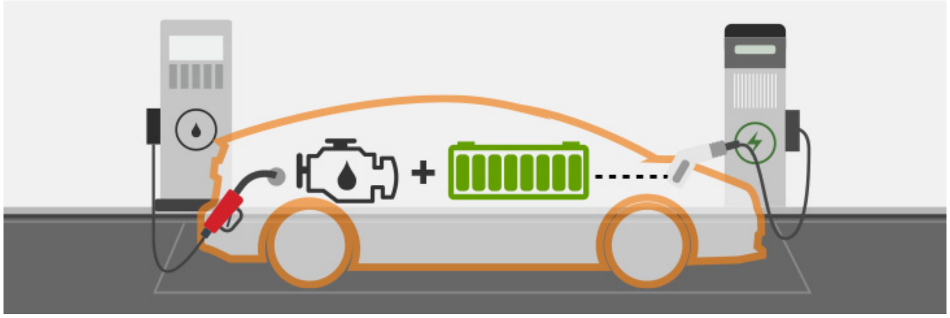

Modelling effects of real world driving characteristics on catalytic converter performance and energy use for different PHEV designs

Master's Thesis for the degree of
Master of Science in Sustainable Energy Systems

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Abstract

This project focuses on the how trip characteristics affect the behaviour of several PHEV components in order to investigate the energy use and harmful emissions. A secondary goal is to determine which parts of a PHEV are mostly needed to be investigated in analyses of this type. This was carried out by developing several models that simulate driving conditions and outputted variables related to the main purpose of the project. The model-outcomes are gone through a series of sensitivity analyses to determine how the behaviour of the catalyst and power sources use is influenced by certain PHEV functionalities. The results show that the motor, and battery capacity as well as the functionality of the charge sustaining mode are the most important components that influence the catalyst's and power sources use behaviour. The fuel use as well as the CO2 emissions reach their maximum decrease rate with the introduction of a relatively small battery and electric motor. As for the emissions of other harmful gases, represented by the catalyst's operation, it can be said that its overall use is slightly worse on a PHEV than a CV. However, it is important to mention that the various combination of battery and motor capacity can influence the catalyst's operation.

Contents

1 Introduction

1.1 Problem Description

Conventional vehicles (CVs) which use gasoline as their single source of energy are dominating the market currently. Greenhouse gas (GHG) emissions due to the transport sector has been an intensely-considered matter for several decades. The minimisation of hydrocarbon-based fuels is considered to be one of the most critical problems worldwide. According to the World Bank [1], the first visible reductions of the global CO2 emissions due to the transport sector (compared to the total fuel combustion) was during the 1970s and since then it's been fluctuating with an increasing tendency. Narrowing the issue's effect to Sweden, it can be observed that the share of CO2 emissions due to the transport sector has the increasing tendency presented in Figure 1. During 2013, the share of CO2 coming from the transportation sector was over 50 percent. A possible explanation for such patterns could be related to Sweden's retrofitted and constantly improving heat and electricity system [2], but it still shows that the transport sector is not keeping up.

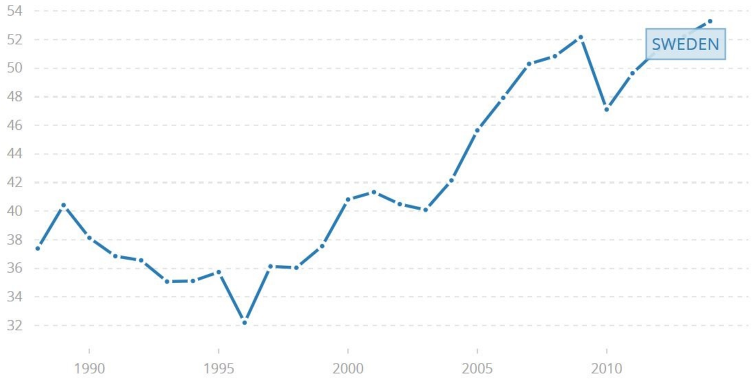

Figure 1: Sweden's CO2 emissions from transport (% of total fuel combustion)

This reveals the need to improve the transport system in terms of making it more environmentally friendly. Automotive manufacturers and the transportation sector in general are investing and researching intensively for alternative vehicle-powertrain solutions. One of the topics under heavy research is the electrification of the transportation sector for the reduction of harmful emissions. Part of the transportation sector's transformation includes the use of Plug-in Hybrid Electric Vehicles (PHEVs). This vehicle type combines the use of a conventional power source – an internal combustion engine (ICE) – as well as one or a couple of electric motors.

However, the way emissions would be affected when using PHEVs requires further research; a PHEV's ICE is expected to have significantly increased starts and stops which raises the question of how much the ICE would be used and how would its catalytic converter behave.

1.2 Aim and Scope

The main purpose of this project is to investigate how trip characteristics affect the behaviour of two fundamental elements when using PHEVs:

- The at-wheel and fuel energy use
- The regulated emissions from the ICE

A secondary question has arisen from the studying of the above topics: which PHEV components and functionalities are important in measuring the above-mentioned elements? The scope of the thesis is closely related to the available tools and various limitations. The main tool used is a corpus containing driving data. The available data were measured through GPS sensors in 432 cars driving in Västra Götaland. Examples of trip characteristics are the vehicle's velocity per timestep and a trip's duration.

As mentioned before, one of the factors under investigation is the at-wheel and fuel energy use; it is generally more common to examine the energy use of a vehicle by measuring the amount of fuel spent, however. This would require making the assumption of using a specific PHEV (because each vehicle operates in different ways), and would also require an ICE model to calculate its efficiency at given timesteps. Additionally, the long-term marginal power generation technology's total efficiency (from fuel to consumer efficiency) in Västra Götaland's electricity system would be needed, which would also require more than the time available for a master's thesis.

Emissions estimation is a topic which is difficult to investigate due to many unknown factors such as which exact PHEV is used. Hence for simplification purposes, the emissions estimation in this thesis is reduced to the total time that the ICE is used on a PHEV and the temperature behaviour of the catalytic converter.

2 Background

2.1 Alternative vehicles and relevant terminology

During the past decades, the automotive industry has invested in the development of new types of vehicles which use alternative fuels. Their main focus is to create fuel-flexible, pollution-free and safe vehicles. Electric vehicles seem to be the most promising alternative vehicles that have the potential of making an environmentally friendly transportation system [5]. However, battery technology is still immature which slows down their flourishing. Hence, at least for the short-term future, hybrid electric vehicles (HEVs) are the inevitable substitute[5].

The alternative technologies to CVs are several, some of which are almost as old as they are; the ICE vehicles as well as the first EV go back to the early 19th century. Another technology under research is the fuel cell vehicle (FCV), which use the chemical energy in the fuel, avoiding its combustion [6]. A combination of the above-mentioned technologies would be a fuel cell HEV which makes use of electric energy coming from both a battery and a fuel cell. Other types of HEVs use an ICE and an electric motor similar to plugin hybrid electric vehicles which are studied in this project.

One could wonder what the difference is between the above-mentioned HEV and PHEV, due to their obvious resemblance. They both use the same propulsion technologies (ICE and electric motor). They both also fluctuate between the uses of their energy supplies according to their power demand. However, their energy use management differs which influences their efficiencies[5].

More specifically in the case of an HEV, when the vehicle is functioning at a low speed, its power demand is fulfilled by the electric motor. Once the driver increases speed and hence the power demand, the HEV would use the ICE instead. In cases of even larger power demand, the hybrid would use both propulsion systems to move. In other words, HEVs use electricity (not from the gird) to complement their main power source which is usually gasoline[5].

Contrary to an HEV, a PHEV uses electricity as the main power source. This means that as long as the battery has enough energy in it and the electric motor is able to provide enough power, it is solely used to propel the vehicle; at this state, the vehicle is in a charge-depleting mode. The energy in the battery is tracked by a variable called state of charge (SoC). SoC reveals the charge percentage in the battery which is available. Once the SoC reaches a predetermined level (around 30%), the vehicle enters a charge-sustaining mode where the ICE is turned on and functions in an optimum (efficient) way to supply power to the motor. When there is excess power generated from the ICE (since it operates in a standard point), it acts as a generator for the battery. The above function is used in parallel type PHEVs which are also investigated in this thesis.

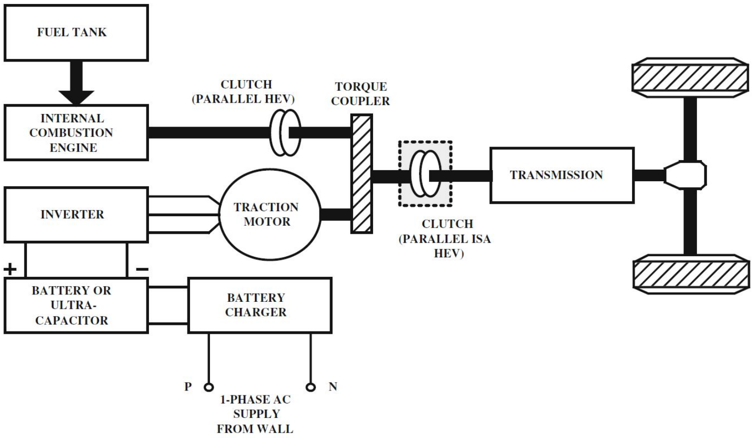

Figure 2: Parallel PHEV power train configuration [5]

The main advantage of PHEVs compared to other alternative vehicles is that they can store energy in their batteries from the city's electrical grid. This leaves an open door to renewable energy sources to enter the transportation sector and make it more environmentally-friendly.

The main goals of HEVs are to have efficient fuel use, reduce harmful emissions and provide safe and steady driving experiences. To achieve that, these types of vehicles have different operating states [8]. A combination between a driving state and other variables make a driving mode. More specifically, in various driving modes, the ICE and electric motors interact in different ways. Driving modes can be found in the literature under different epithets; the following table illustrates them:

Table 1: Driving modes

Electric Driving	The electric motor is used alone. Possible only with PHEVs	Charge depleting
Hybrid driving	Both ICE and electric motor(s) are in use. ICE is used in a specific operating point depending on SOC (SOC>30%).	Charge depleting
Boosting	ICE and electric motor(s) both in use. The propulsion systems work in full torque to cover the demand.	Charge depleting
Generator operation	The battery SOC is lower than 30% so the ICE produces more power in order to charge it.	Charge sustaining
Recuperative braking	The power demand is negative and used to charge the battery. More about this in the next chapter.	Charge increasing

2.2 Regenerative Braking

A very important common function in HEVs and PHEVs is the ability to generate energy when the vehicle is braking. This mechanism is called regenerative or recuperative braking. In contrast to CVs, the energy flow in the propulsion system is not only in one direction as shown in Figure 3 – it can flow from the battery to the wheels and vice versa.

When CVs are braking, the kinetic or potential energy is absorbed by the brakes in the form of heat; while in vehicles that recharge, the energy passes to the battery. Regenerative braking's working principle is to slow the vehicle down by converting its kinetic (or potential) energy into electricity or mechanical energy in other cases [6], which can be stored until it's needed. The most important advantage of this function is that it may increase the range of the vehicle substantially.

