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Master Thesis

Vehicle Modelling for the Simulation of Energy Consumption and CO_2-Emission in a Real-World Driving

carried out for the purpose of obtaining the degree of Master of Science (MSc or Dipl.-Ing. or DI), submitted at TU Wien, Faculty of Mechanical and Industrial Engineering, by

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Vienna, 12-2022

I confirm, that going to press of this thesis needs the confirmation of the examination committee.

Affidavit

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I. Abstract

Simulations can help to predict results without a big effort. In this thesis a vehicle model was built to simulate the energy consumption and the CO_2-emission of a Plug-in Hybrid Electric Vehicle. The vehicle was operated in different environmental settings and drive modes using more electric energy or fuel. The speciality of this model is a black-boxed power train, which is assumed to provide any possible driving force. The energy consumption is calculated with simplified linear equations, that considers time-depending consumptions, as well as power-depending consumptions. This separation is important for real-world drive simulations because auxiliary power consumers need energy all the time, independent of the distance driven. A comparison to an alternative model working with look-up tables show the advantages of this separation. The results show that auxiliary power consumers have a bigger influence on slower traffic and while driving with the electric motor. The simulations also show that driving in the all-electric mode can save energy on the vehicle and reduce the CO_2-emission. But it doesn't consider the whole life cycle nor a comparison between different vehicles of the same type with different power train electrifications.

II. Deutsche Kurzfassung

Simulationen sind ein gutes Werkzeug zur Vorhersage von Ausgangsgrößen unter verschiedenen Bedingungen. Das im Rahmen dieser Arbeit angefertigte Simulationsmodel berechnet den Energieverbrauch, sowie die CO_2-Emissionen, eines Plug-in Hybrid Electric Vehicle. Die Besonderheit dieses Models ist, dass die Antriebseinheit nicht modelliert wurde, sondern eine Black Box die erforderliche Antriebskraft zur Verfügung stellt. Der Energieverbrauch wird anschließend über vereinfachte, lineare Gleichungen berechnet. Diese Gleichungen trennen den Verbrauch dabei in einen zeitabhängigen Term und einen leistungsabhängigen. Diese Aufteilung ist wichtig bei der Simulation von Realfahrten, da somit Nebenverbraucher, die permanent mitlaufen und nicht von der Fahrleistung abhängen, richtig abgebildet werden können. Ein Vergleich mit einem alternativem Modell, welches mit Look-up Tabellen arbeitet, zeigt den Vorteil dieser Aufspaltung. Die Simulationen zeigen, dass der Einfluss der zeitabhängigen Nebenverbraucher bei Fahrten mit geringerer Durchschnittsgeschwindigkeit oder im elektrischen Antriebsmodus größer wird. Die Simulationen zeigen auch, dass der Energieverbrauch am Fahrzeug und der CO_2-Ausstoß in elektrisierten Antriebsmodi verringert werden kann. Es darf jedoch nicht außer Acht gelassen werden, dass diese Simulation ausschließlich den Fahrbetrieb untersucht und keine Lebenszyklusanalyse bietet, sowie dass ein Fahrzeug in verschiedenen Betriebsmodi simuliert wurde und kein Vergleich verschiedener Fahrzeuge gleicher Klasse mit unterschiedlichen Antriebseinheiten verglichen wurde.

III. Content

IV. List of Figures

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VI. List of Abbreviations and Symbols

Abbreviation	Full Text
AC	Alternate Current
AVM	Average Value Model
BEV	Battery Electric Vehicle
CO2	Carbon dioxide
CO2-Em.	CO2-Emission
DC	Direct Current
EM	Electric Motor
EC.	Energy Consumption
EV	Electric Vehicle
Gt	Giga tones
HEV	Hybrid Electric Vehicle
ICE	Internal Combustion Engine
JC08	Japanese Drive Cycle
kg	Kilogram
km/h	Kilometres per Hour
km/h	Kilometre
kWh	Kilowatt-hour
LTM	Look-up Table Model
m	Meter
m/s	Meters per Second
NEDC	New European Drive Cycle
PHEV	Plug-in Hybrid Electric Vehicle
PSD	Power Split Device
PSF	Power Split Function
rev/min	Revolutions per Minute
rrc	Rolling Resistance Coefficient
s	Second
SoC	State of Charge
SUV	Sportive Utility Vehicle
VBA	Visual Basics for Applications
WLTC	Worldwide Harmonized Light Duty Traffic Cycle

1. Introduction

To save energy is nowadays one of the most important goals of our society to protect our environment from further harm and global warming. Transportation and traffic are big energy consumers worldwide and responsible for approximately 8 Gt of CO_2 per year [1], so it is worth to take a closer look at them, in terms of energy reduction. Simulations can help to improve technical systems without big efforts, which saves money, time, and energy. However, it should not be forgotten, that simulation models are not the reality and can't depict the real world exactly. But a simplified model can be found, to depict the real world good enough to draw conclusions from it.

The topic of this work is, to create a model, that depicts a Plug-in Hybrid Electric Vehicle (PHEV) and simulates the whole energy consumption. The energy consumption of an PHEV sums up from the two different energy sources, the fuel tank on the one side and the external charged battery on the other side. From these separated consumptions, the CO_2 emissions can be calculated easily. This model should be able to simulate standardised drive cycles like the NEDC or JC08, measured real drives, and synthetic drives with a target velocity.

The speciality of this model should be, that for real-world drives, the auxiliary power consumers like the air condition can be turned on. Nowadays, vehicles are fitted with more luxury gadgets, which need energy. But those consumers are not considered in standardised fuel consumption tests, what leads to big differences, between the certification measurement and the real behaviour of the car. The goal of this work is to show the impact of auxiliary power consumers and give a picture of the influences on the energy consumption, such as traffic stops or efficiency rate.

As part of the student exchange program at the Nagoya Institute of Technology this model should be compared to the model, which is used at the Kosaka/Matsumori Laboratory. Prof. Kosaka's model is used to simulate the energy consumption of a Battery Electric Vehicle (BEV), based on look-up tables for the efficiency rate of the electrical motor (EM). To compare these two models, the PHEV model must be used in the all-electrical mode only, which lets the car operate like a BEV.

2. Methodology

The used model is based on the energy flow of the system and simplifies the power unit by considering it as a black box, which provides a stepless driving force to move the car. To calculate the energy consumption for this black-boxed power unit, the driving power will be split up into an electrical and a combustion engine path. The therefore used power split function also considers the power of the auxiliary power consumers, which gives a complete picture of the power used in the vehicle. For those auxiliary consumers an averaged power, based on literature research, will be assumed, and added to the power flow of the system, hence these auxiliary consumers are therefore subject to the system efficiency. Simplified, linear equations are introduced to calculate the fuel mass flow for the ICE, and the power used from the battery respectively. These equations are based on time-depending and power-depending energy consumptions, as well as on averaged efficiency rates. These efficiency rates are fix and do not change depending on the engine speed nor the engine torque. The model considers only longitudinal drive, what keeps the vehicle dynamics simple.

The advantages of this method will be analysed in a comparison to an alternative simulation model. The alternative model works with look-up tables and depicts the vehicle's power train in detail, but it doesn't consider auxiliary power consumers.

To show the impact of specific influences, the used parameters, such as efficiency rate and auxiliary power consumption will be varied ceteris paribus, compared, and discussed. Also, the influence of the car's size and weight will be shown in a comparison of two different vehicles, one compact EV and one Full Size SUV PHEV.

3. Model

The Model used for this work was created with Simulink from MathWorks and contains several MATLAB functions. For the preparation of drive cycle data some MATLAB files and Excel Macros has been written. All these calculations shall be introduced in this Chapter.

3.1. Overview

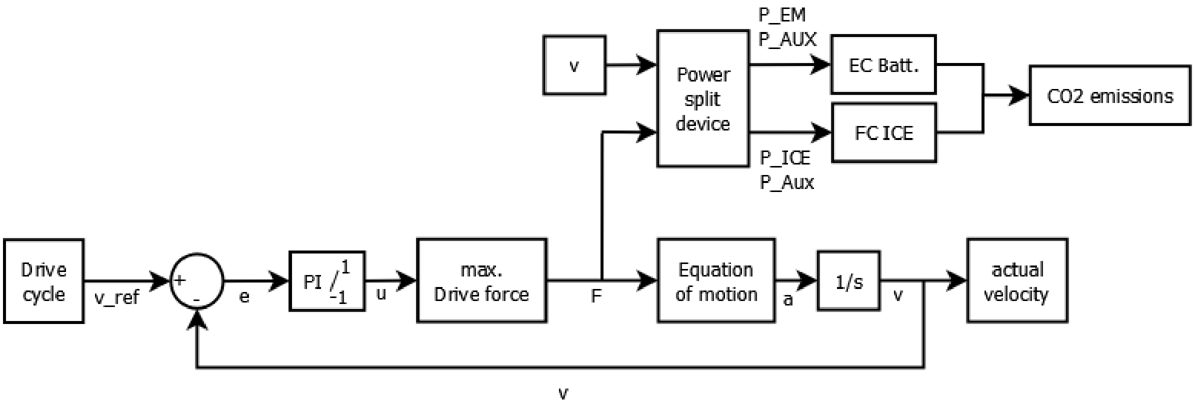

Figure 1 Flow Chart Overview of the Used Simulation Model

v… velocity, v_ref… reference velocity, e… error, PI… PI controller, u… controller output, P_EM… power of the EM, P_ICE… power of the ICE, P_AUX… auxiliary power, EC Batt… energy consumption of the Battery, FC ICE… fuel consumption of the ICE

Figure 1 depicts an overview of the used simulation model. The model consists of two parts, the lower part is the drive cycle part, which is basically only a control loop to simulate the actual velocity from a target velocity given by drive cycle block. The driver is modelled by a simple PI controller with the error between the reference and the actual velocity as input signal. The output is limited from -1 to 1, what gives a percentage of the maximum available drive force, that is required to reach the target velocity. The vehicle's acceleration is calculated in the equation of motion by comparing the driving force to the driving resistances. Only longitudinal drive is considered for the vehicle dynamics in the simulation of the driving resistances. The actual velocity results from the integration of the acceleration.

With the required force and the actual velocity, the upper part in this flow chart simulates the energy consumption of the car. Since a PHEV contains two different energy sources, the required power must be split up to the electrical path and the combustion engine path. The blocks "EC Batt." and "FC ICE" contain MATLAB function for the calculation of the energy consumption of the battery and the fuel consumption of the internal combustion engine, respectively. With those separated consumptions the overall CO_2-emissions can be calculated easily.

The present model works with a big simplification in the power train. It skips the entire power unit and just assumes an available driving force. But how this driving force is produced is not part of this simulation. This means that the efficiency rates of the ICE and the EM, that are usually known from an efficiency map cannot be used, since the engine speed and the engine torque are unknown. So, an alternative equation for calculating the energy consumption is introduced. These simplifications will be discussed more in detail in the following chapters.

All these depicted blocks represent MATLAB functions that needs input information, which comes either from other blocks via a connecting signal or is given as a parameter. Examples for such parameters are physical constants like the gravitational acceleration g or vehicle specific characteristics like maximum power or weight. To make the Simulink model independent from other files these parameters are stored directly in the simulation workspace and can be tuned there. The simulation uses a fixed time step size of 0.1 s.

3.2. Used Functions

3.2.1. Drive Cycle Source

The drive cycle block is the first block in the flow chart and is responsible for the reference velocity. It gives a velocity signal over the time. The used block is already prepared and available in Simulink. It contains standardised drive cycles, like the JC08 or the NEDC by default, but is also able to provide a target velocity form an external source. This Simulink block can give a gear change signal as well, but this function is not used for this work. The advantage of this drive cycle source is, that it can update the simulation time to the duration of the cycle or can repeat the velocity profile cyclic [2].

In this simulation the drive cycle source should be able to provide a profile from a standardised drive cycle, a measured real-world drive, or a made-up synthetic drive. So, only using the prepared sources is not enough. To set up the data for a measured real-world drive, is also quite easy, because they can be available in an Excel file, or a Mat file. In this case Excel was used since the data from the measurement came in an Excel file. Important for the input is, that for every timestep a momentane velocity is available and that the timesteps are uniform. But they don't have to match the timesteps of the simulation, since this block can interpolate the velocity between the given points.

The input data for a synthetic drive has the same requirements as for the measured drive. But, in contrast to a measured drive, the data must come from a different source. The GPS data are taken from Google Maps and are plotted to a tabular form via a GPS Visualizer. However, to convert the data from Google Maps to a tabular form, a commercial Google account is required. The tabular data contain the geographical coordinates, the height, and the distance. This data muss be prepared in Excel, for what a VBA script was written. Street classes with target velocities can be assigned to the data. Statistically distributed stops can also be added to create a more realistic drive in a city traffic. This velocity profile depicted over the distance has to be converted in a profile depicted over the time, which is not a big problem, since the velocity and the stop times are given. For this transformation a MATLAB script was made, it also uniforms the timesteps and can adjust the speed ramps, if the car is supposed to accelerate more smoothly. If the ramp is not adjusted, the acceleration depends on the controller and the available power of the simulated vehicle.

3.2.2. Controller and Maximum Drive Force

The controller can be seen as the driver in the drive cycle part of the simulation. It controls the vehicle's speed by applying a required drive fore. It uses the difference between the target velocity and the actual velocity as input and gives an output between -1 and 1, what can be seen as the percentage of the maximum available driving force required to accelerate to the target velocity. If the target velocity is higher than the actual velocity, the difference is positive, hence the controller gives a positive output value, what leads to a positive driving force, and the vehicle will accelerate. If the actual velocity is higher than the target velocity, the difference and hence the output will be negative, what leads to a negative driving force and braking will occur.

The used controller block is a prepared PID-Controller from Simulink [3], it has one entry and one exit. The controller function can contain a proportional part, an integrative part, and a derivative part. For depicting a driver, a PI controller is the best, so the derivative part was switched off. The proportional part of the function takes care, that the gap between the target and actual velocity is closed, but it always needs a little gap to keep the velocity. The integrative part ensures that the actual velocity reaches the target velocity. The tuning of the controller can be done by Simulink with an autotune function integrated in the PID-Controller block. For matching the fixed step size of simulation, the controller has to be set in discrete mode and inherits the step size from the simulation. The compensator formular is given in Eq. (1).

$$u = e * (P + I * T_s \frac{1}{z-1}) \tag{1}$$

u… controller output, e… controller input (error), P… proportional gain, I… integrative gain, T_s… sample time, z… z-variable for Z-transformation

The driving force block uses the controller output as input and multiplies it with the maximum available driving force. It is assumed, that any force within the physical boarders is available. The physical borders for the maximum driving force are on the one side the friction, on the other side the maximum power output of the power unit. The mathematical formulations of these restrictions are given in the following Eqs. (2), and (3).

$$F_{D,max} = m * g * f_f \tag{2}$$

$$F_{D,max} = \frac{P_{max}}{v} \tag{3}$$

$F_{D,max}$… maximum driving force, m… vehicle mass, g… gravitational acceleration, f_f… friction coefficient, P_{max}… maximum available power, v… actual velocity

While the friction border Eq. (2) restricts the maximum driving force at lower velocity, the maximum power border Eq. (3) limits the force at higher speed levels. The maximum available power from the power unit depends on the driving mode, if the vehicle is operating in the all-electrical mode, only the power of the EM can be used, otherwise the system power gives the border. To consider this distinction, the current driving mode must be inputted to the maximum drive force block.

3.2.3. Equation of Motion and Driving Resistances

The equation of motion Eq. (4) calculates the vehicles acceleration and is basically the principle of linear momentum divided by the mass. The input to the equation of motion block is the current driving force and the variables needed to calculate the driving resistances, which get explained more in detail in the following. The output is the actual acceleration, which is integrated afterwards to calculate the actual velocity.

$$a = \frac{1}{m * \lambda} * (F_D - F_{Drag} - F_{Roll} - F_{Grade}) \tag{4}$$

a… acceleration, λ… inertia mass factor, F_D… driving force, F_{Drag}… drag force, F_{Roll}… rolling resistance, F_{Grade}… grade resistance

The acceleration resistance is depicted by the principle of linear momentum. The force of the acceleration momentum given in Eq. (5) is the left side of the principle of linear momentum and has to be applied to overcome the inertia. This force can also be seen, as the force that must be applied to increase the kinetic energy. A closer look to the kinetic energy of a vehicle shows, that in addition to the translational share, there is also a rotational share, which considers e.g., the rotating shafts and wheels of the vehicle. For producing the rotational share of the kinetic energy, a torque must be applied. However, to simplify the equation of the resistance the torque is neglected and an inertia mass factor λ is introduced, to represent the rotational inertia. Since a lot of rotating parts are connected to the translational movement via a transmission, λ depends on the gear.

$$F_{acc} = m * g * \lambda \tag{5}$$

F_{acc}… acceleration resistance

The drag force in Eq. (6) gives the losses due to the displacement of the surrounding air. It depends on the velocity by the power of 2, which brings the need of an input signal of the actual velocity. Further, it depends on the air density, the vehicles projected cross-sectional area, and the drag coefficient, which gives a measure of aerodynamics. These three values get inputted as parameters.

$$F_{Drag} = \frac{\rho \cdot v^2}{2} * c_d * A \tag{6}$$

ρ… air density, c_d… drag coefficient, A… projected cross-sectional area

The rolling resistance in Eq. (7) gives the losses occur on the rolling movement of the tires. It is influenced by the vehicle's mass and the rolling resistance coefficient (rrc) of the tires. The rrc is a measure of the flexing in the tires and is given in kilogram per ton, or in a physical unit of 1. So, this coefficient gives a theoretical replacement mass, that have to be pushed forward to keep the vehicles velocity. All the used variables are given as parameter.

$$F_{Roll} = m * g * f_r \tag{7}$$

f_r… rolling resistance coefficient

The grade resistance in Eq. (8) can be positive, when the vehicle is driving upwards and the grade is positive, or negative, if the vehicle's motion is downwards. The grade resistance gives the force that is needed to raise the potential energy of the vehicle's mass.

$$F_{Grade} = m * g * \sin(\alpha) \tag{8}$$

α… grade angle

The mass and the gravitational acceleration are given as parameter. The grade *sin(α)* is an input to the function and given by a signal generator. The signal is coming from a variable stored in the model workspace, which gives the grade over the travelled distance. To generate this variable a MATLAB script was written, that can ether generate a grade signal from a GPS file created by Google Maps, by dividing the height difference by the lateral difference and generating a sine signal with the use of angle functions. Or the function generates the grade signal from a measurement using the GPS height data and divides the difference between two points with the travelled distance, calculated with the velocity and the time.

