Electrically Propelled Semi-trailer

Dimensioning and Packaging of an Electrical Powertrain in a Semi-trailer

Master's thesis in Mobility Engineering

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Gothenburg, Sweden 2023
www.chalmers.se

Master's thesis 2023

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Master's Thesis 2023
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Cover: First generation E-Trailer

Typeset in LaTeX
Printed by Chalmers Reproservice
Gothenburg, Sweden 2023

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Abstract

This thesis set out to dimension an electrical powertrain and package it in an existing chassis. The thesis started with benchmarking an existing E-Trailer together with the responsible people. The pre-study started with a market analysis of other companies to better understand what they were developing. But to get a deeper understanding of what the companies were developing the market analysis transformed into a patent search. The pre-study resulted in a list of requirements for the E-Trailer.
To find out what dimensions the motor needed to execute functions such as increasing the startability and reversing only using the trailer's powertrain several hand calculations were made. To optimise the powertrain for fuel efficiency on different routes several drive cycles simulations were made. Once the dimensions of the motor and the batteries were decided it was time to select components that were available or soon to be available within Volvo Group. When the components were selected a rough CAD assembly was created to find out if the powertrain would work in the special chassis. The E-Trailer is expected to save up to 42% fuel compared to a conventional setup on a predetermined route.

Keywords: Electromobility, E-Mob, E-mobility, E-Trailer, Electric Trailer, Electric Powertrain

Acknowledgements

First of we would like to thank our supervisors **Clive Misquith**, **Emil Petterson**, **Lena Larsson** and **Per Axel Ohlsson** for their support through out this thesis. The insights and knowledge they have shared have been of great help in this thesis.

We would also like to thank the following persons for their support and advice during this thesis:

- **Per Björe**, CPAC
- **Olof Cronquist**, CPAC
- **Lennart Cider**, Expert Product Dev./Engineering, Volvo Technology
- **Niklas Fröjd**, Expert Technology Specialist-Handling, Volvo Technology
- **Geert Iven**, Goodyear
- **Klara Pålsson**, Product Architect, Volvo Technology

Lastly, we would like to thank the HCT group at Volvo Technology for including us in their group and giving us the support needed to make the best out of this thesis.

Anton Gustafsson
Eric Olsson
Gothenburg, June 2023

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis:

E-Trailer	Semitrailer with electric powertrain
SoC	State of Charge
ICE	Internal Combustion Engine
HCT	High Capacity Transportation
GCW	Gross Combination Weight
GTT	Group Trucks Technology
E-Axle	Driven axle with integrated Motors
GBG	Gothenburg
EDB	Engineering Database
AVP	Automated Vehicle Packaging
EM	Electric Machine
CAD	Computer Aided Design

Nomenclature

Below is the nomenclature of parameters and variables that have been used throughout this thesis.

Parameters

c_f	Rolling resistance coefficient
m_i	Mass of the component i
$A_{frontal}$	Frontal area of the truck
c_d	Drag coefficient
ρ_{air}	Density of the air
g	Gravity
a_{shift}	Acceleration during shifting
μ	Friction coefficient
r_w	Radius of the wheel
$Cost_k$	Cost of the component k
t_l	Time of instance l
v_{max}	Maximal Velocity
B_{window}	SoC window
θ	Angle of friction force
V_{start}	Initial velocity
$t_{shifting}$	Time to shift
l_n	Length of component n
h_m	Height of component m
α_{slope}	Angle of the slope

Variables

P_{ij}	Power on/from component ij
N_{ji}	Normal force on/from component ji
F_j	Force on/from component j
d_{max}	Maximal distance traveled in a day

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Introduction

New long-term goals of global emissions such as the 'Paris Agreement', which partly states that there should be a decrease of emissions such that the general temperature only rises with 2°C [5] and the 'European Green Deal' which states that until 2030 Europe should have a decrease of 55% compared to the carbon footprint of 1990 as well as being CO_2-neutral by 2050[3] creates the need of change within the mobility industry. There is an interest in realizing projects that can help Europe become the first climate-neutral continent. One of the many steps towards this is to make transportation more sustainable and less dependent on resources that contribute to the negative effects on the climate.

The move towards more sustainable transport solutions is making the transport industry move towards different energy sources than traditional fossil fuels. Volvo Trucks plans to have a fossil-free product range by 2040 with the help of battery-electric and fuel-cell electric vehicles [16]. This change in energy sources also brings changes in how truck manufacturers look at their product range. These new energy sources are less energy dense compared to liquid fossil fuels, like diesel, which means that the available transportation range is more limited than before. This requires the transportation solution to be more tailored to the specific type of transport and route. Together the fact that the customer does not want to pay for, potentially, over-dimensioned components that could be a result of limited customization, shows that the need for more customization will be even more preferable in the future. This can be hard to meet at the large scale of a truck manufacturer, like Volvo Trucks, due to each truck being built requiring more manual work than before to meet the customer's expectations and requirements. A commonly used solution to this is to make the trucks modular. With the change in fuel and powertrains, this appears to be even more important, to make a competitive package for the new trucks compared to the old variants.

A promising idea that should decrease the carbon footprint is to integrate an electrical propulsion system in a semitrailer, further E-Trailer. This makes it possible for the semitrailer to help the truck during several operations. One example of an operation is highway driving. The highways often have elevation differences where the E-trailer could make it possible to help propel the truck during uphills while recuperating energy during downhills. The downhill recovery will also help with improving the stability of the truck-trailer combination compared to a regular semi-trailer. Other benefits could be to use the propulsion system in the semitrailer to help with operations such as reversing and pushing extra power during heavy starts, which would decrease the energy usage from the diesel engine.

1.1 Aim

The aim of this thesis is to present a deeper understanding of the capabilities, benefits, and general pros and cons of having an electrically propelled trailer and how, or if, they change depending on the route. This knowledge will help and guide the future development of the E-Trailer at Volvo Trucks. The thesis also aims to present a design suggestion of how a modular packaging solution for such an E-Trailer could look like.

1.2 Limitations

This thesis work will be done during the spring of 2023 and covers 30 credits per person, in total 60 credits for two students.

- Existing simulation tools for powertrain simulation will be used.
- Only one type of diesel truck will be considered when simulating.
- Only currently or soon to be on the market component from Volvo will be considered in the design and simulations.
- Supplier proposals and quotations from suppliers not included.

2

Background

In the following chapter background knowledge used in this thesis will be described as well as some necessary central concepts.

2.1 Use Cases for an E-Trailer

In the introduction, it was stated that an E-Trailer can be used to reduce fuel consumption by hybridization of existing trucks, but it is not the only way it could be beneficial. In this section, some of these secondary features will be brought up to show some other benefits that an E-Trailer could come with, beyond fuel savings.

2.1.1 Reversing and arranging at terminals

Traditionally, when reversing, the truck is pushing the trailer creating a twisting torque over the axle groups. This makes the trailer steer in the opposite direction of the steering wheel input. For an experienced driver, this phenomenon is not hard to counter when reversing a single trailer. However high capacity transport, HCT, projects at Volvo Trucks are testing with longer combinations, coupling two regular trailers together in the Autofreight project [6] for example. This increases the difficulty of reversing due to more joints being introduced and the input of the traction force and steering now comes from the last unit in the combination. In this scenario, it would be beneficial to have the last unit supplying the majority of the traction force required to reverse the combination. With an E-Trailer as the last unit, this would be possible, making the reversing of such a long combination much easier in theory. The truck would still add enough traction force to support itself making the electric powertrain of the E-Trailer only have to pull the trailers. Expanding on this, the last axle of the last trailer in the combination could also be steered to act as the main steering axle when reversing, and having axles on the second trailer also steered would increase the maneuverability of the combination as well. Having lifted axles on the trailers would also decrease the twisting torque required to steer the trailers making the combination even more maneuverable. In figure 2.1 a two-trailer combination reversing using the E-Trailer powertrain can be seen as well as where steerable axles could be placed to increase maneuverability.

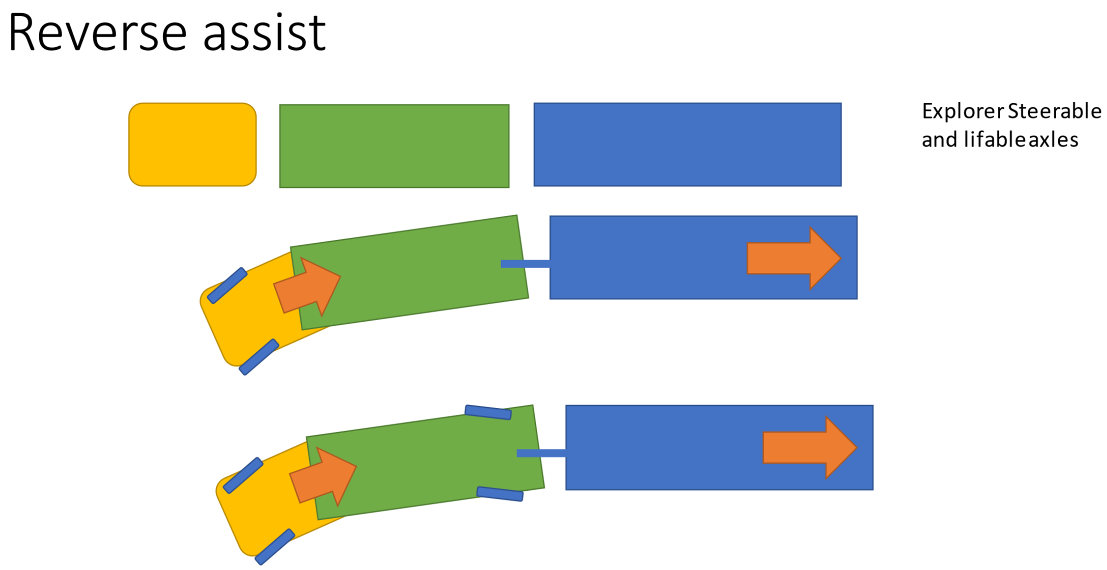


Figure 2.1: Reverse assist for longer combinations. Idea by Lena Larsson and Emil Petterson.

2.1.2 Startability

Naturally, the E-Trailer adds more traction force to the combination. This is because the normal force from the trailer's mass now can be used as traction force. This allows the combination to start from steeper slopes or to be able to start with higher gross combination weights. By having an axle on the trailer the traction force is more spread out over the entire vehicle combination. Because of this, the vehicle combination will not be as sensitive to surface friction. The driven axle/axles on the truck could have too little traction to deliver the required traction force to move the combination. With the help of the E-Trailer, the extra traction force could be applied to a surface with better friction and propel the combination.

The E-Trailer also would allow driving uphills at a more constant speed since the electric powertrain could support with extra traction force. This extra traction force would also allow the truck to run in higher gears while going up the hill, making the ICE run at lower RPM and thereby saving fuel.

2.1.3 Stability while descending

The HCT group at Volvo Trucks also works with running heavier combinations to decrease the number of transports required and thereby decreasing the emissions. Making heavier combinations able to stop and brake efficiently is of course a concern, especially in long descents where brakes easily can get overheated, which reduces their efficiency. A solution to this problem is that the E-Trailer uses its electric motor to brake. By running the electric motor in reverse, the energy that would have been transformed into heat is instead transformed into usable electricity. This means that the conventional brakes can be used less, since less energy is needed to be transformed into heat and that the conventional brakes can be used for longer periods of time without getting overheated due to heavy usage. Applying the brake force at the end of the combination will also increase the stability of the combination making it less prone to jack-knife, which is a scenario where the trailer pushes the truck, making it spin and fold towards the trailer.

2.2 Regulations and Standards

The modular concept is a way of building vehicle combinations with the help of different types of trailers and trucks [14]. The types of trailers are usually full trailers, semi-trailers, link trailers, converter dollys, and center-axle trailers while the trucks usually are rigid trucks and tractors. All these road train components are illustrated as a table in figure 2.2.

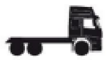
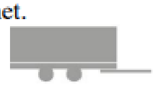
Lastbil (Engelska: Rigid truck)	Dragfordon med lastutrymme 
Dragbil (Engelska: Tractor)	Dragfordon utan eget lastutrymme. Den kopplas till en påhängsvagn 
Semitrailer (Engelska: Semi-trailer)	Släp med axlar baktill och kopplingstapp fram 
Släpvagn (Engelska: Full trailer)	Släp med axlar både baktill och framtill. De främre axlarna är styrande och följer med dragstångens vridning. 
Link (länkpåhängsvagn) (Engelska: Link trailer)	Påhängsvagn med vändskiva baktill för tillkoppling av ytterligare påhängsvagn 
Kärra (släpkärra) (Engelska: Centre-axle trailer)	Släp med dragstång, och axlarna centrerade ungefär kring mitten av lastutrymmet. 
Dolly (Engelska: Colly or Converter dolly)	Släp utan eget lastutrymme. Den har dragstång framtill och en vändskiva över axlarna för tillkoppling av påhängsvagn. 
Fordonskombination (Engelska: Vehicle combination)	Ett dragfordon med ett antal tillkopplade släp. Exempel Lastbil med dubbla påhängsvagnar, typ AB-dubbel 

Figure 2.2: Components that could be used in a vehicle combination [7]

2.2.1 Standard Weights

How much a truck and trailer combination is allowed to weigh depends on what bearing capacity class the road itself has. The bearing capacity classes differ between countries and roads within the specific country. The different national transportation agencies determine what bearing capacity class the roads can take with regard to several factors from the vehicle combinations, mainly from the axle loads which include the total number of axles, axle configurations, distances between the axles/axle configurations, and total vehicle combination lengths but also from the overall condition of the road as well as its maintenance schedule [13].

Sweden has 4 different bearing capacity classes [8], BK1-BK4.

- BK1, max 64 tons, can be lower depending on distances between axles and their axle loads
- BK2, max 51.4 tons, can be lower depending on distances between axles and their axle loads
- BK3, max 37.5 tons, can be lower depending on distances between axles and their axle loads
- BK4, max 74 tons, can be lower depending on distances between axles and the same axle loads as BK1

The Swedish public road network mainly consists of roads that are classified as BK1. This is because there are a lot of country roads within the Swedish road network has the BK1 rating. The road ratings within cities are usually rated as BK2 which can be seen in figure 2.3 that illustrate the road network classifications within Gothenburg, Sweden [10]. Roads that are particularly soft or include obstacles that have a specific load capability such as bridges usually gets a BK3 rating. Since the BK4 classification allows for the highest max loading the routes that are BK4 rated are limited and almost exclusively highways.

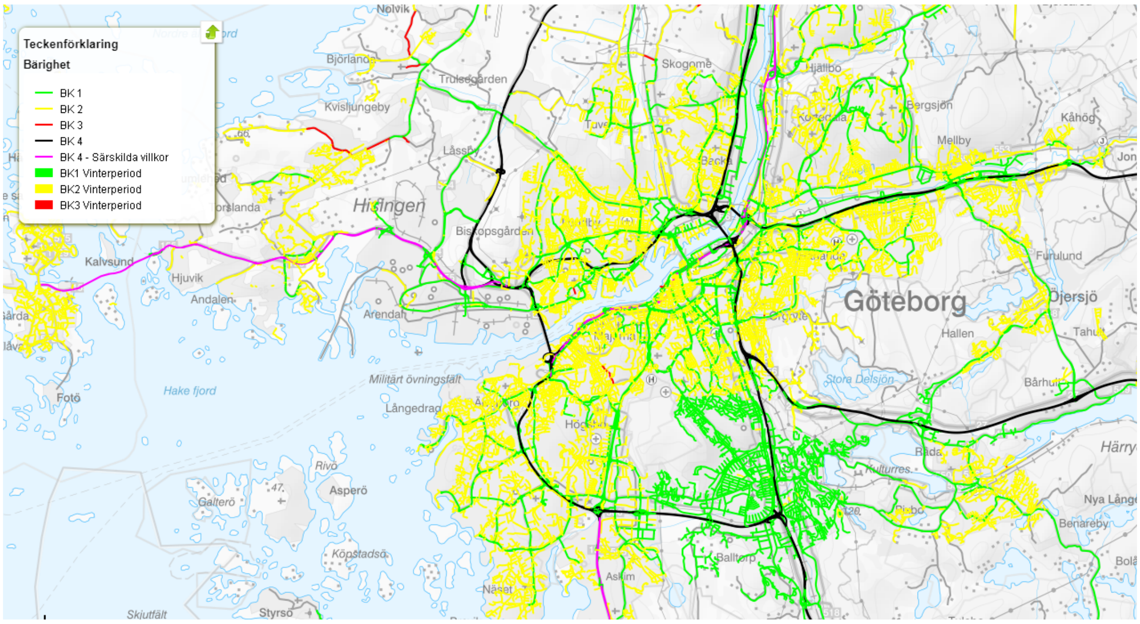


Figure 2.3: Bearing capacity classes of roads within Gothenburg [10]

2.2.2 Standard Lengths & widths

The longest length of a vehicle combination that is allowed on public Swedish roads is 25.25m long, considering they are following the common rules within the European Union. The European standard contains two different lengths and two different widths of trucks and trailers [14]:

- 7.82m long
- 13.6m long
- 2.55m wide
- 2.60m wide, only for temperature-controlled structures with minimum 45mm insulated walls

This makes it possible to create the most common combinations which are visible in figure 2.4, where the trailers named "A" has the 7.82m lengths and the trailers named "B" has the 13.6m lengths. Figure 2.4 also shows how the different combinations of link trailers, semi-trailers, dollys, and center-axle trailers should be used.

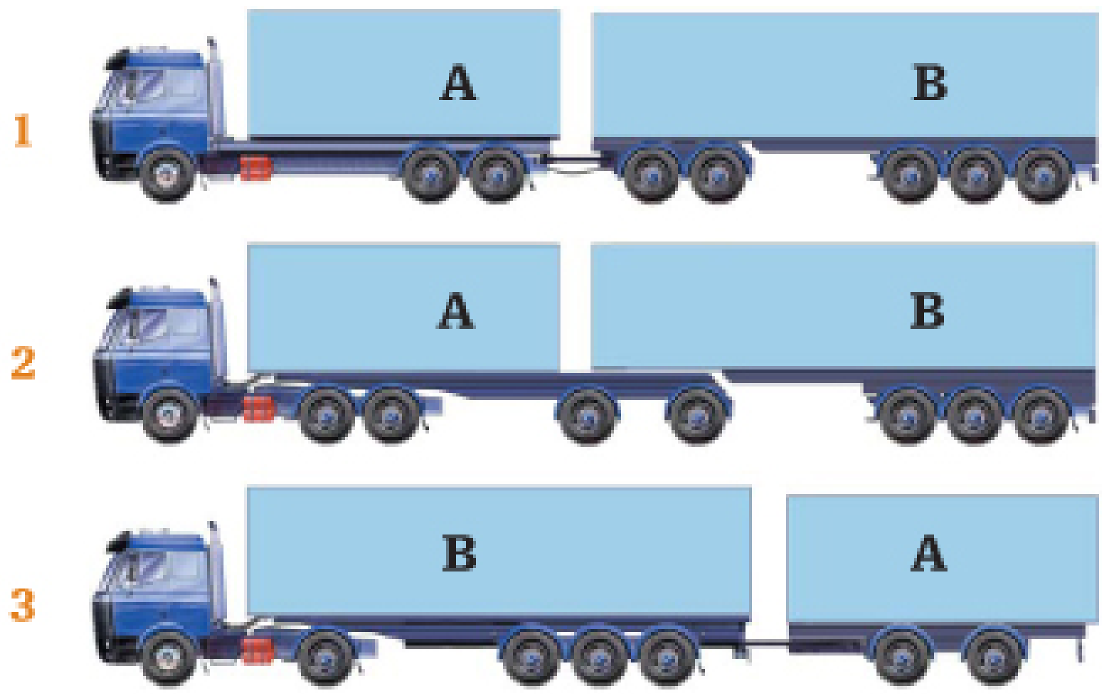


Figure 2.4: Visualization of the longest vehicle combinations from the 25.25m regulation [14]

To ensure that the truck and vehicle combination can safely maneuver the roads in Sweden there are turning requirements. These turning requirements are for both the truck itself, but there are also requirements on the entire vehicle combination. The requirements differ a bit between the two cases considering the different lengths that are in place. In figure 2.5 the outer radius and inner radius requirements for an entire vehicle combination are shown. The vehicle combination has to be able to turn with an outer radius of 12.5m and an inner radius of 2.0m. The only difference between the entire vehicle combination and the requirements for a single truck is that the inner radius requirement increases from 2.0m to 5.3m.

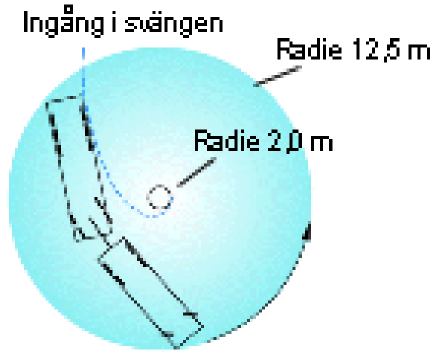


Figure 2.5: Turning radius requirement

There are also several rules and exceptions that are not mentioned regarding the distances from the kingpin to the axle configurations, the total length of the cargo spaces, the distance from the middle axle to the rearmost part of the cargo space (overhang), braking requirements, rules of the fifth wheel on all trailers/trucks/-dollys, etc. More about the regulations can be read on the national transportation agency's web page [9] and their explanatory legal loading document [13].

2.2.3 High Capacity Transportation

High capacity transportation (HCT) is a study on how even heavier and longer combinations affect the climate compared to the already legal combinations. According to the report about HCT combinations[7] where figure 2.6 is taken from, the fuel savings of a 90ton weight limited transportation compared to a 60ton should be around 22%.

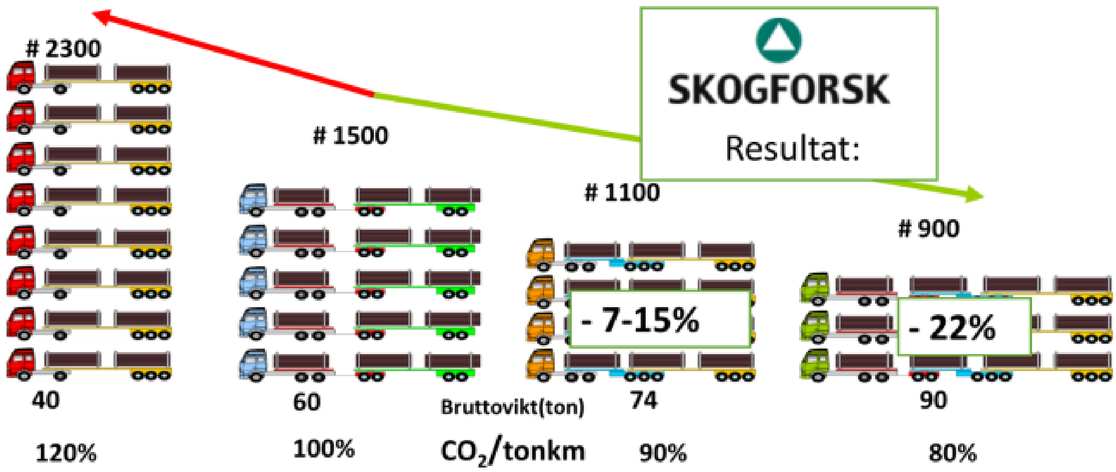


Figure 2.6: Carbon footprint of different weight limited transportation. Green boxes indicate measured fuel savings[7]

The same report also mentions that for volume-limited transportation the total length of the vehicle combination is more important. The decrease in vehicles needed for the same amount of transported cargo can be seen in figure 2.7. The longer combination also has a lower carbon footprint and fewer drivers which could lead to cheaper and more environmentally friendly transportation.

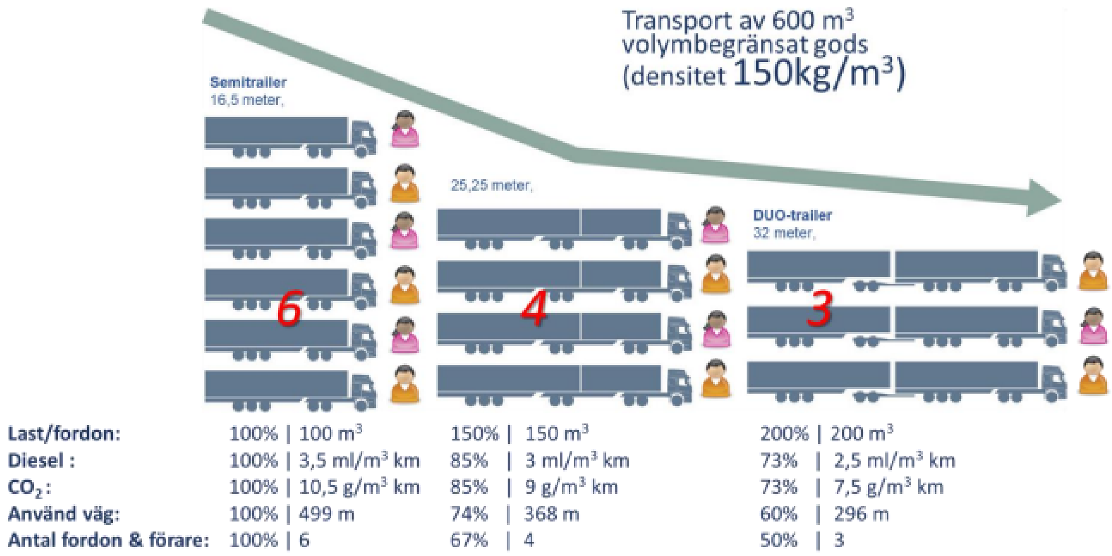


Figure 2.7: Decrease of vehicles needed for the same volume transported [7]

The fuel savings shown makes the argument to open up more of the road network to a higher rating than BK4 (which currently is the highest-rated road). Sweden has since 2020 started tests with vehicle combinations up to 100 tons and 32.5m. Finland has already opened up a lot of its public roads to 76 tons and 34.5m combinations, while they are also testing up to 104 tons combinations [7].
Heavier transportation could see the benefit of having functions such as better stability, reversing, and power shifting. These functions could all be done with the help of an E-Trailer.