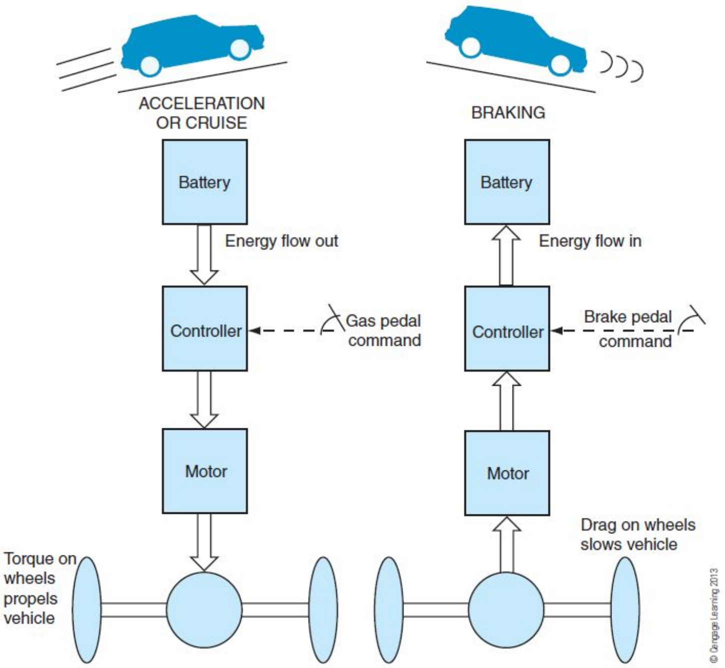

Figure 3: Recuperative braking principal

Numerous control strategies have been developed aiming for the most efficient energy regeneration for certain conditions like the cooperatively braking system or the cooperative braking manoeuvre[8].

2.3 Batteries

One of the most important technologies in alternative vehicles are batteries. This is because their extensive cost makes alternative vehicles significantly more expensive than conventional gasoline vehicles. A typical cost of a Li-Ion battery is 250 $/kWh [5].

The basic battery characteristics needed for modelling are the following:

- **Battery Capacity** is a variable describing the charge that can be extracted from the battery until it gets fully discharged. It is usually measured in Ampere-Hour (Ah). However, by multiplying it with a battery's steady voltage, this unit can be converted in kWh.
- **C rate** is a variable ndicating how fast the battery is charged (kWh/h).
- **State of Charge** (SoC), as mentioned before, is a variable tracking how much energy is left in the battery
- **Energy Density** is defined as the total energy of a charged battery per size unit (volume or mass)
- **Charging and Discharging Efficiency** are indicators related to the energy losses during the battery's processes.

- However, we assumed that a vehicle can only be fully charged during a pause of either 10h (accounting overnight charging) or 4h (including charging while the vehicle is parked during working hours). In this way the parameters of C rate and charging efficiency where not considered.
- The modeling of the battery's size was out of the scope of this thesis, so the Energy Density was not considered.

2.4 Catalytic converters

Vehicles that use hydrocarbons as fuels emit hazardous greenhouse gases to the environment. Since the PHEVs investigated in this thesis are assumed to have an internal combustion engine, they are responsible for CO2 and other hazardous gases emissions. One of the main research questions investigated in this project is related to the comparison of hazardous emissions between CVs and PHEVs.

The vehicle's component responsible for minimising harmful emissions is the catalytic converter. Catalysis is a chemical process using a catalyst to speed up chemical reactions without changing the catalyst itself [10]. Catalysts are widely used for reducing carbon monoxide (CO) and hydrocarbon (HC) emissions and are placed in the exhaust of automobiles.Their main function is to oxidise the substances mentioned above and release to the environment carbon dioxide (CO2) and water (hydrogen oxide, H2O). An additional function of catalytic converters is to reduce nitrogen oxide (NOx) emissions to nitrogen (N2). In other words, three chemical reactions usually take place in a catalytic converter: two oxidations (for CO and HC) and a reduction (for NOx). This is why they are called three-way catalytic converters[4].

The interior of a catalytic converter consists of a honeycomb ceramic structure in order to come in contact with as much pollutant gas as possible. This increases the converter's efficiency. However, a catalyst has to be warm to be effective.

An important factor to be considered in driving modelling, as performed in this thesis, is the temperature-soaking process of the catalytic converter; this is a phenomenon of the component's cooling down process after the engine has shut down. The reason behind this is to take account of parking time on the temperature of the catalyst and track for how much time the catalyst is operating under and over the light-off temperature.

The ultimate goal of a catalytic converter is to operate above the light-off temperature as much as possible to minimise hazardous emissions. Therefore, its location is constantly moved closer to the engine so it's exposed to higher temperatures [13]. As a result, the soaking process is highly affected [11].

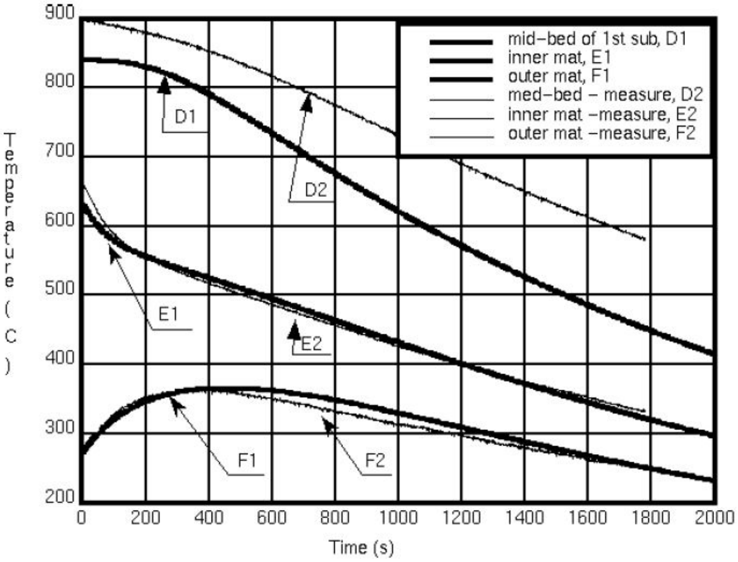

Figure 4: Catalytic converter soaking process [11]

Something to be considered here is that after the engine is shut off, in a CV, the catalytic converter is going to increase slightly in temperature due to the cooling systems' shutdown. However, in PHEVs the vehicle might be still moving and operating, allowing outdoor air to flow around the component and cool it.

2.5 Fuel Use

One of the most important factors related to this project, and probably many other studies of automotive vehicles, is the fuel use. The scope of this thesis involves the driving simulation of several hundreds of vehicles, so finding out their fuel use behaviour would be very important.

There are many ways of estimating the fuel use of an automobile. Since in this thesis the engine's power demand will be calculated (as it will be described in the next chapters), the Willans line method can be effectively used to estimate the ICE's fuel use. The Willans line can describe the correlation between the engine's power demand to its fuel consumption in an almost linear way [14].

The following figure describes the above mentioned relationship:

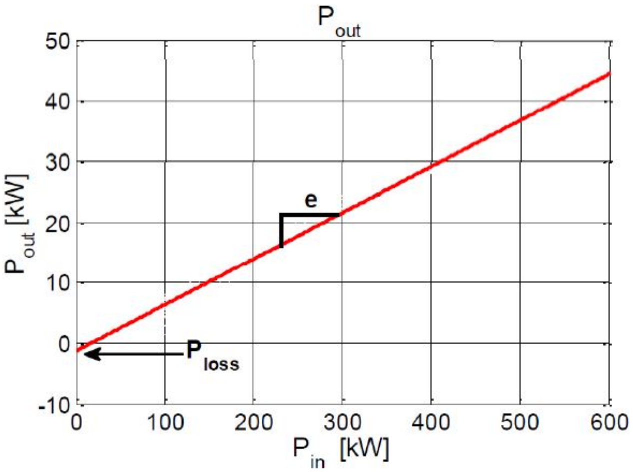

Figure 5: Relationship between input fuel power and output engine's demand power. [14]

The factors of the Willans line are the following:

$$\begin{aligned} &P_{out} : The\ engine's\ power\ demand \\ &P_{in} : Input\ fuel\ power \\ &e : Energy\ conversion\ efficiency \\ &P_{loss} : Losses\ due\ to\ mechanical\ friction,\ alternator,\ auxiliaries[14] \end{aligned} \tag{1}$$

In order to estimate the energy conversion efficiency and the engine's losses due to friction, further variables should be taken into consideration. However, this topic will be further elaborated in the Methodology section.

3 Methodology

To carry out this project, several models were created that receive some input data. After simulating the driving process, these models output some other variables. The output variables are closely related to the project's aim, which is to investigate the behaviour of the energy use and ICE emissions of PHEVs. This section's main purpose is to describe all the assumptions and calculations made in order to develop the above-mentioned models as well as to show the models' functionality.

What should be kept in mind at this point is that the models were developed in order to simulate the driving process multiple times, starting with various input variables, so that their effect on the output variables can be observed and studied. Examples of input variables are battery capacity or maximum motor power capacity, while output variables may be the total duration of ICE use or total duration of catalyst operation under the light-off temperature.

3.1 Assumptions and Calculations

The detailed modelling of the concepts described in this section is out of the scope of this thesis because of their complex function. This is the reason why some assumptions were made concerning them.

3.1.1 Regenerative braking

Regenerative braking was taken into consideration in this thesis. However, it is remarkably difficult to have an accurate model of its function because it is strongly dependent on the way vehicles are driven. [3]. The modelling of the braking mechanism for the purpose of this thesis relied on the following characteristics [3]:

Regeneration power limit [kW]	≤40
Regeneration speed limit [km/h]	≥5
Regeneration two-way efficiency [%]	=0.64

3.1.2 Catalytic Converter

The simplifications made for the use of battery modelling are presented below:

- The light-off temperature is around 230 Celsius [9]
- In order to meet European legislation, the catalytic converter should meet the light-off temperature in 25 seconds [7]
- The catalytic converter has a binary function: it either works when it's above 230 Celsius or it does not work if it's below 230 Celsius.
- The soaking process of the catalytic converter follows the D1 graph in Figure 4

The warm-up and cooldown graphical representations are shown in Figure 6 and their functions resulted are the following:

$$\begin{aligned}
&Warmig-up\,temperature\,function\\
&temperature(t)=120\,log_2(t-21.5)\;when\;t\in\{25-150\} \qquad (2)\\
&temperature(t)=8.28\,t+15\;when\;t\in\{0-25\}
\end{aligned}$$

$$\begin{aligned}
&Cooling-down\,temperature\,function\\
&temperature(t)=829.4\,0.999635^{t}+11\;when\;t\in\{0-14613\} \qquad (3)
\end{aligned}$$

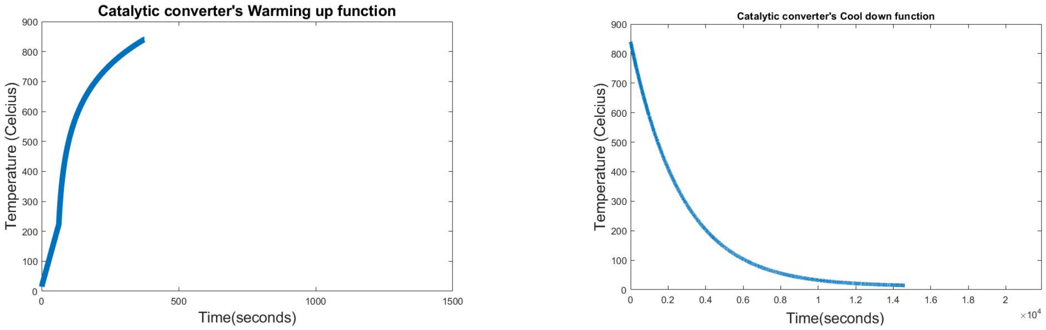

Figure 6: Catalytic converter Warming-up and Cooling-down functions.

