CHALMERS
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Energy Analysis of Battery and Hydrogen Driven Construction Equipment

A Comparative Study of Green Fleet Alternatives

Master's thesis in Sustainable Energy Systems

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Abstract

As sustainability becomes increasingly important in society due to climate change, the transition towards more sustainable vehicle alternatives is crucial. The articulated hauler, a heavy-duty vehicle designed for transporting materials in challenging terrains, serves as the focal point of this study. The aim of this thesis is to evaluate three different propulsion technologies for articulated haulers: the conventional diesel Internal Combustion Engine Vehicle (ICEV), the Battery Electric Vehicle (BEV), and the hydrogen Fuel Cell Electric Vehicle (FCEV). Additionally, a comparison is made between two different transmission systems for electrical powertrains: one equipped with three gears and the other with four gears, with a specific focus on energy efficiency. The thesis is based on logged data from a large number of ICEV operating worldwide, collected continuously during one year.

The results indicate that both transmission alternatives for the electrical powertrains would provide the same efficiency from the electrical motor to the wheels. Considering the entire powertrain, the BEVs offer the highest average efficiency at 73%, compared to 34% for FCEVs and 29% for ICEVs. Additionally, BEVs consume 35% of the energy required by ICEVs, while FCEVs consume 77%. BEVs would provide the lowest well-to-wheel carbon footprint in most cases, but this is highly dependent on how the energy carriers have been produced. FCEVs also have the potential for a significant reduction of the carbon footprint compared to ICEVs if renewable resources are utilized for the production of hydrogen. Comparing the range of the alternatives, the average operating hours before refueling or charging are 26.5 hours for ICEVs, 5.5 hours for BEVs, and 6.5 hours for FCEVs. Additionally, the average charging time for one hour of driving is 11 minutes for BEVs, compared to 0.5 minutes of refueling for ICEVs and 1.5 minutes for FCEVs.

It can be concluded that all alternatives have advantages and challenges, and there are trade-offs between different parameters to ensure the most optimal alternative in various situations. It is important to note that the study contains several limitations and simplifications, and further research could enhance the results and accuracy. The study is limited to one manufacturing company with unique factors, which should be considered when applying the findings to other contexts.

Keywords: Construction Equipment, Propulsion technologies, Electric vehicles, Battery, Hydrogen fuel cell, Internal combustion engine, Energy efficiency, Energy consumption, Carbon footprint, Data analytics

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Matilda Karlsson, Gothenburg, May 2024

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

B	Brake
BEV	Battery Electric Vehicle
C	Clutch
CFP	Carbon Footprint of Products
FCEV	Fuel Cell Electric Vehicle
GHG	Greenhouse Gases
HR	Hub Reduction
ICE	Internal Combustion Engine
ICEV	Internal Combustion Engine Vehicle
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory analysis
LCIA	Life Cycle Impact Assessment
MTW	Motor To Wheel
PS	Primary Stage
PT	Planetary Transmission
PTO	Power Take-Off
RPM	Revolutions Per Minute
SoC	State of Charge
TTW	Tank To Wheel
VCE	Volvo Construction Equipment
WTT	Well To Tank
WTW	Well To Wheel

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1

Introduction

The average global temperature on Earth has risen by about 1.2°C since pre-industrial levels, due to the emissions of greenhouse gases (GHGs) from human activities into the atmosphere [1]. The effects of the increased global average temperature are significant and will for example result in more extreme weather, sea level rise, and biodiversity loss. The Paris Agreement, signed by 196 countries, is an international agreement aimed at limiting the increase of temperature to below 1.5°C [1]. To reach this goal it is important to develop new technologies that can contribute towards significant reduction of GHG emissions.

Volvo Construction Equipment (VCE) is a part of Volvo Group and is one of the world's largest manufacturers of construction equipment [2]. One of VCE's products is the articulated hauler, a heavy machine used for transporting materials in tough and uneven terrain, for example at construction sites or for mining [3]. Currently, commercial machines use an internal combustion engine (ICE) with diesel, resulting in emissions of carbon dioxide, nitrogen oxides, and particulate matter [4]. Today this is a well-known, cheap, and reliable technology, but VCE needs to be prepared for stricter environmental regulations and laws in the future, which might reduce the possibility of continued use of today's diesel engines. Stricter regulations and economic incentives can have a significant impact in reducing GHG emissions, according to The Intergovernmental Panel on Climate Change [5].

In the transportation and construction sectors, which contribute significantly to GHG emissions, development is crucial for sustainable progress. Low-emission hydrogen, biofuels, or synthetic fuels can help reduce CO2 emissions from heavy-duty vehicles. Furthermore, electric heavy-duty vehicles show considerable potential for emission reduction, particularly when powered by electricity from renewable resources and with advancements in battery technologies [5].

To reduce the carbon footprint, Volvo Group has committed to the Science Based Targets initiative, which is an organization that provides businesses with pathways to reduce their emissions to meet the Paris Agreement [6], [7]. The goal for Volvo Group is to reach net-zero emissions of carbon dioxide before 2040. To meet this target, VCE is currently developing future solutions for green fleet alternatives. They have for example built a prototype of an articulated hauler with a hydrogen fuel cell and a battery electric vehicle [8]. However, these vehicles are still in the development phase, and several challenges remain. Determining the most suitable option for different situations and designing powertrains to maximize system efficiency and minimize the carbon footprint are key questions. The different power options need further investigation and adaptation to meet customer needs. Different powertrain alternatives for future haulers will be further investigated in this thesis.

1.1 Aim

The aim of this thesis is to compare various propulsion technologies for articulated haulers, including the conventional Internal Combustion Engine Vehicle (ICEV), the Battery Electric Vehicle (BEV), and the Fuel Cell Electric Vehicle (FCEV). Additionally, two different designs of transmission systems for electrical powertrains are compared, focusing on energy efficiency. The study analyzes data from current operations and evaluates power alternatives considering energy efficiency, energy consumption, carbon footprint, and charging/refueling times.

1.2 Specification of Problem Being Investigated

The aim has been specified with two main research questions, which are shown in the following list.

- How does the energy efficiency vary between different powertrain alternatives?
  - A comparison of the efficiency from the electrical motor to the wheels for a vehicle with a three-speed gearbox and a vehicle with a four-speed gearbox.
  - A comparison of the efficiency from the tank/battery to the wheels for the BEV, the FCEV, and the ICEV.
- What engine/power option should be recommended for different user cases, considering energy consumption, charging/refueling times, and carbon footprint?

1.3 Limitations

The study is limited to three different propulsion alternatives including diesel ICEV, hydrogen FCEV, and BEV. Furthermore, the study is limited to one machine size of the articulated haulers. VCE offers several different machine types that are excluded from the scope of the study.

Although data have been continuously collected from more than 1000 machines over the course of a year, they are presented as distributions (see Section 3 for further details). As a result, the datasets are not interconnected. This format limits the possibility of performing detailed analyses such as assessing correlations, evaluating the influence of specific variables, or investigating how variable interactions affect specific outcomes, such as energy consumption.

The study is also limited to one manufacturing company and it can therefore be difficult to generalize the results and findings to other industries due to unique factors, processes, and circumstances specific to the company.

The problem of recommending propulsion technology is a complex issue affected by numerous parameters. The project will be limited to some of these parameters (energy efficiency, energy consumption, carbon footprint, and charging/refueling times). More research and time would be needed to cover the whole picture.

2

Literature Review

This section presents a review of the current state of propulsion technologies for construction equipment. The different propulsion technologies and energy carriers are described and compared, as well as parameters affecting the energy consumption of a vehicle.

2.1 Current Status in the Construction Industry

The development of electric passenger vehicles has been rapid in recent years. However, there are some principal differences between lightweight road vehicles and construction equipment, which make the transition towards sustainable alternatives more complicated within this field [9]. The challenging driving conditions and heavy loads for articulated haulers result in the need for high power output and high energy consumption of the vehicles [9]. Moreover, the low energy density of batteries becomes more challenging for construction equipment due to the tough driving conditions and the lack of electricity infrastructure in remote construction sites. Most construction equipment still uses ICEs with diesel, as it provides high power output and long range. Another advantage is the available infrastructure for refueling diesel and the shorter refueling times [10]. However, there are ongoing developments of more environmentally friendly alternatives, but the advancement is slower compared to other fields [9]. This difference highlights the specific challenges involved in adopting environmentally friendly propulsion technologies in the construction equipment sector. It shows the importance of finding customized solutions and concentrating research efforts to overcome these obstacles.

2.2 Propulsion Technologies

The main components of the three different propulsion technologies investigated in this study are shown in Figure 2.1. The advantages and challenges associated with each technology are summarized in Table 2.1. Each vehicle, along with its respective advantages and challenges, is described in further detail in the upcoming sections.

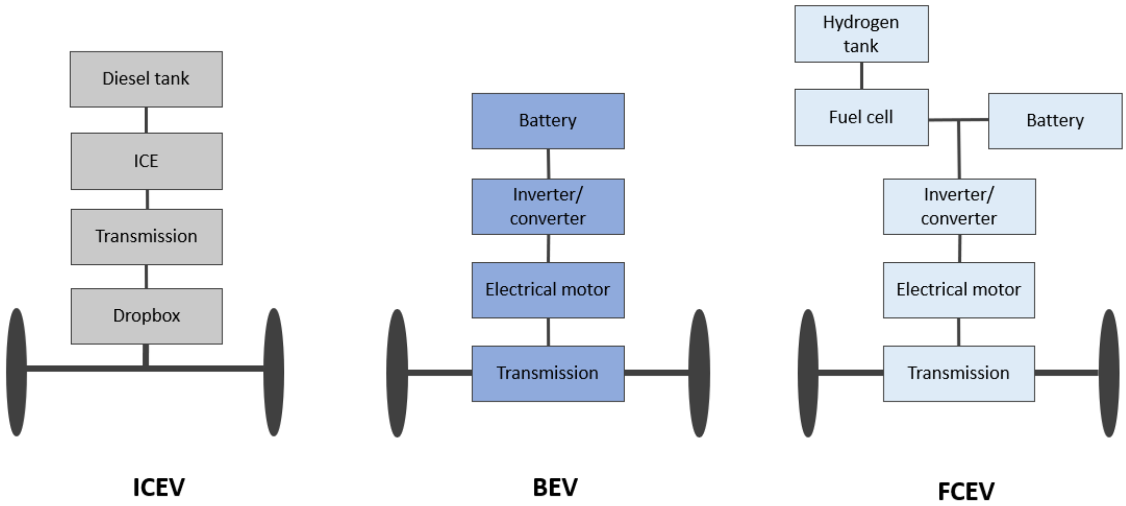


Figure 2.1: Simplified illustration of the components in the different powertrain alternatives, including ICEV, BEV and FCEV.

Table 2.1: Summary of advantages and challenges with each vehicle alternative.

	ICEV	**BEV**	**FCEV**
Advantages	Knowledge Refueling times Energy density Diesel infrastructure	No emissions during operation High efficiency Regenerative braking	Refueling times No emissions during operation Regenerative braking
Challenges	Emissions during operation Low efficiency	Charging times Charging infrastructure Energy density Battery degradation Temperature dependence Battery manufacturing	Hydrogen infrastructure Hydrogen production and storage Low efficiency Energy density Fuel cell degradation

Internal Combustion Engine Vehicle

The Internal Combustion Engine Vehicle (ICEV), which incinerates diesel, is the most common alternative in today's articulated haulers. The main components of the powertrain are the diesel tank, the ICE, the transmission system and the dropbox. In the ICE, the chemical energy in the fuel is converted into mechanical energy through a series of four stages: intake, compression, combustion, and exhaust. In the intake stage, air enters the combustion chamber followed by compression, where the air is forcefully compressed, raising the temperature significantly. The injection of the diesel in this stage will result in a spontaneous ignition of the fuel, which increases the pressure and temperature. The piston moves downwards and converts into rotational motion through a crankshaft which propels the vehicle. Exhaust gases, including pollutants like CO2, NOx and particulate matter, are emitted through the exhaust pipe [4].

The crankshaft is connected to a transmission system and a dropbox which have important roles in transferring the mechanical power to the wheels. The transmission contains a series of gears of different sizes. These gears can be shifted to appropriate gear ratios, which determine the relationship between the engine speed and the wheel speed. Lower gears provide more torque for acceleration, while higher gears allow for higher speeds at lower engine RPMs. The different gears make it possible to operate the engine at an efficient level across different driving conditions [10].

Battery Electric Vehicle

The battery electric vehicle (BEV) is propelled by an electrical motor powered by a rechargeable battery. A battery converts stored chemical energy into electrical energy through an electrochemical reaction. A battery consists of several different cells, which can be made from various materials. Lithium-ion batteries are the most commonly used material for vehicles due to their high energy density compared to other battery materials [11]. However, batteries have a lower gravimetric energy density compared to diesel and hydrogen fuels, resulting in heavier powertrains [10]. The electrical motor system converts the electrical energy from the battery to mechanical energy, which can propel the wheels. The electrical motor can operate efficiently at a wide range of speed and torque levels, as well as deliver torque from standstill. This makes it possible to operate at a wide range of driving conditions with a less complicated transmission design and fewer gear ratios. However, previous studies have shown that the design of the transmission system can have an important impact on energy consumption [10].

Compared to internal combustion engines, the BEV has no emissions during operation. However, it is important to consider the carbon footprint from a lifecycle perspective, including emissions from the production of electricity, which varies depending on the resource used [10]. The manufacturing phase of vehicles is also important in Life Cycle Assessments (LCA), as evidenced by previous studies. Research on electric vehicles has underscored the significant impact of battery manufacturing on the carbon footprint since that is an energy-intensive process. This leads to increased emissions in the manufacturing phase of BEV compared to ICEV [12]. Further studies validate these findings [13], [14]. Batteries also require critical minerals, which have raised concerns regarding material supply. This highlights the importance of improving battery recycling processes [5].

Another advantage of battery electric vehicles is their high efficiency compared to other technologies and the possibility of regenerative braking, which would reduce energy consumption compared to ICEV [11]. One important factor to consider is the charging time, which is longer than the refueling time for liquid fuels. Furthermore, the lifespan of the battery is a concern affected by several parameters such as the number of charge cycles, the state of charge, and the operating temperature [11].

Fuel Cell Electric Vehicle

The hydrogen fuel cell electric vehicle (FCEV) is similar to the BEV, as it also consists of an electric motor. The difference is that electricity is produced onboard the vehicle in the fuel cell through an electrochemical reaction. The fuel cell comprises a membrane with a catalyst that separates hydrogen molecules into hydrogen ions and electrons. Hydrogen ions can pass through the membrane while electrons flow through an electric circuit and generate electricity. Oxygen in the air can then react with electrons and hydrogen ions to produce water. The electricity produced can be used to generate mechanical energy in the electrical motor, similar to the BEV [11]. Excess electricity can also charge the battery, which has the main purpose of providing peak power when needed. Since the FCEV also consists of an electrical motor and a smaller battery, some energy can be recuperated when going downhill or when braking [15].

The overall efficiency of the FCEV is lower than for the BEV. During operation, the use of hydrogen in a fuel cell would result in zero emissions of GHGs, NOx, and particulate matter, as the only product from the electrochemical reaction is water. However, it is also important to consider the hydrogen production method, explained more in Section 2.3, as well as the manufacturing phase of the vehicles. Previous studies have shown that the GHG emissions from the manufacturing phase of FCEVs are higher than ICEVs, mainly due to the hydrogen tank [12].

When using hydrogen in a fuel cell, there are stricter requirements for the purity of the fuel compared to internal combustion engines. To avoid destruction of the fuel cell material, it is preferable to use hydrogen produced from the electrolysis of water [11]. Hydrogen also has low volumetric energy density, which means that storage is a challenge. Hydrogen can, for example, be stored as a compressed gas or as a cooled liquid, which both require energy-intensive processes [16].

2.3 Energy Carrier Production

The energy carriers used in the different propulsion technologies can be produced using various methods and from different resources. This is important to consider when calculating the carbon footprint for the usage phase of the vehicles.

