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XC90 Plug-in Hybrid Customer Usage

Master's thesis in Applied Mechanics

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Department of Mechanics and Maritime Sciences
CHALMERS UNIVERSITY OF TECHNOLOGY
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Abstract

In order to meet present and future climate requirements, Volvo Car Corporation has announced that all passenger cars will be equipped with at least one electric machine by 2019. For the Transmission department, this change requires development of new concepts. To accurately predict loads on these new concepts, simulations and vehicle measurements require representative assumptions about how customers use their cars in reality. This can be achieved with so-called diagnostic readout (DRO) data, which is logged in cars and extracted at repair shops. This project has specifically focused on data related to hybrid-specific functionality. To facilitate readings and analysis of this type of data, a Python tool with an accompanying graphical interface was developed. The tool was then used to analyze the behavior of more than 12 000 XC90 T8 Plug-in hybrid customers world-wide. The average customers drive about one third of the distance electric (with combustion engine off). The Hybrid mode is used most frequently (more than 80 % of the time) and the Pure mode next most frequently. The average customer also spend more time driving in Sustain mode than in Depletion mode. In addition 56 % of the time is spent driving with a battery SoC below 35 % (the combustion engine can be used to charge the battery up to a SoC of 33 %). The Brake mode is used 12 % of the time and the vehicle speed distribution looks different for electric drive and drive with combustion engine on. A comparison between behavior of real customer population and the synthetic population used in the requirement setting procedure at the Transmission department pointed out following: the time spent in Pure mode and in Depletion mode are underestimated, but the time spent in Hybrid mode and the amount of electric drive are overestimated. Future work can use the results as a foundation for design of future transmission concepts. In addition it is recommended to establish a requirement setting procedure, based on simulations and vehicle measurements, which reduces the observed differences between synthetic and real customer population.

Keywords: Diagnostic Readout Data, Simulation Methodology, Electric Vehicles, Data Analysis Tool, Graphical User Interface (GUI), Python

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Last but not least, I would like to thank Peter and my family for all the love and support that you have given me throughout my years at Chalmers.

Linda Pipkorn, Gothenburg, January 2018

Nomenclature

- ACC - Adaptive Cruise Control
- AWD - All Wheel Drive
- BECM - Battery Energy Control Module
- BEV - Battery Electric Vehicle
- CAN - Central Area Network
- DRO - Diagnostic Readout
- DTC - Diagnostic Fault Code
- ECU - Electronic Control Unit
- ECM - Engine Control Module
- EV - Electric Vehicle
- GUI - Graphical User Interface
- HEV - Hybrid Electric Vehicle
- ICE - Internal Combustion Engine
- IEM - Inverter Erad Module
- NaN - Not a Number
- OBC - On Board Charger
- OBD - On Board Diagnostics
- PHEV - Plug-in Hybrid Electric Vehicle
- SOC - State of Charge
- TCM - Transmission Control Module
- VCC - Volvo Car Corporation

Contents

1
Introduction

The focus of this master's thesis is on how diagnostic readout (DRO) data, data logged in cars and extracted at repair shops, can be used in order to analyze customer behavior. This is important knowledge for performing accurate computer simulations and requirement setting in vehicle development. The thesis will focus on the usage of Volvo XC90 T8 Plug-in hybrid (XC90 T8 PHEV), which is of interest for the development of future transmission systems for electrically propelled vehicles. This chapter outlines the background of the project, followed by the purpose, objectives and limitations.

1.1 Background

The development of passenger cars, as a result of the invention of the internal combustion engine (ICE), might be seen as one of the greater achievements of today's technology. This new invention, however, also brought some problems. The large number of vehicles on the roads have a negative impact on the environment as well as human life. Global warming, air pollution and the decrease in petroleum sources drive the development of clean and efficient transportation.

Volvo Car Corporation (VCC) is committed to minimize its environmental impact and, thereby, make future cities cleaner. With the goal of having a completely climate neutral production in 2025, the focus will be on reducing carbon emissions (CO_2) from both products and plants. One step towards this is that all car models launched from 2019 onward will be equipped with at least one electric machine for propulsion and regeneration. To achieve this, VCC will launch a number of electrified car models in its model program, which will consist of pure (battery) electric cars, plug-in hybrids and mild hybrids [1].

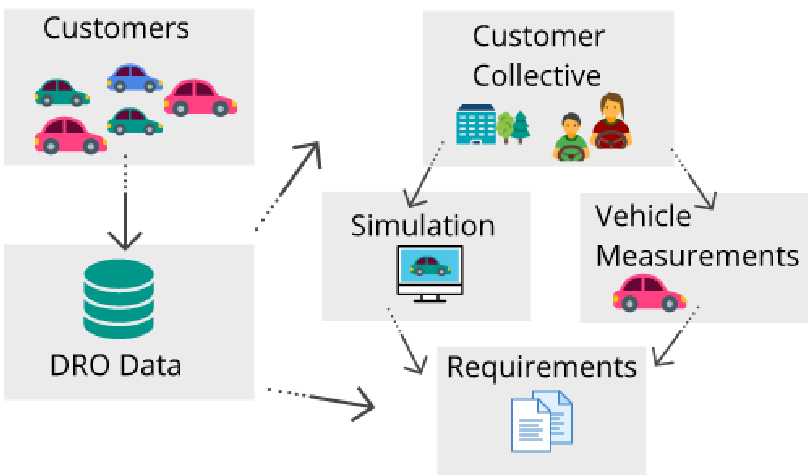

Figure 1.1: How DRO data is used in the development of transmission systems and components

At the Transmission department, computer simulations are being used for developing transmission systems and components for new car models. This reduces the amount of physical vehicle tests (which are still used to a certain extent), and thus saves resources. For simulations to be efficient and to produce accurate results proper assumptions about the customer usage has to be made. This is important since components withstanding their life time is essential for satisfied customers. Furthermore, a climate-friendly product development process should also avoid over-dimensioning the systems and components. The department did earlier not have the opportunity to correlate assumptions with real customer usage, which lead to over-dimensioning of transmission components and systems to withstand different load cases. The introduction of diagnostic readout (DRO) data in the development process, see Figure 1.1 provided an opportunity to better understand customer behavior. DRO data can both be used as a foundation for the creation of synthetic customer populations or to directly produce requirements. This data has at the department successfully been used to produce requirements, for conventional vehicles, more in line with real customer usage [2].

For hybrid vehicles, however, little is known about the customer behavior. Figure 1.2 presents a comparison, for a petrol (T6), a diesel (D5) and a hybrid (T8) XC90, between requirements based on current requirement setting procedure, based on simulations and vehicle measurements, and DRO data from the field. The figure displays the predicted and actual loads (represented by the so called Duty value) for each gear for a 90^{th} percentile customer. For the conventional vehicles (petrol and diesel) the requirement line curves are smoother and indicates a clearer correlation than the ones for the hybrid. The behavior of the hybrid requirement curve, however, indicates uncertainties in the methodology. DRO data shows that the hybrid is loaded similarly as the petrol for gear 3-6 and 8. The requirement curves, however, do not show the same trend. The first two gears are for the hybrid loaded significantly less. Note that the diesel engine can deliver higher torque which explains the higher loads on almost every gear.

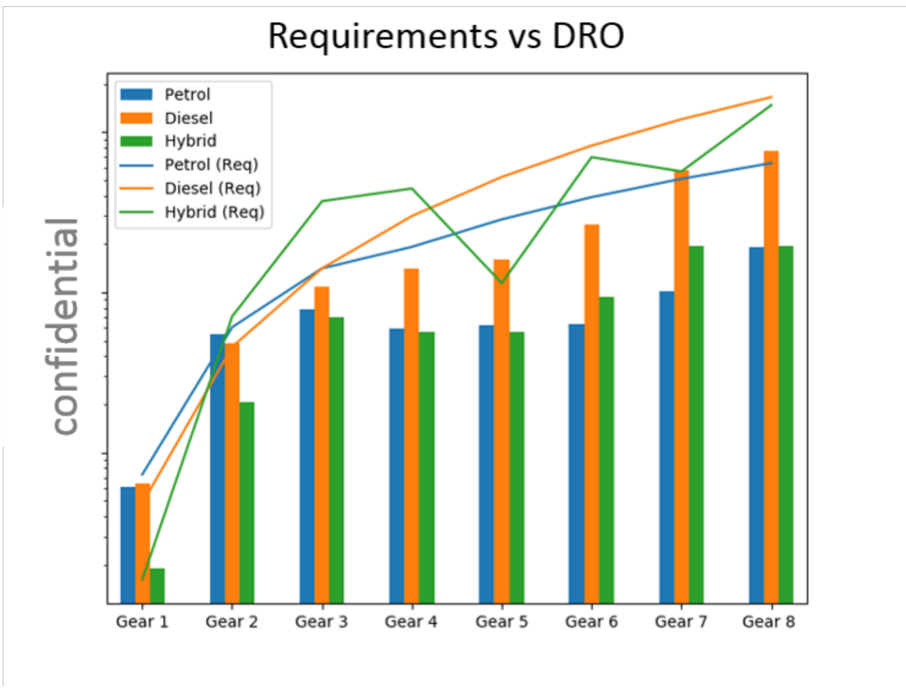

Figure 1.2: DRO data (bars) and requirements (lines) for a 90^{th} percentile customer and XC90 T8 PHEV, D5 Diesel and T6 Petrol

The introduction of electrified car models from 2019 requires refinement of existing requirement setting procedure. In addition brand new transmission concepts will be developed. For both matters, questions arise of how these cars will be used. If this knowledge is obtained, it can both be used to improve existing simulations of hybrid vehicles but also provide a foundation for the development of new transmission systems for electric vehicles. If representative assumptions about driving behavior are introduced at an early stage in the development process the amount of resources and time needed for a satisfactory result is reduced.

1.2 Purpose

The purpose of this master's thesis is to analyze the XC90 T8 PHEV customer behavior by the use of DRO data. The result should be used to improve existing simulations of hybrid vehicles as well as to provide a foundation for computer simulations of new transmission concepts. To make frequent readouts efficient, a data analysis tool is developed.

1.3 Objectives

The project will focus on the XC90 T8 PHEV and the following objectives shall be met.

- Investigate what DRO data (Logdata) is being logged in the vehicle's different electronic control units, and how the data can be used to describe real world usage.
- Develop a Python tool with a graphical user interface (GUI) for hybrid-specific DRO data.
- Study the customer usage and present statistics. Is there a difference in customer usage between different countries?
- Use the result (real-world behavior) to validate assumed customer behavior used in current simulations at the Transmission department and give recommendations for future simulations.

1.4 Limitations

The data analysis in the project is limited to use the DRO data logged in the different control units and can be extracted at the project start. The data is assumed to be accurate enough based on assurances of responsible departments.

The thesis will cover the simulation and testing procedures at the Transmission department in general, but will not go into details regarding specific components such as gears, splines, bearings etc.

The statistics describing customer usage will for simplicity reasons be compared to simulation assumptions from VSim only and not from physical vehicle measurements or simulations in CarMaker.

How often the customers use the adaptive cruise control (ACC), an optional system assisting the driver by maintaining a certain speed and distance to the vehicle in front, is not studied in this thesis. The reason is that the Transmission department does not consider it of importance for dimensioning of systems and components.

2
Theory

This section presents relevant background information about how data is used in vehicle development at VCC. Moreover, general information about electric and hybrid vehicles is outlined and followed by a detailed description of the XC90 T8 PHEV. Finally, an overview of the requirement setting (simulations and vehicle measurements) procedure at the Transmission department is presented.

2.1 The Use of Data in Vehicle Development

The use of data in vehicle development emerged as a result of the increasing competition in the automotive market. It has provided opportunities to meet the quickly changing customer preferences, the increasing development costs and the tighter regulations. The automotive life cycle has turned into a feedback loop where data produced in vehicles on the roads is used to shape the vehicle all over its automotive lifetime [3].

2.1.1 Different types of data for data logging

Data logging, the process of collecting and storing data over a period of time, is commonly used in vehicle development. There are different types of data such as non time-resolved, time-resolved and large data streams such as videos. The former typically requires the least amount of memory and the latter the most. A signal (i.e vehicle speed) measured over time produces time-resolved data or a variable, i.e v(t), where each point in time corresponds to a certain vehicle speed. If another signal is measured simultaneously (i.e acceleration) these two signals can be compared or combined. If the data is non time-resolved, however, this is not the case. This type of data is produced by saving scalar values in different categories or bins, i.e accumulated time driven in certain velocity intervals (see Figure 2.1). The advantage of this type of data is that it can be stored within the limited space of the electronic control units (ECU). The diagnostic readout (DRO) data used in this thesis is of the non-time resolved type. This type of data will throughout the thesis be referred to as Logdata.

