Investigation of the potential of e-axles for trucks

MARINA FERNÁNDEZ CARNOTA
Investigation of the potential of e-axles for trucks

MARINA FERNÁNDEZ CARNOTA

Master programme in Vehicle Engineering
Date: November 23, 2020
Supervisor: Jenny Jerrelind (KTH) and Bo Höglander (Scania)
Examiner: Jenny Jerrelind
Date of presentation: September 18, 2020
Swedish title: Undersökning av potentialen för e-axlar för lastbilar
I would like to thank my family and friends for supporting me during this time. Special thanks to Borja and Ximena for being always there ready to help. Also, I want to thank my supervisors, both at KTH and Scania, for helping me complete this thesis. Special thanks to Scania RSMP for giving me the opportunity to investigate this topic and helped me during the investigation. Also, thank you to everyone in Stockholm that made this two years a great adventure and fun times.
Abstract

As a step to reduce emissions of trucks, Scania investigates different solutions related to electrification to contribute with more environmental friendly vehicles. The aim of this project is to investigate the potential of electrified axles, e-axles, to use in Scania trucks. Not only from a performance point of view but also from a business and industrialisation point of view. The e-axe is a compact unit which integrates an electric motor, power electronics and transmission. It is used as a power source for the vehicle and it is a more efficient solution for the electric vehicles, eliminating losses and saving space.

Through a market analysis, gathering of information and knowledge about electrified solutions for trucks, interviews with Scania staff and product specification five different concept are identified, evaluated and compared. These concepts are the following:

- Concept 1- Electric motor within a mechanically driven axle
- Concept 2- Electric motors in a non-driven axle
- Concept 3- In-wheel motors
- Concept 4- Electric motors in a rear support axle
- Concept 5- Electric motor in a diesel truck with a generator

A concept selection matrix was set-up to find the best solution. In the evaluation of the concepts different CAD models are developed, based on mainly existing models at Scania. The difference between the concepts is based on the different axle possibilities to locate the electric motors. The best two concepts were identified as concept 2 and concept 4.

For future work, the two best concepts should be used for a deeper study, obtaining a final design layout and realising an structure analysis of them to verify the designs.

The market analysis shows that there will be a market for the product, but it will require an extensive design and development phase. This thesis sets the ground for the development of a new product towards the electrification of trucks.
Sammanfattning


Genom en marknadsanalys, insamling av information och kunskap om elektrifierade lösningar för lastbilar, intervjuer med Scania:s personal och produktspecifikation har fem olika koncept identifierats, utvärderats och jämförts. Dessa koncept är följande:

- Koncept 1- Elektrisk motor i en mekaniskt driven axel
- Koncept 2- Elektriska motorer i en icke-driven axel
- Koncept 3- Hjulmotorer
- Koncept 4- Elektriska motorer i en bakre stödaxel
- Koncept 5- Elmotor i en diesel lastbil med en generator


För framtida arbete bör de två bästa koncepten användas för en djupare studie, för att få en slutlig design layout och genomföra en strukturanalys av dem för att verifiera designen.

Marknadsanalysen visar att det kommer att finnas en marknad för produkten, men det kommer att kräva en omfattande design- och utvecklingsfas. Detta examensarbete lägger grunden för utvecklingen av en ny produkt mot elektrifiering av lastbilar.
## Contents

1 Introduction 1
  
  1.1 Project aim 2
  1.2 Outline 3

2 Market analysis and product specification 4
  
  2.1 Needs analysis 4
    2.1.1 Customer analysis 5
  2.2 Risk analysis 6
  2.3 Analysis of competitors 8
  2.4 Patent study 13
  2.5 Product specification 13
    2.5.1 Driving scenarios 13
    2.5.2 Hybrid truck 14
    2.5.3 Competitive advantage 14

3 Background 15
  
  3.1 Wheel configuration 15
  3.2 Traction 16
    3.2.1 Traction calculations for slippery surfaces 16
  3.3 Electrified vs conventional powertrain 17
  3.4 Electric motors 18
  3.5 Chassis height 18
  3.6 Axles 19
  3.7 In-wheel motors 20
  3.8 Suspension 20
    3.8.1 Individual suspension 20

4 Methodology 22
  
  4.1 CAD modelling 23
Introduction

Different studies show that the e-axles market is expected to rise in the coming years. The e-axle is defined as an electric axle, one with an integrated electric motor, power electronics and transmission units in the axle itself. It is a new technology that will allow silent and emission-free driving, which will become very important due to the restrictions in the cities on emissions and noise (e.g. night deliveries). Also, the e-axle can solve a demand of extra traction in specific situations where the vehicle is in need.

Extra traction for heavy-duty trucks is important due to the complicated roads and path conditions. A loss of traction can end up in a need for other wheels to help, making it possible to escape the situation. AWD (All Wheel Drive) vehicles avoid this problem, but at the same time, fuel consumption increases drastically.

In the case of urban trucks, extra traction can be really useful when there is snow, light off roads or stop and go conditions. If the truck is electrified with an e-axle, it is also a way to go on emission-free driving in short distances in places like cities or closed spaces.

To give extra traction to the truck in the liftable axle or the front axle (on-demand traction) can give a big advantage to these vehicles when working in operations like tunnel construction, sand or slippery surface circumstances.

Nowadays, there are hydraulic solutions for extra traction in the front axle, but no electric solutions in the market yet. This product, the e-axle, is not intended to be utilised during the whole run of the vehicle, only when it is necessary and at low speeds (less than 30
km/h). If the trucks exceed this limit, the system will be turned off and the wheels will spin freely. The extra traction solutions offered currently in the market are made for the front axle, working with hydraulic systems. There are no offers for extra traction on demand on one of the rear axles.

1.1 Project aim

The aim of this project is to investigate the potential of the e-axles to use in Scania trucks. This application can be useful to solve different challenges like giving extra traction in moments of need, emission-free driving and the possibility to have front wheel drive combined with low chassis height. This thesis will act as a first investigation to evaluate the possibilities of the e-axles in the Scania environment.

A needs and risk analysis shall be performed as well as an analysis of competitor solutions and possible patents in the field. During the work the following specific questions shall be investigated:

- What are the pros and cons with an electrically driven front axle or an electrically driven rear bogie axle
- What are the pros and cons using existing Scania axles and just mount an electrical motor on the axle gear compared to use an purpose built e-axle
- What limitations will Scania have if electrifying Scania’s existing axles?
- What other customizations will Scania have to do to be able to run fully electric for short distances? E.g. lubrication and cooling of the gearbox when the combustion engine is shut down
- Can Scania’s standard brakes be used and what is the potential of braking with the e-motor?
- What are the pros and cons with an extra light axle
- What is the potential to use it for emission-free driving (e.g. garage, city, short distances)

The work will be performed by benchmarking, gathering of information and knowledge about electrified solutions for trucks, interviews, definition and evaluation of possible
concepts. In the evaluation of the concepts different CAD models will be developed, based on mainly existing models at Scania. The CAD tool used will be Catia V5.

The market research has to be focused on two different paths: electrified axles for trucks and systems that will give extra traction in specific moments of the driving.