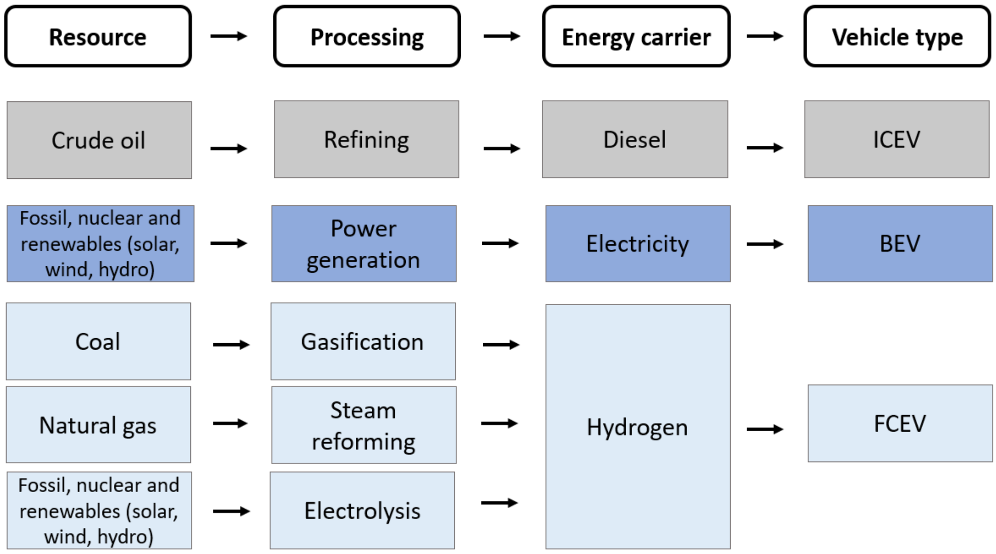


Figure 2.2: Overview of production methods and resources used for the different energy carriers in the vehicle alternatives.

The most common way of producing diesel is through the refining of crude oil. The use of diesel in the ICEV will result in emissions both during the production phase of the fuel and when driving the machine [17]. A previous study conducted by VCE has shown that the usage phase of the ICEV accounts for approximately 95% of the CO2eq emissions per operating hour from a life cycle perspective [18]. However, there are also other production methods of diesel. Electro-diesel is an example of a synthetic fuel produced from electricity, water, and carbon which potentially can reduce the carbon footprint of the production phase of the diesel [19].

The electricity used in the BEV can be produced from various resources, including fossil, nuclear, and renewable. Each country has a specific grid mix, resulting in different amounts of carbon dioxide emissions. Therefore the geographic location will have an important impact on emissions from the the electrical machines [17]. In France, where the grid mix consists mainly of electricity from renewable and nuclear resources, the carbon footprint from power generation is approximately eight times lower than in the USA, where a significant portion of power is derived from fossil fuels [17].

There are several production methods for hydrogen, such as electrolysis of water, steam reforming of natural gas, and coal gasification. Hydrogen can be classified into different colors, depending on which resource and method that is used for the production. Today, almost 95 % of the hydrogen produced worldwide is classified as grey, which means that it is produced through steam reforming of natural gas. Only a small part of the hydrogen is green and produced from the electrolysis of renewable resources [16]. The different hydrogen colors will have different environmental impacts. The carbon footprint of hydrogen produced from electrolysis is highly affected by the carbon intensity of the grid mix [17].

2.4 Power and Energy Consumption of Vehicles

The power and energy consumption of a vehicle is affected by numerous different parameters. The power needed at the wheels (P_{wheels}), is a function of the tractive force ($F_{tractive}$) and the velocity of the vehicle (v), according to Equation 2.1 [20].

$$P_{\text{wheel}} = F_{\text{tractive}} \cdot v \tag{2.1}$$

The different forces acting on the vehicle are illustrated in Figure 2.3. The tractive force at the wheels is a function of the mass (m), acceleration (a), rolling resistance (R_r), slope resistance (R_g), and aerodynamic resistance (R_a) according to Equation 2.2. Where R_r, R_g and R_a can be calculated from Equation 2.3, 2.4 and 2.5 [21].

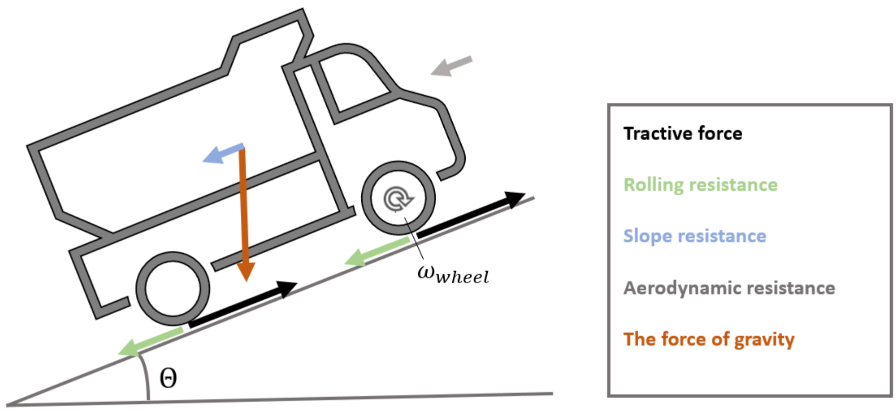


Figure 2.3: The forces acting on the vehicle.

$$F_{\text{tractive}} = m \cdot a + R_r + R_g + R_a \tag{2.2}$$

$$R_r = f_{\text{r}} \cdot mg \cdot \cos(\Theta) \tag{2.3}$$

$$R_g = mg \cdot \sin(\Theta) \tag{2.4}$$

$$R_a = \frac{1}{2}\rho C_d A v^2 \tag{2.5}$$

Here f_r represents the rolling resistance coefficient between the tires and the road surface, g is the gravitational acceleration, θ is the angle of the slope, ρ is the density of the air, C_d is the drag coefficient and A the cross-sectional area of the vehicle. For articulated haulers, the aerodynamic resistance is negligible at low vehicle speeds [22].

Furthermore, the input power (P_{input}) is a function of the power needed at the wheels and the efficiency of the powertrain ($\eta_{powertrain}$), according to Equation 2.6. The efficiency of the powertrain includes all heat losses in the different components due to friction but also the energy used for auxiliaries and Power Take-Offs (PTOs) such as air conditioning, heating, cooling, and pump work for the hydraulic system [21].

$$P_{\text{input}} = \frac{P_{\text{wheel}}}{\eta_{\text{powertrain}}} \tag{2.6}$$

The input power can then be integrated over time to receive the energy consumption of the vehicle. For electric vehicles, the energy consumption is affected by the amount of regenerated power during braking and when going downhill, described with Equation 2.7. The amount of regenerated power is affected by the rolling resistance, the slope and length of hills, and the load of the vehicles. Therefore, the amount of regenerated power varies a lot between different sites. For ICEV, this energy is lost as heat [20], [21].

$$E_{\text{input}} = \int P_{\text{input}}(t)\,dt - \int P_{\text{regeneration}}(t)\,dt \tag{2.7}$$

From the equations above it can be concluded that the power and energy consumption of vehicles are affected by numerous different parameters, which have been summarized in Table 2.2. The parameters have been separated into internal factors connected to the vehicle design and external factors such as environmental conditions and customer behaviors.

Table 2.2: Internal and external factors affecting the power and energy consumption of a vehicle.

	Parameters affecting the energy consumption
Internal factors	Powertrain efficiency Mass of the vehicle Tires design
External factors	Topography Road Surface Driving behavior (velocity, acceleration etc.) Loads Ambient temperature

Both the tire design and the vehicle weight will have an impact on the driving resistance of the vehicle, while the design and efficiency of the powertrain will have an impact on the energy that reaches the wheels [23]. The internal factors are parameters that the manufacturing company can affect when designing the vehicle to minimize energy consumption. Since the range of battery electric vehicles is limited it becomes increasingly important to maximize the efficiency of the powertrain and minimize the parameters affecting the rolling resistance [20].

The external factors include parameters that are connected to the surroundings and driving behavior of the customer. These parameters are more difficult for the manufacturing company to affect. The road surface is an important parameter that will have a large impact on the rolling resistance of the vehicle [23], especially since the articulated hauler drives in tough and uneven terrain. Furthermore, topography has an impact on energy consumption. A more hilly environment increases energy consumption but would also result in the possibility for more regenerative braking for electric vehicles [23]. Previous studies have also shown that the ambient temperature will have an impact on the energy consumption of vehicles, due to a need for more heating or cooling and lowered efficiency of the batteries for electric vehicles at extreme temperatures [24].

3

Data

This thesis is based on data from one machine size of the articulated haulers which uses an internal combustion engine with diesel for propulsion. The data are logged from a large number of machines (>1000) operating worldwide, collected continuously during one year, from 2022-01-01 until 2022-12-31. The data are anonymous and can not be connected to a specific site or machine, but can give a good overview of the driving patterns of the customers as well as the environment they drive in. The data used in this thesis include parameters such as velocity, fuel consumption during driving and during idling, the proportion of idling time, market category, and engine torque. The data are available in the form of distributions for single machines and for the whole population. However, the data are not interconnected which limits the possibility for detailed calculations. Figure 3.1 shows the distribution of the proportion of idling time for the population as an example of the available data. Distributions of the other relevant parameters are available in Appendix A.

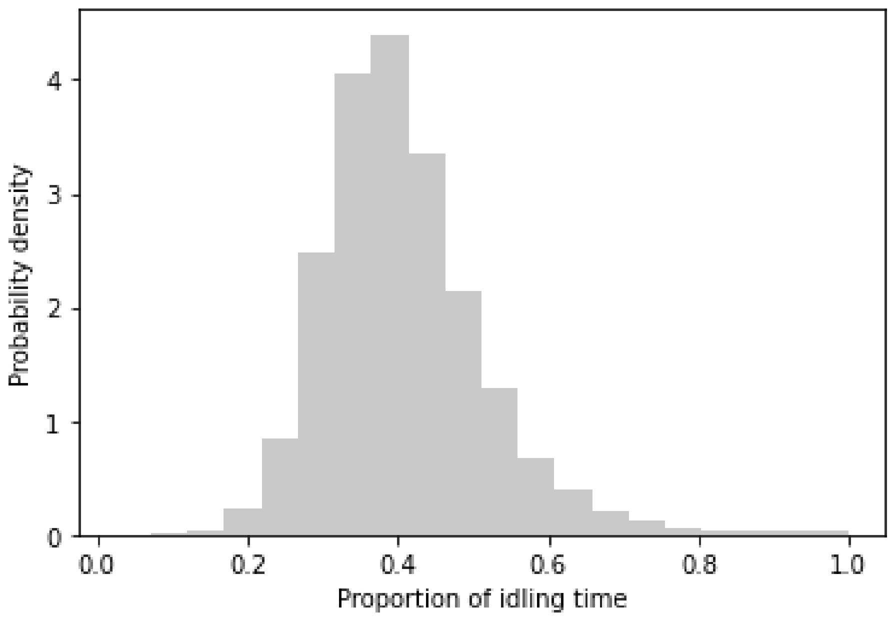


Figure 3.1: The distribution of the proportion of idling time for the population of articulated haulers.

3.1 Integrity and Ethics

In this project, it is also important to consider the ethical aspects associated with data handling. This involves ensuring that data collection and analysis are conducted in accordance with ethical principles and guidelines. Integrity is important for VCE and all data that is used will be anonymous and can not be connected to a specific site or machine [25].

4 Methodology

This chapter describes the methodology of the thesis. The first part of the study was the energy efficiency evaluation of different powertrains. Based on the efficiency evaluation and logged data from the current operation, the energy consumption was estimated. The charging and refueling times and the carbon footprint were calculated based on energy consumption distributions, which resulted in a comparative analysis of propulsion technologies for different scenarios. The methodology is illustrated in Figure 4.1.

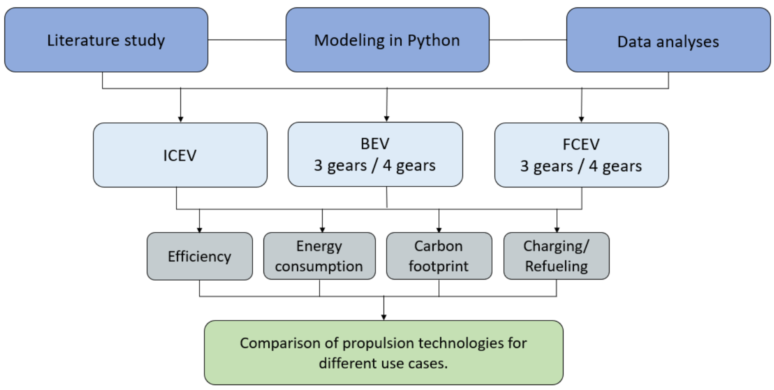


Figure 4.1: Overview of the methodology of the thesis project.

4.1 Powertrain Efficiencies

The first step was to identify and map all losses in the different powertrain alternatives. The efficiencies for BEV and FCEV were calculated based on vehicle design specifications and data logs. The losses in the conventional ICEV have been calculated in prior studies by VCE, providing a basis for comparison with the new electrical powertrains. Future research should consider conducting a similar study for the ICEV as for the electrical machines to compare the same methodology and to ensure model accuracy.

The losses for ICEV, BEV, and FCEV have been illustrated with Sankey diagrams, shown in Figure 4.2, 4.3, and 4.4. Every component in the powertrain results in some losses. The useful energy in this picture is represented by the energy needed at the wheels to move the vehicle forward, which is the main purpose of the engine/motor. Some energy is also used for auxiliaries and PTOs such as pump and fan work for the cooling system, which also are illustrated as losses in the figures. One difference between the ICEV and the electrical alternatives is the possibility for regenerative braking, which means that some of the energy can be recovered when going downhill, and the electrical motor can be used as a generator to charge the battery again [21].

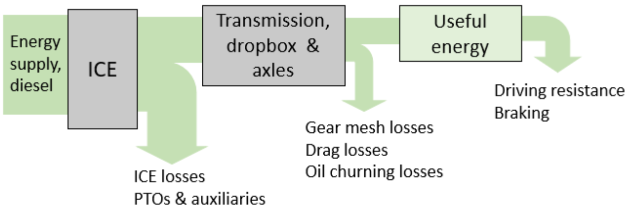


Figure 4.2: Sankey diagram for the ICEV to illustrate the energy flows and losses in the vehicle.

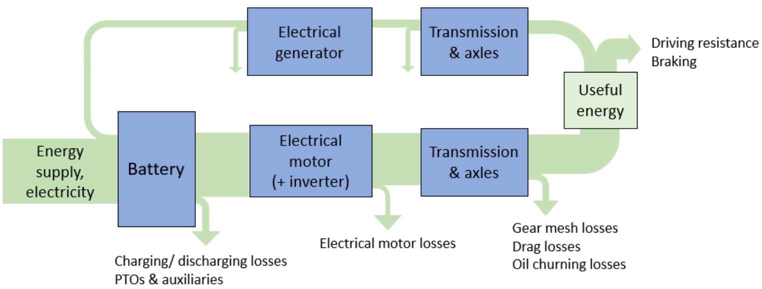


Figure 4.3: Sankey diagram for the BEV to illustrate the energy flows and losses in the vehicle.

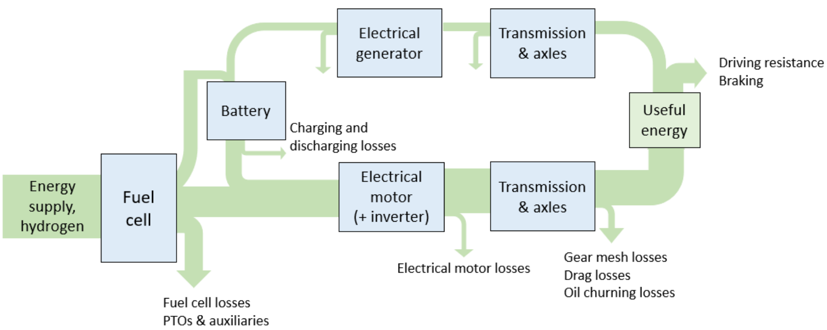


Figure 4.4: Sankey diagram for the FCEV to illustrate the energy flows and losses in the vehicle.

Electrical Powertrain for BEV and FCEV

There are a lot of uncertainties and questions regarding how the new electrical powertrains should be designed. Since it is extremely important to maximize the efficiency of the powertrains due to the limited range of batteries [20], the losses of the electrical powertrains were calculated for two different transmission alternatives. These two alternatives can be used for both the BEV and the FCEV. One alternative of the electrical powertrain has a transmission with three gears (Three-speed), and the other alternative has a transmission with four gears (Four-speed), which are summarized in Figure 4.5. In contrast to ICEVs, the electric powertrains considered in this study have one electric motor and one gearbox on each of the three axles.