2.3 Naming conventions and basic concepts

In the trucking and transport industry, there are some commonly used names to describe different types of axle configurations for how many axles a truck or trailer has, which are driven, which are liftable, which axles are steerable, etc. These naming conventions will be used throughout this report and are therefore important to fully understand.

2.3.1 Axle variants and configurations

On a truck, the number of axles is counted from the front of the truck and backward, the same applies for trailers. A three-axled truck with two of its axles driven is denoted as a 6x4 truck. The first number, 6, describes the total amount of wheel hubs the truck has. The latter number, 4, describes the number of driven wheel hubs the truck has in total.

There are several axle configurations possible on a truck since the number of axles can be as much as 5. Some common configurations for trucks are 6x4, 6x2, and 4x2. When there are two rear axles on a truck, such as the 6x2 or 6x4 variants, the rear axle configuration is known as a bogie. For semi-trailers, the conventional configuration is to have 3 axles. These configurations can be built up with different numbers of driven axles and also different positions of the driven axles. A truck or trailer might also have liftable and/or steerable axles to suit their transport requirements better. Because of this, there are some terms and concepts that need to be known.

Tandem

A tandem bogie is defined as a bogie where both axles are driven. This will generally allow the traction force to be distributed, which could improve the traction if the ground surface is slippery. A tandem might have the possibility to disengage one of the driven axles if needed. This decoupling will allow for the possibility of lifting one of the axles. According to the "Tandem Axle Lift" in appendix F, this is especially beneficial for energy consumption and also allows for better maneuverability or stability.

Tag axle

A tag axle is defined as a non-driven axle behind the driven axle, it "tags along" the driven axle. It might be liftable, steerable, or both.

Pusher axle

A pusher axle is defined as a non-driven axle in front of the driven axle. The driven axle is pushing the axle in front of it. Like the tag axle, it can also be lifted and steered, however, it can only be steered hydraulically. This is because of the lateral dynamics of a truck, where if the pusher axle were to be self steered it would always contradict the wanted lateral movement.

Liftable axles

As the name suggests, a liftable axle is an axle that can be lifted if necessary. If it is the first axle in an axle combination it will improve the turning radius by moving the rotation point close to the combination. By moving the rotation point closer to the vehicle the low-speed maneuverability of the entire combination becomes better, meaning that the inner turning radius will increase. But because the rotation point is closer to the vehicle combination the high-speed stability will be worse than if the axle were not lifted. Lifting axles is also a very common practice to reduce fuel consumption. Another benefit is that lifting axles shifts the loads to other axles. This could be beneficial if the trailer has a driven axle and needs an increase in traction force for a start.

Steerable axles

Steerable axles come in two different layouts, actively steered or self-steered. The benefit of steerable axles comes when the truck and trailer are loaded to a point where lifting the axles no longer is an option. The hydraulically steered tag axle uses a hydraulic system to actively steer the axle. The axle's steering angle can reach a maximum of 11.5°. According to the datasheet "Hydraulically steered axle" in Appendix F the axle allows for the maximal steering angle up to a vehicle speed of 0-15 kph. When the truck reaches 15 kph the steering angle starts to decrease until it reaches 38 kph when it becomes fixed. The self-steered axle is pneumatically controlled and allows for steering up to 25 kph. According to the datasheet "Self Steered Axle" in appendix F the control cylinder locks itself in the rigid position when it reaches 25 kph. When the truck reaches 25 kph the control cylinder locks itself and becomes fixed.

E-Axle

An E-Axle is a driven axle that could house part of an electrical powertrain. The E-Axles come in several different configurations. The minimal requirement is that one or several electrical motors should be mounted to the axle. This could be in order to save space, reduce the need for propeller shafts, etc. It can include a gearbox or even inverters and other power electronics.

2.3.2 5th Wheel and Kingpin

Using a fifth wheel combined with a kingpin is the conventional method of mounting semi-trailers to a tractor. The kingpin is a solid cylinder that is mounted to the bottom side of the frame of the trailer. The fifth wheel sits on top of the frame of the tractor and provides a flat surface that supports the trailer frame. The fifth wheel also provides a locking mechanism that will hold the kingpin to the fifth wheel. This setup allows the trailer to rotate around the kingpin's axis when the truck is turning.

2.4 Maneuverability and Stability

Where and how axles are placed on a truck, trailer or a combination of both depends on many things. First are the legal requirements for how much axle load a certain axle is allowed to have. After that, it is a trade-off between high-speed stability and maneuverability. A longer wheelbase, the longitudinal distance between the axles, will result in a more stable vehicle or combination. However, the combination will have a larger turning radius making it harder to maneuver in tight spaces. In the case of a short wheelbase the effects are reversed, meaning that it will be more unstable at higher speeds, but easier to maneuver. For a truck and trailer combination, this trade-off between long and short wheelbase becomes more important since such a combination is inherently large, but the necessity for maneuverability still exists. To solve this problem it is common to use liftable and steerable axles to get the wanted traits from both a long and a short wheelbase, as mentioned earlier.

3
Method

In the following chapter, the methods used in this thesis work will be presented. It will begin with an overview of the methods used in this project followed by more in-depth explanations of how and why each method was used.

3.1 Method Overview

The thesis work started with a prestudy of how Volvo Trucks built their first generation of E-Trailer, what weaknesses and strengths it had as well as what the competitors' solutions look like. The prestudy also included an inventory of what electric powertrains Volvo already had in-house. From the prestudy a list of requirements was set that included both requirements that a new E-Trailer should fulfill, but also desirable features that were set as goals for the new E-Trailer. These requirements focus both on the performance of the powertrain as well as how it will be integrated and mounted on the trailer chassis. The performance requirements were calculated using a baseline truck and trailer combination and simple vehicle dynamics calculations in different scenarios.

With the list of requirements set, drive cycle simulations of different battery and motor sizes on three different routes were conducted. The three routes consisted of one mostly flat, one very hilly, and one route with a mix of both. The aim was to get a better understanding of how different powertrain parameters affected different performance parameters such as fuel consumption and profitability, compared to the base combination on the same routes. This was done without any relation to what was available at Volvo, but instead to see trends in which powertrain variables affected performance parameters the most and if there were any breaking points where certain powertrain variables stopped or had less effect on the performance parameters. These trends were then used, together with the list of requirements, to decide which existing powertrain solutions that could be suited for each route. These trends also made it possible to leave recommendations for what an optimal powertrain for an E-Trailer could look like.

With the selection of powertrain components completed, a packaging study was carried out in order to make sure the selected components would be possible to mount in the trailer. The decision on the powertrain layout was influenced by the selected components interfaces, the list of requirements, and common practices. A package solution for the E-Trailer was then done using PTC Creo. The packaging was done as a base to start from and to be changed further down the line so that lessons learned from unexpected changes could be implemented.

3.2 The Prestudy

The prestudy was initiated by gathering information about how Volvo Trucks built their first E-Trailer. This was done by reading internal documentation and reports from the creation of Volvo's first E-Trailer, see Appendix F. Reports and documentation from other electromobility and high capacity transportation, HCT, projects at Volvo were also included to get a better understanding of what similar concepts had already been investigated and what was learned from them. Simultaneously, there were ongoing discussions with the engineers involved in the creation of the first E-Trailer about how and why certain decisions were taken, filling in information gaps that the reports did not cover or what they thought was important to investigate further in a future generation of the E-Trailer.

An analysis of the current market and competitors was also carried out during the prestudy, with the intention of widening the understanding of the market and current solutions. Since the concept of an electrically propelled trailer still was in its initial stage of development, even for competitors, information was difficult to gather. Volvo Trucks had done a market analysis for the development of the first E-Trailer where the most information was gathered by networking, conferences, and press releases. The result of this market analysis turned out to cover most of the competitors and was deemed to still be valid and useful for this project. As an extension of the market analysis, a patent search was also conducted to get a better picture of what competitors could be working on or if any other competitors could be expected to enter the market in the future.

3.2.1 Internal Reports, Experiences, and Testing

The overall conclusion drawn from the knowledge gathered was that it is possible to package an electrical powertrain in a trailer. It also showed some very promising results in terms of decreased fuel consumption. However, the battery's SoC window and motor torque were two limiting factors that were discovered in the first prototype. Especially when it came to reversing the truck and trailer only using the electric motor on the trailer. The motor could just supply enough power to reverse the truck and trailer straight and on very flat ground. The SoC window of the batteries was set between 30-70 % which was very conservative but still managed to show a positive effect on the fuel consumption on Landsvägsbanan at Hällered. A bigger SoC window or more capacity would have been interesting to be able to test for longer instances and take more advantages of regenerative braking.

What was learned during the building of the E-Trailer was mainly that the usage of two cooling mediums, requiring two separate loops was not recommended in future builds. Why this was done in the first E-Trailer was due to the approach taken during designing it. The approach was to build it with what was available "in the yard" and make the best out of these components.

A similar project that was of interest was the E-Dolly, an electrically powered dolly that was built a couple of years before the first E-Trailer. The most interesting aspect of this project was the powertrain and its layout. It had the last axle driven meaning that a propeller shaft passed over the first axle to the two electric motors. Such a layout would open up the possibilities of axle configurations on a future E-Trailer. Having different configurations possible could allow a selection from the customer to optimize for their needs.

From the discussions with the engineers involved in the first E-Trailer, it was decided that this E-Trailer should be a three-axled trailer like the first generation. Due to it being a common configuration of axles for a trailer. The previous E-Trailer was based on a container trailer and a decision was made to stick with this type of trailer for this E-Trailer as well. A container trailer is a cheap chassis to buy, easy to work on, and flexible to test with due to the ease of changing the gross combination weight, GCW, by changing containers or their contents. It is also decided that powertrain components should be sourced from what was available at Volvo Group. This was to make the building easier and less costly.

3.2.2 Market Analysis

The following subsection will briefly describe the competitors' E-Trailers in terms of specifications and choice of powertrain. It will also bring up how far they have come in their development.

Trailer Dynamics

Trailer Dynamics has three different versions of their E-Trailer, all with continuous power of 360 kW and peak power of 580 kW. The difference is the battery capacity with a 300 kWh, a 450 kWh, and a 600 kWh configuration. Trailer dynamics includes a 44 kW charger, the system runs on 800 V and the 600 kWh configuration has a claimed 21.4-ton payload capacity.
Trailer Dynamics uses an E-axle for their powertrain and it's placed as the second axle on the trailer. Their E-axle allows for a compact design that does not seem to interfere with their axle placement. Batteries are located in front of the first axle in a modular system. The inverters and other electronics seem to be placed behind the third axle. Figure 3.1 shows the trailer and powertrain layout.

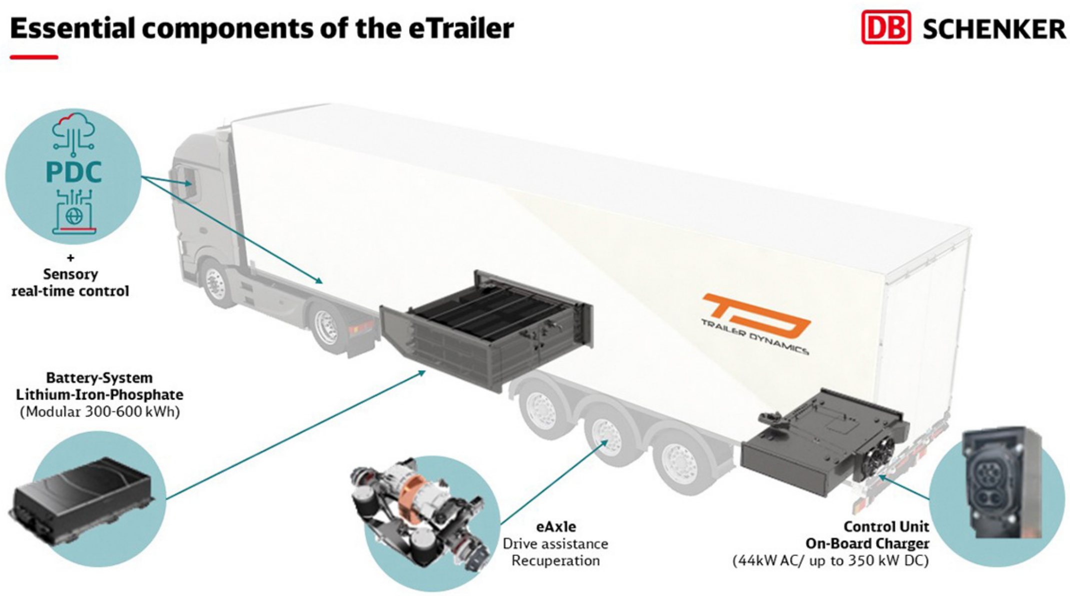


Figure 3.1: Powertrain layout of Trailer Dynamics E-Trailer.

In April of 2023 Trailer.se wrote an article about DB Schenkers field testing of Trailer Dynamics E-Trailers [1]. The claimed results showed a decrease of fuel consumption between 24-55 % according to DB Schenker. They also claimed that the fuel savings were just 0.7 to 0.9 % off from the expected values.

ZF

ZF bought WABCO on the 29th of May in 2020 and thereby acquired their E-Trailer product. WABCO's design, from 2019, had the motor powering the third axle with the motor placed behind it. The batteries were placed in front of the first axle, like Trailer Dynamics. The inverter and the cooling system were both placed behind the third axle on each side of the motor. The ZF layout, presented in 2021, was slightly different from the WABCO design. It seemed to have the second axle driven with an E-axle and the inverters packaged between the batteries and axles.
The specification of the motors and batteries were not disclosed by either WABCO or ZF. Judging from the short clips and images that were available it seemed like it is a smaller battery and motor compared to other competitors. This assumption was also backed up by a ZF press release seen in Appendix B (also have this link to the same thing, where they estimate up to 16 % fuel and CO_2 savings on shorter routes and up to 7 % on longer routes. Figure 3.2 shows the trailer and powertrain layout.

Figure 3.2: Powertrain layout and components description of ZF's E-Trailer.

Randon

The Brazilian trailer manufacturer Randon also provides an E-axle solution. It consists of two electric motors mounted to the axle. They have the possibility to have the driven axle as either the first, second, or third. In a commercial clip, however, the axle is placed as the second axle with batteries and inverters in front of the first axle. Randon also seems to go down the route of smaller batteries and motors making their powertrain very compact and easier to package on the trailer. This should also result in less cost for the final product which is also an important aspect.

VAK

The Finish trailer and body builder VAK is currently working on a pilot project for an E-Trailer that they aim to commission during 2023. It consists of an E-axle propelling the second axle. Battery and cooling are mounted in front of the first axle and by the presented specifications the capacity is 15 kWh. VAK estimates 2-10 % lower fuel consumption with this powertrain. VAK also claims that the whole powertrain will only add 1000 kg to an existing trailer. Figure 3.3 shows the trailer and powertrain layout.

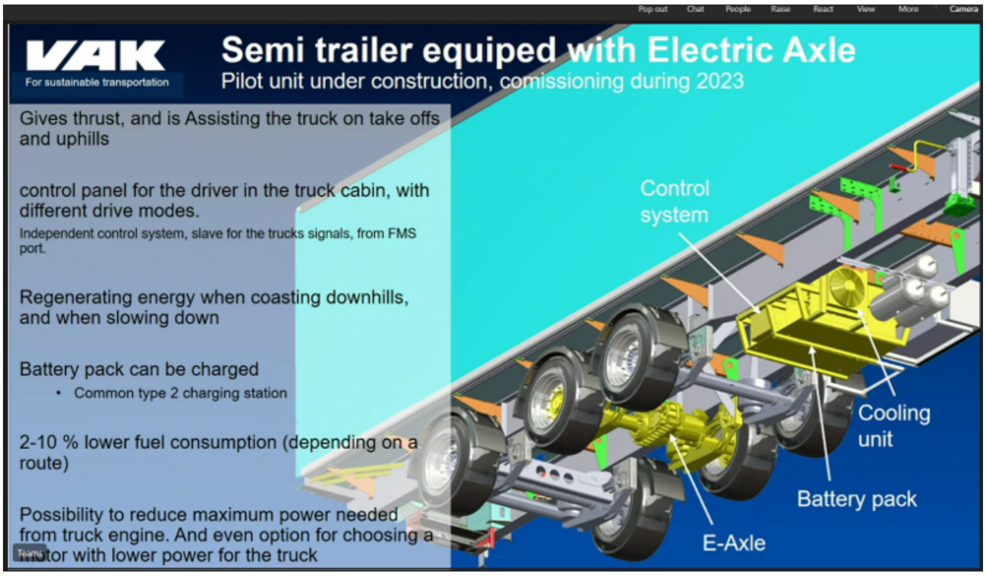


Figure 3.3: Powertrain layout and specifications of VAK's E-Trailer.

3.2.3 Patent search

As a part of the market analysis, a patent search was also carried out to obtain more information about the market and the competitors. Due to the E-Trailer concept still being in the research and design phase a patent search could give more information about which companies that could be venturing into the market and in what way.

The database Espacenet was used and the keywords used are found in the list below. Not all keywords resulted in relevant results and therefore all results will not be covered in this report. Instead, a summary of the most relevant results will be presented in the following subsections.

- Electric
- Semi-Trailer
- Semitrailer
- Trailer
- Propelled
- Driven
- ZF
- Trailer Dynamics
- Actuated
- Self propelled
- Self driven
- Electrified

From the patent search, a few patents stood out as being more interesting or relevant. Some patents found even described the whole concept of an E-Trailer and gave a glimpse into what the competitors might be trying to develop. It was also discovered that many patents cover the concept of a driven trailer and that these patents were quite similar. Therefore not all of them will be covered here and instead, only the ones that are more applicable to the thesis. In the following sections, these patents will be shortly described.

DE102021202321A1

Published: 15-09-2022
Keywords: "ZF" and "trailer" and "propelled"

This patent from Zahnradfabrik Friedrichshafen, ZF, describes a truck towing (with a traction battery and a charger) and a trailer (which is also carrying traction batteries and a charger). The patent covers how the distribution of energy could be done during charging and during driving, i.e. which traction battery to use up first, if the second one should charge the first one, etc. It also mentions that the trailer could include a motor to provide extra power/energy when needed.

DE102020108391A1

Published: 30-09-2021
Keywords: "ZF" and "trailer" or "propelled" or "driven"

Similar to DE102021202321A1 this patent, also from ZF, describes a trailer that includes an electric drive unit. The patent focuses more on the control methods of the electric machine, how to know how much energy to deploy, and how to deploy it.

DE102010042268A1

Published: 12-04-2012
Keywords: "ZF" or "trailer" or "propelled"

This patent from ZF describes a hydraulically driven trailer where each of the two driven wheels are powered separately. This gives the possibility to control the torque on each wheel resulting in less tire wear and added control of the trailer. The hydraulic propulsion system can also be used as a generator which provides electrical energy while braking.

EP4059755A1

Published: 11-03-2022
Keywords: "trailer dynamics"

Trailer Dynamics is as company developing E-Trailers. This patent describes how their driven axle is packaged and how the power is transmitted from the electric motor or motors to the wheels through gearboxes and driveshafts. It also describes the layout of the powertrain. This results in a fairly compact powertrain which becomes easier to integrate into a trailer.

CN105691479A

Published: 22-06-2016
Keywords: "propelled" and "semi-trailer" and "semitrailer" and "trailer"

This patent describes the basics of an electrically propelled trailer towed by an electric truck. It includes both battery mounting locations on the truck and trailer as well as a trailer with either one or two electrically driven axles.

GB1385172A

Published: 26-02-1975
Keywords: "electric" and "semi-trailer" and "semitrailer" and "trailer"

A solution where each driven axle on both truck and trailer is powered by hub motors. The generator is located on the truck and provides power to the trailer. The patent mentions the benefit of the electric motors on the trailer when braking due to them reducing the risk of "jack-knifing".

US11453292B2

Published: 27-09-2022
Keywords: "propelled trailer"

In this patent, a driven trailer is described. The method of propulsion covers hydraulic motors, pneumatic motors, and electric motors. It mentions that the driven axle also acts as an electric brake when deceleration is needed. The patent aims to solve driving scenarios where there is no space for both a truck and a trailer. Since the trailer is smaller this patent wants the trailer to be equipped with a full powertrain that can therefore propel itself into smaller spaces. The patent also covers how the transmission of power from the motor to the wheel will be carried out.

3.3 List of Requirements

The prestudy resulted in a list of requirements that the new E-Trailer should fulfill, see appendix A. The list covered both general requirements such as ground clearance and the number of axles on the trailer to specific scenarios where the E-Trailer was required to meet certain performance targets. These scenarios and performance targets were based on testing on the current E-Trailer together with discussion with the thesis supervisors and other engineers at Volvo Trucks and CPAC. Some wishes were also added to the list. These were features or functions that were not deemed absolutely necessary for the E-Trailer to fulfill its main goal of lowering the energy consumption from the ICE in the truck. All requirements and wishes were based on information gathered in the prestudy.

3.3.1 Vehicle Dynamics

The following scenarios were used to set requirements on the output torque and rotational speed of the powertrain. To get a measurable value on the scenario or requirement some vehicle dynamics modeling and calculations were done. Below are the scenarios and requirements listed and in the following subsections it is also described how they were modeled and calculated.
Scenarios and requirements modeled and calculated:

- Being able to start/reverse straight with a base-loaded combination on level ground up to 4 km/h.
- Not losing any speed when up-shifting gears by having the electric motor support during the time it takes to shift.
- Contribute sufficient to power up to 90 km/h.
- Maximize the possible angle between the truck and trailer when reversing by only using the E-Trailer.

3.3.1.1 Baseline truck and trailer

To ensure that the calculations and simulations resulted in realistic values, a baseline truck and trailer were used. Since a truck and trailer can vary a lot in weight, axle distances, power output, etc, it was decided to select a truck and trailer that was representative of the routes and cargo hauled on the route and not change them between the calculations. The same truck and trailer were also used in the simulation to get a baseline consumption on the route. This also allowed the simulation results to only be isolated to the difference in the powertrain and not the combination. Another benefit was also the fact that the results could be more representative of how the different powertrains should perform in real life.

The base truck was based on a truck used in the Auto-Freight project at Volvo Trucks. The truck was operating the route between the Gothenburg harbour and Viared in Borås daily. This was a very well-documented route for fuel consumption which made it easier to compare and validate the simulated values and by that also get a better approximation of what an E-Trailer could perform on the same route. The truck's usual commission, to transport containers from Gothenburg harbour to Viared, was also deemed as a realistic scenario where an E-Trailer could be used in the future. In table 3.1 are some of the specifications for the truck listed. These are mostly taken from the real truck using Transportstyrelsen [12], otherwise taken from in-house reports.

Table 3.1: Base truck specifications.

Chassis	6*4
Axle distance, 1-2 axle	3600 [mm]
Axle distance, 2-3 axle	1370 [mm]
Weight	10000 [kg]
Engine	d13, 375 [kW]
Gearbox	Automatic, 12-speed

The base trailer was decided to have the same axle distances as the first generation of the E-Trailer. The weight was specified as the weight of the first-generation E-Trailer without any powertrain components installed. In table 3.2 the specifications for the base trailer are presented.

Table 3.2: Base truck specifications.

Chassis	3 axles
Axle distance, kingpin to 2 axle	7900 [mm]
Axle distance, 2-3 axle	1350 [mm]
Weight	6500 [kg]

3.3.1.2 Base cargo weight

Similar to the base truck and trailer a base cargo weight was also set to keep the simulations and calculations comparable and was set to 15 tons. This was derived partly from discussions with Emil Pettersson and Clive Misquith about their experience of what type of cargo weight a semi-truck and semi-trailer are transporting on average. According to Lennart Cider, an engineer at Volvo Trucks, most transports are volume-limited and not weight limited. It was also partly derived from data from the Auto-Freight project of transports on the Gothenburg-Viared route. The data, see "Autofreight Project Data" in Appendix F, covered the GCW of a duo-trailer combination that partially also operated on the route with only one trailer. When only one trailer was used it could be seen that the average GCW was 29 tons. From this, the baseline GCW was set to be 31 tons to have some margin.
Using the baseline truck and trailer, mentioned earlier, a baseline cargo weight, m_{cargo}, could be calculated with equation 3.1.

$$m_{cargo} = GCW - m_{truck} + m_{trailer} \tag{3.1}$$

This resulted in a m_{cargo} of 15 tons which were used in all simulations and calculations in the thesis.