3.1.3 Batteries

Assumptions and simplifications regarding the temperature behaviour of the catalytic converter are presented below:

- A vehicle can only be fully charged during a pause of either 10h (accounting overnight charging) or 4h (including charging while the vehicle is parked during working hours). In this way, the parameters of C rate and charging efficiency are not considered.
- The modelling of the battery's physical size was also out of the scope of this thesis, so the Energy Density is not considered.

3.1.4 Optimum ICE operation point

Since in the final model of this project the charge sustaining mode of a PHEV will be introduced, it was required to assume the output power of an ICE's optimum operation point. When the vehicle entres the CS mode, the internal combustion engine operates providing a specific output to cover the demand, and in cases that the demand is lower than that specific output the battery is charged with the excess power. The output power of the above mentioned optimum ICE operation point was assumed to be 33kW.

3.1.5 CO2 Emissions

In order to calculate the CO2 emissions, another calculation should take place first. In section 2.5 the fuel use was briefly discussed. It was also mentioned that several factors of the an automobile's use should be taken into consideration in order to estimate the vehicle's fuel use. These factors have to be assumed:

- Crank of revolutions for each power stroke per cylinder: $n_R = 2$
- Bore = 72 mm
- Stroke = 84 mm
- Engine's displacement = 2000 mm^3

So the first thing to be calculated is the Willans line:

$$P_{in}(kW) = \frac{P_{out}(kW) + P_{loss}(kW)}{e} \tag{4}$$

The values of e and P_{loss} were derived from the same source [14], to be:

- e = 0.31784
- $P_{loss} = 3.27$ kW

By using Equation (5), under the result of the whole simulation the result would be the fuel demand in terms of energy (kWh). Taking this one step further to calculate the CO2 emissions from the use of that fuel would require the specific CO2 content of gasoline (assuming that the PHEVs simulated have a gasoline ICE).

The specific CO2 content of gasoline would be: $0.26\frac{kg_{CO2}}{kWh}$ [15]

3.1.6 Data and Tools Description

The main tool to be used to carry out this thesis is a data corpus containing trip data. The variables were measured through GPS sensors in 432 cars driving in Vastra Gotaland. The measurements' timestep is 0.4 seconds keeping track of the location of each vehicle. Trip characteristics like the vehicle's velocity, acceleration for each time step and trip duration are also included. Additionally, the power demand was calculated as followed[3]:

$$\begin{aligned}
&P(t) = P_{acc}(t) + P_{grade}(t) + P_{air}(t) + P_{roll}(t)\\
&P_{acc}(t) = m * a(t) * v(t)\\
&P_{grade}(t) = m * g * sin(a(t)) * v(t)\\
&P_{air}(t) = \frac{1}{2}\rho_a * A * C_d * v^3(t)\\
&P_{roll}(t) = C_r * m * g * v(t)
\end{aligned} \tag{5}$$

where:

- P(t): power-at-the-wheels
- $P_{acc}(t)$: acceleration power
- $P_{grade}(t)$: power required in a road gradient
- $P_{air}(t)$: power needed to overcome air drag
- $P_{roll}(t)$: power needed to overcome rolling resistance
- m: mass of the vehicle
- a(t): acceleration for each timestep
- v(t): vehicle speed
- ρ_a:density of surrounding air
- A: frontal car-area
- C_d: air drag coefficient
- g: gravitational acceleration

The date was divided in two types of corpora. More specifically, the first part is related to trips and the data have the form presented in the example below:

where:

Table 2: Example of the first type of data

Device #	173	**Pause before [s]**	275
Trip ID #	2	**Duration [s]**	477
Average velocity [km/h]	44.7	**Start time [yy-mm-dd hh:mm:ss]**	2010-07-03 08:56:13
Distance [km]	5.97	**Stop time [yy-mm-dd hh:mm:ss]**	2010-07-03 09:04:11

- Device: is a unique number describing the GPS component placed on a vehicle
- Trip ID: is an number indicating a device's trip
- Average velocity of the vehicle during the trip
- Distance covered during the trip
- Pause before: shows the time a vehicle was parked before the trip
- Duration of the trip
- Start time: shows date and time information of when the trip was initiated
- Stop time: shows date and time information of when the trip was ended

The above example only shows part of the data that was useful for the thesis.

The second part of the dataset involves detailed information per timestep of each trip. The following table is an instance of a given timestep:

Table 3: Example of the second type of data

Speed [km/h]	17.4	**Power Gradient [W]**	-10650
Altitude [m]	232.4	**Power Acceleration [W]**	3336.7
Acceleration [m/s^2]]	1.65	**Power Rolling Resistance [W]**	713
Road Gradient [degrees]	-0.72	**Power Air Resistance [W]**	47.9

Where:

- Speed: is the vehicles velocity during a given timestep
- Altitude: describes the the geographical altitude of the vehicles location
- Acceleration: describes the vehicle's acceleration during a given timestep
- Road gradient: shows the slope of the vehicle's movement during a given timestep
- Power characteristics are described in Equation 6

Apart from the data, an external tool was used to calculate the mathematical functions of the catalytic converter's warming-up and cooling-down processes. The tool is provided by Lumen Learning [12] and is called 'Horizontal and Vertical Translations of Exponential Functions'. Its input variables are points of the Cartesian coordinate system, while its output is a logarithmic or exponential function satisfying them.

For the model development, MATLAB was used; more information about the code functionality will be shown in the following sections.

3.2 CV Reference model

The model presented in this chapter is the conventional vehicle model. Its complexity is the simplest in this thesis as it only makes use of the first dataset which involves characteristics per trip (not per time step). The aim of this model is to create a reference to be compared with the rest of the models. Additionally, information about CV driving conditions may be extracted like the pause distribution for Swedish drivers as well as the temperature distribution of the catalytic converter. The following chart explains the functionality of the model, or in other words, how the MATLAB code works.

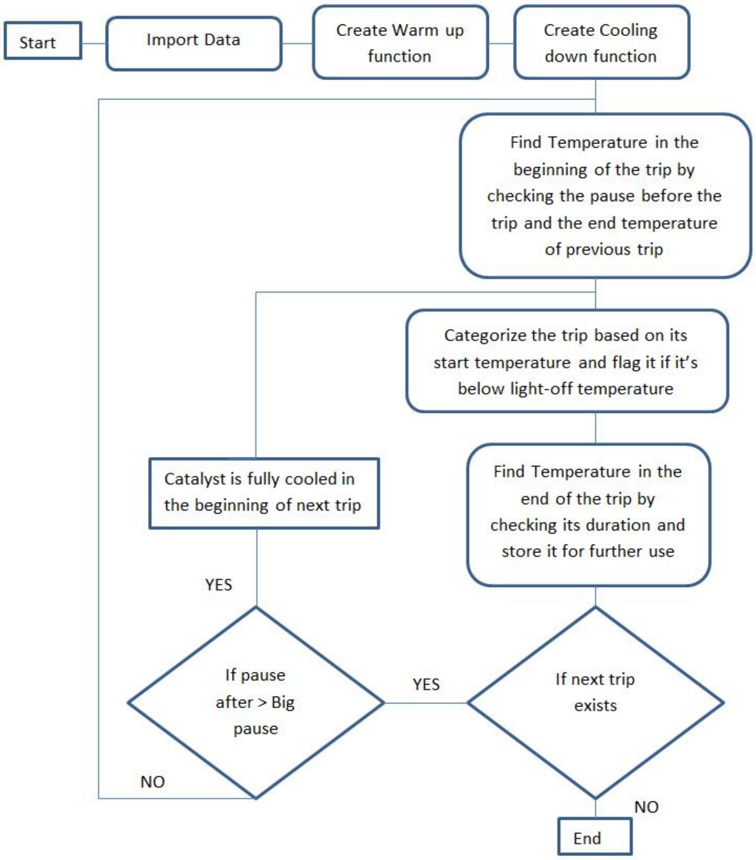

Figure 7: Conventional Vehicle model flowchart

The first part of the process involves the data import and creation of the catalytic converter's warm-up and cooldown functions. The data, as mentioned in Chapter 2.5, have the following form:

Table 4: Example of the first type of data

Device #	**Pause before [s]**
Trip ID #	**Duration [s]**
Average velocity [km/h]	**Start time [yy-mm-dd hh:mm:ss]**
Distance [km]	**Stop time [yy-mm-dd hh:mm:ss]**

During the next step, each trip is investigated separately. Firstly, the trip's pause before its initiation is examined. If a trip is the first one in a car device, it is assumed that it had a pause large enough to charge the battery before. Investigating the pause before the initiation and the ending temperature of the previous trip (if it exists), the start temperature is determined. At this point it can be seen how much time the vehicle will function while the catalytic converter is under the light-off temperature and keep track of it.

In the next stage, the ending temperature is calculated. It cannot be assumed that the catalytic converter will reach the maximum temperature because trips exist with small durations.

During the next step, it's examined if the pause between the current and the next trip is larger than a big one. What is considered a big pause is the only input variable in this model. A big pause is classified as a pause large enough to charge the battery. If there is a big pause between two trips, it can be assumed that the start temperature of the next trip will be the minimum possible. A big pause was assumed to be either at least 10 or 4 hours charging overnight or at work respectively. This part is useful for avoiding calculation and saves processing time.

Once the procedure goes through all the trips, the simulation process ends.

3.3 Basic PHEV model

For the creation of this model, an assumption has been made: during the corpora data collection, PHEVs were driven instead of conventional vehicles. As a result, an ICE and a battery variable were included in the model to keep track of their use. The main purpose of the model is to simulate the energy use of the vehicles and keep track of the amount of time that the catalytic converter was operating beneath the light-off temperature.

For this model, as well as for the following models, the data used are in a different form than the conventional vehicle model presented in Chapter 3.1. More specifically, a simulation going through these models iterates over each driven time step instead of each trip. The structure of the data is followed in Table 5.

Table 5: Form of the PHEV models' data

Speed [km/h]	Power Gradient [W]
Altitude [m]	Power Acceleration [W]
Acceleration [m/s^2]]	Power Rolling Resistance [W]
Road Gradient [degrees]	Power Air Resistance [W]

This, being the most basic PHEV model, includes the modeling of three fundamental PHEV parameters:

- The battery SoC
- The ICE use
- Regenerative braking

Table 6: Model's input and output data

Input variables:	**Output variables:**
Length of a big pause	Battery SoC per time step*
Battery Capacity	Demand covered by the motor per time step
	Demand covered by the ICE per time step
	Temperature of catalyst per time step
	Ratio of beneath light-off temp to total time steps

Table 7: Model's input and output data

* Battery SoC is tracked for both cases of having regenerative braking and not.

