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Balancing and optimizing electric long-distance transportation within the E20 transport corridor.

A case study for Volvo

Bachelor's thesis in Science in Engineering

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CHALMERS UNIVERSITY OF TECHNOLOGY

Gothenburg, Sweden 2025

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ACKNOWLEDGEMENTS

This bachelor thesis was executed in the spring of 2025 as part of the bachelor program Economics and Production Engineering at Chalmers University of technology. This thesis was carried out as a case study for Volvo.

First, we would like to thank our supervisor at Chalmers, Violeta Roso, whose support, inspiration and guidance has been very valuable for this thesis work. We would also like to express our gratitude to our supervisor at Volvo, Henrik Engdahl, for your commitment, support and valuable guidance during the work process. Your expertise and constructive feedback have helped us develop, deepen our reasoning, and move our work forward.

Finally, we would like to thank all who participated in interviews and shared their experiences and insights. Your time and knowledge have been crucial to our work and your perspectives have contributed to valuable understanding.

ABSTRACT

Freight transport plays a crucial role in modern society, but it also accounts for approximately 50% of the transport sector's CO2 emissions. The freight transport sector needs to be more sustainable and an approach to reducing CO2 emissions in freight transport is the adoption of battery electric vehicles (BEVs). While battery electric trucks are currently used in urban transport, their limited range, operational constraints and complex scheduling pose challenges for long haul truck transports. Volvo has implemented a green corridor concept operated by 6 BEV trucks. If this concept can be scaled up, it has the potential to demonstrate that long distance transport by electric trucks is both economically and environmentally sustainable.

Given this context, this thesis aims to investigate and evaluate whether the green transport corridor along E20 can be scaled up considering existing infrastructure. In addition, the possibility of three shifts was examined. Furthermore, this thesis investigates how to increase volume in the corridor by horizontal collaboration and what requirements are needed to be a suitable partner in this concept. This thesis was carried out as a case study for Volvo. Three main questions were conducted which considered relevant topics with lacking previous comparable research. To conduct this study, a combination of semi structured interviews and observations was applied. In addition, primary data from Volvo has been used to analyze several important factors.

The conclusion of this thesis is that nine BEV trucks on each side of the corridor represent the maximum number that can operate without infrastructure expansion. Moreover, recommendations and proposals were given to Volvo regarding what is required for three shifts to be theoretically feasible. Furthermore, it is concluded that the most critical criteria for collaboration are met. To enable horizontal collaboration, partner companies need to be able to transport their goods in a trailer, with relatively large and consistent volumes.

Key words: electric truck, horizontal collaboration, green transport corridor, trailer swap, optimization.

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1. Introduction

Today organizations, companies and consumers need a constant flow of goods, therefore freight transport plays a crucial role (Gillström et al., 2024). Freight transport is responsible for close to 50% of the sector's CO_2 emission and is estimated to increase to 160% by 2050 (Schiffer et al., 2021). This estimate assumes that the freight demand will be tripled by 2050. Internet of things and shared economy are two trends that will increase the need for more freight transport (Xue et al., 2024). Freight transport faces several challenges including climate impact, rising fuel costs, and regulatory pressures. Furthermore, the number of truck drivers is decreasing and more of them prefer to sleep at home every night instead of along the road (IRU, 2024). This puts pressure on the industry to solve these challenges and to meet customer and regulatory demands for sustainable transport solutions.

The Paris Agreement and the EU's climate goals have put pressure on companies to reduce emissions of carbon dioxide, CO_2 (Europeiska parlamentet, 2023). To achieve this, the European Union, EU, has set a target of reducing net greenhouse gas emissions by at least 55% to 2030 compared to 1990 and reaching climate neutrality by 2050. Today, road transport accounts for 24,9 % of Europe's freight transport and 23 % of EU's CO_2 emissions (Eurostat, 2024; Naturvårdsverket, 2024).

To meet these goals, a transition to more sustainable freight transport is necessary. One alterative that has gained attention is the use of battery electric vehicles (BEVs). The advantages of electric trucks are better working environment, less noise level and improved air quality in cities, compared to fossil-driven trucks (Volvo trucks, n.d). As well as minimal CO_2 emissions when operating electric trucks, given that the electricity comes from a renewable energy source (Schiffer et al., 2021).

A study made by Suttakul et al. (2022) demonstrates that BEV trucks have lower energy consumption than ICE (Internal combustion engine) and PHEV truck (Plug in hybrid). This results from the fact that an electric motor has higher efficiency than a combustion engine, in other words converts more electric energy to mechanical energy. However, despite these benefits, the electrification of trucks faces a more limited range, more boundary conditions to consider, charging infrastructure struggling to keep pace and higher initial costs when investing in an electric vehicle (Kumar, 2024).

Every freight transport company aims to optimize schedules to enhance routes and operational resources (Gillström et al., 2024). A study made by Xuel et al., (2024) attempted to reduce fuel consumption and increase utilization by applying a swap trailer system. This study demonstrated that a well-structured schedule and a close collaboration could increase utilization rate, decrease fuel consumption by 34% and reduce the number of overtime working hours. A study by Abideen et al. (2023) shows that horizontal collaboration can increase utilization and performance of a logistics system by cooperating with other companies to solve the problem of inefficient logistics solutions.

In a step towards a more sustainable transport system, Volvo implemented the green corridor concept in December 2024 where they test electric truck transports.
This project has the potential to be a pioneer for Volvo and other companies in the transport and logistics sector. Scaling up the project can show that this concept of electric long-distance transport is not only possible, but also competitive and sustainable, both economically and environmentally. Volvo wants to take the next step, which is to increase the number of trucks in the project to be able to meet the demand.

1.1 Purpose

The electrification of road transport and efficient transport solutions has received growing attention. However, much of the existing research has focused on either urban last-mile distribution, conditions affecting the performance of the truck or transport corridors operated by conventional trucks. There is a lack of studies that investigate the use of BEV trucks in a long-distance transport corridor and how to use horizontal collaboration to achieve this. Further, information about expanding such pilot projects is lacking in terms of examples and their effects.

The purpose of this thesis is to analyze, optimize and scale up this green transport corridor and thereby address the research gap. The focus of this thesis lies on how electric trucks can be used in a transport corridor and how to increase the utilization rate. Further, how collaboration between Volvo and other companies can increase the utilization rate of the load capacity without extensive infrastructure expansion. This is done through a current state description, a scaled-up schedule based on current situation, an optimized schedule and a proposal on how to enable three shifts.

1.2 Problem description and research questions

The integration of electric trucks within long-distance transportation corridors comes with many challenges and opportunities. To make the corridor concept profitable and financially sustainable the pilot project needs to be scaled to increase the utilization of electric trucks. To enable effective electrification of transport, it is necessary to understand the capacity of existing infrastructure. The first research question focuses on how many BEV trucks can be deployed without major investments.