3.3.1.3 Reverse straight

In this scenario, the E-Trailer was reversed in a straight line by only using the trailer's electric motor. The goal was to calculate how much traction force and thereby how much torque the electric motor needed to provide to reverse the base truck and trailer with the base cargo weight. Figure 3.4 shows a schematic picture of the combination. Some simplifications and assumptions were also done to make the calculations easier to carry out. The assumptions and simplifications for this were:

- The three-axle trailer is seen as a single-axle trailer, but with the rolling resistance of a three-axle trailer.
- The normal force of the trailer is acting on the middle axle of the trailer.
- The truck is a 6x4 configuration but the last axle pair is seen as one.

- The traction force of the truck is seen as one common force from the two driven axles.
- The normal force on the driven axle pair is acting in the middle of the two axles.
- The truck and trailer are viewed as one solid body when connected. No coupling forces are taken into consideration.
- The truck and trailer are in steady state and no load transfer is taken into consideration.
- The truck and trailer are standing on level ground.
- Both truck and trailer have a weight distribution rear/front of 50/50.
- Aerodynamic forces are not considered since we are considering the start-ability of the combination.

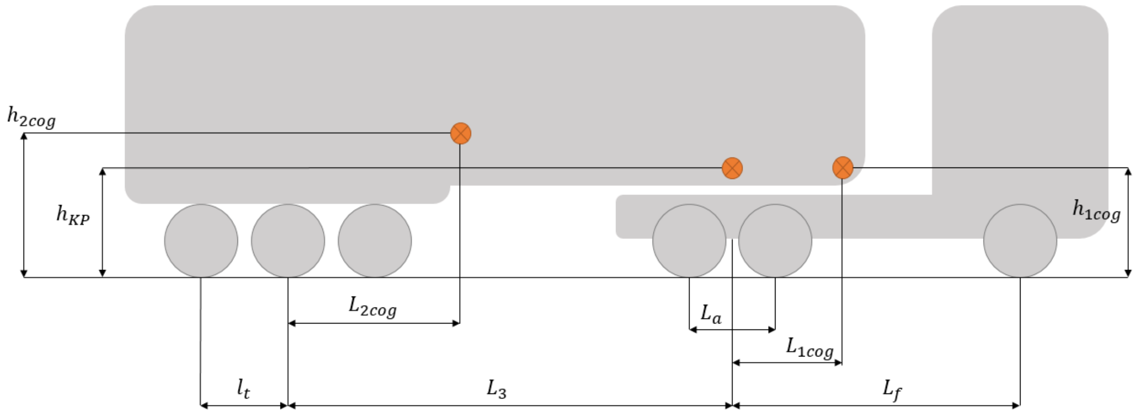


Figure 3.4: Schematic view of the base truck and trailer combination with measurements.

Figure 3.4 shows the majority of the measurements used during the calculations. The measurements have the following values:

Table 3.3: Lengths of truck and trailer.

Constant	Value	Unit
h_{1cog}	1	m
h_{2cog}	1.5	m
h_{KP}	1	m
L_f	3.6	m
L_a	1.37	m
L_{1cog}	3.0425	m
L_{2cog}	3.275	m
L_3	7.9	m
l_t	1.35	m

In the figure 3.5 the forces that are acting on the combination can be seen. The truck has the mass of a standard 6x4 Volvo truck which weighs roughly 10000 kg.

The mass of the trailer is divided into several masses since it is easier to compare the E-Trailer to a conventional combination. The weight of the trailer itself is roughly 6500 kg, the weight of the powertrain is 2000 kg and the payload is 15000 kg. The gradient of the slope α_{slope} is 0°for the base calculations. α_{slope} could, however, be used iteratively to find the maximum gradient this maneuver could be performed in with a specific powertrain.

Table 3.4: Constants and their values used for calculating the force needed to start reversing straight.

Constant	Value	Unit
m_{truck}	10000	kg
$m_{basetrailer}$	6500	kg
$m_{payload}$	30000	kg
$m_{powertrain}$	2000	kg
α_{slope}	0.0	°
c_f	55/(g*1000)	[-]

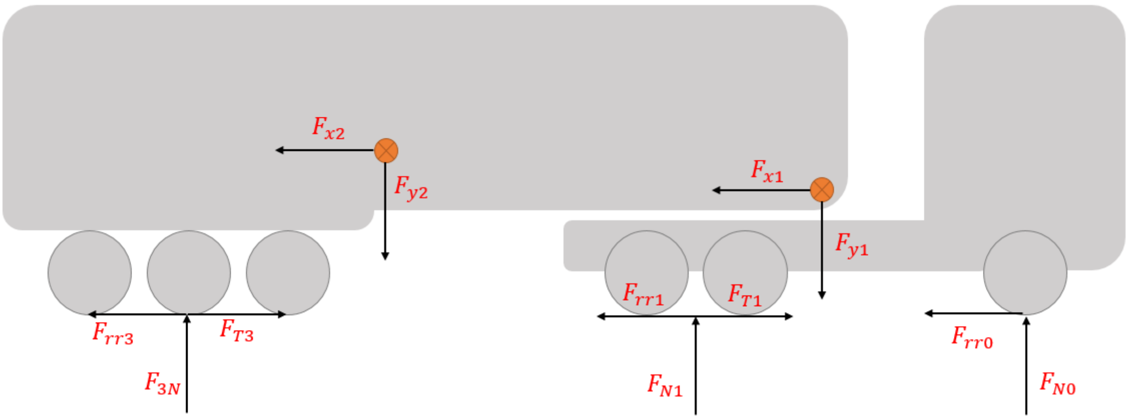


Figure 3.5: Free body diagram of the truck and trailer configuration, not including kingpin forces.

From the free body diagram in figure 3.5 both a vertical and a horizontal equilibrium equation can be extracted:

$$m_{trailer} = m_{basetrailer} + m_{payload} + m_{powertrain}[kg] \tag{3.2}$$

$$c_f = \frac{55}{1000 * g}[N/N] \tag{3.3}$$

$$F_{y1} = m_{truck} * g * cos(\alpha_{slope})[N] \tag{3.4}$$

$$F_{y2} = m_{trailer} * g * cos(\alpha_{slope})[N] \tag{3.5}$$

$$F_{x1} = m_{truck} * g * sin(\alpha_{slope})[N] \tag{3.6}$$

$$F_{x2} = m_{trailer} * g * sin(\alpha_{slope})[N] \tag{3.7}$$

$$F_{rrx} = F_{Nx} * c_f[N] \tag{3.8}$$

$$F_{N0} + F_{N1} + F_{N3} = F_{y1} + F_{y2} \tag{3.9}$$

$$F_{T1} + F_{T3} = F_{rr0} + F_{rr1} + F_{rr3} + F_{x1} + F_{x2} \tag{3.10}$$

With the help of the free body diagrams, in figures 3.6 and 3.7, the following equations were extracted:

$$F_{N0} * L_f = F_{y1} * L_{1cog} \tag{3.11}$$

$$F_{N3} * L_3 = F_{y2} * (L_3 - L_{2cog}) \tag{3.12}$$

By doing a moment equilibrium equation of the truck around point A in figure 3.6, equation 3.11 was derived. It was done at this point since the kingpin and traction force would be excluded, making the calculations easier. The equation 3.12 was acquired by doing a moment equilibrium equation around point B in figure 3.7. It was done at this point to exclude both the traction force on the trailer and the kingpin force.

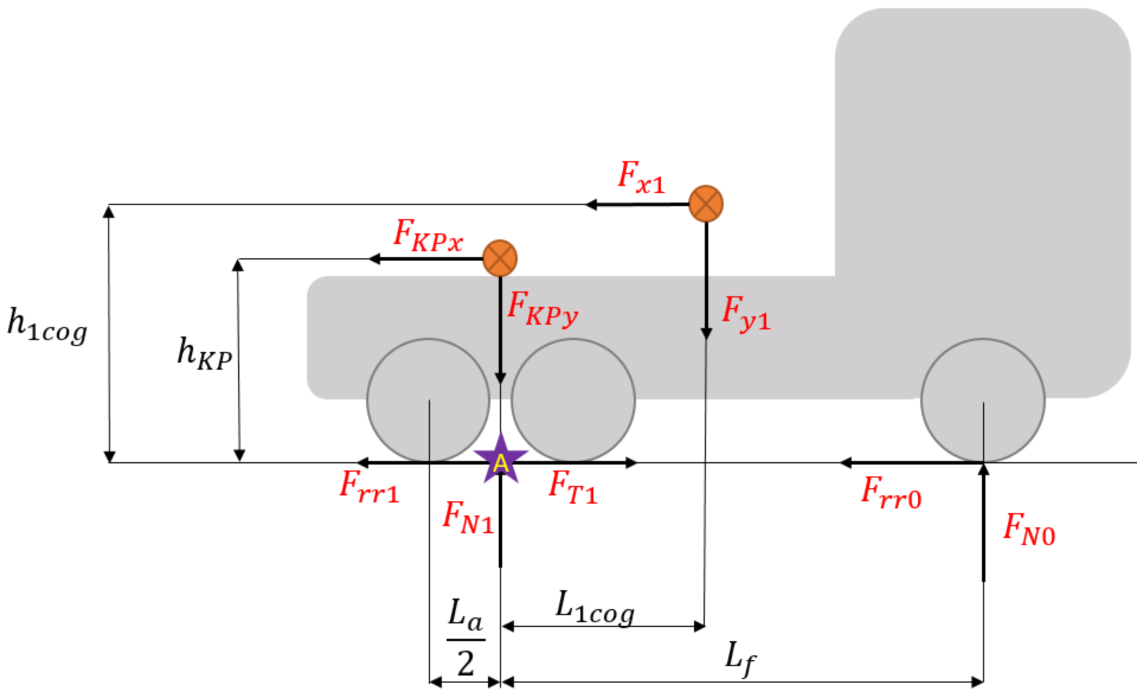


Figure 3.6: Free body diagram of the truck.

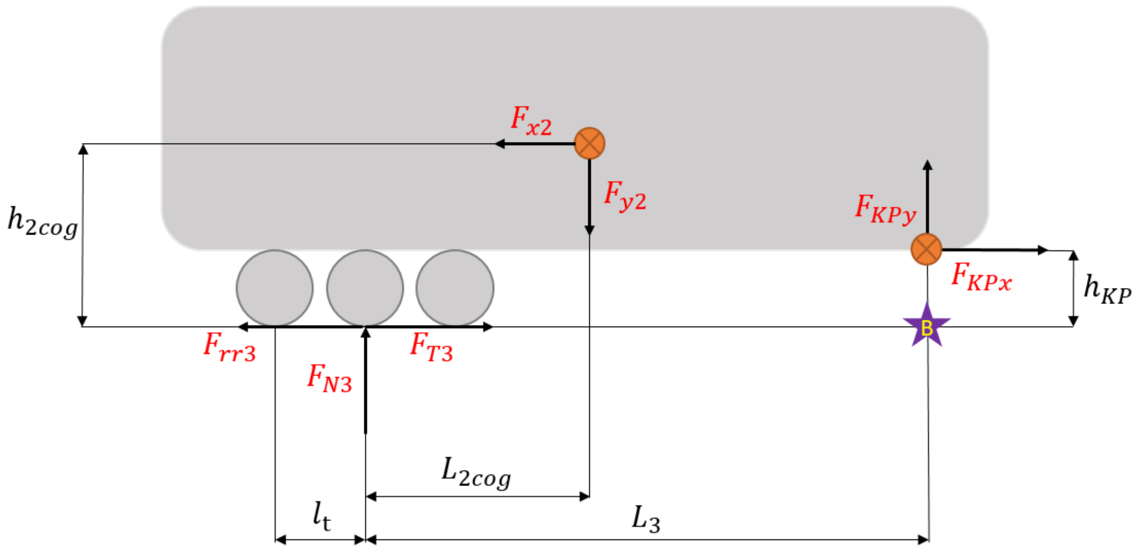


Figure 3.7: Free body diagram of the trailer.

To solve the system of equations consisting of 3.2 to 3.12 the split of traction force from the truck and the trailer needed to be determined. To determine the minimum traction force that is required from the trailer's electrical powertrain the traction force from the truck is set to zero.

3.3.1.4 Power shifting

The power shifting criteria is wanted because it would make it possible to perform an up-shift without ever losing any velocity. This would make it possible to save fuel since there is no need of accelerating back up to the velocity from where the shift started. A secondary benefit is that this would enable a smoother shifting experience for the driver since the driver would not feel any difference in acceleration. Power shifting could possibly increase the life of components within the powertrain. The power shifting criteria set a demand on what peak power the electrical motor can output. It sets a demand on the peak rather than the continuous power because a shift to a higher gear never exceeds 10 seconds (a very small duration).

To calculate the energy that was lost by changing gear the existing energy of the vehicle combination had to be calculated. Figure 3.8 shows the forces that act on the vehicle combination during a gear shift in a slope. Equation 3.13 is the total energy the vehicle combination has before the gear change. There is no potential energy due to the height reference point being set when the gear shift starts. One of three possible losses is the aerodynamic drag, the force produced by the aerodynamic drag is described in equation 3.14. The second loss is the rolling resistance, the force created by the rolling resistance is estimated by the rolling resistance coefficient c_f and the total load that acts on the tires. The force created by the rolling resistance can be seen in equation 3.15. To ensure that equation 3.19 was as accurate as possible the addition of the truck's inertia was added. Equation 3.16 shows a simple expression of how the inertia of the truck can be calculated. In order to validate equation 3.19, the variable a_{shift} was determined from iterative testing. This was done by comparing real-life data of how long it takes to shift gears in a truck with a trailer attached and what velocity it had after the up-shift. The velocity the vehicle combination should have after the up-shift is described by equation 3.18. Equation 3.19 overestimates the energy lost compared to the real data due to the magnitude of the variable a_{shift}, which acts as a safety factor. Equation 3.20 then calculates the peak power needed from the electric motor in order to "powershift". The power needed with regards to different angles of the slope and different masses, the values of α_{slope} and $m_{trailer}$ used are shown in table 3.6.

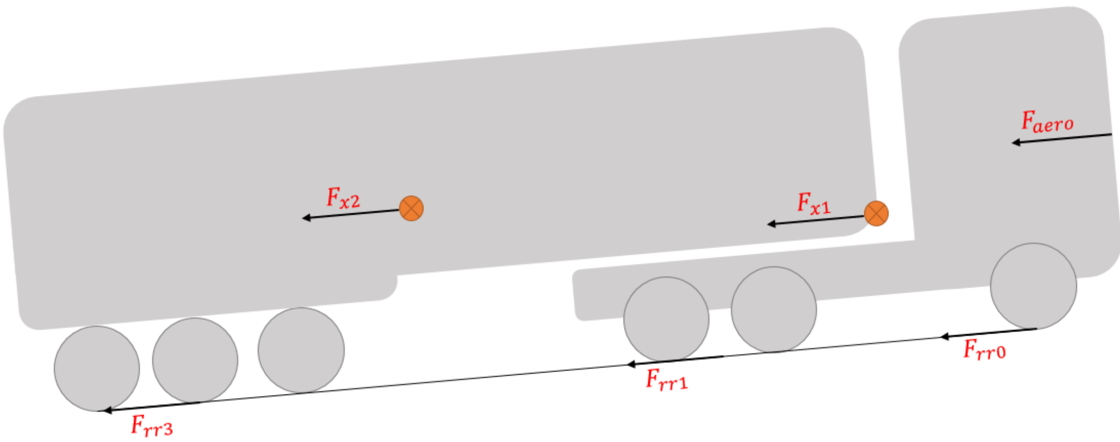


Figure 3.8: Forces that act on the combination while shifting in a slope.

fig

$$E_{KE1} = (m_{trailer} + m_{truck}) * V_{start}^2 [J] \tag{3.13}$$

$$F_{aero} = \frac{c_d * A_{frontal} * \rho_{air} * V_{start}^2}{2} [N] \tag{3.14}$$

$$F_{rr} = c_f * (F_{N3} + F_{N1} + F_{N0}) [N] \tag{3.15}$$

$$F_{inertia} = (m_{trailer} + m_{truck}) * a_{shift} [N] \tag{3.16}$$

$$E_{PElost} = (m_{truck} + m_{trailer}) * g * V_{start} * t_{shifting} * \tan(\alpha_{slope}) [Ws] \tag{3.17}$$

$$V_{after} = \sqrt{\frac{E_{KE1} - E_{Lost}}{m_{truck} + m_{trailer}}} [m/s] \tag{3.18}$$

$$E_{Lost} = E_{PElost} + V_{start} * t_{shifting} * (F_{rr} + F_{aero} - F_{inertia}) [Ws] \tag{3.19}$$

$$P_{neededEM} = \frac{E_{lost}}{t_{shifting}} [W] \tag{3.20}$$

Table 3.5: Values used for calculating the energy lost during an up-shift.

Constant	Value	Unit
m_{truck}	10000	kg
$m_{trailer}$	38000	kg
c_d	0.8	[-]
c_f	55/(g*1000)	[-]
$A_{frontal}$	10	m^2
ρ_{air}	1.293	kg/m^{-3}
V_{start}	19.5	m/s
a_{shift}	0.3	m/s^2

Table 3.6: Values of α_{slope} and $m_{trailer}$ used for testing.

α_{slope}	0	1	2	3	4	5
$m_{trailer}$	10	15	20	30	40	50

3.3.1.5 Reverse with angled truck

The end scenario of reversing with the E-Trailer is to replace the usage of the diesel engine when arriving at terminals. To make sure that the electric machine can be used for even longer periods of time (compared to straight reverse) the decision was made to calculate how much more torque would be needed to enable corrections while reversing (steering maneuvers).

Calculation

In order to turn the combination there has to be an angle between the trailer and the truck, this is the articulation angle α, and a steering wheel angle β. Because of the angles β and α in figure 3.9 there will be a force component acting as friction on the wheels of the truck. This will increase the total force needed compared to a straight reverse. This friction force's magnitude is particularly hard to estimate because it requires deep knowledge about how tires work and also depends on the angles α and β, loads, and velocities. The resulting force due to this friction force and its angle θ is visualized in figure 3.10. Because no data on the tires were available, the different θ angles were changed iteratively in the equation 3.21 with the values seen in the tables 3.7 and 3.8.

$$T_{hub} = r_w * (c_f * (F_{N0} + F_{N1} + F_{N3}) + F_{N1} * \mu * sin(\theta_{rear}) + F_{N0} * \mu * sin(\theta_{front})) \quad (3.21)$$

Table 3.7: Angles used for iterative testing.

θ_{front} [deg]	0	1	0	1	2	1	2	3	2	3	4	3	4	5	4	5
θ_{rear} [deg]	0	0	1	1	1	2	2	2	3	3	3	4	4	4	5	5

Table 3.8: Constants and their values used for calculating the force needed to reverse with the truck in a angle.

Constant	Value	Unit
m_{truck}	10000	kg
$m_{basetrailer}$	6000	kg
$m_{payload}$	30000	kg
$m_{powertrain}$	2000	kg
c_f	55/(g*1000)	[-]
μ	0.8	[-]
r_w	0.5	[m]

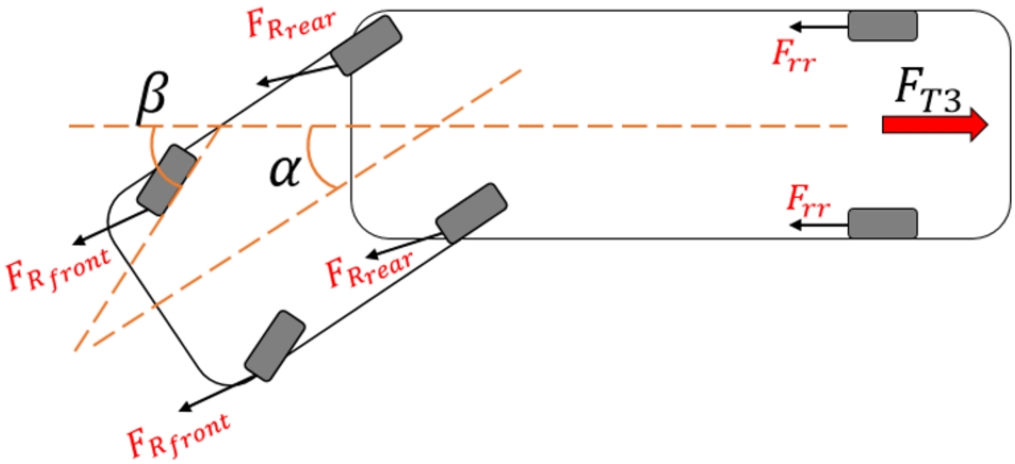


Figure 3.9: Free body diagram of the vehicle combination doing a angled reverse

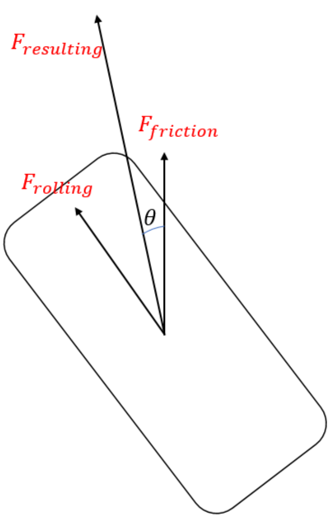


Figure 3.10: Free Body diagram of a tire in the angled reverse scenario

Simulation

The angled reverse was also simulated in a Volvo tool called VTM with the help of Niklas Fröjd. A meeting with Niklas was set up to discuss the case of reversing with an angle and having the trailer pull the truck instead of having the truck pushing the trailer. The simulations were done using the base trailer. The simulation starts with the wheels being straight as well as the entire combination. The trailer then starts to pull the truck, while the truck starts doing the normal reversing maneuvers. The simulations, therefore, tested different steering angles and articulation angles and resulted in different torques on the driven trailer axle.

Testing

The case of reversing with articulation and a wheel angle was also tested with the first-generation E-Trailer. This was done by driving the truck and the first generation E-Trailer into different articulation angles while having the steering wheel straight (same as the articulation angle). From this position, the E-Trailer attempted to reverse the entire combination.

3.3.1.6 Sufficient power at 90 km/h

To make it possible for the electrical powertrain to support the diesel engine at all times it is vital to make sure that the powertrain is able to deliver power at any velocity of the vehicle combination. To make sure this was the case equation 3.22 was used. All of the gear ratios (from the motor output shaft to the hub) need to be known as well as the motor's maximal rotational speed. The minimal velocity the powertrain has to be able to output is 80 kph since it is the maximal velocity a heavy truck is allowed to drive in Sweden.

$$velocity = \omega_{motor}/(i_{total} * 2 * \pi * r_w) \tag{3.22}$$

3.3.2 Other requirements

The remaining requirements and wishes on the list were based on information gathered from discussions with the people who were involved in the building of the first-generation E-Trailer.

3.4 Simulations & Dimensioning of Components

A simulation program developed in-house by Per Björe at CPAC was used as the base tool to simulate different powertrain configurations and routes. Some modifications were made to the program to make it easier to change variables and analyze the result, but the base logic and calculations were kept the same. The program returns estimated results of saved carbon dioxide and fuel compared to a regular truck and trailer combination. For this thesis, the amount of saved fuel, or efficiency gained, was used as the value to compare the different motor and battery configurations. The choice of comparing saved fuel was due to it being the main goal for Volvo

Trucks with the E-Trailer concept. Therefore the simulation program was created to have it as one of its outputs, making the comparison easy to do. Estimated profitability on the route was also deduced from the results form the simulations. This was done to evaluate if there was any potential money to be saved with the use of an E-Trailer. In the case that many powertrain combinations had similar fuel savings, the profitability was used as a second value to decide which combination was the most beneficial on a specific route.

The simulations were done in two main stages; the sweep simulations and the final simulations. Both types will be described more in-depth in section 3.4.3 and section 3.4.6 respectively. In short, the sweep simulations were done with a fixed set of motor sizes and a fixed set of battery sizes. All combinations were simulated on all routes and the motors and batteries had no connection to existing components. The goal here was only to see if there were any trends in what type of combinations were more beneficial on a route or if there were any other trends to be seen. The trends and results found from these sweep simulations were then used as a guide for selecting an existing motor and battery that would be the most optimal for a selected route. These selected components were then to be simulated to estimate how much fuel that could be saved on this route with this final powertrain.

3.4.1 Simulation Logic Description

In the following section, the basic logic of the simulation will be described as well as some comments and limitations that the set logic causes.

Truck and Trailer Propulsion Separate

The simulation tool was built in a way that the trailer only propels its own weight and never helps propelling the truck. This is because of safety reasons but also a big limitation of the program. An example when this matters is when the trailer is unloaded, this means that the motor only propels a small portion of what it is capable of. This results in that a powerful motor is not going to save any more energy than a less powerful motor, considering they both have enough energy from the battery. This could be optimised further to decrease the fuel consumption.

Deployment Strategy

The deployment strategy used is very basic and can be improved immensely. It works is by setting a target velocity the vehicle combination will deploy energy to maintain it. If the battery has energy stored and the vehicle is in a short uphill we can deploy peak power from the motor, otherwise it outputs continuous power. If there is no energy in the battery the motor will only act as a generator until there is enough energy to start acting as a motor again. The rest of the required energy has to come from the truck's diesel engine.