The functionality of the model is more complicated than the one from the previous chapter since the data used are more explicit. Additionally, the amount of iterations that the MATLAB code has to go through is significantly larger, which makes the process very time consuming. The model's main operations are described by Figure 8 which shows how it operates during the simulation of a single timestep.

The first part of the model is similar to the conventional vehicle model regarding the data importing and the creation of the catalytic converter's temperature functions (this part is not illustrated in the following graph in order to keep it simple and easy to read). A small difference in this case is that additional data (from Table 5) are imported.

This leads up to the first conditional statement where if the demand is not positive then the model checks if there is a possibility of regenerative braking (the conditions related to regenerative braking are described in Chapter 2); in this case the model reducing the catalyst temperature because the ICE is not functioning (the battery might be charged). On the other hand, in the case where the demand is positive, another conditional statement related to the size of the demand comes up. If the battery SOC is large enough to fulfill the demand, the ICE is not used which implies that the catalytic converter is decreasing in temperature. Additionally, the full amount of power (per time step – energy unit) is reduced from the battery. If the demand is too large for the battery to fulfill it, the ICE takes care of the leftover demand. Since the ICE operates, the catalytic converter is operating too, so its temperature increases. Whenever the ICE is on, the catalytic converter's temperature is checked to examine whether it is below light-off or not.

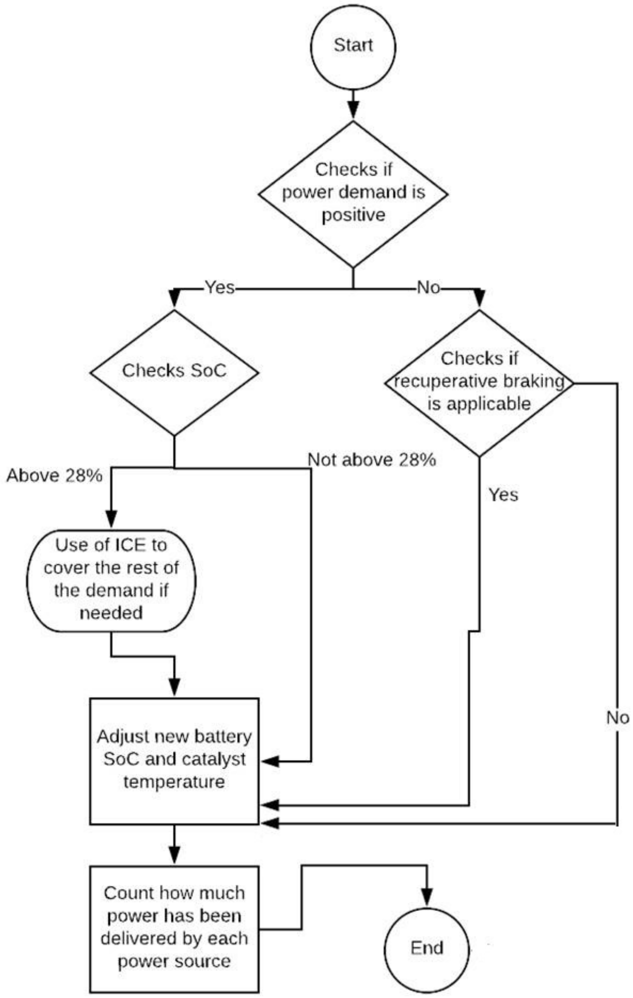

Figure 8: Basic PHEV model flowchart

In either of the above cases, the amount of power delivered by the ICE or the electric motor is measured at the end of the iteration (it can be zero). Once all time steps are examined, the simulation is over.

To visualise the outcome of this model, the following figure was generated which only simulates a small fraction of the data:

The battery SoC starts at the maximum level and it declines while the vehicle is driven. The blue part of the graph illustrates the driving simulation with no regenerative power while the red part includes it. This is the reason why it is visible that the red part of the SoC decreases slower than the blue, and forms some small peaks when the battery SoC is at minimum level. The vertical increases of the SoC represent the big pauses between the trips.

Decreasing the time scope reveals more information about the model operation in Figure 10:

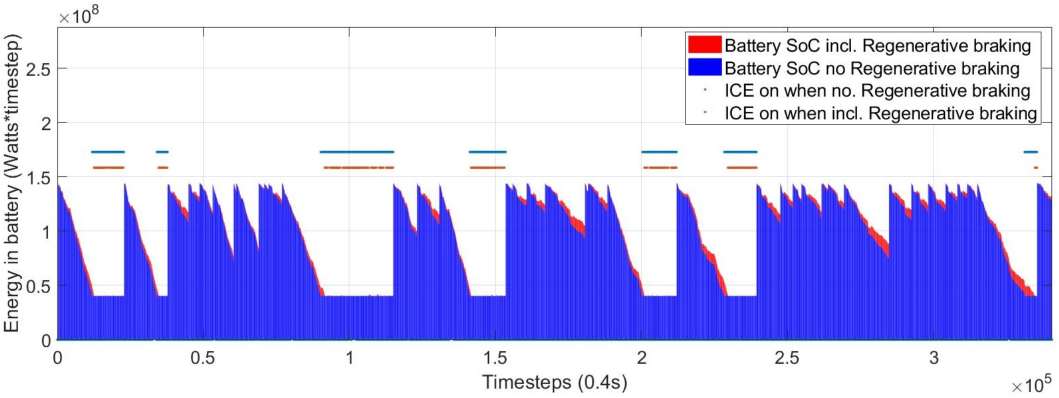

Figure 9: Example of basic model output 1

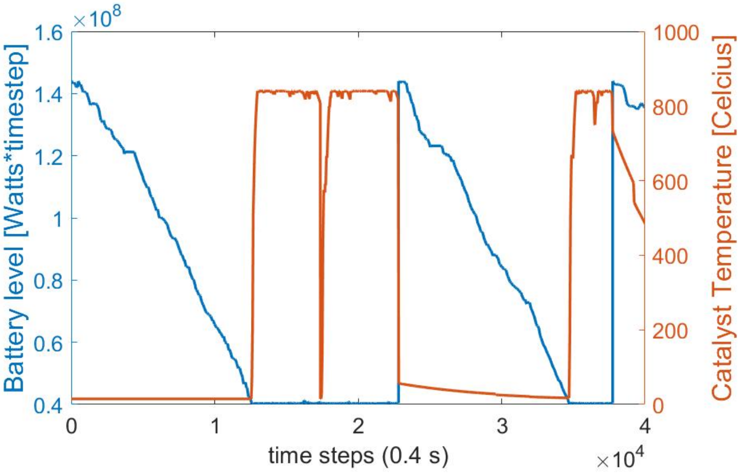

Figure 10: Example of basic model output 2

In Figure 9, both the SoC (blue) and catalyst temperature (red) are illustrated. Horizontal parts of the SoC curve represent time steps that have negative power demand but don't fulfil the conditions to charge the battery. Vertical drops of the catalyst temperature represent long pauses, though these are not necessarily long enough to charge the battery.

The aim of the above figures is to describe the functionality of the model and not its results. The input variable values for the above figure generation are:

- Length of a big pause: 10 hours
- Battery Capacity: 10 kWh

3.4 Intermediate PHEV model

The intermediate PHEV model includes the modelling of an extra parameter in the driving process. More specifically, the motor has the capability of providing a certain amount of power in each time step. This is a factor that may vary in different plug-in hybrid models on the market, which is also the main reason to take it into consideration as an input variable in the driving model.

By including the maximum motor power in the model, it is expected to observe an increased use of the ICE compared to the basic PHEV model since the power demand might not be able to be covered by the use of electricity even if the battery SOC is sufficient. What is not so obvious is if the catalytic converter's total operation time under the light-off temperature is lower or higher than the previous model. In particular, having the ICE operating for more time means that the catalyst is operating more too, which might imply that it cools down less often. More information about this issue will be discussed in the results section.

The data used for the model's development are described in Table 5 in the same manner as the basic PHEV model. However, there is a difference in the input and output variables which are shown in the following table:

Table 8: Model's input and output data

Input variables:	**Output variables:**
Length of a big pause	Battery SoC per time step
Battery Capacity	Demand covered by the motor per time step
Maximum motor capacity	Demand covered by the ICE per time step
	Temperature of catalyst per time step
	Ratio of beneath light-off temp to total time steps

The functionality of the model is more complicated than that of the basic model even if they have many similarities. Once a time step's power demand is positive, the algorithm compares it to the maximum motor power capacity as shown in the following operation schematic:

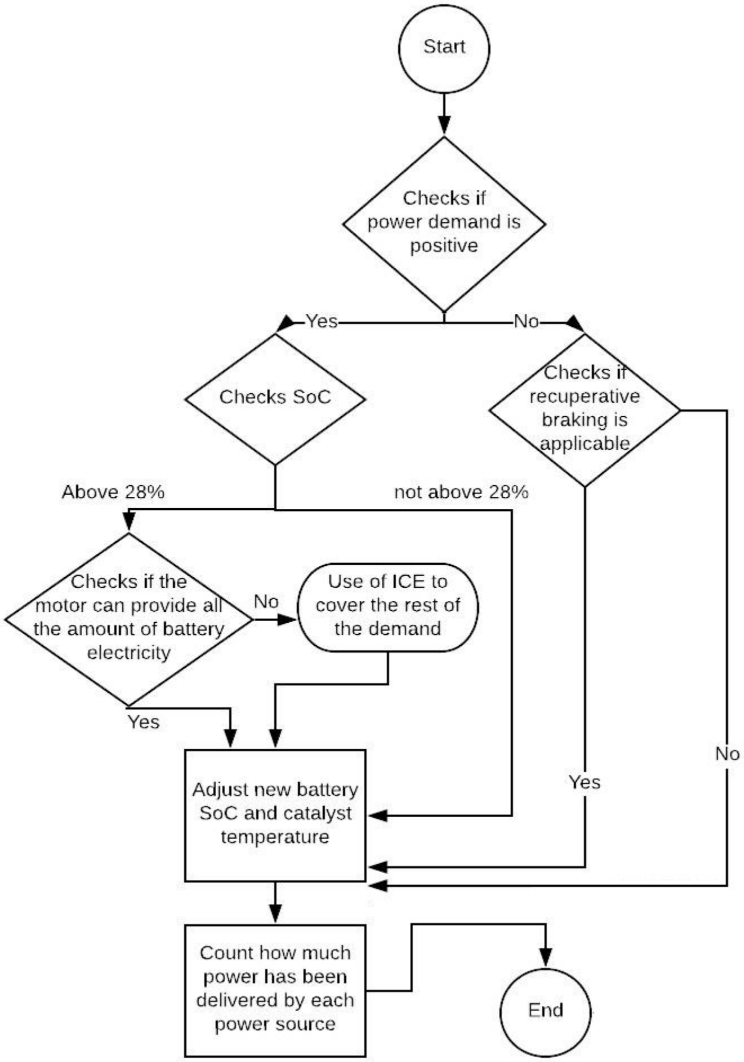

Figure 11: Intermediate model functionality flowchart

Besides the comparative condition referring to the motor's capability, the rest of the model remains very similar to the basic PHEV model. More specifically, if the motor is able to provide the full power demand to the wheels, then the functionality remains exactly the same as in the previous model.