2.1.2 Diagnostic readout data

VCC started to collect data generated by sensors in their vehicles in 1999. This diagnostic readout (DRO) data provides information about vehicle performance and possible component failure under actual field conditions. The data collection continues even when a vehicle is sold, to ensure the possibility of verifying the performance of systems and components. This is part of a service agreement between VCC and their customers [4].

When the car is at service DRO data from diagnostic functions built into the electronic control units (ECUs) can be accessed via the central area network (CAN) bus and the on-board diagnostics (OBD). Modern vehicles are complex electro-mechanical systems with a number of ECUs controlling different parts of the vehicle. A control unit is a small computer which controls actuators based on information given to it from different sensors. Examples of ECUs are the engine control module (ECM) and the transmission control module (TCM). A modern car might have up to 70 ECUs. These are connected via the CAN bus, which enables communication between the units.

The OBD is the vehicle's built in self-diagnostic system [5][6].

At the service occasion the car mechanic connects the OBD scanner to the OBD 16 pin connector in the vehicle. The tool enables communication and data transfer from the relevant ECUs via the CAN bus. With this the diagnostic fault codes (DTCs) can be read and the issue can be understood. Simultaneously logged and stored DRO data is transferred and uploaded to the vehicle manufacturer's database. From the database it is easily accessed by the engineers who can use it for statistical analysis assessing the real usage of the components. To handle large quantities of data, as is the case with DRO data, efficient processing techniques are needed. Programming languages such as Matlab or Python are recommended rather than Excel [4].

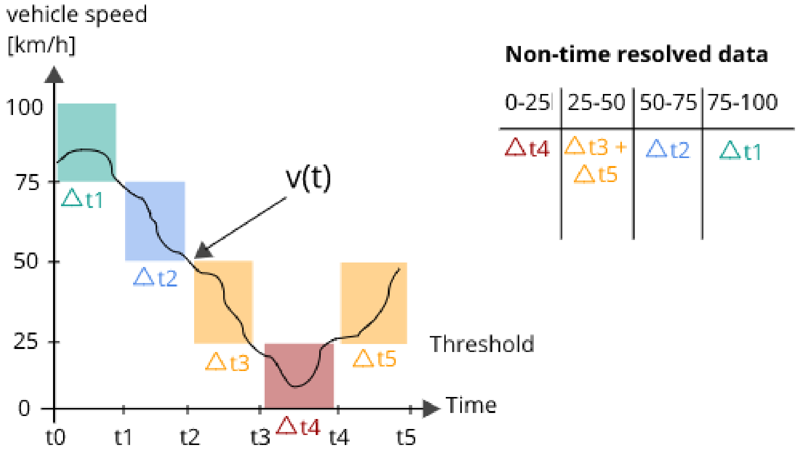

Figure 2.1: How non-time resolved data is sampled from a signal in time v(t)

2.2 Electric Vehicles

As an important step in reducing carbon emissions and the dependency on fossil fuel, vehicle manufacturers have started projects about electric vehicles (EVs) with promising solutions for the future [7]. In comparison to the conventional ICE-based vehicles with fossil fuel as main energy carrier, EVs are characterized by the presence of an electrochemical or electrostatic energy storage system (battery). In addition at least one electric machine is responsible for the vehicle propulsion, partially or totally [8].

The EVs are here divided into battery electric vehicles (BEVs) and hybrid electric vehicles (HEVs). BEVs roughly consists of an electric storage system, normally a battery, and an electric machine with its controller. Even though BEVs can offer clean and efficient transportation it does have its limitations. Battery degradation, higher costs compared to conventional vehicles and the limited range hinder the adoption [9]. A solution, on the way to zero emission vehicles, is the hybridization of the automobile drive train [10]. HEVs combine combustion engine, electrical machines and power electronic equipment [7]. A distinction is usually made between the conventional HEV and the plug-in hybrid electric vehicle (PHEV). The HEV is dependent on petroleum fuels for generating the required electricity on board whereas the PHEV is equipped with a battery pack that can be fully charged by plugging it into a standard electrical outlet [10].

2.2.1 Battery

One of the key components in EVs is the battery. Batteries can transform stored chemical energy into electrical energy or the reversed. A battery is typically characterized by its energy, W, measured in kWh, telling how much energy that is stored in the battery. The battery delivers its energy at a certain rate determined by the power, P. For an electric potential, V, constant in time, and the amount of charge, Q [C], the energy and power are related as:

$$W = QV \Rightarrow P = \dot{Q}V + Q\dot{V} = \{\dot{V} \approx 0\} = \dot{Q}V \tag{2.1}$$

Another important characteristic is the dimensionless parameter state of charge (SoC), describing the amount of energy left in the battery. It is the ratio of the electric charge Q [C] that the battery can deliver to the nominal capacity of the battery Q_0 [C].

$$SoC(t) = \frac{Q(t)}{Q_0} \tag{2.2}$$

The battery typically operates between a minimum and maximum SoC value. These limits are the minimum SoC attained during discharging and the maximum SoC reached during charging. [8].

2.2.2 Electric machine

Another key component of EVs is the electric machine. The electric machine can operate in two different ways. The machine can work as a motor and propell the vehicle by converting electrical power from the battery into mechanical power. The machine can also work as a generator converting mechanical energy from drive train. Electric machines are usually found as two types, alternating current (AC) and direct current (DC). Both types consists of a stator and a rotor and converts electrical energy into mechanical energy by inducing a magnetic field. The rotor is connected to the output shaft where the torque is acting [8].

2.2.3 Volvo XC90 T8 plug-in hybrid

The XC90 T8 Twin Engine Plug-in Hybrid is a parallel hybrid with two separate propulsion systems, see Figure 2.2. The first consists of a gasoline engine, connected to an eight-speed automatic transmission, powering the front wheels. The second consists of a hybrid battery and an electric machine connected to a single stage transmission powering the rear wheels. Depending on selected drive mode (see section 2.2.3.2) and the battery SoC, the two systems can be used in tandem or separately. In Figure 2.3 the different configurations can be seen. If the ICE and the electric machine are used together they provide for all wheel drive (AWD).

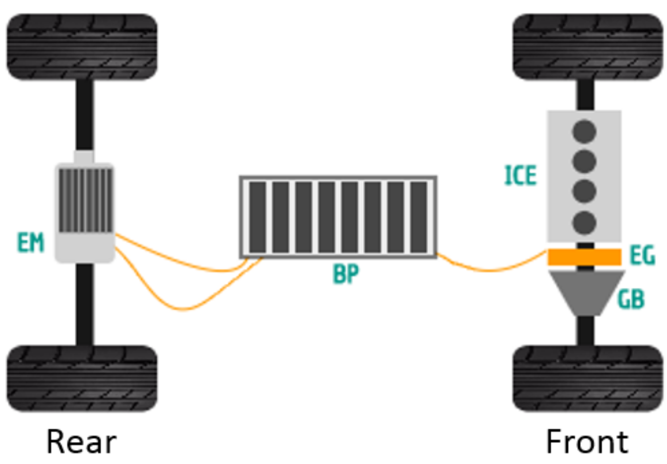

Figure 2.2: XC90 T8 PHEV Powertrain topology
EM = Electric Motor, BP = Battery Pack, ICE = Combustion Engine, EG = Electric Generator, GB = Gear Box

The battery can be charged in several ways. The two first ways are by either connecting a charging cable from the vehicle to a 120/230-volt AC socket or with the gasoline engine. The latter is possible with the generator placed between the ICE and the gearbox on the front axle. Finally, engine braking with the electric machine can be used to convert the vehicle's kinetic energy into electric current to recharge the battery (regenerative braking). Engine braking with the electric machine is by default used when the brakes are applied lightly and at speeds between 5-150 km/h, instead of the normal friction brakes (which is the case for a conventional ICE-based vehicle). The friction brakes are used for speeds outside of this range or during harder braking. The customer can also select a specific gear position, the Brake mode (B). In this mode engine braking with the electric machine is activated when the accelerator pedal is released [11].

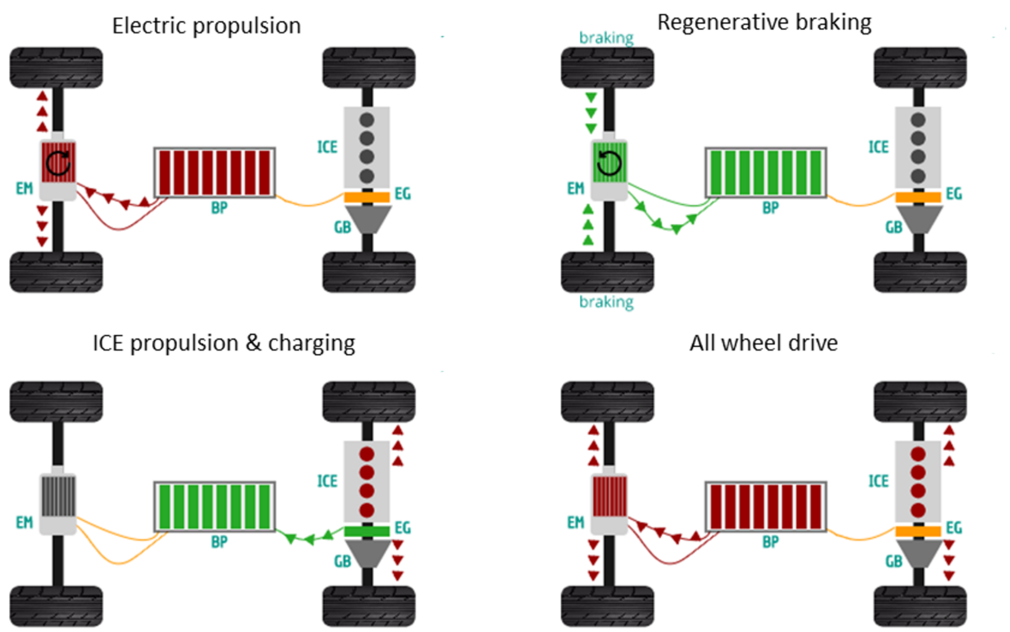

Figure 2.3: The hybrid powertrain can be utilized in different ways (green = charging battery, red = using battery or ICE for propulsion)

2.2.3.1 Specifications

Following list presents specifications for major components [12].

- **ICE Power:** 313 hp/233 kW at 6000 rpm
- **ICE Torque:** 400 Nm at 2200-5400 rpm
- **Electric machine Power:** 87 hp/65 kW at 7000 rpm
- **Electric machine Torque:** 240 Nm at 0-50 rpm
- **Transmission:** 8-speed automatic (TG-81SC)
- **Battery type:** Lithium-ion
- **Battery Capacity:** 9.2 kWh
- **Brakes:** 2 circuit hydraulic brake system with friction brakes on all wheels

2.2.3.2 Drive modes

The XC90 T8 PHEV has five available drive modes, that the driver can choose between (see Figure 2.4). As can be seen in the figure most modes are activated and deactivated by the user or when the vehicle is turned off. Note that the driver can also switch directly to another mode (i.e from Save to Pure) but in order to avoid clutter this is not included in the figure.

The default mode is the **Hybrid mode** which the vehicle starts in and it will always be active unless the driver selects an alternative mode. In order to obtain good levels of performance, comfort and fuel consumption the engine management system uses the electric machine as a motor and the gasoline engine separately or in tandem. The amount of electric drive is determined by the available battery state of charge (SoC) as well as the need for heating/cooling the passenger compartment. If sufficient battery charge electric drive will be available when the driver presses the accelerator pedal up to a certain limit. When this level is reached, the ICE will be turned on. If the battery SoC is low, the ICE starts more often for conservation of electrical energy.