Scania has decided to be the truck manufacturer that is "driving the shift" towards electrification, so it is important to investigate broadly different concepts and options to offer more variants of electrical drivetrains than the actual options (wheel configuration 4x2 and 6x2) as hybrids or fully electrical battery vehicles.

The new components need to be redistributed along the chassis and the weight of the new materials cannot result in a big increase because the payload will be reduced.

1.2 Outline

The outline of the report is as following:

- First, in chapter 2, a needs analysis is performed both from the customers side as well as for the manufacturer Scania. This is followed by a risk analysis and an analysis of competitors and a review of available patents.
- In chapter 3, a frame of reference is presented to explain important concepts for this project and the driving scenarios that will be analysed.
- In chapter 4, the method of Ulrich and Eppinger is explained which will be used in this project.
- In chapter 5, the different concepts proposals are presented and compared to select the best option for the e-axle.
- Finally, in chapters 6 and 7, some conclusions and recommendations on future work are exposed.
2 Market analysis and product specification

2.1 Needs analysis

To develop a needs analysis, the method described by Ulrich and Eppinger will be followed [1]. It is important to identify the needs that the customers require to create a valuable product. Not only the explicit needs are necessary to identify but also the hidden or latent ones. They are the most difficult ones considering that they might not be known by the supplier or the customer. Later on, it is needed to ensure that no critical needs for the customer are missing in the analysis. Following the process, the needs will be classified by importance on a scale from 1 to 5 (where 1 means low importance and 5 is an essential need). This analysis of needs is useful to define the product and choose its specifications to fulfill the customer’s criteria as well as the requirements set by Scania. Taking this into account it is necessary to distinguish between two different types of needs: interpreted needs from Scania and interpreted needs from the customer. In the Table 2.1 the different needs are listed and their importance has been classified.
### Table 2.1: Interpreted needs

<table>
<thead>
<tr>
<th>Number</th>
<th>From</th>
<th>Need</th>
<th>Importance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Scania</td>
<td>Follow the modularisation system</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>Scania</td>
<td>Easy to assemble</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>Scania</td>
<td>Follow the legal requirements</td>
<td>4</td>
</tr>
<tr>
<td>4</td>
<td>Scania</td>
<td>Provides good customer value</td>
<td>5</td>
</tr>
<tr>
<td>5</td>
<td>Customer</td>
<td>Low purchase cost</td>
<td>3</td>
</tr>
<tr>
<td>6</td>
<td>Customer</td>
<td>Easy maintenance</td>
<td>4</td>
</tr>
<tr>
<td>7</td>
<td>Customer</td>
<td>Easy to operate</td>
<td>4</td>
</tr>
<tr>
<td>8</td>
<td>Customer</td>
<td>Not breakable/failure</td>
<td>4</td>
</tr>
<tr>
<td>9</td>
<td>Customer</td>
<td>Optimum performance</td>
<td>5</td>
</tr>
<tr>
<td>10</td>
<td>Customer</td>
<td>More profitable than AWD</td>
<td>4</td>
</tr>
<tr>
<td>11</td>
<td>Customer</td>
<td>Higher payload than AWD</td>
<td>3</td>
</tr>
<tr>
<td>12</td>
<td>Customer</td>
<td>No extra lead time</td>
<td>3</td>
</tr>
<tr>
<td>13</td>
<td>Customer/Scania</td>
<td>Possible for different axle combinations</td>
<td>3</td>
</tr>
<tr>
<td>14</td>
<td>Customer</td>
<td>Emission-free driving</td>
<td>4</td>
</tr>
</tbody>
</table>

#### 2.1.1 Customer analysis

The electrified market is expected to continue to increase, and some researches predict that by 2050 there will be only zero emissions vehicles (ZEV) on the streets [2] as it can be seen in Figure [2.1].
CHAPTER 2. MARKET ANALYSIS AND PRODUCT SPECIFICATION

It is important to analyse what are the customers benefits when choosing an e-axle. Three ideas are categorized by importance when selecting this new solution:

- **Level of importance 1:**
  - It provides extra traction

- **Level of importance 2:**
  - It enables chassis height low/normal
  - It is silent and emission free

### 2.2 Risk analysis

Due to its technology, long term prevision (it requires a long development plan) and unpredictable market scenarios (which produces a big uncertainty), this product can be considered a high risk product. As it can be seen in the Figure 2.2, the opportunity horizon divides the opportunities in categories (horizons of uncertainty), opportunity horizon 1 embraces reduction of costs in existing products and existing markets. Horizon 2 opportunities are a less know territory in market or the technology of the product, and the horizon 3 opportunities represent new opportunities with the largest level of uncertainty [1]. The opportunity horizon of this product is considered to be of class 2/3. It is a need in a market that is growing, offering a new generation product (or new solution) to fill it in. Class 2/3 horizon means that the risk is high as well as the uncertainty and it
can be considered a new category product (new technology).

The risk analysis is carried out to understand the possible problems that can be found when developing this product and its usage phase. Different types of risks will be taken into account: market (How big is the market?, do customers want this?, etc), technical (will it work? is it possible to do it?), money and timing (will it be on the market when is it suppose to? will it cost more than expected and will not be possible to produce?).

The risks estimation will be classified in a scale 1-5 (trivial risk to intolerant risk), by probability of appearance 1-3 (from not probable to occur to mostly happening), and by its consequences, being the seriousness of the possible damage EH (Extremely Harmful), H (Harmful) and SH (Slightly Harmful). They will be analysed and considered where to take action or not, by prioritising them for the definition of the product in the next stage. If the risks are not taken into account from the beginning, the product might end up in a failure, or increasing the costs. The Table 2.2 shows the analysis of the risks found.

Figure 2.2: Opportunities horizon [1]
Table 2.2: Risk analysis

<table>
<thead>
<tr>
<th>Identified risk</th>
<th>Probability</th>
<th>Consequences</th>
<th>Risk estimation</th>
<th>Action taken?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Failure of electric machine</td>
<td>2</td>
<td>EH</td>
<td>5</td>
<td>Yes</td>
</tr>
<tr>
<td>Overheating of components</td>
<td>2</td>
<td>EH</td>
<td>4</td>
<td>Yes</td>
</tr>
<tr>
<td>Long exposure to vibrations</td>
<td>3</td>
<td>EH</td>
<td>4</td>
<td>Yes</td>
</tr>
<tr>
<td>Complicated to reach</td>
<td>2</td>
<td>SH</td>
<td>1</td>
<td>No</td>
</tr>
<tr>
<td>Exposure to bumps, rocks, etc</td>
<td>3</td>
<td>H</td>
<td>3</td>
<td>Yes</td>
</tr>
<tr>
<td>Exposure to wet surfaces</td>
<td>3</td>
<td>H</td>
<td>2</td>
<td>Yes</td>
</tr>
<tr>
<td>Durability problems</td>
<td>1</td>
<td>H</td>
<td>3</td>
<td>Yes</td>
</tr>
<tr>
<td>Not noticing failures/broken parts</td>
<td>1</td>
<td>EH</td>
<td>2</td>
<td>No</td>
</tr>
</tbody>
</table>

As shown in Table 2.2, six risks have been chosen to take action on them. The preventive methods that will be applied to improve the product and customer safety are presented now for every identified risk.