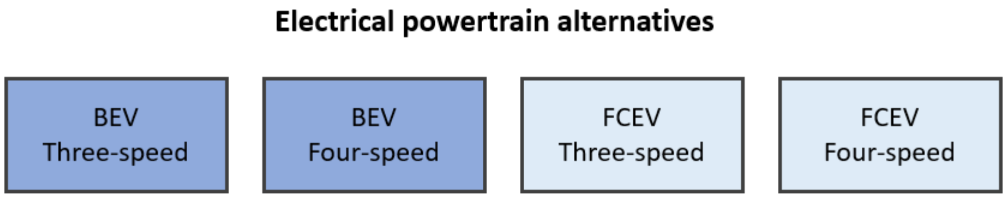


Figure 4.5: Alternatives for the electrical powertrains included in the study.

The losses in the electrical powertrains are listed in Table 4.1. The losses from the electrical motor system to the wheels will be the same for all electrical powertrains, regardless if they are connected to a battery or a fuel cell. To get the overall efficiency for the whole vehicle, the charging and discharging efficiency for the battery or the efficiency of the fuel cell needs to be included, which was based on literature reviews. The power used for PTOs and auxiliaries was assumed to be the same size as for conventional machines.

Table 4.1: The power losses in the powertrain for BEV and FCEV.

Losses	**Nomenclature**	**BEV**	**FCEV**
Battery (Charging and discharging)	P_{loss_B}	x	
Fuel cell (+ Battery)	P_{loss_FC}		x
PTO and auxiliaries	P_{PTO}	x	x
Electrical motor system, including inverter/converter	P_{loss_EMS}	x	x
Gear mesh losses	P_{loss_GM}	x	x
Clutch/Brake drag losses	P_{loss_D}	x	x
Oil churning losses	P_{loss_OC}	x	x

The losses are dependent on both the rotational speed, ω, and the torque, T, resulting in different efficiencies for different operating points. The traction force, F, and velocity, v, were calculated for different combinations of power levels, rotational speeds, and torques of the electrical motor, according to Equation 4.1-4.5. The traction force of the vehicle was then plotted as a function of velocity for different power levels of the electrical motor. Each point in the graph has a specific efficiency from the electrical motor to the wheels. This was done for the different gear ratios, GR, in the different transmission alternatives. Input data for the different alternatives can be found in Appendix B.

$$P_{\text{motor, out}} = T_{\text{motor}} \cdot \omega_{\text{motor}} \tag{4.1}$$

$$GR = \frac{w_{\text{motor}}}{w_{\text{wheel}}} \tag{4.2}$$

$$v = w_{\text{wheel}} \cdot r_{\text{wheel}} \tag{4.3}$$

$$P_{\text{wheel}} = P_{\text{motor, out}} - P_{\text{loss\_GM}} - P_{\text{loss\_D}} - P_{\text{loss\_OC}} \tag{4.4}$$

$$F = \frac{P_{\text{wheel}}}{v} \tag{4.5}$$

Data from current operations were used to determine where customers operate within the efficiency map. Velocity distributions and turbine torque distributions for different gears from conventional machines were utilized (See Appendix A). The turbine torque was converted into tractive force in the same way as for the electrical machines (Equation 4.1-4.5). It was assumed that the tractive force and velocity were the same as those of conventional machines, meaning that the driving conditions and the weight of the vehicles were kept constant. It is important to note that the mass difference is an uncertain parameter that will increase the tractive force needed for BEV due to heavier powertrains. Furthermore, it was assumed that the load was evenly distributed between the three axles, which varies in real life depending on the driving conditions.

Since the data logs are not interconnected and do not provide exact combinations of velocity and tractive force, Monte Carlo simulations were used. These simulations randomly select combinations based on distributions and probability numerous times, allowing for the generation of efficiency distributions for different machines within the population. The Monte Carlo simulations were considered accurate when the result stabilized and remained unchanged. The procedure was repeated for many machines to get distributions of average efficiency within the populations for the three-speed and the four-speed alternatives.

The upcoming sections describe the different power losses in the electrical powertrains from the electrical motor to the wheels.

Electrical Motor System

The losses in the electrical motor are dependent on both the torque, T, and the rotational speed, ω. Each operating point of the electrical motor corresponds to a specific operating efficiency, which can be determined from the electrical motor efficiency map (see Appendix B.1). The highest efficiencies and the most optimal performance are obtained in the middle of the graph.

Gear Mesh Losses

The gear mesh losses in the system represent the energy dissipation due to the friction between the rotating gear wheels, which have been calculated by VCE in previous studies. The data for the different gears are available in Appendix B.2 [22].

Drag Losses in Clutch and Brakes

Wet clutches and brakes are common components in modern vehicle drivetrains. Open clutch and brakes will result in drag losses. The drag torque in the transmission represents the losses due to the shearing force between the oil and the discs. Figure 4.6 shows a representative drag torque curve. The first part represents a linear increase of the drag torque. In this state, the oil film between the plates is full, and the centrifugal effects are low, which results in the surface tension being the dominant force due to low rotational speed. At a certain point, the critical speed, the oil film breaks and consists of small air pockets which gradually become bigger while increasing the rotational speed. In the last part of the curve the drag torque starts to increase again due to a mist being formed of the air and the oil [26].

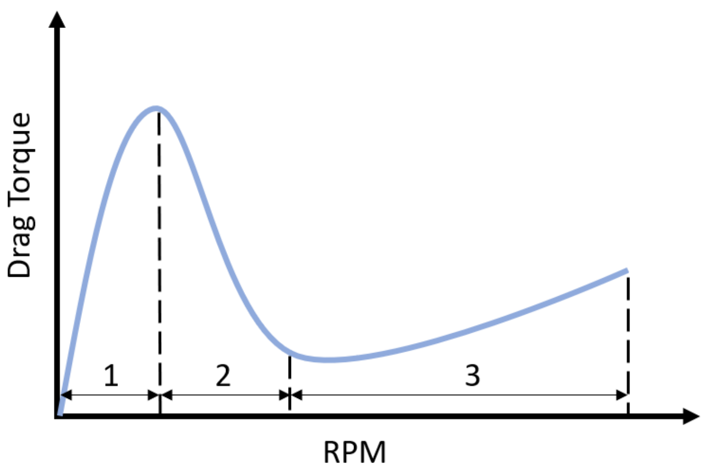


Figure 4.6: The typical shape of the curve for drag torque as a function of the rotational speed in the transmission system.

The development of a precise mathematical model to predict drag torque is essential. While considerable research has been conducted in this field, existing models have not yet achieved the level of accuracy required for engineering applications, which indicates that more research would be needed within this field [27].

The drag torque losses can be calculated using various models, and in this project, the surface tension model was utilized. This model assumes that the fluid is in a steady state and incompressible, the clutches are smooth, and the flows operate in turbulent regions[28].

The drag torque losses have been calculated for the two different transmission alternatives. For the three-speed alternative, there will always be two open clutch/brakes causing drag losses, while for the four-speed alternative, there will always be three open clutch/brakes causing drag. The different drag losses for all gears have been combined to calculate the total drag torque losses for each gear in the two transmission options.

The first step of the model was to calculate the critical radius of the oil film, r_c. At this point, centrifugal effects begin to dominate, and the oil film starts to contain air pockets. This has been done with Equation 4.6.

$$\frac{\rho(\Delta\omega)^2}{2}(f+\frac{1}{4})r_c^2-\frac{\mu Q}{2\pi r_m h^3 G_r}r_c+\frac{\mu Q}{2\pi r_m h^3 G_r}r_i-\frac{2\sigma\cdot\cos\theta}{h}-\frac{\rho(\Delta\omega)^2}{2}(f+\frac{1}{4})\cdot r_i^2=0 \tag{4.6}$$

G_r and f are turbulence coefficients and have been calculated with Reynolds number, Re, according to equation 4.7, 4.8 and 4.9.

$$Re_h=\frac{\rho\Delta\omega r_i h}{\mu} \tag{4.7}$$

$$f=\begin{cases}0.885\cdot Re_h^{-0.367} & \text{if } Re_h\geq 500\\ 0.09 & \text{if } Re_h<500\end{cases} \tag{4.8}$$

$$G_r=\frac{1}{12}(1+0.00069Re_h^{0.88}) \tag{4.9}$$

The drag torque losses, T, due to the resistance between the fluid and the discs can then be calculated with Equation 4.10.

$$T=2\pi N\int_{r_i}^{r_c}\left(\frac{\mu\Delta\omega r^3}{h}\right)\left(1+0.0012\cdot Re_h^{0.94}\right)\,dr \tag{4.10}$$

The nomenclature for the different parameters in Equation 4.6 - 4.10 are shown in Table 4.2.

Table 4.2: Nomenclature for the parameters used to calculate the drag torque with the Surface Tension Model.

Symbol	Parameter	Unit
f	Turbulence coefficient	-
G_r	Turbulence coefficient	-
h	Clutch clearance	m
N	Number of friction interfaces	-
Q	Oil flow	m^3/s
Re_h	Reynolds number based on clutch clearance	-
r_i	Inner radius of disc	m
r_o	Outer radius of disc	m
r_m	Average radius	m
r_c	Critical radius of disc	m
T	Drag torque	Nm
ρ	Density of oil	kg/m^3
μ	Dynamic viscosity of oil	Pas
σ	Surface tension coefficient	N/m
θ	Contact angle between the oil film and disc	rad
$\Delta\omega$	The relative angular velocity	rad/s

Oil Churning Losses

The oil churning losses represent the losses due to the movement and turbulence of oil within the axles, which will result in resistance and energy dissipation in the system. These losses are also dependent on the rotational speed and for this project, these losses have been assumed to be in the same size as for the conventional machines. A correlation between the vehicle velocity and the oil churning losses from previous studies conducted by VCE has been used and is available in Appendix B.3. Reducing the axles losses could be a potential to increase the energy efficiency of the system, hence a sensitivity analysis was made for this parameter where the oil churning losses were reduced to 50 % of the original power loss [22].

4.2 Energy Consumption

The energy consumption for each vehicle type was estimated based on the logged data on fuel consumption and idling time for the conventional machines and the efficiency evaluation described in Section 4.1.

The data on fuel consumption is separated into fuel consumption during driving and fuel consumption during idling. The distribution of average fuel consumption for many haulers operating worldwide is available in Appendix A. The energy content, E, in the fuel was calculated with equation 4.11. CF is the calorific value or the heating value of the fuel and F represents the fuel consumption. This was done for both the driving and idling fuel consumption, and the total energy consumption per operating hour was calculated with Equation 4.12.

$$E = F \cdot CF \tag{4.11}$$

$$E = E_{\text{burn}} \cdot (1 - t_{\text{idling}}) + E_{\text{idling}} \cdot t_{\text{idling}} \tag{4.12}$$

When converting this energy consumption into electricity consumption and hydrogen consumption, the estimated efficiencies, η, of the different powertrain alternatives were used, according to Equation 4.13. This was done for the driving consumption. For electric vehicles the idling consumption will be much lower than for ICEV and has therefore been assumed to be negligible [29].

$$E_{\text{electrical}} = \frac{E_{\text{diesel}} \cdot \eta_{\text{total, diesel}}}{\eta_{\text{total, electrical}}} \tag{4.13}$$

In the calculations, the energy needed at the wheels to move the vehicle forward was assumed to be the same for all alternatives, meaning that the driving resistance and driving behavior were kept constant. Important to note is that the possibility of regenerative braking has not been considered. Neither has the mass differences between the alternatives. Since the energy density differs between the alternatives, that would affect the energy consumption. More data would be needed to include them in the model, but simplified sensitivity analyses were made.

4.3 Charging and Refueling Times

Two different parameters were calculated to compare the three different vehicle alternatives in terms of charging and refueling times. The first one is the number of operating hours before refueling or charging is needed, and the second parameter is minutes of charging/refueling per hour of driving.

These parameters were estimated based on the calculated energy consumption described in Section 4.2, assumptions regarding onboard energy capacity, and data from literature about refueling and charging times. Assumptions regarding battery capacity and volume of hydrogen tanks have been made based on the volumetric densities of the energy carriers. Furthermore, the assumptions were discussed with industry representatives from VCE to ensure reasonable assumptions. The State of Charge (SoC) of batteries is also an important parameter since it affects the amount of useful energy in each charging cycle of the battery. The SoC of the batteries highly affects their efficiency, lifespan, and degradation process, and it is therefore important to take this into consideration [30].

4.4 Well to Wheel Carbon Footprint

Life Cycle Assessment (LCA) is typically used to assess the environmental impact of products and services over their entire life cycle. In previous estimations, VCE followed the standardization ISO14044, focusing on the global warming potential [31]. ISO14067 is the standardization of Carbon Footprint of Products (CFP) calculations that describe the part of ISO14044 that is relevant for the global warming potential. In this thesis, a simplified CFP estimation was made, focusing mainly on the usage phase (Well to Wheel). According to ISO14067 and ISO14044, LCA contains four main steps: The goal and scope definition, the Life Cycle Inventory analysis (LCI), the Life Cycle Impact Assessment (LCIA), and the Interpretation [32], [33].

The first part of the CFP calculations is the definition of the goal and scope. The goal of this project was to compare the emissions from the usage phase (Well To Wheel) for the three different vehicle alternatives, including the ICEV, BEV, and FCEV, for different customer groups. The functional unit for the study is kg CO2 equivalents per operating hour, which is the standard unit for construction equipment and the unit VCE uses for their estimations [31]. The system boundary for this thesis project, as well as the system boundary for VCE, is shown in Figure 4.7.

Previous studies conducted by VCE have highlighted that the usage phase accounts for the largest part of greenhouse gas emissions for ICEVs [18]. Therefore, it is important to reduce emissions during this phase. However, it is also important to consider the manufacturing and end-of-life phases in the decision-making process, as written in Chapter 2. Variations in these phases among alternatives can influence which option is the most environmentally friendly in terms of global warming potential. From the literature review, it can be concluded that the batteries and the hydrogen tanks would increase the CFP for the manufacturing of the vehicles. Still, these parts have been excluded from the scope of this project.

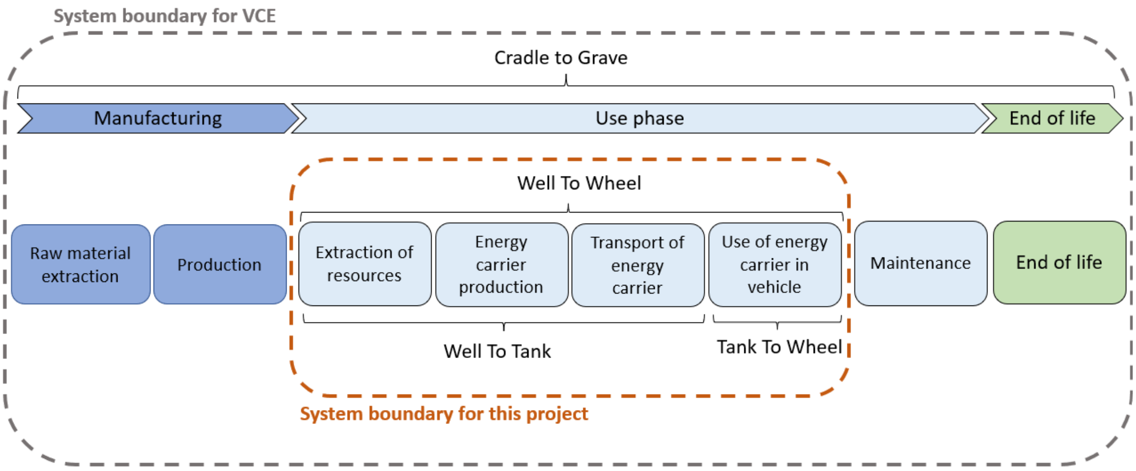


Figure 4.7: The system boundary of the CFP estimations for this project as well as the system boundary for VCE.

The LCI involves gathering data from different parts of the system. This project includes calculating energy consumption for various vehicles as explained in Section 4.2, analyzing customer usage data, and collecting emission factors from literature for different types of energy carriers.

The third step, LCIA, is to calculate the global warming potential for different vehicles and user cases from the data collected in the LCI, which will end up in kg CO2eq/operating hour for different vehicles and scenarios. During the process, it is important to analyze and understand the results from the calculations, which includes a discussion around limitations with the methodology and other parameters that may influence the results.

5

Results and Discussion

The following section presents the results from the study, which include the energy efficiency evaluation for different powertrains as well as energy consumption, carbon footprint, and charging and refueling times for different scenarios. The results are analyzed and discussed, and sensitivity analyses are used to understand how variations in input variables affect the outcomes.