3.2.4. Power Split

The most important function is the Power Split Function (PSF). It emulates the Power Split Device (PSD) in an HEV. The task of the PSD is to combine and distribute the power of the EM and the ICE which is realised with a planetary gear set. The PSF also takes over the regulation of the power split, which is usually made by the car control unit. This function controls how much power is supplied by the ICE or the EM. Also, the energy source for the auxiliary power consumers is decided by the PSF. This function can operate in four different driving modes.

The first mode is the ICE mode. In the ICE mode all the power required to drive the car and all the power, that is required to run the auxiliary power consumers is delivered from the ICE. The EM doesn't use any Energy. For simplification, this mode doesn't work with a Start/Stop function to turn off the Engine while standing still.

The second mode is the Electric mode. This mode is the opposite of the first one and all the power used is provided by the battery.

The third mode is the hybrid mode. In this mode both power sources are used for driving. While the small electric consumers are either powered by the ICE, if it is running or the battery in case, that the ICE is shut off, the big electrical consumers are only powered by the battery. The hybrid mode rises the efficiency of the vehicle's powertrain, by using the ICE in a good operation point and recovering energy while braking. The hybrid mode controls the power train operation in a way to keep a constant battery state of charge (SoC).

If the car is driving on low speed, the ICE is shut off and the car operates like in the Electrical mode. If a velocity threshold is exceeded, the driving power is supplied by the ICE. This threshold depends on the SoC of the battery. If the battery is lower than the initial SoC, the velocity threshold is lowered, to save electrical energy. If the SoC exceeds the initial SoC due to energy recovering, this threshold is lifted to save fuel and lower the CO_2-emission. However, if a big power output is required, the ICE boosts also below this threshold. It is assumed, that the ICE has the best efficiency rate, when it produces the maximum torque. So, the minimum power that should be delivered by the ICE is the maximum torque multiplied with the minimum rotational velocity, which is assumed with 1000 rev/min. If the driving power is lower than this minimum power, the power output of the ICE is raised by using the EM as generator und recharging the battery. This Energy can later be used for slow driving but is produced in a better operation point of the ICE, which raises the overall efficiency. If the required power is higher than the maximum power of the ICE, the EM is used as a booster. While the vehicle is braking, the EM is used as a generator to rechange the battery with the recovered energy. This recovery however is limited to the maximum charging power of the battery.

The last operation mode is the Plug-in hybrid mode. This mode works quite similar to the hybrid mode, but the velocity threshold to swich from EM to ICE is minimum at 10 m/s. This means that the battery SoC might decrease, and the battery uses external energy, which has to be charged in beforehand. The advantage is that less fuel has to be used and the CO_2-emissions can be reduced, even when the CO_2-emissions of the production of the electrical energy is considered. If the threshold would be fixed, the disadvantage would be that some drive cycles have low power requirements, what leads to an increase of the SoC, due to too much recharging from the ICE, hence the fuel consumption and the CO_2-emissions increase. To compensate this disadvantage a controller was installed, to increase the threshold, if the SoC raises above the initial SoC but doesn't lower it, like in the hybrid mode.

For a real drive scenario, the PSF changes the driving mode automatically to hybrid drive, if the SoC falls below 10%. This task is switched off for all-electric vehicles and the simulation of standardised driving patters when the electrical reach is simulated.

3.2.5. Fuel Mass Flow

The calculation of the fuel mass flow of an internal combustion engine is basically a power balance equation. On the one side of the equation is the fuel mass flow measured in weight per time, which is a power after multiplying it with the energy density of the fuel. On the other side of the equation is the required power multiplied with an efficiency rate. This means, the higher the required power, the more chemical energy has to be supplied to the engine. The required power consists of two parts, the power that is needed to drive the vehicle and the power used by auxiliary power consumers. In this simulation, it is assumed, that small consumers are powered by the ICE, and also the recharging, as described in chapter 3.2.4., counts as an auxiliary power consumer for the fuel mass flow calculation. The used efficiency rate is usually given as the specific fuel consumption in mass per energy, which has to be multiplied by the energy density to result in a real efficiency rate but is convenient since it can be used directly for the calculation of the fuel mass flow.

The specific fuel consumption depends on the engine torque, or the effective pressure of the combustion respectively and the engine speed. Since the engine speed is unknown in this simulation the current specific fuel consumption cannot be used. A simplified linear equation Eq. (9) was introduced by Cachon and is used for this simulation as well [4]. This equation considers the power-depending consumption, which are needed to drive the car, hence they depend on the driving Power, but also the time-depending consumption, caused by the inner friction of the engine and the auxiliary power consumers, which are consuming fuel all the time, independent of the driving power. It is assumed that the specific fuel consumption is constant at the best point and only increases because the time-depending consumption becomes more weighted when the vehicle is moving slower.

The time-depending consumption is split into two parts, a basic consumption, the engine needs to run itself, and a part that considers the auxiliary power consumers. In this simulation the required power of the auxiliary power consumers will be estimated and multiplied with the specific fuel consumption to receive a fuel mass flow needed to power the auxiliary. The basic consumption to consider e.g., the inner friction of the engine or the ignition power, can be assumed as the consumption of the engine running in neutral gear without auxiliary power consumers. In fact, the inner friction is raising with higher engine speed, but this effect is neglected in this work, since it is assumed that the engine speed is set to a low ideal value with the 8-speed gear box.

$$\dot{m}_{Fuel} = \dot{m}_{td} + \dot{m}_{pd} = \dot{m}_0 + b_{e,spec} * P_{Aux} + b_{e,spec} * F_D * v \qquad (9)$$

$\dot{m}_{Fuel}$... fuel mass flow, $\dot{m}_{td}$... time-depending fuel mass flow, $\dot{m}_{pd}$... power-depending fuel mass flow, $\dot{m}_0$... basic consumption, $b_{e,spec}$... specific fuel consumption, P_{Aux}... power of auxiliary power consumers, F_D... driving force,

Figure 2 gives an impression on the impact of the time-depending consumption. The total energy consumption, depicted in the lower image is constantly rising, even if the velocity is zero, shown in the upper image.

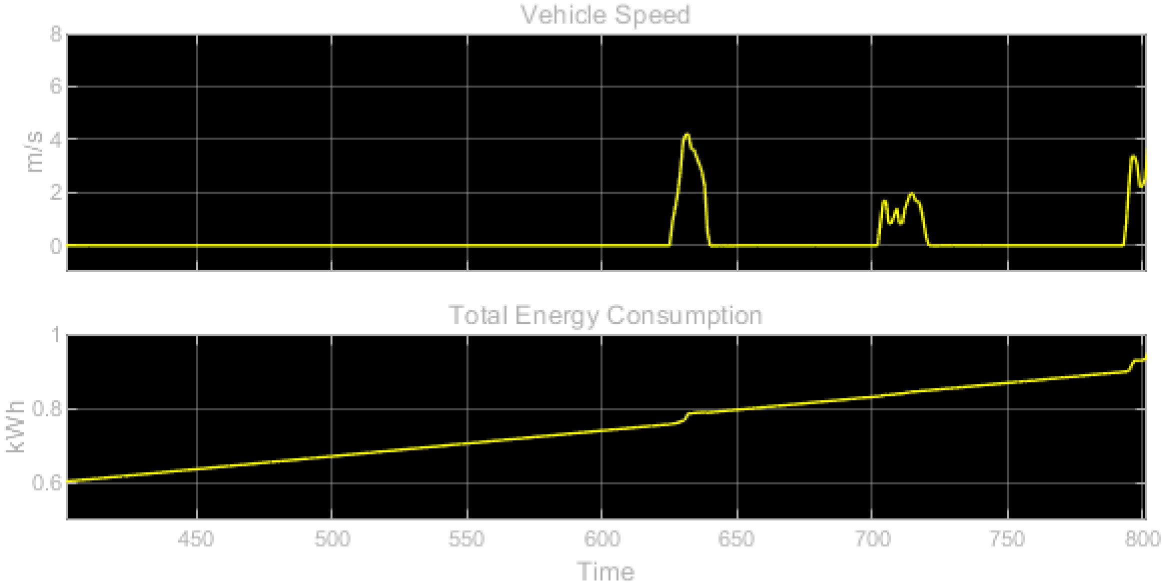

Figure 2 Energy Consumption while Standing Still

The separation of the time- and power-depending consumption is important for the distance-related energy consumption. It might seem, that the higher the velocity of the car is, the higher is the energy consumption, but this is only valid for the time-related consumptions. But, since the purpose for the most drives is to cover a path, the distance-related consumption is more important. Figure 3 gives an impression on how the behaviour of the time- and distance-related consumptions look like at different velocities. This graphic shows an average car driving with a constant velocity, on a flat road and auxiliary power consumers running on a usual level.

With the travelling time rising due to lower velocities the time-depending consumptions causing a higher overall fuel consumption at a constant distance, so the distance-related consumption is rising. Due to the influence of the speed on the driving resistances, the power-depending consumptions are rising with the velocity over proportional, hence at a certain velocity the distance-related consumptions are rising again. In this case, the minimum distance-related consumption is at 50 km/h with 4.44 l/100km.

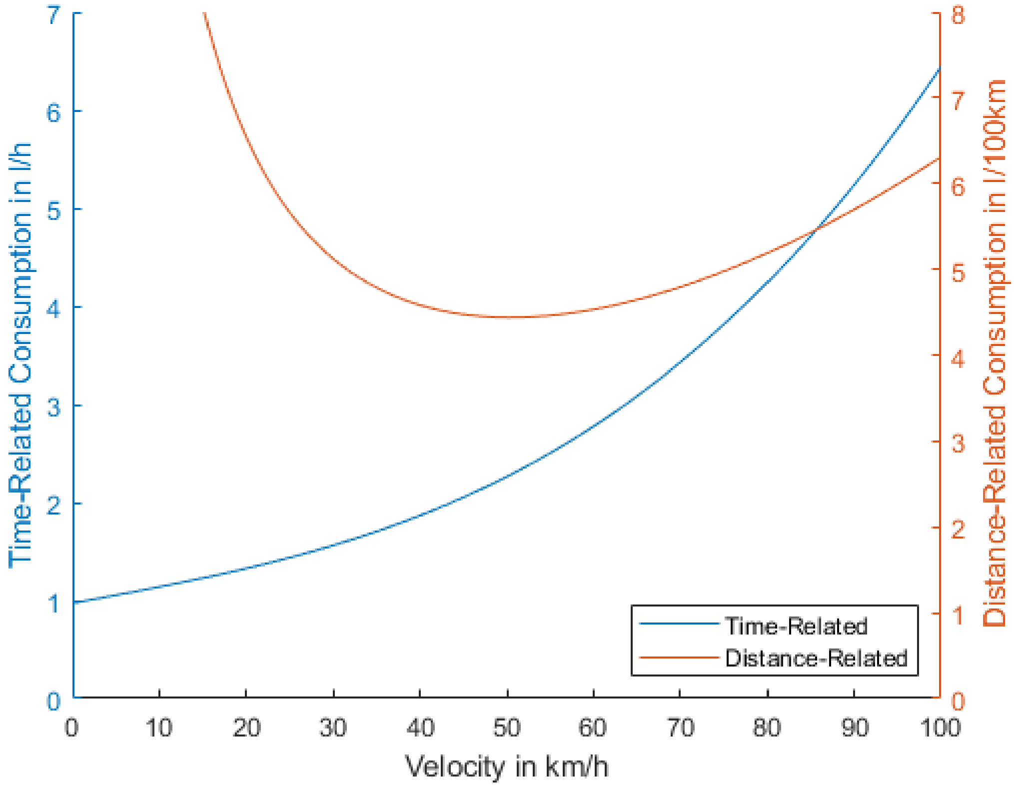

Figure 3 Behaviour of Time-Related and Distance-Related Consumptions of an ICE vehicle

3.2.6. Battery Power Flow and State of Charge

The equation to calculate the battery power flow Eq. (10) is similar to Eq. (9) for calculating the fuel mass flow, but this time it is a real power balance. On the left side is the power obtained from the battery. On the right side are three terms, at first a time-depending consumption with again consists of a basic power consumption of the battery, which considers the battery management and temperature conditioning, and the power obtained from the auxiliary power consumers. The second term consists of the power-depending consumptions, which considers the driving power from the EM. This first two terms have to be divided by the efficiency of the electrical path to obtain the electrical power of the battery. The third term considers the battery charging from braking and the ICE and is multiplied with the efficiency rate. A positive sign is defined as power consumption, while a negative sign is defined as recharging. So, the first two terms have a positive sign, while the third term has a negative sign.

The efficiency of the electrical path contains next to the efficiency of the electrical machine itself those of the inverter, the battery charging and the mechanical losses in the transmission of the electrical path. The efficiency rate of the auxiliary is in fact not the same, as that for the electrical machine. But, since every part has its own efficiency rate and they all have to be assumed, they are assumed to be the same as a simplification.

$$P_{Bat} = \frac{(P_{Bat,0} + P_{SC})}{\eta_{ep}} + \frac{P_{EM}}{\eta_{ep}} - P_{rec} * \eta_{ep} \tag{10}$$

P_{Bat}… battery power, $P_{Bat,0}$… basic consumption of the battery, P_{EM}… power needed by the electrical motor, P_{SC}… power of auxiliary power consumers, P_{rec}… recharging power, η_{ep}… efficiency rate of the electrical path

Figure 3 shows the behaviour of the time-related and distance-related fuel consumption of an ICE. A similar shape also applies for the energy consumption of an EV. Figure 4 shows that the minimum energy consumption of the same vehicle occurs at a lower speed of 40 km/h, due to the lower basic consumption of an EM.

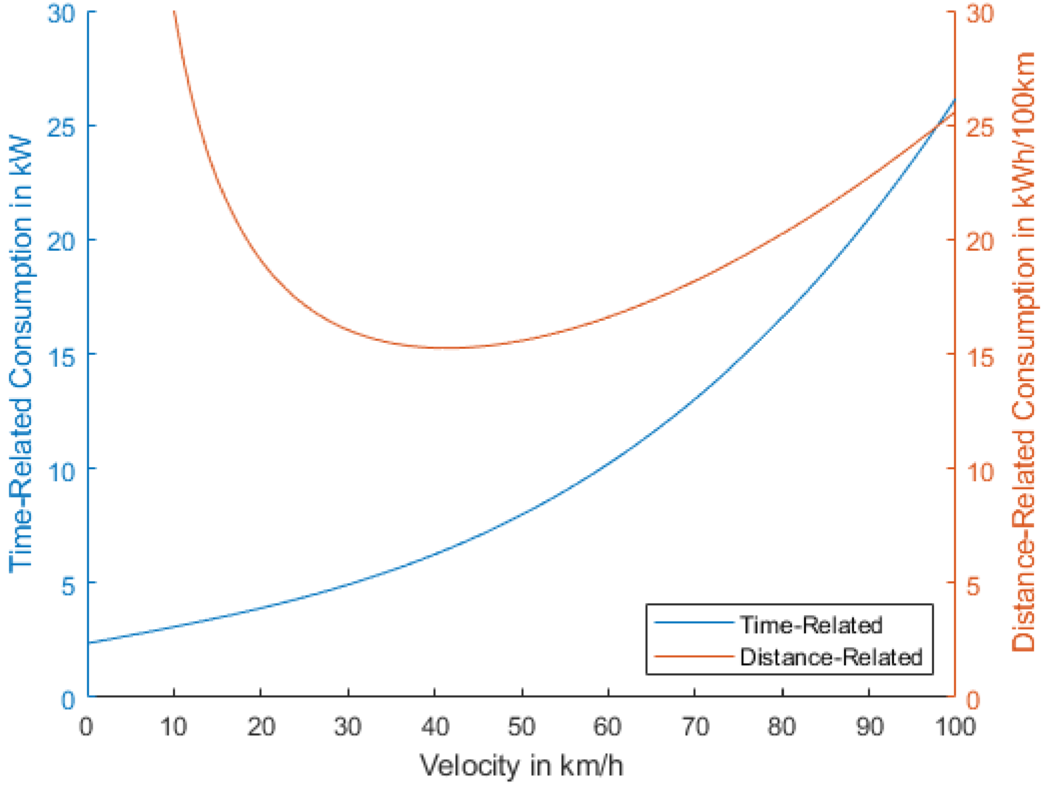

Figure 4 Behaviour of Time-Related and Distance-Related Consumptions of an EV

3.2.7. Energy Consumption and CO_2-Emissions

The overall energy consumption can easily be calculated by adding the two separated energy consumptions. The energy consumption of the battery is the temporal integration of the battery power calculated in Eq. (10). The energy consumption of the ICE is the consumed fuel mass multiplied by the energy density.

For the calculation of the overall CO_2-emissions the separated energy consumptions are multiplied with their specific CO_2-emission and summed up afterwards.

3.3. Alternative Model

The model used in this work is based on major simplifications by skipping the power unit and using averaged values, so it will be referred as averaged value model (AVM). Another way to simulate the energy consumption of a vehicle is using look-up tables, like the model created by Yu Inoue and used by the Kosaka-Matsumori Laboratory of the Nagoya Institute of Technology. This model will from now on referred as look-up table model (LTM).

The LTM is also created with MATLAB/Simulink and gives a more detailed model. While in the AVM e.g., one efficiency rate covers the whole spectrum, the look-up table gives specific values for the efficiency rate depending on the motor speed and the motor moment, which depicts the real world better and is more flexible in terms of different driving situations. Figure 5 gives an overview.