To avoid failure of the electrical machine, the action taken is to find a reliable electric motor and use it according to its specifications, choosing the most suitable one for this application. To avoid overheating of components, it is needed, in the design process, to make sure that the components have enough space for ventilation, or investigate the possibility to introduce a cooling system. Concerning the long exposure to vibrations, they will be taken into account during the whole development process. Making sure that the pieces will stand bumps and small crashes is crucial for this application, with the possibility of creating a recovery piece to protect the e-axle in case of danger of damage. The components must be waterproof since water, mud, snow will appear on this application. For the durability problem, the solution needs reliable components although this might imply an increase in the price.

2.3 Analysis of competitors

To study the competitors, Porter’s five forces analysis is followed [3]. It consists of an estimation of the potential in the present and future that the product has in the medium and long term. As Porter mentions: “The goal is to find a position in the industry where the company can defend itself better against forces or influence them to be favorable to them”[3].

It is not useful only for seeing the opportunities of the market, but to see the threats that may appear. The Porter’s five forces analysis deeply analyses the sector.
• Rivalry among existing competitors: this is the most important force in the model.
  – For the e-axle, it can be considered that the number of competitors will increase as well as the industry since it is a new solution and any company can join the market. However, taking into account that the e-axle is a very specific product due to its application in heavy vehicles, companies might not invest in it making it the only offer for it in the market. For the reasons presented, the rivalry can be considered a medium market.

• Bargaining power of suppliers: This force is useful to understand the power of a supplier in the market. It means that if it is a monopoly or many suppliers that can offer the product.
  – For the e-axle, the suppliers have low negotiating power since the products needed are basic and offered by a lot of different ones (electric motors, gearboxes, etc) and they are not differentiated (same quality, price and offer). The suppliers chosen need to be reliable to get the pieces in time.

• Bargaining power of buyers: this force focus on the power of the customer and how it can affect price and quality.
  – For the e-axle, the buyers have low power of negotiation because there are not (many) substitute products in the market offering the same services.
• Threat of new entrants: This force tells how easy it is for the competitors to join this market.

  – It is meant to analyse the specific market, so in this case the front e-axles and how easy it is for new competitors to join this market. Since it is a new product to develop, it makes it easy to join this market. Not only for truck companies, but new companies that are dedicated to the electrified future and will be appearing on the way. These new companies will also have the opportunity to collaborate with truck companies in the development of this product. It has to be taken into account the brand image, where the market is not that easy to join since customers usually prefer what they already know that will work. In this case, it is a competitive advantage that Scania has a strong image in terms of quality and reliability but the threat of new entrants is big in this "e-market".

• Threat of substitute products: this force is about the possibility of substituting this product, for example instead of electrified axles the consumers prefer a hydraulic system.

  – For the e-axle, substitute products are an important threat. The e-axles will be a small part of the extra traction options. Not only because it will be on-demand traction (specific use for specific moments and speed), but because it is for the front axle making a market option open for the rear axle as well. The hydraulic front axle traction is a substitute product that already exists and can affect this market. The threat compared to this product can be differences in price and quality. As Figure 2.4 shows, the prevision for the e-axle market is that it will grow with a CAGR (Compound Annual Growth Rate) of 34.6% from 2018 to 2025, so it can be considered that the e-axle is the substitute product [4].
In the Table 2.3, some of the different competitors in the market and the systems they use for extra traction or electrified drive are shown [5]. Not all the competitors show characteristics of their product so the table is filled with all the data that has been found. From this table, there is one competitor and one supplier that must be highlighted: Elaphe and MAN. MAN hydrodrive and Elaphe in-wheel motors will be studied deeper for the accomplishment of this thesis.
Table 2.3: Available options in the market

<table>
<thead>
<tr>
<th>Company</th>
<th>System</th>
<th>Power (kW)</th>
<th>Weight (kg)</th>
<th>Intended vehicle category</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meritor</td>
<td>e-axle</td>
<td>150-200</td>
<td>-</td>
<td>Commercial vehicles</td>
</tr>
<tr>
<td>Magnet-Motor</td>
<td>e-axle</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Bosch</td>
<td>e-axle</td>
<td>-</td>
<td>-</td>
<td>Heavy duty trucks</td>
</tr>
<tr>
<td>Bosch</td>
<td>e-axle</td>
<td>50-300</td>
<td>90</td>
<td>Up to 7.5 ton</td>
</tr>
<tr>
<td>Protean electric</td>
<td>in-wheel motors</td>
<td>-</td>
<td>28-36</td>
<td>Heavy duty trucks</td>
</tr>
<tr>
<td>GKN</td>
<td>e-axle</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>AVL</td>
<td>e-axle</td>
<td>148</td>
<td>-</td>
<td>Urban trucks</td>
</tr>
<tr>
<td>Allison Transmission</td>
<td>e-axle</td>
<td>-</td>
<td>-</td>
<td>Heavy duty trucks and buses</td>
</tr>
<tr>
<td>Axle Tech</td>
<td>e-axle</td>
<td>350</td>
<td>-</td>
<td>Off-highway</td>
</tr>
<tr>
<td>Axle Tech</td>
<td>e-axle</td>
<td>200</td>
<td>-</td>
<td>Heavy duty special</td>
</tr>
<tr>
<td>Dana electrified</td>
<td>e-axle</td>
<td>-</td>
<td>305</td>
<td>Medium duty trucks and buses</td>
</tr>
<tr>
<td>Michelin</td>
<td>in-wheel motors</td>
<td>55</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>ZA</td>
<td>in-wheel motors</td>
<td>120</td>
<td>-</td>
<td>Commercial and heavy duty</td>
</tr>
<tr>
<td>Schaeffler</td>
<td>in-wheel motors</td>
<td>33</td>
<td>53</td>
<td>Urban vehicles</td>
</tr>
<tr>
<td>BorgWarner</td>
<td>in-wheel motors</td>
<td>165</td>
<td>57.2</td>
<td>Urban vehicles</td>
</tr>
<tr>
<td>Elaphe</td>
<td>in-wheel motors</td>
<td>70</td>
<td>40</td>
<td>Heavy duty</td>
</tr>
<tr>
<td>MAN</td>
<td>hydraulic</td>
<td>-</td>
<td>400</td>
<td>Trucks</td>
</tr>
<tr>
<td>Mercedes</td>
<td>hydraulic</td>
<td>-</td>
<td>400</td>
<td>Trucks</td>
</tr>
<tr>
<td>Volvo</td>
<td>hydraulic</td>
<td>-</td>
<td>-</td>
<td>Trucks</td>
</tr>
<tr>
<td>Renault</td>
<td>hydraulic</td>
<td>-</td>
<td>500</td>
<td>Trucks</td>
</tr>
<tr>
<td>DAF</td>
<td>hydraulic</td>
<td>-</td>
<td>450</td>
<td>Trucks</td>
</tr>
</tbody>
</table>

Elaphe is a company that offers different in-wheel motor solutions for different applications. One of them is called M1100 and it is intended for heavy-duty applications in tough conditions. The weight of each electric motor is 40 kg with a continuous power of 70 kW [6].