5.1 Powertrain Efficiencies

The initial phase of the study is an evaluation of the efficiencies of various powertrains. The results for this part include the efficiency for different combinations of tractive force and vehicle velocity, as well as the typical operating conditions based on logged data from current operations. This results in the distribution of vehicle efficiencies across the customer population for various powertrain alternatives.

Figure 5.1 shows the torque as a function of rotational speed for different power outputs of the electrical motor, which serves as the basis for further calculations.

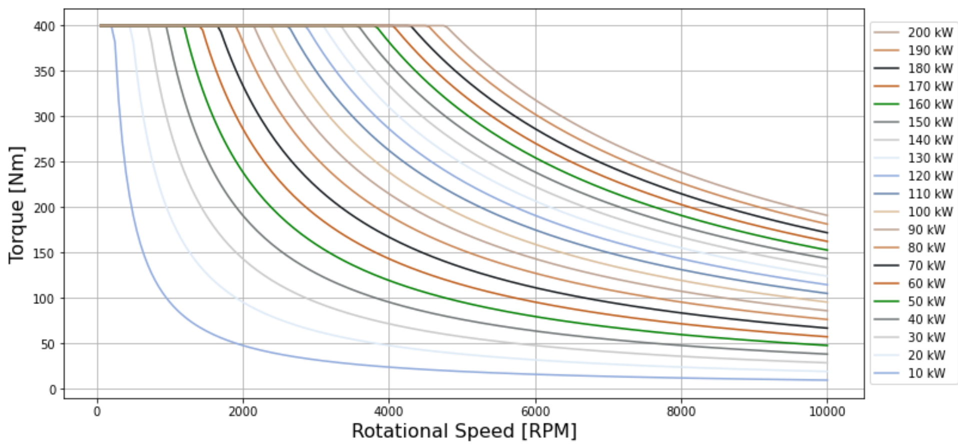
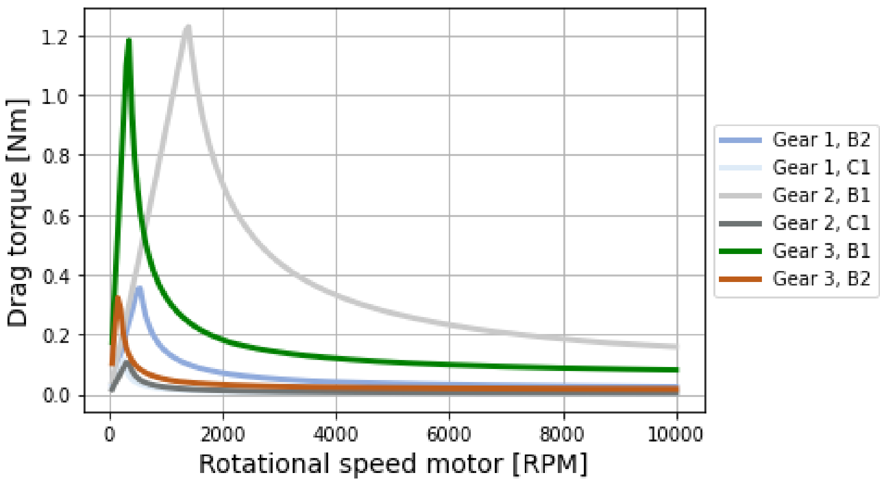
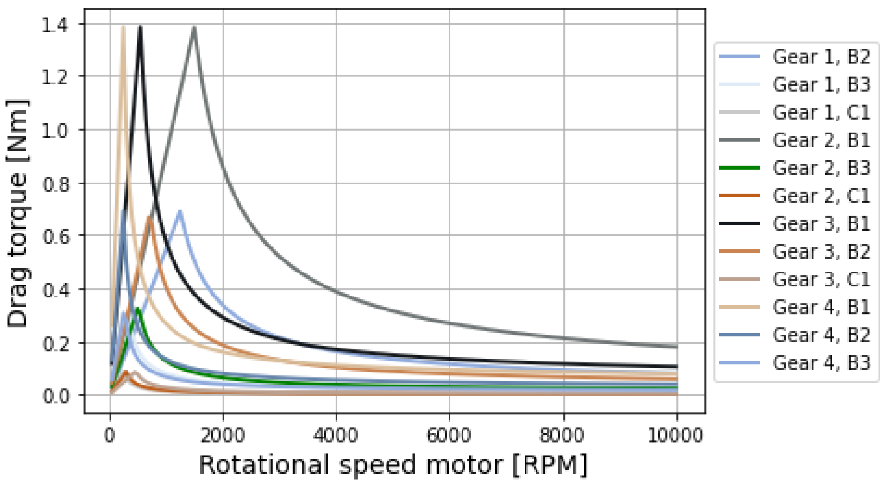


Figure 5.1: Torque as a function of RPM for different power levels of the electrical motor.

The drag torque losses for each transmission alternative are presented in Figure 5.2. The calculated drag torques at different RPMs closely align with the expected behavior for part one and two illustrated in Figure 4.6. However, the third part was not captured with the model used, which indicates that future research should consider exploring alternative models as a comparison.



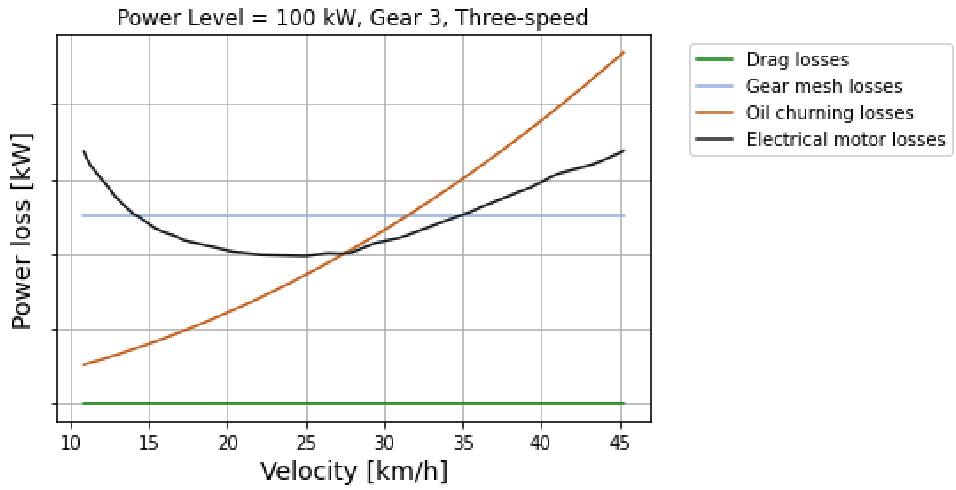
(a) Three-speed alternative.



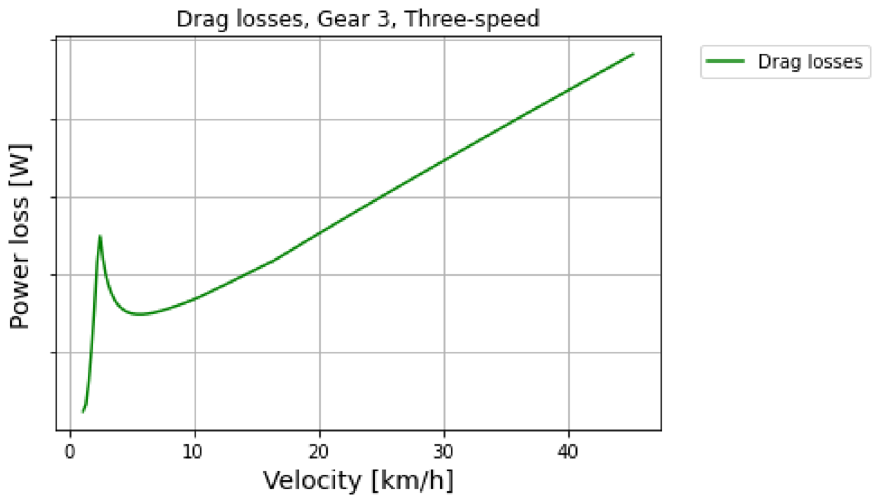
(b) Four-speed alternative.

Figure 5.2: The drag torque losses for open clutch (C) and brakes (B) for the two different transmission alternatives, calculated with the Surface tension model.

It can be concluded that the drag losses are minimal compared to other power losses, as shown in Figure 5.3, which displays the various power losses as a function of vehicle speed for a single power level and gear. The figure shows that oil churning losses increase with vehicle speed, constituting a small portion of the total power loss at low speeds and a significant portion at high speeds. For the electrical motor system, a minimum point of power loss exists that corresponds to the mid-range of the motor efficiency map. However, losses increase at the edges of this map. Gear mesh losses remain constant for a given power level. Figure 5.3b illustrates the variation in drag power losses with adjustments made to the y-axis scale, focusing specifically on the drag losses.



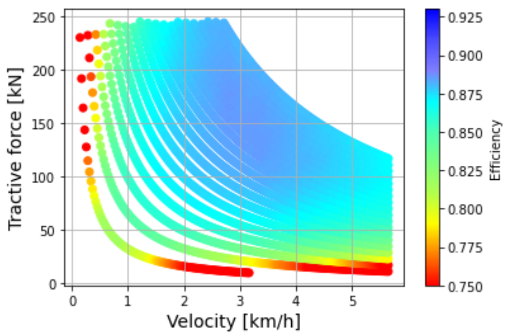
(a) The different contributions to the total power loss from the motor to the wheel as a function of the velocity of the vehicle, for gear 3 in the three-speed alternative.



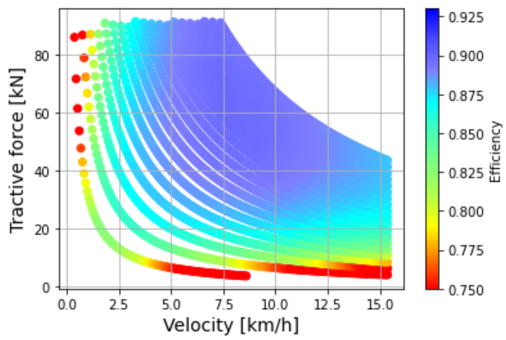
(b) The drag power losses as a function of velocity for gear 3 in the three-speed alternative.

Figure 5.3: The different contributions to the total power loss from the motor to the wheel as a function of the velocity of the vehicle.

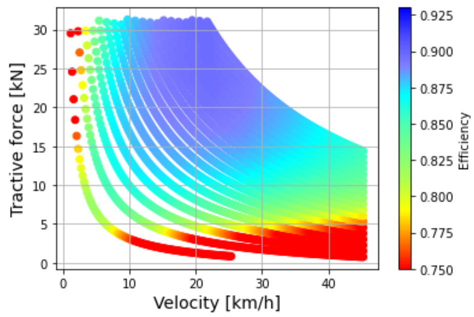
For each operating point of the electrical motor, shown in Figure 5.1, the tractive force and velocity are calculated, and the corresponding efficiency from the electrical motor to the wheel. The calculations are done for each gear in each transmission alternative. The results are presented as efficiency maps for the operating areas as shown in Figure 5.4 and 5.5. The Figures show that the highest efficiencies are obtained in the middle of the velocity range for high power levels. In combination with high velocities, lower power levels result in the lowest efficiencies.



(a) Gear 1

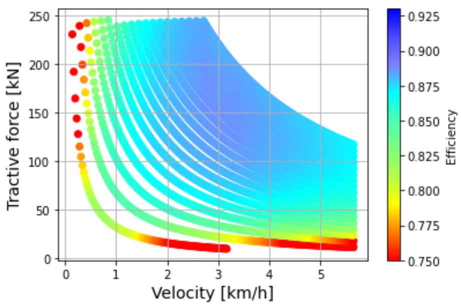


(b) Gear 2

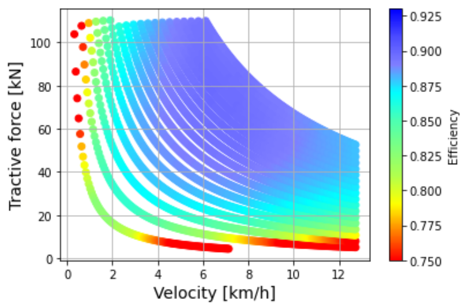


(c) Gear 3

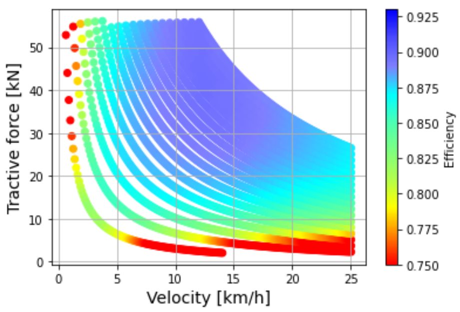
Figure 5.4: Powertrain efficiencies from the electrical motor to the wheels for different combinations of tractive force and velocity for the three-speed alternative.



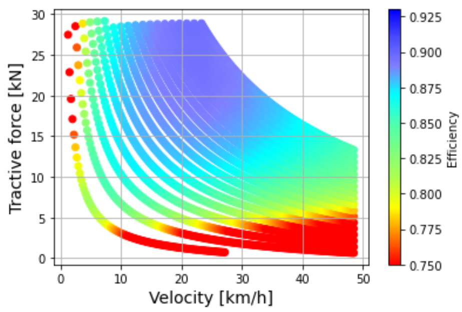
(a) Gear 1



(b) Gear 2



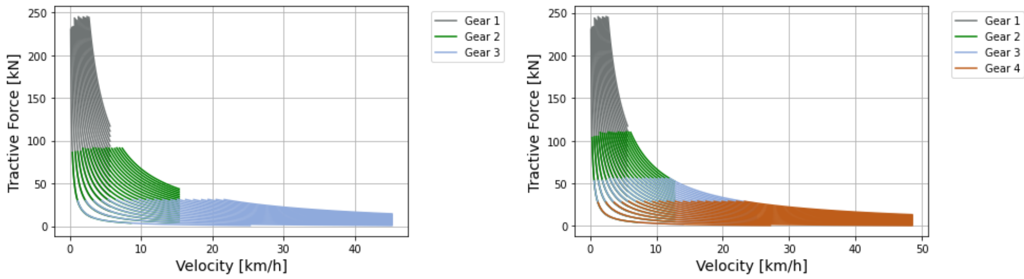
(c) Gear 3



(d) Gear 4

Figure 5.5: Powertrain efficiencies from the electrical motor to the wheels for different combinations of tractive force and velocity for the four-speed alternative.

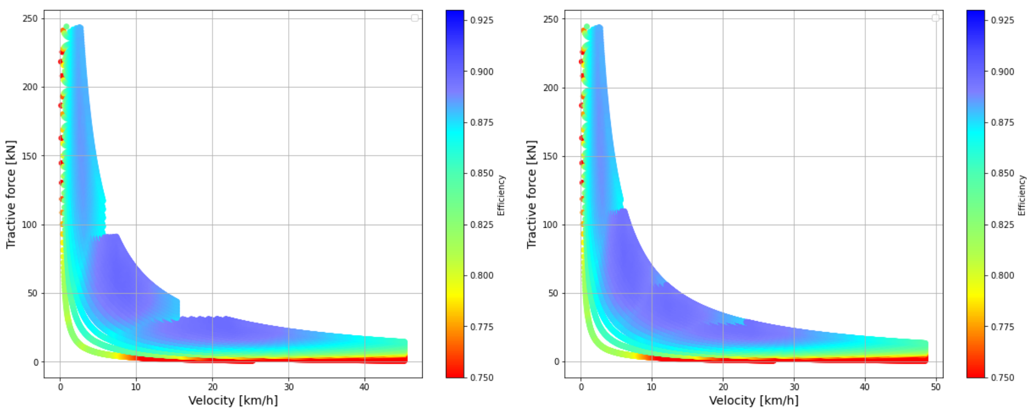
Combining the different gears in each alternative makes it evident that there are overlaps between the gears, allowing for multiple gear options at specific operating points. Figure 5.6 illustrates the operating areas for the gears in the two alternatives and their corresponding overlaps. The figures show that the three-speed alternative has fewer overlaps than the four-speed alternative. Another difference is that the four-speed alternative allows for higher vehicle speeds.