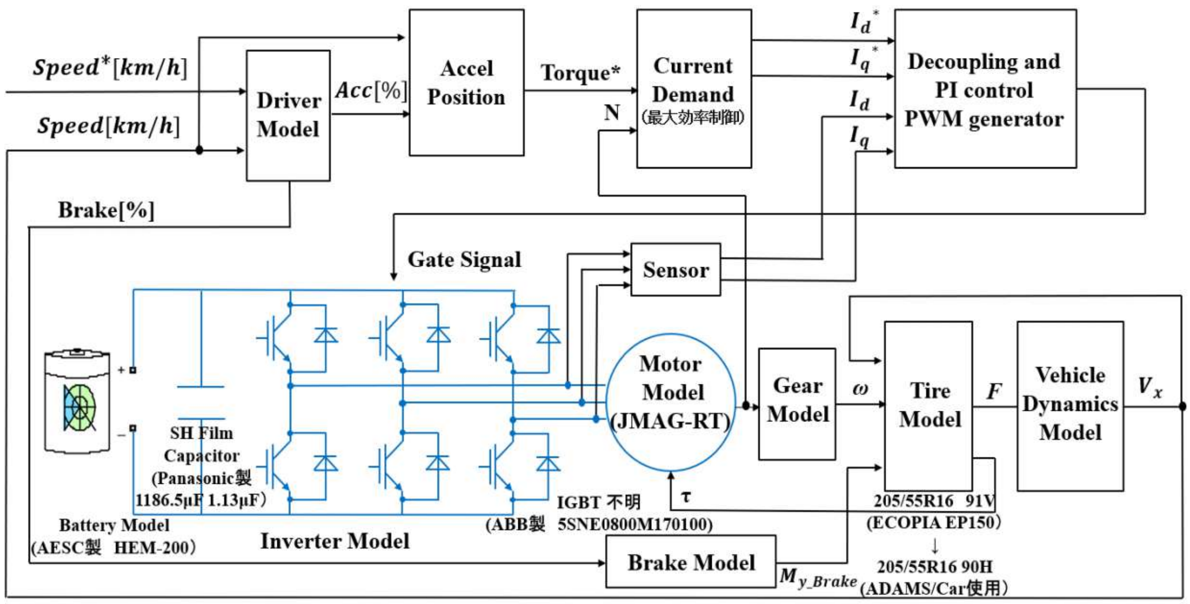

Figure 5 Look-up table model overview [5, p. 19]

The LTM also works with an inputted target velocity, but however, the driver's model is quite different. While the AVM uses a simple feedback control loop to regulate the velocity, the LTM combines a feedback control loop with a feed forward controller, which estimates the driving resistances from the target velocity and calculates an acceleration percentage required to generate the needed torque, by a look-up table. The command from the feedback loop is added to equalizes the error and is needed for the braking command. The summed-up acceleration percentage is multiplied with the maximum available torque, at the current motor speed, obtaining the data form a N-T (motor speed – torque) look-up table.

In the next step the LTM uses look-up tables, which gives the needed current to generate the required torque at the actual motor speed. There are a lot of combinations of i_d and i_q to produce the torque. The look up tables give the combination that has the best efficiency rate. The data for i_d and i_q were obtained from a two-dimensional finite element magnetic analysis with the JMAG-Designer. In connection the currents from the d/q system are converted to the three-phase u/v/w system. These currents from the three-phase system are inputted to the inverter model, which considers the switching losses in the inverter. The output of the inverter model is the DC current and voltage to calculate the power of the battery on the one side. And on the other side, the inverter model passes on the AC currents and voltages, which are used to simulate an electrical machine by using a simulation block for 3-phase synchrony electrical machines. The AC currents and the voltages are inputted as well as the mechanical load of the motor, which is assumed to be equal to the driving force acting on the tires. This block outputs a lot of data used for further calculation, one of them is the motor speed, which is multiplied by the gear ratio and used for the calculation of the vehicle's movement. To calculate the forces acting on the wheels, the magic formula is implied.

From the vehicle's movement the velocity and the travelled distance can be obtained. The velocity is used for the feedback loop of the diver model. The travelled distance is important for the calculation of the energy consumption rate. In Japan the energy consumption of a car is given in travelled distance per energy, means the distance from the movement has to be dived by the integrated battery power.

This model neglects auxiliary power consumers completely. [5] [6]

4. Simulation Set-Up

4.1. General and Environmental Parameters

4.1.1. Specific CO_2-Emissions

For a fair comparison of the CO_2-emissions, a Well-to-Wheel value must be applied for both energy sources, electrical energy in the battery and gasoline in the tank, respectively. The Well-to-Wheel value considers the direct emissions at the car, also known as Tank-to-Wheel emissions, as well as the indirect emissions from the energy production, so called Well-to-

Tank emissions. This work considers the CO_2-equivalent emissions, which includes next to CO_2 also other greenhouse gases and converts them to a mass of CO_2 of the same impact to climate.

The combustion of the fuel causes an emission of 2.289 kg $CO_{2\text{-}eq}$/l fuel [7], which is the Tank-to-Wheel emission. But, for the promotion of crude oil and the conversion to gasoline 0.603 kg CO_2-eq/l fuel [7] are emitted, which is the Well-to-Tank emission and must be added. In the sum the Well-to-Wheel emission is 2.892 kg $CO_{2\text{-}eq}$/l fuel. With an averaged density of 0.74 kg/l [8], and an energy density of 9.2 kWh/l [9], the massive emission is 3.908 kg $CO_{2\text{-}eq}$/kg fuel and the energetic emission is 0.314 kg $CO_{2\text{-}eq}$/kWh, respectively.

Since the conversion of electrical energy to mechanical energy in the electric machine doesn't produce onboard emissions, the Tank-to-Wheel emission is zero. But due to the production process of the electrical power, there are still Well-to-Tank emissions, which must be considered for the calculation. These production emissions depend on the primary energy source, while fossil energy sources have very high emissions, the CO_2 balance can be improved with renewable sources, like wind or hydro energy. So, the specific CO_2-emission for electrical power depends on the domestic consumption mix. The simulations in this work will take place in Japan and Austria, hence these two countries must be considered. While Japan uses since the tsunami in 2011 a high share of about 75% of fossil primary energy, the specific CO_2-emissions are 506 g$CO_{2\text{-}eq}$/kWh [10], Austria can push it down to 219 gCO_2/kWh [7] due to a high share of over 40% of hydro energy. The following Table 1 will summarize the used specific CO_2 emissions.

Table 1: Summarized Specific CO_2-Emissions

Energy	**Volumetric emission**	**Massive emission**	**Energetic emission**
Gasoline	2.892 kg$CO_{2\text{-}eq}$/l	3.908 kg$CO_{2\text{-}eq}$/kg	0.314 kg$CO_{2\text{-}eq}$/kWh
Electrical Power Japan	-	-	0.506 kg$CO_{2\text{-}eq}$/kWh
Electrical Power Austria	-	-	0.219 kg$CO_{2\text{-}eq}$/kWh

4.1.2. Auxiliary Loads

An important part of this simulation is to calculate a real-world drive, means in comparison to a standardised test procedure, some auxiliary consumers are switched on. These auxiliary consumers are time-dependent consumers because they are not involved in the vehicle movement, but consuming energy at the time the car is driven. The auxiliary loads can be considered into two separate categories. First there are small auxiliary consumers, such as light, radio, power steering and for EVs also the brake assistant, because they can't use the under pressure from the combustion Engine. These small consumers are assumed to add up for a power of 750 W in an averaged European car [11]. The second category are big consumers, consisting of the air condition and other big electrical consumers like seat heating or window defroster. The maximum power for the air condition is assumed with 3kW and can be tuned to 4 equal distanced stages from 0-3 kW [12]. The other big consumers can be switched to 4 equal distanced stages from 0-1500 W, e.g., heated seats need 400 W, windscreen heater 500 W, or an electrical booster heater 1000 W [11]. In case of a standardised test cycle, the big auxiliary loads are turned off completely, but also some of the small consumers can be switched of, so that the power for the small consumers can be reduced to 350 W [11]. Table 2 summarizes the used power consumptions for the auxiliary loads.

Table 2: Summarized Auxiliary Loads

Auxiliary load	**Stages**	**Maximum power**
Small consumers	1	750W
Small consumers test cycle	1	350W
Air Condition	4	3000W
Big electrical consumers	4	1500W

4.1.3. Efficiency Rates and Basic Consumptions

For the basic consumptions of the battery, the battery thermically conditioning is the key factor. The literature gives a wide range of power consumptions of the battery cooling, depending on the size and the power of the battery. For a mild hybrid with a small battery Krüger found an averaged power consumption of approximately 90 W in standardized test cycles with maximum power peaks at 5000 W. It was also shown that more dynamic drive leads to higher cooling power, due to more dynamic recharge and discharge occurrences [13]. For EV with a bigger battery the power can arise up to 6.6 kW [14] which is significantly higher, so the averaged load for real-drive battery management was assumed to be 250W.

As explained earlier in chapter 3.2.6 the calculation uses a fixed, averaged efficiency rate for the whole electrical path. Grunditz showed that the powertrain efficiency rate of BEVs ranges from 82% to 90% during propulsion and is a little bit lower 80% to 88% during braking. The overall efficiency correlates with the average velocity, means that the efficiency in high-speed drive cycles appears to be higher, than in low-speed cycles. This effect results from the behaviour of the electrical machine and the inverter, which shows the same correlation, while the battery and transmission losses keep constant. The highest losses arise in the electric machine itself followed by the inverter in the case of low-speed driving, or the transmission in case of high-speed driving [15]. So, for this simulation the overall efficiency rate was assumed to be 85%, which is in the middle, because it has to represent both, the propulsion, and the braking. It is also assumed that the electrical path of an PHEV has the same overall efficiency as a BEV, so the numbers provided by Grunditz are valid too.

For the calculation of the fuel consumption with Eq. (9) from chapter 3.2.5 the neutral gear consumption can be assumed as 0.5 l/h which equals $1.0278*10^{-4}$ kg/s and the nowadays highest best point specific fuel consumption can be supposed by approximately 200 g/kWh [16]. Table 3 summarizes the used efficiency rates and basic consumptions.

Table 3: Summarized efficiency rates and basic consumptions

Consumption Type	Formula sign	Specific consumption	Efficiency rate
Battery basic consumption	$P_{Bat,\,0}$	300 W	-
EM efficiency rate	η_{EM}	1.176 kWh/kWh	85 %
ICE neutral gear consumption	$\dot{V}_0$	0,5 l/h	-
ICE best point specific fuel consumption	$b_{e,\,spec}$	200 g/kWh	40.2%

4.1.4. Driving resistance

The most parameters used to simulate the driving resistances are vehicle specific parameters and given in the following section with the simulated vehicles. The only real environmental parameters are the air density and the gravitational acceleration. The air density depends on the ambient temperature and the altitude. It also effects beside of the air drag resistance the performance of the ICE, lower density leads to lower output power and higher specific fuel consumption [17]. This effect however is neglected in this simulation. For the impact on the air drag resistance, the effects of the temperature and the altitude are neglected as well, and a fixed value is assumed. Vienna is on an altitude of approximately 150 m above the sea level and has an average temperature of about 10°C [18], which results in an air density of 1.2245 kg/m³ [19]. Nagoya is at the sea level and has a mean temperature of about 15°C [20] which leads to an air density of 1.225 kg/m³ [19]. Those two values are close enough to each other that the rounded value of 1.225 kg/m³ can be used for all simulations.

For the simplification of this model, some vehicle specific parameters are assumed as general parameters as well. First of all, the tires get uniformed, means all simulations are assumed to perform with the same tire and the same road conditions, what effects the rolling resistance coefficient and the maximum friction coefficient for the acceleration. Tires are split up in energy efficiency classes according to the rrc. The best category A includes tires with a rrc below 6.5 kg/t, while the worst category G stores those with a rrc above 12.1 kg/t. In 2015 the average tire sold in the EU had a rrc of 9.25 kg/t [11], why this value was chosen for the simulation. The friction value depends more on the road conditions. For a dry road all types of roads reach a maximum friction coefficient of 1 - 1.2. Under wet conditions the friction factor for cobblestones falls down to 0.4 [21]. For this simulation dry roads are considered and a mean value of 1.1 is supposed for all simulations.

The inertia mass factor of the acceleration resistance is of course a totally vehicle dependant factor. But, as explained in section 3.2.3 it depends on the gear ratio as well as on the moment of inertia of a lot of spinning car parts. Both of them are unknown and due to the simplification of the power unit, it isn't even possible to calculate the exact inertia mass factor. So, a fixed value has to be assumed. Miller calculates for a hybrid vehicle driving in 4th gear an inertia mass factor of 1.0648 [22] which will be assumed for the simulation. The used parameters for the driving resistance can be taken from Table 4.

Table 4: Summarized Parameters for the Driving Resistances

Parameter	Formula sign	Value
Air density	ρ_{Air}	1.225 kg/m³
Rolling resistance coefficient	f_r	9.25 kg/t
Road/Wheel maximum friction coefficient	f_f	1.1
Inertia mass factor	λ	1.0648

4.2. Simulated Vehicles

The first car that was used for the simulation is a BMW X5 40e, a full-sized SUV with a plug-in hybrid electric power train. This car was used for a real-world drive validation measurement. The kerb weight of the vehicle is 2230kg [23] but, to drive the car, a driver and fuel are necessary. For the diver the weight of an averaged Austrian man of 84.6kg [24] was considered. The car is assumed to start with a full tank, which has a capacity of 85l [23], hence 62.9 kg have to be added, what leads to a rounded driving weight of 2377 kg. The used data [23] is available in the following Table 5.

Table 5: Vehicle Data BMW X5 40e

Data	Formula sign	Value
Brand and Model	-	BMW X5 (F15) 40e
System power	P_{max}	358 HP / 253 kW
Electric motor power	P_{EM}	113 HP / 83 kW
Internal combustion engine power	P_{ICE}	245 HP / 180 kW
Internal combustion engine minimum power	P_{min}	30 kW
Net battery capacity	C_{Bat}	6.8 kWh
Maximum recuperation power	$P_{rec, max}$	20 kW
Vehicle mass	m	2377 kg
Approximated cross-sectional area	A	3.5 m²
Drag coefficient	c_d	0.31

The second vehicle, which was simulated is the Nissan Leaf, a compact hatchback electric vehicle. This car was used for the look-up table simulation of the Nagoya Institute of Technology in the first place and should be the object of comparison in this work. The kerb weight is 1505kg [25], fuel is not needed since this car is an electric vehicle. For a better comparison to the BMW X5 the same driver's mass is considered, hence a driving mass of 1590 kg is assumed for the simulation. The used data [25] are given in Table 6.

Table 6: Vehicle Date Nisan Leaf EV

Data	Formula sign	Value
Brand and Model	-	Nissan Leaf I (ZE0) 24 kWh
Electric motor power	P_{EM}	109 HP / 81 kW
Net battery capacity	C_{Bat}	22 kWh
Maximum recuperation power	$P_{rec, max}$	20 kW
Vehicle mass	m	1590 kg
Approximated cross-sectional area	A	2.75 m²
Drag coefficient	c_d	0.28

4.3. Drive Cycles

4.3.1. JC08

The JC08 was the official Japanese drive cycle for measuring the fuel consumption and exhaust gas emissions, until it got replaced by the WLTC in 2018. However, the cars used for this simulation was launched bevor this replacement and so the official consumptions were measured in the JC08 mode, hence it will be used for the comparison.

The JC08 depicts city drive as well as highway drive. The driven distance is 8.16 km within 1204 s. While the average velocity is 34.2 km/h, the peek speed is at 81.6 km/h. This is significantly slower than the WLTC with an average speed of 46.5 km/h and a maximum speed of 131.3 km/h. But the speed limits in Japan are low, with a limit of 100 km/h at the highway. So, the JC08 was meant to depict the slower traffic. Figure 6 shows the velocity profile over the time of the JC08 mode and summarizes the key data of the pattern [26].

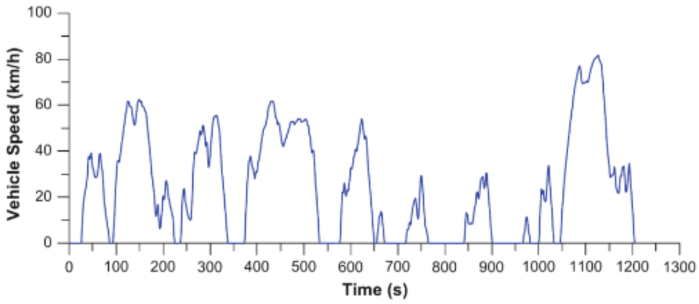

Figure 6 Velocity profile of the JC08 mode [26, p. 131]

Table 7: JC08 Key Data

Data	Value
Duration	1204 s
Distance	8159 m
Max. Speed	81.6 km/h
Average Speed	24.4 km/h
Idling time	28.7 %

For the fuel economy in the JC08, the pattern is measured twice. At the first time with a cold engine, at the second time with a hot engine. A weighted average value is calculated form these two measurements [26]. The influence of the engine temperature cannot be simulated with this model hence the weighing is neglected and only one value will be compared. The air condition is switched off [26].

4.3.2. New European Drive Cycle (NEDC)

Starting from the year 1992 European passenger cars' exhaust emissions were tested with the drive cycles ECE for city traffic and EUDC for higher velocity traffic. Before the measurement started, the engine had 40 s to heat up. In the year 2000 this heat up time was eliminated, and the two cycles together were called New European Drive Cycle (NEDC). The total duration of the NEDC is 1180 s and the travelled distance is 11 km [26]. Figure 7 shows the plot of the velocity distribution over the time and Table 8 summarizes the key data.

The criticism on this driving pattern were the static velocity and the very low accelerations with a maximum of 1.04 m/s². This results in a very low driving power of the vehicle and producers could optimize their vehicles for this power field. The NEDC was replaced by the WLTC in the year 2018 [26].

