle technology explanation.
- Upgrade of an existed interactive vehicle simulator, especially in the area of powertrain simulation.
- Develop a methodology for evaluation of EV and HEV systems and HMI.
- Perform a set of experiments for the verification of the methodology.

It started with the introduction to the EV and HEV technology. Moving deeper to the description of problems associated with their technology and proving the hypothesis that the EV and HEV vehicle will substitute the majority of ICE vehicles in the next few decades. And that new concepts and technology shift the problem of human-machine interaction for a vehicle (not only for EV and HEV) towards more complex concepts. These new EV and HEV vehicles undergo a lot of changes and not only from a technological point of view but also from a perspective of driver vehicle, road user vehicle, and passenger vehicle interactions. Instead of evaluating direct control and feedback effect of an interface on a driver, now a common interface for the vehicle, infrastructure, and the user has to be approached as the interface to the new intact system.

Development of the ADAS and telematics embedded system integrated into cars and mobile devices already started to form an Internet of things and Internet of services in a smaller scale bringing to the idea of Smart Cities closer to reality. Where each of the "inhabitants" (not only people but also vehicle, infrastructure, and services) are having their virtual representation and providing interface for communication between each other. Project INDUSTRY 4.0 put a plan for the development of research activities conducted in the area of IT systems for these systems and High-Tech strategy until the year 2020. This includes development in the area of HMI:

*"Human/machine interaction with language and media technologies, bioanalogous information processing, service robotics and usability"[33]*This means that a lot of new approaches and solutions will be developed in the near future thus creating a challenge to test, evaluate and compare these approaches against each other.

All mentioned above brought a crucial need to develop a new set of tools and measures to evaluate new systems and concepts The second part of the work was focused on the development and integration of these tools and measures. This set of tools were developed following the principle of high modality and upgradability, allowing fast and easy implementation and simulation of new technology, including powertrain simulation of complex HEV systems, HMI simulation of modern vehicles, and measurement device integration. And includes several developed and integrated modules and software packages these are:

- Modulization of existed vehicle simulator.
    - Adding a replicable module for EV and HEV powertrain simulation.
    - Developing the main components for the module.
    - Integration of the module into the existed simulator.
- Creation of a universal test platform for HMI.
    - HMI interface simulation software.
    - Integration of eye-tracking module.
    - Development of data analysis tools.

The third part of the thesis was focused on the review and development of special metrics and guidelines which should help to improve the process of experiment design and analysis of experiment results. Special metrics were developed for the EV and HEV vehicles to evaluate the energy efficiency of their ADAS systems or HMI

In the fourth part, developed tools and measures then were validated on experiments focused on several subjects such as HMI and performance evaluation, and development and evaluation of ADAS system in terms of user acceptance and energy efficiency improvement. Obtained results and feedback proved the validity of created tools and a possibility to use them further in the research area.

Another challenge which can be approached with developed tools is the topic of autonomous (AV) and semiautonomous vehicles (SAV) and processes where the notion “driver” or “controller” transform to the “passenger” and “user”. When an Artificial Intelligence (AI) is taking actual control and copes with low-level tasks such as vehicle handling and control and “user” is left with high level of control. It is expected to see the first fully autonomous vehicle in the next ten years on public roads [86]. In automotive world it means a whole set of new related issues and problems especially in the transaction stage when users who are not familiar with the technology will face them for the first time, and when an AI and humans would have to communicate their intentions to each other. Top-level issues are listed below.

- Assuring the user about his safety.
- Interaction with other road participants as pedestrians and usual cars.
- Study of means of communication with AI and appropriate feedback.
- Studying user acceptance on satisfaction with the system.
- Human AI control transferring (SAV only).

Combination of SAV or AV technology with HEV can increase energy efficiency even further allowing the AI to control vehicle dynamics and acceleration-deceleration strategies. Thus, gives another opportunity to VAP users. Such as:

- A vehicle can automatically search for the closest charge station when the driver left for a suitable amount of time.

- Drive back, when needed. Automatically free a charger when fully charged or on driver demand.
- Drive a vehicle in a battery safe mode, if needed, giving a possibility for an onboard computer to estimate vehicle range with much higher precision (removing of human factor).

This set of tools should form a solid background to support research in this area. Allowing students and researchers to study them in much greater details, bringing energy efficiency and safety to the next level.

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Abbreviations

ADASIS	Advanced driver assistant system
CAE	Computer aid engineering
CFD	Computational Fluid Dynamics
CPE	Car physical engine
CS	Charging station
DAE	Differential algebraic equations
DE	Deferential equations
DLL	Dynamic link library
EM	Electric machine
ET	Eye tracker
EV	Electric Vehicle
GHG	Green House Gases
HEV	Hybrid Electric Vehicle
HMI	Human Machine Interface
I2I	Infrastructure to infrastructure
I2P	Infrastructure to person
IC	Internal combustion
ICE	Internal combustion engine
ITS	Intelligent Transport System
ODE	Open Dynamic Engine
OOA	Object of interest
P2I	Per to infrastructure
P2P	Per to per communication
PAV	Powertrain Simulation Library
PSL	Powertrain simulation library
RB	Regenerative braking
RB	Regenerative braking
SDLP	Lateral position standard deviation.

SOC	State of charge
TLC	Time to line-crossing metrics
V2I	Vehicle to infrastructure
V2P	Vehicle to person
VAP	Vehicle Alternative Propulsion
VDM	Virtual Dashboard module
VGM	Virtual Gauge Module
WOT	Wide open throttle

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Project participation

[1] SGS15/224/OHK2/3T/16 Pokročilé asistenční systémy a jejich uživatelské rozhraní pro eletrická a hybridní vozidla budoucnosti
[2] SGS16/186/OHK2/2T/16 Studium tolerance a dodržování rychlosti určovaných systémem Proměnných Rychlostních Limitu při využití Simulatoru Řizeni a zařízení Eye Tracking
[3] VG20122014085 Zvýšení bezpečnosti vozidel při přepravě cestujících i nákladů na kritických bodech infrastruktury
[4] TA02031465 Automatické sledování agresivních a nebezpečných řidičů motorových vozidel
[5] TA01030574 Výcvikové pracoviště pro řidiče kamionů vybavené pokročilým interaktivním simulátorem s možností sledování a analýzy psychofyziologických, psychologických a výkonnostních parametrů
[6] TA02031414 Vývoj pokročilého simulátoru pro účely základního i následného výcviku řidičů osobních automobile
[7] TA04031752 Působení rušivých vizuálních vlivů na bezpečnost jízdy

Appendix

Developed code modules and read me documentation are located at:

- Modelica code for aditional components
    - https://bitbucket.org/rozhddmi/library_modelica_ode
- Dashboard software module
    - https://bitbucket.org/dsrg/dashboard - windows version
    - https://bitbucket.org/dsrg/androiddashboard - android version
- Dashboard IO board shchematic
    - https://github.com/rozhddmi/Lada_v.2
- FMU integration library
    - https://bitbucket.org/rozhddmi/fmi_powertrain
- Data analysis software
    - https://bitbucket.org/rozhddmi/data_analysis

Vehicle simulator source code including eyetracker synchronization module is licensed by FD CVUT Ustav Dopravnich prostredku and is not avaliable for public access, change introduced to the code are stored on internal repositorie.