Mass Never Unloaded

Transportation of goods are usually transported from one place and then offloaded. The truck can pick up other cargo and bring it back to where it started In the simulation tool, there is no way of changing the mass during the drive cycle making the scenario simulated less accurate to reality.

Battery/Motor power limit

The program also takes into account what component will be the limiting factor. For example, if the battery has a lower continuous power output than the motor it will limit the total output to the battery's continuous output. This impacted the way the sweeping simulations were done. Since the max/continuous power output from the motor was a parameter that affected the results heavily the max/continuous power from the battery also had to be changed to match the motors.

3.4.2 Simulation Tool Validation

To see how accurate the simulation tool was, a validation study was conducted. The validation was done by comparing both a simulation of a truck and trailer combination without an electrical powertrain and by simulation of the first-generation E-Trailer on a route that has measurements from the real vehicles available.

3.4.2.1 Diesel Truck Comparison

The first comparison was to compare the results from the code with the data collected from the Autofreight vehicle. The Autofreight vehicle does not have an E-Trailer which means that this comparison is only for the truck's diesel engine and weight.
The data collected from the Autofreight vehicle is shown in "Autofreight Project Data" in Appendix F. The data includes which route, all the axle loads, container weights, distance traveled, weather, and fuel consumption. The simulations were then conducted with a standard trailer.

Table 3.9: Values used in the simulation tool to validate the diesel consumption of a conventional truck.

Attempt	Truck mass	Trailer mass
1	10 [ton]	17 [ton]
2	10 [ton]	42 [ton]
3	10 [ton]	25 [ton]

3.4.2.2 E-Trailer Comparison

The other comparison was to simulate the powertrain part and compare it to real data collected from testing of the first-generation trailer. To be able to do this the data had to come from where the E-Trailer already had been tested, which means that the elevation profile has to be taken from Hällered proving ground. This route at Hällered had already been integrated into a file by Per Björe at CPAC. The weight and target speed were transferred to the simulation tool and the simulations were run with the powertrain settings of the first-generation E-Trailer. The masses, SoC, and target velocity that was used can be seen in table 3.10. The simulations were also run with the correct masses but without the electric powertrain turned off in order to get a baseline. The fuel consumption with the electric powertrain turned on was then compared to the baseline result. The validation data for the fuel savings were taken from a test of the first-generation E-Trailer. This test was done by driving 9 laps around the test track at Hällered. 3 laps were done with a higher SoC, 3 without the powertrain activated, and 3 with the SoC being at the lowest limit. The three laps with the powertrain deactivated resulted in average fuel consumption of 3.87L diesel. All of the real tests of the powertrain on the E-Trailer are compared to this average consumption.

Table 3.10: Values used in the simulation tool to validate PT part of code.

Attempt	Truck mass	Trailer mass	Initial SoC	Target velocity
1	10 [ton]	37 [ton]	37%	70 [km/h]
2	10 [ton]	37 [ton]	32%	70 [km/h]
3	10 [ton]	37 [ton]	28%	70 [km/h]

3.4.3 Sweep simulations

This section of simulations were done by "sweeping" over a selected range of battery capacities and motor sizes. It was done by selecting one motor size and then changing the battery capacity, "sweeping" over the batteries, for each simulation. When all battery capacities were simulated with that motor, the motor was changed and the process was redone. This ensured that all combinations of motor torque and battery capacities were methodically simulated. Only these two parameters were changed between the simulation to keep the combinations to a minimum and also to make the result easier to analyze.

The selected motor sizes and battery capacities were, as mentioned earlier, not related to any existing components. The range of motor sizes ranged from 250 Nm of peak torque to 2500 Nm of peak torque. The batteries ranged from 50 kWh to 2000 kWh. In table 3.11 the full list of motor sizes is presented. To avoid limiting the motors, by having lower power ratings from the battery, the battery's peak, and continuous power were changed to the same as the motor's.

Table 3.11: Selection of motors that were used in the sweep simulations.

Peak torque [Nm]	Continuous torque [Nm]
250	250
500	300
750	400
1000	600
1500	800
2500	1400

3.4.3.1 Parameter Determination

In order to make the simulation results more realistic parameters needed to run the simulations had to be derived. The following section will describe how this was done.

Base Trailer Weights

A conventional trailer is neither equipped with an electrical powertrain, heavy-duty drive axles nor a second chassis. This means that there is a lot of added mass, which is not only coming from the electrical powertrain. To make the simulations as realistic as possible the E-Trailer was compared to a conventional semi-trailer and not the E-Trailer without its powertrain. A conventional container semi-trailer weighs approximately 5 tons while the first generation E-Trailer without its powertrain weighs roughly 6.5 tons according to internal reports. To find the difference, a simulation was done to compare the different masses. The simulation showed that an additional 50 kWh was needed to compensate for the E-Trailer's additional weight on the route that goes from Gothenburg to Borås three times, which can be seen in figure 3.11.

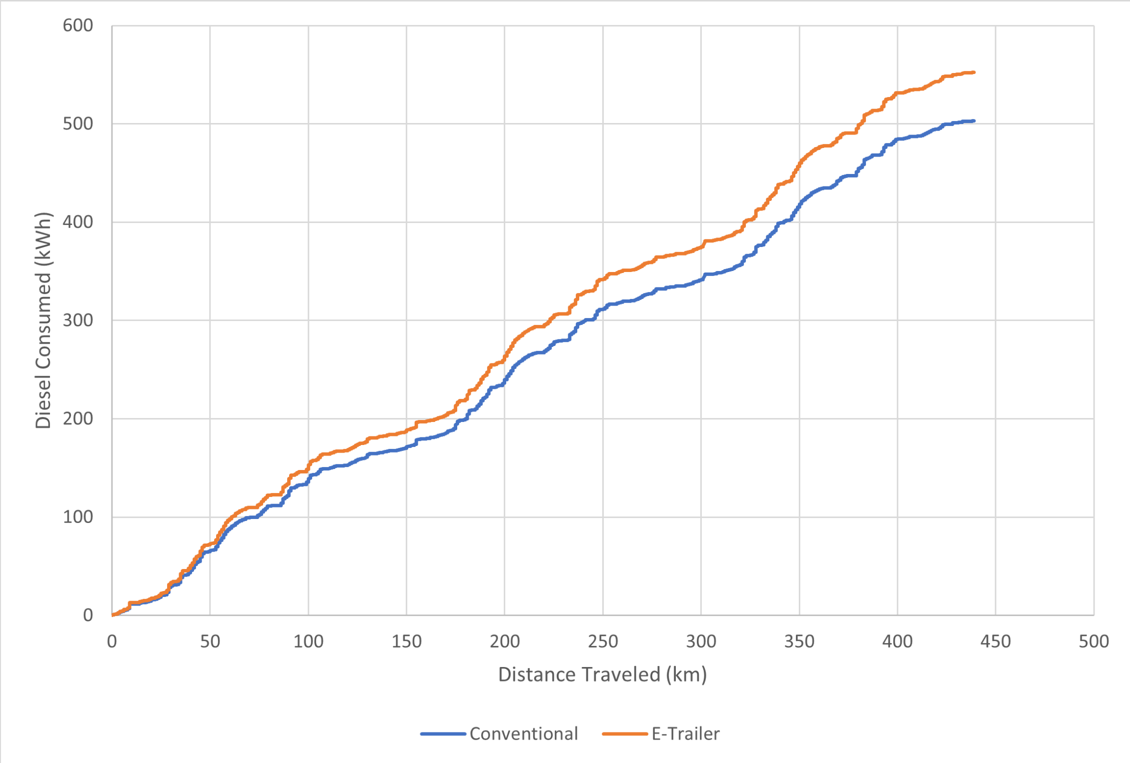


Figure 3.11: Fuel consumption comparison of E-trailer weight and a conventional trailer when loaded with 15 ton payload

Powertrain Weights

With higher battery capacities and motor torques also comes a higher weight. To take this into consideration a ratio between capacity and weight as well as between peak power and mass was calculated. To calculate the battery ratio, values of capacity and weight from an existing battery currently used in the Volvo group were used. The same was done for the motor ratio. Here the motor is one of the ones currently used in electric Volvo trucks. In table 3.12 the values and ratios are presented.

Table 3.12: Ratios for calculating the mass of motors and batteries depending on peak power and capacity.

	Mass [kg]	kWh or kW	Ratio, i
Battery	563	66	8.5 [kg/kWh]
Motor	87	160	0.54 [kg/kW]

These ratios were then used to calculate the weight of the E-Trailer in each simulation to determine how efficient each combination was. The weight was calculated by using equation 3.23. The weight of the trailer, $m_{trailer}$, and the mass of auxiliary components, m_{aux}, were estimated from the current E-Trailer. These corrections mainly were done to the weight of the auxiliary components such as; cooling, inverters, and mounting and were done consent with the thesis supervisor from Afry, Clive Misquith, who is involved in the E-trailer project as well. The values used are shown in the tables 3.12 and 3.13.

$$m_{E-Trailer} = m_{trailer} + m_{aux} + (i_{motor} * P_{peak}) + (i_{battery} * E_{battery}) \tag{3.23}$$

Table 3.13: Values of constants used to calculate trailer weight.

Constant	Value	Unit
$m_{trailer}$	6500	kg
m_{aux}	250	kg

Power Scaling from wanted Torque

The gear reduction built into the motors was not changed during the sweep simulations. This variable is useful if the rpm range of the electrical motor is too large and needs to be reduced to fit existing final gear ratios. However, for the sweep simulations, the max rpm was set constant to replicate a diesel engine.
The different motors were all scaled from the wanted torque output and the rpm range was derived from the final drive ratio and wanted velocity. The max/continuous power output was calculated from the wanted torque and estimated rpm range.

Initial SoC & SoC window

After some initial simulations, it became apparent that the SoC window and the initial SoC affected the simulation results heavily. For all simulations, the SoC window was set to 30%-70% and the initial SoC was set to 50% of the battery size. This will affect the sweeping simulations since the larger capacity batteries will have more initial energy and therefore an advantage. A fixed value would mean that all benefits of a bigger battery would not be considered unless the max energy of the battery would be reached during regenerative braking.

3.4.3.2 Route selection

To gather data on how different powertrains perform depending on the route, three different routes were chosen. One route had an aggressive elevation profile, one had a relatively flat profile, and one had a profile somewhere in between the two previous routes.
To simulate a full day of driving equation 3.24 was used. The maximum allowed time to drive each day is 9 hours [11] and with a maximum velocity of 80 km/h the maximum distance traveled in a day will never exceed 720 km.

$$d_{max} = t_{max} * v_{max} \tag{3.24}$$

Tampere to Helsinki

The driving cycle chosen to simulate a quite flat elevation profile is the route between Tampere and Helsinki. This route has an elevation difference of roughly 140m. This is not very flat, but the big elevation difference is located close to Helsinki and is very local, see figure 3.12. The driving cycle is both starting and ending in Tampere (roughly 360 km), this is because in most cases the haulage contractors have a location where they park their trucks. Starting and ending the route at the same place also makes sure there is no natural gain of potential energy. The highest elevation the route reaches is almost 140m and the lowest is sea level.

Figure 3.12: Altitude profile of the route Tampere to Helsinki to Tampere

2 × Tampere to Helsinki

To simulate a full day of driving the normal Tampere-Helsinki route was done twice, resulting in 718km. This distance is barely possible on a normal day but can be made possible through extra time according to Trafikverket [11]. The elevation profile is shown in figure 3.13.

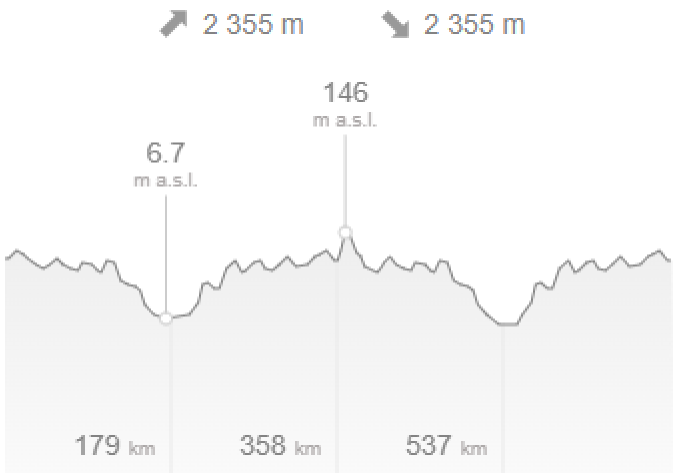


Figure 3.13: Altitude profile of the route 2x Tampere to Helsinki to Tampere

Kurtalan to Bahçesaray to Cizre

These cities are located in the Taurus mountains in the southeast of Turkey and were chosen in order to simulate how different powertrains would perform in hilly conditions. The cumulative height gain of the route was almost 11000 m and can be seen in figure 3.14 while the cumulative height loss was a bit more than 11000 m. During this route there is some potential energy to gain, it is however considered neglectable due to the characteristics of the route. The total distance of this route is roughly 450 km and the elevation differs between 400-2500 m .

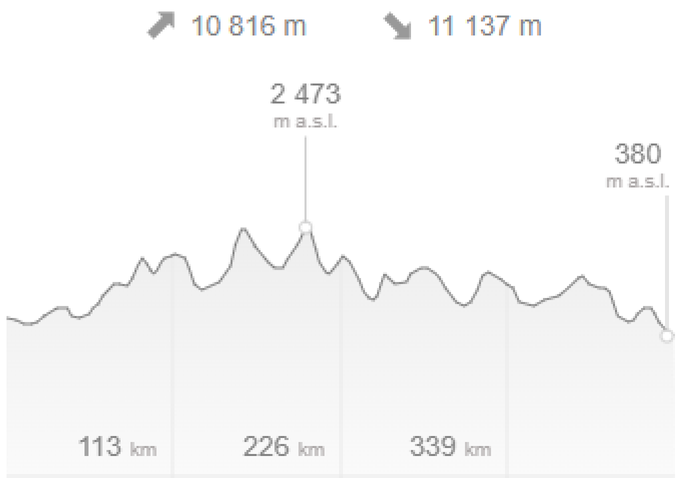


Figure 3.14: Altitude profile of the route from Kurtalan to Bahçesaray to Cizre

Kurtalan to Bahçesaray to Cizre to Kurtalan

In order to simulate a full day of driving the initial route in Turkey was extended by going back to Kurtalan. This resulted in the trip being a total of 610km with the elevation profile shown in figure 3.15. It also results in the route not gaining any potential energy.

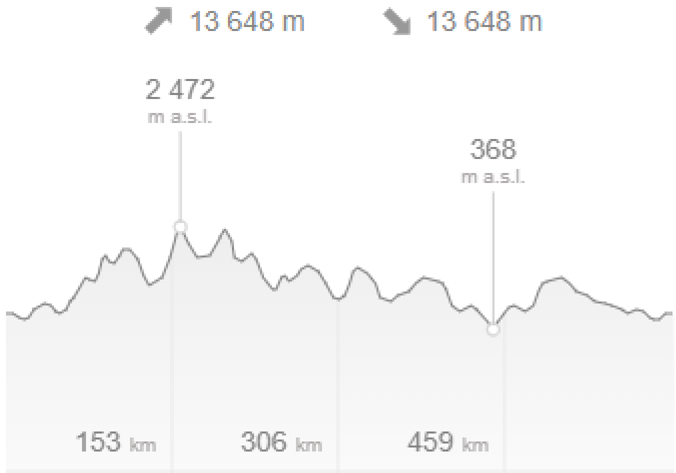


Figure 3.15: Altitude profile of the route from Kurtalan to Bahçesaray to Cizre to Kurtalan

Gothenburg to Viared to Gothenburg

The third route was between the Harbour in Gothenburg and the industrial area Viared which is located outside of Borås. This route is somewhere in between the routes in Turkey and Finland. The elevation stretches from sea level to roughly 200m above and is almost 150 km long. The elevation profile can be seen in figure 3.16 and has a cumulative height gain of 1000m.

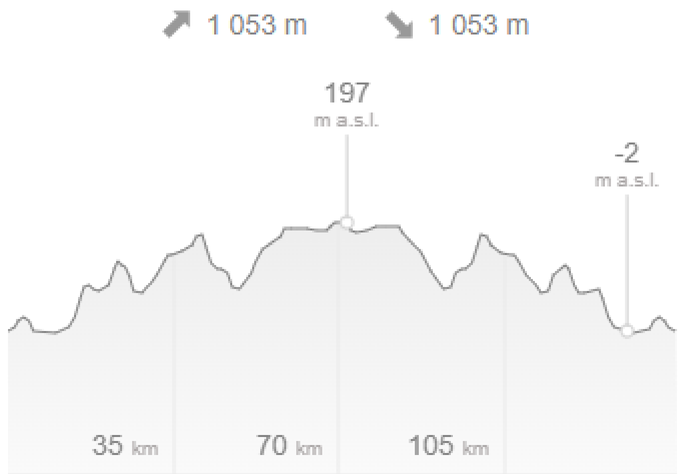


Figure 3.16: Altitude profile of the route Göteborg to Viared to Göteborg

3 × Gothenburg to Viared to Gothenburg

The trip from Gothenburg harbor to Viared can be made three times each day according to the Autofreight project at Volvo Trucks Technology [6]. This can be seen in the elevation profile shown in figure 3.17. Doing this trip three times a day extends the distance traveled to 430km.

Figure 3.17: Altitude profile of the route 3x Göteborg to Viared to Göteborg

3.4.4 Powertrain Comparisons

As mentioned earlier, the main goal of the E-Trailer is to save fuel for an ICE-powered truck and therefore the fuel saved or increased fuel efficiency was mainly compared. The increased efficiency was calculated with equation 3.25, where the $E_{convetional}$ is the energy required from the ICE to drive the route with a standard ICE truck and trailer and $E_{E-Trailer}$ is the required energy from the ICE to drive the same route, but with the assist of an E-Trailer. Both values were calculated by the simulation program and measured in kWh.

$$(1 - \frac{E_{convetional}}{E_{E-Trailer}}) \cdot 100 \tag{3.25}$$

A higher percentage indicated more diesel saved and potentially a better combination. However, since these batteries and motors were not based on existing or near-future components some of these combinations were not realistic. To filter these out and end up with more realistic combinations some other aspects were taken into account.

Physical limitations

To narrow down the results even further, a maximum battery capacity of 750 kWh was set. This was based on what Volvo currently have in their trucks. A similar approach was taken to determine the maximum motor torque. A solution with three motors is currently in use for Volvo Trucks' electrical truck, the FM electric, with a torque output of 1200 Nm. With this information, it was determined that a realistic, maximum, motor torque would be 1500 Nm. The simulation results for higher capacity batteries and higher torque motors were still used to identify trends and to observe if any of the trends dropped off if the motor or battery capacity got bigger. The results could also be used as pointers to what could be possible to achieve in the future if the battery and electric motor technology becomes better and more affordable.

Profitability

By taking the diesel and electricity costs into account it was possible to calculate if a combination was also saving money and therefore could be seen as beneficial in that aspect as well. This was done by calculating the cost of the diesel required to drive the route with a conventional truck and trailer and comparing it to the diesel and electricity cost required to drive with an E-Trailer on the same route. Equation 3.26 was used to calculate the cost of the consumed diesel for the conventional truck and trailer. Equation 3.27 was used to calculate the cost of charging the E-Trailer and using equation 3.28 the combined cost of driving an ICE truck with an E-Trailer. The difference in cost was then calculated using equation 3.29.

Since these prices always fluctuate, some limitations had to be set to get a fixed value that represents reality as well as possible. The price for the diesel was derived from taking the diesel price of the day from the closest gas station in Sweden and subtracting 25% for taxes.

According to InCharge [15] the cost for electricity, grid, and taxes results in a cost between 2-4 SEK/kWh depending on which company supplies the electricity, in what area of the country you are located, what time of day the charging takes place and what electricity contract you have. Since the price of charging varied significantly and had a big impact on the profitability of the E-Trailer a sensitivity analysis was carried out. The analysis was done after the sweep simulations were done to select a powertrain configuration that would be realistic, one for each route. The sweep simulations were all done with a charging price of 2 SEK/kWh. All three routes were included in the analysis and it was done by changing the charging price from 1-5 SEK/kWh and seeing how it affected the profitability on the selected powertrain and the routes. It was also assumed that the charging also only took place at night since the prices were lower and it also represented a realistic case, where the night was usually the only time a trailer was standing still for a longer amount of time and therefore could be charged a considerable amount. In table 3.14 the derived prices for diesel and electricity can be found.

$$Cost_{convetional} = \frac{Cost_{diesel}}{10} E_{convetnional} \tag{3.26}$$

$$E_{charged} = E_{battery-capacity}(B_{window-high} - B_{window-low}) SoC_{initial} \tag{3.27}$$

$$Cost_{E-Trailer} = \frac{Cost_{diesel}}{10} E_{E-Trailer} + Cost_{electricity} E_{charged} \tag{3.28}$$

$$Cost_{difference} = Cost_{convetional} - Cost_{E-Trailer} \tag{3.29}$$

With the help of these limitations, it was possible to narrow down which motor and battery would be the most beneficial powertrain to reduce diesel consumption without costing too much money and be realistic in the near future. The process of deriving these powertrains was initiated by finding which powertrain that was within the mentioned limitations. This was done using an if-statement in Excel. It checked

Table 3.14: Prices used to calculate energy costs.

Source	Price	Unit
Diesel	16.5	SEK/liter excl. tax
Electricity	2	SEK/kWh excl. tax

if a powertrain's $Cost_{difference} \geq 0$ and if its battery capacity and motor torque were within the specified limits. From the remaining powertrains, that fulfilled these requirements, the one which had the greatest fuel savings was selected as the best possible powertrain for that specific route. This was done for each route to determine the most optimal powertrain for each.

3.4.5 Final Powertrain

In this subsection, the setup for the simulation of the final powertrain will be described. It will cover the route selection, powertrain parameters, and other parameters used in the simulations.

3.4.5.1 Selection of components

The component selection was based on the simulations for the selected route, 3 × Gothenburg-Viared-Gothenbrug, and narrowed down using the methods described earlier. This route was selected since Volvo Trucks already has field vehicles operating it daily, making it well known and also well covered when it comes to reference data. The optimal configuration specifications were then as closely matched as possible with in-house components, motors, and batteries, available at Volvo Group.

3.4.5.2 Final Powertrain Simulations

With the components selected, final simulations were carried out. The setup for these simulations differed from the earlier, sweep simulations, in the fact that parameters that were previously unknown, and therefore left unchanged, now could be changed due to real components being used. Which parameters were changed depended on if they could be obtained or were described in the technical documentation related to the components. For the parameters that were not found the previous values were used.
In these simulations, the initial SoC, payload, and routes were also altered to see how different scenarios affected the performance of the powertrain.

Powertrain Parameters

To find the data needed to start the final simulations the datasheets for both the battery and motors were used.

In the datasheet for the batteries, it was concluded that the peak power output is 173 kW and that the continuous power output is 91 kW.

In the datasheet for the motors, there is a constant for both the peak power and the continuous power. Where the peak power is 150 kW for 150 seconds and for 10 seconds it is 160 kW. A mean value of these two where selected (155 kW). The motors can deliver 105 kW continuously. The datasheet does not give the torque/power/rpm curves of the motor. The motors can deliver 266 Nm continuously for 0-38% of the speed range. This results in the motor's starts to field weakening in order to increase the rpm at this point (3800 rpm), which then gives us the graphs needed.

3.5 Concept ideas

The main focus of the design and packaging aspect of the thesis included the axle configuration of the E-Trailer and the powertrain packaging. The specified requirements were the foundation of the concept and had a big influence on how the final design was done.

3.5.1 Axle configuration

From the list of requirements, it was stated that the E-Trailer required a three-axle combination. In the market analysis, it was also shown that a three-axle combination is the most common axle configuration for these types of trailers.

There were several different variants within the three-axle configuration, not including the driven axle, as well. Each with its own benefits and drawbacks. The main variants of axles are;

- Liftable
- Steerable
  - Self steered
  - Hydraulically steered
- Liftable and steerable

A conventional trailer usually does not have these variants, due to the increased price of adding such features. However, it is becoming more common to have a first liftable axle on the trailer to decrease rolling resistance and fuel consumption according to L. Cider [2]. This together with the wish of having both steerable and liftable axles on the E-Trailer, led to the decision to implement both liftable and steerable axles in the concept.

3.5.1.1 Choice of driven axle

The choice of which axle would be the most beneficial to have driven was derived from which axles would be preferred to have liftable. Inspiration was taken from four-axle trucks and how they usually are configured as well as the reasoning behind why such a configuration was the most beneficial in terms of weight distribution and drivability. The following reasoning was based on the criteria that two of the three axles were liftable on the trailer to fulfill the wishes from the list of requirements.

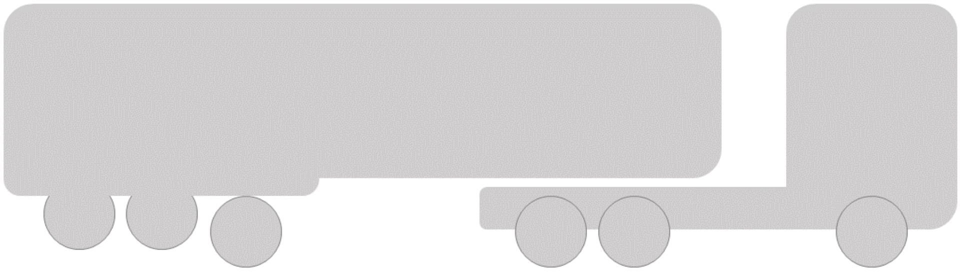


Figure 3.18: Truck and trailer combination with second and third axle lifted.