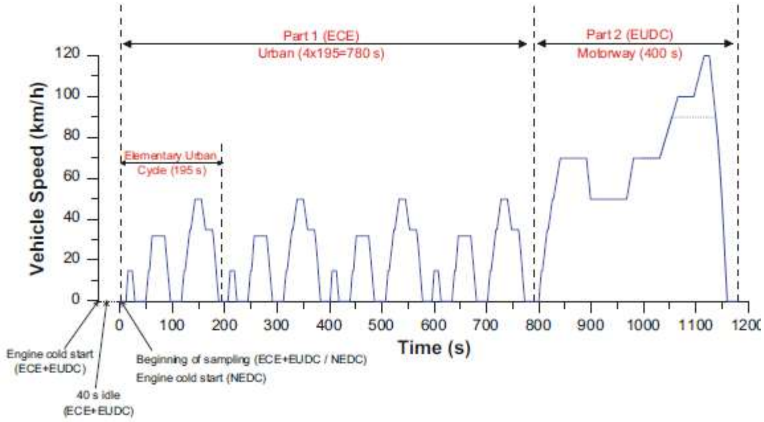

Figure 7 Velocity Profile of the NEDC [26, p. 72]

Table 8: NEDC Key Data

Data	Value
Duration	1180 s
Distance	11000 m
Max. Speed	120 km/h
Average Speed	33.6 km/h
Idling time	23.7 %

4.3.3. Real-Word Drive

The real-world drive is a measured velocity profile, driven on the Ring, a main street of Vienna. The drive starts at the TU Wien, cycling the city centre of Vienna, and is ending at the former emperor’s castle. The characteristic of this route is urban drive, and the traffic was high at the measured time, hence the average speed is only 14.2 km/h and a lot of stop times are included using 42% of the time. The finish is 4.8 m more above the sea level, than the start and the maximum difference between the lowest point and the highest points is 17.2 m. Figure 8 gives the plotted GPS route, Figure 9 the measured velocity profile over the time, and Figure 10 the used height profile over the travelled distance. Table 9 summarizes the key data.

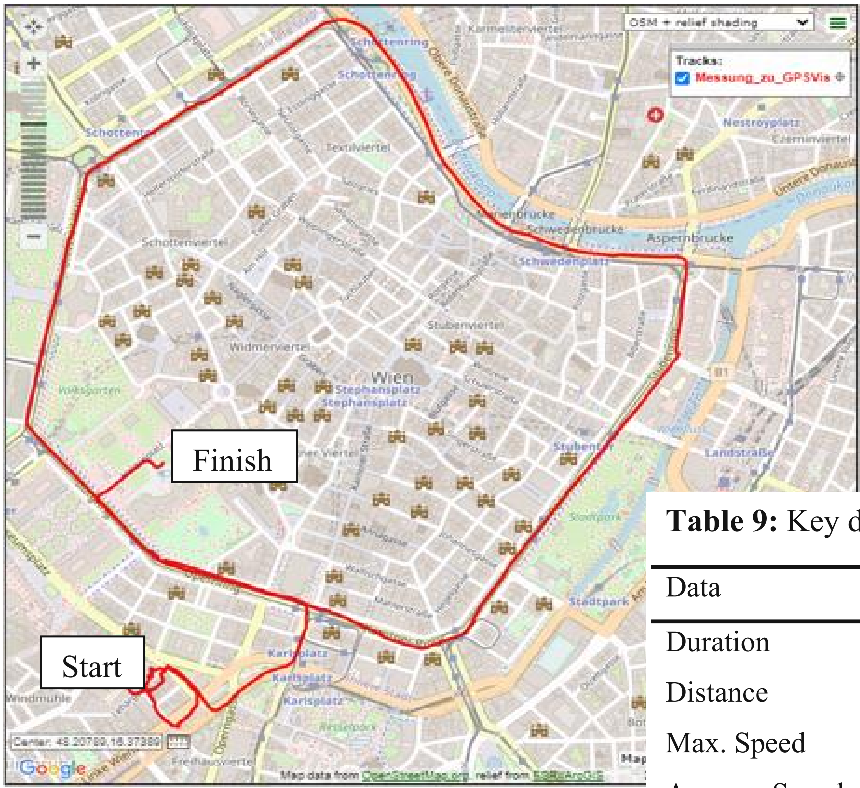

Figure 8 GPS-Plot of the Measured Real-World Drive

Table 9: Key data real-word drive

Data	Value
Duration	1866 s
Distance	7364 m
Max. Speed	59 km/h
Average Speed	14.2 km/h
Idling time	42.8 %
Heigh difference	
Maximum	17.2 m
Start-Finish	+4.8 m

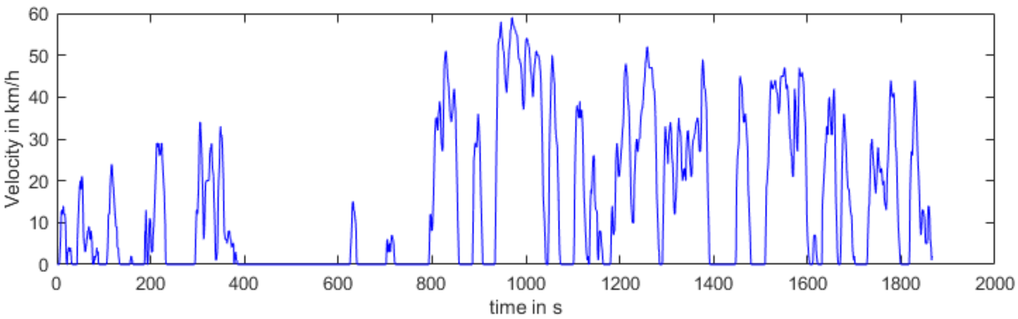

Figure 9 Velocity Profile of the Measured Real-World Drive

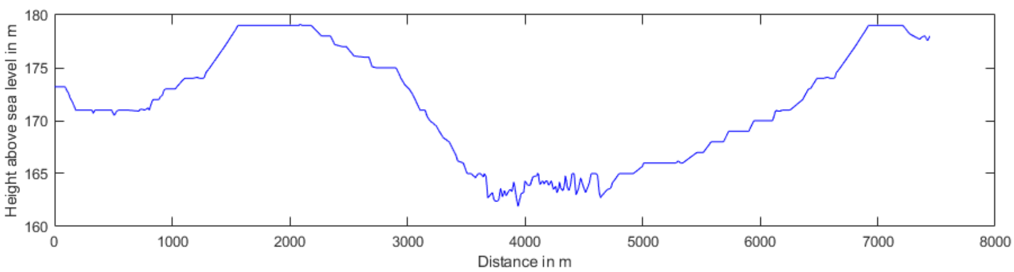

Figure 10 Height Profile of the Measured Real-World Drive

4.3.4. Synthetic Drive

The synthetic drive was created in in the city of Nagoya. The start and the finish are at the Nagoya Institute of Technology. The track leads over smaller and major city roads to the Nagoya Castle and enters there the city highway for the return trip. The whole trip is 10,223 m long and has a maximum height difference of 37.7m. The characteristic of the first half is marked by city traffic and traffic lights with stop times. The return trip flows on a constant velocity. Figure 11 shows the constructed route in Google Maps and Figure 12 the matching height profile, Table 8 shows the key data.

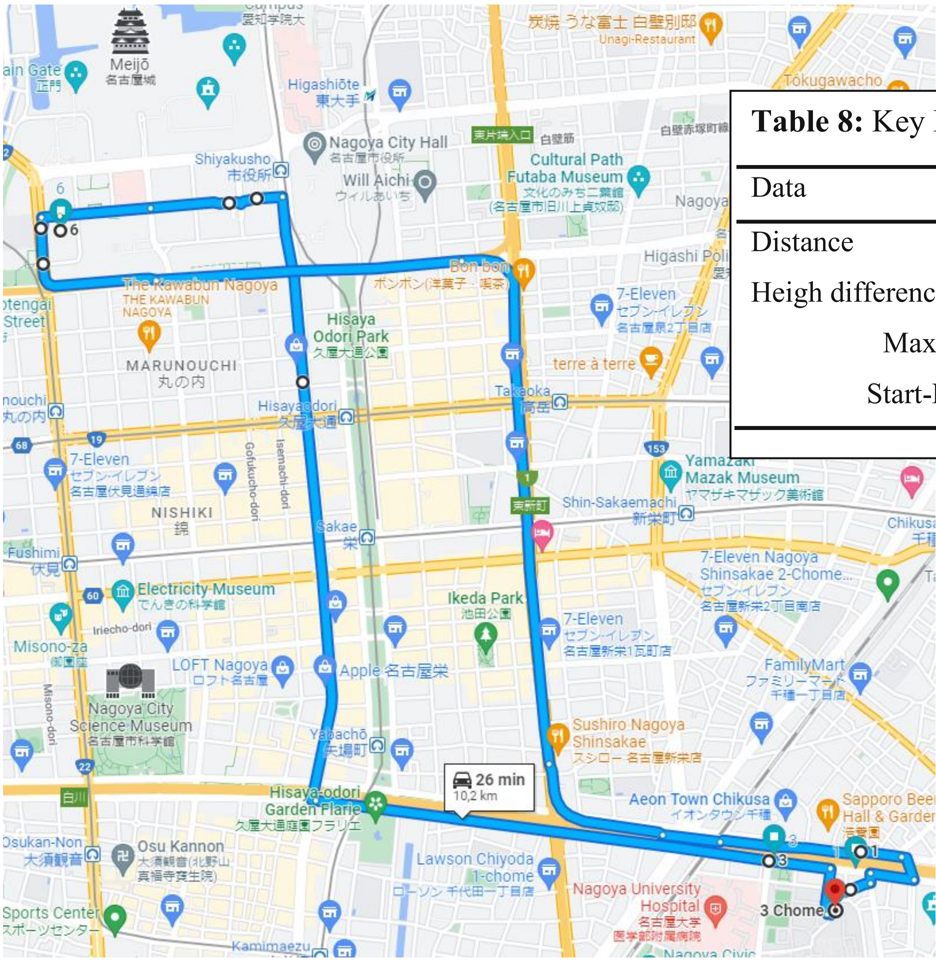

Table 8: Key Data Nagoya Drive

Data	Value
Distance	10223 m
Heigh difference	
Maximum	34.7 m
Start-Finish	0m

Figure 11 Route of the Synthetic Drive in Nagoya

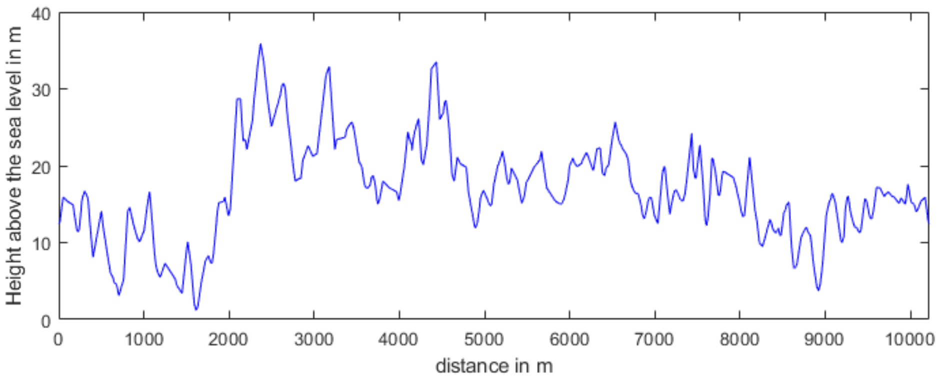

Figure 12 Height Profile of the Synthetic Drive in Nagoya

The velocity Profile is not fix, as in the other three drive cycles. It depends on the set up for the target velocities and the frequency and duration of traffic stops. For the variation four different velocity profiles will be simulated. The first one, from now on referred as "Profile 1", is the basic drive cycle and is characterized by a smooth flow and short stop times. The target velocity for small streets is set for 30 km/h, on main streets for 50 km/h and on the city highway for 80 km/h. The stopping frequency on main streets is 700 m and the stops will last 20 s, on smaller streets, the stop frequency is every 100 m and will last for 2 s, this should simulate the turns and short stops for looking, if the road is free. The same target velocities are assumed for the second profile, from now on referred as "Profile 2", but the stop frequency on main roads is varied to every 300 m, and the stop time increases to 40 s. In the second variation, form here on referred as "Profile 3", the stopping frequency and the duration will be the same as in the original drive, but the target velocities will be increased to 50 km/h, 70 km/h, and 110 km/h. This shows a more likeable speed distribution for Nagoya since the city residents are feared in Japan for rude driving. Their driving style even as an own name "Nagoya-Bashiri". The last velocity profile, referred as "Profile 4" gives a counterexample to Profile 3, where the speed goals were set to 20 km/h, 30 km/h and 60 km/h. Table 9 summarizes the varied parameters for the synthetic velocity profiles.

Table 9: Target Speed and Stop Parameters for Synthetic Drives

	Small city streets			Main city streets			Highway
Profile	Speed	Stop frequency	Stop Time	Speed	Stop frequency	Stop Time	Speed
Profile 1	30 km/h	100 m	2 s	50 km/h	700 m	20 s	80 km/h
Profile 2	30 km/h	100 m	2 s	50 km/h	300 m	40 s	80 km/h
Profile 3	50 km/h	100 m	2 s	70 km/h	700 m	20 s	110 km/h
Profile 4	20 km/h	100 m	2 s	30 km/h	700 m	20 s	60 km/h

Figure 13, Figure 14, Figure 15 and Figure 16 show the velocity profiles and the Table 10 summarizes the key data.

Profile 1:

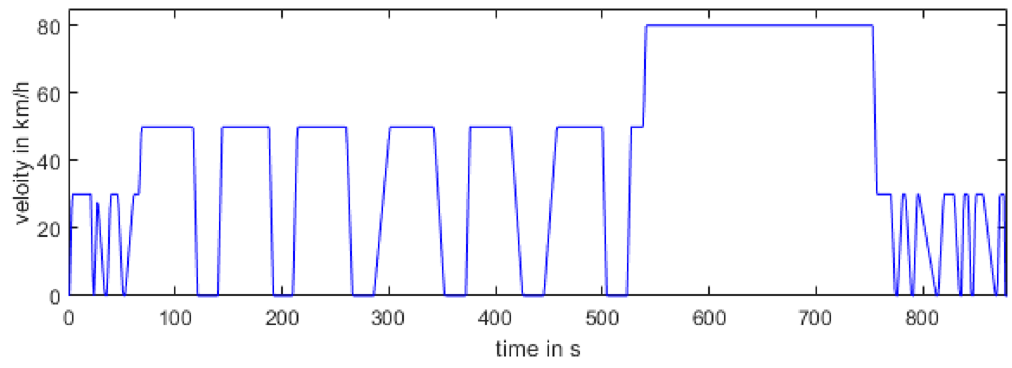

Figure 13 Velocity Profile 1

Profile 2:

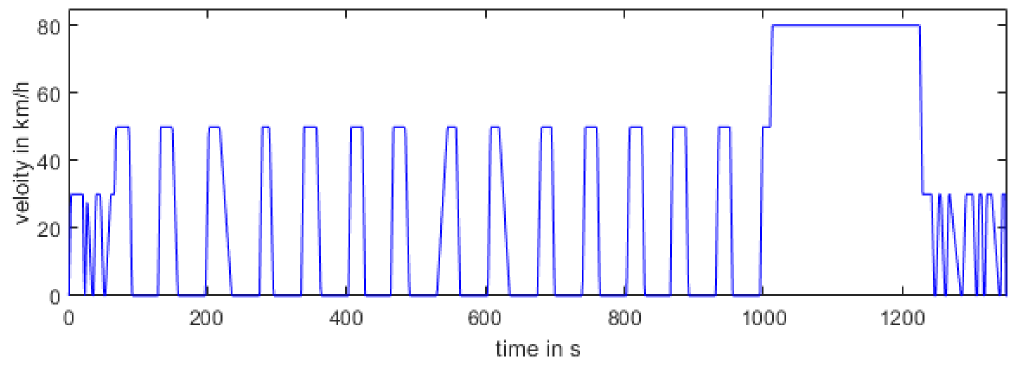

Figure 14 Velocity Profile 2

Profile 3:

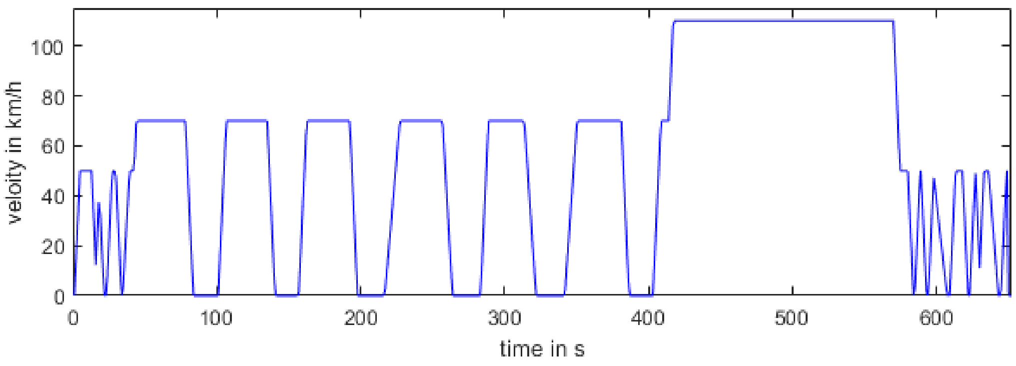

Figure 15 Velocity Profile 3

Profile 4

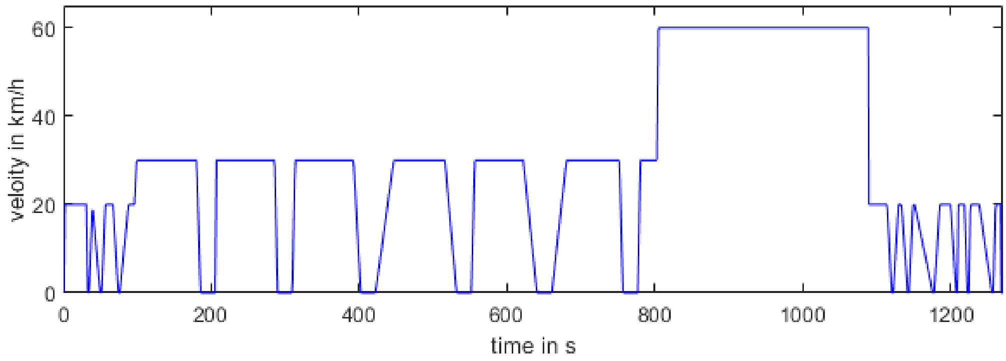

Figure 16 Velocity Profile 4

Table 10: Key Data of Synthetic Drive Velocity Profiles

Profile	Duration	Max. Speed	Average Speed	Idling time
Profile 1	879 s	80 km/h	41.7 km/h	15.9 %
Profile 2	1351 s	80 km/h	27.2 km/h	42.3 %
Profile 3	652 s	110 km/h	56 km/h	19 %
Profile 4	1271 s	60 km/h	28.92 km/h	11.2%

The idling time percentage of Profile 3 is higher than the one of Profile 1, because both have the same stop time, since the stops depend on the distance, but the duration of Profile 3 is shorter, due to the higher velocity, hence the relative time of the car not driving becomes higher. The same effect but in the opposite direction is the reason for the lower idling time of Profile 4.