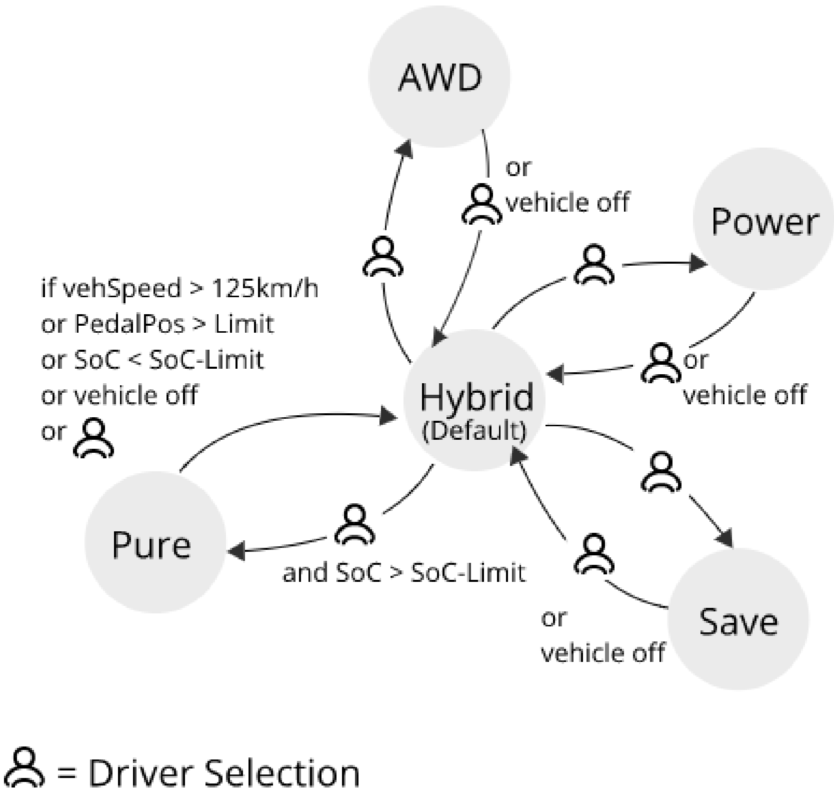

Figure 2.4: The five different drive modes can be selected by the driver

If the battery is sufficiently charged the **Pure mode** is available and activates the electric machine only. The gasoline engine will however be turned on (Pure mode deactivated) for speeds above 125 km/h, if the charge level gets below a certain limit or when acceleration pedal is pressed over certain limit. For the **AWD mode** and **Power mode** both the electric machine and the gasoline engine are used continuously to provide for four-wheel drive and greater traction. For the AWD and power mode the fuel consumption will increase either because ICE is used to charge the battery or since ICE and electric machine are both turned on. The **Save mode** is for drivers who would like to save battery charge for later times when the electric drive is sufficient e.g. when driving in cities. If the mode is entered with a SoC-level below 33% the ICE will be used to charge the battery up to that level. If the mode is selected for SoC-levels above 33% the current SoC will be set as a threshold which will be kept [11].

2.2.3.3 Updated functionality from model year 2016

The Save mode was present in the vehicles, of model year (2015), produced until 2016 week 17. After that the mode was replaced by two buttons, "Charge" and "Hold", in the touch screen. These buttons give similar functionality as the Save mode did but can be selected in every drive mode. The Hold button can be pressed regardless of SoC-level and current battery charge will be reserved for later use. The Charge button can be activated for low battery SoC and the battery will be recharged up to a SoC-level of 33%. When that limit is reached the hold function is activated automatically.

At the same time as Save mode disappeared a new mode became available - **Off Road mode**. The Off Road mode can help driving in difficult terrain or on poor roads by maximized ground clearance, light steering and all wheel drive. This mode can only be activated at low speeds and will automatically switch to AWD if the speed is above a certain limit.

2.2.3.4 Sustain and Depletion

Another characteristic for a HEV is two battery-related modes - **Sustain** and **Depletion** - which cannot be selected by the driver. They are determined by the present charge of the hybrid battery (see Figure 2.5) or by the Save mode/Charge and Hold buttons. If the current charge is above a set limit (SoC > SoC-Limit) the so called Depletion mode is active. In this mode the battery can be depleted. When the SoC-limit is reached the mode is switched to Sustain. In this mode the battery SoC is kept around a certain threshold. The Sustain mode will be kept until the vehicle is charged again. The SoC-limit and the threshold differs slightly dependent on selected drive mode. When Save mode or Hold button is selected the vehicle is always in Sustain since the threshold is moved to the SoC available when the mode is entered.

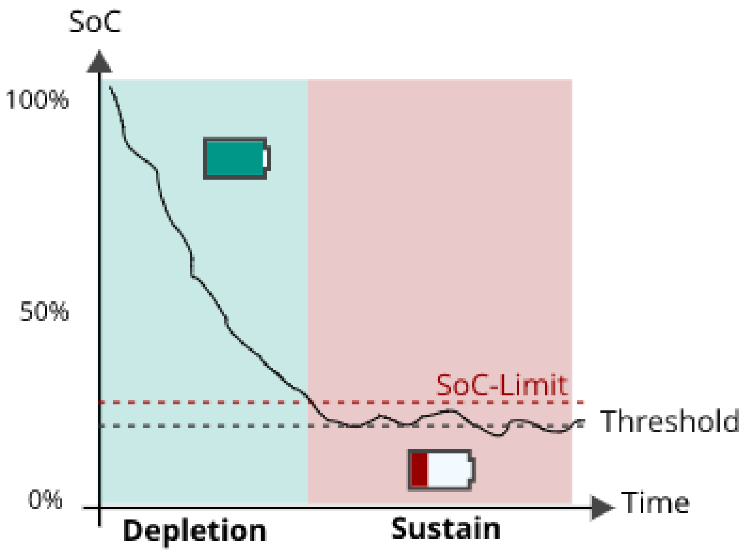

Figure 2.5: Sustain and Depletion mode are controlled by the hybrid battery SoC-level

2.3 Requirement Setting Procedure

Today, the transmission systems and components mounted in the customer vehicles are delivered to VCC by suppliers. In order for the suppliers to create components meeting the standard set by

VCC, requirements are needed. These requirements are produced by the transmission department by using a combination of simulations and vehicle measurements.

The service life of transmission components is dependent on both environment and driver behavior. Together they create load on the transmission and failure due to fatigue overload might occur. A driver, driving with a certain behavior and in a specific environment is here defined as a customer. At VCC synthetic customer populations are used both in simulations and in physical vehicle measurements to predict the service life. The output from simulations and vehicle measurements respectively is load collectives for each synthetic customer. From these load collectives the so called Duty value (see section 2.3.3) is calculated. The Duty value is used to determine which customer to use for the requirement setting and for that specific customer the load collective is given to the suppliers as the requirement. The transmission department is responsible for the dimensioning of several parts including the gears, drive- and cardan shafts, bearings and splines. The requirement setting procedure, based on simulations and vehicle measurements, is applicable for all areas but with slight differences that will not be covered in this thesis.

2.3.1 Customer collective: driver behavior and environment

As part of creating the synthetic customer population three different driver types, to represent the variation in real customers, are defined. The profiles are mild, moderate and aggressive. The different drivers are assumed to have a certain distance-% of aggressive, moderate or mild driving behavior (see Figure 2.6). This means that for a distance-resolved simulation as one example, the driver might behave aggressive for some part and moderate and mild for other parts. This, since even an aggressive driver will not be able to drive aggressive 100% of the distance. The aggressive driving is assumed to reflect the 90^{th} percentile customer (when 100%-distance reflects the most aggressive behavior). The moderate driving a 50-70^{th}percentile customer and mild driving a $< 50^{th}$percentile customer. What mild, moderate and aggressive driving means in terms of driver behavior can be different for simulations and vehicle measurements. The reason is often that simulations are more constrained (less degrees of freedom) than a driver performing a physical vehicle measurement. In order to explain the percentiles an example with a distance-resolved simulation will be given. Let's assume a simulation will be performed where a vehicle and its driver are following a certain drive cycle (vehicle speed as function of distance). If the level of aggressiveness is defined by the mean vehicle speed for the total drive, the mild customers will be all customers with a mean vehicle speed lower than the median or 50^th percentile. The aggressive drivers will have a mean vehicle speed larger than for 90% of the customer population. The moderate drivers are somewhere in between.

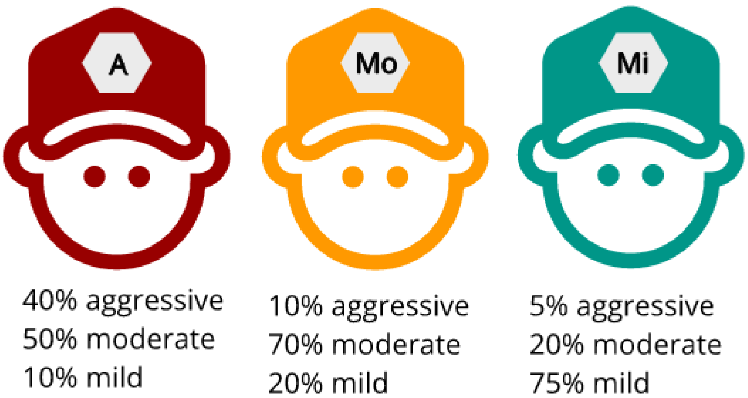

Figure 2.6: Distance-percentage share for the three driver types

The next important step in creating a customer population is to define the environments where the customers are driving. At VCC these are characterized by eight different drive cycles, both in real driving environment and on test tracks. The different drive cycles are city, rural, mountain, gravel, highway and autobahn. In addition drive cycles for trailer driving and hill starts are included. These different environments are combined according to a set scheme (see Appendix 1) to create 20 different customer types. Examples are Plain city driver, Highway driver and Mountain driver with trailer. These customers can then be mild, moderate and aggressive, resulting in 60 customers (20 x 3 driver types). These customers are then assumed to be distributed according to a certain Weibull distribution and 2000 customers are extracted by assuming a population share of 10% aggressive, 40% moderate and 50% mild customers [13].

The customer population is used to create load collectives and calculate Duty values for transmission systems and components both in simulations and vehicle measurements. The aim is that the two methods will produce correlating Duty values. In addition the Duty values should be in line with real customer data obtained by DRO.

2.3.2 Simulations and vehicle measurements

For the physical vehicle measurements three different drivers (mild, moderate and aggressive) are driving the different drive cycles in the real world and on test tracks. Sensors are used to measure torque over time.

The simulations aim at virtually reproduce the physical vehicle measurements. At the transmission department the tool currently used for simulations is VSim, which is a Matlab/Simulink based tool, developed in-house. The application is used for complete vehicle fuel economy and performance simulations. A schematic overview of a simulation or a vehicle measurement can be seen in Figure 2.7. Note that a vehicle measurement is not as strict in terms of driver and environment profile.

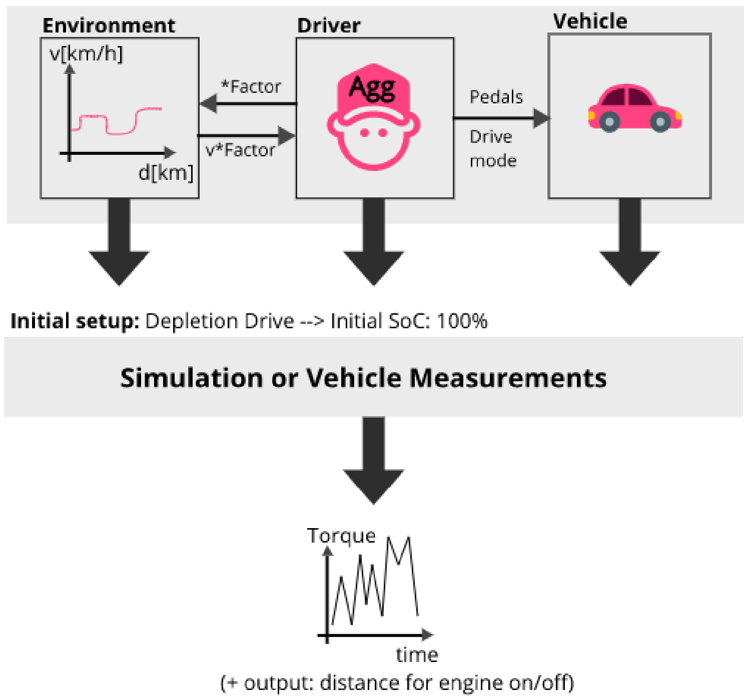

Figure 2.7: A schematic overview of a simulation or a vehicle measurement setup. Inputs are environment, driver and vehicle model and output is a torque signal

For simulations three inputs are needed: the environment, the vehicle model and the driver model. The environment is specified by a drive cycle where the velocity [m/s] is known for a certain distance point. In VSim the different driver types (aggressive, moderate, mild - see section 2.3.1) differ only in a factor which is multiplied with the velocity profile. An aggressive driver drives slightly faster than the moderate and the mild driver is the slowest. The velocity profile then affects the driver behavior in terms of the use of acceleration and brake pedals. For a hybrid vehicle the driver can control the pedals (similarly as in a conventional vehicle) but also specify a drive mode (Hybrid, Pure, Power, Save or AWD) as can be seen in Figure 2.7. Before a simulation is started initial and boundary conditions can be set. Examples are which fuel to be used, ambient temperature, initial battery SoC etc. The output from the simulations and vehicle measurements at the transmission department is a torque signal which is used to calculate the Duty value.

This thesis will foremost focus and discuss simulation assumptions and output from VSim simulations. It is however worth mentioning that another tool, CarMaker, is also used at the department. In this tool the engineer has more freedom when specifying driver behavior i.e. lateral and longitudinal accelerations etc. Throughout the thesis when "simulations" is mentioned, it is referring to the simulations made in VSim.

2.3.3 Duty value

As previously mentioned, when customers drive their vehicles, torque loads are applied on the transmission and can be measured. For the development of transmission components the number of rotations n_k at certain torque levels T_k are of interest. By performing rain flow analysis on the torque load signal this can be achieved.