R1: How many BEV trucks can be used in a scaled version of the green transport corridor without extensive infrastructure expansion?

Based on knowledge gained from research question 1 the possibilities of operating three shifts are investigated to further increase the utilization rate of the electric trucks. Therefore, research question 2 examines the possibility of implementing a three-shift schedule.

R2: How to make it feasible to operate three shifts using electric trucks within the green corridor?

The utilization rate of the trucks can also be increased by horizontal collaboration between companies in the industry. The third research question examines the requirements to make it possible to scale up a pilot project and the enablers to perform a good cooperation. Further, what is required from a company to be able to start a good cooperation with the purpose of increasing the utilization rate of the trucks?

R3: What is required to scale up the green transport corridor through horizontal collaboration, and what requirements are there for a company to become a suitable partner?

1.4 Delimitations

Below is a description of the delimitations that have been made in this work to keep the analysis focused and relevant:

- The work is limited to only investigating the green transport corridor on E20 and already existing infrastructure will be used when scaling the project.
- This is an improvement project and thus aims to develop an existing pilot system.
- Consideration is given only to current technologies, with minor speculation on future innovations.
- This work only examines battery electric trucks and does not consider gas-powered trucks, hybrid trucks, or trucks powered by other renewable alternatives.
- In this study, exact cost estimates for proposed measures are not considered. Economic aspects are only discussed at a general level.

2. Method

This section describes the work process for how the study was conducted to fulfil the described purpose. The main processes of the work are illustrated in the figure below.

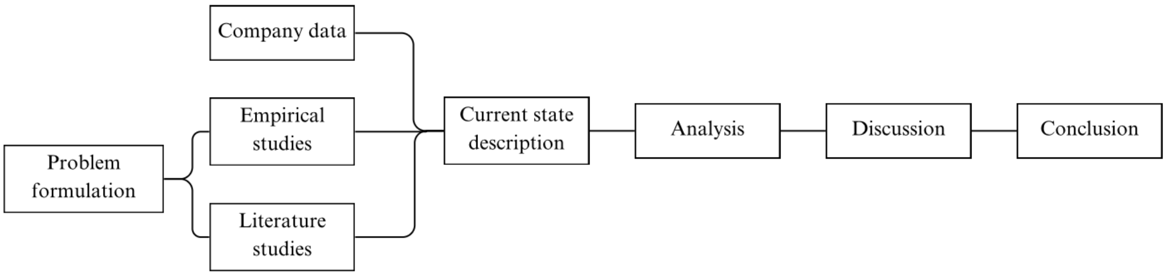

Figure 1: Illustration of the working process.

Initially, a basic understanding of the problem was created to identify a problem definition and plan for how the thesis should be built. Then a literature review and subsequently an empirical study was conducted, where interviews and observations were used to obtain data. Additionally, data collected by Volvo covered both the overall performance of the trucks, and particularly their charging capacity. Based on empirical studies a description of the current situation was made. Finally, the analysis and discussion were performed based on empirical studies, literature studies and the data collected by Volvo to provide clear answers to the research questions. To finish the thesis, a conclusion was formulated to conclude the analysis.

Both primary and secondary data were used to write this thesis. Data collected by the researchers themselves using established methods are primary data (Olsson & Sörensen, 2011). The method was determined by the type of data collected, whether it was quantitative or qualitative. Secondary data is already collected data including statistics, general information and published scientific articles.

During this thesis the main method was qualitative, although it contains a combination of quantitative and qualitative methods. Bryman (2012) says that qualitative methods are to emphasize words instead of quantifying data as well as investigating the relationship between theory and research. Qualitative research was used through qualitative interviews and literature studies. On the other hand, quantitative research gives a logical relationship between theory and research (Bryman, 2012). Observations and data provided by the company were the main methods to perform quantitative research. According to Bryman (2012) the difference between them is often exaggerated, he says that they can be used simultaneously complementing each other to give a better understanding. To connect these two methods triangulation was used, where information from the interviews was cross-checked with information from the data of the truck's performance.

2.1 Literature studies

Secondary data was collected through the literature study which started early in the process and continued throughout the first part overlapping the beginning of the empirical studies. This was made to gather information by reading previously published studies and relevant books to do a well-informed work. According to Bryman (2012) previously published studies in the field is important to read to understand the current state of research and to clarify this thesis contribution and credibility. Moreover, sources were used to create a solid introduction, background, theory and method.

The search engines used to find scientific articles and reports include Google Schoolar, SienceDirect, Scopus search engine and its AI searching tool. Examples of keywords that were used are internal logistics, collaborative logistics, green transport corridor, logistics network design, electric road logistics systems and horizontal collaboration. Additionally, course literature from previous courses or from Chalmers Library was used. Further, websites such as Volvo and Eurostat were used to obtain important statistics. The sources were reviewed critically to understand their importance and relevance for this thesis. To ensure that the sources got reviewed correctly the CRAAPP-model (Currency, relevance, authority, accuracy, purpose, publication) was used (Chalmers Library, n.d).

2.2 Empirical studies

Through empirical studies, primary data was collected in different ways, mainly through interviews and observations. Below are the different methods that were used to collect the data.

2.2.1 Observations

Observations of the transport system were carried out through journeys along E20 between Gothenburg and Lindesberg. Two times from a truck that operates in this system and ones from a journey with a car along the green corridor. The intention with the trips was to collect the following data:

- What types of trucks and how many are driving on this route now.
- Which companies operate along the E20 and run transport on this route.
- How does the use of the charging station look like, whether queues form and how synchronized the handover and charging must be.
- Variances in the runs and examine how well the schedule is held.

Since the concept is relatively new and unexplored, observations were a good method to collect data (Queirós et al., 2017). To understand the system in more detail quantitative data was provided by collections made by Volvo. The disadvantages of observations are the time-consuming process and solid preparation required to perform good observations (Queirós et al., 2017). The advantage is that data can be collected while the system runs, without disturbing it, making it a flexible method.

The observations were conducted within certain parts of the process to better understand the operations with greatest impact. This type of observations is often called field studies since they give an in-depth view of an area (Queirós et al., 2017). However, it might be difficult to document such large amounts of data when an in-depth perspective is needed, therefore a mix between general observations and field studies was used.

2.2.2 Interviews

During the studies, interviews were used as an additional method to collect primary data. The respondents were chosen from proposals by supervisors at the company. All interviews were semi-structured and questions for the interviews were written beforehand and shared with supervisor at the company and at Chalmers to be evaluated and improved. Semi-structured interviews are when a list of predefined questions is used, but it opens for follow-up questions and further discussion (Queirós et al., 2017). The questions do vary between different interviews.