However, if the motor can only provide part of the power demand, the ICE starts, which has the result of an increasing catalyst temperature and a SOC reduction equal to the maximum motor power. If the power demand is negative to begin with, there is no change in the algorithm's functionality.

For better understanding of the model's outcome, the following figures describe a short-period driving simulation:

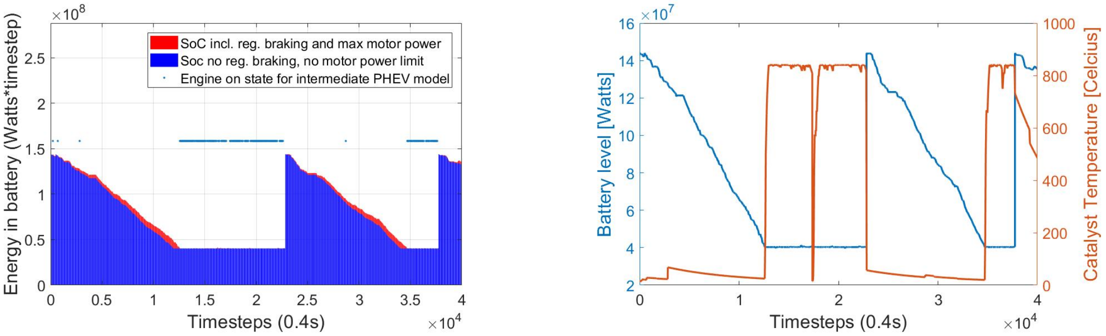

Figure 12: Examples of intermediate model outputs

The input variables used for the above exemplary simulation are the following:

- Length of a big pause: 10 hours
- Battery Capacity: 10 kWh
- Maximum Motor Capacity: 50kW

As mentioned before, the ICE seems to operate in some cases where the battery SoC is relatively high.

3.5 Advance PHEV model

This model is the last and most complicated developed in this thesis. It is also the most realistic to real driving conditions because it takes into consideration both types of PHEV modes: charge depleting (CD) and charge sustaining (CS). As described in Section 2.1, the PHEV modes are described in Table 9:

Table 9: PHEV modes

Driving modes	**Charge depleting**	**Charge sustaining**
Electric Driving	The electric motor is used alone. Possible only with PHEVs	
Hybrid Driving	Both ICE and electric motor(s) are in use. ICE is used in a specific operating point depending on SOC (SOC>30%).	
Boosting	ICE and electric motor(s) both in use. The propulsion systems work in full torque to cover the demand.	
Generator operation		The battery SOC is lower than 30% so the ICE produces more power in order to charge it.
Recuperative braking	The power demand is negative and used to charge the battery. More about this in the next chapter.	

It should be mentioned at this point that for Hybrid Driving and Generator Operation, the difference is the energy use priority. More specifically, in the first case, the electric motor is prioritised and used in full capacity, while the rest of the power demand is fulfilled by the ICE. If there is leftover power from the ICE, it is used to charge the battery. If in Generator Operation mode, only the ICE operates, and if there is excess power, it is used to charge the battery. This results the effect of having the battery charge declining until it drops low enough to enter the charge sustaining mode. Once the vehicle is on charge sustaining mode, the SoC is either increasing or dropping with a less steep slope as the ICE is operating too.

The inputs and outputs of this model are presented in the following table:

Table 10: Model's input and output data

Input variables:	**Output variables:**
Length of a big pause	Battery SoC per time step
Battery Capacity	Demand covered by the motor per time step
Maximum motor capacity	Demand covered by the ICE per time step
Percentage of SOC to be maintained	Temperature of catalyst per time step
ICE operating point power production	Ratio of beneath light-off temp to total time steps

The functionality of the model is presented in Figure 13.

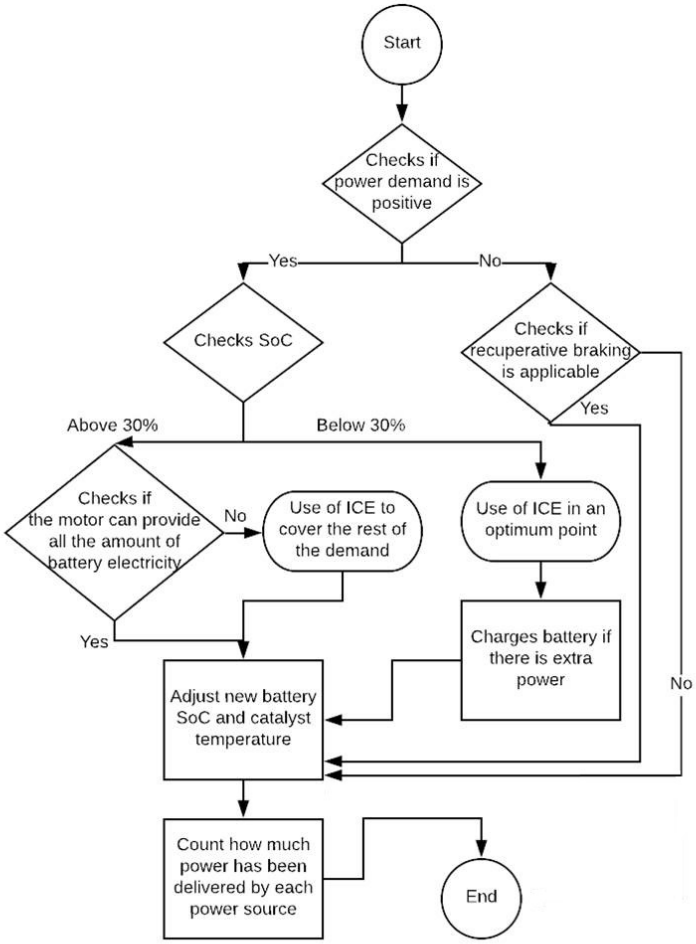

Figure 13: Advanced Vehicle model flowchart

The main difference between the previous model's functionality and this one's is that in the latter, during a time step, the current SOC is checked, and the demand is fulfilled in different ways depending on the SOC level. More specifically, if the battery SOC is 31% or more then the electric motor's use is prioritised and if the ICE is needed, it works with a specific power output as described in Function

1. If there is excess power from the ICE, it is used to charge the battery. The motor power conditions and brake charging remain the same.

In case the SOC level is below 31% , then the vehicle prioritises the ICE use. This means that the ICE is used at an optimum point to cover the demand and, if possible, to charge the battery with the remaining power.

Regardless, if the demand is unable to be fulfilled by the ICE in its optimum operation point and electric motor, the vehicle enters its booster mode where the ICE provides more power while being at a non-optimum operation point.

The following figure shows the model's operation in a small period of time and its purpose is to show how the SOC and catalyst temperature behave:

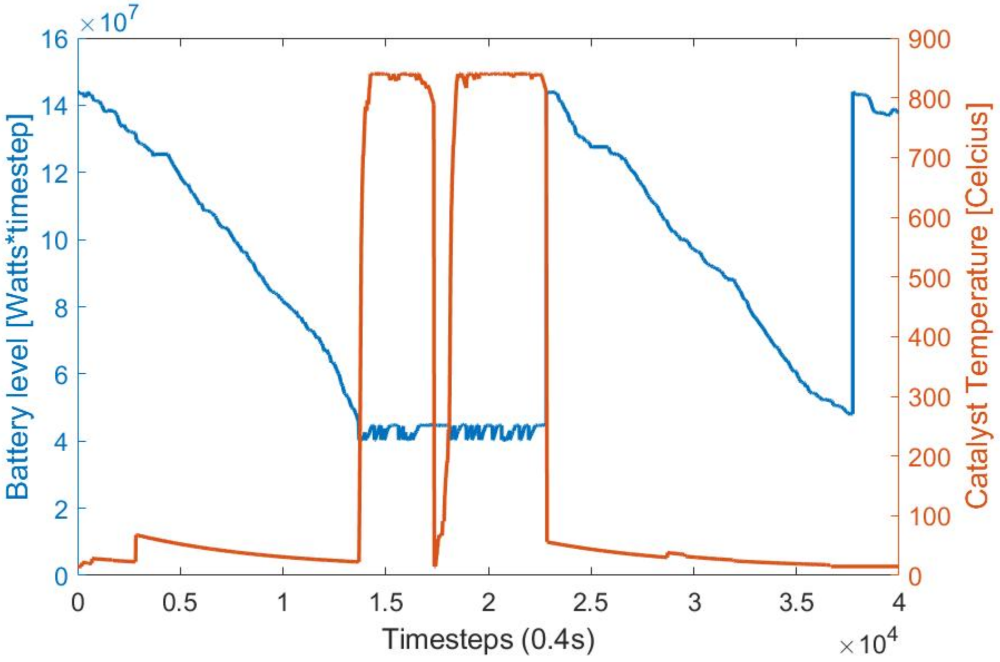

Figure 14: Example output of advanced model

As it can be observed in Figure 14 that the vehicle enters the charge sustaining mode after it first reaches the minimum SOC limit. Hence, once the vehicle reaches a low SOC level, the battery begins to charge until a specific point by using the ICE and then discharges again.

4 Results

The primary goal of this thesis has two tracks; the first one is related to the PHEVs energy usage , the second one involves an investigation concerning their emissions. The latter is a subject with two streams, CO2 emissions and emissions that occur while the catalytic converter operates in a 'cold' condition (catalyst below light-off temperature). In such cases the hazardous-gas emissions take place. To reach this goal, several driving models where developed in order to simulate the driving process and make relevant estimations.

Additionally, another indirect result arose from this investigation. It answers to the question of which components or PHEV-functionalities modelled influence significantly the results of the primary goal. A result like this could be useful for the determination of the boundaries for potential future research in this field.

The purpose of this chapter is to visualize and explain the results produced by the above-mentioned models.

4.1 Conventional Vehicle Model

Upon the creation of this model, two main outputs were introduced. The first one is related to the pause-between-trips distribution. These data are not particularly related to the thesis scope however, it might be useful for further research of the topic, since there are no similar data in the literature currently. The second output concerns the starting temperature of the catalytic converter between trips.