These numbers can then be used to calculate the Duty value, which is a measure of accumulated load. At VCC the Duty value is used to find the synthetic customer used for requirement setting. Assuming a torque collective is divided into m number of classes k, then the total Duty value can be expressed as:

$$DV = \sum_{k=1}^{m} n_k \cdot T_k^{W_e} \tag{2.3}$$

The equation comes from combining Basquin's equation for a straight S-N curve $S = S_f \cdot (2N)^b$ in a log-log diagram with the Miner-Palmgren equation $\sum n_k/N_k = constant$. This holds for the assumption of a linear relationship between the applied torque and the resulting component stress. W_e is the so called Wöhler exponent which is related to the slope of the S-N curve and thus relating the load (stress), S, to the number of cycles to failure, N. Here S_f and $b = -1/W_e$ are material parameters

2.3.4 90^{th} percentile customer

At VCC the 90^{th} percentile is frequently used for dimensioning of components or systems. A percentile is calculated by organizing a dataset from lowest to highest. The lower quartile is then represented by the 25^{th} percentile, the median by the 50^{th} percentile etc. The 90^{th} percentile is then obtained as the value for which 90% of the data points are smaller (see Figure 2.8).

For the requirement setting procedure used at the transmission department the Duty value (variable of interest) is calculated for all the 2000 customers. From the resulting distribution (customers on x-axis and Duty value on y-axis) the 90^{th} percentile customer is selected. The load collective for this specific customer is the requirement given to the suppliers.

2.3.5 Additional assumptions for hybrid vehicles

The same procedure as previously explained is used for the simulation of hybrid vehicles with some additional assumptions about how the hybrid specific functions, such as drive modes and

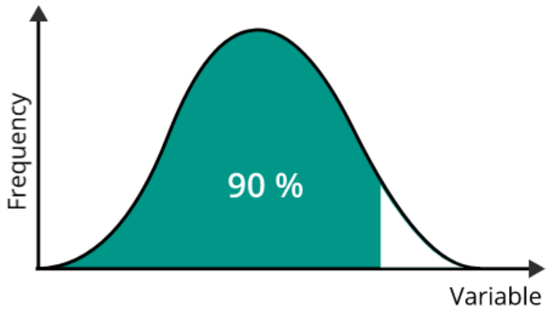

Figure 2.8: 90^{th} percentile

Sustain/Depletion modes are used (see Table 2.1). It is assumed that all customers drive 5 % of distance (distance-%) in Power mode and the rest 95 distance-% in Hybrid mode. For simulations these values are the same in % of time (time-%) since the velocities driven in Power mode and Hybrid mode are the same.

	Dist-% ICE off	Time-% Depletion	Dist-% Depletion	Time/Distance-% Power mode	Time/Distance-% Hybrid mode
Minimum	23	14	13	5	95
Average	40	22	21	5	95
90^{th} percentile	49	31	27	5	95
Maximum	50	36	30	5	95

Table 2.1: Minimum, maximum, average and 90^{th} percentile simulation assumptions

The distribution of Sustain and Depletion for both Power and Hybrid mode is assumed to be dependent on the environment (city, rural etc.) which is detailed in Appendix 1 in Figure **??**. The synthetic population (2000 customers) have an average of 21 distance-% (22 time-%) Depletion drive which corresponds to an average of 79 distance-% (78 time-%) Sustain drive. The maximum customer drive 36 time-% in Depletion and the minimum 14 time-%. The time percentage is converted from distance-% with the mean vehicle speed each drive cycle (city, rural, mountain etc.) is driven with. The initial SoC-values for a Sustain simulation is 20 SoC-% and for a Depletion simulation 100 SoC-%. These levels change during the simulations dependent on different factors i.e engine braking with the electric machine increasing SoC and propulsion with the electric machine decreases SoC. With the assumptions mentioned above the simulations result in: the customer with the maximum share electric drive does it 50 distance-% and the minimum 23 distance-% (average = 40 distance-%, 90^{th} percentile = 49 distance-%).

3
Methods

This section describes the methods used in the project. The project was initiated by exploring the DRO data available for XC90 T8 PHEV. The results from this phase were then used to extract the data of interest, which was the foundation for building the data analyzing tool in Python. The tool was used to obtain statistics describing real world customer usage of the XC90 T8 PHEV.

3.1 Data Investigation

In order to find Logdata of interest to assess real world customer usage of the XC90 T8 PHEV, data in different ECUs was considered. The specific ECUs were Transmission Control Module (TCM), Engine Control Module (ECM), Battery Energy Control Module (BECM), On-board Charger (OBC) and Inverter Erad Module (IEM). The Logdata used in this thesis is triggered when "Drive Cycle Active". This means that data is logged even though the ICE might be off or the car stands still, i.e when stopping at a red light.

3.2 Data Extraction

The DRO data uploaded from the repair shop is stored in a database from where it can be accessed. For the purpose of this project the data was extracted with following queries (detailed information in Appendix 1).

- **Readout-time:** 1st of June 2015 until 4th of September 2017
- **Mileage:** The total vehicle mileage had to be greater than 1000 km
- **Vehicle Type:** XC90 T8 PHEV (SPA platform)
- **Locations:** World-wide (see Figure 3.1)
- **Logdata:** Vehicle speed (ICE off and ICE on), distance (ICE on, ICE off and ICE idle), time in drive modes, time in Sustain/Depletion and time in Brake mode - explained further in section 3.3.3

The query can be updated for future data extractions. The data sheet was downloaded in Excel format.

3.3 Data Analysis Tool with GUI

In order to provide for the possibility of updating the statistics for a greater number of vehicles a Data analysis tool in Python was developed. The graphical user interface, which was created with the Tkinter toolbox, can be seen in Figure 3.2. The user is provided with the options to import a data file, filter the data, select analysis and percentile, plot and export the results (average and percentile customer).

3.3.1 Step 1: Import file

The user will start by importing an Excel file with Logdata extracted from the database. Initial filtering is performed in the backend to remove overlapping vehicles. The reason for the duplicated

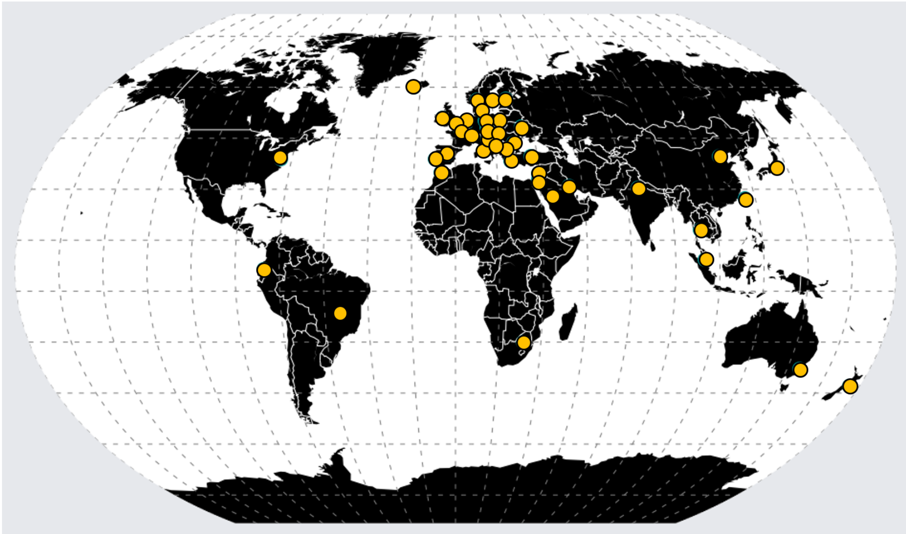

Figure 3.1: Data is logged in vehicles all around the world (markers placed in capital location of country

data is that data is saved every time a vehicle is brought in to service, without reset. The initial filtering of the data guarantees that only the most recent data is being used for the analysis.

3.3.2 Step 2: Filter data

The user is provided with an option to apply additional filters. This gives the user the opportunity to look at i.e certain countries, a specific model year etc.

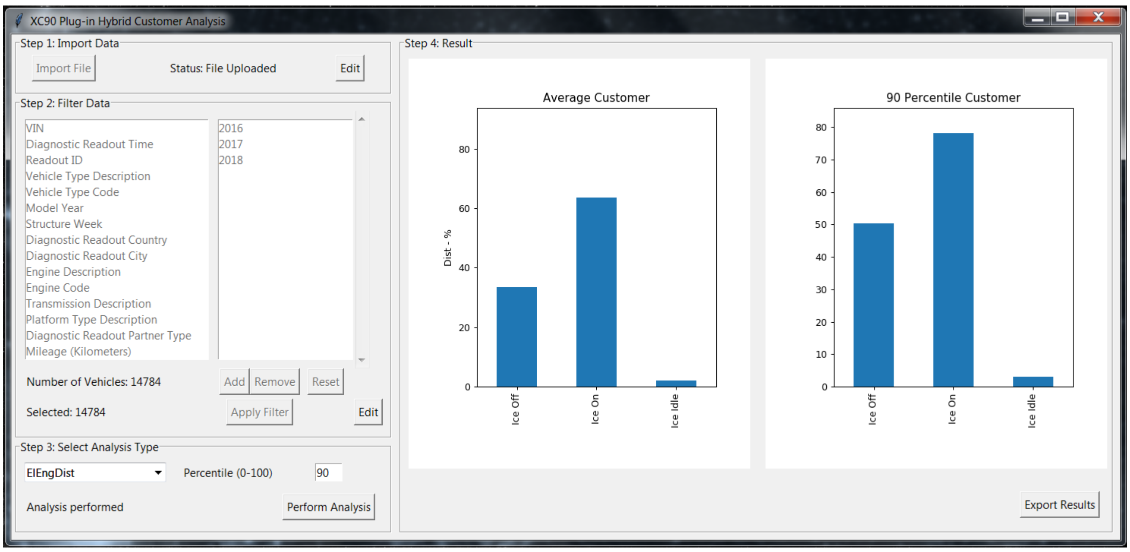

Figure 3.2: Graphical User Interface

3.3.3 Step 3: Select analysis type

Seven different analysis types have been created. All require data relevant for the specific analysis and a percentile number as input and will return statistics for the average and percentile customer.

The data obtained from the database was for all analysis types accumulated time or distance in separate bins i.e Sustain/Depletion or different vehicle speed intervals. The time-% or distance-% was calculated by dividing the data in each bin with the total time or total distance, obtained by summing the data for all bins. For all analyses, vehicles with missing data (NaN) will be excluded. Specific filtering for each type will be explained further down in this section.

The available analysis types are:

- SusDep (Time-% in Sustain or Depletion mode)
- HModes2016 (Time-% in the different drive modes) - only valid for model year 2016
- ElEngDist (Distance-% for ICE on, ICE off or ICE idle)
- ElEngTime (Time-% for ICE on, ICE off and stand-still for ICE on and ICE off separately (based on Vehicle Speed data for ICE on and ICE off)
- BatSoc (Time-% in different SoC intervals)
- BrakeMode (Time-% with Brake mode selected)
- VehSpeeds(el) (Time-% in different vehicle speeds (ICE on and ICE off separately))

For *SusDep* and *HModes2016* the data obtained from the database was the accumulated time for each mode and the percentage could easily be calculated as described above. For *BrakeMode* the process was similar, but to be able to calculate the time-% the total time was obtained from summing the time in Sustain and Depletion. *BatSoC* was also obtained in the same way, but with the difference that the data from database on HEX format and therefore had to be converted to decimal before the percentage could be calculated. If time was found in the first (<=15) and last (95 <) SoC bins those vehicles were excluded since responsible person for BECM meant that this was often a sign of faults in the data logging.

For *ElEngDist* the accumulated distance was logged, as well as the total distance. To check the logging accuracy the logged total distance was compared with the vehicle mileage. Vehicles were excluded if they did not have a quote (TotalDistance/Mileage) between 0.99 and 1.01.

The remaining two analysis types *ElEngTime* and *VehSpeeds(el)* both uses the same data from the database. In order to obtain the percentage time the customers drive with ICE on or ICE off (assumed electric drive) data for vehicle speeds was used. The accumulated time driven in different vehicle speed intervals (0-0.5, 0.5-5, 5-30, 30-40, 40-80, 80-120, 120-160, 160, 190, > 190 km/h) are logged when drive cycle is active and engine speed is < 500rpm. The rest of the time when drive cycle is active and engine speed > 500rpm (time driven with ICE on) is saved in another category. The time driven with ICE off was obtained by summing the time logged in the different vehicle speeds. The stand still time for ICE off was obtained from the first vehicle speed interval (0-0.5 km/h). To obtain the stand still time for ICE on the vehicle speeds for ICE on logged in TCM was used and the first column represented stand still time (< 1 km/h). The interval sizes are not exactly equal but the errors that might occur were assumed to be negligible. To make sure the logging in TCM and ECM were made in a similar manner a check similar to the one for ELEngDist was performed but here with a quote between the total times obtained by summing vehicle speeds when ICE off and vehicle speeds for ICE on.