If the first axle was unliftable, the overhang of the trailer, with the two last axles lifted, would have been too large. This overhang would lower the kingpin pressure by "lifting" the trailer at the kingpin. By lowering the kingpin pressure, the axle pressure on the trailer will increase, potentially becoming too much, resulting in a lower cargo weight. The lower king pin pressure also decreases the axle pressure on the driven axle/axles on the truck decreasing the traction force and with that a decreased cargo weight. For the drivability of such a combination, it would be easy to maneuver at lower speeds due to its shorter wheelbase. However, it could be unstable at higher speeds. Since these trailers mostly are driven on highways at high speeds an unstable combination was not acceptable. In figure 3.18 a schematic figure of this scenario is shown.

In the case of the third axle being the unliftable the problem with weight distribution becomes the opposite with an increased kingpin pressure due to there being too little overhang. This could also result in a lower maximal cargo weight. When it came to the drivability of such a combination, the combination would have a longer wheelbase making it stable at higher speeds, which was preferable, but more difficult to maneuver at lower speed. In figure 3.19 a schematic figure of this scenario is shown.

The last case of having the second axle unliftable became a compromise between the two earlier cases. It created a smaller overhang, decreasing the kingpin pressure, as well as moving more weight in front of the balancing point, by lifting the first axle, increasing the kingpin pressure. In figure 3.20 a schematic figure of this scenario is shown.

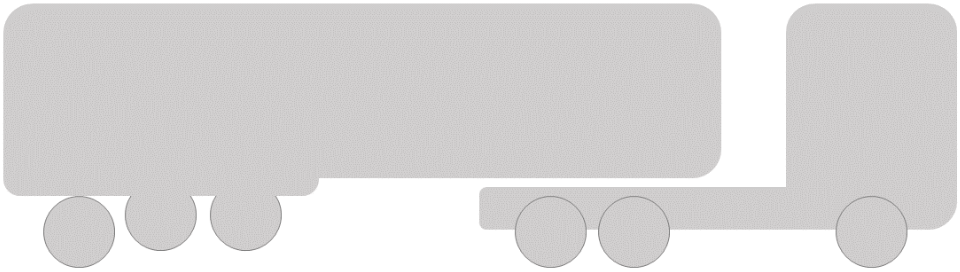


Figure 3.19: Truck and trailer combination with first and second axle lifted.

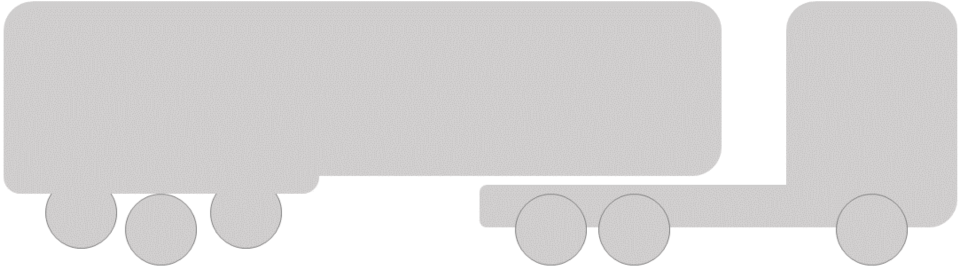


Figure 3.20: Truck and trailer combination with first and third axle lifted.

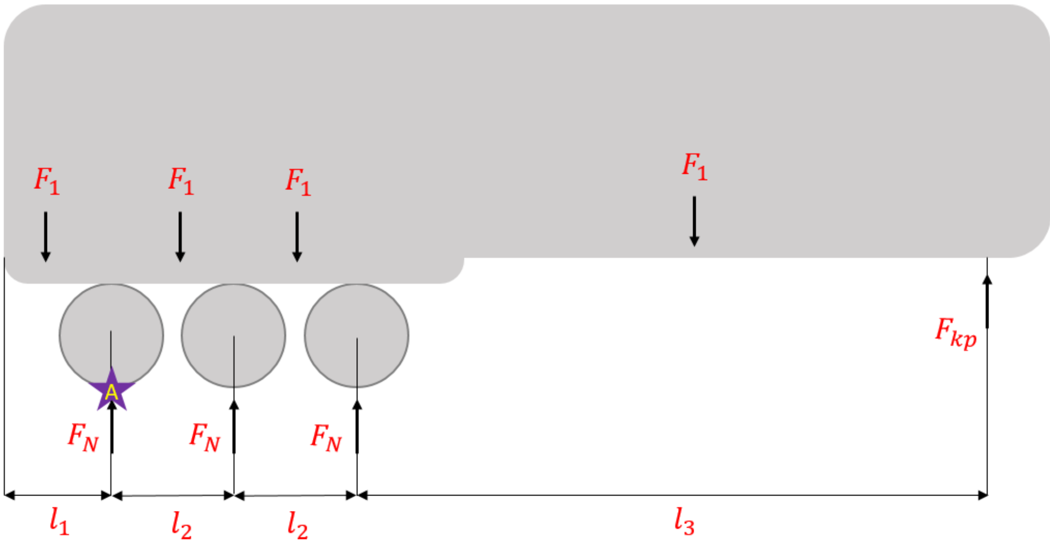


Figure 3.21: Free body diagram of the trailer with no axles lifted.

This unchanged kingpin pressure was also tested by calculating the difference in the kingpin pressure between having all three wheels on the ground compared to having the first and third axles lifted. This was done by making a free-body diagram of the trailer with all three wheels on the ground, figure 3.21. From the free body diagram two equilibrium equations were derived, equation 3.30 and 3.31. From these equations, the kingpin force, F_{kp}, was solved. The same was done for the case of having the first and third axles lifted. Figure 3.22 shows the free body diagram of that case and equation E.2 and E.2 was the derived equations from that free body diagram. The same was also done for the first and second cases described above. The free body diagram and equations for those cases can be found in appendix E.

$$-\frac{F_1 l_1}{2} + \frac{F_2 l_2}{2} + F_3(l_2 + \frac{l_3}{2}) + F_4(l_2 + l_3 + \frac{l_4}{2}) - F_{kp}(l_2 + l_3 + l_4) - F_N l_2 - F_N(l_2 + l_3) = 0 \tag{3.30}$$

$$3F_N + F_{kp} - (F_1 + F_2 + F_3 + F_4) = 0 \tag{3.31}$$

$$-\frac{F_1 l_1}{2} + \frac{F_2 l_2}{2} + F_3(l_2 + \frac{l_3}{2}) + F_4(l_2 + l_3 + \frac{l_4}{2}) - F_{kp}(l_2 + l_3 + l_4) - F_N l_2 = 0 \tag{3.32}$$

$$F_N + F_{kp} - (F_1 + F_2 + F_3 + F_4) = 0 \tag{3.33}$$

In both cases, it was assumed that the load on the trailer was equally distributed over the trailer and that the three axles also had equal load distribution. Equation 3.34 was used to calculate the distributed load coefficient, q. Axle distances and payload were taken from the base trailer and calculated the payload used earlier. Table 3.15 shows the values of the constants used in the calculations. The moment was

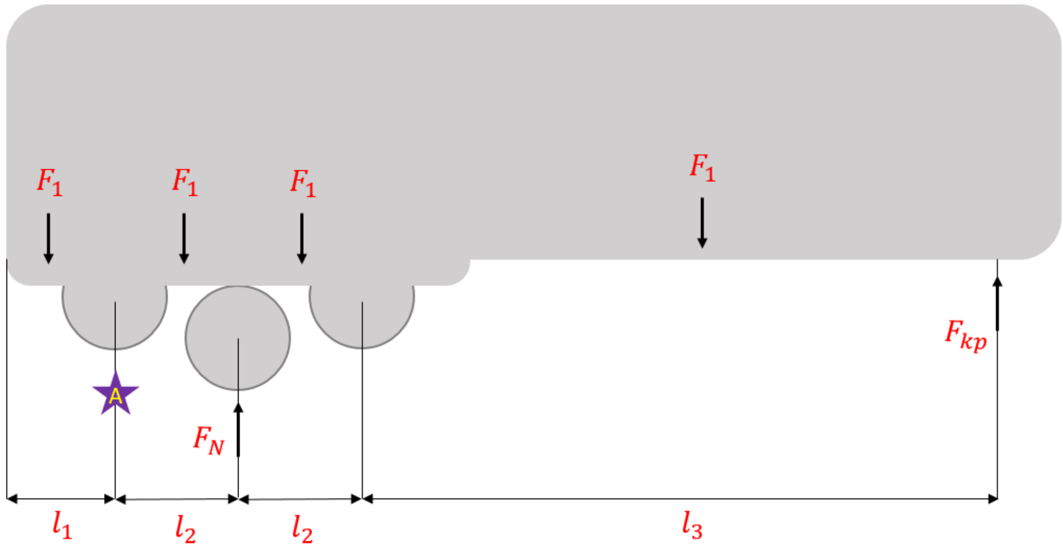


Figure 3.22: Free body diagram of the trailer with first and second axle lifted.

Table 3.15: Values of base trailer constants used to calculate the kingpin forces, F_{kp}.

Constant	Explanation	Value	Unit
l_1	distance from end of trailer to third axle	1.675	m
l_2	distance from third to second axle	1.35	m
l_3	distance from second to first axle	1.35	m
l_4	distance from first axle to kingpin	7.05	m
$m_{payload}$	mass of payload on the trailer	15000	kg

taken around the contact patch of the third axles tire, marked with "A" in the figures.

$$q = \frac{m_{payload}g}{l_1 + 2l_2 + l_3} \quad [N/m] \tag{3.34}$$

Using the distributed load coefficient, q, the forces F_{1-4} was calculated using equations 3.35 - 3.38.

$$F_1 = \frac{ql_1}{2} \tag{3.35}$$

$$F_2 = q(l_1 + \frac{l_2}{2}) \tag{3.36}$$

$$F_3 = q(l_1 + \frac{3l_2}{2}) \tag{3.37}$$

$$F_4 = q(l_1 + 2l_2 + \frac{l_3}{2}) \tag{3.38}$$

With all forces and distances known, the kingpin pressure, F_{kp}, for both cases were solved for and compared using MATLAB.

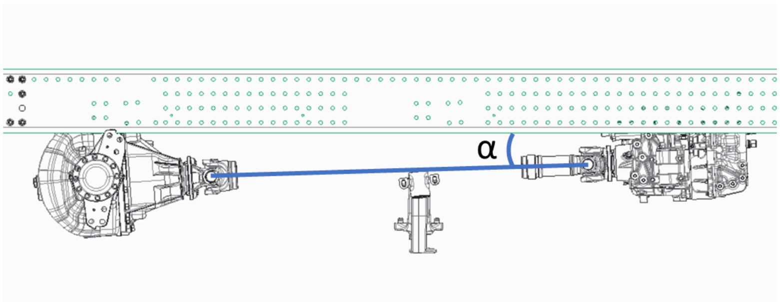
Having the second axle unliftable, and thereby driven, also brings another benefit when it comes to maneuverability with all axles down. The resulting rotating center for the three axles ends up in the second axle. Having the second axle being the driven axle helps the rotation of the trailer since the driving force is acting on the same axles as the trailer rotates about. If the first axle would have been driven, the axle would have pulled the trailer straight instead of helping the rotation. The same logic applies if the third axle would have been driven, but instead of pulling it straight, it would have pushed it straight. For 8x2 trucks, which also have a three-axle combination in the rear, that operates on roads in good condition it is common to have this axle configuration.

3.5.2 Powertrain layout

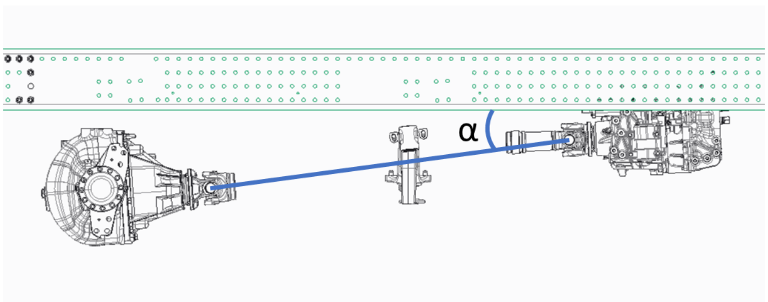
From the market analysis, it was clear that the powertrain of an E-Trailer could be designed in many different ways and that every solution had its pros and cons. Because of the list of requirements, some concepts could be ruled out. This was mainly because the thesis aims to only use existing Volvo Group components.

The use of a propeller shaft was looked into. It was due to that current electric Volvo trucks were using it. The components available are designed to be used with a propeller shaft. A propeller shaft was also beneficial since it moved the motors and eventual gearboxes away from the axles, where there is space for them.

Since the axles can move up and down, due to the suspension and road surface, as well as be lifted it was important to ensure that the propeller shaft and the pusher axle would not clash in any scenario. To test this, a worst-case scenario was set up. If the propeller shaft cleared the pusher axle it was deemed to work in any scenario. The test setup was inspired by a similar test that was conducted in Emil Olsson's report regarding the packaging and design of the first E-Trailer. In the scenario where the first axle, the pusher, is lifted up and the second, driven axle, was dropped. These values used were the maximum bump and droop distances that the axles were designed for. By lowering the driven axle the propeller shaft angle, α, decreases. This also decreased the clearance to the pusher axle and by having the pusher axle lifted, the clearance became the smallest possible, making it the worst-case scenario. In figure 3.23 this decrease of α is visualized. A normal ride height scenario, with both axles at ride height, and a scenario with a full bump on the driven axle and ride height on the pusher axle were also carried out to ensure no unexpected clashes would appear. The change in travel from normal ride height for each axle and scenario can be found in table 4.20



(a) The angle α during normal ride height.



(b) The angle α during full droop on the driven axle.

Figure 3.23: Propeller shaft angle, α, is dependent of the vertical position of the axles.

Table 3.16: Positive distance indicates the compression of the suspension and the axle moves up. A negative indicates the opposite and the axle moves down.

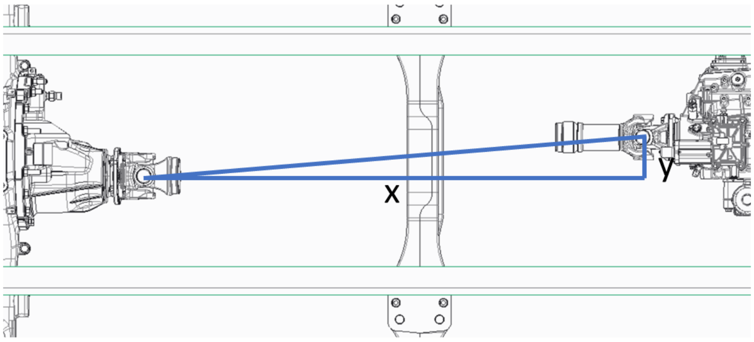
Scenario	First axle [mm]	Second axle [mm]	Explanation
1	90	-178.5	Worst case scenario
2	0	0	Normal ride height
3	0	90	Full bump on the second axle

Each scenario was tested by positioning the axles in CAD with the gearbox and the propeller shaft in their respective positions. A drawing was then created to measure clearance distances between the propeller shaft and the axle as well as to ensure that the angles and distances of the propeller shaft were within the specified ranges. The gearbox and motor placement were then changed in order to obtain the right angles and distances as well as to prevent clashing.

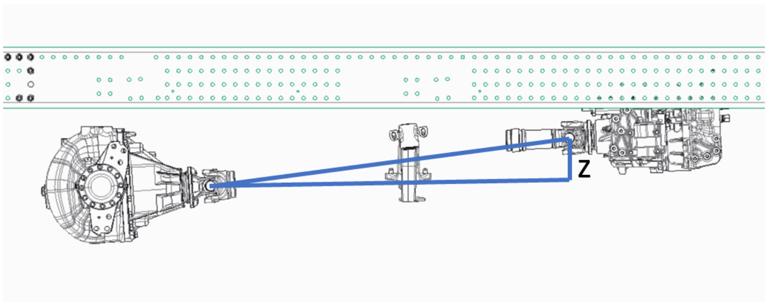
Since the propeller shaft moves with the driven axle its length varies. By testing these scenarios it also showed how much this movement affected the length of the propeller shaft. Due to an offset between the gearbox flange and the driven axle, the y-distance, and the height difference between the two, the z-distance and the length of the propeller shaft, l_{prop}, were needed to be calculated in 3D. To calculate the length Pythagoras theorem in 3D was used, see equation 3.39. In figure 3.24 the required distances to do the calculations are shown. To get both the full range of lengths the propeller shaft could encounter the distances were measured in all three cases described earlier in this section. Then the smallest and largest measurement was taken to be the extremes for the propeller shaft length.

$$l_{prop} = \sqrt{x^2 + y^2 + z^2} \tag{3.39}$$

Emil's report stated some important limits of the propeller shaft. First, the maximum length of the propeller shaft should not exceed 2100 mm. Secondly, the working range of the universal joints on the propeller shaft was between 1-6° with the axles in normal ride height. This meant that the propeller shaft angle could exceed this range in shorter periods of time if necessary. However, if the angle were to exceed this range continuously the expected lifetime would decrease. As explained earlier the propeller shaft operates in the 3D-space and there are two angles to take into account, the α-angle described earlier, and the angle β shown in figure 3.25. The latter only needed to be checked once since it does not change regardless of the scenario. This is due to that the y-distance never changes since the suspension does not move in the lateral direction while in use. Because of these requirements, the motor/gearbox was placed and packaged first, since they largely affect the propeller shaft's angles and length.



(a) The x and y distances was measured from the top view.



(b) The z distance was measured from the side view.

Figure 3.24: Side and top view of the distances needed to calculate the propeller shaft length.

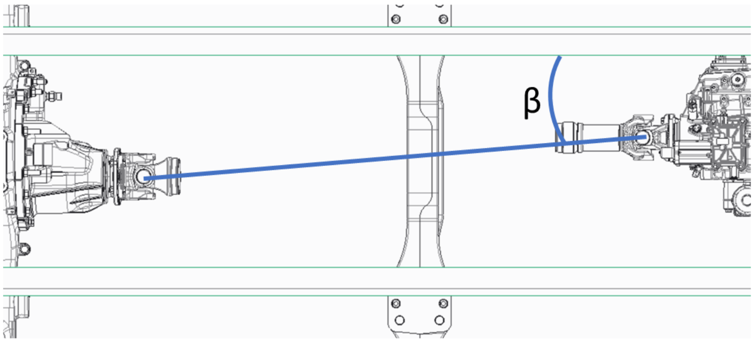


Figure 3.25: Propeller shaft angle, β, is not dependent on the vertical position of the axles.

The scenarios were tested using CAD. The axles were put in position together with the gearbox and the propeller shaft in their respective positions. A drawing was then created to measure clearance distances between the propeller shaft and the axle as well as to make sure that the angles and distances of the propeller shaft were within the specified ranges. Gearbox and motor placement were then changed until there was no clashing of the axles or propeller shaft.

The placement of the batteries was decided based on where space in the chassis was available as well as how they would affect the center of mass of the trailer. Since the batteries were the heaviest component their placement could affect both the drivability and loading capacity of the trailer. Looking at competitors and where they placed their batteries as well as where they were located on the first generation E-Trailer, a possible solution was to place them between the first axle and the support legs of the trailer. This space was not occupied by anything on a regular trailer and was often left empty or used to package cooling units for the trailer. In figure 3.26 and 3.27 the placement of the batteries can be seen.

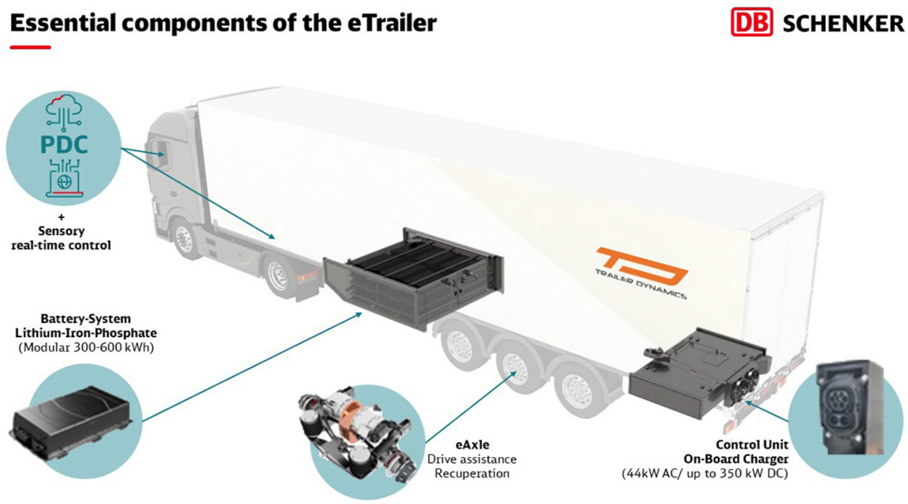


Figure 3.26: Trailer Dynamics packaging of their powertrain.

Figure 3.27: Battery position on the first generation of the E-Trailer at Volvo Trucks.

This location was also beneficial in terms of positioning the center of mass. Since it was centered on the trailer making the potential shift of its position minimal. This minimal change in center of mass also resulted in the axle and kingpin pressures would remain similar to a regular trailer, just with a greater magnitude.

Other electrical components, like the inverter and charger, had greater degrees of freedom in terms of positioning since they were smaller and lighter. However, looking at an electrical schematic of an electric powertrain, the inverter will be located between the batteries and the motor and the charger will be connected to the battery. Which made it beneficial to also package them close to their connected components. For the inverters, it meant being close to the batteries and the motors. The charger could, as seen in figure 3.26, be placed behind the third axle together with other auxiliary components. It was preferred to have the charger closer to the batteries in order to keep the entire powertrain as centered as possible.

The positioning of the cooling components mainly focuses on the placement of the radiators since they are the most important. The main requirement was to have sufficient airflow through the radiators. The first E-Trailer positioned the radiators in front of the batteries, one on each side, see figure 3.28. This feeds the radiators with clear air without anything to obstruct it. Other positions for the radiators could have been between the batteries and the first axle or behind the third. The problem with these positions was that the front of the radiators would have been blocked by either the batteries or the rear fender, decreasing the amount of air naturally passing through.

Figure 3.28: Radiator placement on the first E-Trailer

3.6 Packaging of the powertrain

The packaging of the selected components was done in the CAD software CREO PTC, a CAD software used at Volvo Trucks. Most of the components, like motors, batteries and various mounts for these already exist and were used as much as possible. This made the packaging and design process more simple since new parts were kept to a minimum. Emil Olsson's report on the first E-Trailer, was used as a guide and reference material in this packaging study of this E-Trailer, see appendix F.

3.6.1 Obtaining CAD models of components

The CAD model was structured into three main sub-assemblies. In the list below are these main sub-assemblies listed.

- Chassis
- Electrical powertrain
- Mechanical powertrain

Since most parts included in this model were already existing components at Volvo Group, they were located from already built trucks with the right configuration or parts. The components were obtained using Volvo software.

3.6.1.1 Chassis

The chassis sub-assembly contained two assemblies, the Parator chassis and the Volvo Chassis. The Parator chassis is the upper chassis that carries the containers. It also included the kingpin to connect the trailer to the truck as well as the support legs and lights. Figure 3.29 shows a CAD representation of the Parator chassis. It was taken from the previous E-Trailer since it was not going to change and be built by Parator. It was mounted to the Volvo chassis using the mounting method derived from a previous thesis report [4]. The Volvo chassis was the lower chassis built by Volvo Trucks. It consists of Volvo frames rails, cross members, towing members etc. These parts were carried over parts from the previous E-Trailer design. Axles and suspension components were sourced from existing trucks using the described method above.

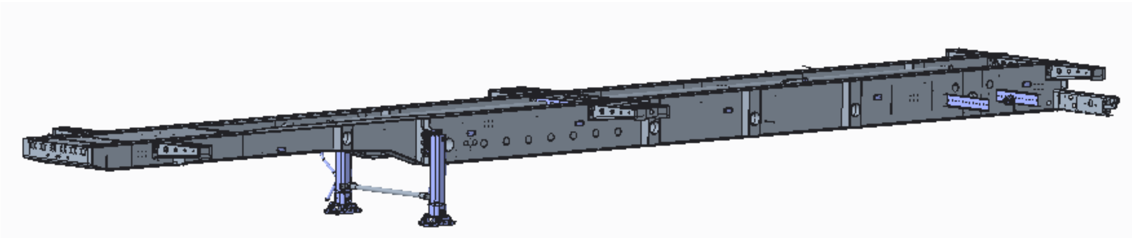


Figure 3.29: ISO view of the Parator Chassis.

3.6.1.2 Electrical powertrain

The electrical powertrain assembly contained the following components:

- Inverter
- Batteries
- Charger
- Junction boxes
- Radiators

3.6.1.3 Mechanical powertrain

The mechanical powertrain assembly contained the following components:

- Motors
- Gearbox
- Propeller shaft

4
Results & Discussion

This chapter contains the results found gathering information from different sources, what the list of requirements included, what trends were accumulated from the simulations, the dimensions of the final powertrain, the fuel savings on the different routes and how the final powertrain is packaged inside the trailer. Once the different results are presented there will also be a discussion with thoughts and reasoning around the results.