The MAN hydrodrive is made for road vehicles that occasionally need to travel off-road. Compared to the All Wheel Drive (AWD), to use the hydrodrive reduces the weight 750 kg. A hydropump on the gearbox output supplies the wheel hub drives at the front axle. It has a switch in the cab where you can activate this mode. Once the speed reaches 28 km/h it turns off automatically [7].

The companies that offer the e-axle system are currently in a concept or prototype phase. AVL r-axle for heavy duty trucks is in a concept level, but they claim: "the actual E-axle itself is not primarily intended to be offered as a plug-and-play solution for OEMs but rather to act as a technology reference proving our capabilities to develop such systems" [2]. An OEM is defined as an Original Equipment Manufacturer and it refers to the original producer of a vehicle’s component.
2.4 Patent study

It is important to be aware of the patents that can exist already on the market related to e-axles. Apart from getting information on what has been done already, it is important to not reinvent technology during this project. For that reason, a meeting with the Scania patent department was held to know how to search in the right way for possible patents that can affect this work.

No patents have been found for the front axle that could affect the project at its beginning. There is a patent from Ding Desheng and Liang Yijie about an auxiliary electric rear axle of front-drive vehicle [8]. It is about a front driven vehicle that gets extra traction on the rear when the complex pavement produces insufficient traction. This patent was only active in China but was withdrawn in 2018 and it is therefore free to use.

2.5 Product specification

To be able to create a product specification, the analysis carried out in the previous section are needed. With the the information obtained in the analysis of needs and the risk analysis, the product can be defined in a way that the customer is considered, avoiding possible problems later during the development process.

For the front axle option, the product will be focused on giving extra traction for specific moments and speed for trucks. The speed limit will be around 30 km/h for the usage of the axle with extra traction. For the rear axle option, the focus will be to reduce emissions and noise in the ride. It is strongly recommended that the truck to use e-axles at Scania shall be the hybrid model as the base vehicle. A hybrid truck already has batteries, battery management, charging systems, voltage cables, etc. that will also be necessary when adding an e-axe.

2.5.1 Driving scenarios

The driving scenarios that are taken into account for this project are construction, long haulage and urban trucks. For the urban truck scenario, a 4x2 will be used and for the construction and long haulage scenario it will be a 6x2.

With the driving scenarios chosen, the product will be compared with two other Scania trucks, a 4x2 and a 6x2. The comparison will be made about the transformation of the 4x2
into a 4x4 and the 6x2 to a 6x4 on diesel trucks, or using the hybrid truck configurations 4x2 and 6x2 and adding the e-axles to convert them into a 4x4 and a 6x4.

2.5.2 Hybrid truck

The hybrid option for a truck will be considered as a prerequisite for this project and the reason behind it is to make the development easier. The wheel configurations available for the hybrid truck are 4x2 and 6x2, that when adding the e-axles can become 4x4 and 6x4.

The reason behind it is because it already has electric components that can be used for the new e-axle (like cables and multi-batteries). This is an advantage because it will imply to need less extra components and "reduce" weight, as well as save money.

The combustion engine selected for this truck is the smallest one (7 liters) because it is the one that occupies less space and weights less.

2.5.3 Competitive advantage

The product needs to have a feature that makes it superior versus its competitors. In this case, the competitive advantage is reliability, and it is including different “meanings” in it. By reliability it is referred to savings, sustainability, new technology and simplicity. The fuel usage will decrease when using the electric motors, maintenance will be avoided since it has less mechanical pieces, changing oil will be delayed, etc.

Sustainability is the biggest advantage for this product since it will allow the trucks to run on emission-free and silent mode, allowing them to drive when the cities put bans on emissions or noise restrictions at nights. Talking about simplicity, electric machines are known for having less losses than any other and simpler connections, less pieces, and faster responses which makes it again more reliable.
The theoretical background to execute this thesis is based on the request for the e-axle. To be able to investigate different e-axle concepts and analyse their potential, a background regarding the product trucks and their components is needed which is given in this chapter. Parts that do not exist today on a Scania truck but will be involved in the concept evaluation will also be described such as individual front suspension and in-wheel motors.

### 3.1 Wheel configuration

The type designation system used in this project is the model designation used by Scania. The first part of the wheel configuration, for example the 4 in 4x2, indicates the number of load carrying wheels, and the number of driving wheels is indicated in the second part (2). In the case of a 4x4, all the wheels are driven. As it can be seen in the Figure [3.1] the driven wheels are colored to be identified easily. There are more types of wheel configurations that will not be used in this project, and for that reason, they will not be explained.

![Figure 3.1: Example of wheel configurations](image)
3.2 Traction

This concept is relevant due to the possibility of the e-axles function of giving extra traction to the truck in moments of need. Traction is “the action of drawing or pulling something over a surface” [10]. It is needed to move a truck over the road, but depending on the surface there is a different friction coefficient that will affect the traction of the vehicle. The data for the friction coefficients used in this investigation is taken from Scania Vehicle Optimizer.

<table>
<thead>
<tr>
<th>Surface</th>
<th>Friction coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry asphalt</td>
<td>0.8</td>
</tr>
<tr>
<td>Wet asphalt</td>
<td>0.6</td>
</tr>
<tr>
<td>Asphalt/Gravel</td>
<td>0.5</td>
</tr>
<tr>
<td>Soft gravel</td>
<td>0.4</td>
</tr>
<tr>
<td>Terrain</td>
<td>0.3</td>
</tr>
<tr>
<td>Snow/icy road</td>
<td>0.1-0.4</td>
</tr>
</tbody>
</table>

If the truck cannot provide enough traction, it will get stuck, and as it can be seen in soft gravel and terrain the coefficient will decrease the traction by more than 50%, as well as in the icy and snowy roads. The extra traction needed for a truck to get out of complicated situations will be explained with calculations.

3.2.1 Traction calculations for slippery surfaces

The calculations for the traction needed to escape a slippery surface like sand or mud are different than for a normal situation. This kind of surfaces are considered plastically deformable, and the rolling resistance becomes larger as the tyre pressure increases. A smaller contact patch area with an equal amount of vertical force will make the tyre to sink deeper into the surface [12].

There is an extra resistance created by the slippery surface. For this extra resistance, a rolling resistance coefficient $kr,pl$ is defined. It is a linear relation between the rolling resistance force $Fr,pl$ and the vertical force $Fz,w$.

If the tyre pressure increases while the vertical force ($Fz,w$) remains constant, the rolling resistance ($Fr,pl$) will be decreased. Some calculations have been done [12] in the
coefficient $kr_{pl}$, as shown in the Table 3.2.