5. Simulation Results

5.1. Comparison to Measurements

To show the accuracy of the model some measured drives were simulated and compared. This is no problem for the all-electric Nissan Leaf, because the simulated values from the standardised test cycles can be compared directly. For the BMW X5 40e is a measurement of the JC08 available, driven with the ICE in km/l. The measurement of the real-world drive was made in hybrid mode and air conditioning running on a low level. There are only fuel consumption data available, but the battery SoC was kept almost constant. The air conditioning was represented by an average power of 1000 W in the simulation and the battery SoC decreased by 2 percent points.

Table 11: Summarized Values of Comparisons to Measurements

Drive Cycle	Measured Value	Simulated Value	Simulated Value	Deviation
Nissan Leaf EV		In kWh / 100km	In km / kWh	In %
JC08	8.06 km / kWh	12.37	8.084	0.3
NEDC	15 kWh / 100km	13.65	7.326	9
BMW X5 40e		In l / 100km	In km / l	In %
JC08	13.8km / l	7.43	13.47	2.4
Real-World Drive	7.74 l / 100km	8.66	11.55	11.9

The results from Table 11 show that the deviation from the measurement is not constant but depends on the drive cycle. A good comparison are the two official values of the Nissan Leaf, because they were both simulated under the same conditions and with the same efficiency rate. But obviously the assumptions made fit the JC08 better than the NEDC. The high deviation of the real-world drive could be a result of wrong assumptions in the power split, or wrong assumptions of the auxiliary power consumers since they were not measured.

5.2. Comparison of the Simulated Vehicles

The simulation results in this chapter show the influence of the vehicle type. In this case the comparison is between a compact vehicle and a SUV. For the comparison all settings were set equally. Both cars are operating in the all-electric mode since the Nissan Leaf is a BEV, and the efficiency rate of the electrical power train path is set to 85 %. The big auxiliary power consumers are switched off, and the small auxiliary power consumers are switched to the minimum of 350 W for the standardized driving patterns. For the real-world drive and the synthetic drive, the small consumers are switched to real world conditions with 750 W and the air conditioning is running with a power of 1000 W. The specific CO_2-emissions of the electric power were set to the Japanese value for the simulation of the JC08 and the synthetic drive since they take place in Japan. For the other simulations the Austrian power mix was used.

While the Nissan has a total weight of 1589.6 kg, the BMW X5 weights 2377.5 kg, which is an increase of 49.6 %. The vehicle's weight influences three driving resistances directly. The only resistance that is independent from the weight, is the air drag resistance, which is influenced by the cross-sectional area of the car and the drag coefficient. As a SUV, the

BMW has a cross-sectional area of 3.5 m², which is 27.3 % bigger as the one of the compact vehicle. Also, the drag coefficient of the SUV is bigger than the one of the compact vehicle. The difference looks small with an absolute value of 0.03 but this means an increase of 10.7 %.

The following Table 12 shows the simulation results for the different driving patterns and an average value for both cars, as well as the percentage increase from the Nissan's value to the BMW's value. The compared results are the distance-related power consumption rate in kWh/100km and the total CO_2-emission in kg. Since the CO_2-emission depends linear on the energy consumption, the percentage increase must be same.

Table 12: Energy Consumption Rate and CO_2-Emission Comparison of the Simulated Vehicles

Vehicle	JC08	NEDC	RWD	SDP1	Average
Nissan Leaf EV [a,b]	12.37 / 0.51	13.65 / 0.33	27.51 / 0.44	21.73 / 1.12	18.82 / 0.6
BMW X5 40e [a,b]	17.48 / 0.72	19.92 / 0.48	33.46 / 0.54	30.4 / 1.057	25.32 / 0.83
Percentage Increase	+41.31 %	+45.93 %	+21.63 %	+39.9 %	+34.55 %

[a] All values are given in the scheme "Energy consumption rate / CO_2-emission"
[b] All values are given in the units "kWh/100km / kg"

The simulation gives a clear picture, that the SUV has a bigger energy consumption and CO_2-emission for every drive cycle. The averaged value raised by 34.55 %, due to the bigger weight and the taller surface. There is also a significant increase between the standardized drive cycles to the real-world cycles. This comes from auxiliary power consumers. Since they are equal for both cars, the percentage increase between the cars is getting smaller under real-world conditions.

5.3. Comparison of Power Train Electrification

This simulation model can also be used to show the efficiency of the different electrification stages of the power train. The BMW X5 can be simulated in the four different operation modes described in chapter 3.2.4. A comparison of the vehicle's energy consumption and a comparison of the CO_2-emission for the four different drive cycles will be made in this chapter. Table 13 shows the energy consumption rates of the vehicle, the values are given in kWh/100km. Table 14 gives the absolute CO_2-emissions of the drive cycle in kg for the Austrian and the Japanese power mix. The big auxiliary power consumers are switched of, and the small auxiliary power consumers are switched to 350 W for the two standardised driving patterns. In the simulation of the real-world drive and the synthetic drive, the auxiliary power consumers were switched to real-world conditions with air conditioning using 1000 W.

Table 13: Energy Consumption Rate with Different Driving Modes

Mode	JC08	NEDC	RWD	SDP1	Average
All electric	17.48	19.92	33.46	30.4	25.31
Plug-in hybrid	37.43	43.68	60.64	67.03	52.2
Hybrid	40.12	48.04	70.6	68.69	56.87
ICE	68.3	63.0	124.9	91.53	86.93

All values are given in kWh/100km

Table 14: CO_2-Emissions with Different Driving Modes

Mode	JC08	NEDC	RWD	SDP1	Average
All electric	0.31 / 0.72	0.48 / 1.11	0.54 / 1.25	0.68 / 1.57	0.5 / 1.16
Plug-in hybrid	1.25 / 1.32	1.99 / 2.07	1.67 / 1.99	2.87 / 2.92	1.94 / 2.07
Hybrid	1.37 / 1.4	2.25 / 2.25	2.12 / 2.25	2.94 / 2.99	2.17 / 2.22
ICE	2.37 / 2.37	2.95 / 2.95	3.91 / 3.91	3.96 / 3.96	3.3 / 3.3

All values are given in the scheme “Austrian power mix / Japanese power mix”
All values are given in kg

Figure 17 gives an impression how much energy on the vehicle and CO_2 can be saved, if the power train is electrified in comparison to the classic ICE. The blue points show the percentage energy consumption saving on the vehicle and doesn’t give an overall energy saving. For the overall energy saving the primary energy to produce the electric power must be analysed. However, since the specific CO_2-emmisions are Well-to-Wheel emissions, their savings can be seen as an overall saving. This graphic also shows the importance of the used power mix. With the lower specific CO_2-emission in Austria, the saving is about 30 % higher than in Japan. Due to the higher energetic specific CO_2-emission of the Japanese power mix in comparison to fuel, the CO_2 saving is lower, than the energy saving.

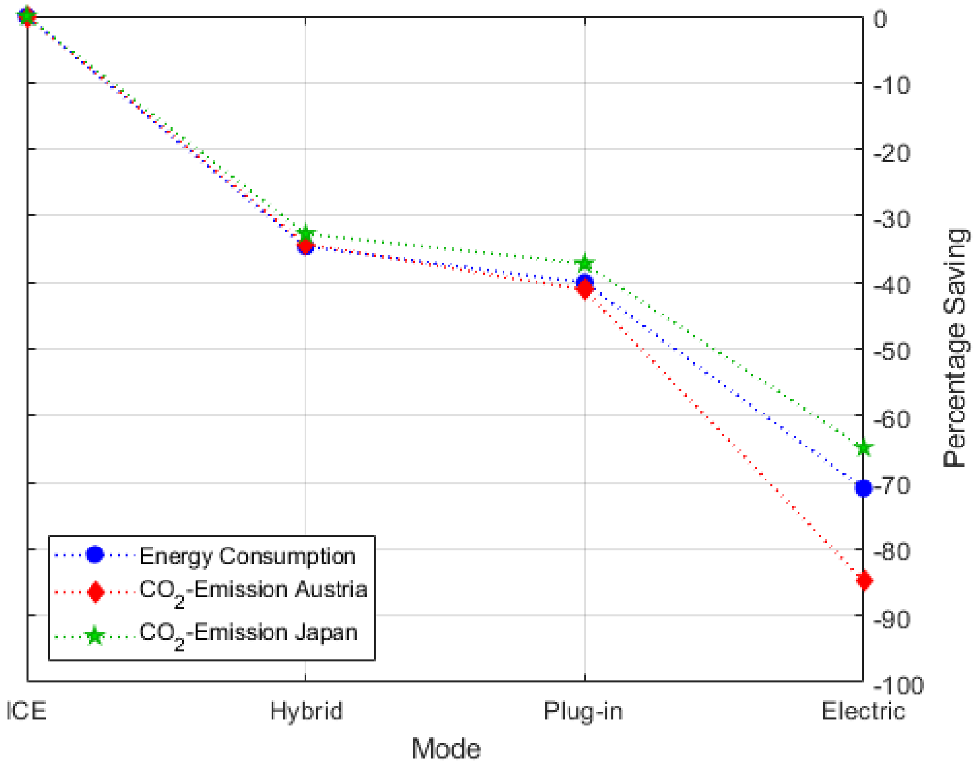

Figure 17 Percentage Energy and CO_2 Saving for Different Electrification Stages

5.4. Influences on the Simulation

The advantage of a simulation is that it can easily be shown, how much a variable change influences the result. In this chapter some important vehicle parameters will be varied, and the changes of the energy consumption will be discussed.

5.4.1. Variation of the Efficiency

Since this model doesn't take a closer look at the technical details of the power train, it is easy to assume an efficiency. In the default setting, the electrical path is assumed to have an efficiency rate of 85 % and the ICE's best point specific fuel consumption is assumed as 200 g/kWh. Now it should be imagined that the power train is modified, so that the electrical path reaches an efficiency of 90 %, which is the highest value given by Grunditz, or decreases to 80 %, which equals the lowest value [15]. After an improvement the ICE's best point specific fuel consumption will go down to 188 g/kWh, while a deterioration let it grow to 212 g/kWh. The change of the specific fuel consumption was chosen to +/- 6 % to be equivalent to the change rate of the electrical efficiency.

The variation of the efficiency is simulated with the velocity and height profile of the real-world drive. The air conditioning is running on a low level with 1 kW, the small consumers are switched to 750 W, like it is usual for a real-world drive. The following Table 15 shows the energy consumption rate in kWh/100km and the percentage improvement or deterioration of the energy consumption in comparison to the reference value.

Table 15: Energy Consumption and Percentage Change Rate with Different Efficiency Rates

Electrical efficiency rate	Specific fuel consumption		
All-Electric	188 g/kWh	200 g/kWh	212 g/kWh
80%	36.91 / +10.32 %	36.91 / +10.32 %	36.91 / +10.32 %
85%	33.46 / 0 %	33.46 / 0 %	33.46 / 0 %
90%	30.31 / -9.42 %	30.31 / -9.42 %	30.31 / -9.42 %
Plug-in	188 g/kWh	200 g/kWh	212 g/kWh
80%	62.88 / +3.7 %	65.62 / +8.22 %	68.37 / +12.74 %
85%	58.08 / -4.22 %	60.64 / 0 %	63.2 / +4.22 %
90%	53.69 / -11.47 %	56.07 / -7.53 %	58.46 / -3.6 %
Hybrid	188 g/kWh	200 g/kWh	212 g/kWh
80%	69.91 / -0.98 %	73.48 / +4.08 %	77.05 / +9.13 %
85%	67.13 / -4.92 %	70.6 / 0 %	74.08 / +4.92 %
90%	64.32 / -8.91 %	67.69 / -4.13 %	71.06 / +0.65 %
ICE	188 g/kWh	200 g/kWh	212 g/kWh
80%	119.34 / +4.44 %	124.9 / 0 %	130.45 / +4.44 %
85%	119.34 / +4.44 %	124.9 / 0 %	130.45 / +4.44 %
90%	119.34 / +4.44 %	124.9 / 0 %	130.45 / +4.44 %

All values are given in the scheme “Energy consumption rate / Change rate”
All energy consumption rate values are given in kWh/100km

Figure 18 gives a colormap of the change rate of the energy consumption, over the percentage change of the efficiency rates. On the x-axis is the change of the specific fuel consumption. The y-axis gives the change of the efficiency rate of the electric power train. The blue and green points show an improvement of the energy consumption, the yellow and red ones a deterioration. To get a reliable colormap a variation of 25 different efficiency rates each were combined and simulated. The points in between were linearly interpolated.

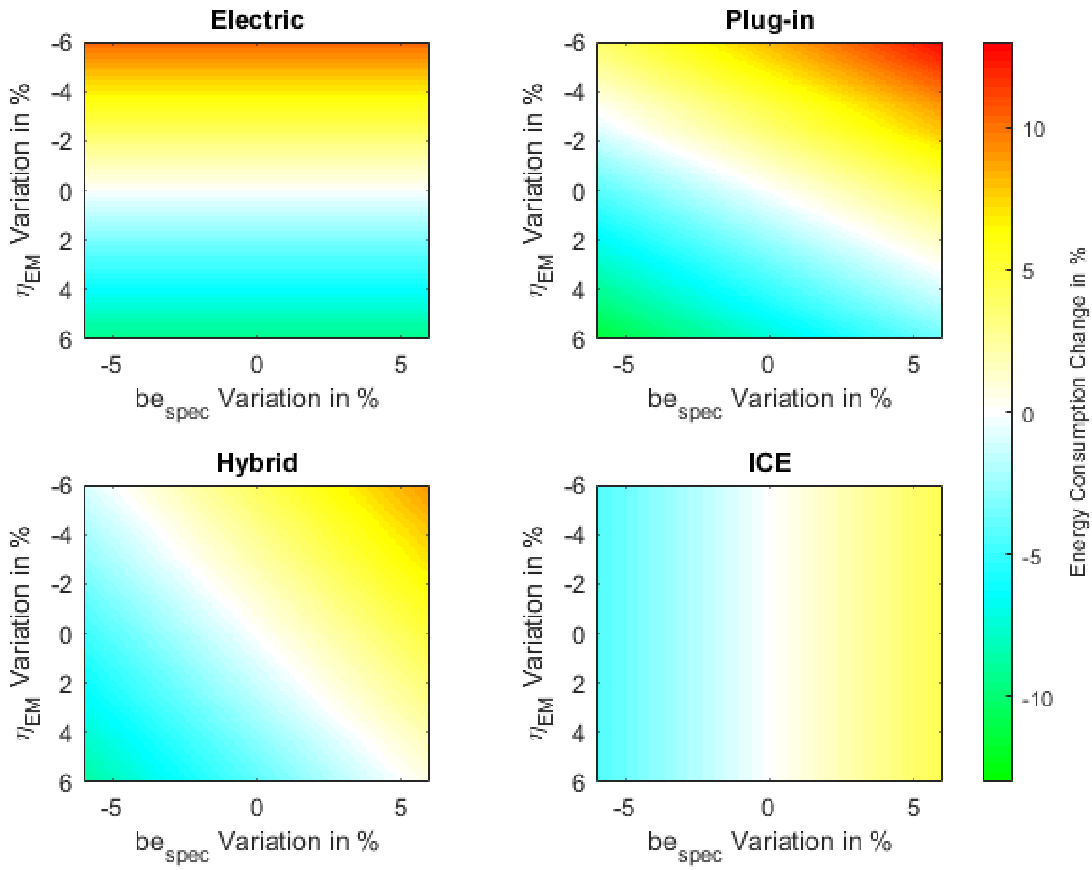

Figure 18 Percentage Change of the Energy Consumption under the Influence of Various Efficiency Rates

Since the same drive cycle was simulated under the same conditions in every variation of the efficiency, the output energy to move the vehicle and power the auxiliary power consumers must be constant. Due to the simplifications in this simulation, the efficiency is multiplied to the output energy and defines the needed input energy. In the non-hybrid modes all-electric and ICE, it is obvious that only one efficiency rate defines the input energy, and that the change of this input energy must follow the characteristics of Eqs. (9) and (10), which defines the energy consumptions. In case of the ICE mode, the energy consumption is a linear equation depending on the specific fuel consumption, hence the change is equal in positive and negative direction and under proportional, due to the time dependent components and the disability of recuperation. In case of the electric mode, the equation of the energy consumption is not linear depending on the efficiency rate. So, the increase of the energy consumption is higher than the decrease, if the efficiency rate falls and raises, respectively. It is also not obvious how big the change rate is, but the simulation shows an over anti proportional behaviour. The modes plug-in and hybrid show a mixed form and depend on both efficiency rates. Obviously, the plug-in mode depends more on the efficiency rate of the electrical path, since more electrical energy is used than in the hybrid mode.

Figure 19 shows the change rate of the CO_2-emissions for the same points shown in Figure 18. Since the CO_2-emission is linear depending on the energy consumption, these graphics look very similar. For the all-electric and ICE mode, the percentage change is exactly equal. For the hybrid modes it changes a little bit. If the specific fuel consumption becomes worse, the CO_2-emission tends to rise more than the energy consumption. If the electrical path efficiency becomes worse, the CO_2-emission tends to rise less than the energy consumption. This is explainable by the different specific CO_2-emissions. The Austrian power mix was used for the simulation.