(a) Three-speed alternative (b) Four-speed alternative

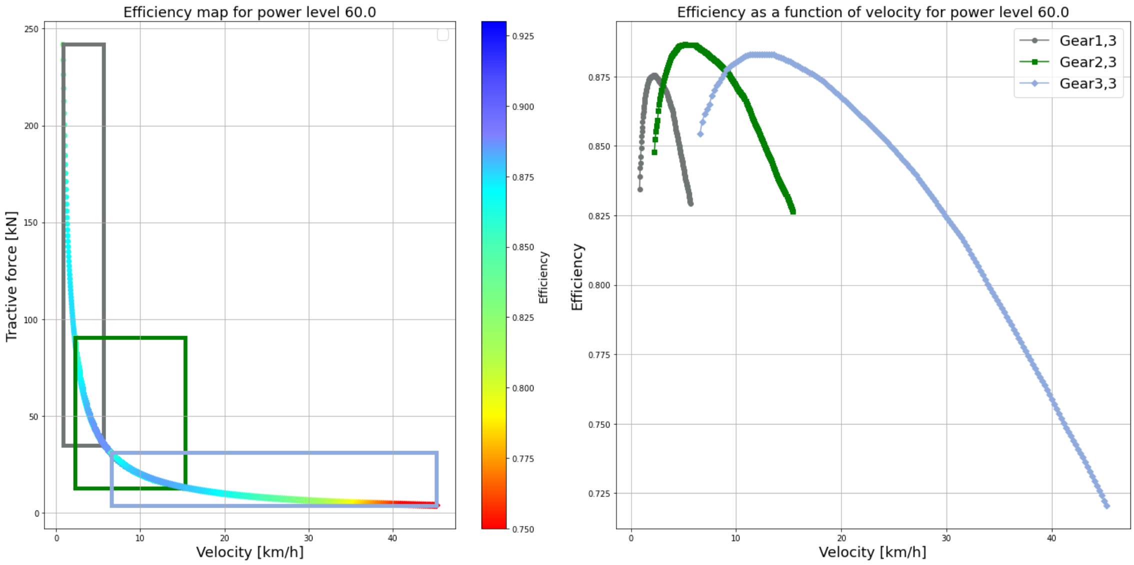
Figure 5.6: Tractive force as a function of velocity for different power levels and gears for one axle, for the two transmission alternatives.

Figure 5.7 shows efficiency maps for the three- and four-speed alternatives when choosing the highest efficiency for each operating point. Figure 5.8 shows as an example how the different gears overlap and how the efficiency varies for different gears for a single power level. Similar figures for different power levels are available in Appendix D.

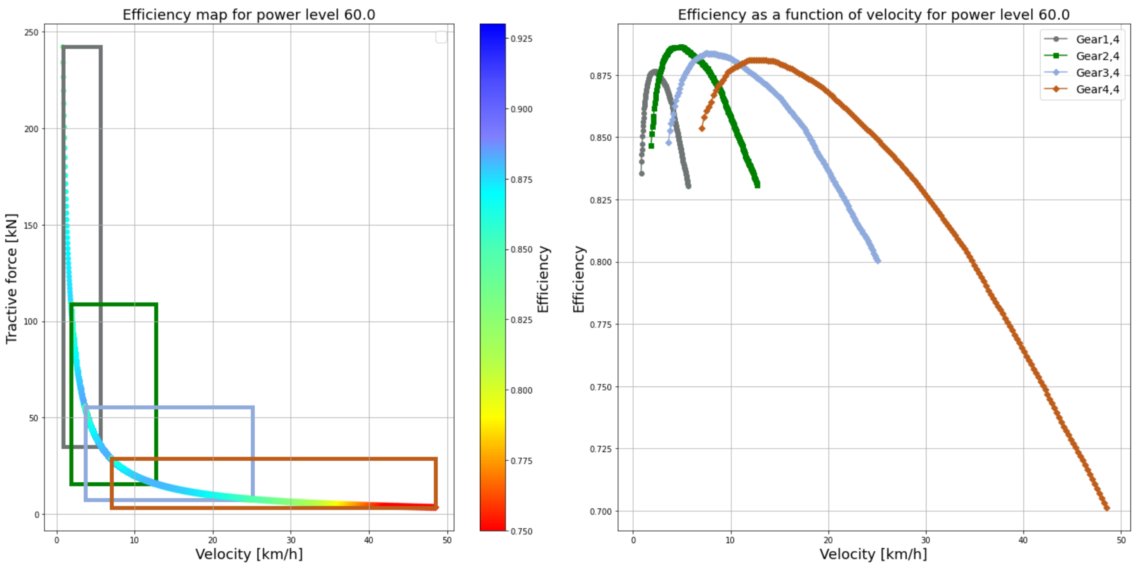


(a) Three-speed alternative (b) Four-speed alternative

Figure 5.7: Efficiency maps for the total operating area for one axle, including all gears for each transmission alternative.



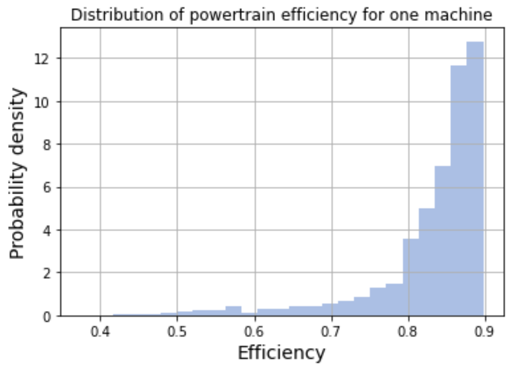
(a) Three-speed alternative, Power level = 60 kW



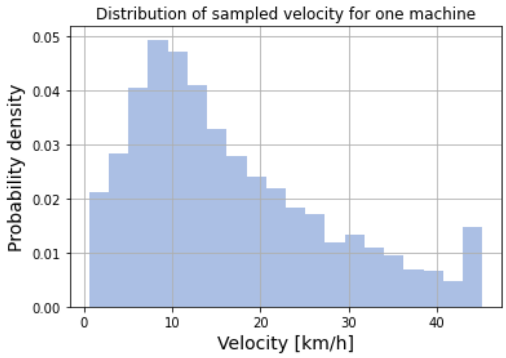
(b) Four-speed alternative, Power level = 60 kW

Figure 5.8: Illustration of variation of efficiencies for a single power level. The highest efficiency for each operating point was chosen when the graphs overlap.

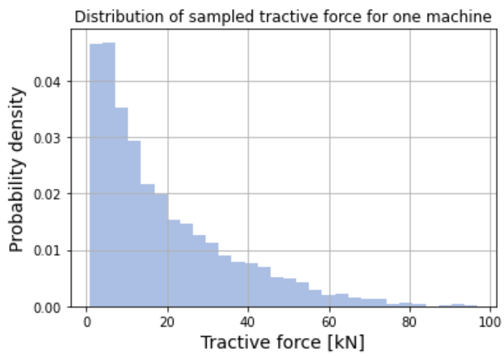
Figure 5.9 shows the results from the Monte-Carlo simulations for one randomly selected machine within the population. Figure 5.9a illustrates the efficiency distribution. The efficiency for this machine varies between approximately 50% and 90%. 5000 iterations were made for each machine since that resulted in a stabilization of the result. By plotting the sampled velocities and sampled tractive forces for a single vehicle and comparing them to the distributions used for sampling, it can be concluded that enough iterations were made to obtain a reliable result. This is because they closely resemble the original distributions shown in Appendix A. The Monte-Carlo simulations were repeated for many machines within the population. From the efficiency distribution, the average efficiency for a large number of machines was calculated.



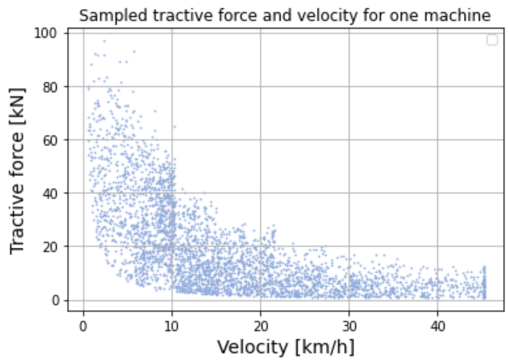
(a) Efficiency



(b) Sampled velocity



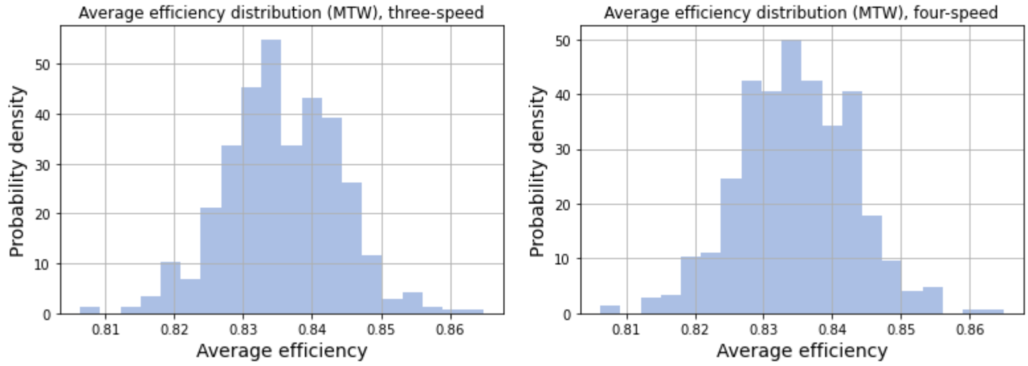
(c) Sampled tractive force



(d) Velocity and tractive force

Figure 5.9: Efficiency, velocity and tractive force distribution for one randomly selected machine within the population.

Figure 5.10 shows the average powertrain efficiency from the motor to the wheel for 500 articulated haulers operating worldwide. The mean value of the average efficiencies among the population is 83.52% for the three-speed alternative and 83.41% for the four-speed alternative. It can be concluded that both alternatives have a distribution that varies between approximately 81% and 86% for the different machines, which indicates that the number of gears does not significantly impact the overall powertrain efficiency.



(a) Three-speed alternative **(b)** Four-speed alternative

Figure 5.10: Distribution of average powertrain efficiencies for a large number of machines based on the efficiency evaluation and data from current operation.

Figure 5.11 shows the distribution of efficiency (motor to wheel) for an increased velocity for the three-speed alternative. It can be concluded that increased vehicle speed reduces the average efficiency of the vehicle and higher vehicle speed results in greater variation in efficiency. This can be explained by increased oil churning losses at higher speeds and decreased electrical motor efficiency at the edges of the efficiency map. However, the median remains high, indicating that the majority of points continue to cluster towards the upper section of the figure, even at higher velocities. The behavior is similar for the four-speed alternative.

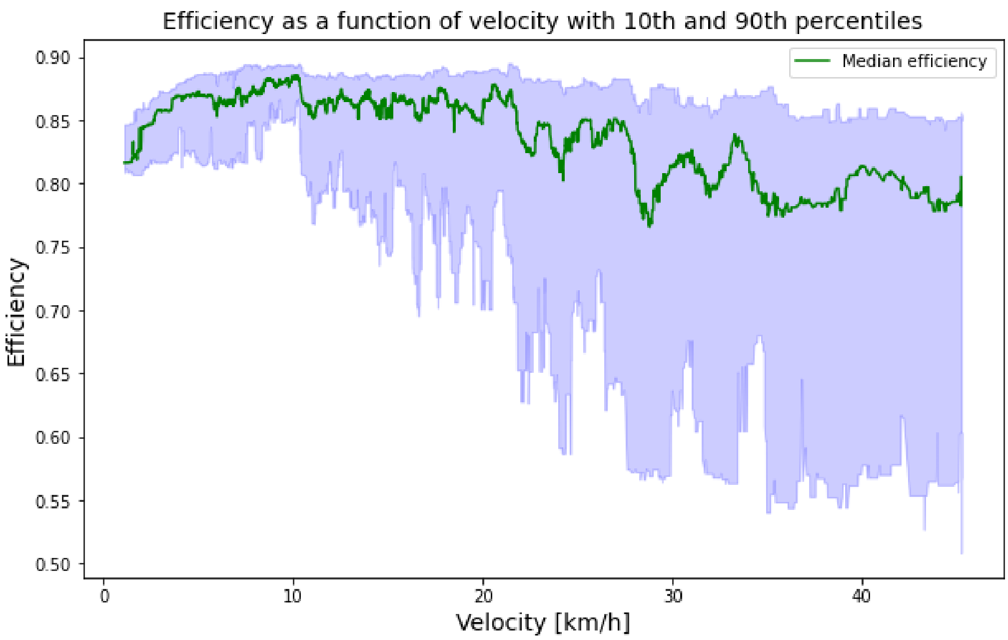
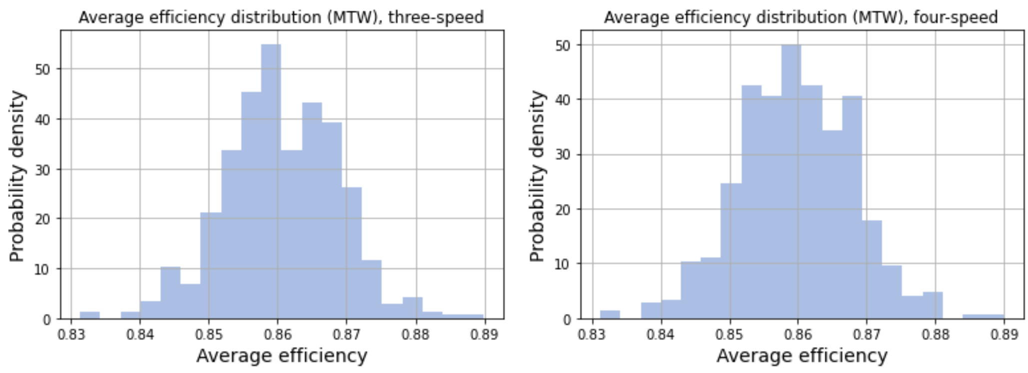


Figure 5.11: The distribution of efficiency as a function of velocity for the three-speed alternative.

Since the four-speed alternative has a higher maximum velocity than the three-speed alternative, this factor might negatively affect the four-speed efficiency. Therefore, the efficiency distribution calculations were repeated with the same maximum velocity for both alternatives. The mean average efficiency for the 500 machines for the four-speed alternative would be 83.44% when reducing the faster driving possibility. The difference became very small, which can be explained by the fact that the difference in velocity is small between the three-speed and four-speed alternatives, and the vehicles do not spend that much time in the highest velocities, according to the velocity distribution in Appendix A.

The oil churning losses contribute significantly to the total losses, making it desirable to reduce them by designing the powertrain differently. This is an area that VCE is actively working on, with the potential for significant reductions [22]. Therefore, all calculations were repeated with 50% of the oil churning losses compared to the conventional machines, rather than assuming them to be the same. The distributions of the average efficiencies are shown in Figure 5.12, and from the graphs, it can be concluded that the efficiency would increase by approximately 2.5 percentage points for both alternatives. Efficiencies maps for the two alternatives with 50% reduction of oil churning losses are available in Appendix D.



(a) Three-speed alternative

(b) Four-speed alternative

Figure 5.12: Distribution of average powertrain efficiencies for a large number of machines when oil churning losses are reduced to 50% of the conventional ICEV.

The efficiency evaluations from the electrical motor to the wheels for the two transmission alternatives are summarized in Table 5.1.

Table 5.1: The average efficiency from the electrical motor to the wheel for the different powertrain alternatives included in the study.

Transmission	Max velocity [km/h]	Oil churning	Efficiency [%]
Three-speed	45.2	Same as ICEV	83.52
Four-speed	48.5	Same as ICEV	83.41
Four-speed	45.2	Same as ICEV	83.44
Three-speed	45.2	50 % of ICEV	85.92
Four-speed	48.5	50 % of ICEV	85.80
Four-speed	45.2	50 % of ICEV	85.82

The efficiency evaluation has now been presented from the electrical motor to the wheels. To obtain the overall efficiency of the electrical powertrains, it is essential to include the efficiency of either the battery or the fuel cell, as well as the PTOs, as explained in Section 4.1. The efficiencies of the powertrains for BEV and FCEV are presented in Table 5.2. The table also provides a comparison with the efficiency of conventional machines, which has been calculated by VCE in previous studies. The battery, fuel cell, and ICE efficiencies are derived from the literature and from discussions with industry representatives [29], [34], [10], [22]. The PTOs and auxiliaries are assumed to be the same size as the conventional ICEV, and powertrain losses for ICEV have been calculated by VCE in previous studies [22].