Initially, interviews were performed with two of the drivers from Actor A (simultaneously with the ride in the truck), a logistic coordinator at Actor A and a logistics planner at Volvo. All interviews were conducted face-to-face and lasted about one hour each. The intention of these interviews was to:

- Get an understanding of the current situation.
- Understand which factors are most favorable to focus on when improving the system.
- See if the charging station works as it is supposed to and if the range of the truck matches expectations.
- How the drivers feel that the system works, whether they have discovered shortcomings, as well as pros and cons.

Later in the process a digital interview was conducted with two coordinators at Actor B. The intention with this interview was to identify which companies receive cargo through the Port of Gothenburg and deliver cargo along the E20 that could fit within Volvo's transportation. Additionally, interviews with the CEO of Actor C were held with the same intention, to find cargo that is transported along the same route today with conventional trucks and possible to implement in the concept with electric trucks.

All interviews except with Actor B were recorded, with permission from the respondents, to be able to verify the information afterwards. According to Bryman (2012) recording the interviews are favorable since it enables accurate capture of the information. Though, it is important to keep confidential information secret to ensure the security of the participants. Afterwards, all interviews were summarized to have easier access to the information since they were not transcripted.

Respondent	**Description of job position:**	**Date:**
Respondent 1	Respondent 1 works as a logistics planner at Volvo	26-02-2025
Respondent 2	Respondent 2 works as a logistics coordinator at Actor A	06-03-2025
Respondent 3 & Respondent 4	Respondent 3 & Respondent 4 works as truck drivers at Actor A	19-03-2025
Respondent 5 & 6	Respondent 5 & 6 works as coordinators at Actor B	24-03-2025
Respondent 7	Respondent 7 works as CEO at Actor C	22-04-2025

Table 1: Description of the respondents who has been interviewed.

2.2.3 Data provided by the company

Company internal data was used in some areas of the report to be able to perform the analysis needed. When using private information, it is important to use it the right way and ensure that consent is informed by the company in this case (Bryman, 2012). Some documents were given to us by our supervisors at the company and other data by the persons interviewed during the interview. For example, quantitative data about the trucks' performance and efficiency regarding charging, battery usage and weather conditions was collected by the company. This data was given to us by the logistics planner at Volvo during the interview. This data helped us perform quantitative analyses of the system.

2.3 Ethical aspects

Some documents used to gather information for this thesis were public while others were internal for the company. Consideration was taken to avoid using documents or information that are restricted or confidential without permission. Additionally, to respect all participants integrity no names nor company names are used in this essay. A discussion with the supervisors at the company before publishing the report was held to avoid this. Sources used were critically reviewed using the CRAAPP-model (Chalmers Library, n.d).

Scopus AI tool has been used in search of sources, primarily to find relevant scientific articles. Since the articles were provided by AI consideration was taken to the possibility that some information might be missing or shown from a questionable perspective. To make sure that the information used in this thesis is correct all information was double-checked and made sure to be valid and accurate in this context. Furthermore, AI was used as a supporting tool to help with ideas of interview questions, find synonyms/translations for certain words and review grammar. However, all written content in this thesis was produced entirely by us (the writers).

3. Frame of reference

The following chapter presents the theoretical and conceptual foundation for the study. It outlines key concepts, theories and previous research to understand the scope of the study and the approach taken in the analysis and discussion.

3.1 External and internal factors affecting range of an electric truck

Several factors affect the range of a BEV truck (Suttakul et al., 2022). Ambient temperature is a factor that affects range the most where the performance of the battery is affected. The most effective temperature for the battery is 22–25 °C (Zhou & Luo, 2021). Weather and season are two factors that affect battery range (Singh & Kumar, 2024). The longest range is available in spring or summer when it is sunny. When it is cold, the range is reduced due to unfavorable ambience temperature. Winter conditions reduce the range as the weather affects battery performance, increasing friction from snow, and more energy is required to heat the cabin. The worst weather conditions from a range perspective are when it is raining, since the friction between the tires and the road increases (Singh & Kumar, 2024).

According to Suttakul et al. (2022) another factor that affects the range is the road topography the truck will drive in. For example, whether the truck is going to be driven in a city or on a motorway will affect energy consumption since there are different traffic conditions. Additionally, a road with many slopes requires less energy and increases energy recovery. Two other factors with a major impact on range are the driving style and the use of vehicle amenities. For example, the use of air conditioning or defrost requires a lot of energy. On the one hand, a driver who drives gently with smooth pedal movements and constant speed reduces energy consumption, resulting in longer range. On the other hand, a driver who drives aggressively with strong accelerations will have higher energy consumption (Suttakul et al., 2022).

Real-time planning requires several factors such as traffic, infrastructure and the truck's fuel. The road traffic system is a system of high uncertainty, unpredictable and time-varying (Zhou & Luo, 2021). The vehicle's wind resistance and weight are two factors that affect energy consumption. A vehicle that is heavy and has poor aerodynamic design will require more energy to drive forward.

3.2 Barriers to the adoption of electric trucks

The initial investment cost of a BEV truck is currently higher than a conventional truck (Gillström, 2024). However, electric trucks can be more cost effective to operate, assuming the BEV trucks are utilized at a higher rate (Gao et al., 2017). However, several uncertainties persist in this matter. Despite the current cost advantages of electricity to run BEV trucks, there remains a risk of varying electricity prices (Gillström, 2024). The electricity price can vary from day to day and between different locations in Sweden, which makes it hard for logistics companies to predict the cost.

Logistics companies need to perform their deliveries with high performance, such as good responsiveness and reliability to maintain their customer base (Gillström, 2024). Many logistics companies fear that the delivery performance will be affected negatively by using BEV trucks. Because the usage of BEV trucks needs a more advanced and complicated schedule due to the new restrictive factors such as shorter range, longer charging times and required charging infrastructure. Due to the limited range of BEV trucks, it is hard to avoid time-consuming recharging stops during daily missions (Schiffer et al., 2021).

An efficient logistic system schedules every assignment in detail to be able to optimize routes and resources (Gillström et al., 2024). Planning becomes even more important when using an electric truck as consideration needs to be given to the truck's range to ensure that it reaches its destination or a charging station. Reduced payload, both in volume and weight, is common for a BEV due to high battery weight (Gillström et al., 2024). As a result, the company may need to have larger or additional vehicles than before to compensate for the volume and weight loss.

3.3 Charging of an electric truck

One important factor to consider is the charging infrastructure as BEV trucks often need chargers at the cargo terminal, truck stops and along the routes, though it depends on the length of the route (Gillström, 2024). There is a risk of loss of load capacity and uncertainty of which strategy should be used for charging BEV trucks (Gillström et al., 2024). To be able to operate a BEV truck as much as possible, it is essential to identify charging opportunities that don't interfere with the daily operations. For instance, during the drivers break or during loading and unloading the truck (Engdahl, 2023).