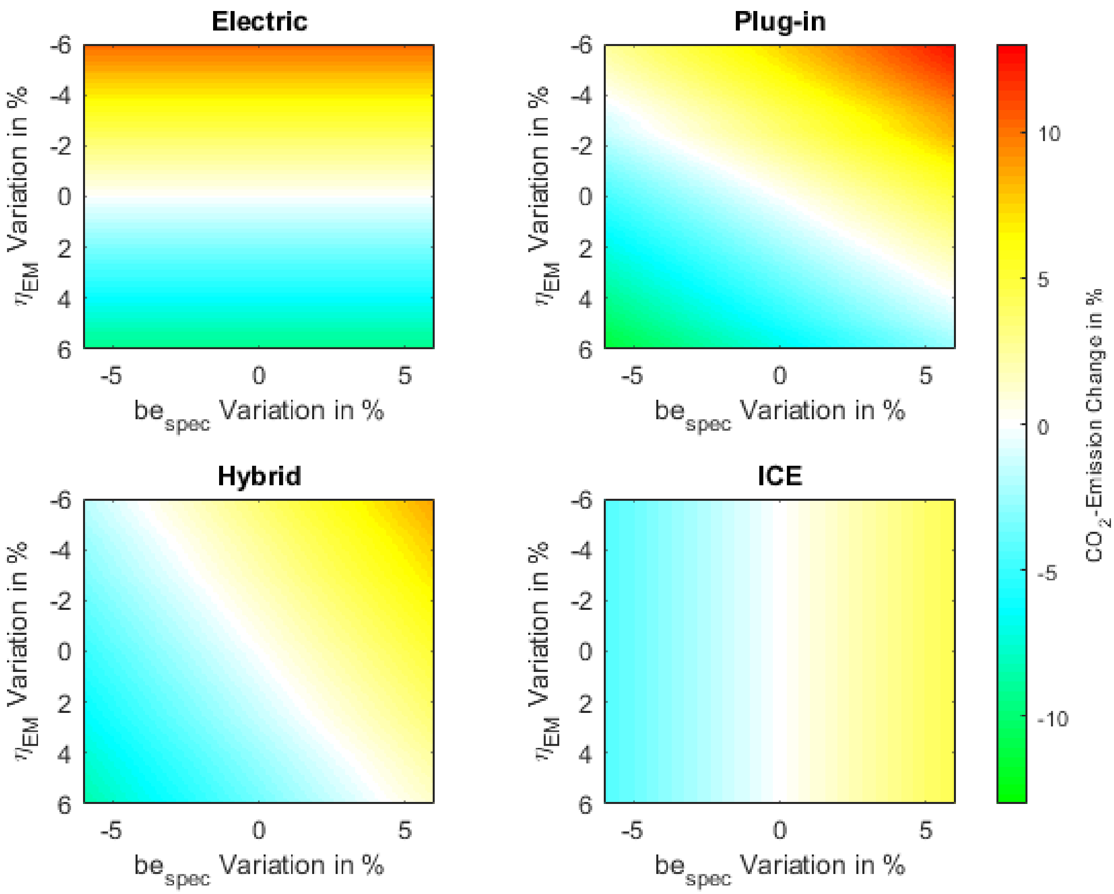

Figure 19 Percentage Change of the CO_2-Emission under the Influence of Various Efficiency Rates

5.4.2. Variation of Weight

The comparison of a compact vehicle and a SUV in chapter 5.2 shows that a heavier and bigger vehicle needs more energy for the same drive. In this chapter, a variation of the BMW's weight should show the direct influence on the energy consumption. The reference value of the weight is 2377 kg, as explained in chapter 4.2. In the first variation the weight will be increased by 10% up to 2615 kg, which roughly corresponds to the weight of the BMW X5 45e, the plug-in hybrid version of the next generation. The weight probably raised by over 200 kg due to the bigger battery. In the second variation, the weight will be increased by 20% from the reference value to 2853 kg, which is almost the maximum weight of the car.

The drive cycles for the simulations are the real-world drive and the synthetic drive Profile 2, which has a lot more acceleration phases, due to the large number of stops. The auxiliary power consumers are switched to real-world conditions and the air condition is operating with 1 kW. The driving mode is plug-in with an initial battery SoC of 100%. Table 16 shows the distance-related energy consumption rate in kWh/100km and the total CO_2 emission in kg. The real-world drive was driven with the Austrian power mix and the synthetic drive was driven with the Japanese power mix.

Table 16: Energy Consumption Rate and CO_2-Emissins under Different Vehicle's Weight

	Real-World Drive		Synthetic Drive Profile 2	
Weight	EC. Rate [a]	CO_2-Em. [b]	EC. Rate [a]	CO_2-Em. [b]
2377 kg	60.64	1.668	77.71	3.405
2615 kg	64.01	1.765	84.15	3.683
2853 kg	67.36	1.861	90.65	3.965

[a] All values are given in kWh/100km
[b] All values are given in kg.

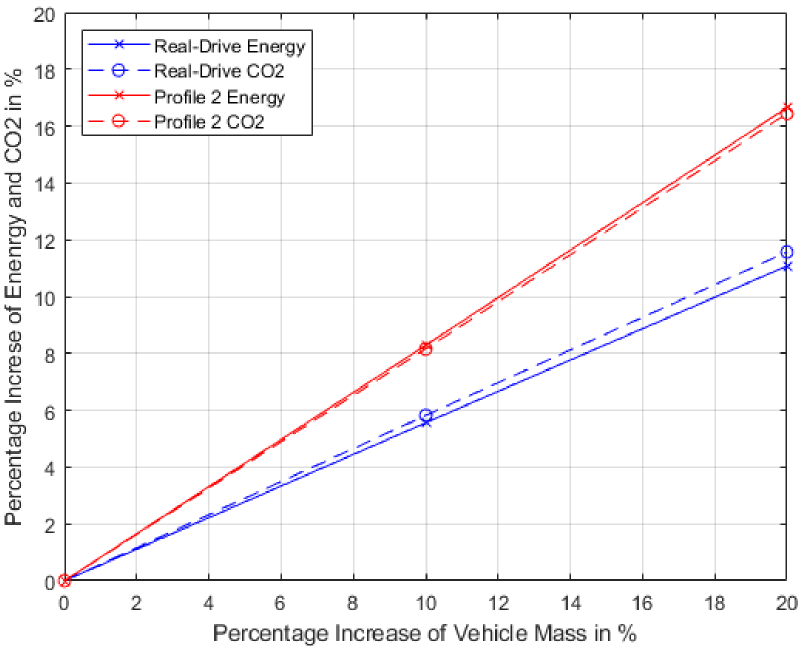

Figure 20 Percentage Increase of the Energy Consumption and the CO_2 Emission over the Percentage Increase of the Weight

Figure 20 shows the percentage increase of the energy consumption and the CO_2-emissions over the percentage increase of the weight. The increase is linear, since the vehicle's mass is a linear factor in the driving resistances, and due to the linearization of the energy consumption. The higher weight has a bigger influence on the synthetic drive Profile 2, due to the larger amount of acceleration phases. As it can be seen in the diagram, the CO_2-emission of the real-word drive rises stronger than the energy consumption. This is explainable with the higher power required to accelerate the vehicle, so the ICE has to help the EM earlier in the acceleration phases, and a bigger share of the additional energy is provided by fuel, which has a higher specific CO_2-emission. With the Japanese power mix used for the synthetic drive, CO_2-emission rises a bit less, because fuel emitters less CO_2 per kWh, than the domestic power mix.

5.4.3. Variation of Auxiliary Power Consumers

The auxiliary power consumers are a central part in this work. Since they don't contribute to driving, they get forgotten quickly. Auxiliary power consumers are running the whole time, doesn't matter if the car is driving or standing due to traffic conditions, hence they are time-depending consumers. In this chapter a ceteris paribus variation of the auxiliary power consumers will show the influence on the distance-related energy consumption rate. The BMW X5 will be simulated in the all-electric mode and the hybrid mode on the measured real-world drive, with a low average velocity and on the synthetic drive Profile 3 with a high average velocity. The auxiliary power consumers will start with 350 W like for standardised driving patterns. The next step is with small consumers on real world conditions with 750 W but no big consumers. Then the big consumers will be turned on step by step, up to 4500 W. The initial SoC is 100 %. The used power mix for the real-world drive is the Austrian, and for Profile 3 the Japanese one. Table 17 summarizes the energy consumption rate in kWh/100km and CO_2-emissions in kg of a selection of auxiliary power consumers' power.

Table 17: Energy Consumption Rate and CO_2-Emission under the Influence of Auxiliary Power Consumers

Drive Mode	350W	750W	750W+1000W	750W+2500W	750W+4500W
All-Electric					
Real-World	21.87 / 0.35	25.18 / 0.41	33.46 / 0.54	44.88 / 0.74	62.44 / 1.01
Profile 3	40.11 / 2.06	40.95 / 2.08	43.05 / 2.22	46.2 / 2.38	50.4 / 2.59
Hybrid					
Real-world	48.18 / 1.47	54.96 / 1.68	70.6 / 2.12	100.8 / 3.02	149.7 / 4.54
Profile 3	95.69 / 4.13	96.61 / 4.17	96.85 / 4.18	100.4 / 4.35	105.8 / 4.61

All values are given in the scheme "Energy consumption rate / CO_2-emission"
All values are given in the unit "kWh/100km / kg"

These data show, that the slower real-world drive uses less energy than the faster Profile 3 with low auxiliary power consumers' power. But if more auxiliary power consumers are switched on, the real-world drive needs more energy per distance than the Profile 3. The time-depending auxiliary power consumers have a bigger absolute impact on the real-word drive, since it takes three times as long as the synthetic drive but has a shorter distance.

These data also show the potential harm for the environment, due to auxiliary power consumers. Driving the real-world drive with full auxiliary power consumers' power, the CO_2 emission increases by 417 gCO_2/km, in contrast to the standardised testing conditions. This extreme situation seems a little too high, for running all the time but also the usually used 1000W for big consumers causes an increase of 87 gCO_2/km.

Figure 21 shows the percentage increase of the energy consumption relative to the energy consumption under standardised driving pattern circumstances with 350 W small consumers and no big consumers. The x axis shows the total power of the small and big auxiliary power consumers in W, the y-axis depicts percentage increase.

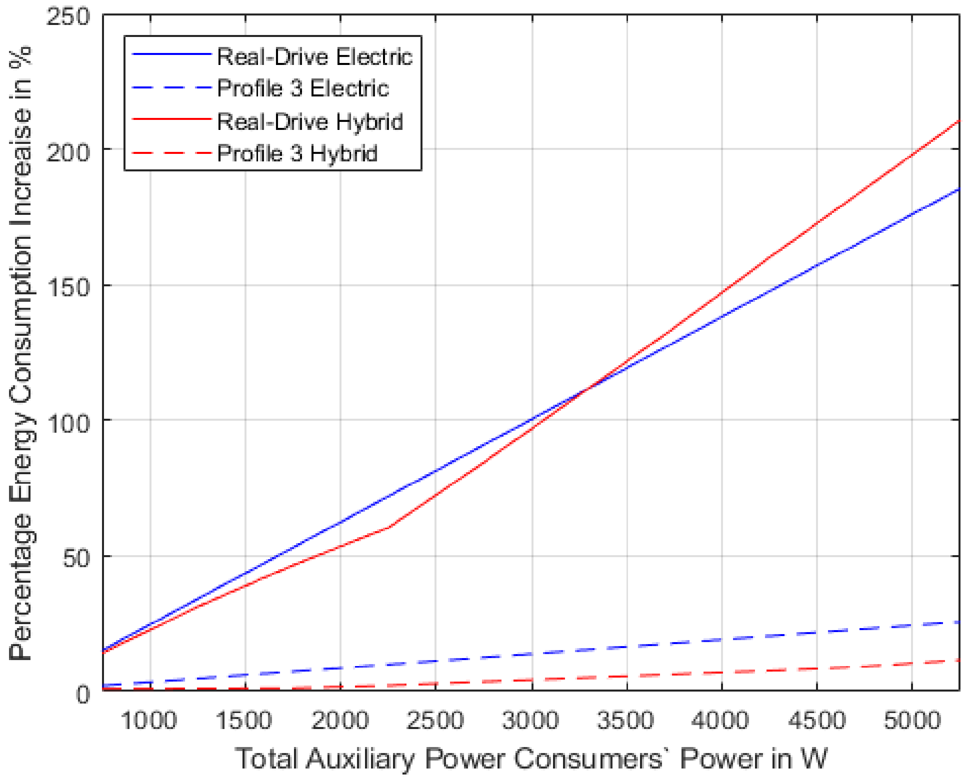

Figure 21 Percentage Energy Consumption Increase under the Influence of Auxiliary power consumers

It is recognizable, that the energy consumption of the real-world drive depends more on the auxiliary power consumers than the consumption of Profile 3. This can be explained by the significantly lower average velocity of the real-world drive and the fact that time-depending consumptions make a bigger influence on lower velocities, since the time needed for a certain distance rise. Due to the linearized equations for the energy consumptions of the ICE and the EM the increase is linear, with one exception for the real-world drive simulated with the hybrid mode. This curve makes a kink at a total auxiliary power consumers' power of 2250 W. This kink comes from the power-split function. The vehicle is trying to hold the initial SoC in the hybrid mode, which would be a 100%, but to keep some battery capacity for recuperation the ICE is not charging the battery over a SoC of 90%. So below this threshold of 2250 W the SoC is never under 90% and the energy for the auxiliary power consumers can be supplied form the battery and the recuperation. With a higher auxiliary power consumers' power, the SoC falls under 90% and the ICE is used to recharge the battery, what uses more energy due to the lower efficiency rate, hence the gradient of the curve jumps, and a kink appears. Above this threshold the additional energy is supplied by the ICE and this consumption is linear again. However, the gradient for Profile 3 driving in hybrid mode is lower than in all-electric mode, because the SoC never drops below 90% and the power for the auxiliary power consumers can be supplied by the battery and recuperation, which is almost the same as in all electric mode. But the absolute energy consumption is higher, hence the relative increase must be lower.

The percentage increase of the CO_2 emissions is similar to the energy consumption. In the all-electric mode, it is the same since the equation is linear. In the hybrid mode, the percentage increase is a bit lower, because the SoC is decreasing and so, some of the extra energy is supplied by electricity from the battery, which has a lower specific CO_2 emission.

Figure 22 gives a look on the impact of auxiliary power consumers on the drive efficiency. Drive efficiency is in this case defined as energy used to move the vehicle relative to the used energy by the vehicle. The drive efficiency assumes complete recuperation for the energy to move the vehicle. So, every energy that is not used for driving itself, or cannot be recuperated, is seen as a loss. This also includes auxiliary power consumers, which is not really a loss, since the energy is used for cooling e.g., but it is not used for moving, which is the purpose of the drive.

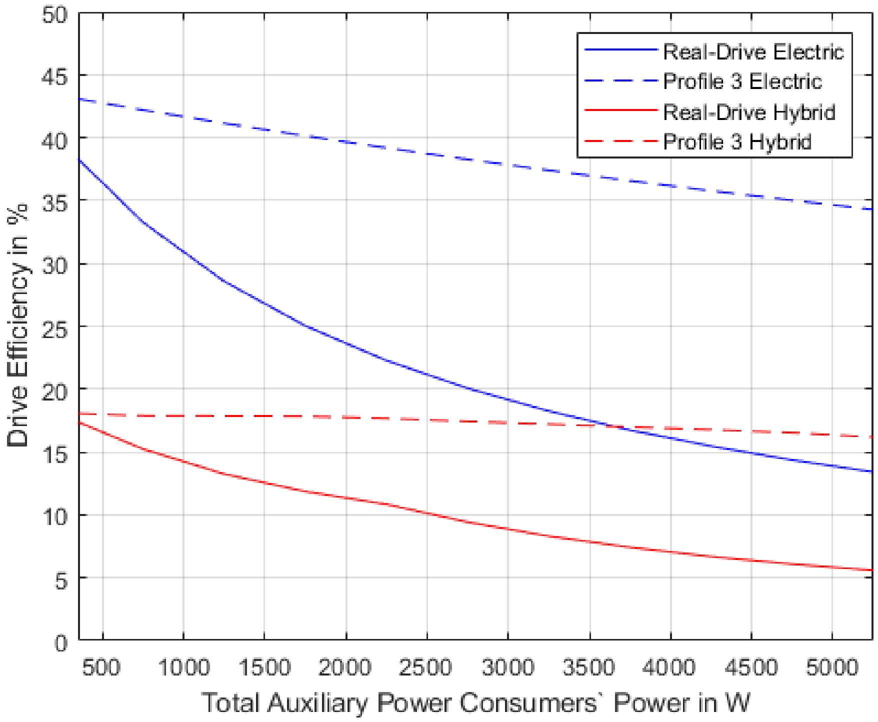

Figure 22 Drive Efficiency under the Influence of Auxiliary Power Consumers

Figure 22 confirms the bigger influence on the real-world drive. The reason why the drive efficiency becomes so low is that the average drive power is 1.2 kW and hence not even a quarter of the maximum auxiliary power consumers' power.

Chapter 3.2.5 and 3.2.6 showed the influence of the time-depending consumers to the distance-related consumption over the velocity. Figure 23 depicts a similar graphic and shows the distance-related consumption of an ICE and an EM over the velocity. The vehicle used for the calculation is the BMW X5 40e. One time the auxiliary power consumers have a power of 350 W, which is equal to standardized measurements and one time the auxiliary power consumers were switched to full power of 5250 W. The energy consumption is higher with higher secondary consumer's power. But the higher the velocity becomes, the closer gets the cap between those two lines, because the power-depending consumptions are rising and carry a higher share of the overall consumption. Also, the point of the minimum consumption is moving to the right. In case of the ICE, the velocity of minimum consumption increases from 44 km/h to 64 km/h. In case of the EM, it increases by 30 km/h to 59 km/h.