Table 5.2: The powertrain efficiencies from tank/battery to wheel for BEV, FCEV and ICEV. The values within parentheses represent efficiencies when oil churning losses are halved.

BEV	**Efficiency** [%]
Battery, discharging	≈ 93- 98
PTOs and auxilieries	≈ 92
Motor to wheel	≈ 81 - 86 (84 - 88)
Total	≈ 70 - 78 (72 - 80)

FCEV	**Efficiency** [%]
Fuel cell (+battery)	≈ 40 - 50
PTOs and auxilieries	≈ 92
Motor to wheel	≈ 81 - 86 (84 - 88)
Total	≈ 30 - 39 (31 - 41)

ICEV	**Efficiency** [%]
Engine	≈ 35 - 45
PTOs and auxilieries	≈ 92
Transmission, dropbox and axles	≈ 80
Total	≈ 26 - 33

In conclusion, BEV exhibits the highest efficiency, while ICEV demonstrates the lowest. However, it is important to note that the efficiency for ICEV is a rough estimation based on previous calculations by VCE. In reality, efficiencies vary significantly, and to enhance the comparison, it would be beneficial to conduct a similar evaluation as done for electrical powertrains, which was excluded from the scope of this study. Average values of these approximated values have been used for further calculations to estimate the energy consumption, carbon footprint, and charging and refueling times of the vehicles.

5.2 Energy Consumption

The estimated distribution of energy consumption for ICEV, BEV, and FCEV are presented in Figure 5.13. As can be seen from the figure the ICEV has the highest energy consumption per operating hour, while the BEV has the lowest. This is due to the difference in energy efficiency of the different powertrain alternatives, presented in Table 5.2. The difference is also affected by the fact that electrical powertrains are more efficient during idling than ICE.

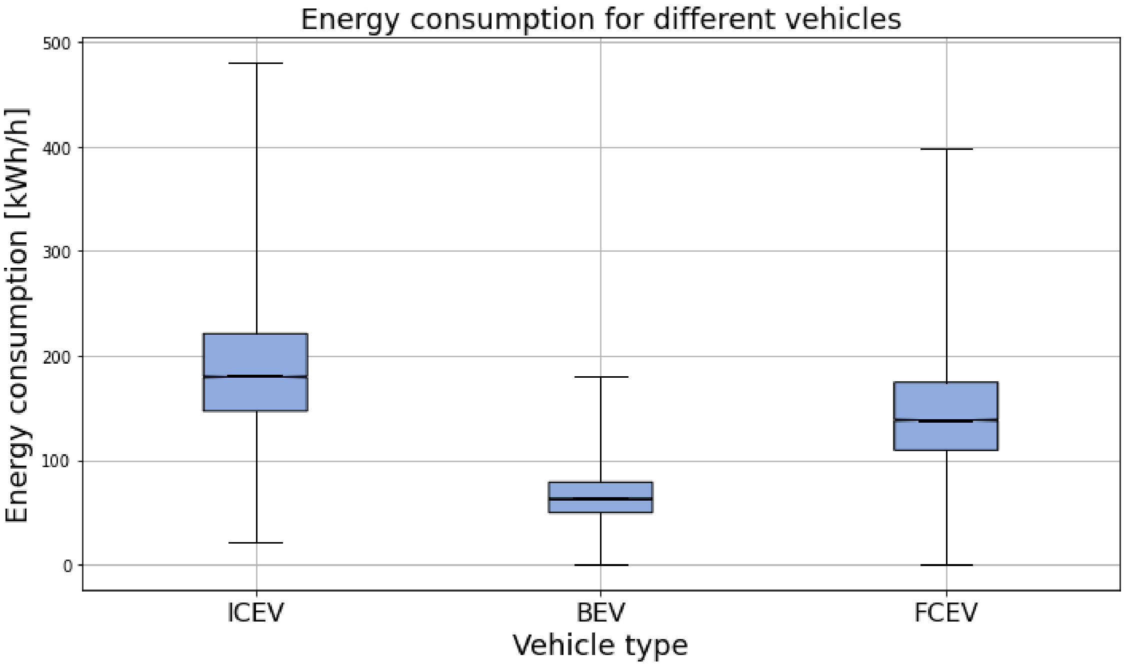


Figure 5.13: Energy consumption for ICEV, BEV and FCEV estimated based on data of fuel consumption and idling time for the ICEV, and the efficiency evaluation.

However, there are some parameters that affect the energy consumption in different ways. One important factor to consider is the weight difference between the vehicle alternatives. Since batteries have lower energy density than diesel and hydrogen, the BEV would result in a heavier powertrain and increase the tractive force needed at the wheels, increasing the energy consumption. From Equation 2.2 - 2.7 presented in Section 2.4 it can be seen that an increase of mass with 5% would increase the tractive force with 5% as well, assuming that the aerodynamic resistance is neglectable. This would also increase the energy consumption during driving with the same percentages. Previous studies have shown that the vehicle mass would increase with approximately 5 - 10 % for the BEV compared to ICEV [22].

Another aspect that is important to consider is the degradation of the battery and the fuel cell, which will decrease the efficiency of the components over time. How much and how fast this degradation process occurs is an uncertain question affected by numerous different parameters such as the SoC, number of charging cycles, and the operating temperature [30].

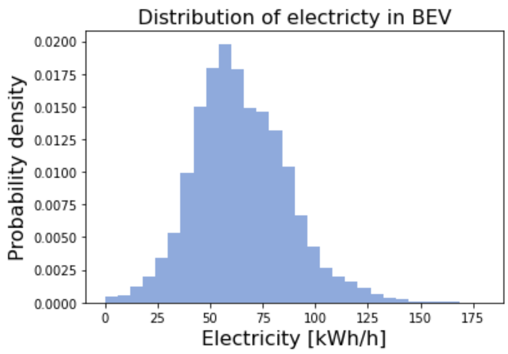
The possibility of recuperation for the electrical powertrains is a parameter that would reduce energy consumption. The vehicle's driving conditions highly affect how much energy that could be regenerated and stored in the battery again. More data would be needed to include this parameter in the model. The amount of regenerated energy is affected by numerous different parameters such as the load of the vehicle, the road surface, the slope and length of hills, and driving behavior, as explained in Section 2.4. If the articulated hauler drives in mud or sand, it will stop immediately due to the rolling resistance, and no energy will be recovered.

From the efficiency evaluation, it was also concluded that a reduction of oil churning losses by 50 % could increase the efficiency of the electrical powertrains by 2.5 percentage points. This could also reduce the energy consumption of the electrical vehicles.

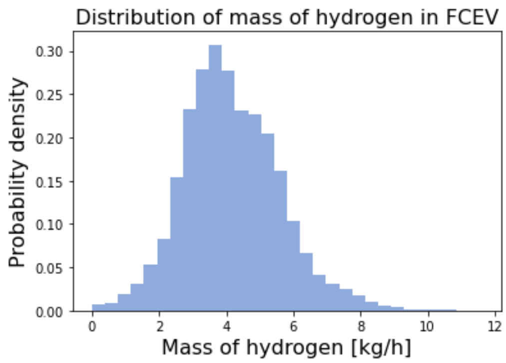
It can be concluded that there are several uncertainties and limitations with the methodology, which may affect the results of energy consumption and, therefore, also affect the calculations of charging and refueling times as well as the carbon footprint. More data and further research would be needed to make the model more robust and accurate.

5.3 Charging and Refueling Times

Figure 5.14 shows the distribution of electricity and hydrogen needed in the BEV and the FCEV per operating hour for the population, which have been calculated from the estimated energy consumptions.



(a) Electricity, BEV



(b) Hydrogen, FCEV

Figure 5.14: Distribution of the amount of electricity and hydrogen needed in the BEVs and the FCEVs.

Table 5.3 shows the amount of onboard energy that is assumed in the calculations based on the volumetric densities of the energy carriers. A hydrogen tank with 22 kg compressed hydrogen to 700 bars would result in the same volume as a 480-liter diesel tank. The onboard capacity is converted into onboard energy in kWh equivalents, which shows that the ICEVs have the possibility to transport much more energy due to higher energy density. The SoC window for the BEV is assumed to be 60 %, and the reason behind this assumption is the degradation process of batteries. To ensure optimal performance, a battery should not be charged and discharged fully, and the optimal SoC is from 20% to 80% of the full capacity [30]. For the ICEV and the FCEV, 90 % of the onboard energy is assumed to be used before refueling. The table also shows the assumed charging power level and flow rates for refueling based on literature reviews and discussions with industry representatives [35], [10], [36] [22].

Table 5.3: Assumption regarding onboard energy capacity on the different vehicle alternatives along with charging and refueling rates.

Vehicle	Onboard capcity	Onboard energy [kWh eq]	Refueling rates
ICEV	480 l/tank.	4920 (4430, 90%)	40 l/min
BEV	540 kWh	540 (325, 60%)	350 kWh/h
FCEV	22 kg/tank	833 (750, 90%)	3 kg/min

Figure 5.15 presents the distributions of potential driving hours before the vehicles need charging or refueling based on energy consumption estimations and the assumptions in Table 5.3. As shown, the ICEVs can drive almost four times longer than BEVs and FCEVs. For the 25 % of the population with the highest energy consumption, the FCEV and the BEV would have to charge more often than every fourth hour, which can be seen as a limiting factor for those vehicles. This is because of the lower energy density of batteries and the limited onboard energy storage for electric vehicles. By increasing the SoC window to 80 %, the operating hours before charging or refueling is needed could increase, but this would also result in faster degradation of the batteries and lower efficiency over time. Hydrogen also has a lower energy density than diesel, and it could be possible to increase the size of the tank to increase the number of operating hours before refueling, but more volume for the hydrogen tanks would be required.

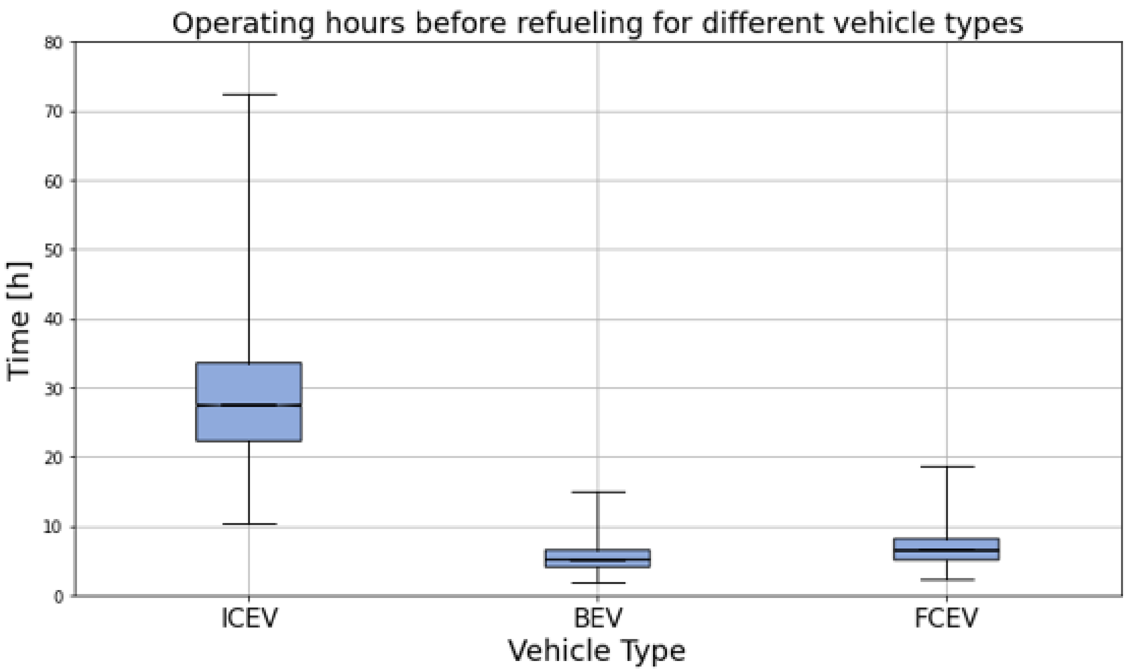


Figure 5.15: Operating hours before refueling/charging for ICEV, BEV and FCEV.

Figure 5.16 shows the distribution of an average number of minutes of refueling or charging for one hour of driving for different machines within the population. As can be seen, the BEV has a disadvantage here. The average charging time for one hour of driving for BEVs would be 11 minutes compared to 0.5 minutes for ICEVs and 1.5 minutes for FCEVs. It can be concluded that even though the FCEVs have a limited range, they would have to spend less time refueling than BEVs due to the faster refueling times.

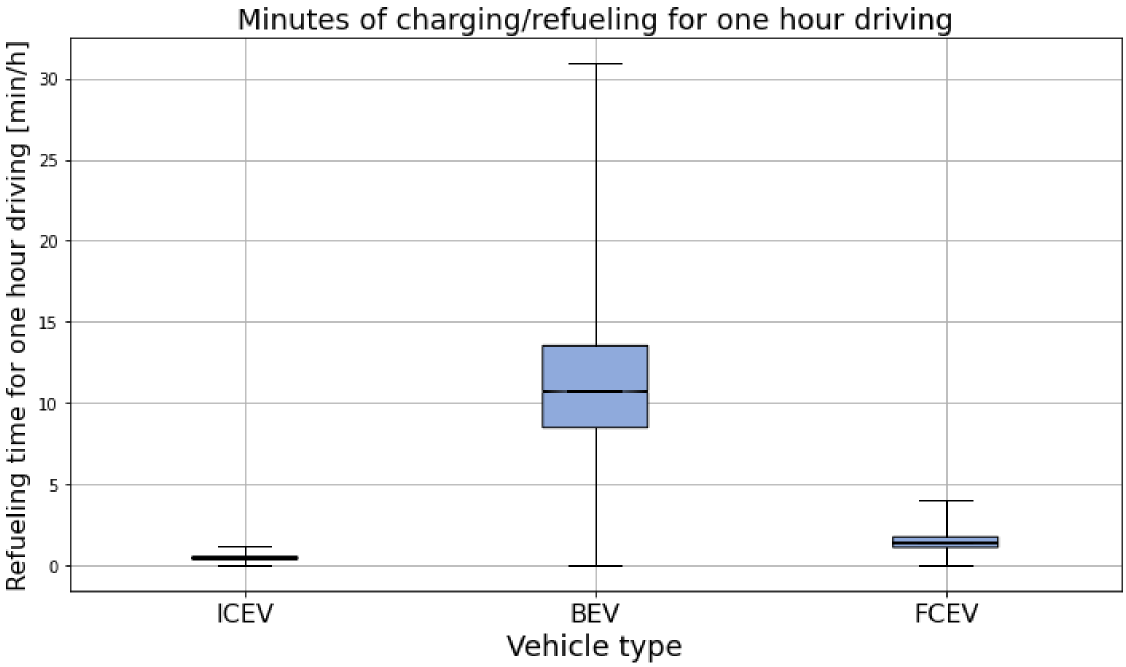


Figure 5.16: Minutes of charging/refueling per driving hour for ICEV, BEV and FCEV.

The frequency of charging required by customers also depends on their daily operating hours. Utilizing data logs of daily operating hours can facilitate further research to understand how much time customers actually spend driving and whether the charging duration necessitates behavioral adjustments. The challenges related to charging time and the limited range of the BEVs can also be mitigated by introducing new charging strategies such as battery swapping, which has shown to be a promising alternative in previous research [37].

5.4 Well to Wheel Carbon Footprint

The WTW CFP distributions for each vehicle type and for different energy carriers are presented in Figure 5.17 - 5.19. The WTW CFP is highly dependent on the energy consumption of the vehicles and on how the energy carriers have been produced. Since there are various hydrogen and electricity production methods, the CFP varies a lot for different user cases. Emission factors used for the calculations are available in Appendix C.

In Figure 5.17, a comparison is made between the ICEV, BEV, and FCEV, considering Europe as the geographic location. The diesel is assumed to be produced from the refining crude oil, and the electricity used in the BEV and for the production of hydrogen is considered as the European grid mix. From the graph, it can be concluded that the BEV for articulated haulers would result in approximately 3 times less kg CO2eq per operating hour than the ICEV, while the FCEV would only result in a small reduction of GHG emissions considering the WTW phase. This can be explained by lower energy consumption and overall higher efficiency from WTW for the BEV compared to FCEV.