Table 3.2: Rolling resistance coefficient on different surfaces [12]

<table>
<thead>
<tr>
<th>Roadway surface</th>
<th>Coefficient $kr_{pl}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hard asphalt, concrete</td>
<td>0.005-0.015</td>
</tr>
<tr>
<td>Hard-packed gravel</td>
<td>0.02-0.03</td>
</tr>
<tr>
<td>Tarred gravel</td>
<td>0.04-0.04</td>
</tr>
<tr>
<td>Well-maintained dirt roads</td>
<td>0.05-0.15</td>
</tr>
<tr>
<td>Soft and wet surfaces</td>
<td>0.15-0.35</td>
</tr>
</tbody>
</table>

3.3 Electrified vs conventional powertrain

The cost of an electric vehicle is higher than a traditional mechanical powertrain. This is due to the new technology it has and cost of investigation and application of it. It is an advantage for the conventional vehicles when the customer is trying to decide which one to buy, but as the years pass by the price difference will be lower or even disappear. It is also needed to take into account that electricity’s price is lower than (fuel/gas) and that with more kilometers the total cost of ownership (TCO) will become more even between these two technologies. In the case of trucks, they are intended to do a lot of km per year so it becomes an advantage for the electrified powertrain and savings on the lifetime of the vehicle [13].

An electrified powertrain can provide emission free driving, while the conventional will contribute to pollution. Comparing an all wheel drive (AWD) vehicle with an electrified one, the second one will have a higher payload and will be more profitable than an AWD system when performing the same task (fuel is more expensive than electricity and more payload). Even though pieces of electric vehicles are more expensive than conventional ones, they are cheaper to maintain, have less components and are more reliable.

The electrified powertrain will be more efficient than the conventional since the efficiency of an electric motor compared to a combustion engine is much higher. The efficiency of an internal combustion engine can be on a range between 20% to 45% of efficiency while an electrified powertrain range is between 70% and 95% [14]. Nowadays, conventional powertrain vehicles are able to travel for longer distances while electrified powertrain is more useful for city scenarios. Since cities are restricting pollution to improve air quality, to have a electrified powertrain will make the customer still be able to drive around without bans or penalties. The European Comission has a plan of zero emissions by
2050, so having an electrified powertrain vehicle will be the only way to drive in at least 49 countries [15].

The usage of electric vehicles will also increase in the future since it is still a new technology, the development of charging structures is increasing all over the world and fossil fuels are exhaustible resources (petroleum is expected to run out in 50 years approximately).

### 3.4 Electric motors

A hybrid vehicle is the one that uses at least two different sources of power. In this case, the hybrid is considered to use a combustion engine plus an electric one. The electric motors are in charge of converting the electrical power into mechanical power and rotate the wheels. They can use Direct Current (DC) or Alternating Current (AC). The torque required will be chosen based on the MAN hydrodrive system [7] as a reference, so it will be aimed for 14000 Nm, where the power needed can be calculated to approximately 110 kW. The voltage aim is to use 650 V because that is the voltage used by Scania in the hybrid truck. A different voltage could be used but it will imply to add more components like a DC-DC converter to the e-axle.

### 3.5 Chassis height

The customers can today choose between different chassis heights: extra-low, low, normal and high. Depending on the combination chosen for the vehicles, the height can be chosen or restricted to a certain option. The distance specifies the relative chassis height based partly on the distance from the frame top edge to the rear drive shaft centre, and partly from the frame top edge to the front axle centre [16].

For the AWD vehicles, the only option available is to have chassis height high (H) due to the space needed between the engine and the axle housing.
3.6 Axles

There are two different types of axles for the front: driven axles and non-driven axles. Depending on the axle chosen, other characteristics of the truck, like the chassis height, are affected.

For the front driven axles, the only chassis height available is high. The reason is that more space is needed for the axle not to crash with the engine. For the non-driven axles or rear driven axles any chassis height can be chosen.

With respect to the rear axles, apart from the driven and non-driven axles, there is an option to have a liftable axle. This type of axle can be raised from the ground and used on demand depending if the truck is loaded or unloaded. In the case of the rear axles, the chassis height is not affected by the type of axle used. A tag axle is another option of rear axle and it is defined as a non-driven axle located in the truck behind the driven axle.

There are different "axle drops" which means how much the axle is angled down. There are straight axles, which have 0 drop and up to 170 mm axle drop.
3.7 In-wheel motors

The in-wheel motor systems modify the hub of the electric vehicle wheel by adding a complete drivetrain that supplies torque to its associated tyre [17]. The in-wheel motors are not available nowadays in the truck market.

The use of in-wheel motors reduces the losses even more since they are directly inside the wheels and can be used as part of the braking system. This will allow the brakes to be reduced in size, but a mechanical braking system will still be needed (it is necessary for emergency braking when maximum torque is needed or in the case the electric system fails).

3.8 Suspension

The suspension is in charge of the motion between the vehicle and its wheels. There are two main types of suspensions: dependent or independent (individual). For the dependent suspension, there is an axle connecting left and right wheel. It is cheap to manufacture and used for vehicles that demand durability. With respect to the individual suspension, it does not use a bar connecting both wheels and it is usually used to give increased comfort. The independent suspension will be explained further in the next subsection. Scania offers both leaf and air suspension on trucks.

3.8.1 Individual suspension

An individual suspension is formed by articulating joints and rigid elements that connect the vehicle’s body to the wheel carrier using intermediate links [12]. It provides the wheel with an extra degree of freedom, allowing vertical movement of only one of the wheels with respect to the body. If there are road irregularities, it reduces or eliminates the vibrations produced on the vehicle.

There are different types of individual suspension: two-point link, three-point link, four-point link and the strut-type suspension. From this link types, different configurations can be used to obtain individual suspensions (see Figure 3.3).
CHAPTER 3. BACKGROUND

The double wishbone suspension is one type of individual suspension which is currently used at Scania for buses. It consists of two three-point links and one extra two-point link. The configuration must follow some rules: one of the links must be above the wheel center and one of the links must be below the wheel center, in order to be able to resist the forces and moments acting on the wheel. A third link is used for the control of toe and steering. Ball joints and rubber bushings are needed at the ends of the links to resist lateral and longitudinal forces. It is considered an advantage if the upper link is shorter than the lower link because it reduces camber and track width changes during wheel travel.

Advantages of using the double wishbone suspension are that it provides a large amount of design freedom, high lateral stiffness and good handling. On the other side, the disadvantages come from high manufacturing costs, spacing, the forces applied to the chassis-side connection points require the use of a chassis subframe and that the payload will be reduced.
In this chapter, the methodology followed in this project is divided into two sections: a pre-study phase and a concept phase. This methodology has been used in a previous thesis in a similar field.

The pre-study phase includes doing benchmarking, gathering information and knowledge about electrified solutions for trucks. The method followed for the pre-study can be considered applied research, exploratory and inductive. The applied research relies on developing the project, exploratory research is about exploring the main aspects of an under-researched problem and the inductive method aims to develop a theory [18].

The pre-study also includes interviews with people from different departments at Scania. Getting first-hand information is the best way to learn about the subject, and people usually have different visions and ideas over the field so they can be used for developing new concepts. The interviews took place with several people within the Research and Development group that had projects related to electrification, powertrain, axles, suspensions and brakes. The answers and conclusions obtained for the interviews were used to obtain the concept possibilities and conclusions of this thesis. The interviews can be considered semi-structured interviews, before the interview the topic was studied and questions written down to ask the experts but as the interview goes along new questions appear and the conversation flows. This research method can be considered primary, a mix of qualitative, quantitative and descriptive. It is primary because the data is collected directly through interviews. For the data collection it is a mix of a quantitative and a qualitative method because it takes into account not only interpretation of data but also
statistics. It can be considered descriptive due to the fact that the data is gathered without controlling any variables [18].