To optimize the use of a BEV truck it is important to decide the location for charging (Gillström et al., 2024). Either at a depot, along the road or at the destination while the product is being unloaded. The company also needs to decide whether to charge at a public or private station. The downside of using a public charging station is that there might be less affordable prices of electricity and a risk of getting stuck in queues to the charger. The advantage with a public charger is that the logistics company doesn't have to invest in a charging station.

A CCS (Combined Charging System) charger is commonly used when charging electric trucks due to its powerful and fast charging capabilities, offering a range between 50 and 400 KW (Volvo Trucks, 2024). When deciding which charging strategy, it is important to reflect on the effect the charge has (Gillström et al., 2024). A charger with low effects has a charging power of approximately 100 kW, while a highly effective charger’s effect ranges from 100 kW up to around 1 MW. When charging an electric vehicle, it's common to use a slower charger but during assignment, a high charger is used to reduce standstill time and try to reduce idle time. Idle time is the time when a vehicle is stationary without generating value, which is why logistics companies strive to reduce idle time to the minimum possible (Jonsson & Mattsson, 2016). All charging time generates no value for the logistics company and is therefore considered idle time (Gillström et al., 2024).

There is limited availability of charging stations which forces the trucking company to charge their BEV trucks overnight at their own depots (Volvo Trucks, 2024). According to ACEA (European Automobile Manufacturers' Association), approximately 7 million charging points will be needed across the EU to meet the climate and emissions reductions target (ACEA, 2022). Today there are approximately 1,000,000 public chargers in Europe (Mcloughlin, 2025). One identified issue is that the utilization rate of public charging stations remains stagnant throughout 2024, which has frustrated charging operators due to low returns on their investment. This is largely caused by the significant price disparity between private and public charging stations. To utilize a BEV truck's full capacity the need for infrastructure investment is needed (Gillström et al., 2024). A challenge around public charging stations, where it is argued who should bear the cost and that the stations should be used enough to be profitable.

3.4 Similar solution of a transport corridor

By changing from a traditional transportation system to a swap-trailer system, empty transports are reduced which increases the utilization rate of the truck (Xue et al., 2024). On the one hand, it reduces the total distance that each truck must drive which leads to reduced fuel consumption and results in saving about 34% in operation costs. The swap-trailer concept additionally reduced working hours and average overtime per driver with 29% and 56% compared to traditional modes. This is a result of the drivers coming home after their shift and that they do not have to sleep abroad, which also leads to happier drivers. To ensure that the right trailer arrives at the right destination, several digital solutions can be used. For example, real-time positioning, sway warnings and barcode reading to ensure who owns the trailer (Xue et al., 2024).

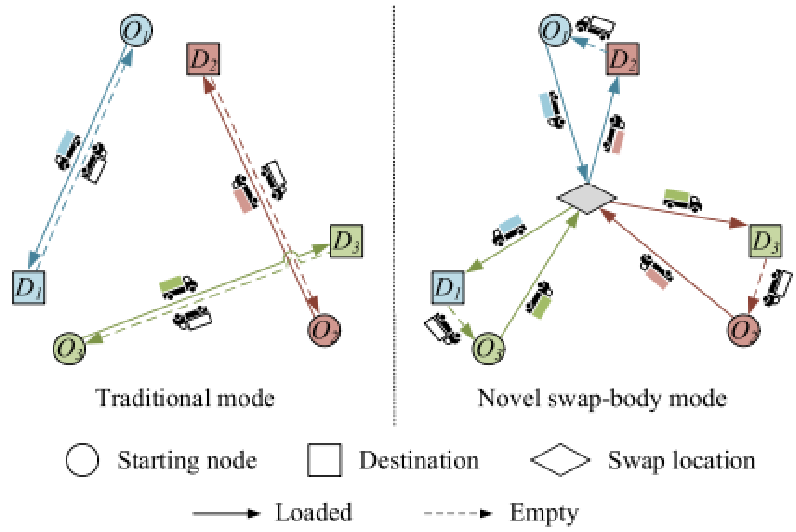

Figure 2: Shows the difference between a traditional transport system and a Swap-trailer system (Xue et al, 2024) © 2024 IEEE

The study identifies two major limitations that such a system can have (Xue et al., 2024). The first is that there should not be too many swapping points, as it will be difficult to coordinate all the trucks and keep track of which truck should go were. The second limitation is that each group of drivers should not be too large. Meaning, there should not be too many drivers who have the same swapping stations since it will be difficult to coordinate. Xue et al (2024) also concluded that swap-trailer mode is best suited for large-scale long-haul transport. Since the longer the distance the transport is, the more you save. Additionally, the analysis that was carried out showed that a swap-trailer system has excellent performance even when there are only a few swapping locations. The concept is robust and can handle disturbances well.

3.5 Horizontal collaboration

Abideen et al. (2023) describes that one of the best solutions of several logistics problems are to build a collaborative logistics system where some companies work towards a common goal. A horizontal collaboration between companies can mean different things, they can share resources such as warehouses and vehicles or plan their transport together. Horizontal cooperation can further improve the market position and financial strength of the parties involved, as they can share resources and information and learn from each other. By sharing both profits and losses, they build a stronger and more sustainable collaboration. The main challenges with this method are that different companies have different goals which might lead to conflicting prioritizations. The quality of information and unfair division between companies are also mentioned as factors that can have a negative impact on cooperation (Abideen et. al, 2023).

A study by Grzybowska et. al (2014) addresses the most important enablers for a sustainable collaboration of logistics companies. The five most relevant factors concluded from the study are information sharing, coordination, trust, willingness to collaborate and communication. The information to be shared can be, customer demands, vehicle resources, technical know-how or warehousing. The information to be shared can be customer demands, vehicle resources, technical know-how or warehousing. Coordination refers to the alignment of project objectives and resources to enable effective collaboration within the supply chain. It is supported by information sharing and involves actions that stimulate growth, redistribute resources, and integrate activities through monitoring and evaluation (Grzybowska et. al, 2014).

Trust is very important since it ensures that parties fulfil obligations, deliver quality, and make timely payments. As cooperation deepens and more participants are involved, trust becomes more complex, increasing both risk and uncertainty. Willingness to collaborate is important since unwilling partners wastes both time and resources. Lastly, Communication is crucial to make sure everyone has the same information and works towards the same goals. It will increase the possibility of achieving the goals significantly (Grzybowska et. al, 2014).