For the *VehSpeeds(el)* analysis the vehicle speeds for ICE off were used and the first category (stand still) was excluded. To able to compare these intervals with the vehicle speeds for ICE off (logged in TCM) new intervals were created with 5 km/h difference. This resulted in 39 new intervals with the lowest bin as 0.5-5 km/h and the highest > 190 km/h.

3.3.3.1 How average and 90th percentile values were calculated

The average and percentile values were calculated for the log variable of interest (distance-% ICE off, time-% Sustain etc.) in the same way for all analysis types. The method will be explained with the example of time-% in Depletion and Sustain mode. Figure 3.3 presents this procedure. For each variable (time-% Sustain respectively time-% Depletion) there are n data points, where each data point corresponds to one customer (as seen in the table on the left side). If all data points are plotted in a histogram (middle of the figure) a distribution is obtained where the x-axis represents the time-% and the y-axis the frequency. Note that the 90^{th} percentile is marked in the histograms with a black vertical line. The average and percentile value is calculated for each variable and are then combined in one bar chart for Depletion and one for Sustain (graphs on the right side in the figure). The average is defined as (where x could either be s or d here):

$$x_{avg} = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{3.1}$$

For the special case of variables summing up to 100% as is the case for Sustain and Depletion i.e. $s_i + d_i = 100\%$, the plot for the average customer will sum up to 100% ($s_{avg} + d_{avg} = 100\%$). This is not the case for the percentile customer. The reason for this is that time-% Sustain and time-% Depletion for one customer are complementary (sums up to 100%). This connection is, however, lost when the 90^{th} percentile is calculated for each variable, since they will not belong to the same customer.

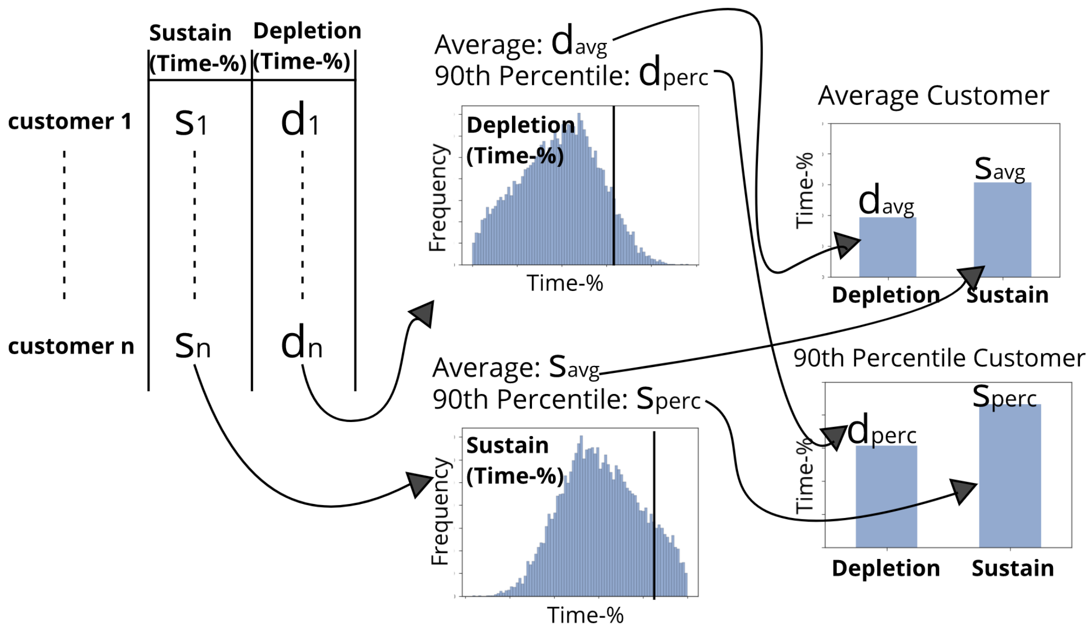

Figure 3.3: Example calculation of average and 90^{th} percentile values for time-% in Sustain and Depletion

3.3.4 Step 4: Display and export result

The result consist of two bar charts displaying the behavior of the average and the percentile customer. The result of the analysis together with filter specifications can be exported to Excel.

3.4 Statistical Analysis

To study the XC90 T8 PHEV customer usage statistics (average and 90 percentile customers) were extracted for a world wide population as well as for selected markets. Different markets were investigated to get an understanding of whether or not environmental factors affect the customer usage. The markets were selected based on the amount of available data as well as their characteristics both environmentally and socially.

The Netherlands (NL) was selected as an example because of their relatively small land area with a dense population and good infrastructure, as well as their near proximity to Germany. Germany (DE) has the autobahn - high speed highways without speed limits. China (CN) has a dense population and a varying infrastructure. Finally, Sweden (S) is sparsely populated with good infrastructure for driving. The US was excluded since the number of vehicles was only three. The number of vehicles included in the analysis (before specific filtering for each analysis) for the countries and the number of vehicles (n) were: Netherlands (n=4585), Germany (n=515), China (n=128) and Sweden (n=846).

For the hybrid-specific functionality having a connection to the simulation assumptions mentioned in section 2.3.5 the full customer distributions were also graphed. The reason was to understand the variation of driver behavior among the population. For the vehicle speed analysis the total vehicle speeds from TCM were also included in the graph for comparison purposes.

4
Results and Discussion

This section presents and discusses the results. To begin with, available Logdata is presented. Thereafter statistics for the customer usage of hybrid-specific functionality such as electric drive, drive modes, Sustain and Depletion, battery SoC, Brake mode and electric vehicle speeds are presented.

The reader should be aware of that the diagrams displaying the percentile customer will not sum up to 100%. This is because each bar represents the 90^{th} percentile value for specific log variable (time-% Sustain, time-% ICE off etc.). This is also how the average values are calculated, but if each log variable sums up to 100% the average values will also sum up to 100%. Therefore, the diagrams can be seen to present information for more than one customer. See section 3.3.3.1 for a detailed explanation of how the average and percentile values were calculated. The reason for displaying the results in this way is to limit the number of figures which would add up fast if each log variable would have had its own graph.

Furthermore, the results for drive modes, electric drive and Sustain/Depletion are compared to current simulation (VSim) assumptions. The section ends with a discussion of how the results can possibly influence the requirement setting procedure used at the department today and in the future.

4.1 Available Logdata in Different Control Units

The control units explored in this thesis (TCM, ECM, BECM, IEM and OBC) contain a lot of Logdata. A selection of this is displayed in Figure 4.1. Unfortunately not all of the Logdata could be investigated due to the time frame of this project. The selection was based on wheter or not the Logdata was validated and approved by responsible department. Furthermore data that could be used to validate current simulation assumptions (presented in section 2.3.5) was prioritized. Based on these selection criteria the data used was from ECM, TCM and BECM.

4.1.1 Accessibility of Logdata specifications and validity

The Logdata in the different modules are specified by responsible departments (i.e Transmission department is responsible for TCM, engine department for ECM etc.). This means that information about the data (what is actually logged) and its validity had to be obtained from the responsible person at the different departments. If this information could be accessed at one time and place it would probably have been more efficient.

The separation of the DRO responsibility between departments also means that data from other control units might be logged in a way that can not be directly used by other departments. One example is the vehicle speeds that are logged differently in ECM and TCM. To combine Logdata from different units requires some extra work.

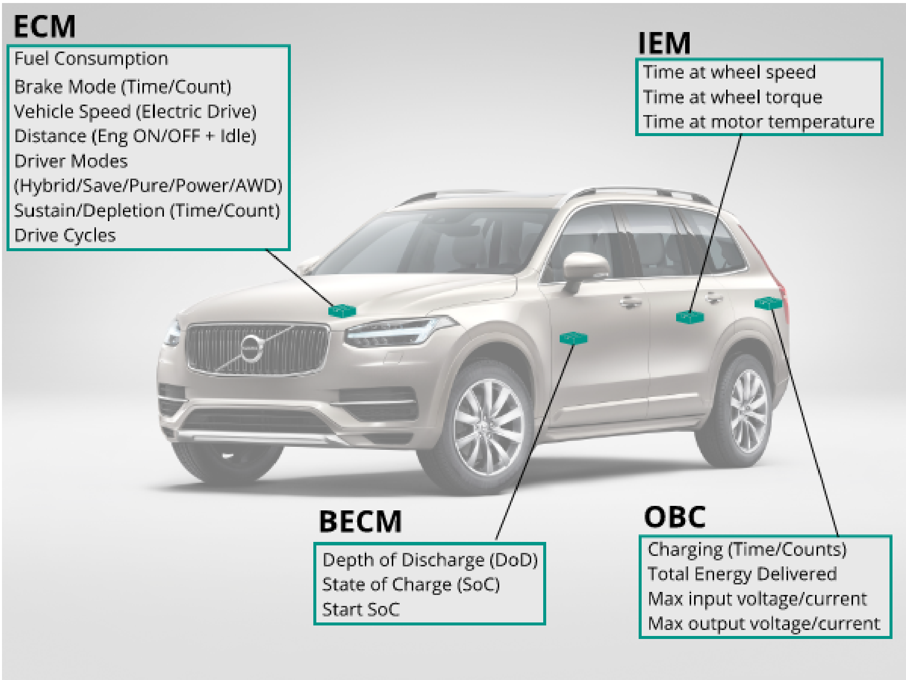

Figure 4.1: Examples of Logdata stored in control units in the vehicle

4.2 Engine vs Electric Drive

How often the customers drive electric (propelled by electric machine only) can be explained with DRO both in terms of time-% (n=4271) or distance-% (n=9302). Depending on which measurement unit that is used different information can be accessed. For both cases (time-% and distance-%) the category **ICE off** is assumed to represent electric drive. **ICE on** on the other hand can include both driving with ICE on or a combination of ICE and electric machine. These results are interesting for the dimensioning of e.g. the gearbox. Since the automatic gearbox is connected to the ICE it is only loaded when the ICE is running. Some parts in the gearbox will rotate during electric drive, but this does not have an effect on the Duty value. In order to prevent overdimensioning these results should be taken into account. Incorrect assumptions about the amount of electric drive could be one of the reasons for the uncertainties in requirement settings for the different gears, as was presented in section 1 in (Figure 1.2). The figure demonstrated that the load on gear 1 and 2 was significantly lower than for conventional vehicles. The reason is likely that the electric drive foremost is concentrated to the lower gears and lower speeds. The requirements, however, underdimensioned gear 1 and overdimensioned gear 2. To get a better understanding of how the electric drive is distributed over the different gears it would be interesting to look at data where the amount of electric drive is logged for each gear. This type of data could not be found in DRO.

4.2.1 Time-based

In Figure 4.2 the time-% ICE on, ICE off and stand-still for ICE off and ICE on respectively is presented. The average customer drives approx 44 time-% electric and 39 time-% with ICE on or combined ICE and electric machine. The (ICE off) 90^{th} percentile customer drives 58 time-% electric whereas the corresponding (not the same) ICE on customer spends approx 54 time-% with ICE on. This result also shows that the average customer stand still with ICE off 12 time-% and with ICE on 4 time-%. Since most time-based Logdata from DRO which is logged when "Drive Cycle On" includes times when the vehicles is standing still it is sufficient to have knowledge about the amount. The different markets seem to behave similarly. China stands out a little with a longer standing still time, and less driving time in general. This seems possible due to the dense traffic situation.

4.2.2 Distance-based

In Figure 4.3 the distance-% ICE off, ICE on and ICE idle is presented. Comparing this result with the one presented in figure 4.2 it can be observed that for the time-based result the average customer spent a similar amount of time-% with ICE on and ICE off, but a greater distance-% for ICE on and a less distance-% for ICE off. This indicates that a greater distance is covered when driving with ICE on than electric (ICE off). The average customer drives approx 33 distance-% electric (ICE off) and 64 distance-% with ICE on or combined ICE and electric machine. The (ICE off) 90^{th} percentile customer drives 50 distance-% electric whereas the corresponding (not the same) ICE on customer spends approx 78 time-% with ICE on. Sweden and China drive slightly longer electric than Germany and the Netherlands. In China the reason might be that the speeds are in general slower and with a smaller speed range. The opposite holds for Germany.

This result can be compared to the simulations (VSim) which assumes that the synthetic average customer drives 40 distance-% electric and the 90^{th} percentile 49 distance-%. Present requirement setting procedure seems to slightly overestimate the distance-% electric drive for the average customer.