4.1 List of Requirements

The result of the prestudy was the list of requirements found in appendix A. The requirements and wishes could be split into two categories: general requirements and target values that were calculated, see the Vehicle Dynamics section below. The general requirements were derived from the experience of building and testing the first generation of E-Trailer. Such requirements could be to have the charger port on the right side of the trailer or have the ability to heat the batteries. Other general requirements were more basic and tied to the problem that the E-Trailer was created to solve, for example, reducing energy consumption from the ICE or using an electric powertrain.

4.1.1 Vehicle Dynamics

The results from the hand calculations, simulations and the testing of the presented vehicle dynamics scenarios will be shown in this chapter.

4.1.1.1 Straight Reverse

The result of the hand calculations is presented in table 4.1. The equations are used to focus on calculating the torque needed on the hub, which then is divided with different gear ratios to calculate what peak torque is needed from the motor. This can be seen in table 4.1 where the torque needed from the motor, for a 33-ton GCW is 220Nm with a 4.11 ratio on the rear axle.

Table 4.1: Results of hand-calculations for reversing straight

GCW [ton]	Torque hub [Nm]	Gear ratio 4.11 [Nm]	Gear ratio 3.52 [Nm]
33	908	220	258
48	1320	321	375
63	1735	422	492

4.1.1.2 Angled Reverse

The function of reversing with an articulation and steering angle was calculated, simulated and tested.

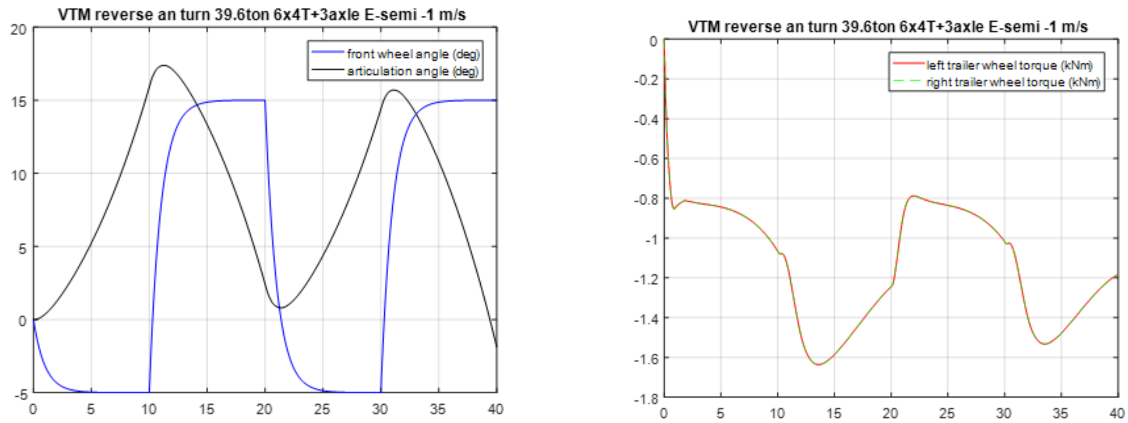
Calculations

The calculation part was done iteratively, and the result can be seen in table **??**. The torque is calculated at the hubs of the drive axle and is measured in the unit kNm.

θ_{front} 0	1	0	1	2	1	2	3	2	3	4	3	4	5	4	5
θ_{rear} 0	0	1	1	1	2	2	2	3	3	3	4	4	4	5	5
T_{hub} 1.3	1.8	2.6	3.1	3.6	4.4	4.9	5.3	6.1	6.6	7.1	7.9	8.4	8.9	9.7	10

Simulation

The x-axis in the figures 4.1 represents the time in seconds. The x-axis times are the same for both 4.1a and 4.1b. The y-axis in figure 4.1a shows the articulation angle and the steering wheel angle in °. The blue line represents the steering wheel angle, which ranges from -5 °to 15 °. The black line in the same figure represents the vehicle's articulation angle during the reverse. The y-axis in figure 4.1b shows the torque needed on each driven hub of the trailer. The torque is negative because of the direction the combination has, since it is reversing the torque is negative. The maximal torque needed according to the simulation is roughly 1.6 kNm on each hub. Thus resulting in a total torque need of 3.2 kNm.



(a) Steering wheel angle and articulation angle simulated

(b) Torque needed on each hub from the simulated articulation and steering angles

Figure 4.1: Angled reverse simulation results

Testing

The result from testing the first generation E-Trailer was that the motor can not pull the vehicle combination from any significant angle. It was also very sensitive to the slope of the ground, where even small slopes made significant differences.

Discussion

The angled reverse is a very difficult area to fully comprehend. The calculations depend on tire data that is determined from testing, according to the simulation tool the first-generation E-Trailer is enough, and the testing of the first-generation E-Trailer suggests that it definitely is not possible. If the function of reversing with angles is a function that is wanted the E-Trailer has to be built and tested. An E-Trailer with higher gear ratios from the motor to the ground will most definitely deliver enough traction force to test this more thoroughly and thereby deliver the minimum traction force needed.

4.1.1.3 Powershift

The calculations made for the powershift function resulted in the values that can be seen in table 4.2. In the table the mass of the trailer ($m_{trailer}$) is given in tons, the angle α_s is given in °and the power needed from the electric motor (P_{EM}) is given in kW. Since an up-shift is not going to be more than 10s the power needed from the electric motor can be assumed to be peak power.

Table 4.2: Values of $m_{trailer}$ and α_{slope} and the resulting power need from the EM at 40km/h initial Velocity

$m_{trailer}$	α_s	P_{EM}	α_s	P_{EM}	α_s	P_{EM}	α_s	P_{EM}	α_s	P_{EM}	α_s	P_{EM}
10	0	45	1	84	2	122	3	160	4	198	5	236
15	0	50	1	98	2	146	3	194	4	241	5	289
20	0	55	1	113	2	170	3	227	4	284	5	342
30	0	65	1	142	2	218	3	294	4	371	5	447
40	0	75	1	171	2	266	3	362	4	457	5	553
50	0	85	1	200	2	315	3	429	4	543	5	658

Discussion

A quite powerful motor is needed to have the powershift function. For completely flat roads the needed power is relatively low, however, it is important to know that no roads are completely flat and the needed motor power increases significantly between 0°and 1°.
A 300kW motor seems to be a size that can handle a spread of masses/angles very well. It is important to know that the steps in table 4.2 will affect these values. If for instance, the steps of the variable $m_{trailer}$ would have been 5 tons the needed motor size would be different. Therefore it is important to know the expected payload on the trailer that the powershift function will be dimensioned for.
The initial velocity of 40km/h where chosen as the average speed of the powershift calculations. This means that with larger velocities the peak power needed of the motor will increase. The table 4.2 is therefore only valid for velocities of 40km/h or below.

4.2 Simulation & Dimensioning

During this chapter, the results from the simulation tool validation and the sweeping simulations will be presented. The results will also be discussed succeeding the presented results.

4.2.1 Simulation Tool Validation

The simulation tool was validated in two different ways, validating towards a diesel truck and the E-Trailer itself. The results and discussions of the validations will be presented below.

4.2.1.1 Diesel Truck Validation

When running the simulation tool with the data from the Autofreight vehicle on the same route (Gothenburg to Borås). Three simulations were made from real data and their results are shown in figure 4.3.

Table 4.3: Diesel consumption from Autofreight vehicle compared to simulation tool

Attempt	1	2	3
Real Consumption [kWh]	22.4	40.4	27.4
Simulation Consumption [kWh]	29.4	47.	35.2

Discussion

The amount of fuel that is consumed seems to always be higher in the simulation tool when compared to real data. We believe this might be because the simulation savings of diesel is scaled from how many kWh of fuel is needed. This means that the amount in liters is calculated by using the efficiency values of different parts of the powertrain. These efficiency values are estimations and might be different in reality. An example of this is the efficiency of the diesel engine, where the value for the diesel engine's efficiency was 30%. In reality, it might be higher which would result in fewer liters of diesel consumed. As long as the simulation is consistent and calculates the fuel consumption equally for the E-Trailer the percentage of fuel savings should be similar. The exact amount of fuel consumed should however not be trusted fully.

4.2.1.2 E-Trailer Validation

The fuel saved in percentage, can be seen in table 4.4, are quite close when the battery is not reaching its "safe state" where it starts limiting the power output which can be seen by the SoC value in attempt 1. This is, however, the only attempt where the end SoC from the simulations differs from the real-life data. During the other attempts the end SoC from the simulations follows the actual end SoC while the fuel-saving percentage differs. The simulation tool saves up to 5% more fuel than the real data in attempts 2 and 3.

Table 4.4: Results from real test data and simulation data

Real Fuel Savings [%]	23.8	18.6	15.5
Simulation Fuel Savings [%]	24.3	23.8	19.5
Real End SoC [%]	32	30	27
Simulation End SoC [%]	34	30	27

Discussion

In attempt 1 it can be seen that the simulation has not used as much energy compared to the real data. This means that the simulation tool saves the correct amount of fuel but is not draining the battery correctly. In attempts 2 and 3 it can be seen that the SoC at the end of the route is following the real value while the fuel-savins are more than in the real-life data. We think this means that the battery runs out later than it should. This will lead to the battery lasting longer and the total fuel savings at the end of a route are going to be more than it should be.

Having more real testing data would also be useful in order to simulate more and higher levels of SoC. This could lead to more data and would make it easier to draw a conclusion about the simulation tool.
The Simulation tool is most likely overestimating the electrical powertrain. We decided due to time limitations that we would use this simulation tool with increased mass as safety-factor and would not spend time on making changes in order to improve it.
The conclusions from the simulation validation are that the tool itself is not perfect. But since the intended simulation tool was not an option, we had to go with the next best thing, which was this tool.

4.2.2 Sweep Simulations

In the following section, the results from the sweep simulations will be presented. Due to the number of sweep simulations, only some powertrains and their results will be presented in order to make the results easier to grasp. The full results from the simulations can be found in "Simulation Results" in Appendix F.

4.2.2.1 3 × Gothenburg-Borås-Gothenburg

The best match of motor and battery size of the sweep simulations on the route three times Gothenburg to Borås (Viared) back to Gothenburg can be seen in table 4.5. A maximal fuel saving of 38.9% is achieved by the motor with 1500 Nm of peak torque when it is combined with a battery size of 650 kWh. Another powertrain that was simulated consists of a motor that delivers 750 Nm peak torque and has a battery with a capacity of 550 kWh. This powertrain will save roughly 30.2% fuel compared to a conventional combination.

Table 4.5: Results of sweep simulations on the route 3xGBG-Via-GBG

Motor Size [Nm]	Battery Size [kWh]	Maximal Fuel Savings [%]
250	250	10.7
500	450	22.4
750	550	30.2
1000	600	34.6
1500	650	38.9

Discussion

That the maximal fuel savings are archived by the biggest powertrain is not a surprise since it will also be the most expensive one with its 650 kWh of battery capacity. In table 4.5 it can be seen that the increase in battery capacity is not linear. This is because of the different motors' possibility to regenerate potential energy back to electric energy. Where the bigger motors regenerate more energy, therefore the powertrains with bigger motors do not have the need for a linearly increased battery capacity. But a bigger motor will need an increase in battery capacity because a bigger motor consumes more energy. In the same table, it is also evident that the total fuel savings increases with the bigger powertrains, however, the amount it saves decreases with each step of powertrain size. For example, between the 250 Nm motor and the 500 Nm motor, the total fuel savings increased by 11.7 percentage units. Between the 500 Nm motor and the 750 Nm motor, the fuel-saving increase is 7.8 percentage units. From the 750 Nm motor to the 1000 Nm, the increase is 4.4 percentage units. While a bigger step of motor size (500 Nm instead of the previous 250 Nm steps) from the 1000 Nm to the 1500 Nm motor is only 4.3 percentage units.

It is also important to remember the price of the components. Bigger components will cost more money. Increasing the battery capacity is the most costly part of the powertrain. This means that the battery capacity should be minimized. Minimizing the battery capacity will also decrease the cost of charging it fully. Since electricity is expensive compared to diesel the bigger powertrains will in general cost more each day. Increasing the battery size would also increase the total mass of the trailer. Due to axle loads and distances the trailer has a maximal cargo weight. By increasing the mass of the trailer the maximal cargo weight will decrease.

Determining which powertrain would be the best is difficult. If the cost of the trailer is not in consideration the best powertrain would be the biggest powertrain since it would save the most fuel. The most efficient when considering fuel savings per kWh battery would be the 500 Nm motor. And a middle ground would be the powertrain with the 750 Nm motor.

4.2.2.2 2 × Tampere-Helsinki-Tampere

The results of the simulations on the route that starts from Tampere, goes to Helsinki and then back to Tampere 2 times in a day can be seen in the table 4.6. The maximal fuel saving is made with the powertrain that consists of the motor with 1500 Nm peak torque and a battery capacity of 1000 kWh. Another powertrain consists of a motor that delivers 500 Nm peak torque combined with a battery pack with a capacity of 750 kWh.

Table 4.6: Results of sweep simulations on the route 2xtamp-helsi-tamp

Motor Size [Nm]	Battery Size [kWh]	Maximal Fuel Savings [%]
250	500	13.3
500	750	22.8
750	1000	29.6
1000	1000	32.4
1500	1000	33.0

Discussion

The maximal fuel savings is still achieved by the largest powertrain possible. The largest powertrain simulated can be seen in table 4.6 where the 1500 Nm and its 1000 kWh battery capacity saves roughly 33% fuel compared to the conventional combination. But if the cost of the batteries and motors is considered this changes quite drastically. This can also be seen in table 4.6 where the best battery capacities for each motor size are shown. The increased fuel savings between the 1500 Nm motor and the 1000 Nm motor is only 0.6 percentage units, and the fuel savings between the 750 Nm and the 1000 Nm motors are only 2.8 percentage units. This is most likely due to a bad match between the bigger motors and their batteries and the bad match is a result of not simulating bigger batteries than 1000 kWh. This is because it would be incredibly expensive to put more than 1000 kWh of batteries on the trailer. The step from the 500 Nm motor to the 750 Nm motor is a significant 6.8 percentage units, but the 750 Nm motor requires a battery capacity of 1000kWh. This battery size is right now unrealistic because of its specific energy and cost. Batteries with a capacity over 750 kWh are therefore not fulfilling the requirements. This means that the 750 kWh needed with the 500 Nm motor is considered the most optimal for this route.

4.2.2.3 Kurtalan-Bahçesaray-Cizre

The results of the best powertrain combinations that were simulated can be seen in table 4.7. The maximal fuel savings comes from the powertrain combination that has a motor with 1500Nm peak torque and a battery capacity of 200 kWh. On this route, the most optimal powertrain is also the powertrain with the highest fuel savings.

Table 4.7: Results of sweep simulations on the route Kurtalan-Bahçesaray-Cizr

Motor Size [Nm]	Battery Size [kWh]	Maximal Fuel Savings [%]
250	50	-1.3
500	50	4.0
750	100	8.9
1000	150	13.7
1500	200	22.4

Discussion

This is the only route where the powertrain that saves the most also is quite realistic. Table 4.7 shows that the maximal fuel savings are around 22.4% with a 1500 Nm motor and a 200 kWh battery. However the table 4.7 does not show how the fuel savings differs between different battery capacities and the same motor. In this case, the best fuel savings for the 1500 Nm motor is the 200 kWh one, but it does not show that the 100 kWh battery capacity saves 22.0% when it is compared to a conventional combination. The fuel savings between a 200 kWh battery and a 100 kWh battery is therefore only 0.4 percentage units. In this case, the extra fuel savings from a 200 kWh battery does not make up for having an extra 100 kWh of battery capacity. It is important to know that this route is an absolute extreme and has the extra cost, both weight-wise and the price of the 100 kWh extra battery capacity. It might be beneficial on routes that are similar but not exactly as extreme. Deciding an absolute optimal is therefore more difficult on this route than the others, but the trend of having a big motor combined with a relatively small battery is evident.

4.2.2.4 Sensitivity analysis of charging price

The result of the sensitivity analysis on each route is presented below as well as what powertrain that was compared and its reduction in fuel consumption.

3 x GBG-Viared

Powertrain specs: 1000 Nm, 600 kWh battery and saving 34,6% fuel

Table 4.8: Sensitivity analysis of charging price for GBG-Viared.

Charging price [SEK/kWh]	Profitability [SEK/day]
1	53,7
2	-186.3
3	-426.3
4	-666.3
5	-906.3

2 x Tempere-Helsinki

Powertrain specs: 750 Nm, 750 kWh battery and saving 23,7% fuel

Table 4.9: Sensitivity analysis of charging price for Helsinki.

Charging price [SEK/kWh]	Profitability [SEK/day]
1	-7,95
2	-307.95
3	-607.95
4	-907.95
5	-1207.95

Turkey

Powertrain specs: 1500 Nm, 100 kWh battery and saving 22,0% fuel

Table 4.10: Sensitivity analysis of charging price for Turkey.

Charging price [SEK/kWh]	Profitability [SEK/day]
1	474.8
2	434.85
3	394.8
4	354.8
5	314.8

Discussion

The charging price has a big effect on if it is possible to save money using an E-Trailer due to lower fuel consumption. It can clearly be seen in the results above and shows that the price of liquid fuel, diesel in this case, is very cheap for the amount of energy it carries compared to electricity. The outlier here is that the route in Turkey actually being profitable regardless of the change in charging price. This follows a trend seen on the other routes as well being that the larger battery capacity the trailer is equipped with, the less profitable it becomes. This can be traced to the fact that the scenario tested is with a fully charged battery. The more the customer has to charge the battery, the more energy needs to be regenerated to make up for that initial cost. On routes where the "free" regenerative energy is less available, such as more flat routes like Helsinki-Temper, fewer opportunities are there to gain back that initial investment. On the other hand, on a route like Turkey where the route is very hilly, the opportunity of using regenerative braking to get back electric energy is easier. Once again, this shows that regenerative braking is very important to make both more effective, but also potentially profitable as well. It is important to remember that the E-Trailer is not aimed to make transport more profitable, but rather reduce emissions by reducing fuel consumption, to meet potential future regulations. Such an adaptation will most likely cost the customer and the question becomes more of: "How much is a customer willing to pay to reduce emissions by X%?". Which is a question only a potential buyer of an E-Trailer can answer.

4.3 Final Powertrain

This section will cover the selected powertrain components and their specifications compared to the ones derived from the sweep simulations. It will also show the simulation results of the selected powertrain both on its designated route, Gothenburg-Viared, with the standard 15 tons of payload, but also how it performs on the other routes and with varying conditions such as SoC and payload.

4.3.1 Powertrain selection

In table 4.11 the selected powertrain components are listed. Less critical systems such as cooling and mounting solutions are not included.

Table 4.11: Selected in-house components.

Part	No of units
Electric motor	2
Battery	4
Inverter	2
Gearbox	1

In table 4.12 and 4.13 the selected component's specifications are compared to the targeted specifications.

Table 4.12: Specification for the selected components used in the final simulation.

Specification	Selected motor	Target values
Peak torque [Nm]	800	750
Continuous torque [Nm]	510	600
Peak RPM	10000	3250
Peak power [kW]	310	125
Continuous power [kW]	210	75
Gearing	First: 1:9.26, Second: 1:3.52	1:1
Peak torque at hub [kNm]	First: 30.4, Second: 11.6	4.11
Continuous torque at hub [kNm]	First: 19.4, Second: 7.4	2.5

Table 4.13: Specifications of the batteries used in the final simulations

Specification	Selected battery	Target values
Capacity [kWh]	360	550
Peak power [kW]	173	125
Continuous power [kW]	90	75
SoC window [%]	10-90	30-70
Usable SoC at 100% SoC	288	220

Discussion

The selected powertrain components do not match the specification of the targeted powertrain derived from the sweep simulations perfectly. This has a lot to do with the SoC window used in the sweep simulations. Because of the small SoC window, a big increase in battery capacity was needed which also increases the mass of the trailer.

Comparing the battery capacity it might look like the batteries are even further away from what the initial simulations suggested. But in the end, they ended up carrying more capacity than the wanted 550 kWh. This is due to their larger SoC window compared to the simulated batteries. As mentioned earlier the SoC window during the sweep simulations was between 30-70 % and the final batteries had a simulated window of 10-90%, which also included a ~ 5 % safety margin to what their specified window was. This difference was due to the large safety margins taken when testing the first E-Trailer where the SOC window was set to be 30-70%. A range that became the only reference before the specification sheet for the selected, "Cube", batteries were found. In the end, this was a positive discovery and the effective capacity aimed for had to be calculated from the stated capacity in the simulations to get the required usable capacity. Since the selected batteries had a larger SoC window this meant a decrease in total battery capacity needed, fewer battery modules needed, fewer components to package and a lighter E-Trailer.

The biggest difference we saw during the powertrain selection was the addition of a gearbox. This addition is because there are no electrical powertrains available at Volvo that do not include one. The most common powertrain includes an automatic 12-speed gearbox which would be unnecessary for the E-Trailer. The smaller trucks have another gearbox that is only 2-speed. Because the gearbox with 12 gears was deemed unnecessary the configurations with the 2-speed gearbox were selected. This left the choice between EPT402 and EPT802. Both configurations come with the same electric motor, where the EPT402 configuration only has 1 motor and the EPT802 configuration has 2 of them. The motor can deliver a peak torque of 400 Nm, but together with the highest gear of the gearbox, the torque to the drive axle is around 1400 Nm. According to the sweep simulations, the EPT402 configuration would therefore be more than enough. But during some initial simulations of this powertrain, it became evident that the EPT402 did not drain the batteries (with the new battery capacity and mass). Instead of further decreasing the battery capacity the EPT802 was simulated. The EPT802 drained the battery more and was therefore a better match with the battery than the EPT402 configuration.

From these specifications, it can also be seen that the powertrain is power limited by the batteries. Meaning that the motors can push and regenerate more power than the batteries can handle. This is not ideal of course, especially when considering the effect of regenerative braking. When the electrical powertrain is limited by the batteries and not the motors, the effect of having bigger motors will be neglected and thereby some energy will not be transferred back to the batteries.

4.3.2 Final Powertrain Simulations

The final simulations altered the different routes, the initial SoC and the payload to see what fuel savings we could expect from the final powertrain. The first couple of simulations were made on the route between Gothenburg and Viared. The results are presented as a percentage fuel saving compared to a conventional combination and can be seen in table 4.14. The maximal fuel saving reached 42.1% and is reached when the E-Trailer is fully charged when leaving Gothenburg and pulling 15 tons of payload. The fuel needed from the truck's diesel tank is visualized in figure 4.2, the figure also shows how much the conventional combination would consume.

Table 4.14: Results of final powertrain simulations on the route 3xGbg-Borås-Gbg

Payload [ton]	Initial SoC [%]	Maximal Fuel Savings [%]
15	100	42.1
15	50	27.0
15	10	1.2
30	100	41.2
30	50	23.2
30	10	3.8
45	100	35.6
45	50	20.4
45	10	5.9

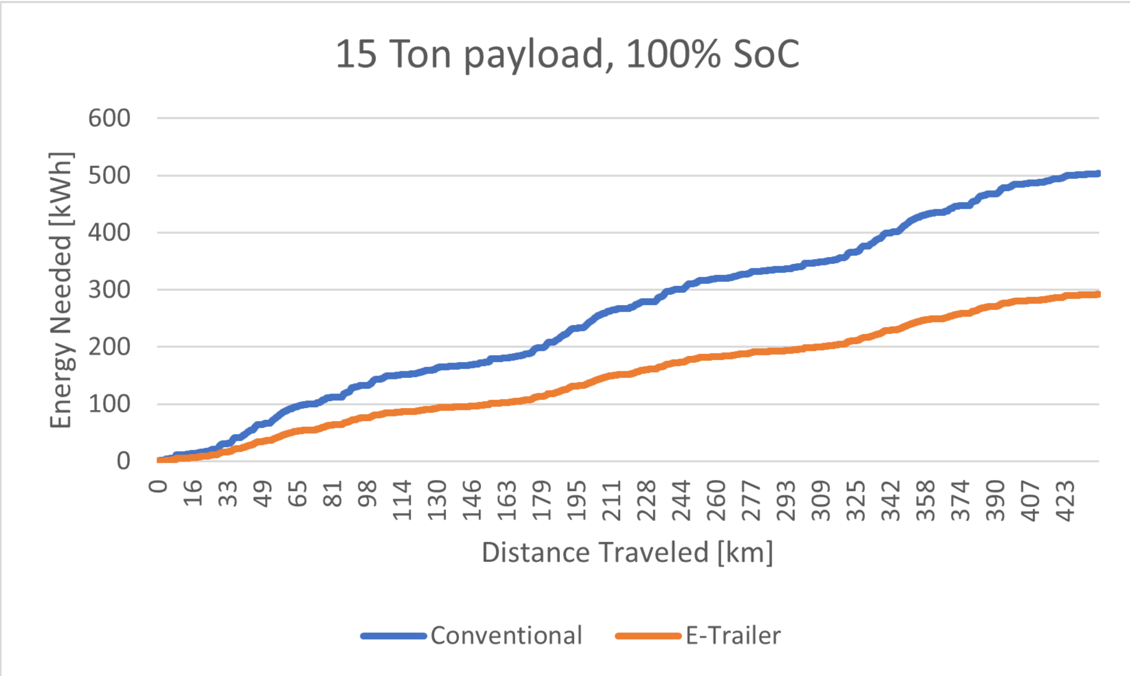


Figure 4.2: Energy needed from the trucks diesel tank with E-Trailer compared to a conventional trailer on the route Gothenburg to Borås

The final powertrain was also simulated on the route that starts in Tampere and goes to Helsinki then back two times. The results of the powertrain pushing different payloads while having different initial SoC are presented in table 4.15. The maximal fuel savings is 30.6% with the E-Trailer compared to the conventional trailer. This was also done with the least amount of payload (15 tons) and a fully charged battery and can be seen in figure 4.3.