3.6 Strategies and requirements to scale up a pilot project

Scale up or scalability is defined as the ability for a system to meet an increased volume by expanding the system and subsequently maintaining its performance and its function in the scale-up stage (Bonnefoy, 2008). Pilot projects are projects that focus on finding and testing new solutions to a problem (Cooley & Kohl, 2005). The solution must be either technical, organizational or a process for it to be a pilot project that can be scaled up with the following technologies. Cooley & Kohl (2005) further argue that in the first stage pilot projects focus on efficiency, to be as efficient as possible based on the conditions. When scaling these at a later stage, the focus shifts to expansion. During the expansion phase, there are three different methods that can be used, expansion, replication or collaboration.

Expansion means increasing the operational area of the project, by for example finding new customer groups or more product variants, called growth strategy (Cooley & Kohl, 2005). Another example of expansion is called spinning off, where parts of the first organization develop their own teams that work individually. The second method, called replication, involves expanding the use of specific processes or techniques to get outside parties to implement the system.

Finally, there is collaboration, which is a combination of the two previous methods (Cooley & Kohl, 2005). This means that the expansion is driven by partnerships between companies, formal as well as informal. These are then used to expand the pilot project further with help from partners to reach new markets and customer groups. Collaboration is best used when companies have complementary skills or resources to best help each other move forward (Cooley & Kohl, 2005). Through horizontal collaboration similar companies with the same goals collaborate and achieve economies of scale, through for example shared transports (Abideen et al., 2023).

For a system to be possible to scale up, it must, according to Simmons et al. (2002) fulfil as many of the following aspects as possible:

1. Credible, it should be based on data accepted and respected by institutions and larger companies. In addition, there must be previous research on it that proves its credibility.
2. Observable, it should be possible to observe and measure the results in practice.
3. Relevant, it should address relevant and existing problems.
4. Relative advantage, there should be some advantage over existing systems, something that makes this system stand out and change something.
5. Adoptable, it should be easy to transfer and adapt to other conditions, such as increased volumes and other geographical locations.

6. Compatible, it must be compatible with existing users of the system and established norms and values
7. Able to be tested or tried, that the system does not have to be implemented in its entirety to be tested and evaluated.

4. Empirical findings and Analysis

The following chapter presents the empirical findings collected throughout this study and an analysis of the findings is performed. The data presented has been collected from interviews and observations and works as the foundation of the analysis.

4.1 Current state description

The current situation description is based on interviews with logistics planners and the drivers in the green corridor. In addition, data collected by Volvo is used to create a clear and accurate picture. Theoretical insights from the literature study are considered to get a deeper context and understanding of the system.

The green corridor is divided into two parts, the southern and northern part, with a charging station and swapping point in the middle in Mariestad. The southern part is served by three Volvo FH Electric trucks and runs either between the factory in Tuve, Gothenburg or the Port of Gothenburg and the swapping point in Mariestad, a distance of 190 km. The parts transported to the Port of Gothenburg are later delivered by ferry to the production site in Ghent, Belgium. The northern part, which is also operated by three Volvo FH Electric trucks, runs between Mariestad and the subcontractor of front and rear axles in Lindesberg, a distance of 155 km. The corridor goes south with axles and north with empty racks that go back to the subcontractor.

At present, the flow is unbalanced, with a predominance of goods going south from Lindesberg to Gothenburg with finished assembled components. Today a part of the transport is driven by conventional trucks as a complement to the corridor. Two trucks with drawbar trailer take about the same load as three trucks with a trailer. As the concept requires the cargo to be transported by trailers to be able to perform a swap in Mariestad. To transport the same volume using electric trucks, more trips will be needed compared to driving with conventional trucks.

The current schedule operates with two rounds every day, one round goes directly to the factory in Tuve, and the other round goes to the Port of Gothenburg. The southern part of the system starts with fully charged trucks in the depo and a trailer filled with empty racks from Ghent that is then transported to Mariestad. In Mariestad, the truck fully charges its battery and swap trailer during a 2-hour scheduled time slot. So, this truck gets a trailer filled with components that are to be delivered to the production site in Tuve. While the truck from the northern part takes responsibility for the trailer with empty racks to be transported back to Lindesberg. In Tuve, a sequence flow is used which means that the arriving load goes directly into production with minimal buffer storage. Because of this, the system becomes vulnerable since a small disruption in transport can cause a stop in production.

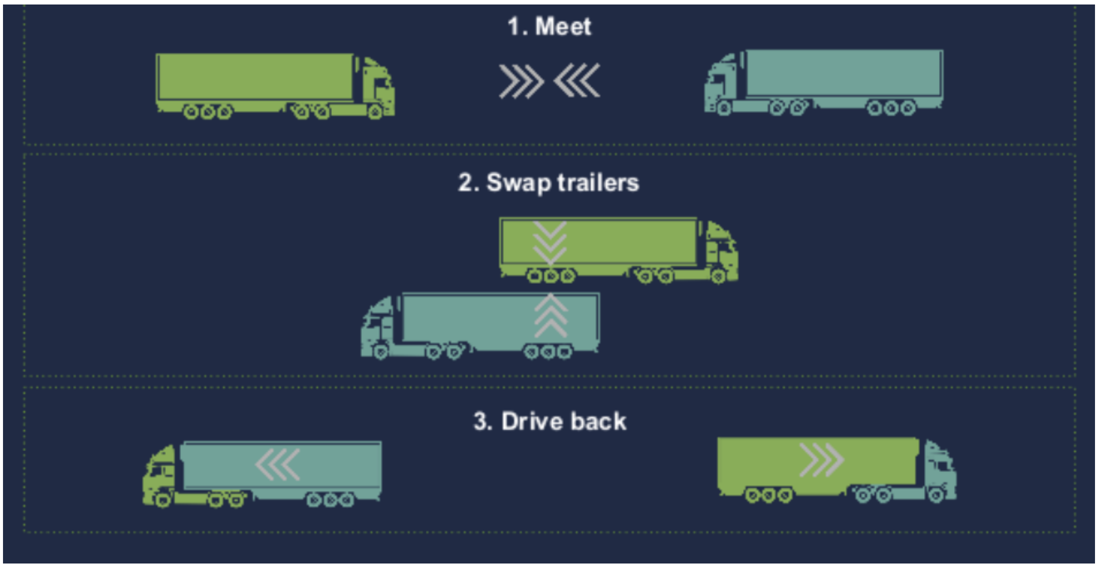

Figure 3: Shows how the change between trailers takes place in Mariestad. (Used with permission from Volvo).

When this trailer has been unloaded and reloaded with empty racks in Tuve, it goes on to Actor C's/Actor A's depot to charge. When the battery has been fully charged, the truck drives back to Mariestad with the empty racks and the truck fully charges and change trailers again. The new trailer is loaded with components that are destined for the Port of Gothenburg and onwards to Ghent.