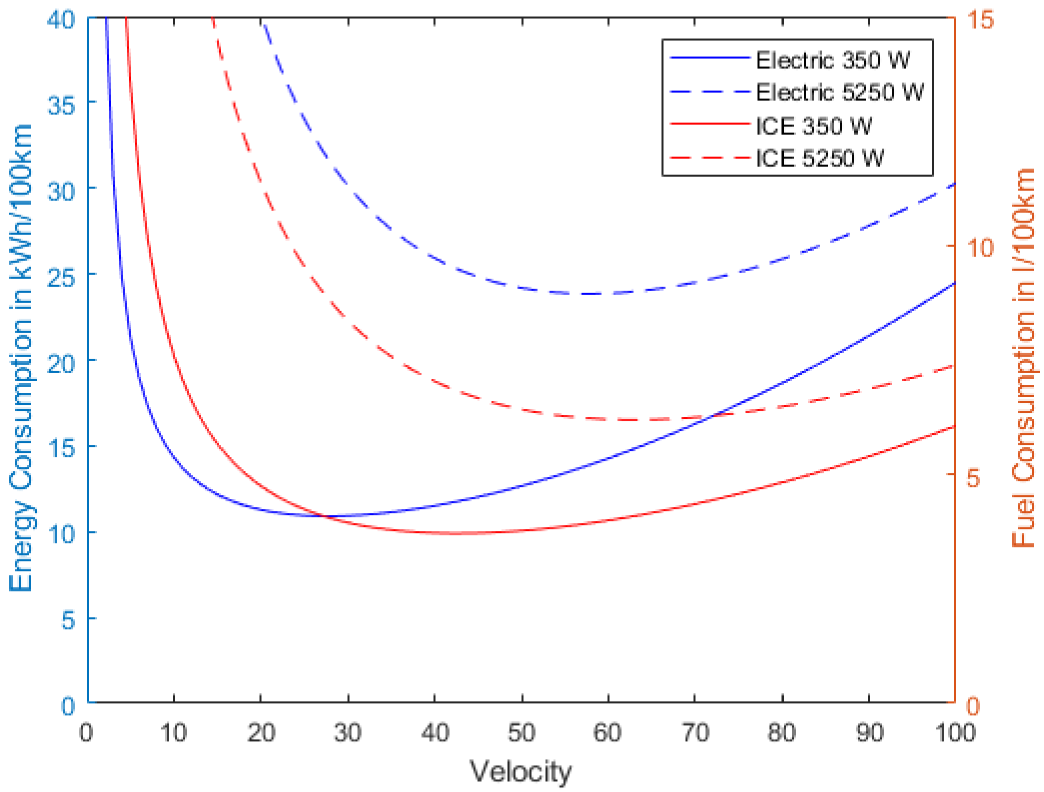

Figure 23 Energy Consumption over Velocity with Different Auxiliary Power Consumers Power

5.4.4. Variation of Traffic Conditions

The traffic conditions can make a huge difference for the energy consumption. The synthetic drive can be simulated with different velocity profiles, which represent different traffic conditions. In this chapter the BMW X5 is simulated to drive the four different velocity profiles. The auxiliary power consumers where set to real world conditions and the air condition is turned to a low stage with a power of 1 kW.

The difference between Profile 1 and Profile 2 is the longer idling time, which results in an increase of the travel time of 53.7 %, and this leads to an absolute increase of the time-depending energy consumption. But due to the same maximum velocities, the physical work the vehicle has to do stays almost the same, hence the power-depending consumption can be assumed to stay almost constant. And, since the travelled distance stays constant, the distance-related energy consumption rate has to raise. This phenomenon is depicted in Table 18 which shows the distance-related energy consumption rate in kWh/100km for Profile 1 and Profile 2 and the percentage increase for all four driving modes.

Table 18: Comparison of the Energy Consumption Rate between Profile 1 and Profile 2

Velocity Profile	All-Electric	Plug-in	Hybrid	ICE
Profile 1 [a]	30.4	67.03	68.69	91.53
Profile 2 [a]	37.1	77.71	80.65	114.4
Percentage increase	22.04%	15.93%	17.41%	24.99%

[a] All values are given in kWh/100km

Profile 3 shortens the traveling time by 25.8 %, but the increase of the average velocity comes from an increase of the maximum velocity, what results in an increase of the needed physical work of 44.2 %, due to higher air drag resistance. So here are two phenomena work against each other, on the one hand side, there is an absolute decrease of the time-depending energy consumption, but an increase of the power-depending consumption. The simulation shows that the increase of the power-depending consumption has a bigger influence, and the total energy consumption raises. Table 19 shows the energy consumptions of Profile 1 and Profile 3 and the percentage difference between those two.

Table 19: Comparison of the Energy Consumption Rate between Profile 1 and Profile 3

Velocity Profile	All-Electric	Plug-in	Hybrid	ICE
Profile 1 [a]	30.4	67.03	68.69	91.53
Profile 3 [a]	43.05	96.44	96.85	113.2
Percentage increase	41.61%	43.88%	41%	23.68%

[a] All values are given in kWh/100km

The same two phenomena working against each other in the opposite direction when it comes to a comparison of Profile 1 and Profile 3's counterexample Profile 4. Due to the lower driving resistance the physical work decreases by 24.7% but the duration increases by 44.6%. The simulation shows a similar result in the vice versa direction and the energy consumption is reduced, due to the lower power-depending consumption. Table 20 shows the energy consumption rate of Profile 1 and Profile 4 and the percentage difference between those two.

Table 20: Comparison of the Energy Consumption Rate between Profile 1 and Profile 4

Velocity Profile	All-Electric	Plug-in	Hybrid	ICE
Profile 1 [a]	30.4	67.03	68.69	91.53
Profile 4 [a]	25.4	49.13	57.75	87.25
Percentage increase	-16.45%	-26.7%	-15.93%	-4.68%

[a] All values are given in kWh/100km

It is noteworthy that the percentage increase or decrease of the ICE mode is significantly lower than those of the electrified modes. It has also the highest rise in the comparison between Profile 1 and Profile 2. This can be traced back to the higher time-depending, basic energy consumption of the ICE compared to the EM. It is also remarkable that the increase of the energy consumption of Profile 3 is noticeably higher, than the decrease of Profile 4. This might be the bigger effect of the time-depending consumption in a lower power range. An exception is the plug-in mode, which shows a huge energy saving potential in the slower Profile 4. This is explainable with the more often use of the EM instead of the ICE. In comparison to that, the hybrid mode has to lower the velocity threshold for driving with the EM to save battery capacity.

Another interesting detail gives a view on the drive efficiency in dependence of the average velocity. Figure 24 shows that the higher the average velocity is, the higher becomes the drive efficiency. With one exception of the plug-in mode, due to reason explained earlier.

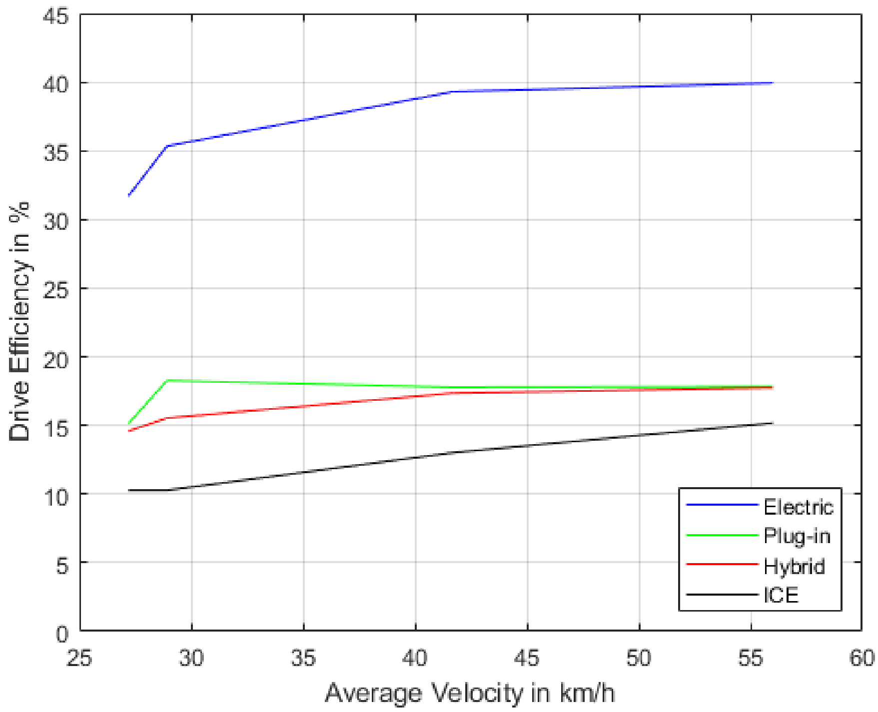

Figure 24 Drive Efficiency over the Average Velocity

5.4.5. Influence of the Height Profile

One of the four driving resistances is the grade resistance, which represents the work that has to be done to higher the potential energy of the vehicle. On the other side the grade resistance becomes negative and produces work if the potential energy is lowered. So, if the starting point and the end point of a track is on the same geographical height, the accumulated work must be zero. But since the vehicle is not able to recuperate all the energy, it still needs more energy to drive upwards, than getting back, while driving downwards, hence the energy consumption has to rise with a height profile in comparison to a flat road drive. Table 21 shows a comparison of the energy consumption, between a drive with a height profile and one without. The drive cycle for all simulations is the synthetic drive with velocity Profile 1 since the start and end points are on the same geographical height. The auxiliary power consumers are set for real drive conditions with air conditioning working on 1 kW. The comparison was made between the ICE mode, which cannot recuperate at all, the all-electric mode, which can recuperate until 20 kW and a theoretical electric mode, which can recuperate unlimited power. Table 21 shows the distance-related energy consumption rates in kWh/100km and the percentage increase of the simulation with a height profile compared to the flat street scenario.

Table 21: Comparison of the Energy Consumption Rate between a Flat Street Scenario and a Street with a Height Profile

Scenario	ICE	All-Electric	Unlimited Recuperation
Flat Street [a]	69.14	25.09	21.96
With Height Profile [a]	91.53	30.4	24.87
Percentage Increase	32.36%	21.16%	13.25%

[a] All values are given in kWh/100km

The ICE mode and the all-electric mode show an expected picture. The percentage increase of the ICE mode is significantly higher, due to the recuperation ability of the all-electric mode. The increase of the all-electric mode was also expected under the before mentioned conditions. The decrease of the energy consumption under the theoretical unlimited recuperation mode compared to the all-electric mode is explainable with the recuperation of the acceleration energy. The still existing increase due to the height profile can be explained by the efficiency rate. Since the outgoing energy of the battery is higher than the used energy of the vehicle and the incoming energy is smaller than the produced energy, there must be always a gap.

5.4.6. Variation of the Driver Model

A central point of a simulation is the controller. In this case the controller represents the driver of the vehicle and has to control the speed of the vehicle to follow a given driving pattern. The driver can be set more aggressive, means it will try to reach the target velocity as fast as possible, with the danger of overshooting. It can also be less aggressive, but this will produce a bigger error to the target velocity. The set-up is complicated, since the controller has to fit the control loop and there is no unique universal set up.

The auto tune function of Simulink gives an ideal set up with a proportional gain P=1 and integrative gain I=0.097334. Now some small adjustments are made to show the influence on the relative control error, given in Eq. (11) and the energy consumption rate. For the comparison the vehicle was set to plug-in mode and the drive cycle was the synthetic drive Profile 1. The auxiliary power consumers were set to real drive conditions and the air conditioning was switched on and working with 1 kW. Table 22 shows the energy consumption rate in kWh/100km and the relative control error in percent for different controller constants.

$$e_{rel} = \frac{\int_{t_0}^{t_{end}} \left| v_{target} - v_{actual} \right| dt}{\int_{t_0}^{t_{end}} \left| v_{target} \right| dt} \tag{11}$$

e_{rel}... relative control error, t_0... start time, t_{end}... end time, v_{target}... target velocity, v_{actual}... actual velocity

Table 22: Energy Consumption Rate and Relative Error under the Influence of Controller Constants

Integrative Gain	I=0		I=0.097334		I=1	
Proportional Gain	EC. Rate [a]	Error	EC. Rate [a]	Error	EC. Rate [a]	Error
P=1	66.71	0.6106 %	67.03	0.526 %	68.52	0.3606 %
P=1.5	66.95	0.3871 %	67.06	0.34 %	68.08	0.3276 %

[a] All values are given in kWh/100km

It is recognizably that the higher the controller constants are, the smaller becomes the error. The higher P constant makes the controller more sensible for speed deviations, hence the system reacts more aggressive by applying higher forces to close the gap. This leads to smaller errors, but not to a big increase of the energy consumption rate. The higher I constant helps the controller to close the velocity gap over a longer period, but tends to overshoot, hence the relative error becomes smaller, but the energy consumption rises significantly, due to the higher power need of the overshooting.

Figure 25 shows a plot of the controller output, the absolute velocity error and the overlap of the target velocity and the actual velocity over the time. The overlap is pretty high since the absolute error hardly exceeds 0.5 m/s. So does the controller output, what means, that the maximum available force is never required.

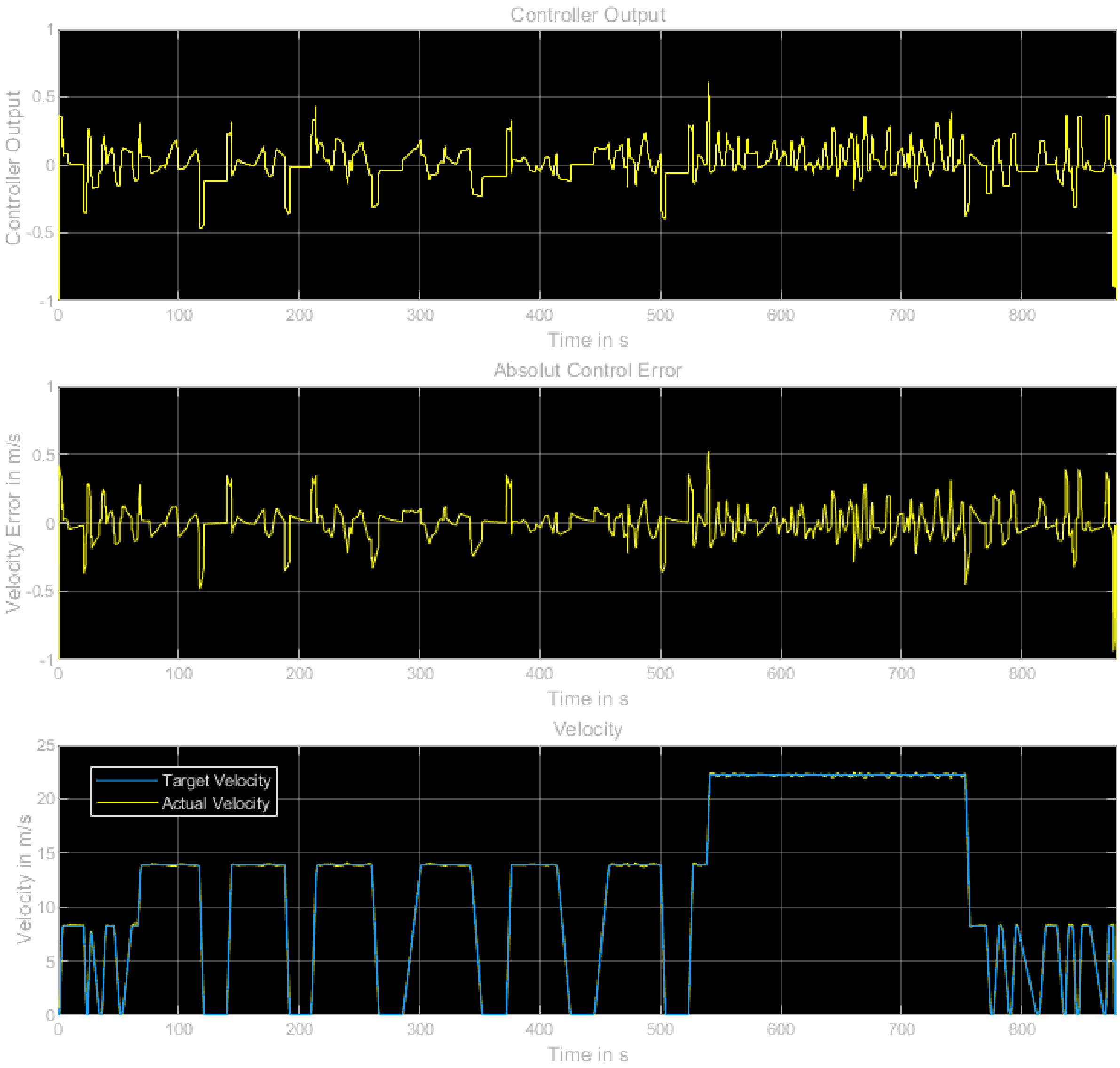

Figure 25 Standard Controller Output

If the proportional gain P is tuned too high, the controller will be too aggressive. An example gives the following variation with P=10 and I=0. The relative error becomes 2.673% and the energy consumption increases to 537.5 kWh/100km. Figure 26 shows that the controller is no longer able to hold a constant velocity, since a small error leads to a high correction and overshooting. Also, the zero can't be hold without a limitation of the velocity. The absolute error increases and the controller output uses the whole range and goes to the limitation all the time. This means, that the vehicle alternates between full throttle and full brake all the time and this increases the energy consumption a lot. The energy consumption is even so high, that the battery is empty bevor the drive cycle ends, so the simulation brakes up early.