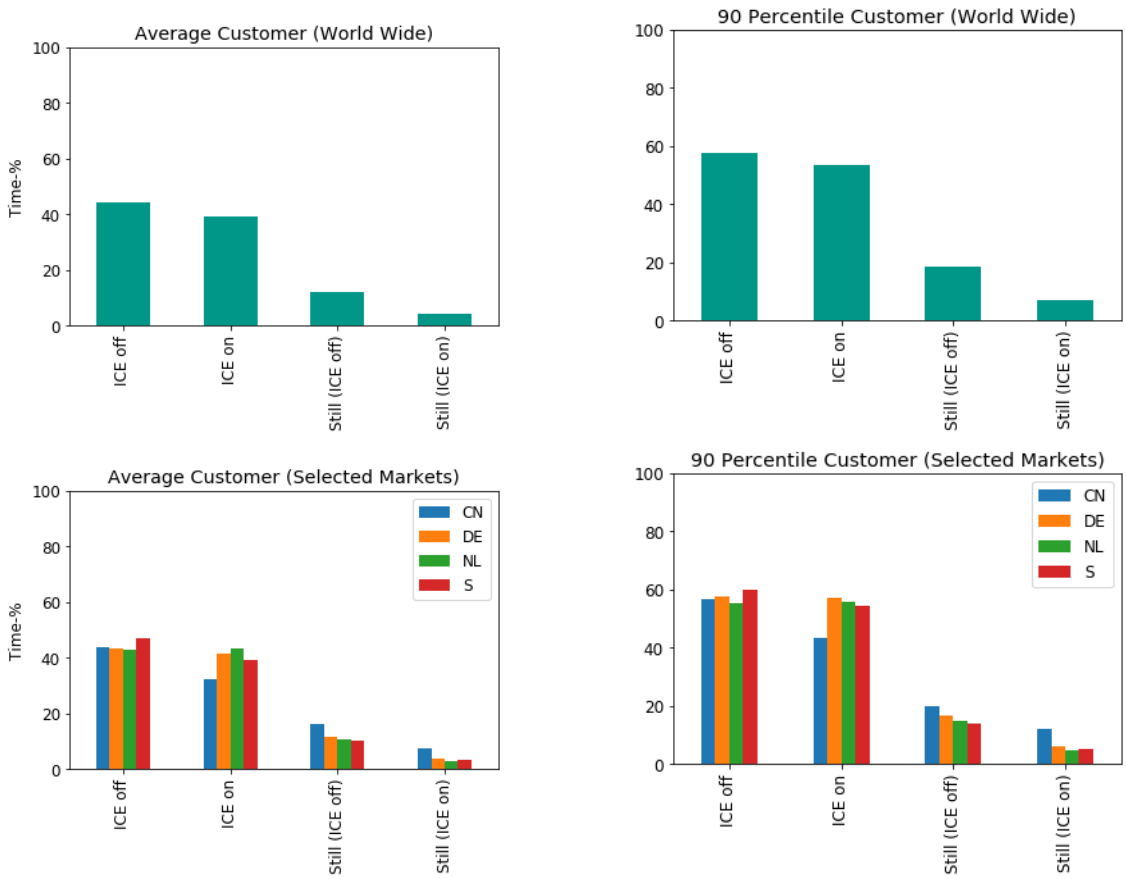

Figure 4.2: Time share driven Electric (ICE off) or with ICE on for average and 90^{th} percentile customers - world wide and for China, Germany, Netherlands and Sweden.

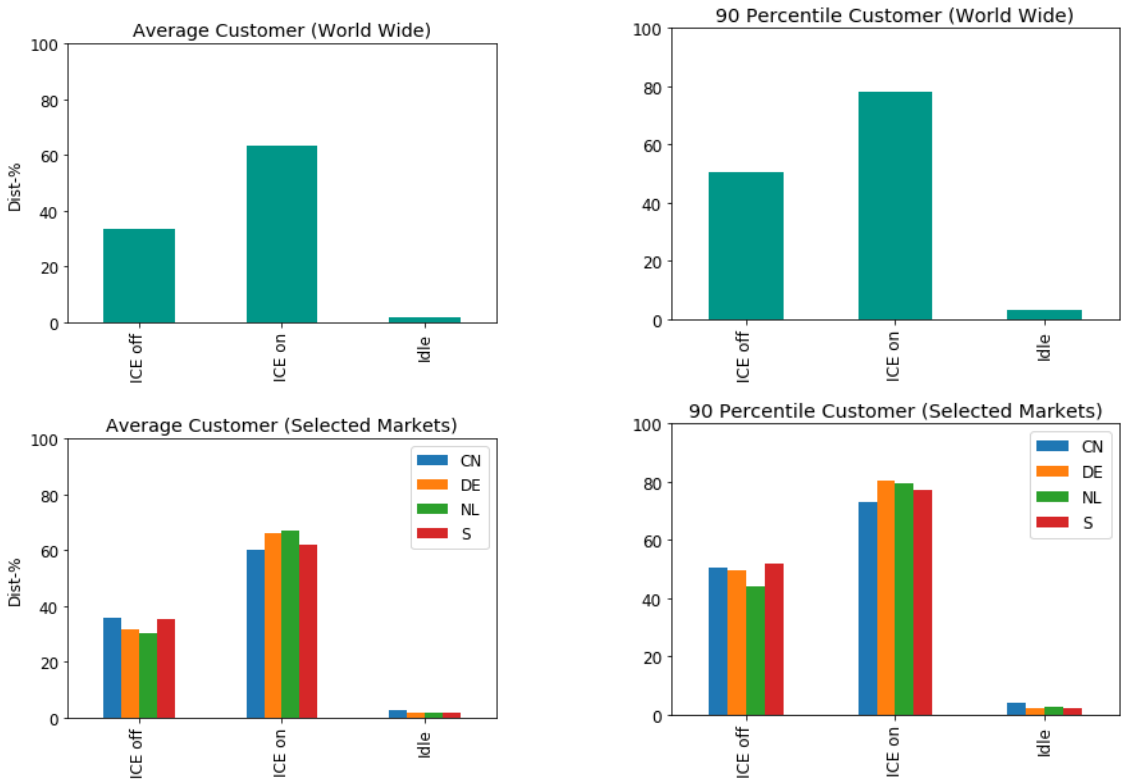

Figure 4.3: Distance-% driven Electric (ICE off) or with ICE on for average and 90^{th} percentile customers - world wide and for China, Germany, Netherlands and Sweden.

4.3 Depletion and Sustain Drive

The total amount of vehicles included in this analysis was 12631. Figure 4.4 presents the time-% driven in Sustain and Depletion for the average and the 90^{th} percentile customer. The average customer drives 39 time-% in Depletion mode and 61 time-% in Sustain mode. The 90^{th} percentile Depletion customer drives 61 time-% in Depletion (means 39 time-% in Sustain) whereas the corresponding (not the same) Sustain customer spends 86 time-% in Sustain (means 14 time-% in Depletion). This result shows that the customers drive a longer time with energy from the ICE (Sustain mode) instead of using energy from the battery (Depletion). China stands out among the other countries with the least amount of time in Depletion.

This result can be compared to the simulations assuming that the synthetic average customer drives 22 time-% in Depletion and the 90^{th} percentile 31 time-%. Present requirement setting procedure seems to underestimate the time-% Depletion drive for the average customer. One explanation to the difference could be that the conversion between distance-% to time-% for the simulations assumed the same mean velocity for Depletion drive and Sustain drive. This might be insufficient since electric drive and Depletion might occur more frequently at lower speeds and Sustain at higher speeds. This would have increased the time-% Depletion for the simulations and would then approach the results based on DRO data. To get a better understanding of this result it could help to log accumulated distance with Sustain and Depletion instead of time.

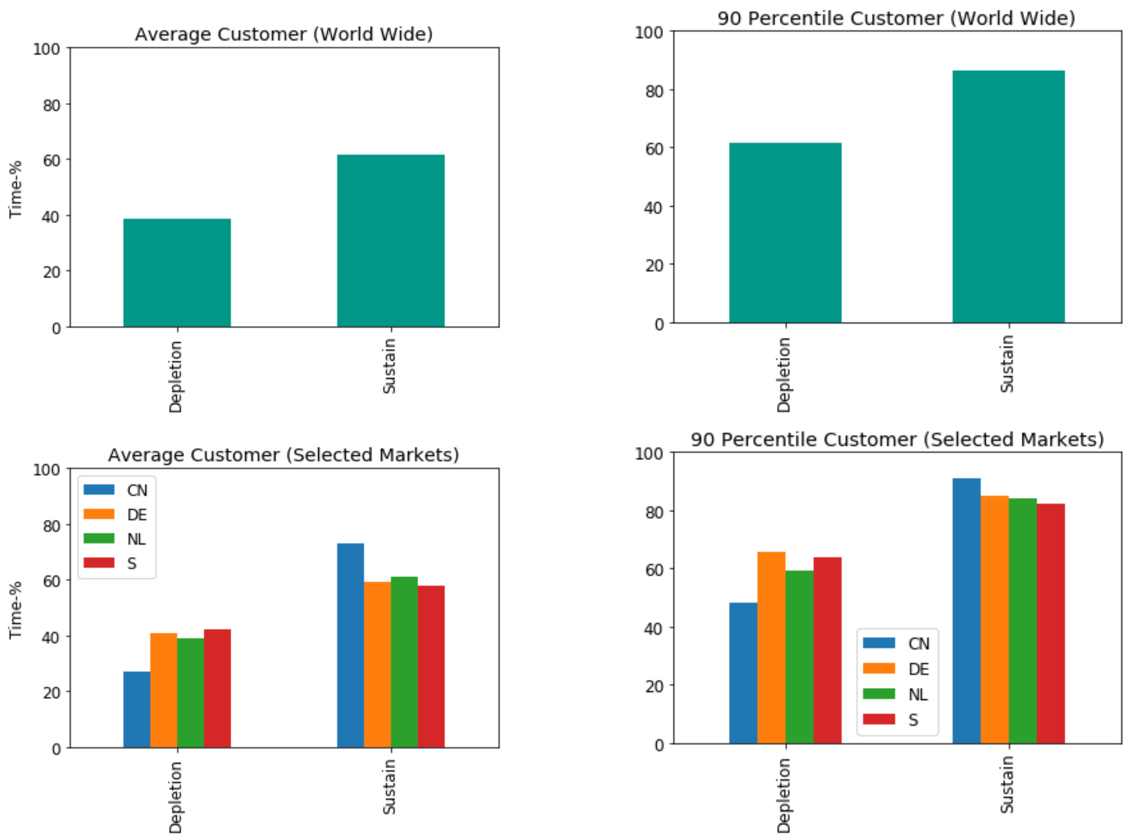

Figure 4.4: Time-% driven in Sustain and Depletion mode for average and 90^{th} percentile customers - world wide and for China, Germany, Netherlands and Sweden.

4.4 Drive Modes

The time-% spent in different drive modes for average and percentile customers is presented in Figure 4.5. Due to the change in functionality (see 2.2.3.3) this result is divided into vehicles of model year 2016 (top graphs) and vehicles of model year 2017-2018 (bottom graphs). For model year 2016 and 2017-2018, 6633 respectively 5962 vehicles were included in the analyses.

4.4.1 Model year 2016

The customers drive most frequently in the Hybrid mode (average customer 81 time-% and 90^{th} percentile 98 time-%). This result seems possible since this mode is by default selected when the car is started. Some customers might never find the other modes or they might try them just a few times and then forget about them. The next most frequent mode is Pure (average customer 8 time-% and 90^{th} percentile customer 25 time-%). This also seems likely, since some customers might have bought a hybrid vehicle with the purpose of driving electric most of the time. The Power mode, which is of interest for the Transmission department, due to possible higher component and system loads, is used 4% of time by the average customer and 11% of the time for the 90^{th} percentile customer. The two remaining modes, save and AWD, are used 4 time-% and 2 time-% by the average customer and 13 time-% respectively 4 time-% for the percentile customer.

4.4.2 Model year 2017-2018

The Save mode was removed in the vehicles from model year 2017. This explains why the data shows zero usage of the Save mode in the graphs. The removal of the functionality only seems to have affected the time-% spent in Hybrid mode (average 85 time-% and 90^{th} percentile 99 time-%) and AWD mode (average 3 time-% and 90^{th} percentile 6 time-%). The time spent in Pure and Power remained the same.

These results can be compared with the simulation assumptions that all customers drive 5 time-% in Power mode and the rest 95 time-% in Hybrid mode. That the Power mode is used 5% of the time seems to be a good assumption, since the average customer uses it 4-time% both before and after the change of functionality. The other simulation assumption that the Hybrid mode is used 95 time-% for all customers is an overestimation for all model years. Some of the current time-% in Hybrid mode should probably be considered as driven purely electric in Pure mode. This, however, would possibly increase the distance driven with ICE off which is already overestimated.

Germany utilizes the Hybrid mode a little less than other markets and consequently most frequently uses the other modes. China on the other hand shows the least motivation in utilizing the other drive modes and mostly sticks to the default mode.