For the northern part of the system between Mariestad and Lindesberg, a similar schedule is used. Where the truck starts at the depo fully loaded with components and they drive for a swap in Mariestad, these trucks also charge fully there. After the swap, they receive a trailer with empty racks that is driven back to the subcontractor in Lindesberg, and the truck fully charges here as well. This is repeated twice a day using the same process.

The times used for the different operations are 135 minutes driving time both ways for the north loop and 165 minutes for the south loop. The charging and swapping time in Mariestad are 120 minutes for both parts. The unloading in Tuve and charging in the depot for the south loop is scheduled to 150 minutes, where the unloading, according to interviews and data, takes about 45 minutes. To swap trailer in the harbor also takes about 45 minutes. The charging in Lindesberg is scheduled to take 120 minutes, with an additional 60 minutes scheduled for loading and unloading.

Operation	South	North
Depo - Mariestad	165	135
Charging in Mariestad	105	105
Trailer swap in Mariestad	15	15
Mariestad - Depo	165	135
Loading/unloading/trailer swap	45	60
Charging in depo	105	120
Buffer	0	0
Total time	**600**	**570**
Total work time for the driver (minutes)	**495**	**450**
Total work time for the driver (hours)	**8,25**	**7,5**
Total break time driver (minutes)	**150**	**165**

Table 2: Summary of the current operating times.

The schedule is set up so that the charging in Mariestad takes place alternately, with the first group of trucks charging fully. Then the second group arrives, a change of trailers takes place, and the other group charge their trucks before driving back. It is performed like this because the charging station has three charging stations with 6 posts. But when two trucks are charging simultaneously at the same station, the power decreases resulting in longer charging times.

Based on data from Volvo of the trucks in the green corridor, it is possible to see the truck's energy consumption per trip, the proportion of battery capacity used, the average temperature during transport, wind strength and direction and the presence of precipitation in the form of rain or snow. Energy consumption varies depending on several external and internal factors. Energy consumption is usually around 270 kWh from Lindesberg to Mariestad and about 217 kWh from Mariestad to Lindesberg. From Gothenburg to Mariestad the average consumption is 276 kWh and from Mariestad to Gothenburg the average consumption is 322 kWh.

4.2 Optimized schedule without improvements of the previous run times

Observations were made of the current setup and schedule, revealing the possibility of introducing more electric trucks into the current setup. So, based on the times used today and described in the current situation analysis, optimizations were made on the flow with the goal of getting as many electric trucks as possible to operate with the current holding times. The charging station at the swapping point was identified as a limiting factor and the result is based on maximizing utilization of the charging station in Mariestad. Based on interviews and observations, it has been limited to only one truck per charging station, meaning that there are only three charging posts available. This is because the power is significantly reduced, and the charging time is extended so much that it is not profitable to charge simultaneously. The figure below shows a suggestion of the charging schedule in Mariestad.

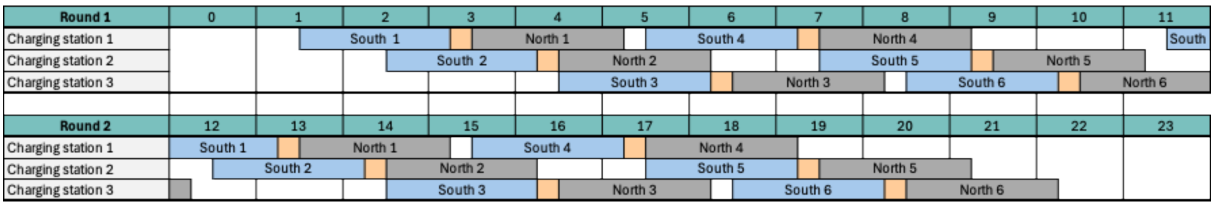

Figure 4: Shows a suggested schedule of the charging station in Mariestad, based on the current schedule and setup (The numbers show the times in whole hours).

The times are based on the fact that both the north and south side charges one hour and 45 minutes each in Mariestad. The south side charges first and then a swap of trailers is made, taking 10-15 minutes (indicated with orange in the figure). Then the truck from the north charges before taking the empty trailer back. This results in Mariestad's charging stations having an occupancy rate of 58% per station each day.

Usage of the charging station in Mariestad	South	North	Total
Charging time per truck each day in Mariestad (hours)	3,5	3,5	7
Number of trucks	6	6	12
Number of charging stations	3	3	3
Total charging time per station each day (hours)	7	7	14
Utilization rate of each charging station			**58%**

Table 3: Illustrates the utilization rate of the charging stations in Mariestad.

As a result of the improved planning of the chargers in Mariestad, the system can run with a maximum of six trucks twice a day, meaning that 12 trips are run per day. The system can in other words be scaled up with a total of 6 additional electric trucks, 3 more in each loop. A more detailed view of the entire schedule is illustrated below. The schedule is based on the operating times used today and adapted to fit the current times of departure from Lindesberg and unloading in Tuve for the first round. The second round goes to the Port of Gothenburg and onwards to Genth and is planned to departure when the truck is back and charged from the first round. In Lindesberg there is a Buffer of 30 minutes between each round. Although, the South loop does not have any buffer between the rounds.

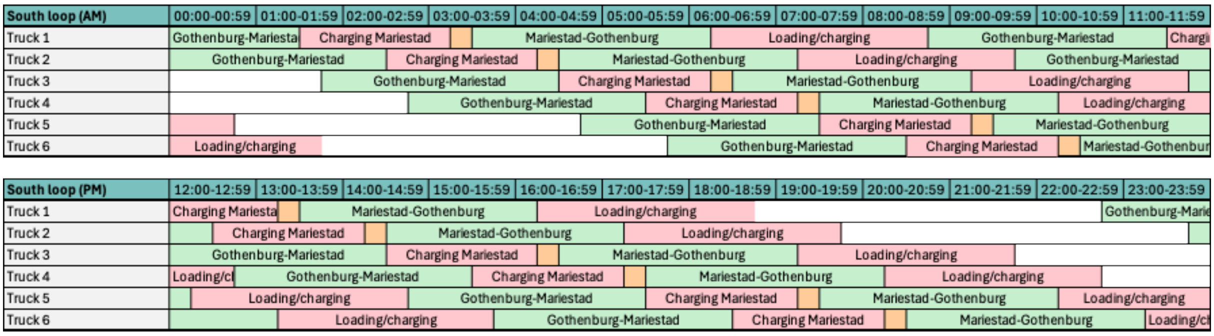

Figure 5: Complete version of the optimized schedule for the south loop.