For the concept phase, different models were chosen and investigated as possibilities, to finally choose the best one and do further development on it. The pros and cons of the different concepts were taken into account as well as opinions from expert engineers. Some concepts will be presented with a rough Catia model.

The best concept or concepts are proposed as candidates to continue its development as a future work. With Catia, the layout of the truck including these concepts were created, with a detailed design explaining all the changes needed for this, new pieces, etc. Also, an economic investigation was made for it.

4.1 CAD modelling

Using CAD to design and analyse the different concepts was an important part of this project. The CAD system used during this thesis was CATIA V5 [19].

Most of the pieces used for this modelling were taken from different existing parts, while some new pieces might need to be created.
In this chapter the concept generation is presented, followed by a concept evaluation and selection. For the concept phase, different models are chosen and investigated as possibilities, to finally choose the best one and do further development on it. The pros and cons of the different concepts are taken into account as well as opinions from expert engineers. Some concepts will be presented with a rough Catia model. The best concept or concepts are proposed as candidates to continue its development as a future work. With Catia, the layout of the truck including these concepts are created, with a detailed design explaining all the changes needed for this, new pieces, etc. Also, an economic investigation is made for it.

5.1 Vehicle properties-level of ambition

The vehicle properties is the list of product and vehicle properties used for target setting and verification of R&D projects at Scania. It is an analysis made on new products to make a realistic evaluation of them. It will help on the selection of the best properties for the product. The properties were evaluated in the three different “scenarios”: long haulage, construction and urban.

The detailed results from this evaluation can not be presented in this report since it contains sensitive material and thereby is confidential according to Scania’s confidentiality policy. However, from the results from this analysis it can be concluded that the product
is probably most valuable for long haulage and urban scenarios.

5.2 Concept generation

Five concepts are identified and analysed in this section. The concepts are generated from the information obtained with the benchmarking, interviews, literature research and discussions with several people at Scania. After the evaluation of concepts the best ones are proposed to do a further development on them. All the proposed concepts can be defined as e-axles.

- Concept 1- Electric motor within a mechanically driven axle: There are two options for this concept. The first one consists of taking away the gearing of the driven axle and introduce the electric motor and components in that space. The second one consists of add the electric motor after the gearing for the rear axle.

- Concept 2- Electric motors in a non-driven axle: It consists of locating two electric motors on both sides of the currently non-driven axle.

- Concept 3- In-wheel motors: It consists of introducing the electric motors within the rim radius.

- Concept 4- Electric motors in a rear support axle: It consists of locating the electric motor in the rear support axle (liftable axle).

- Concept 5- Electric motor in a diesel truck with a generator: It consists of using a generator from the diesel engine to give power to the electric motors.

5.2.1 Electric motor

The electric motors selection is based on the availability of the product at Scania. The supplier chosen for the electric motors is BorgWarner because the product is available and Scania has used it before. There are two electric motors available from BorgWarner HVH (High Voltage Hairpin), HVH250-115 and HVH410-150 [20]. The first engine has
an outer diameter of 250 mm with a peak torque of 410 Nm and a weight of 57.2 kg, while the second engine has an outer diameter of 410 mm, a peak torque of 2200 Nm and a weight of 140 kg.

The advantage when using the HVH250-115 is that it occupies less space but, as a drawback, the gear ratio needed will be around 15 and there are no gears available with this ratio at Scania nowadays. For the HVH410-150 the gear ratio needed will be around 3.5, which is available, but its problem will be the space. There is not much space available to fit the electric motors and the HVH410-150 occupies almost double than the model HVH250-115. For the case of the truck intended, the electric motor HVH250-115 is the one selected to use in the e-axles, even though the drawback with the gear ratio will need to be solved.

Characteristics of the motors are studied and meetings are held with engineers that have worked with them to decide which one could be the best option for this investigation. Since the electric motor is located behind the centre of rotation, a connection is needed between that and the transmission. A gear is selected to put this two points together, the red line in the Figure 5.1 shows the distance between the electric motor and the transmission, the two points that need to be connected.

Figure 5.1: Distance between electric motor and transmission
5.2.2 Concept 1: Electric motor within a mechanically driven axle

The first concept, the electric motor with driven axle, can be used for both front and rear axle.

For the front axle, the concept is based on taking out the gearing located in the center of the axle and use that free space to insert an electric motor, shown in Figure 5.2. The idea behind it is to use the electric motors when extra torque is needed (on demand front wheel drive), for example in a situation where the truck gets stuck or to create a start-stop system which is free of emissions in the city. The system is prepared to work up to 30 km/h so a free-wheeling system must be located for the electric motor to disconnect after the speed limit is reached. Some limitations of this concept are that it can only be used with chassis height high since the driven axle is a straight axle, and that the space of the gearing is not enough to fit the electric motor. The electric motor will crash into the track rod assy (front axle housing) as it can be seen in Figure 5.3, implying a relocation and redesign of components. Since the space for the gearing is not enough and it makes the electric motor to cause collision with other pieces, it is a better option to consider the propeller shaft, keep the gearing and add the electric motor after it.

Figure 5.2: Gearing of driven axle (green)
CHAPTER 5. RESULTS

Figure 5.3: Electric motor located in the gearing position

With respect to the rear driven axle there are 2 options, to locate the electric motor on the last axle of the truck or in any other rear axle. If locating the electric motor after the gearing of the last axle of the truck, there are no spacing problems and it is a simple solution to implement. If the location of the electric motor is on a rear axle that it is not located last on the truck, the next axle also needs to be driven, since the transmission is removed to locate the electric motor. Another good thing about using the rear driven axle is that the chassis height is not affected. Limitations found with respect to the rear is that the torque will not be enough to get out of complex situations while driving. After some simple calculations made on the torque need for escaping complex situations, it is stated that, located in the rear, the torque available with the e-axle will not be enough.

5.2.3 Concept 2: Electric motors in a non-driven axle

The electric motors located in the non-driven axle solve the problem with the chassis height, since it is compatible with any height requested. The concept consists on doing the same as in concept 1, but instead of locating the electric motor on the differential, they will be located one on each side of the axle. This type of axle occupies less space than the driven axle, so more space is available to locate the motors. A bracket must be created to hold the electric motors in place, as well as a gear to connect the motors with the wheels. A new suspension or new axle design are needed for the further development of this concept, which will require extra time on the development.

The limitations are the location of the electric motors due to spacing and vibrations, and the complexity of the design since a new system needs to connect the motors with the wheel, batteries, etc.
5.2.4 Concept 3: In-wheel motors

The in-wheel motors, as its name indicates, consists of having an electric motor in each wheel. To be able to do it, an individual suspension must be used due to spacing reasons. Other types of suspensions occupy space inside the wheel that it is necessary to free to add the electric motors. For this reason, the suspension found to be the best option is the individual suspension, which is developed for buses at Scania.

For the in-wheel motors concept different parts need to be taken into account: electric motors, transmission, brakes, disengagement system and suspension.

The advantages that this concept show are that it can be used with any chassis height and in any axle (front or rear).