4.4.3 Updated functionality

To keep in mind is that there is one new drive mode, Off Road, present from model year 2017. This mode is not included in the graphs since relevant Logdata was not available. This means that the graphs for 2017-2018 are displaying percentage time with respect to a total time based on Power, Pure, Hybrid and AWD mode, but not Off Road. The reason for this is that the DRO log function has not yet been validated. Once validated, this mode should be taken into account to obtain actual time-%. This will probably not affect the result particularly, since Off Road can only be used at low speeds. Logdata describing the usage of the two new buttons, Charge and Hold, which replaced the Save mode could also not be found. This knowledge is of importance if it is interesting to know what in the customer's behavior that is affecting the amount of Sustain and Depletion drive.

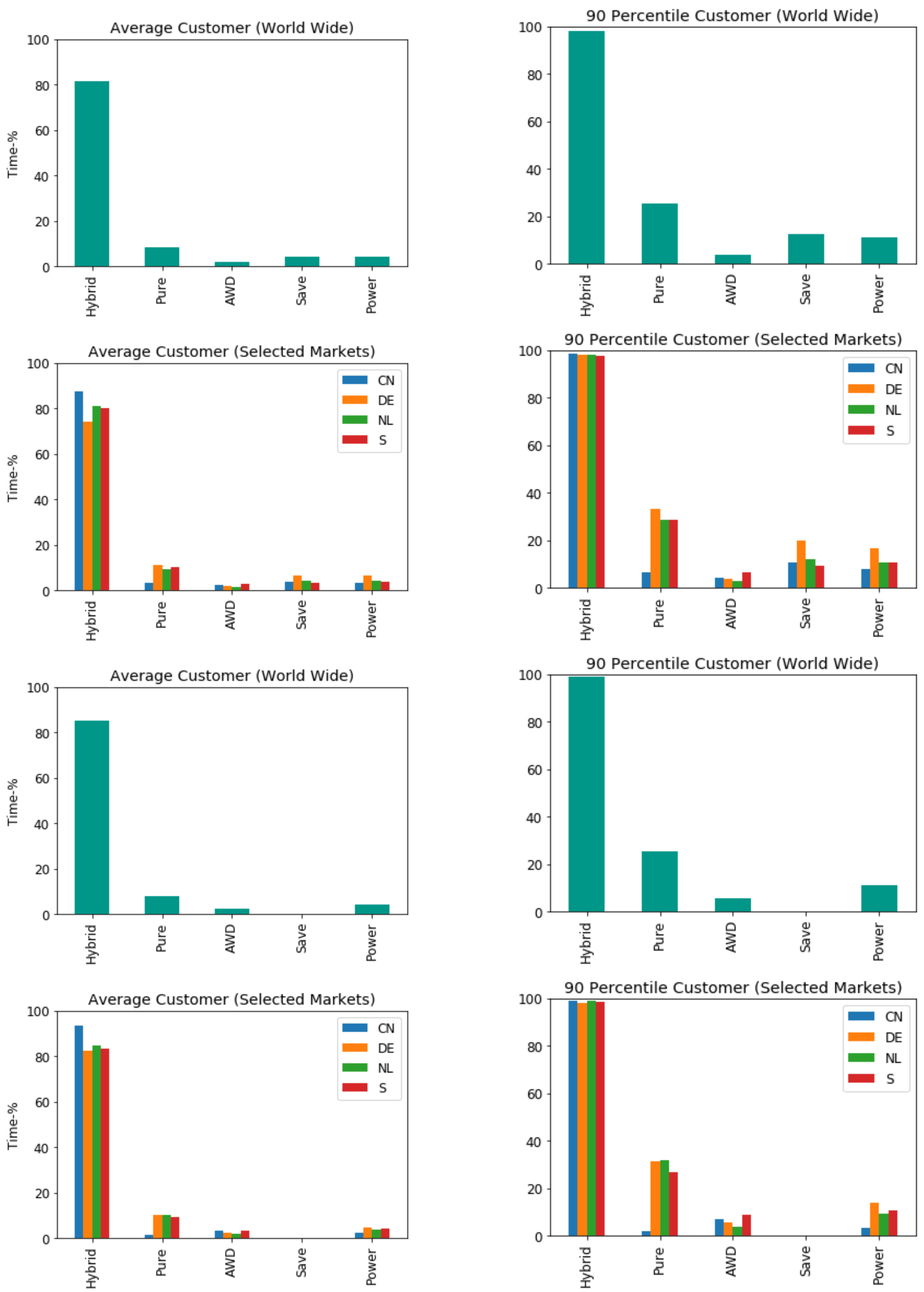

Figure 4.5: Time share driven in different drive modes for average and 90^{th} percentile customers - Top graphs are for model year 2016 and bottom graphs for model year 2017-2018

4.5 Distributions for ICE off/ICE on, Sustain and Depletion and Drive Modes

The results presented in previous sections (4.2, 4.3 and 4.4) provide information about the behavior of the average and 90^{th} percentile customer. Average and percentile values is sometimes not enough to get the full understanding of how behavior is distributed among a population. To get this full understanding, distributions is sufficient. The distributions of the customer behavior for the hybrid-specific functions interesting for current simulation assumptions can be seen in Figure 4.6. The two top graphs show the distance-% in ICE off together with ICE on and the time-% Depletion drive together with Sustain drive. In the bottom graphs the time-% in Hybrid mode and Power mode are graphed separately.

In general current requirement setting procedure is based on a narrow range of customer behavior (presented in section 2.3.5). For example the 2000 customers in the synthetic population are ranged between 21 and 37 time-% Depletion drive and 23 to 50 distance-% ICE off drive. For the drive modes no variation is assumed. Both the maximum and minimum customer drives 95 time-% in Hybrid and 5 time-% in Power mode. The range of real customer behavior, on the other hand, is a lot larger.

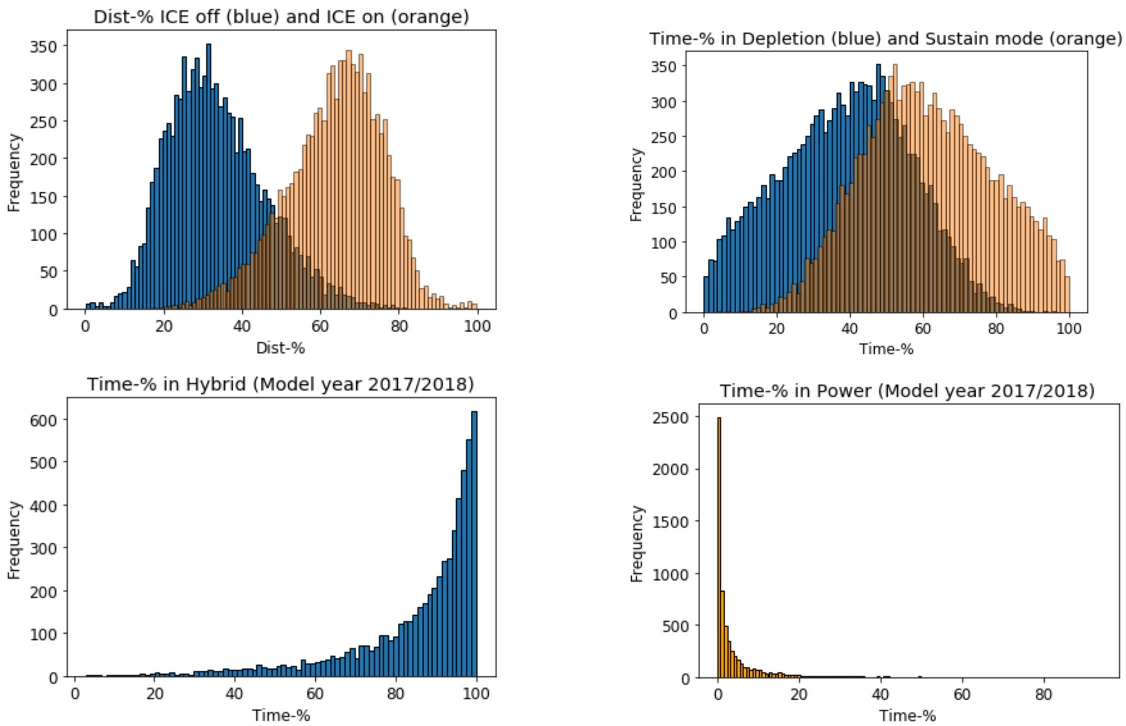

Figure 4.6: Distributions for distance-% ICE off and ICE on, time-% Sustain and Depletion and time-% for Hybrid and Power mode

4.6 Battery State of Charge

Figure 4.7 presents the time-% customers drive in different hybrid battery SoC intervals. Accumulated distance was not logged and distance-% could therefore not be obtained from the database. In total there were 10 175 vehicles included in the analysis. The average customer drives with a state of charge from the two lower intervals (15% < SoC < 35%) 56 time-% and thus 44 time-% is driven with a greater SoC. The PHEV can charge the battery with the help of ICE to a level of 33 SoC-%. This result shows that a minimum of 44% of the time the average customer drives with energy obtained from a plug-in source.

The average customer drives a fairly constant amount of time with SoC above the 15-25% interval. This result can be interpreted in different ways. For a customer that charges the battery from a plug-in source frequently this result could indicate that the capacity of today's batteries are less than what is needed to provide for the customer's full energy needs. The result could however also indicate that there are a lot of customers that do not plug-in their vehicles which then increases the amount of time in the lowest SoC-interval. To gain a better understanding of if the customers uses the plug-in cable, Logdata from OBC is recommended. In OBC the number of times the charger is connected, the amount of energy delivered as well as the total charging time can be obtained. One additional note, before ending this section, is that the SoC-window for a XC90 T8 PHEV is between 15 SoC-% and 90 SoC-%. Therefore, to start the Depletion simulations with a SoC-% of 100 might be an error source.

Figure 4.7: Time-% driven with different SoC-values for average and 90^{th} percentile customers - world wide and for China, Germany, Netherlands and Sweden.

4.7 Electric Vehicle Speeds

For this analysis 4284 vehicles were included. The time-% the average customer drives in vehicle speeds when ICE is off and when ICE is on is presented in Figure 4.8. The vehicle profile is decreasing for electric drive (ICE off) with the maximum time-% at the lowest speed interval (0.5-5 km/h). For drives with ICE on most time is spent with velocities between 30 and 40 km/h.

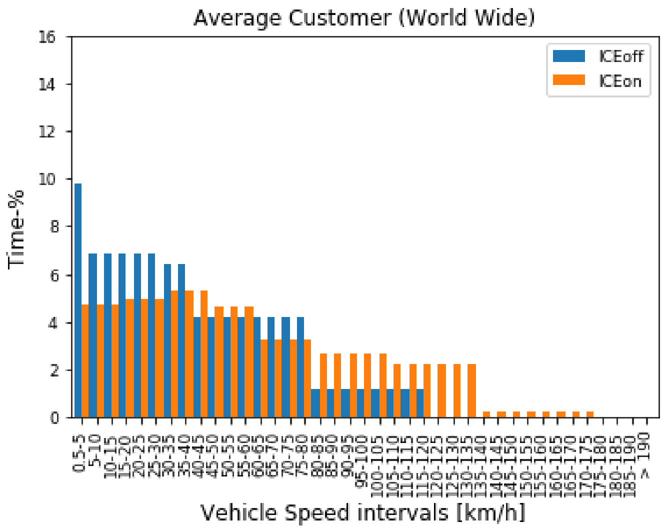

Figure 4.8: Time-% in different vehicle speed intervals for the average customer

For the 90^{th} percentile customer the velocity profiles look similar as for the average customer, as observed in Figure 4.9. If this result would have been distance resolved it could be directly comparable to the vehicle speed profiles used in the requirement setting procedure today.

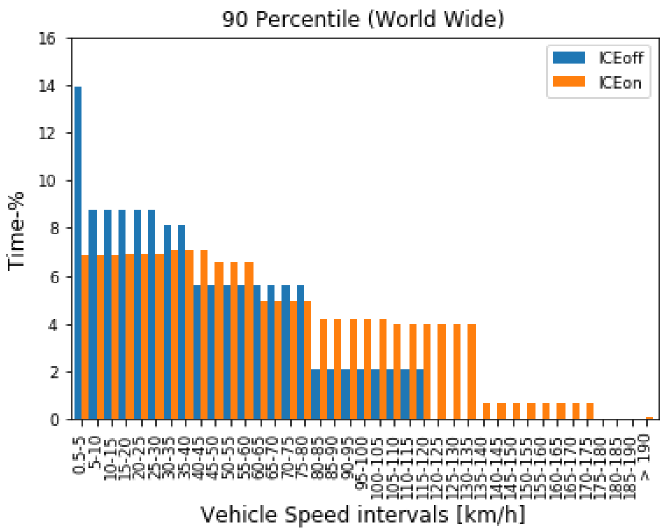

Figure 4.9: Time-% in different vehicle speed intervals for the 90^{th} percentile customer

4.8 Brake Mode

In this analysis 12 482 vehicles were included. Figure 4.10 presents the time-% customers utilize the Brake mode. The more the Brake mode is used the more frequent the electric machine is used as a generator charging the battery. The average customer drives with the Brake mode (gear position selected) 12 time-% and the 90^{th} percentile customer 43 time-%. It seems that a similar trend can be seen here as for the utilization of the different drive modes - far from everyone is utilizing the PHEV functionality.