Table 4.15: Results of final powertrain simulations on the route 2xTampere-Helsinki-Tampere

Payload [ton]	Initial SoC [%]	Maximal Fuel Savings [%]
15	100	30.6
15	50	13.4
15	10	-3.8
30	100	26.3
30	50	12.8
30	10	-0.6
45	100	18.3
45	50	12.0
45	10	1.0

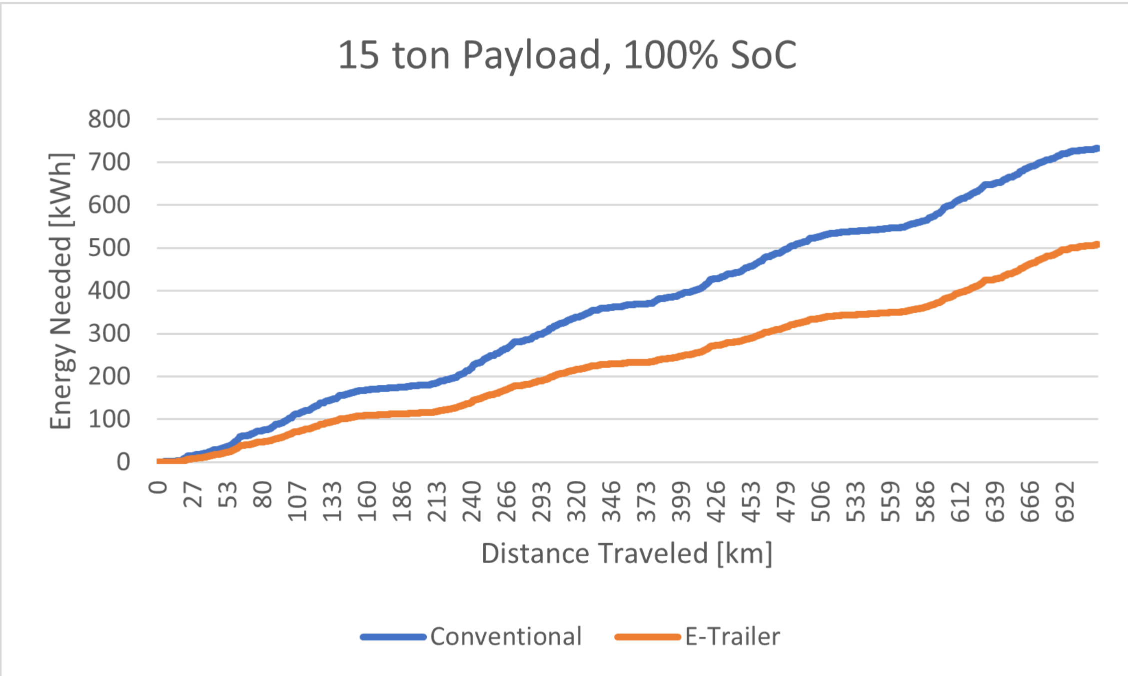


Figure 4.3: Energy needed from the trucks diesel tank with E-Trailer compared to a conventional trailer on the route from Tampere to Helsinki

The final simulations were conducted on the route that starts in Kurtalan and then goes to Bahçesaray and Cizre while ending up back in Kurtalan. The fuel savings that are simulated with the final powertrain with different payloads and initial SoC is presented in table 4.16. The maximal fuel savings is 28.7% compared to a conventional and the difference between the two different combinations is visualized in figure 4.4.

Table 4.16: Results of final powertrain simulations on the route Kurtalan-Bahçesaray-Cizre-Kurtalan

Payload [ton]	Initial SoC [%]	Maximal Fuel Savings [%]
15	100	28.7
15	50	19.6
15	10	10.9
30	100	10.8
30	50	6.3
30	10	2.5
45	100	-2.0
45	50	-2.5
45	10	-3.6

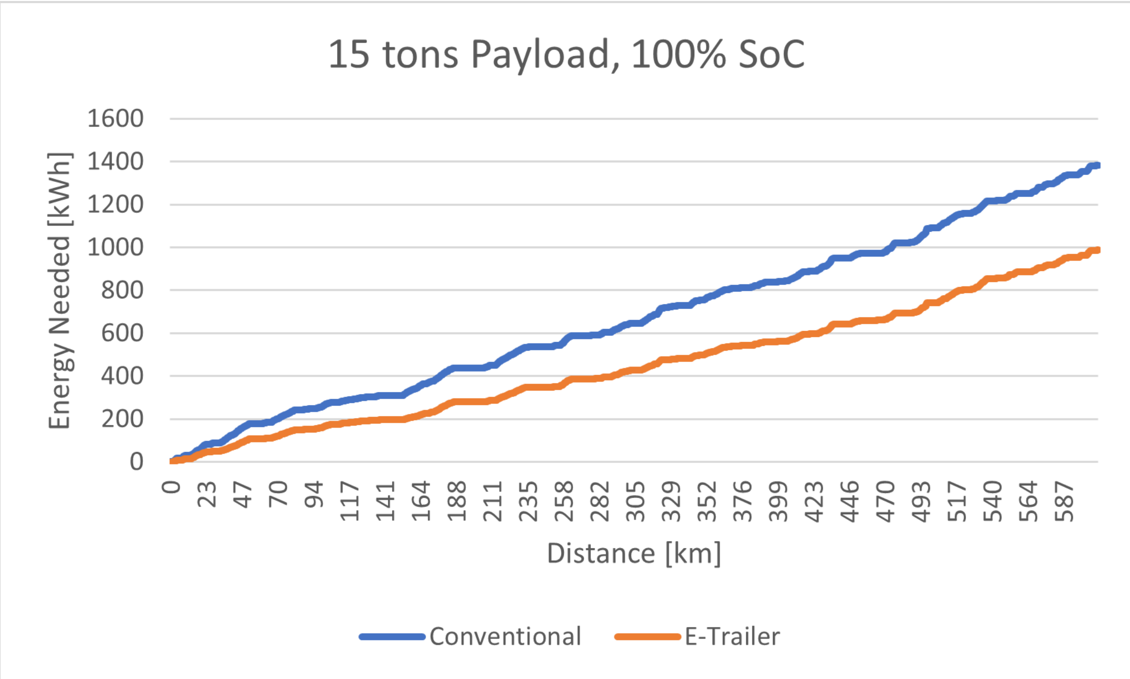


Figure 4.4: Energy needed from the trucks diesel tank with E-Trailer compared to a conventional trailer on the route in eastern Turkey

Discussion

The final powertrain did a lot better than we expected. We think that this mainly has to do with the over-estimated SoC window when doing the first simulations. By increasing the SoC window from 40% to 80% the needed battery capacity was halved. Because of the decrease in needed battery capacity, the total mass of the batteries will also decrease. Another reason is probably that the motor is bigger than the sweep simulations. The final powertrain simulations, therefore, have even better values than the initial sweeping simulations.

The decrease in mass is especially evident in the simulations on the Turkish route. Where the final powertrain improves on all of the initial simulations where the best fuel savings generally was made with a big motor and a small battery.
Even if the simulation tool is not the most accurate, having up to roughly 42% of fuel savings should end up saving fuel on a real truck. To find out exactly how much this E-Trailer can save it has to be built and tested.
It would be interesting to simulate different amounts of cube batteries. For example reducing the amount to 3, 2 or even 1 and see how much a cheaper E-Trailer could reduce the fuel consumption. Maybe even trying the EPT402 configurations together with other amounts of batteries.

4.4 Packaging

The final packaging of the E-Trailer can be seen in figure 4.5 and 4.6. In the following subsections, the final packaging of each subassembly will be presented.

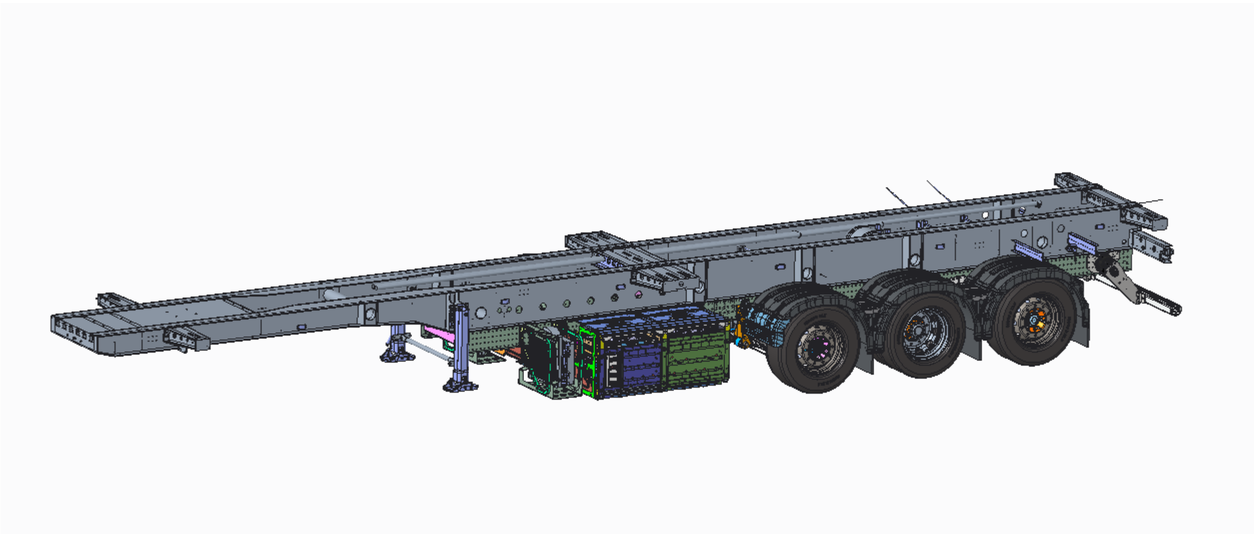


Figure 4.5: Isometric view of the E-Trailer

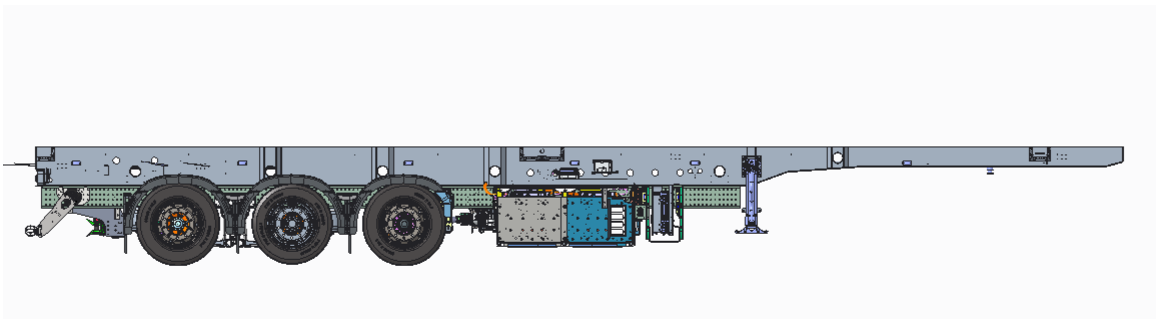


Figure 4.6: Side view of the E-Trailer

4.4.1 Chassis

The chassis contains both the Parator container chassis and the Volvo chassis. The second axle was decided to be the driven one with the first and third liftable. To increase the maneuverability of the truck and trailer combination when it was loaded and can not lift any axles, the third axle was also decided to be self-steered. The first axle was decided to only be liftable.

The axle distances can be found in table 4.17. The final axle configuration was a 3-axle trailer with a pusher axle configuration and the last axle was both liftable and self-steered. The three-axle combination was packaged more similar to what a four-axle truck would have been, with the second and third axle sharing mounting points and the first axle still being a single, compared to the first E-Trailer which had three single axles mounted together. This change should make the ordering and assembly of the trailer slightly simpler since it would follow a more standardized assembly. In figure 4.7 - 4.8 CAD visualization of the chassis is shown.

Table 4.17: Final axle distances for the E-Trailer.

Distance	[mm]
Kingpin to Axle 1	7050
Axle 1 to Axle 2	1350
Axle 2 to Axle 3	1375
Axle 3 to Rear	1712

In table 4.18 and 4.19 the kingpin forces calculated for the four different cases with varying lifted axles are presented. The results in table 4.18 use the base trailer's axle distances and table 4.19 shows the results using the final axle distances shown in table 4.17. The payload used was the previously derived 15 tons for both trailers.

Table 4.18: Resulting kingpin force with different combinations of lifted axles using base trailer distances.

Case	F_{kp} [kN]	Comments
1	5.88	All axles on the ground
2	3.28	Second and third axle lifted
3	7.75	First and second axle lifted
4	5.88	First and third axle lifted

Table 4.19: Resulting king pin force with different combination of lifted axles using final distances.

Case	F_{kp} [kN]	Comments
1	5.89	All axles on the ground
2	3.25	Second and third axle lifted
3	7.80	First and second axle lifted
4	5.86	First and third axle lifted

Discussion

The decision to only have the third axle steered was because the pushed axle can not be self-steered. A hydraulically steered axle would have required an extra hydraulic system which was unwanted due to increased complexity and part count. A hydraulically steered axle could, however, most likely have been implemented if the need for it was expressed by a customer.

As seen in table 4.18 the kingpin force was the same between case 1 and case 4, as expected. The other two cases also produced results that were expected with case 2 reducing the kingpin force due to creating an overhang that counteracts the initial moment pushing down on the kingpin. A similar comment can be said about the third case, where the moment arm, creating the moment pushing the kingpin down, is increased. Since the load is assumed to be equally spread out over the trailer, the increased distance also increases the force that pushes the kingpin down. The same trends can be seen in the final distances with the difference that case 1 and case 4 no longer being exactly the same. This is due to the slightly longer distance between axles two and three compared to the base trailer. The distance from the third axle to the rear of the final trailer is slightly longer on the base trailer making the results differ slightly as well. None of these differences should be noticeable in real life.

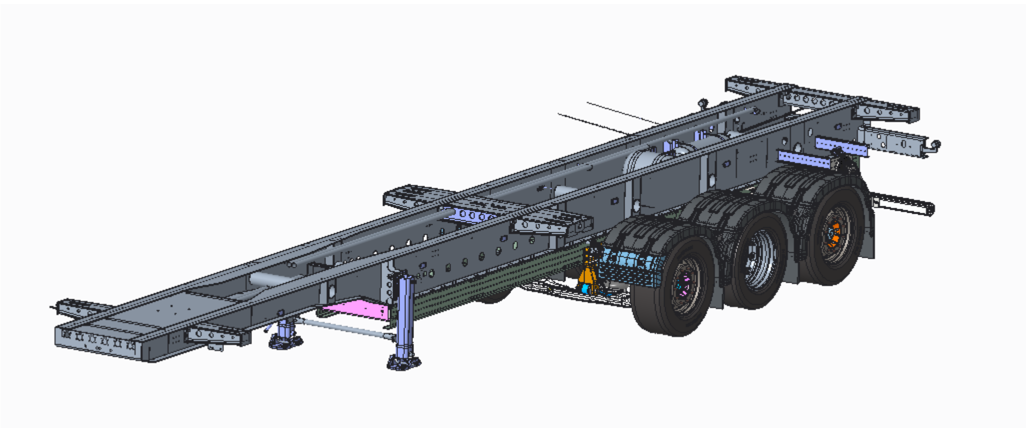


Figure 4.7: Isometric view of the chassis

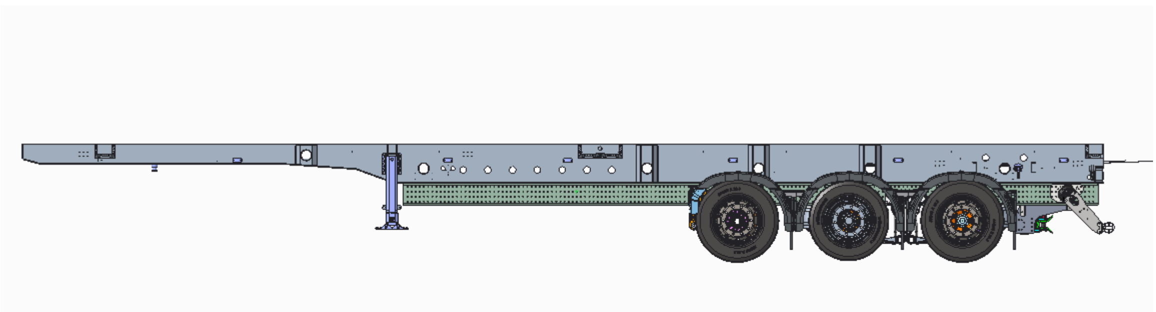


Figure 4.8: Side view of the chassis

4.4.2 Mechanical powertrain

The electric motors and gearbox are connected to the driven axle through a propeller shaft. No support bearings were needed to clear the pusher axle due to its length. The motor was placed as far rearwards as possible, towards the pusher axle, in order to clear the pusher axle and make the propeller shaft shorter. In figure 4.9 and 4.10 the resulting clearances, angles and lengths for the propeller shaft in the worst-case scenario are shown. The propeller shaft's length and angle, α in the three scenarios is shown in table 4.20. In appendix D the measurements for the two other cases are shown. Both the gearbox flange and the axle flange are designed to be mounted to the frame at a $\sim 4°$ angle in reference to the vertical plane.

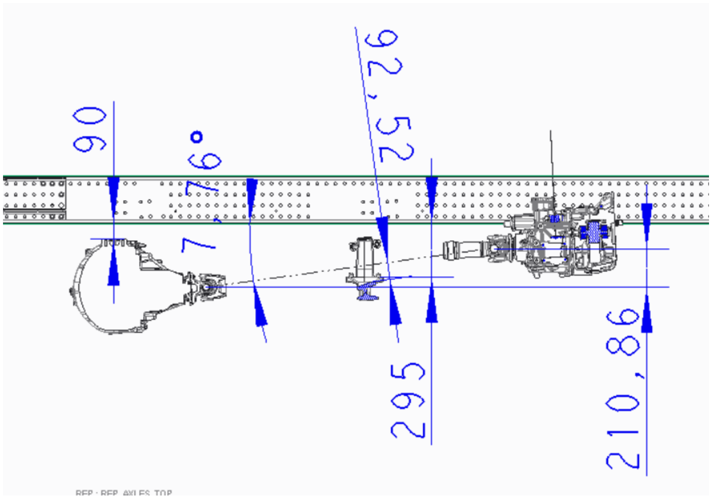


Figure 4.9: Side view of drive axle in full droop and pusher in full bump.

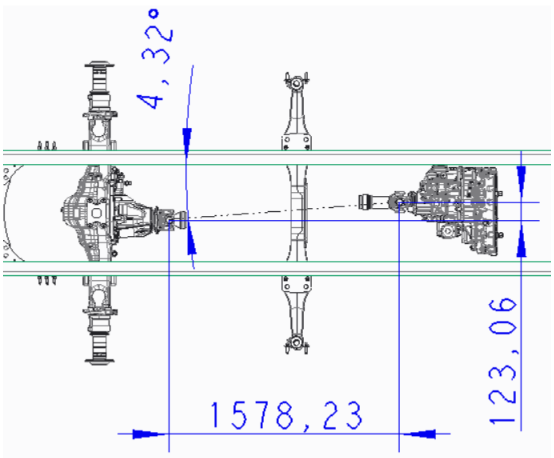


Figure 4.10: Top view of drive axle in full droop and pusher in full bump.

Table 4.20: Resulting values of l_{prop} and α from the three scenarios tested.

Scenario	l_{prop} [mm]	α [°]
1	1597,0	7,76
2	1583,8	1,85
3	1583,5	1,41

The propeller shaft was not visualized in CAD due to issues with the alignment of the universal joints. Below, in figure 4.11 an isometric view of the subassembly can be found. The mounts are the same used for this motor and gearbox combination in production trucks.

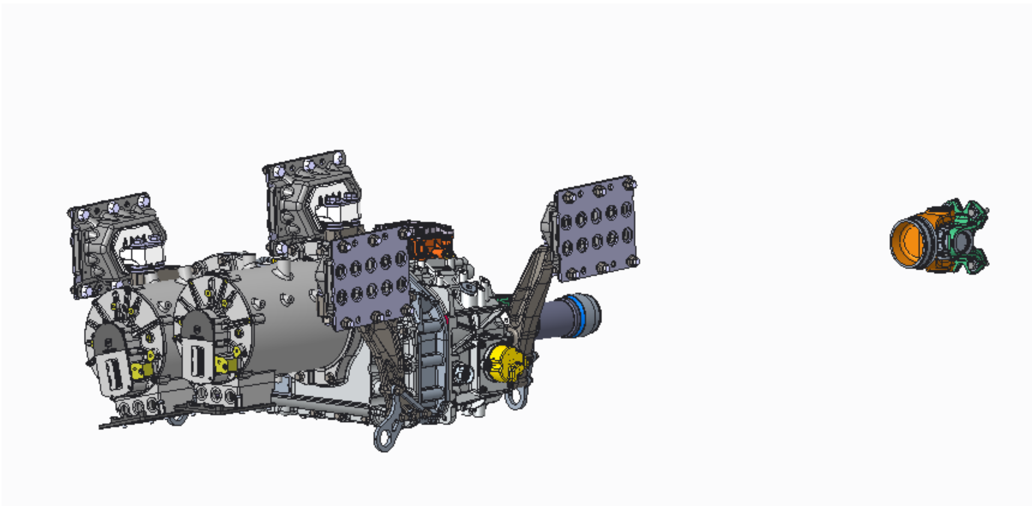


Figure 4.11: Isometric view of the mechanical powertrain

4.4.3 Electrical powertrain

The electrical powertrain was packaged between the supporting legs and the first axle on the trailer. Batteries were mounted using their original mounting solution on the side of the trailer. Inverters and the charger were placed in between the batteries. All smaller components were not included. This was because there was no time to decide upon them. They will be added later and will most likely be placed on top of the batteries for easy access, similar to the first generation of E-Trailer. The radiators were placed in front of the batteries using carryover mounting solutions from the first generation of the E-Trailer. They originate from a hybrid powertrain from Volvo Busses. Figure 4.12 shows an isometric view of the electric powertrain.

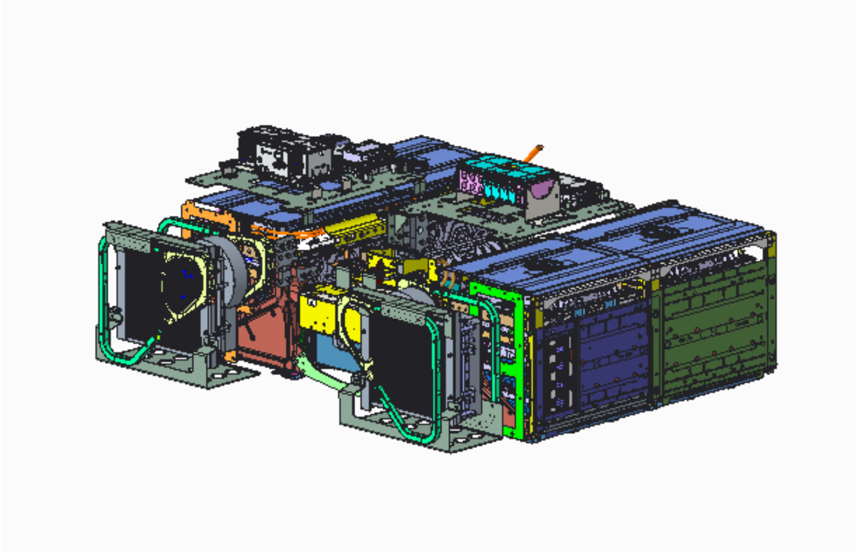


Figure 4.12: Isometric view of the electric powertrain.