To be able to locate the motor inside the wheel another type of suspension is needed (not air or leaf suspension). When using an air suspension for a truck, the electric motor located behind the wheel centre interferes with it, and the same happens when using the leaf suspension. However, the individual suspension is not able to be fit into the truck without modifications on its components (redesign a new suspension) or redesign the frame. It is complicated to fit the system into the conventional suspension for a truck (air or leaf suspension), so a different type of suspension is needed. It is due to spacing reasons because this type of suspension frees the space in the wheel that is necessary for this concept. For this concept, the suspension used will be the independent suspension as mentioned before, already used in Scania with the buses. The first limitation of this concept is to be able to fit the pieces into the truck frame, since the individual suspension developed to fit into a bus frame. The frame of the bus and the truck are very different, it is important to know this because all the pieces taken from the bus system will need to be readapted to this frame. However, it is possible to fit an individual suspension on a truck since Volvo uses it in the Volvo FH model [21].
As it can be seen in the Figure 5.5, the individual suspension crashes when put into the truck layout. Modifications of location of the pieces must be made for this system to fit into the truck. The weight of the suspension will be around 458 kg (double wishbone suspension weight).

The wheel center must be located in the center of the suspension.

The upper part of the triangle link suspension (upper triangle link) position has different limitations. First of all it crashes into the frame, so it needs to be moved downwards in
the layout. When moved from that position it is needed to take into account the engine of the truck as well as the electric motor. When avoiding the crash with the frame, it crashes either with the engine or the electric motor. To avoid the interference with the electric motor it needs to be moved downwards until it does not crash anymore. This position might be too low since the lower suspension has to fit under it as well and the distance between lower and upper part needs to be respected.

For the air bellows of the suspension, in the bus position they are not touching the frame. It is needed to change the support and make a new one that attaches them to the frame.

The shock absorbers are crashing into the frame, so a new position must be found for them. It is not a problem to move the shock absorbers to a different position.

The triangle link suspension crashes into the truck frame and the electric motor. The upper and lower part of the triangle link suspension crash when added to the frame. The brackets can be removed and new ones need to be created that will fit into the truck frame. With respect to the triangle link, it needs to be moved. If it is lowered down, it does not crash with anything else, but might be too low (too close to the ground). Attach it to the frame is another option, but when doing it, it crashes with the engine.

With respect to the transmission system, the simulations made for another project at Scania show that a higher gear ratio would be much better for efficiency in city operations. The limitation found for it is the space available for the transmission in the wheel.

There will be a need to create a disengagement system. This system is needed to let the electric motors disconnect and free-wheel for the times when it is not being used.

The second limitation of this concept is that the electric motor cannot be located within the rim radius due to spacing reasons. The in-wheel distance available is around 183 mm, the wheel inner diameter 575 mm and the rim diameter is 493 mm. Taking these measurements into account, it looks like the HVH-410 fits but because of other necessary pieces, the electric motor cannot be fitted inside the wheel. The transmission and brakes will be fitted in, while the electric motor will be outside of the wheel.

If the electric motors are not inside the wheel it will be difficult to create a system to connect them, so having the axles are a big limitation (gears need to be designed to connect).

The brakes might be different from the usual ones since with the electric motor, mechanic
CHAPTER 5. RESULTS

brakes are only needed for emergency stops. There is a new concept at Scania that uses a brakes system that occupies less space, which means that there is an option of using reduced disk brakes. It could be an option but it is important to say that they are not tested or certified yet and it will add extra time to the project.

It is important to fit the electric motor behind the wheel center to let the steering system work. The steering knuckle assy needs to be able to go forward and back to its original position during driving, so this space must be empty. If using the triangle link suspension, the steering knuckle assy will be removed from the layout.

5.2.5 Concept 4: Electric motor in a rear support axle

For this concept, the electric motors are located in the rear support axle that can be lifted or put into the ground on different moments of the driving. Two options are available for the development of this concept: either use the design for concepts 1 or 2, or buy a complete e-axle from a supplier.

Any type of axle (driven or non-driven) can be used for this concept since it will not affect the chassis height. Additionally, there is more space available in the rear which will make the system easier to fit.

In the case of buying a built e-axle from a supplier, it is important to mention that they are not available yet on the market. They are in the concept and prototype stage and there is no indication on if or when they will be available.

If the tag axle is non-steered, the brake chamber is located on the right side of the axle leaving space on top of the axle to locate the electric motor.

On the other hand, if the tag axle is steered, the brake chamber is on top of the axle so it will be needed to relocate it on the left side. There is less space on this axle because of the steering parts, so a redesign of components might be needed as well.

If the tag axle is steered, a new position needs to be found to locate the brake chamber and put the electric motor on top of the axle.

A gear must be located to connect the electric motor and the wheels. An available gear must be used, making sure that it fits into the available space.
The electric motor will be connected to the braking system located in the wheel. It is needed to verify the installation of the support chosen, the chamber connection, to assure that it can stand the electric motors. It will be connected from the gear to the braking system. A bracket is also needed to hold the electric motor in place.

The brake chamber can be located on different sides of the axle depending on the axle specification. If the axle is steered, the brake chamber is located on top of the axle. If it is a non-steered axle, the brake chamber is located on the right side allowing the electric motor on top of the axle. However, the brake system needs to be modified to be able to connect the electric motors with the wheel.

5.2.6 Concept 5: Electric motor into diesel truck

This concept consists of using an electric motor on the diesel truck, with a generator giving power to it from the combustion engine. After the internal combustion engine of the truck, a generator must be placed. Scania provides different options for this generator.

This concept is discarded because of the selected prerequisite that the truck must be a hybrid. It will not be taken into account for the concept selection.

5.2.7 Concept selection

For the concept selection, the method followed is again Ulrich and Eppinger, with the PUGH’s matrix \[22\]. It consists of analysing every concept comparing it to a reference concept. The reference concept (electric motor with driven axle) is set as every variable is 0, and the rest of the concepts are compared to it with a + if it is better in that aspect, a 0 if it is similar or a - if it is worse. The PUGH’s matrix, Table 5.1 was presented to the department to discuss, get feedback and agree on each parameter.
Table 5.1: PUGH’s matrix

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Concept 1 EM driven axle</th>
<th>Concept 2 EM non-driven axle</th>
<th>Concept 3 In-wheel motors</th>
<th>Concept 4 EM in rear support axle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Durability</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Complexity of design</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>Modularity</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Chassis height</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Payload</td>
<td>0</td>
<td>+</td>
<td>0(+</td>
<td>+</td>
</tr>
<tr>
<td>Performance (torque)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>Redesign of components</td>
<td>0</td>
<td>+</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>New design of components</td>
<td>0</td>
<td>0</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>Fuel consumption</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>Assembly cost</td>
<td>0</td>
<td>+(?)</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>Components cost</td>
<td>0</td>
<td>0</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>Operation cost</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Maintenance cost</td>
<td>0</td>
<td>0</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>Competitively on the market</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td>0</td>
<td>3</td>
<td>0</td>
<td>3</td>
</tr>
</tbody>
</table>

- **Durability**
  
  Concepts 1 and 2 have the same durability, since vibrations on the motor will be the same (if the position of the EM is same or similar). Concept 3 will be better since it is a whole system created to locate the EM (designed specifically for this purpose), which will reduce their "loads" as much as possible. The reasons of the + in concept 4 is that since it is a support axle the usage will be less, durability will increase and since there is more space in the axle there will be more flexibility in terms of sealing, harnessing, etc.