By observing the different markets it can be seen that the Brake mode seems to be used more frequent in Sweden and Germany. The reason could be that these countries are better informed about the existence of the functionality or that people in general are more motivated to utilize the PHEV functionality. A similar result was seen for the Hybrid mode utilization (which is default) where China and the Netherlands used that mode a little more frequently than Sweden and Germany.

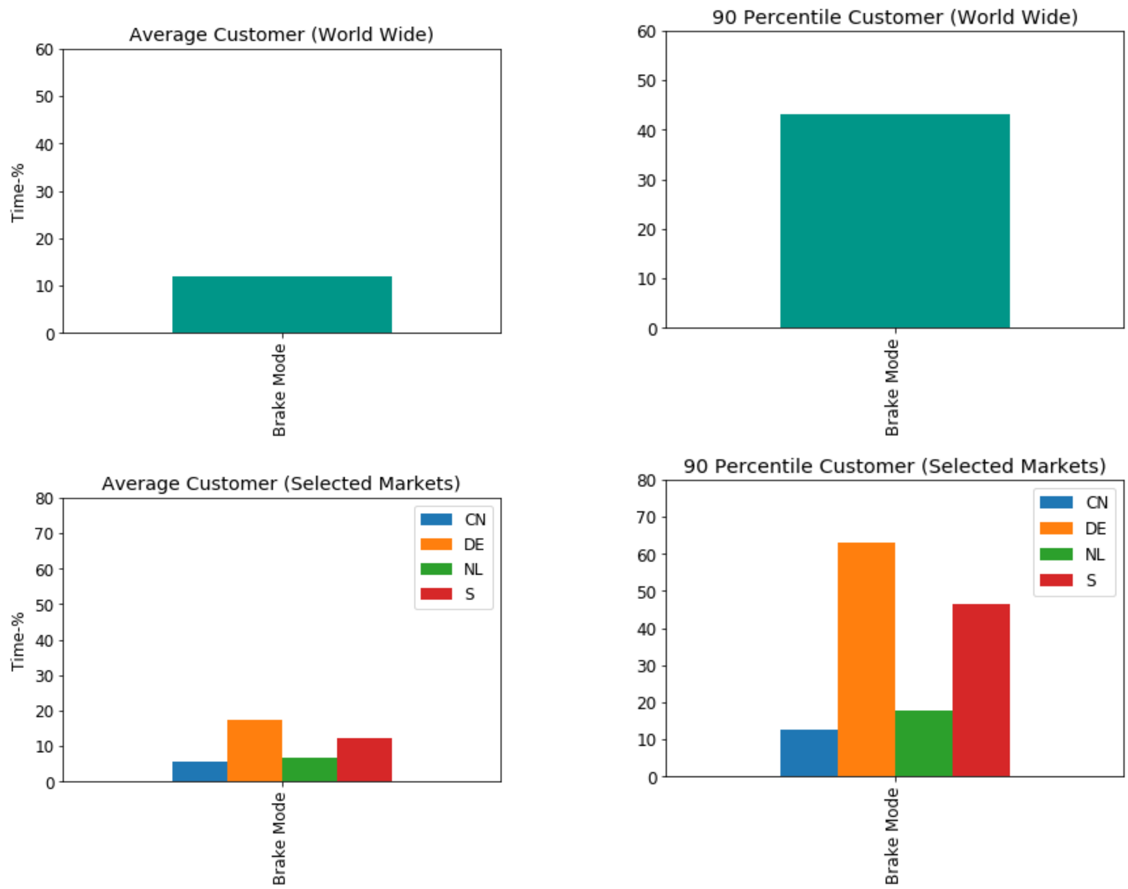

Figure 4.10: Time-% use of Brake mode for average and 90^{th} percentile customers - world wide and for China, Germany, Netherlands and Sweden.

4.9 Potential Influence on Requirement Setting Procedure

The Transmission department aims at having a requirement setting procedure, based on simulations and vehicle measurements, that correlates with real customer usage. DRO data can be used in different ways to check how well this is achieved.

The results from this thesis can be divided into two groups. Both groups present real world usage for an average and 90^{th} percentile customer. The first group consists of results regarding Sustain and Depletion, drive modes and electric drive. These could influence the requirement setting procedure by the behavior of the synthetic customer population used to create load collectives and calculate Duty values. The average and percentile values can be used to validate current synthetic customer population based on assumptions. If average and percentile values are not enough to create a synthetic population that behaves in similar manner as the real population, distributions might be needed. This in order to understand the variation of the behavior among the population.

The other group consist of results regarding Battery SoC, Brake mode and Vehicle speeds for ICE off. These results could be used to answer possible future questions about how often the Brake mode is used, if the mean vehicle speed is different when customers drive electric than with ICE on and which SoC-values that are most frequently used? In addition future simulations might need a better understanding of how often the customers plug in their vehicles. Could it be two different groups of customers - some that plug-in and some that do not which should be treated differently? Are there some extreme customers using the Brake mode a lot more, which would cause extra high loads on the electric machine? Even though it is impossible to predict all possible future questions, this work can hopefully fasten the answering of these questions. This, by providing insight into available Logdata and a methodology that can be used to extract data and calculate statistics. Finally, DRO data can also be used to compare different markets and indicate if VCC should consider different requirement setting for different markets.

5 Conclusions

Diagnostic non time-resolved readout data (DRO data) can be used to understand the world-wide real-world behavior of average and percentile customers as well as the population distribution. This thesis has come to conclusions regarding the real world usage of the XC90 T8 PHEV. It differs in some aspects from assumptions made in present requirement setting procedure. In addition, the conclusions regarding presently logged DRO data is presented.

5.1 Real-life Numbers from a SUV Plug-in Hybrid

The statistics for the XC90 T8 PHEV are as follows:

- The average customer drives 44 time-% and 33 distance-% electric (ICE off). This indicates that electric drive is more frequent at lower speeds. The customers drive a longer time, but not as far.
- The average customer drives most frequently (> 80 time-%) in Hybrid mode and the next most frequently in Pure mode (8 time-%).
- The average customer spend more time driving or standing still in Sustain mode (61 time-%) than in Depletion mode (39-time%). This indicates that energy is more frequently obtained from the ICE than from the battery alone.
- The average customer drives or stands still 56% of the time with a battery SoC below 35%. Consequently a minimum of 44 time-% is spent driving with energy from plug-in source.
- The brake mode is utilized 12 time-% by the average customer. This indicates that the functionality is used by some customers, but far from everybody.
- The vehicle speed profile is different when customers drive electric (ICE off) or ICE on.
- The different markets (China, Germany, Netherlands and Sweden) seemed to have a similar behavior when it comes to utilization of hybrid-specific functionality.

5.2 Simulation Assumptions

It is concluded that, the assumptions used in current requirement setting procedure (based on VSim data and for Duty value predictions) differs from the real world usage based on DRO data. Present requirement setting procedure:

- Predicts a greater distance-% electric (ICE off) drive for the synthetic average customer compared to the real average customer.
- Assumes a lower time-% in Depletion drive for the synthetic average customer compared to the real average customer.
- Assumes a greater time-% Hybrid mode usage and Power mode usage than the synthetic customer population.
- Does not take the Pure mode into consideration, even though the average real customer drives 8 time-% in that mode.
- Is based on a narrow range and does not include the extreme customers.
- Starts the depletion mode simulation with a SoC of 100%. Real batteries don't have an available SoC above 90%.

5.3 DRO Data

The following conclusions can be drawn from the presently logged DRO data:

- In general, if DRO data is used to validate assumptions made in simulations and vehicle measurements distance-based DRO data (instead of time-based) is recommended.
- If time-% electric drive is of interest, log this signal directly instead of translate from vehicle speeds.
- Today there is no way of differentiating between the driven time or distance with ICE only or ICE and electric motor combined. This result could be of interest for dimensioning the electric machine and the transmission connected to it.
- No data is currently logged for Off Road mode or the new buttons charge or hold.
- For the Transmission department it could be of interest to log electric drive (ICE off) per gear.
- To gain further understanding of customer's charging behavior investigate Logdata from OBC.
- Different departments are responsible for which data is logged in the electronic control units as well as its validity. Because of this, information about these things is not easily accessible. A central database for all DRO related information would be beneficial.

6
Future Recommendations

In 2019, electrified car models are planned to be introduced to the market. The Transmission department will have to design transmission systems for different kinds of battery electric vehicles - hybrids and purely electric.

It is recommended to use the results presented in this thesis to improve existing requirement setting procedure based on simulations and vehicle measurements. This could be done by establishing a methodology that reduces the observed differences between synthetic and real customer population. One suggestion is to include usage of Pure mode in the synthetic population. This would include the customers that have made the decision themselves to drive electric (ICE off). This group could potentially be the customers that are extra interested in buying a future BEV, since they have showed an interest in plugging in their vehicle to be able to utilize battery charge for electric drive. Another possible reason for the observed differences between the populations might be the distribution ranges. The range for Sustain and Depletion as well as for the distance-% electric drive was a lot smaller for the synthetic compared to real customer population. If extreme customers are included a more realistic distribution would be obtained. One possibility could be to look into clustering techniques to get a picture of if there are natural groups among the data.

In present requirement setting procedure no difference is made between mild, moderate and aggressive customers when it comes to the utilization of the hybrid-specific functionality. For simulations (VSim), a mild, moderate and aggressive driver is only differed by the velocity profile where the mild and moderate drivers drive slower than the aggressive. CarMaker, however, which is intended to be used in the future, provides the opportunity of having driver types with different acceleration behavior as well. Whether or not utilization of hybrid-specific functionality differs between these groups could be analyzed with DRO data. One question to investigate could be if the Drive modes are used more or less by the different Driver types i.e. do aggressive customers drive more in Power mode than mild customers? It is also recommended to keep in mind that future cars might have a higher level of automation (i.e. adaptive cruise control (ACC) and Pilot Assist) together with electrification. How should one combine these two in order to create a realistic driver model?

Regarding the development of new transmission concepts these results could be used to give an understanding of the utilization of hybrid-specific functionality. The tool developed in the project can also be updated to include additional analysis types to answer possible future questions. This, however, also requires relevant Logdata to be available. The tool is made in such a way that new functionality should be easy to add. It is, however, important to check with responsible person if the data is validated and thrust-worthy. For this project one extra Drive mode was added in vehicles but not in DRO data. This Off Road mode should be included in the mode analysis for completion.

Since simulations and vehicle measurements used at the Transmission department are distance-resolved, distance-based DRO data would make a comparison easier. One relevant question to ask is if and how these results can be used for another HEV or PHEV i.e. with a larger battery. This will probably be dependent on how different these vehicle models are. A larger battery would provide the opportunity of a greater amount of electric drive - but it is not for certain that it would change the customer's plug-in behavior. The same holds for the use of available drive modes and Brake mode. Therefore, a larger battery does not imply that the amount of electric drive will be greater. In order to use DRO data from a HEV to make assumptions for the possible usage of a future BEV one recommendation is to separate the data collected for electric drive and ICE on. This could give a better understanding for how the components are affected by electric only drive. It is however important to keep in mind the differences in management system for a HEV and a BEV. Furthermore, the dimensioning of different gears for future HEVs could possibly benefit from DRO data over the amount of electric drive per gear. Especially the lower gears seem to be loaded less for a hybrid than for conventional vehicles. Today, the DRO data combine the drive with the electric motor and ICE or ICE only. This is because the signals are controlled by the condition if the ICE is on or off. If this information is of interest new Logdata has to be specified.

The use of electric functionality seemed to be similar between different markets. This is still an area to look further into. Additional markets could be taken into account. Especially the US, which is a country built for driving and therefore stands out among other countries, should be analyzed when enough data is collected. Market differences are important to keep in mind, since designing vehicles for the world-average might under-dimension some markets and over-dimension others.

Furthermore, it is recommended to continuously update these results, since the driver behavior of a PHEV might change over time when the customers get used to the new systems. One example is that the customer might obtain a better knowledge about that the driver can select different drive modes and Brake mode. This could increase the use of these functions. In addition, future infrastructure might provide more charging possibilities for EVs. This could influence the charging behavior and the amount of electric drive.

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Appendix 1

A.1 Customer Combination Scheme (Confidential)

A.2 Specifications in Business Objects (Confidential)

A.3 Optional methods and tools for analysis of non time-resolved data (Confidential)

A.3.1 Kmeans Clustering (Confidential)