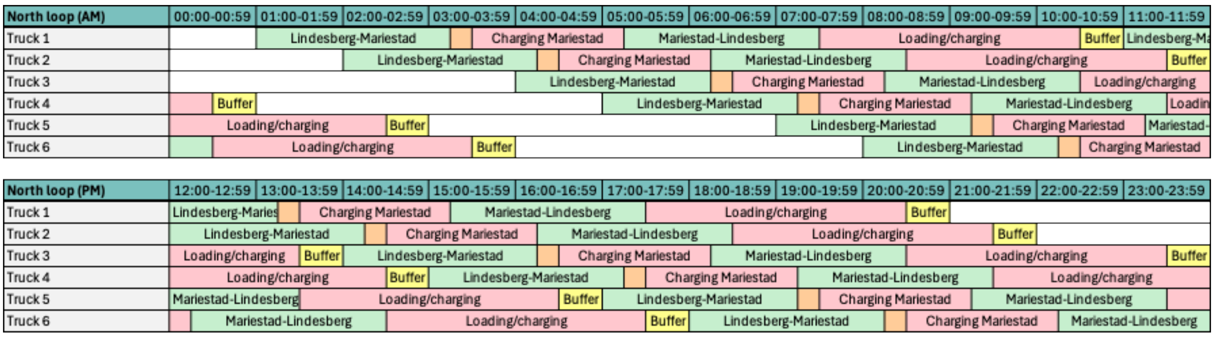

Figure 6: Complete version of the optimized schedule for the north loop.

This schedule results in 45% of the operating time for the southern loop are spent standing still. The corresponding proportion in the northern loop is 55%. The actions included in the standstill time are all activities where the truck does not move, such as charging, breaks, buffer, loading and unloading. The amount of charging time that is spent in correlation to the total operating time is 35% for the southern loop and 38% for the northern. The utilization rate of each truck in the southern loop is 65% and in the northern loop 58%. It is calculated as value-adding time divided by total operating time. Included in the value-adding time are all processes that contribute towards the cargo coming closer to the destination, which is necessary loading and unloading as well as driving time.

	South	North
Operating time of the truck (hours)	20,0	20,0
Standstill time (hours)	9,0	11,0
Standstill time of total operating time	**45%**	**55%**
Total charging time (hours)	7,0	7,5
Charging time of total operating time	**35%**	**38%**
Neccesary loading/unloading/swap (hours)	2,0	2,5
Driving time per day (hours)	11,0	9,0
Utilization rate	**65%**	**58%**

Table 4: Shows a breakdown of the calculation for standstill time and charging time in relation of total operation time, as well as the utilization rate.

4.3 Findings to make an optimized schedule and calculations of the improved charging times

Initially, an analysis was conducted to determine how much the charging time can be shortened to the maximum without leading to delays. In this analysis, the average/median and maximum consumption conducted from the company-data act as reference. By using a charging speed of 200 kW and applying different charging times, it was possible to determine how much kWh the truck had left when arriving at the depo after a trip. Thus, calculating the optimal charging time.

From interviews and observations, it was identified that it was possible to reduce the

Northern part's charging time in Mariestad since they could leave Mariestad 30 minutes earlier than planned. This is supported by data collected from Volvo, which shows that the median energy consumption amounted to 270 kWh and the maximum to 302 kWh. It corresponds to a usage of 71% and 80% of the battery's total energy capacity. This consumption was achieved even though the vehicle was driven with a heavy and full load from Lindesberg to Mariestad. From Mariestad to Lindesberg, the average consumption was 225 kWh which corresponds to 60% of the battery's energy. However, the maximum consumption was 257 kWh which is 68% of the battery.

When optimizing the times of charging for the north part, a criteria was that the truck needed to have 20% (+/- 5%) left of battery when arriving. Another criteria is that the charging level must reach close to 100% when leaving the depo. Based on the above discoveries, it was calculated that the trucks from the northern part need to charge an average of 60 minutes in Mariestad. This results in a battery level of 81% when leaving the Mariestad and 22% when back at the depo. But when maximum consumption is considered, 75 minutes of charging is required in Mariestad to have 18% of the battery left when arriving to the depo and leaving Mariestad with 86%. When considering maximum consumption, 90 minutes of charging is required in Lindesberg to reach around 98%, assuming that the battery level is around 86% when leaving Mariestad. Since there are many factors impacting energy consumption, and some are impossible to calculate the schedule will use the maximum consumption as foundation. When maximum consumption is not reached, the remaining charging time works as a buffer.

	Location	South		North	
Battery usage (max)	To Mariestad	303 kWh	80%	302 kWh	80%
	To Depo	373 kWh	99%	257 kWh	68%

Table 5: displays measured maximum consumption in kWh and battery consumption for each trip.

For the southern part it was identified that it is only possible to reduce the charging time in Mariestad by 15 minutes due to high energy consumption. The consumption from Gothenburg to Mariestad was in median 276 kWh and maximum 303 kWh, which corresponds to 73% and 80% of the battery. The usage of power from Mariestad to Gothenburg was 322 kWh average and 373 kWh maximum. At maximum consumption partial charging along the road was needed since the battery level would be to low otherwise.

To complete a full journey, it is important that the truck from the southern part charges close to 100% in Mariestad as it pulls a heavier load on the way home. To reach 97% in Mariestad at median consumption, it takes approximately 80 minutes. However, it takes up to 90 minutes to reach 100% battery level at maximum energy consumption. Therefore, a charging time of 90 minutes will be scheduled in Mariestad, which is a reduction from the current schedule with 15 minutes. To reach around 100% battery level in the depo a charging time of 90 minutes is needed. However, this assumes that the truck does not come back to the depo with less than 15%. According to interviews the drivers do not want to go below this battery level to feel safe arriving at the destination. Further, to make sure that the trucks do not come back to the depo with less than 15% a time slot of 15 minutes for support charging will be included in the buffer of 30 minutes. This is to be used only if necessary.

	Location	South	North
Battery level before charging (minimum)	In Mariestad	20%	20%
	In Depo	16%	18%
Charging times	In Mariestad	90 min	75 min
	In Depo	90 min	90 min
Battery level after charging (minimum)	Support	15 min	0 min
	In Mariestad	99%	86%
	In Depo	95%	98%

Table 6: Specification of the new charging times and battery level at departure and arrival.

4.4 Design of the optimized schedule

An optimized schedule was developed to show how the current schedule can be scaled up using the times from chapter 4.3. Further, how the utilization rate of the charging station in Mariestad can be maximized. Firstly, the focus is directed towards the charging station in Mariestad since it is, as mentioned earlier, an identified bottleneck. By starting to design the schedule of the charging station in Mariestad, shown in figure 7, it could be seen that the maximum amount of BEV trucks that could operate in the green corridor is 9 trucks, 2 rounds per day. This resulted in an addition of 6 trucks on each side from the original system. When developing the new optimized schedule, a time buffer of 30 minutes was adopted before each round at the charging station in Mariestad. The function of this time buffer is to ensure robustness against delays and charging post-related disturbances. The schedule also works based on the laws that apply to driving and breaks for truck drivers and that the respective truck start times are possible to implement.