- **Complexity of design**
  
  For concept 2 the complexity of the design will be harder since the new drivetrain will have more components that need to be located (and maybe the individual suspension?). On the other hand, for concept 3 a new suspension will be needed (individual suspension of the bus), adding new components and relocating existing pieces. For the concept 4, the EM is in the support axle that can be "disconnected" itself, so there will be no need of free-wheeling system and other components used in other concepts.

- **Modularity**
  
  In this case, concept 3 is better because it could be used for either front or rear axle, when 1 and 2 are only for the front axle and concept 4 is the rear support axle.

- **Chassis height**


Concept 1 can only be used for chassis height high when the rest of the concepts can have any option for chassis height.

- **Payload**
  The payload is better in concept 2 because the non-driven axle weights less than the driven axle and the same happens with concept 4. Concept 3 can be better because the individual suspension weight is better than the any truck suspension, but it might support less weight so it could be similar to concept 1.

- **Traction**
  The traction capacity can be considered the same for the first 3 concepts and worse in the 4th one since for the rear axle the torque will not be enough to get out of complex situations like getting stuck (it is necessary to get the torque on the front axle). There is an exception for concept 4 where it will be a +, if the truck gets stuck when it is loaded, concept 4 will have an advantage on traction.

- **Redesign of components**
  Concept 2 and 3 will need a redesign of a lot of components since there is a need for a new drivetrain in concept 2 and with respect to concept 3, the whole suspension system is not made for a truck configuration. Concept 4 will be better since there will be more space in the support axle.

- **New design of components**
  Concept 3 will need design of new components to adapt the bus suspension. The rest of the concepts will have a similar amount of new components.

- **Fuel consumption**
  The fuel consumption can be improved for concept 3 since the electric motors are in-wheel and it will generate less losses on the system. The rest of the concepts will have a similar fuel consumption.

- **Assembly cost**
  Concept 2 (maybe) and 4 will be easier to assembly because the axles they use are smaller and more space will be available. With respect to concept 3, it will be worse since "everything" is new (it has never been done before).

- **Components cost**
  The cost of components will be similar in all concepts except for concepts 2 and 3, that will need new components and some special ones that will increase its cost.
CHAPTER 5. RESULTS

- Maintenance cost
  Concept 2 maintenance cost will be worse compared to the other concepts due to having more components and more moving parts. Concept 3 will be worse than the reference due to being a more complex system itself. On the other hand, concept 4 will be better since the support axle can be considered "separated" (an individual system) from the truck.

- Competitiveness on the market
  The most competitive concept in the market will be concept 3 because it has less limitations than the rest of concepts. Concept 4 is less competitive because it is limited to trucks with a rear support axle.

From the concept evaluation matrix, it can be concluded that the best two concepts are concept 2 (electric motors in a non-driven axle) and concept 4 (electric motors in a rear support axle).
The aim of this thesis was to investigate the potential of e-axles to use in Scania trucks. Not only from a performance point of view but also from a business and industrialisation point of view. Through market analysis, gathering of information and knowledge about electrified solutions for trucks, interviews with Scania staff and product specification five different concept has been identified, evaluated and compared. Two of them chosen for a further development due to its benefits respect to the others. It can be concluded that an e-axle is a good option for the future of electrification with several benefits. It will increase the customer value of trucks and offer more possibilities of electric drive when buying a truck, since nowadays the hybrid offers either a 4x2 or 6x2 configuration.

At the start of the project a number of specific questions to address during this work were identified:

- What are the pros and cons with an electrically driven front axle or an electrically driven rear bogie axle?
- What are the pros and cons using existing Scania axles and just mount an electrical motor on the axle gear compared to use an purpose built e-axle?
- What limitations will Scania have if electrifying Scania’s existing axles?
- What other customizations will Scania have to do to be able to run fully electric for short distances? E.g. lubrication and cooling of the gearbox when the combustion engine is shut down
Below the questions these questions are addressed.

This study shows, on the one hand, the pros with using an electrically driven front axle are to get a front wheel drive system with capacity to escape difficult situations, while an electrically driven rear axle will be much simpler system to develop due to spacing reasons. On the other hand, the rear driven axle will not have enough power to get out of complex situations and the front driven axle will be complex to design and only allow to have a chassis height high.

One advantage using existing Scania axles and just mount an electrical motor on the axle gear compared to use an purpose built e-axle is that they can be chosen for any chassis height while the built e-axes are straight so the only option is to have a high chassis height. It would be a fast solution to implement in the rear support axle but it is needed to take into account that the built e-axes are still in a concept/prototype phase and it is not sure when they will be available or their future cost. Moreover, it is going to be complex to mount the electric motors system into the Scania axle while the built axles are designed for it.

The limitations that appear when electrifying Scania’s existing axles are that the space available is limited, needing a redesign of components as well as new design of components to fit the new system into the axles.

Scania standard brakes will be needed for the e-axes. First of all due to security reasons. They are needed for emergency stops, not only because the e-braking will not be enough to stop the truck but for the case the system fails there is a need to have a mechanical system working. There is a possibility to reduce the size of the brakes but they will need to be redesigned and certified before it is possible to use them.

An extra light axle will be useful for the city environment, to be able to run in electric mode without needing much payload in the truck. However, it is not a good idea to have an extra light axle since the electric system will add weight to it and it will not be "extra light" anymore, so the payload will be reduced drastically and the axle might not be able to support all the new components in it.

With respect to emission-free driving, all the possibilities mentioned before contribute to reduce emissions. Any chosen concept will allow the truck to run electric for some time, cutting down emissions as well as noise during its performance.

From the investigation, it is concluded that a new suspension must be developed to be
able to fit the electric motors into the wheel, or a redesign of axles and braking system takes place to be able to fit the electric motors. Both options must be designed taking into account the connection with the electric motors and facilitating the modularity options (that it can be adapted to most configurations).

From the selection matrix, concepts 2 and 4 appeared as the best ones. However, to develop a tag liftable axle (concept 2) is the best option since it appears to not be as complex as the other concept when designing it.
Future work

This thesis sets the ground for the development of a new product towards the electrification of trucks. The next steps consist of doing a further development on the concepts selected as the best ones and create a valuable product to introduce into the market.

For the future work of the development of e-axles different things need to be taken into account. The most essential part is to find the best position for the electric motors, where it affects less components and connect them to the wheel. Once the concept is chosen to do this, all the pieces that will be affected by the introduction of the electric motors need to be analyzed. It is needed to do as little new design as possible using existing Scania parts to help the modularisation system and simplify the product creation. It is important to check that these electric motors are still the best ones for the product since it is a market evolving fast where more and more options are coming. Also, to decide about it, it is necessary to be in contact with the different departments involved on this, and stay updated.

It will be interesting to realize a detailed analysis of the chosen concepts, that can create two different follow up works that will expand the knowledge on this field and help to choose the best solution for the future of electrification.
Bibliography