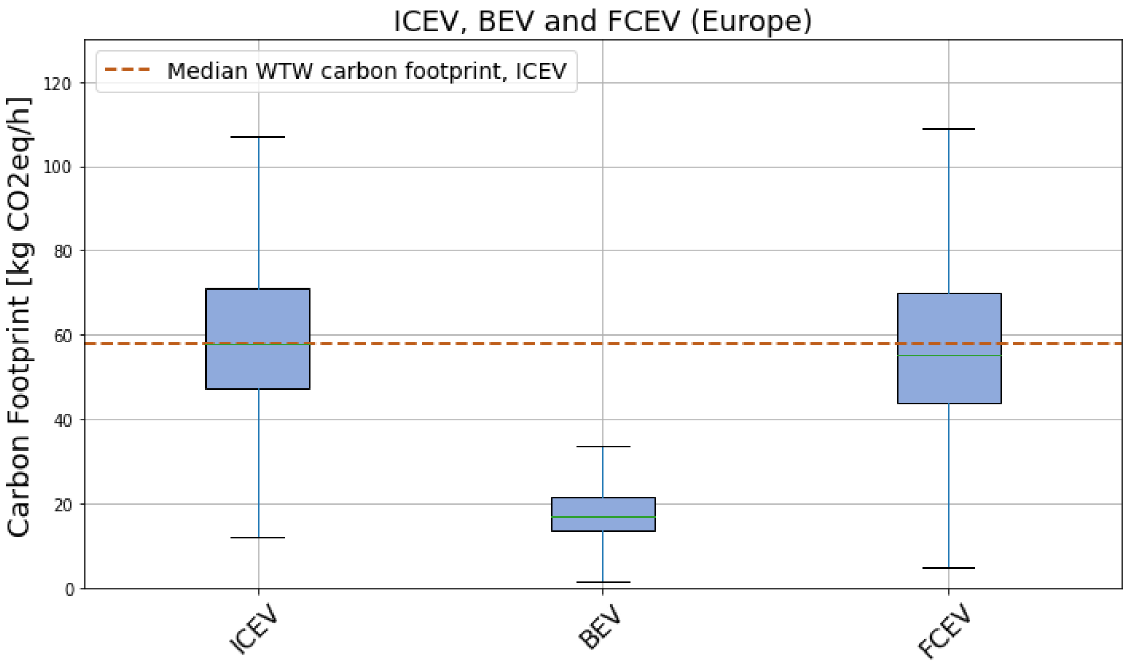


Figure 5.17: The well-to-wheel carbon footprint for different vehicles and different energy carriers considering Europe as the geographic location.

In Figure 5.18, a comparison is made between different geographic locations for the BEV. When the electricity is produced from renewables or nuclear, like in Sweden or in France, the CFP of the BEV results in a significant reduction of GHGs compared to ICEV. If the articulated hauler drives in Poland, where they still have a significant amount of fossil fuel used for power production, driving the BEV instead of the ICEV would not be more favorable. To make the BEV more favorable in all geographic locations, more renewable power production must be implemented in society first.

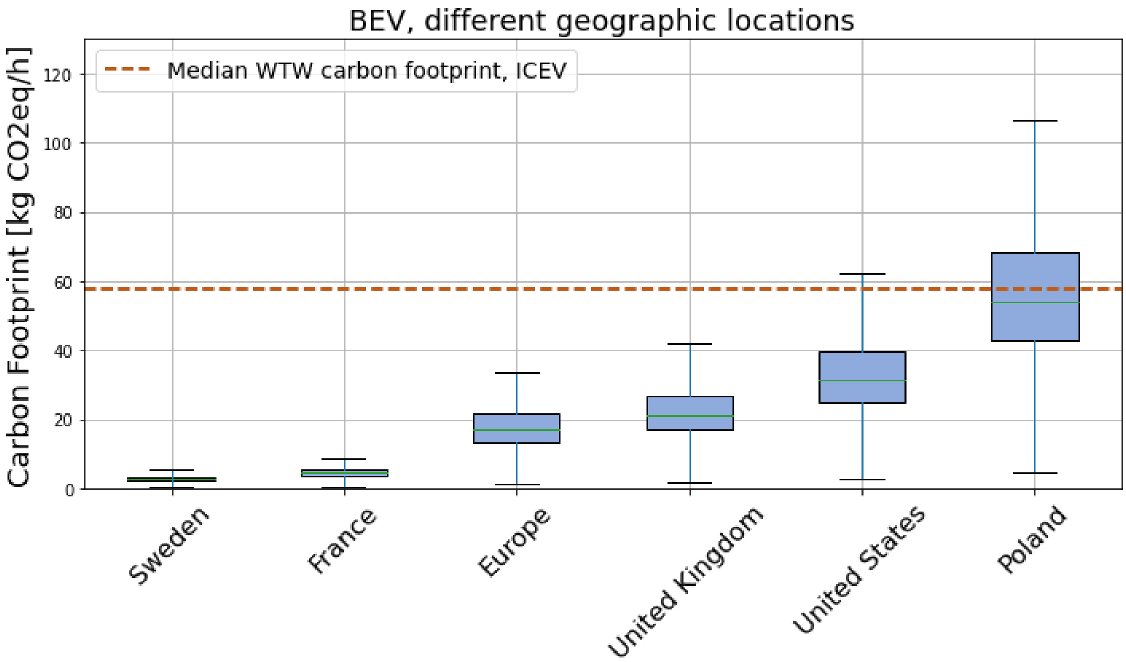


Figure 5.18: The well-to-wheel carbon footprint for the BEV in different geographic locations.

A comparison is also made between different hydrogen production methods, including electrolysis of renewable energy resources (Green hydrogen), the electrolysis from electricity considering the European grid mix, and hydrogen produced from steam reforming of natural gas (grey hydrogen). Even though the FCEV with hydrogen from renewable energy would not reduce the WTW CFP as much as the BEV utilizing renewable energy, it could still have a significant impact. Hydrogen produced from fossil fuel resources would not result in a reduction of CFP.

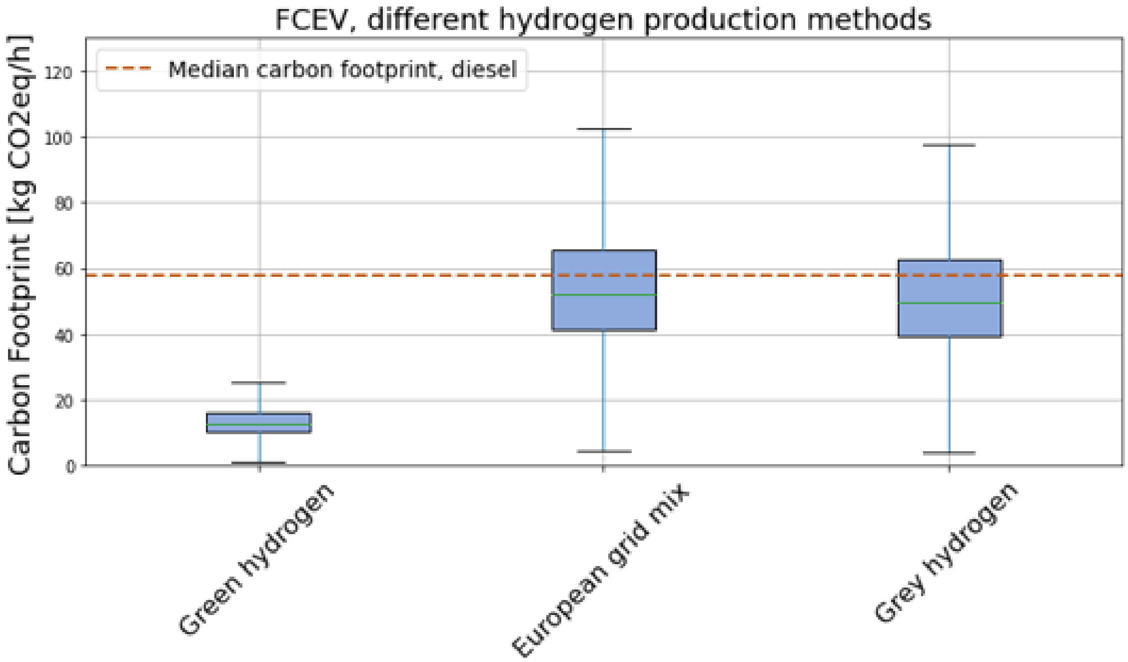


Figure 5.19: The well-to-wheel carbon footprint for the FCEV considering different hydrogen production methods.

Important to note here is that the manufacturing part and the end-of-life part of the vehicles are not included in the calculations. As written in Chapter 2 the CFP from the manufacturing part for BEV would be higher than ICEV, which also is important to consider when choosing the most appropriate technology. This could result in a higher CFP for the whole life cycle when the BEV utilizes electricity in for example Poland.

The functional unit, expressed as kg CO2eq/operating hour, provides a metric for comparing the carbon footprint of different machines. However, it is important to acknowledge its limitations. This unit does not account for the varying levels of work done during one hour of operation. For example, two vehicles might both operate for one hour, but one might transport significantly more material or drive a longer distance.

6

Conclusions

Based on the results of the study, it can be concluded that the energy efficiencies for both the three-speed and four-speed alternatives are similar, from the electrical motor to the wheels. Therefore, other factors, such as costs or usability, should be prioritized when designing the powertrain. One potential way to increase the efficiency of the powertrain is to reduce oil churning losses. A 50 % reduction in oil churning losses could potentially increase efficiency by 2.5 percentage points for the electric powertrains. Additionally, the study indicates that the BEVs offer the highest overall average powertrain efficiency at 73%, compared to 34% for FCEVs and 29% for ICEVs.

To determine the recommended power option for different user cases, energy consumption, charging and refueling times, and the well-to-wheel carbon footprint are compared. According to the methodology and assumptions in this study, BEVs exhibit 35% of the energy consumption of ICEVs, while FCEVs exhibit 77% of the energy consumption of ICEVs. The study also indicates that both BEVs and FCEVs have limited ranges compared to ICEVs due to the lower energy density of batteries and hydrogen compared to diesel. The quartile with the highest energy consumption would need to charge or refuel more often than every four hours for BEVs and FCEVs. Conversely, the quartile with the lowest energy consumption can drive for more than six hours before refueling or charging is needed. Comparing the alternatives in terms of charging or refueling time per hour of driving, it can be concluded that the BEVs have a disadvantage compared to ICEVs and FCEVs. The average charging time for one hour of driving for BEVs would be 11 minutes compared to 0.5 minutes for ICEVs and 1.5 minutes for FCEVs. Whether charging time is a limitation for BEVs depends significantly on the energy consumption levels as well as the number of operating hours per day. For some customers, the BEVs would require a change of mindset among the customers and different charging strategies to mitigate the challenges.

For most user cases, BEVs also have the lowest well-to-wheel carbon footprint. However, this is highly dependent on the production of the energy carriers. In countries like Poland, where the electricity mix includes a significant amount of coal, BEVs may not be more favorable than ICEVs. In countries like Sweden, where the electricity mix contains renewable and nuclear energy, the reduction of carbon dioxide emissions could be significant. FCEVs can also be advantageous compared to ICEVs in scenarios where renewable resources are used for hydrogen production, making them a suitable option in cases where BEVs face challenges with charging times or charging infrastructure. It can be concluded that both alternatives have advantages and challenges, and there will be trade-offs between different parameters in different situations.

6.1 Future Work

It is important to note that the study contains several limitations and simplifications, and more research could be beneficial to improve the results and accuracy of the study. There are several different ways to continue this project and expand the scope of the study.

Firstly, the energy consumption model could be enhanced by incorporating details like regenerative braking, which was excluded due to data limitations. It would also be possible to conduct a similar efficiency evaluation for the ICEV to receive a more precise comparison between the alternatives. To ensure the accuracy of the calculations, it is also significant to validate the energy model through simulations or experiments. The model could also be used to evaluate more diverse use cases, enabling a deeper understanding of the variations among customers.

The environmental focus has primarily been on the usage phase of the carbon footprint. For future research, it is important to broaden the scope to include the manufacturing and end-of-life phases. Additionally, the LCA could include other environmental aspects beyond global warming, such as toxicity or acidification.

Selecting the appropriate propulsion technology for future haulers is a complex issue influenced by various factors. There is potential to expand the research by considering additional aspects, such as Total Cost of Ownership, which holds significant importance for customers.

Exploring alternative propulsion technologies or fuels, such as hydrogen combustion, hybrid concepts, or genset electric vehicles, is also possible, as they could provide promising alternatives for future haulers. Additionally, evaluating different designs of electric powertrains to minimize losses as much as possible is a relevant continuation of the project.

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A

Data from Operation

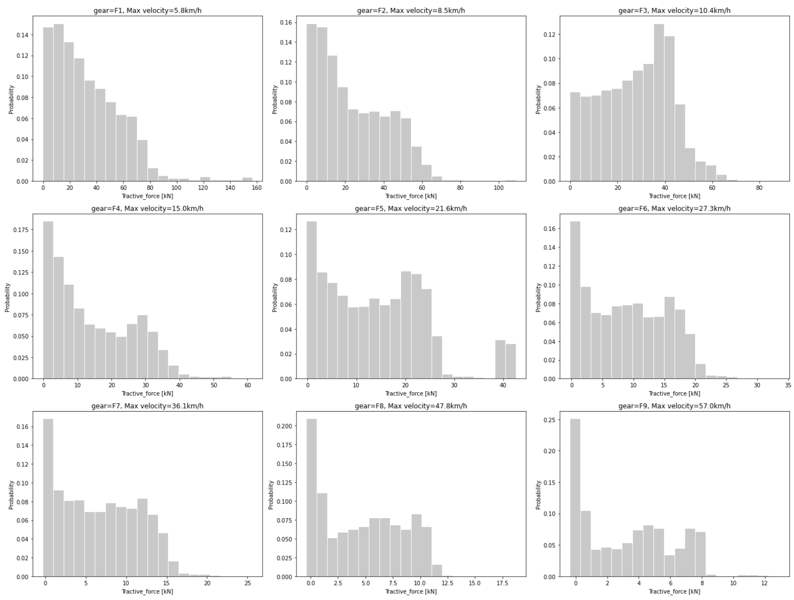


Figure A.1: The distribution of tractive force for different gears, for a large number of machines (ICEV). The values are calculated from logged data of turbine torque for different gears.

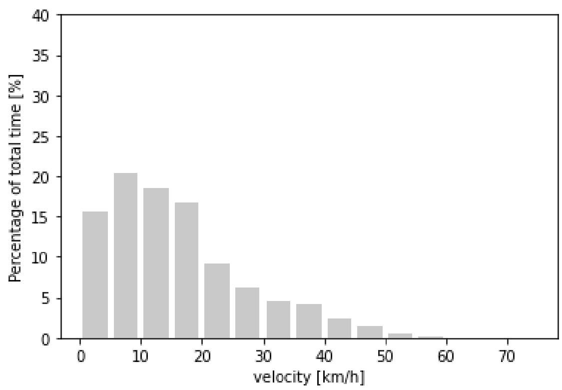


Figure A.2: The distribution of velocity for a large number of machines (ICEV).

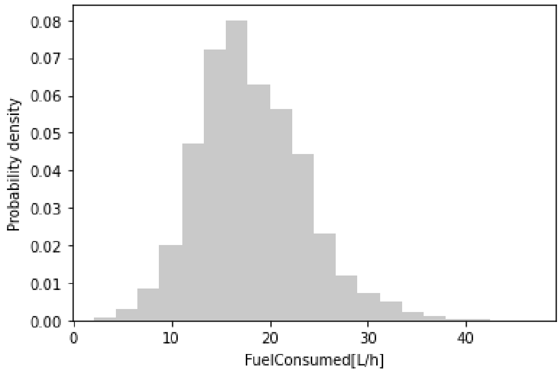


Figure A.3: The distribution of average fuel consumption for a large number of machines (ICEV).