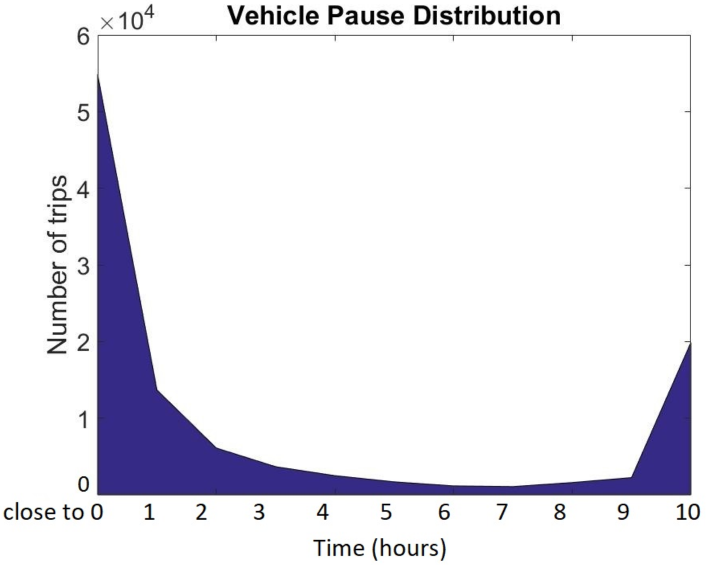

Figure 15: Pause distribution of conventional vehicles

Figure 15 describes the vehicle pause distribution after simulating 432 vehicle trips in Vastra Gotaland. It can be observed that the majority of the pauses are very small, between zero and ten percent of the maximum pause set to ten hours. It's important to highlight at this point that the corpus used contains pauses smaller than a second. The reason behind this phenomenon is, during the data generation, the timestep set was 0.4 seconds. This may explain why it is so common to have a large amount of miniscule pauses. Hence, a pause that seems to have a duration of 0% of a big pause actually means that its duration was very close to zero. The next larger amount of pauses have a ten-hour or larger duration (larger pauses were reduced to ten hours because they do not affect the vehicles temperature any more). From the nature of the above figure someone could observe that the trips simulated are likely to have either very small or very big pauses.

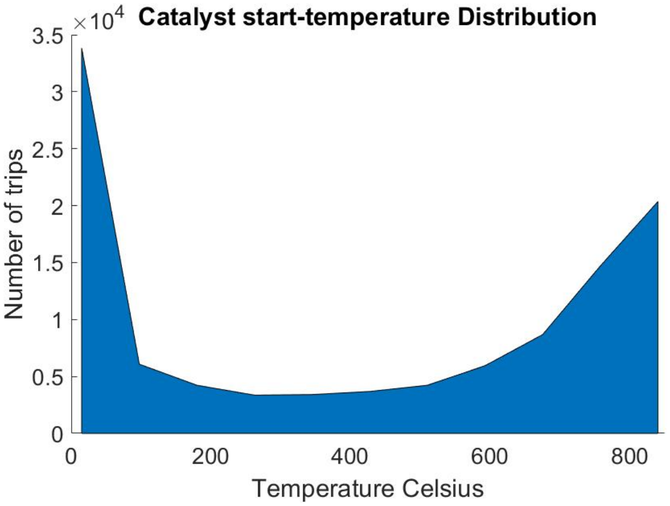

Figure 16: Catalyst start-temperature Distribution

Figure 16 shows the distribution of the catalytic converter's start-up temperature for the total amount of trips in the corpus. More specifically, almost 34000 trips have a minimum (15 degree) temperature in their beginning. As mentioned before, the catalyst's temperature span is between 15 and 840 degrees.

In contrast to the following models, the nature of this model's results concerning the catalytic converter performance is measured by only checking the starting point of a trip. Since the vehicles in this case are CVs, the only case in which the temperature of the catalyst could decrease is during a pause between trips. Consequently, the result-form of this model differs from the next ones. More specifically, the results of this model, could only possibly be compared to extreme PHEV cases with a zero-capacity battery or zero capacity motors, from the following models.

Even if the above two graphs seem to have a similar pattern – the largest group of trips in the beginning of the horizontal axis and the second largest group in the very right of the same axis –, they are not actually comparable. Having a very small start-up temperature in a trip implies that a big pause was before that trip. However, having a very high start-up temperature means that the pause before the trip was not significant, while the previous trip's duration trip was long enough to increase the catalytic converter's temperature to the highest level (840 degrees Celsius).

In contrast to the pause distribution of the trips, the catalyst's temperature distribution does not have as strong binary nature. More specifically it cannot be assumed that a start-up temperature is most likely to be either 15 or 840 degrees. The reason behind it is that the temperature distribution is more distributed over the temperature levels than the pauses. The relationship between the catalyst temperature and the pause before a trip is strongly related to the warm-up and – most importantly – the cool-down functions of the catalytic converter.

Coming to the direct correlations of this model's results and the aim of this thesis, one can observe that the results of this model are only a reference to compare how much less (or more) emissions come from the use of PHEVs. Hence the most important outcome is that the amount of time that the catalyst's temperature is below light-off temperature is 0.0155%.

4.2 Basic Model (1)

This model is capable of performing simulations using power data (the timestep set for the simulations is 0.4 seconds). The simulation's only constraints are the battery capacity and the charging period of the PHEV. For the analysis of this model's results, a sensitivity analysis was performed to determine the influence of the battery capacity.

Figure 17 describes how the power-at-wheel demand is being fulfilled for different levels of battery capacity.

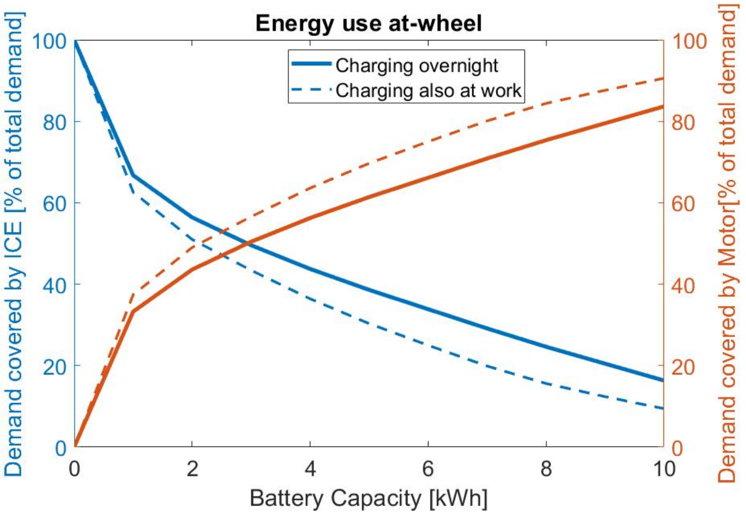

Figure 17: Demand covered by motor against demand covered by ICE

More specifically, having a battery capacity of zero kWh makes the vehicle behave more as a conventional internal combustion engine vehicle. This means that the whole demand during a simulation is fulfilled by the internal combustion engine. As the battery capacity increases it can be seen that there is the tendency to use more motor power to fulfill the demand. The difference between normal and dashed lines in the graph is reflecting the charging period of the PHEVs. Particularly, the unbroken line symbolizes simulations where the vehicles charge only overnight. This means that the charging of the vehicle's battery would occur once a pause before a trip is larger than 10 hours. On the other hand, the dashed line shows how the energy use – battery capacity relationship behaves when a vehicle is also charged during work times. This implies that the charging occurs when a pause before a trip is more than 4 hours.

It can be observed that when the vehicles are charged only overnight the increasing tendency of motor power use is not as strong as when the charging occurs also at work periods. In the first case, once a battery with almost 3kWh capacity is used then the energy use is split by half for the motor and the ICE. In the latter case, the state of having half of the demand being fulfilled by the motor and the rest by the ICE occurs when the battery capacity is around 2 kWh. It should also be mentioned that the increasing motor power use (and decreasing ICE use) happens in a close-to-exponential way. The effect is mostly obvious as the battery capacity stays in short numbers, while it makes much less difference increasing it when it is already high.

Another point that should be highlighted at this point is that the increasing use of motor power and decreasing use of the ICE in Figure 17 are not mirroring lines (even if it is not very obvious in the graph). Actually, the increase of the motor power use has a slightly steeper slope, as a result of recuperating braking. Hence, the modelling of regenerative braking does make a difference in measuring the energy use of PHEVs, concerning one of the thesis aims.

When it comes to the catalytic converter simulation results, Figure 18 describes its performance. The

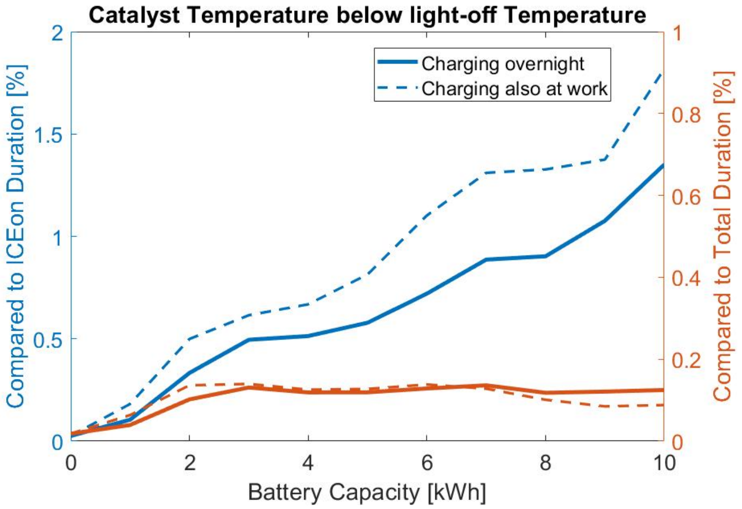

Figure 18: Battery capacity effect on the performance of the catalytic converter.

graph describes two aspects of the catalytic converter behaviour. The first one refers to the time where the catalytic converter is operating below light-off temperature while the ICE is functioning. The other refers its time operating under the light-off temperature during the whole simulation (even if the ICE is not always used).

If one is trying to figure out how much benefit there is in using PHEVs when it comes to the production of hazardous emissions, there are different perspectives to be taken into consideration. Thinking about the ICE performance perspective, according to the above graph, there are cases where the catalyst has been operating below the light-off temperature much more in PHEVs than ICEs. More specifically, by increasing the battery capacity it seems like the performance of the ICE's catalytic converter is declining. However, by taking into consideration the declining need of the ICE when the battery capacity is increased, this doesn't seem so critical.

The duration of operating the catalytic converter below light off temperature is close to zero percent of the driving time in CVs, but in the case of PHEVs it might increase up to around 0.17%. However in more advanced models that will be discussed in the next chapter, it can be seen that by including more variables and factors in the simulations this result will change.

4.3 Intermediate Model (2)

For the analysis of this model, an extra variable was investigated apart from the battery capacity. As mentioned in Chapter 3.4, in this model the motor power limitation was introduced. The purpose of this chapter is to visualize the results of the motor power limit and battery capacity sensitivity analysis.

In this model the ICE is used when the motor cannot provide the demand. This may occur if the battery SoC is not enough or the demand is larger than the motor capacity/limit.

The first aspect to investigate is the effect of the motor limit and battery capacity combined to the energy use of the vehicle. As observed in Figure 19, the demand covered by the motor is ascending relatively to the motor limit increase until it reaches a peak around 10-15kW. If the motor limit increases the electricity from the motor is used more but seems to settle around a value determined by the battery capacity. If the battery capacity is higher the percentage of the demand fulfilled by the electric motor is relatively increased. The opposite stands for the demand covered by the ICE.