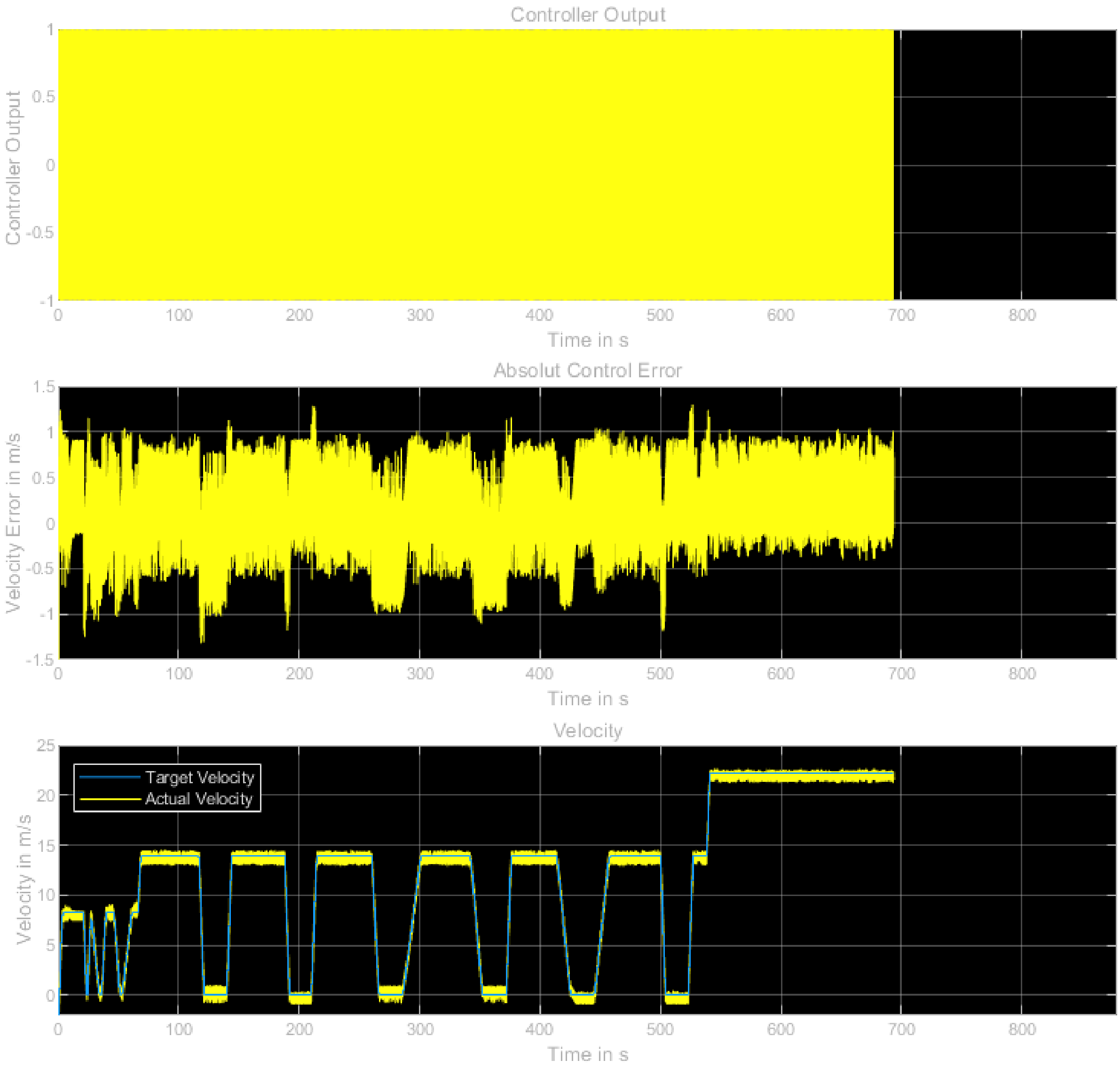

Figure 26 High P Controller Output

The counter example is a controller with a too high integrative gain with P=1 and I=10. Figure 27 shows big troubles with a high acceleration, but the system is able to swing in after a period of time, in contrast to the high P controller. The averaged relative control error rises to 3.322 %, but the energy consumption decreases to 193.7 kWh/100km and the simulation doesn't break up early.

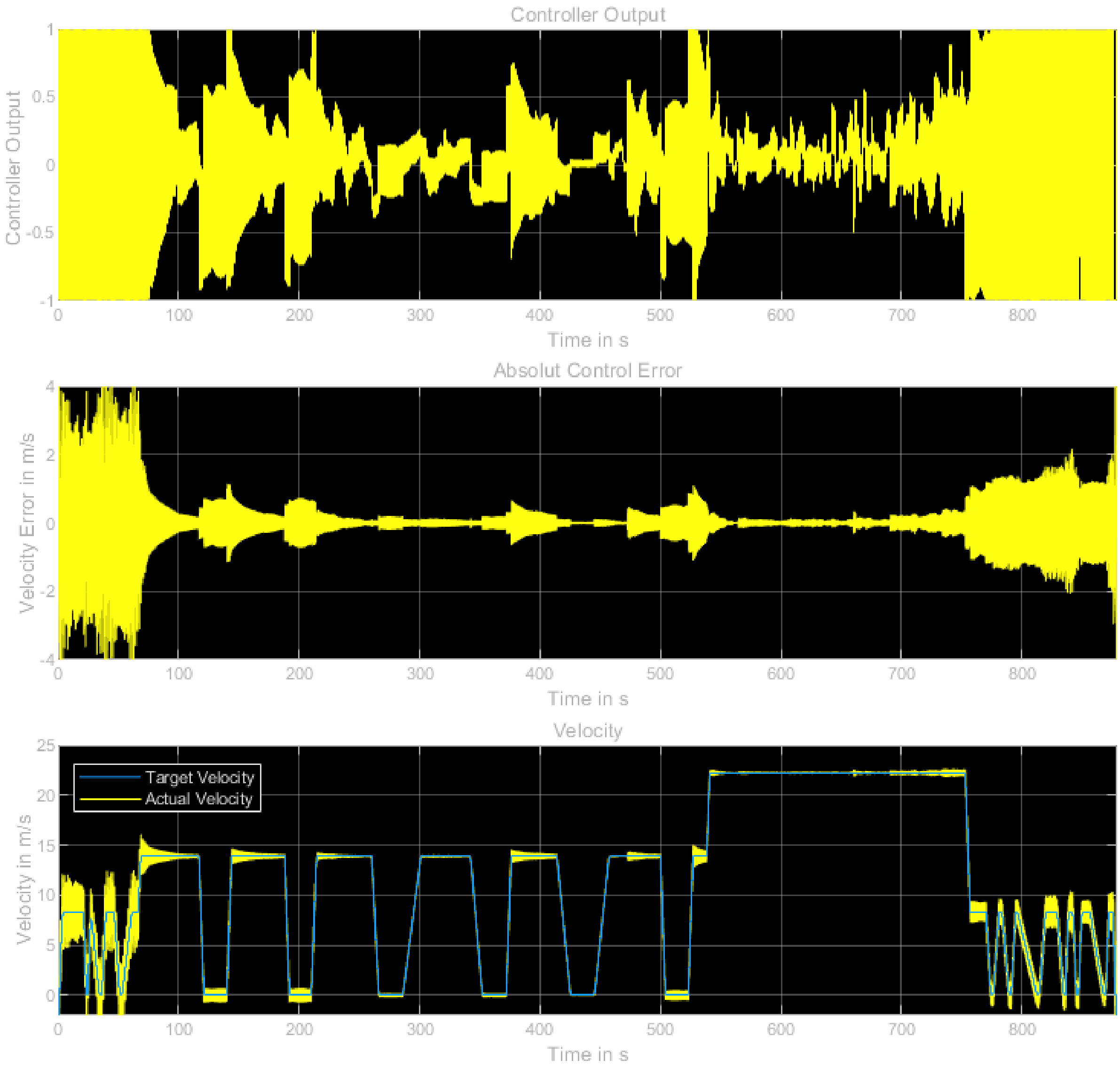

Figure 27 High I Controller Output

5.4.7. Variation of the Recuperation

Chapter 5.4.5 already showed the potential of energy saving for a theoretical unlimited recuperation. The maximum recuperation power is limited to some physical borders. The first border is the power of the EM, which is limited to 83 kW for the simulated BMW X5. The other limitation is the maximum charging power of the battery system to store the energy. It is not known, due to which part the charging capacity is limited at 20 kW, but it is now assumed, that the maximum charging power is increased to 40 kw, 60 kW and 80 kW. For a higher recuperation the EM has to be updated. Also, a comparison to no recuperation at all should be given. Under these circumstances the BMW will be simulated in the all-electric and plug-in mode for the JC08, a drive cycle with no height profile, the measured real-world dive to show a track with low averaged velocity and the synthetic drive Profile 3, a drive cycle with high velocity and high accelerations. Table 23 shows the energy consumption in kW/100km and Figure 28 gives the percentage energy saving related to no recuperation at all.

Table 23: Energy Consumption Rate with Different Maximum Recuperation Power

Drive Pattern	0 kW	20 kW	40 kW	60 kW	80 kW
Electric					
JC08	24.64	17.48	17.04	17.04	17.04
Real Drive	45.79	33.46	31.9	31.82	31.82
Profile 3	49.23	43.05	39.03	36.44	34.65
Plug-in					
JC08	44.64	37.43	37.01	37.01	37.01
Real Drive	63.72	60.64	59.18	59.03	59.03
Profile 3	103	96.44	96.24	96.19	96.14

All values are given in kWh/100km

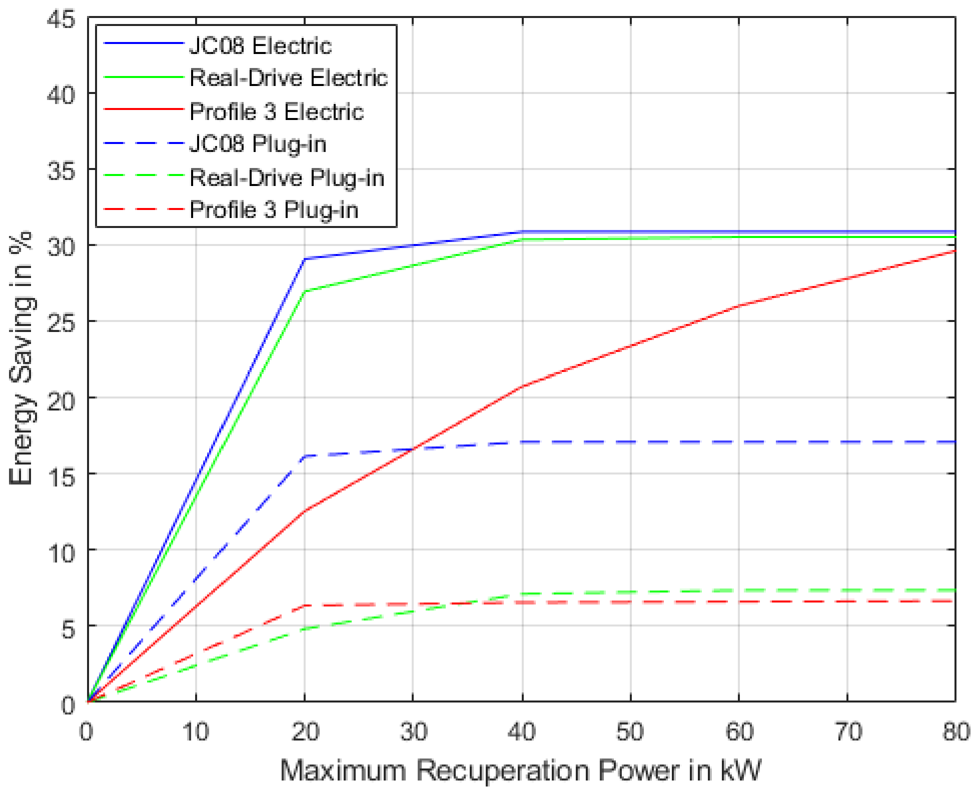

Figure 28 Energy Saving over Recuperation Power

These simulations show a higher energy saving potential for the all-electric mode, due to the inability to recuperate the energy of the ICE in the plug-in mode. They also show, that with exception of the synthetic drive Profile 3 in the electrical mode, almost the whole energy saving potential is exhausted with 20 kW maximum recuperation power. The other five simulations show for 80 kW an averaged energy saving potential of 2.3% related to 20 kW. The reason, why the energy saving is so small for the JC08, and the real drive is, that the braking power almost never exceeds 20 kW and so the recuperation can't be higher. Figure 29 shows the driving power of the JC08 as an example.

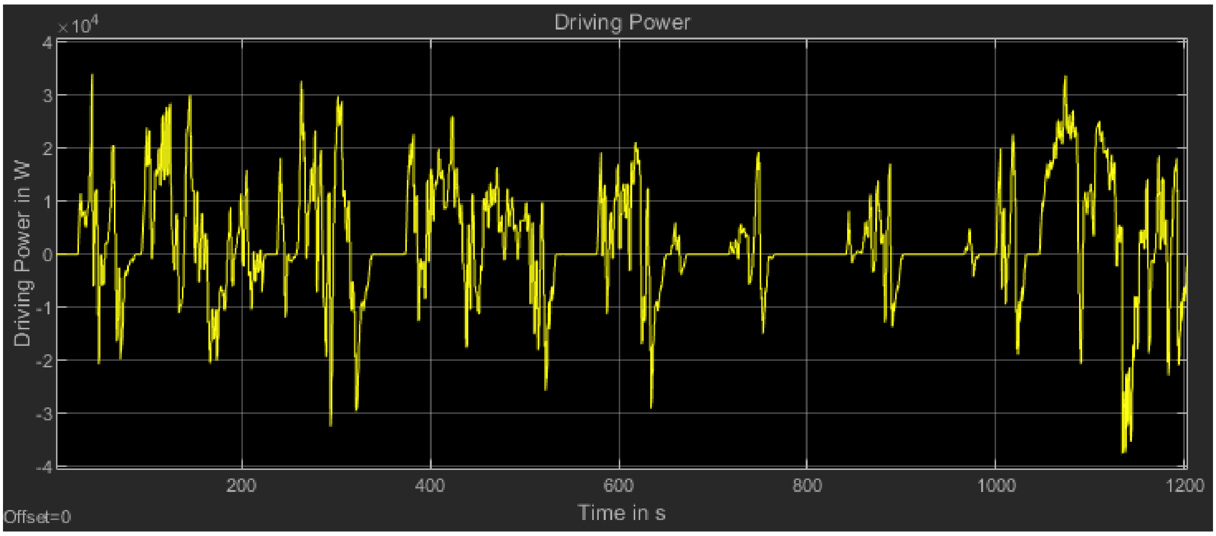

Figure 29 Driving Power of JC08 Mode

The braking power of the synthetic drive Profile 3 is quite higher and exceeds even the 80 kW, that's why the vehicle is able to recuperate more in the electrical mode. But also, the driving power rises, hence the vehicle is driving more with the ICE to generate the required power and the battery is always loaded and cannot absorb the braking energy. If the car starts at a lower battery SoC, the energy consumption can be decreased by 2.4 % with a maximum recuperation power of 80 kW. But in this case the vehicle will use the ICE in low power segments to recharge the battery. This and the higher recuperation power leads to an increase of the battery SoC of 19 percent points, but also of the fuel consumption. So that even with the smaller absolute energy consumption the CO_2 emissions increase by 3 %.

This simulation shows that 20 kW recuperation power is sufficient for most of the use cases of a plug-in hybrid electric vehicle.

6. Comparison to Look-up table Model

The LTM is much more complex, than the AVM. It considers the power unit parts more in detail and depicts them with Simulink blocks, like in the vehicle, while the AVM depicts an energy flow with mathematical formulations in MATLAB functions embedded in the Simulink model.

The driver model of the LTM makes it also more complex, due to the two degree of freedom model. For the feed forward model, the driving resistance has to be approximated from the target velocity, for the feedback loop the vehicle must be simulated with the electrical machine and the tire model, to get an actual velocity. The motivation for the more complex model is, to decrease the error between the actual velocity and the target velocity. Also, the reaction time of the system can be reduced since the feed forward model does not need an error to increase the required torque. However, the averaged relative velocity error with the feedback loop only in the AVM is for the JC08 0.27%, which is accurate enough for the simulation. Of course, this error depends on the simulation setting like controller parameters, what is shown in chapter 5.4.6.

The official catalogue value of the Nissan Leaf's energy consumption rate is 8.06 km/kWh, driven in the JC08. The Nissan Leaf simulated in the LTM reaches a consumption rate of 9.49 km/kWh, which is a deviation of 17.7% [5]. The reasons given for the smaller energy consumption are, the neglecting of the cooling system, which is an auxiliary, time-depending consumer, and the mechanical losses of the gear. A closer look shows, that in an older version of the look up table model, the inverter losses where neglected. With this simplification, the consumption rate increased to 9.6 km/kWh, what gives a deviation of 19.1% to the catalogue value [6]. Hence the inverter loss would be about 1% in this case, what seems to be small, since the average inverter efficiency can be assumed as 92% - 98% and Grunditz found an efficiency rate of 94% - 96% for the JC08 mode [15].

The advantage of the LTM is that it is more detailed and considers the current status of the vehicle parts like motor speed or a velocity-depending rolling resistance, hence it is more flexible for different situation. Due to the detailed simulated powertrain parts, the LTM can show the effects on the energy consumption for modifications in the powertrain. The advantage of the simplification of the AVM is, that it can be easily adopt to every vehicle, without knowing a lot of technical details and it can show the potential of an improvement before a technical solution was made. The AVM can simulate HEV and conventional vehicles as well. The main part of the AVM is however to consider auxiliary power consumer to show the effect on the energy consumption in a real-world drive. For this purpose, the simplification is accurate enough. The LTM is destined to give a detailed EV model to simulate the energy consumption in standardised diving patters, where most of the auxiliary power consumers are switched of, but some auxiliary loads should still be considered.

In conclusion, the use case for both models differs, while the LTM model is more useful for producers to help develop a known vehicle, the AVM gives a holistic energy flow and is more useful for comparisons between different vehicles and various influences on the energy consumption.

7. Discussion and Outlook

The model used in this work is a simple model, working with average values as assumptions and linearized equations for calculating the energy consumption. The simulations made with the model show a clear trend, that the car has a lower energy consumption, if it uses the electrified power train. Due to the lower energy consumption the CO_2-emission decreases too, even with a power mix, that emits more CO_2 per unit energy. However, it should be noted that this model only considers the driving of the vehicle and not a full life cycle. It also only considers different drive modes with the same car and not different cars with different electrification stages of the power train. This is important, because the battery production is very CO_2 intensive and with a bigger battery the vehicles weight will increase, what leads to a higher energy consumption as shown in this work. In a further work, this model could be used to compare vehicles with different degrees of electrification.

In this work an averaged efficiency rate was assumed for all simulations. The comparison to the measurement shows, that this assumption fit some situations better than others. If more measurements were available, an average efficiency rate could be evaluated to fit more simulations properly. Also, the exact working manner of the power split device and the auxiliary power consumers are unknown. So, the power split function will probably work differently, hence the simulation results have a deviation. In chapter 5.1 a comparison to the measured real-world drive was made and this was the simulation with the highest deviation. This could be the case, that the power split function doesn't depict the vehicle properly. The used PSF adjusts the power for small auxiliary power consumers directly to the ICE. This is maybe not correct, the small auxiliary power consumers should be powered by the battery as well as the big auxiliary power consumers, and the ICE should only be used for driving and to recharge the battery.

Since the European electric power grid is merged and power is imported and exported, it might be better to use a European value for the CO_2-emission instead of an Austrian.

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