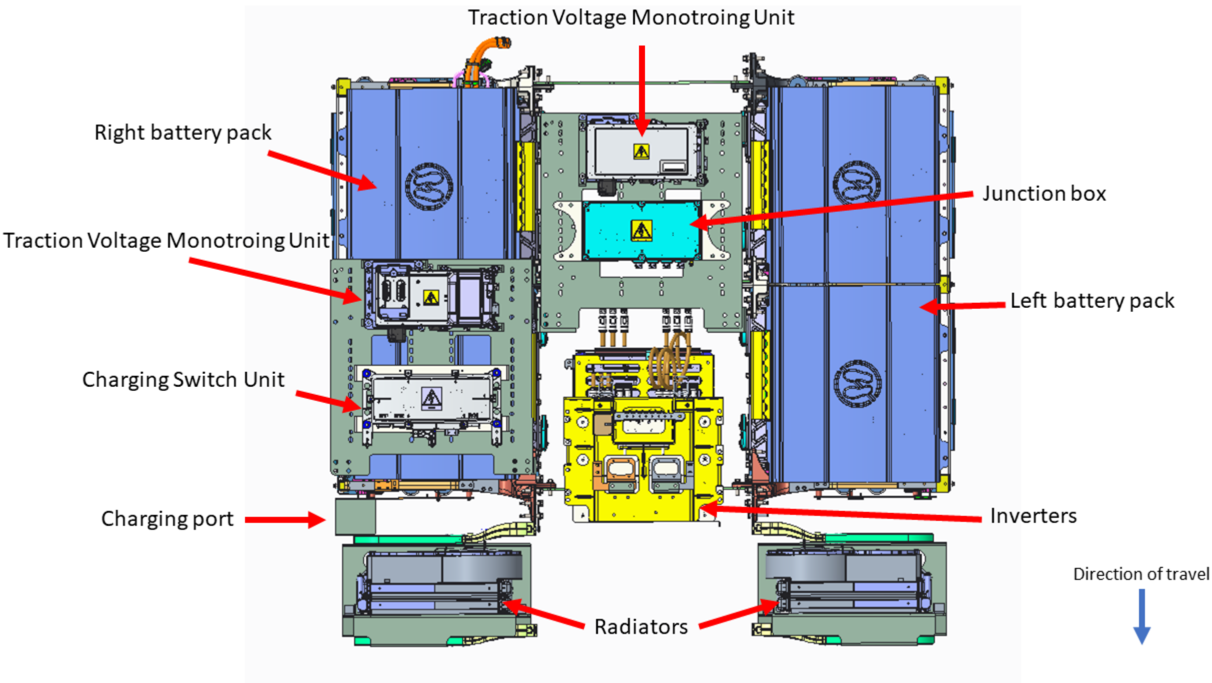


Figure 4.13: Top view of the assembly with components marked out.

4.4.4 Requirement fulfillment

The final choice of powertrain and packaging solution fulfills all of the requirements that were investigated. Some requirements were unfortunately not investigated as the thesis had time limitations. Other requirements were fulfilled because solutions already existed. These requirements were:

- Maintain the rated temperature of the electrical components during driving.

- Be able to heat batteries.

The cooling of the batteries has been brought up earlier, but not fully investigated in this thesis. From testing the first generation E-Trailer as well as the original intended use of the radiators, it seems unlikely that they will be restricting the powertrain. Similar can be said for the heating of the batteries. This function was controlled by an inline heater in the cooling loop both for the first generation of the E-Trailer as well as how the production solution works for electric trucks at Volvo Trucks. Therefore, no effort was put into these two requirements due to the knowledge that both were already solved by standard components that could be easily implemented on the E-Trailer as well.

Most of the wishes were also fulfilled. The ones that are not seen as fulfilled are:

- Maximizing the articulation and steering wheel angle when reversing only using the E-Trailers powertrain.
- Minimize weight.
- Minimizing the length of cooling hoses and cables.

As mentioned earlier no reliable value for the angled reverse case could be derived in this thesis and therefore not possible to judge if the selected powertrains specification could do it or at what angle. Instead, this is recommended to be tested with the selected powertrain.

Due to time and also the requirement of using Volvo components, the wish to minimize the weight of the trailer chassis was not looked into. This was mostly due to no real components design was done in this thesis since all significant components were already designed.

The wish of minimizing the length of cooling hoses and cables was not looked into either since the packaging never was mature enough to a point where cable and hose routing was relevant.

5
Conclusion

In this final chapter conclusions drawn from the simulation results and packaging will be presented together with some thoughts on the whole E-Trailer concept in general. Finally, some recommendations for future studies will be brought up to cover areas that were discovered, but not fully explored in this thesis.

5.1 General conclusions

The thesis fulfilled its aim of presenting a deeper understanding of the E-Trailer concept, what is possible to achieve with it in terms of reduced fuel consumption and other beneficial features that come with adding a second, electric, powertrain to a trailer. The thesis also delivered on the packing aspect of the project by presenting a packing solution that is using mostly standardized Volvo Group components and fulfills most of the requirements. The two unfulfilled requirements both have carry-over production solutions that should fulfill the requirements, but since nothing was tested or validated for this design the requirement was deemed as unfulfilled.

Second generation ended up having a very similar powertrain configuration to the one derived in this thesis. This was due to some late changes, which lead to problems with compatibility between component software. Even without these problems, they would have been similar. This is probably due to the very similar starting points for the two different projects with regard to requirements and limitations. The difference is that the thesis developed one having a stronger, proven, method of coming up with the components and design. Compared to the second generation, which was built more on engineering intuition and experience. The impressive part is that both paths basically lead to the same product. It also shows that, with the current components available at Volvo Group, this is probably the "best" E-Trailer that can be built in the foreseeable future and that future improvements will come from software, as mentioned earlier, or from testing in real-life scenarios. It is therefore recommended to focus on these two areas to develop this concept further. The data available is now analyzed and the result is ready to be tested in order to get more information and learn new things about the E-Trailer concept.

5.2 Simulations

The concept of adding an electric powertrain to a trailer to reduce fuel consumption is viable and the simulations show it very clearly. It might not come as a surprise since it is effectively adding another source of energy to the combination. Since this second source is an electric powertrain there will be a substantial decrease in fuel consumption and thereby carbon emissions. The fact that an electric powertrain adds the possibility to regenerate energy to be reused also adds to the reduction of fuel consumption.

We thought that a more powerful powertrain would lead to increased fuel savings. However, this is not always the case and it was shown in this thesis. The selection of a powertrain is very route dependent and in this thesis, the main goal was to maximize the savings in fuel consumption. This made the selection of the optimal powertrain for each route simple, but maybe not the most realistic or easily defendable when it comes to the investment of the E-Trailer.
Similar results can be had by different powertrain configurations on the same route. This makes the decision of the optimal configuration difficult to decide since the decision comes down to customer specific preferences.
Making the decision of which powertrain size to go with was difficult since it would come down to customer preferences or requirements to truly get the best one. Something that was concluded to be the case for most things when it comes to the trucking and transporting industry.

To make a general, simulation would not be possible and the only realistic way of doing the simulation is to make specific cases to compare against. This is due to the vast amount of variables and customer specific requirements that go into building a truck. Therefore it would be interesting to continue this study with a transport company to get these variables from them and then derive an optimal powertrain for their specific use case and route. Without these customer requirements, it is hard or near impossible to say which powertrain is the best for them, since it depends too much between routes and their requirements.

An interesting trend that was discovered in the simulations was the importance of regenerative braking and how it affected both fuel consumption and how it can make the E-Trailer profitable for a customer. This is not only relevant for the E-Trailer, but for any electric powertrain since the energy that otherwise would be lost now can be transferred back to electrical energy. Making the required battery capacity smaller, making the battery pack smaller and lighter. This sets some requirements on both the motor and batteries as well and in this thesis it was shown that the batteries were the limiting factor in terms of the ability to take care of the regenerated energy in the final selected components.

Regenerative braking is, to some extent, affected by the deployment strategy of the electric powertrain. The strategy used in this thesis was very basic. However, it was not impossible to see how a more adaptive or advanced strategy could save even more fuel and is strongly recommended as something that should be looked into, in order to push the development of the E-Trailer further. Especially since the other limiting factors are hardware related, batteries and motors. Developing better motors and batteries to increase the powertrain's performance in terms of power delivery and regenerative braking is undergoing, but it takes time. Implementing a more advanced deployment strategy should be a better return on investment at the moment since it exists more advanced strategies or technology to make them. The Volvo Trucks function "I-see" is one technology that could potentially be used to develop a more advanced strategy.

It is difficult to say how accurate the simulations of the selected components actually are. Since more specifications were known about the simulated components, the simulations should be more accurate than the sweep simulation, which also correlated fairly well with the real test. Fortunately, the second generation of the E-Trailer ended up with a very similar powertrain to the one derived in this thesis. Therefore it is strongly recommended to do some or all of the test that was carried out in this thesis with that one to have some good data for validation. Especially the arraigning maneuvers described in the vehicle dynamics section should be quick and easy to test since they can be done in closed of areas like Hällered. An important test there would be the reversed at an angle since no real answer was found for that in this thesis.

It is important to know that the simulations are very rough and real data is always preferred. To know for certain if the motors are a good match to the battery capacity is impossible without testing. Therefore we would recommend that this powertrain is tested to gather real information about the powertrain size and how much fuel it actually saves.

It would be very interesting to test the EPT802 motor/gearbox configuration with only one motor running to simulate having an EPT402 configuration instead. Another interesting possibility is to try and match the battery capacity to the EPT402 powertrain. This could be a way of making the E-Trailer concept modular so that customers that do not need the power and capacity from the EPT802 could have a smaller alternative.

5.3 Packaging

The packaging portion of this thesis went as planned and the implementation of a pusher axle on the trailer turned out to be doable. Since it was almost only packaging of Volvo Trucks components, designed to fit together, the process went smoothly. It did not fully reach the level of detail that was initially thought possible. This was due to the process of finding the right components as well as knowing what other auxiliary components, such as coolant pumps and reservoirs, were required. To have this level of detail would have required schematics of the electrical and cooling systems, something that was out of the scoop for this thesis.

With the packaging now done, it would have been interesting to try to fit an E-axle into the E-Trailer but there was no time. It would make the powertrain a bit more compact due to the removal of the propeller shaft and maybe it could be proven that more gears have some benefit in the future.

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A

Appendix A

List of requirements

Requirements:

- Lower energy consumption from ICE.
- Electric powertrain.
- Built with existing Volvo components.
- Minimum ground clearance:
  - Rear axle: 230mm
  - General: 203mm
- All required components are installed on the trailer.
- Use same base mounting solution for different powertrain configurations.
- Being able to start/reverse with a straight base loaded combination on flat ground at 1m/s. Result: provide continuous torque of 908Nm at the wheel hub.
- Not losing any speed when up shifting gears by having the electric motor support with the lost energy during shifting time. Result: 60 kW at 40 km/h on flat ground.
- Be able to add power up to 90 km/h. $\frac{rpm_{max}}{i_{gearbox} \cdot i_{finalgear}} \geq 90km/h$
- Regenerate energy going downhill.
- Charging port on the right side of the trailer.
- External charging possible, DC.
- Maintain the rated temperature of the electrical components during driving.
- Be able to heat batteries.
- Three axle container trailer.

Wishes:

- Minimize weight.
- Two liftable axles.
- Steerable axles.
- Maximize the possible angle between the truck and trailer when reversing by only using the E-Trailer.
- Minimize number of cooling medias.
- Minimize length of cables and cooling hoses.
- Maximize regenerated energy in slopes.

B
Appendix B

Press release from ZF regarding their E-Trailer

Exploring the eTrailer

By admin Categories: Commercial News Published On: Thursday 18 June 2020

Dr. Christian Brenneke, *chief technology officer at* ***Wabco****, discusses the workings of the company's hybrid trailer that can generate, store and re-use electrical energy on the road*

What is the concept behind the eTrailer?

Wabco's eTrailer integrates a powerful (300kW) electric drive in the semi-trailer, and embeds the control of the e-Drive system in the synergistic cooperation of both truck and trailer braking systems.

The eTrailer generates electrical energy during vehicle deceleration via recuperation of brake energy, stores the energy in batteries and then uses the energy for the next acceleration event, the next elevation, to compensate for rolling resistance, or to run electrical on-board units such as reefer cooling systems.

While the space in the towing vehicle is limited, the trailer can be more easily fitted with a system like the e-Drive. All it takes is the installation of a few standardised modular components, whereas the towing vehicle would need complex modifications with expensive components.

Although there are more trailers than tractors to be equipped with an e-Drive system, the longer lifespan of a trailer would undoubtedly compensate for this.

How does the eTrailer work?

The eTrailer recuperates kinetic and potential energy during braking. This energy is temporarily stored in a battery in the trailer. When the situation requires it, the trailer's electronic controller transforms this stored energy back into mechanical energy.

In order to maximise energy recuperation, the electric drive is prioritised in the brake management system of the electronic braking system (EBS) over the friction and endurance brakes. The brake management prioritises which brakes to apply to support the driver's request by maximising energy recuperation.

Through existing communication lines, the trailer EBS (TEBS) and tractor EBS are connected. TEBS supervises the e-Drive system in the trailer and arbitrates demanded power versus capability variations with e-Drive components.

About 72 per cent of the deceleration energy can be accessed for recuperation which would otherwise, as today with standard trailers, be transformed to heat by conventional brakes. In this use cycle, when reusing the energy for traction, 6.5l diesel savings can be realised (VECTO Regional Delivery cycle).

If the energy is used to power a reefer, for example, then the benefits change: instead of saving fuel on the truck, the reefer becomes fully electric and therefore a separate diesel generator is not required. This significantly lowers the noise level to keep cooling the trailer, and allows night transport in noise-restricted areas.

What control systems are required for the eTrailer?

Like electric vehicles, eTrailers require complex control systems. These systems are interconnected in multiple ways to achieve the optimal performance for energy gain, component durability, drive quality, vehicle dynamics and safety.

This includes powering electronics controls, thermal management, as well as a holistic approach for the overall brake system and functions – EBS, ESC and ADAS – that trigger external brake events.

At the heart of the eTrailer concept is the deep integration of the electric drive's energy recovery capabilities into the overall vehicle deceleration and stability control by the EBS system of both the towing vehicle and the trailer.

A point-to-point communication via the standardised ISO 11992-2 data interface integrates the deceleration capabilities of the entire vehicle.

The electronic braking system in the truck sends a balanced torque demand to the trailer's electronic controlled brake system (TEBS), which is the trailer's interface to the e-Drive, comfort and safety functions.

The TEBS controls the positive and negative torque of the e-Drive based on the demand received by the truck. For deceleration this function allows applying braking in the preferred order: recuperative braking (e-machine), driveline retarder (truck), engine retarder (truck) and balanced friction braking of both vehicles.

Continues below

Have you conducted initial tests outside of the lab and what has been tested?

Wabco recently tested the prototype of the eTrailer on its test track in Jeversen, Germany. Driven to achieve as objective and exact values as possible, Wabco has compared vehicle combinations with and without eTrailer under identical weather conditions.

Additionally, we have taken into account gradients, uphill and downhill, road surfaces, as well as long-haul and short haul trips and varied speed ranges. In addition to testing and improving basic and advanced (driving) functions, practical checks were undertaken during prototype validation and the simulation program was validated and optimised.

While fuel economy is a key focus, the testing program also examined the vehicle's behaviour in stability-critical situations. To prevent the drive axle of the eTrailer from spinning or locking during critical driving maneuvers, the control of the e-Drive must be integrated with the ABS, RSS, ATC and EBS stability functions.

Embedding the eTrailer function in the existing EBS and Trailer EBS functions ensures that the vehicle remains stable and the trailer does not slide or push.

As part of the road tests, the potential savings of the eTrailer in the VECTO Regional Delivery Cycle was determined at 6.5 l / 100 km. This is equivalent to a reduction in CO_2 emissions of 172 g/km (16 per cent).

With the eTrailer alone, the interim goal of a 15 per cent reduction in distribution traffic defined in the EU CO_2 regulation for 2025 could thus be achieved.

What implications does the eTrailer have for current vehicle systems?

An important advantage of the eTrailer is its ability to form a hybrid electric vehicle unit together with a conventional truck without additional sensors, ECUs or communication lines other than an ISO 11992-2 standard interface and adapted EBS on truck and trailer.

Where regulations allow trailers with active motor control and EBS with SAE truck-trailer communication standards are established, this approach will be usable worldwide.

When do you expect the eTrailer to be available?

Since unveiling the eTrailer prototype at IAA 2018, significant progress has been made in testing and advancing its capabilities and future potential. Breakthrough technologies such as electrification require significant testing and development before they are launched on the market, and the results so far are greatly encouraging. I am convinced we will see the eTrailer on our roads in the next few years.

www.wabco-auto.com

C
Appendix C

List of motors and batteries at Volvo Group

D

Appendix D

Figures of propeller shaft angles and distances under different scenarios.

Drive axle during full bump, 90mm, and pusher at ride height.

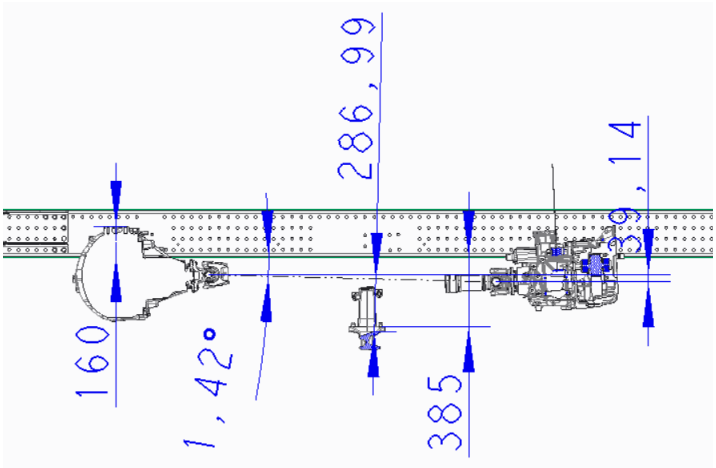

Figure D.1: Side view.

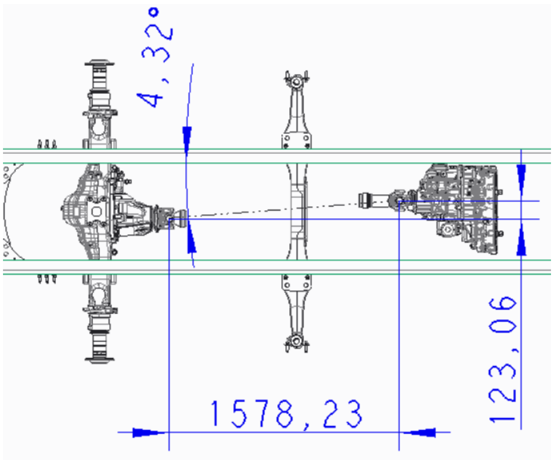

Figure D.2: Top view.

Both drive and pusher axle at normal ride height.

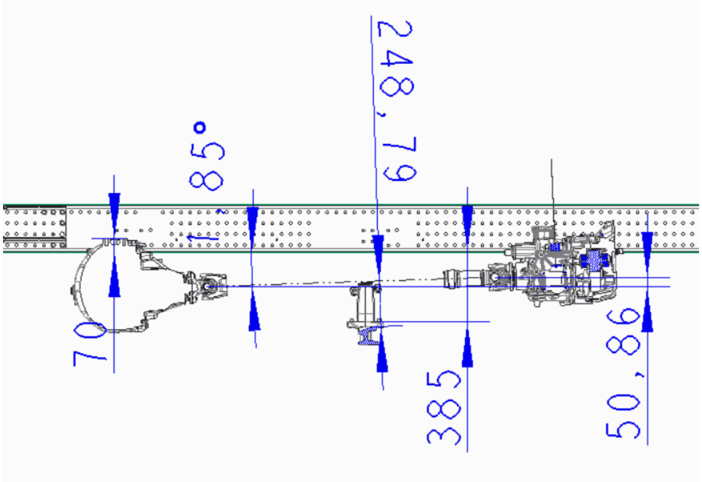

Figure D.3: Side view.

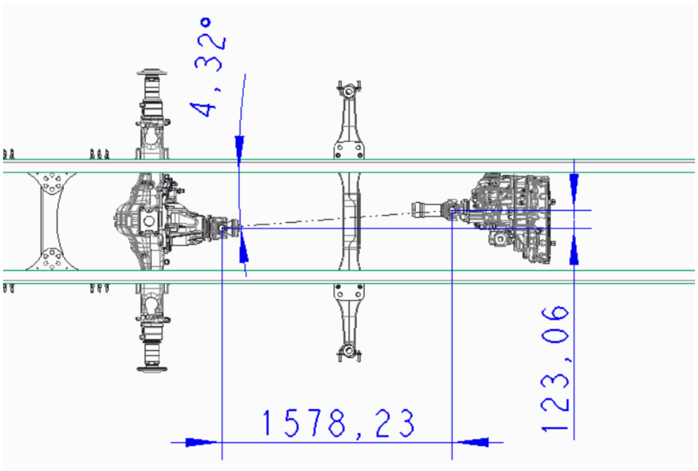

Figure D.4: Top view.

E

Appendix E

Free body diagrams and corresponding equations for different combinations of lifted axles.

E.1 Second and third axle lifted

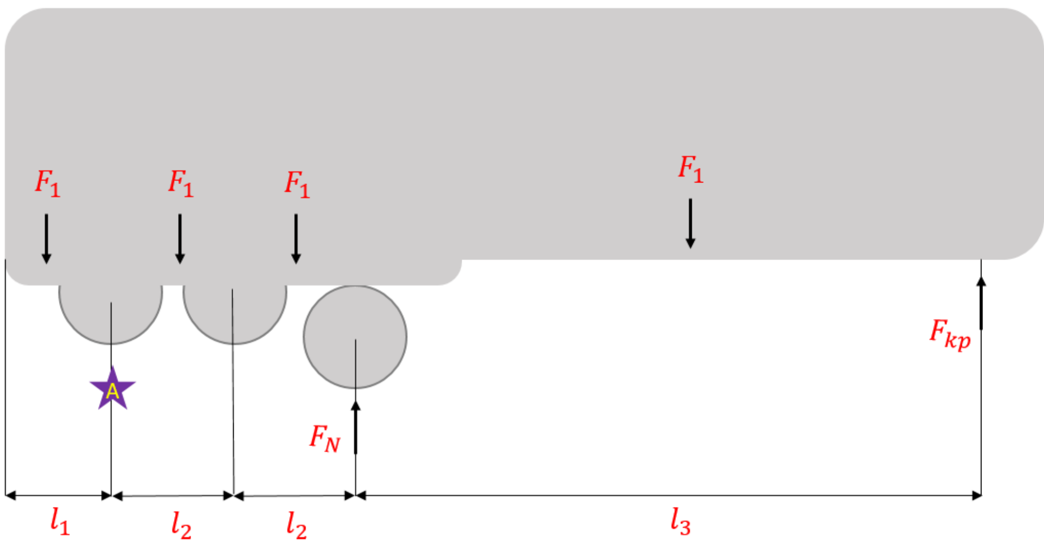

Figure E.1: Free body diagram of the trailer with second and third axle lifted.

Derived equations from free body diagram E.1.

$$-\frac{F_1 l_1}{2} + \frac{F_2 l_2}{2} + \frac{F_3 3 l_2}{2} + F_4(2l_2 + \frac{l_3}{2}) - F_{kp}(l_3 + 2l_2) - F_N l_2 = 0$$

$$F_N + F_{kp} - (F_1 + F_2 + F_3 + F_4) = 0$$

E.2 First and second axle lifted

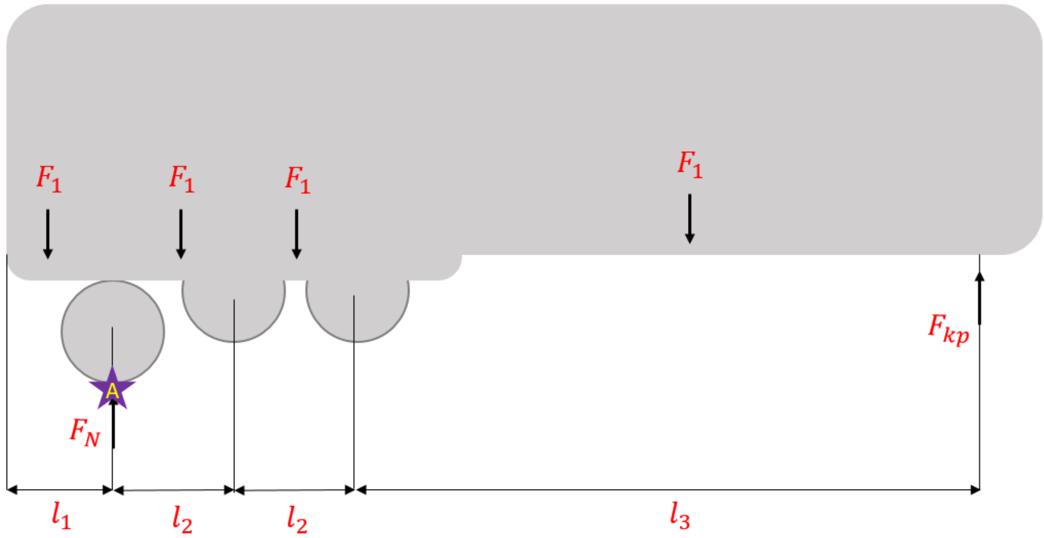

Figure E.2: Free body diagram of the trailer with first and second axle lifted.

Derived equations from free body diagram E.2.

$$-\frac{F_1 l_1}{2} + \frac{F_2 l_2}{2} + \frac{F_3 3 l_2}{2} + F_4(2l_2 + \frac{l_3}{2}) - F_{kp}(l_3 + 2l_2) = 0$$

$$F_N + F_{kp} - (F_1 + F_2 + F_3 + F_4) = 0$$

F

Appendix F

Volvo Reports

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