B

Vehicle Design Data

B.1 Electrical Motor Efficiency

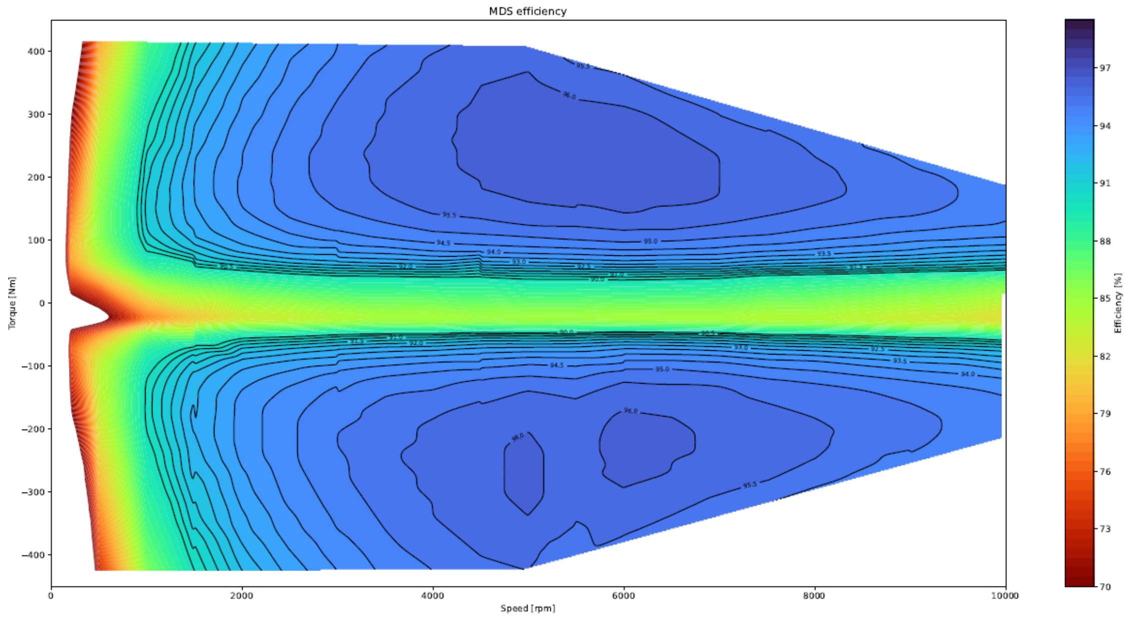


Figure B.1: The efficiency map for the electrical motor system used for BEV and FCEV. Data from [22]

B.2 Gear Mesh Losses

Table B.1: The input data for the three-speed alternative. Data from [22]

Gear	**1**	**2**	**3**
Total gear ratio	592	218	74.0
Gear ratio, Primary stage (PS)	3.70	3.70	3.70
Gear ratio, Planetary transmission (PT)	8.00	2.95	1.00
Gear ratio, Hub reduction (HR)	20.0	20.0	20.0
Efficiency, PT [%]	97.0	98.7	100
Efficiency, PS [%]	98.0	98.0	98.0
Efficiency, HR [%]	96.9	96.9	96.9
Speed at 10000 RPM [km/h]	5.70	15.4	45.2

Table B.2: The input data for the four-speed alternative. Data from [22].

Gear	**1**	**2**	**3**	**4**
Total gear ratio	592	263	134	69.2
Gear ratio, PS	3.70	3.70	3.70	3.70
Gear ratio, PT	8.56	3.80	1.93	1.00
Gear ratio, HR	18.7	18.7	18.7	18.7
Efficiency, PT [%]	97.1	98.5	98.9	100
Efficiency, PS [%]	98.0	98.0	98.0	98.0
Efficiency, HR [%]	96.9	96.9	96.9	96.9
Speed at 10000 RPM [km/h]	5.70	12.7	25.0	48.4

Table B.3: Input data for the nine-speed ICEV. Data from [22].

Gear	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Gear ratio, PT	6.18	4.27	3.49	2.41	1.67	1.32	1.00	0.760	0.520
Gear ratio, Dropbox	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Gear ratio, HR	18.6	18.6	18.6	18.6	18.6	18.6	18.6	18.6	18.6
Efficiency, PT [%]	97.9	98.5	98.1	98.7	98.6	98.8	1.00	97.6	98.2
Efficiency, Dropbox [%]	99.0	99.0	99.0	99.0	99.0	99.0	99.0	99.0	99.0
Efficiency, HR [%]	94.0	94.0	94.0	94.0	94.0	94.0	94.0	94.0	94.0
Max speed [km/h]	5.80	8.50	10.4	15.0	21.6	27.3	36.1	47.8	57.0

B.3 Oil Churning Losses

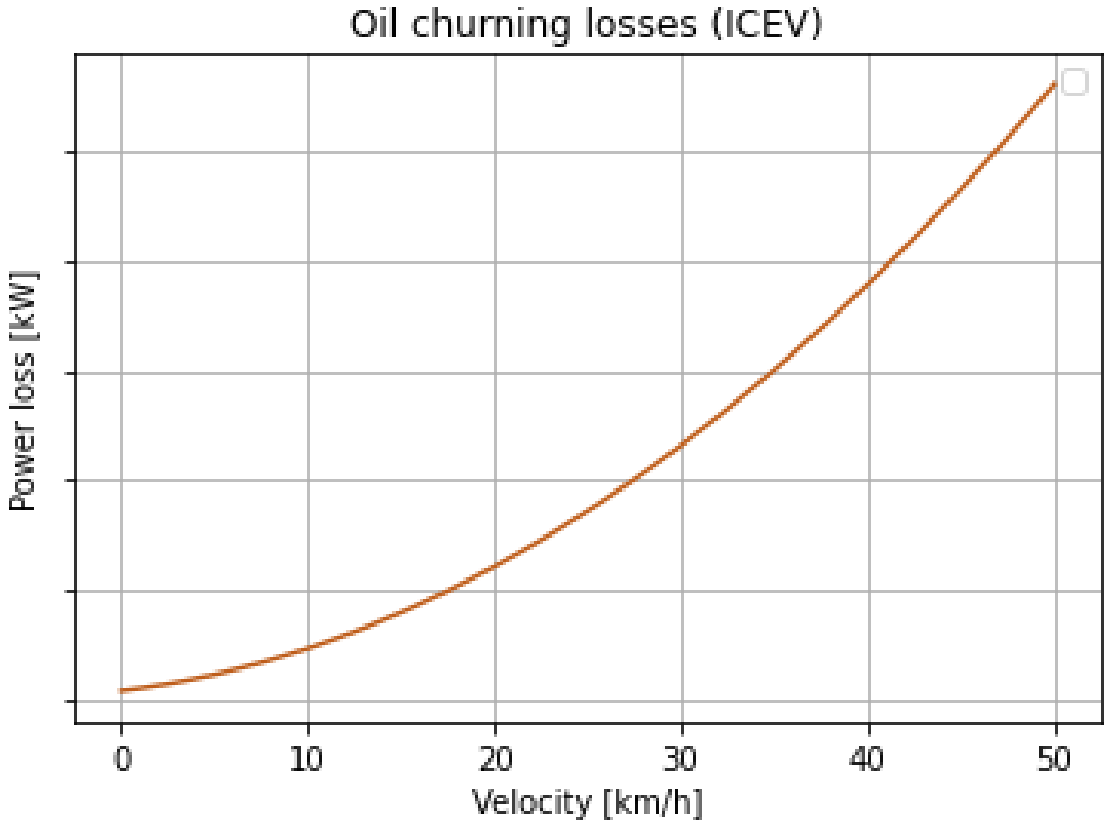


Figure B.2: The oil churning losses per axle in the ICEV as a function of velocity. Data from [22]

B.4 Drag Losses

Table B.4: The input data for the calculations of drag losses for open clutch (C) and brakes (B) for the three-speed alternative. Data from [22]

	B1	**B2**	**C1**
Di [mm]	350	320	190
Do [mm]	380	380	250
h [mm]	1.50	3.00	3.00
Number of friction discs	6	4	4

Relative angular velocity	**B1**	**B2**	**C1**
Gear 1	0	0.325	0.875
Gear 2	0.245	0	0.660
Gear 3	1	1	0

Table B.5: The input data for the calculations of drag losses for open clutch (C) and brakes (B) for the four-speed alternative. Data from [22]

	B1	**B2**	**B3**	**C1**
Di [mm]	360	360	300	175
Do [mm]	400	400	340	220
h [mm]	2.00	2.00	2.00	2.25
Number of friction discs	8	4	3	3

Relative angular velocity	**B1**	**B2**	**B3**	**C1**
Gear 1	0	0.199	0.829	1.199
Gear 2	0.166	0	0.526	1
Gear 3	0.453	0.345	0	0.655
Gear 4	1	1	1	0

C

Emission Factors

Table C.1: Emission factors for electricity consumption in different geographic locations from a life cycle approach, including the production, upstream phase, and transmission (Well to Tank). Data from [38] and [17].

Country	**CO_2eq [kg/MWh]**	**Type of Dataset**
United Kingdom	320	Grid mix
United States	400	Grid mix
France	87	Grid mix
Poland	880	Grid mix
Sweden	27	Grid mix
Europe	270	Grid mix

Table C.2: Emission factors for different hydrogen production methods, including raw material production, hydrogen production, compression, and transportation (Well to Tank). Data from [17] and [39].

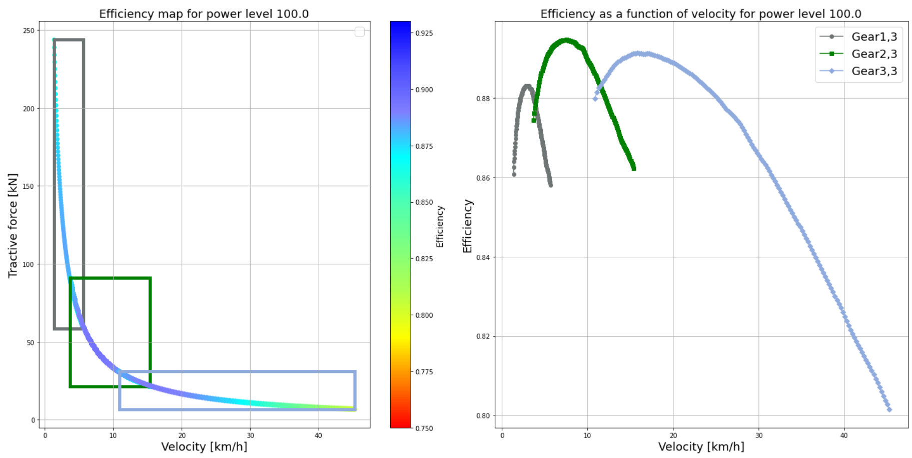
Production method	**Color code**	**CO_2eq [kg/kg]**
Steam Reforming of Natural Gas	Grey	13
Coal Gasification	Black	28
Electrolysis, renewables	Green	3.3
Electrolysis, European grid mix	-	14

Table C.3: Emission factors for diesel production and use. Data from [17].

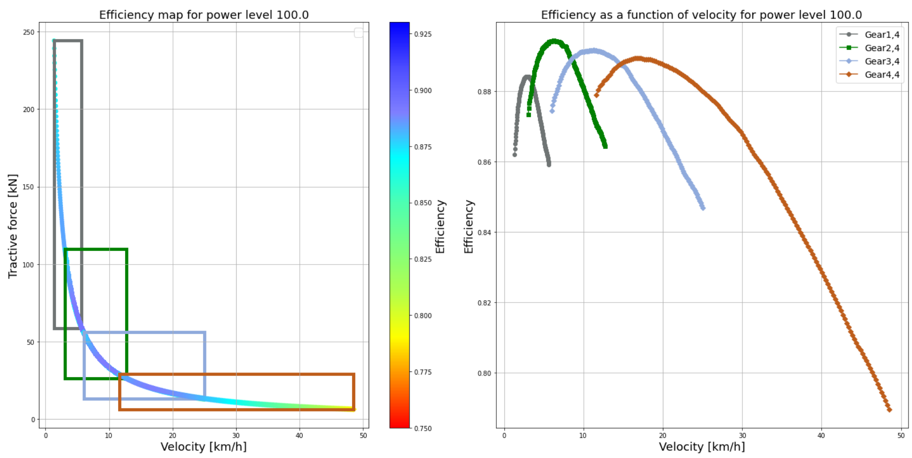
Diesel	**CO_2eq [kg/liter]**
Well to Wheel	3.3
Well to Tank	0.60
Tank to Wheel	2.7

D

Supplementary Results

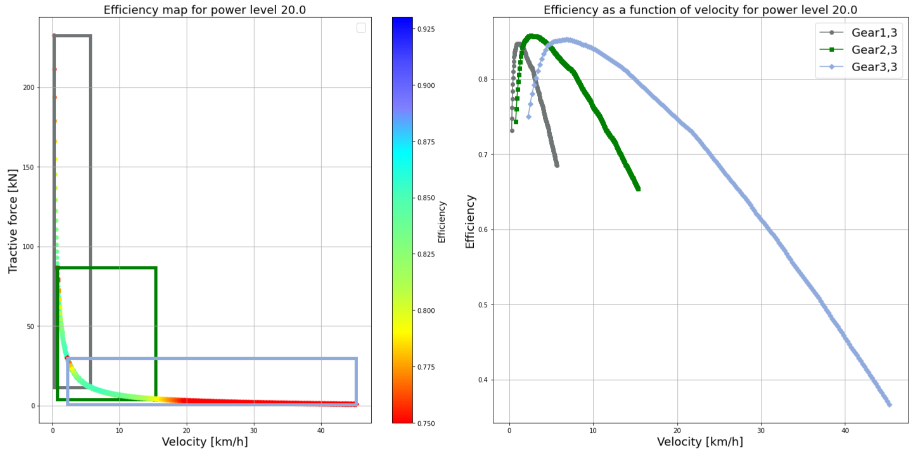


(a) Three-speed alternative, Power level = 100 kW

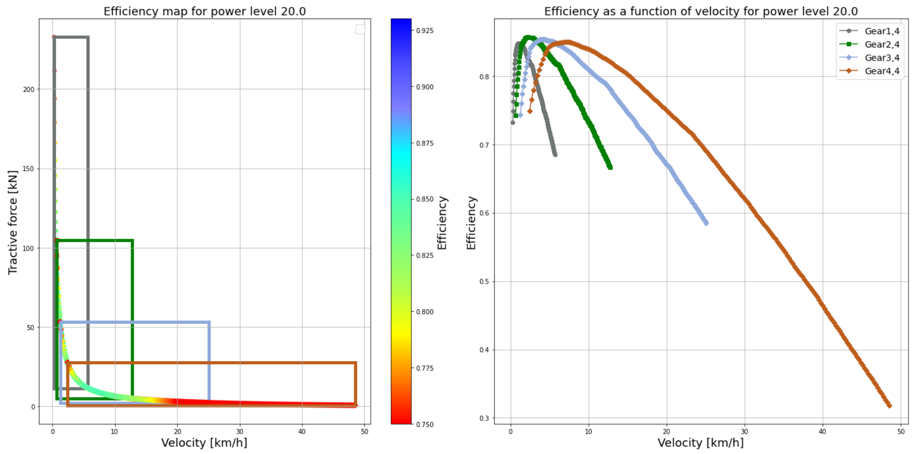


(b) Four-speed alternative, Power level = 100 kW

Figure D.1: Illustration of variation of efficiencies for different gears and power level 100 kW.

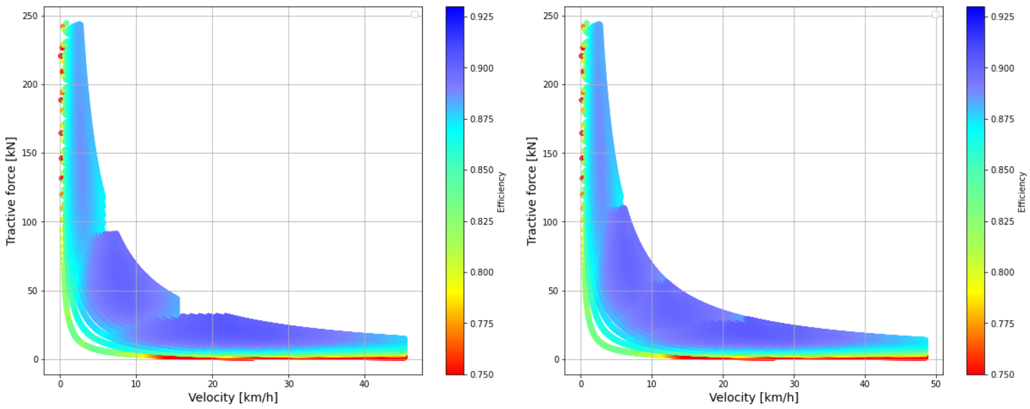


(a) Three-speed alternative, Power level = 20 kW



(b) Four-speed alternative, Power level = 20 kW

Figure D.2: Illustration of variation of efficiencies for different gears and power level 20 kW.



(a) Three-speed alternative **(b)** Four-speed alternative

Figure D.3: Efficiency maps for the total operating area, including all gears for each transmission alternative, when oil churning losses are reduced by 50 %.

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