So it can be observed that by adding the factor of the motor capacity the results differ quite much

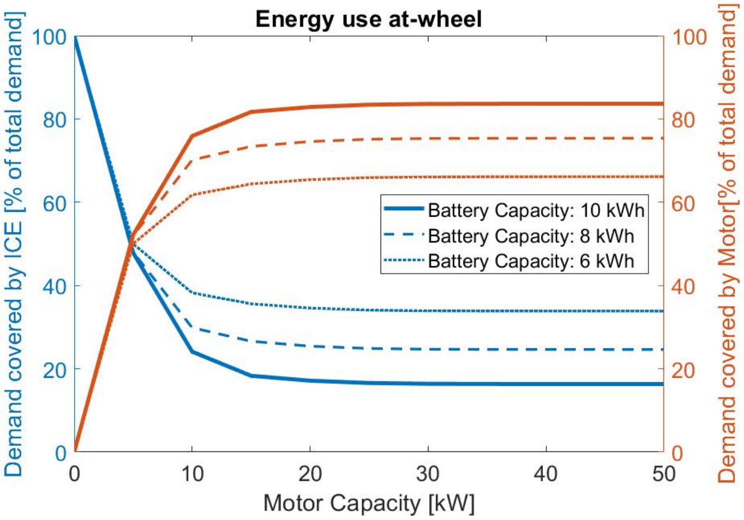

Figure 19: Motor limitation effect on the energy usage at-wheel

compared to the previously described model. It seems that by having a motor capacity of above 15kW can result similar energy use with having one with very much larger capacity. However, this does not seem that it would be a wise choice. By taking into consideration the catalytic converter's performance we can see that things may get a little bit more complicated.

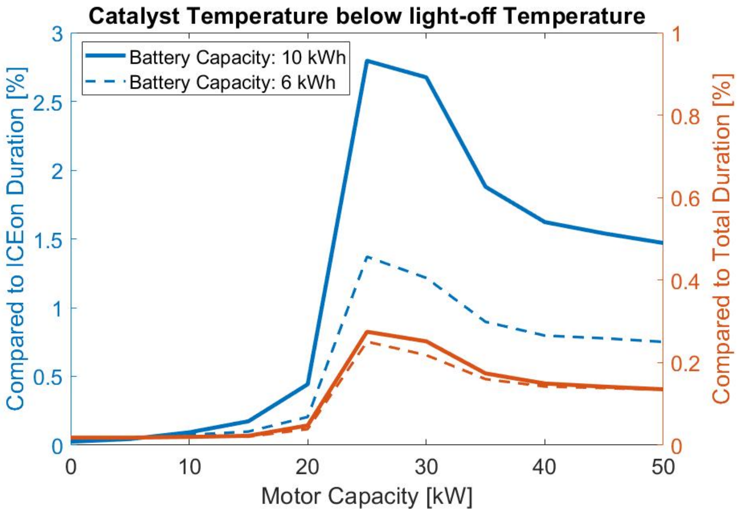

Figure 20: Motor limitation effect on the performance of the catalytic converter.

More specifically, Figure 20 shows the catalytic converters behaviour in a motor capacity sensitivity analysis. The duration of the catalyst operation below the light-off temperature has a fluctuation; increasing in the beginning until it reaches a peak and then decreasing up to a certain point. It can be observed that if the motor used has a capacity between 25 and 35 kW, the catalyst is operated less efficiently. This is most likely because if the motor is too small in size, the ICE is used long enough to maintain the catalyst temperature above light-off for most of the time. On the other hand, when the motor is between 25 and 35 kW, electricity is used enough to keep the engine shut long enough leave the catalyst below light-off temperature for up to almost 0.22% of all driving duration. As the motor power limit is further increased, the ICE is used much less which probably allows the catalytic converter to stay above the light-off temperature for almost as long time as the ICE is needed.

The addition of the motor power made significant difference to this model's results and gave the ability to perform extra sensitivity analyses and observe various behaviours. Hence, it is a component of major significance for PHEV modelling.

4.4 Advanced Model (3)

This model, in contrast to the previous ones, involves also charging PHEVs using the ICE. Similar sensitivity analyses were performed (regarding the battery capacity and motor power limitation).

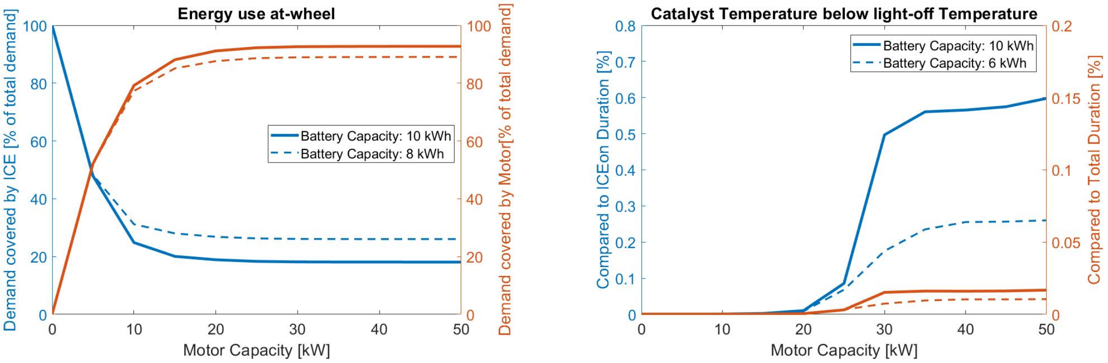

Figure 21: The effect of motor limitation on energy use (a) and catalyst performance (b)

This model is more complicated than the previous one but also closer to how real PHEVs operate. Here, the charge sustaining mode was introduced. By comparing this model's results to the previous one we can see the impact of using the ICE as a battery charger when possible. Of course the results derived by the advanced model are slightly trickier to interpret since the algorithmic operations to it are more complex.

As shown in Figure 21(a) while increasing the motor capacity, the demand is fulfilled using the motor more, and the ICE less; much like in the previous model as seen in Figure 19. Nonetheless, the additional components of this model result a significant difference from the intermediate model. This difference is reflected in Figure 21(a) where the sum of the ICE and Motor energy use result more than 100%. Bear in mind that the maximum demand represented by 100% is the total positive demand derived by the power data. This excess power use shows that the ICE was used more than before, to charge the battery. Hence the battery has extra charge to use and the motor seems to be used more. However, this excess energy is coming from the ICE in reality and represents how much charge has the ICE provided to the battery.

A clearer view of the ICE's charging effect can be seen in Figure 22. We can see that as the Motor capacity is influencing the capability of the engine to charge the motor because if the excess ICE power is more than the motor capacity, then the battery can only be charged the amount of charge which can be delivered by the motor. Additionally, it can be observed that the maximum amount of charge the ICE can provide to the battery occurs when the motor capacity is between 28-32kW. This makes sense because the charge sustaining mode takes place when the ICE performs in an optimal way and only delivers 33kW. Hence, the size of the motor shouldn't probably differ much from the ICE's optimal power capacity. For instance, if another optimum ICE point was to deliver 45kW, then we would observe that the maximum battery charge coming from the ICE would occur when the motor capacity was around 42-45kW.

Once again it should be reminded that the total demand in the above figures represents the positive demand of derived from the power data corpus, meaning that cases that the demand is negative are neglected.

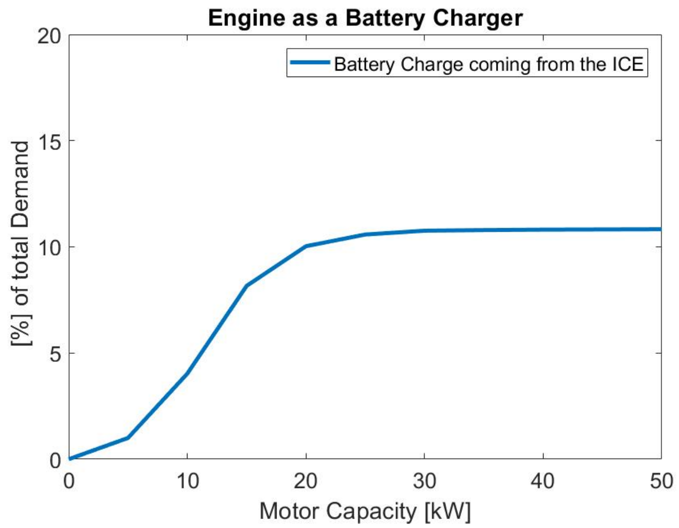

Figure 22: Model comparison on catalyst performance during the whole driving duration.

4.5 ICE use and CO2 emissions

The purpose of this chapter is to reflect the performance of the advanced model, which is the most realistic, to the ICE use and the CO2 emissions. In this chapter some focus will be given to the actual numbers, and questions like how much CO2 emissions we can avoid by using a PHEV will be answered.

The following figure describes the duration that the ICE is used in the PHEV developed models. By trying result data which are closer to reality, we can see that it's of major importance to include a charge sustaining mode in the simulations. This is because its effect is very big on the duration of the ICE use. As observed in Figure 23 the ICE use is reduced by more than 30% in the advanced model compared to the rest of the models. What should also be mentioned here is that a conventional vehicle would use its ICE during the whole driving time.

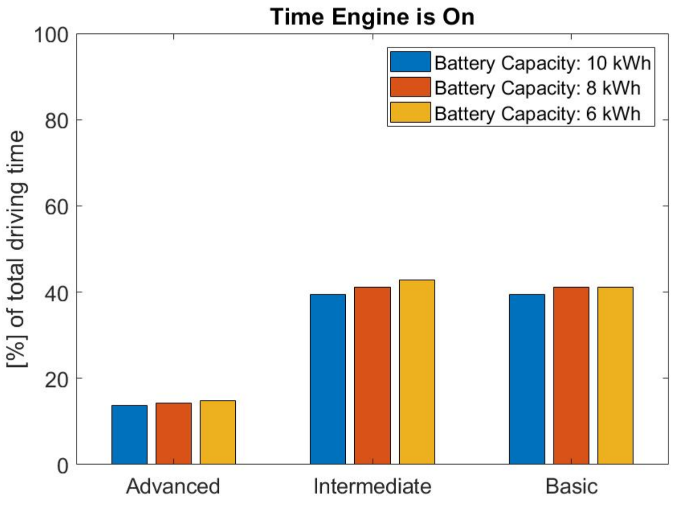

Figure 23: ICE-on duration.

Someone should bear in mind that this doesn't necessarily reflect the power demand cover by the ICE or the fuel use in the same rate. This is because the engine in this model is used to provide at least 33kW per timestep, while in the case of the previous models the engine could even provide a few Watts if needed. This is another reason that this model is more realistic than the previous ones.

Moving to the emissions visualisation, it should be mentioned that the representation of harmful emissions resulted by the inefficient use of the catalytic converter will be described by the duration of its operation below the light off temperature. This is because the in depth modelling of the catalytic converter is out of the scope of this project, however its duration can fairly describe the picture of how 'better' or 'worse' it performs.

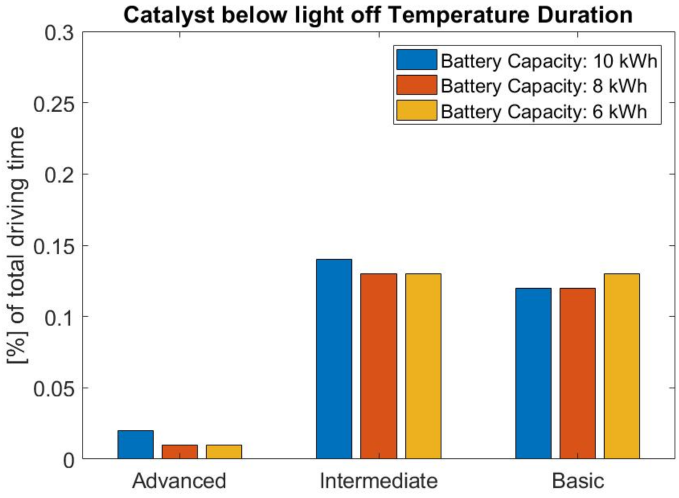

Figure 24: Model comparison on catalyst performance.

Figure 24 shows how much does the performance of the catalytic converter improve once the charge sustaining mode is introduced. This is because the advanced model allowed the ICE to be used for more consecutive time (in the charge sustaining mode) than the basic and intermediate models, which warmed up the catalyst more efficiently. So instead of having charge fluctuation around the minimum Soc, the battery was charged until from 28 to 31% (allowing the catalyst to warm up) before the motor could be used again.

The next figure shows how much fuel use and CO2 emissions occur in a simulation of the advanced model while the PHEV is equipped with different motors.

Besides the self-explanatory nature of this figure, it should be highlighted that most impact in emissions can be achieved once an electric motor is introduced in the vehicle's system, even a relatively small one of 10-15kW. Having a larger motor could benefit the performance of other components of the vehicle like the catalytic converter, but the influence on the fuel use and the overall CO2 emissions is rather similar.

At this point it should be reminded that the system boundaries of this thesis are limited to the fuel used by the ICE and not the electricity provider. This is because it is not known how much CO2 is produced to provide the charge in the vehicle's battery. If someone assume that the electricity comes from CO2 free technologies, then the benefits are maximised. However, this depends in the perspective-dependent marginal technology in the Vastra Gotaland's territory.

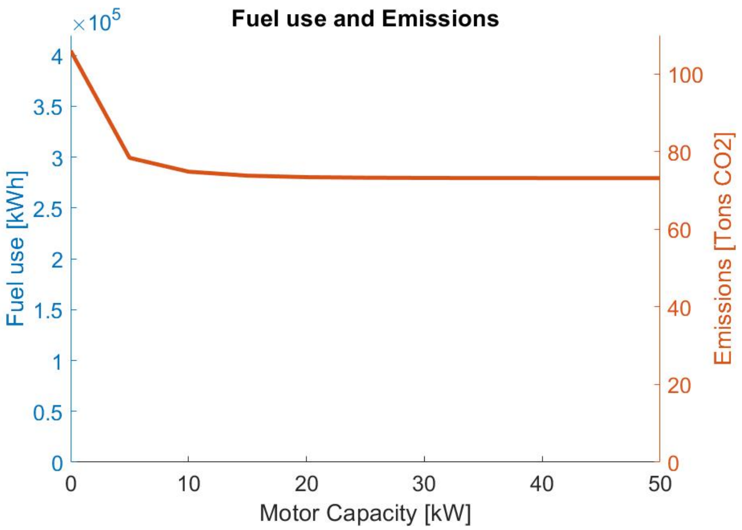

Figure 25: Motor capacity effects on fuel use and CO2 emissions.

5 Discussion-Conclusion

The purpose of this project was to investigate how trip characteristics affect the energy use and emissions for plug-in hybrid electric vehicles. To achieve that, the main tool used was a data corpus consisting of driving characteristics. The corpus's variables were measured through GPS sensors in 432 cars driving in Vastra Gotaland. An indirect outcome of this study also shows which of the components inspected in a PHEV are most important in the above related investigations.

The initial step of the investigation was the development of several models that simulate the driving process and calculate certain output variables; the main output variables are the profile of the catalytic converter's temperature and the energy use mix covering the at-wheel power demand.

More specifically, the first model simulates the driving process of conventional vehicles and outputs the pause distribution of all trips in the corpus as well as their total cold-starts. It should be noted here that the conventional vehicle model simulates trip by trip while the followed models simulate every timestep (0.4 seconds) of the driving period. The next model is the first one that simulates the driving process of a PHEV. The components modeled at this stage are the vehicle's battery and the catalytic converter, which makes it the simplest (basic) PHEV model. In this way, in every timestep, the demand covered by each energy source as well as the temperature of the catalyst, are tracked.

The second PHEV model is much similar to the first concerning its functionality; an electric motor was also modeled, however. The motor's modeling would increase the model's complexity (intermediate model). The motor would provide a limitation of how much electricity can be used in every timestep in order to fulfill the demand. The outputs of each simulation remained the same with the latter model.

The last model developed is the also the most complex as it simulates PHEV driving conditions with the components of the previous model, including the ability of the battery to be charged by the internal combustion engine when the battery's SOC is under a specific level. All the above PHEV models were developed because a secondary outcome of this thesis would be to find out the necessity of each component added in the simulation of PHEV driving. It was expected that each addition to the modeling would result different outcomes, more realistic as increasing the complexity.

The next step after the model development was a performance of a series of sensitivity analyses. The respective variables to be investigated in each PHEV model were the battery and motor size. According to the results of the conventional vehicle model, someone could suggest that in the beginning of each trip performed by a conventional vehicle, it is most likely to have either a cold-start or a very warm one, concerning the catalyst's temperature.

Regarding the basic PHEV model, in which a sensitivity analysis on its battery was conducted, someone can observe that if the battery capacity increases, more of the demand is covered by electricity; it can potentially reach a point where the ICE is not used at all if the battery is large enough. When it comes to the emission factor in the scope of this thesis, it is obvious that the CO2 emissions are decreasing as the battery capacity increases since the ICE is used less; however, the CO2 emissions were calculated for the advanced model. The hazardous emissions resulted by the poor operation of the catalytic converter are always slightly increased (compared to a CV) while the battery capacity ascends but also stabilise when the battery capacity is around 3kWh.

The intermediate PHEV model had the capability for an additional sensitivity analysis to be performed; related to the motor power limitation. The results concerning the energy use at-wheel indicate firstly, that as the battery capacity increases, more power demand is covered from electricity; with the potential of eliminating the use of ICE if the battery and motor capacity are increased enough, just like in the latter model. By having an increase of the motor would start reducing the use of the ICE until it stabilizes in a certain point which is dependent to the battery capacity. When it comes to the harmful emissions, or the catalytic converter's temperature, it seems they are increasing as the motor capacity increases, however, when examining the period that only the ICE is in use, the emissions are increased until the motor has a larger size than 35kW. In such cases the cold operation of the catalytic converter is stabilised to around 0.17% of the total driving time.

The advanced model has similar results to the intermediate one when it comes to the energy at-wheel estimations. Here the charge sustaining mode was introduced. The ICE could be used as a battery charger when it was appropriate, achieving the maximum charging potential when the motor capacity is slightly less than the ICE operating point's capacity. Concerning the energy use at-wheel, the internal combustion engine use has highly decreased, forcing it to be used in an optimum point of 33kW or higher. This model, being the most realistic of all in this thesis, also had a sensitivity analysis on the fuel use and CO2 emissions; it was observed that by introducing even a small motor of 5kW capacity, the CO2 emissions would decrease at almost their maximum potential. When it comes to the catalytic converter's performance, it's much better than the previous models but still slightly higher than the CV's model.

Generally, by driving PHEVs the use of ICE is reduced enough to mitigate the emissions significantly. However, it can decrease the vehicle's catalytic converter operation efficiency and increase slightly hazardous emissions.

6 Next Step

When performing a research of the above project's nature, the ultimate purpose is to meet the demands of today's markets and industries. Hence, this chapter focuses on this study's potential next steps in order to overcome some of its limitations, increase its results accuracy and draw some conclusions more relevant to the current market of PHEVs. More specifically:

- Reduction of the computational time

The first issue to overcome which is also the hardest limitation of the current study is the reduction of the computational time. The tool used was MATLAB however, other tools exist with appropriate features for handling large amounts of data. It should be highlighted here that the corpus is holding data for more than a hundred thousand trips, with a timestep of 0.4 seconds. This would roughly result $1.8 * 10^8$ timesteps to iterate. Additionally, as the models can end up being rather complex, a single simulation may currently take up to a little more than 20 hours to be completed. As an alternative, a more efficient coding standard should be followed aiming to the reduction of the computational time of the current .mat models.

- Model development for cooling-down and warming-up functions for the catalyst

The scope of this thesis was limited on the driving model development, leaving uninvestigated how have the temperature functions of the catalytic converter been developed. More specifically, certain assumptions and curves were found in the literature concerning this issue, but such functions could potentially be developed by modeling the internal combustion engine of a PHEV. Such models are very limited on the current literature and take into consideration factors that are not common in conventional vehicle models. For instance, in a conventional vehicle model, the cooling-down function of the catalytic converter may differ from the one of a PHEV model. This is because in a conventional internal combustion vehicle once the engine turns of, the vehicle stops. This would result the catalyst to increase its temperature for a short period of time before it starts cooling-down as the air flow has stopped. On the other hand, in PHEVs, the vehicle might still be moving when the engine stops which would most probably affect the cooling-down process of the catalytic converter.

- Outdoor and indoor conditions effects

A factor closely related to the latter, is the outdoor climate conditions. For this model it was assumed that the catalytic converter can have a temperature between 15 and 840 degrees Celsius. In reality such an assumption might be arbitrary since if the vehicle starts during a winter night in north Sweden, its catalyst would most probably have a much lower temperature. Additionally, the outdoor conditions would influence demand for comfortable indoor climate conditions. In this case there is also a difference between PHEVs and conventional vehicles. When it comes to heating, conventional vehicles use waste heat to keep the passenger cabin warm. However, a PHEV might use electricity from the motor to heat the cabin or use the ICE similarly to the conventional vehicle.

- Use of time data

An interesting addition to the driving modeling could include the use of the time data in the corpus. For example, instead of assuming that ten-hour pauses represent a night (for charging the PHEV), the actual time at the end of each trip could be checked and act accordingly.

- Economical perspective

One of the most important topics that could complement this thesis would be a techno-economical approach related to the sensitivity analyses. More specifically, since the components investigated in the sensitivity analyses are the battery and motor sizes, their prices could be added as an additional variable and calculate the different costs of having a variety of their sizes.

- Charge sustaining mode

The introduction of the charge sustaining mode had a large effect on the simulations results. This is why it could be very essential to investigate different ways it could be used. For example, having different ICE operation points relevant to the driver's speed could possibly increase the amount of battery charging. Additionally, another interesting functionality to be introduced would be to enter the charge sustaining mode when the driver seems to drive in high speed for a long period of time, even if the battery charge is not low enough, so that it would enter the CS mode anyway.

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