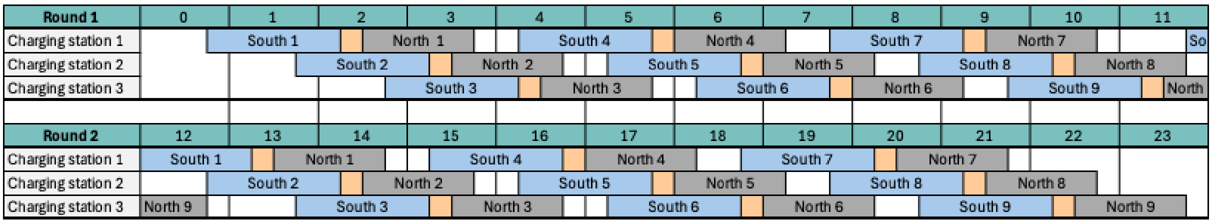

Figure 7: Shows optimized charging schedule in Mariestad per day (The numbers show the times in whole hours).

The new schedule is designed with the same driving times as earlier since it is seen as a constant value. Further, the charging times used are changed to the above mentioned, however the same times as before for loading and unloading the trailer are used, both in Gothenburg and Lindesberg. It emerged in the interviews that those times are accurate and hard to change, as well as the time for trailer swap in Mariestad. To make this schedule able to operate, the times for departure from Lindesberg and the times for arrival in Tuve must be changed to fit this schedule.

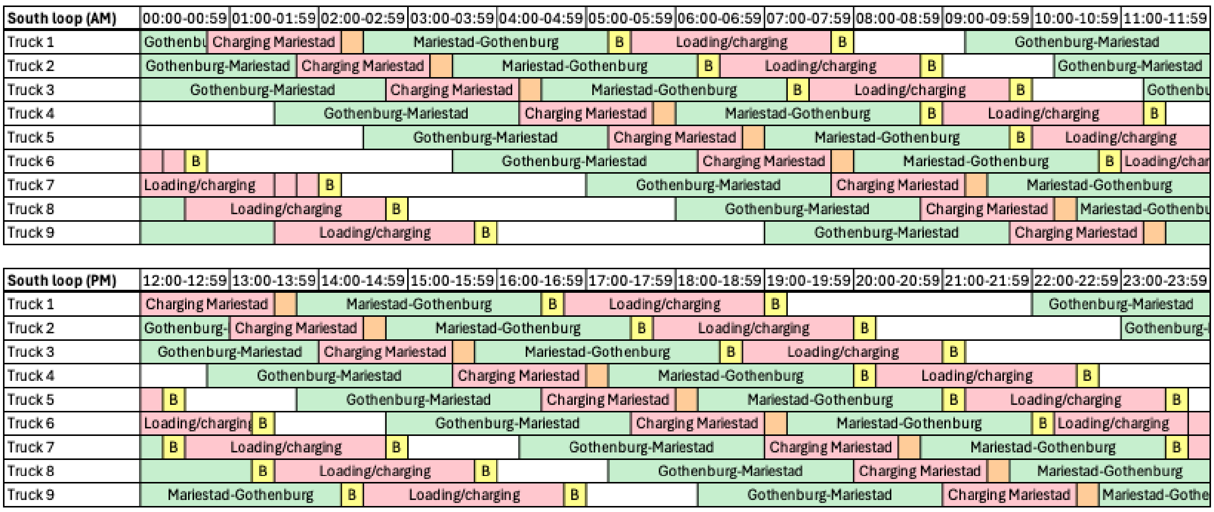

Table 7: Complete version of the optimized schedule with new charging times for the south loop.

North loop (AM)	00:00-00:59	01:00-01:59	02:00-02:59	03:00-03:59	04:00-04:59	05:00-05:59	06:00-06:59	07:00-07:59	08:00-08:59	09:00-09:59	10:00-10:59	11:00-11:59
Truck 1	Lindesberg-Mariestad		Charging Mariest		Mariestad-Lindesberg		Loading/charging		Buffer			Lindesber
Truck 2		Lindesberg-Mariestad		Charging Mariest		Mariestad-Lindesberg		Loading/charging		Buffer		
Truck 3			Lindesberg-Mariestad		Charging Mariest		Mariestad-Lindesberg		Loading/charging		Buffer	
Truck 4				Lindesberg-Mariestad			Charging Mariest	Mariestad-Lindesberg			Loading/charging	
Truck 5	Buffer				Lindesberg-Mariestad			Charging Mariest	Mariestad-Lindesberg		Loading/charging	
Truck 6		Buffer				Lindesberg-Mariestad			Charging Mariest	Mariestad-Lindesberg		Loadir
Truck 7	Loading/charging		Buffer					Lindesberg-Mariestad		Charging Mariest	Mariestad-Lindes	
Truck 8	Mariestad-Lindes	Loading/charging		Buffer					Lindesberg-Mariestad		Charging Mariest	M
Truck 9	Mariestad-Lindesberg		Loading/charging		Buffer					Lindesberg-Mariestad		Charg

North loop (PM)	12:00-12:59	13:00-13:59	14:00-14:59	15:00-15:59	16:00-16:59	17:00-17:59	18:00-18:59	19:00-19:59	20:00-20:59	21:00-21:59	22:00-22:59	23:00-23:59
Truck 1	Lindesberg-Mariesta	Charging Mariest		Mariestad-Lindesberg		Loading/charging		Buffer				
Truck 2	Lindesberg-Mariestad		Charging Mariest		Mariestad-Lindesberg		Loading/charging		Buffer			
Truck 3		Lindesberg-Mariestad		Charging Mariest		Mariestad-Lindesberg		Loading/charging		Buffer		
Truck 4	Buffer			Lindesberg-Mariestad		Charging Mariest	Mariestad-Lindesberg			Loading/charging		Buffer
Truck 5					Lindesberg-Mariestad		Charging Mariest	Mariestad-Lindesberg			Loading/charging	
Truck 6	Loading/charging		Buffer			Lindesberg-Mariestad	Charging Mariest		Mariestad-Lindesberg		Loading/charging	
Truck 7		Loading/charging		Buffer			Lindesberg-Mariestad		Charging Mariest		Mariestad-Lindesberg	
Truck 8	Mariestad-Lindesberg		Loading/charging		Buffer			Lindesberg-Mariestad		Charging Mariest		Mariestad-Lin
Truck 9	Charging	Mariestad-Lindesberg		Loading/charging		Buffer			Lindesberg-Mariestad		Charging Mariest	

Table 8: Complete version of the optimized schedule with new charging times for the north loop.

Based on the optimized schedule, the time that the trucks are stationary for charging has been reduced. For both the southern and northern part, the charging time has been reduced to 33% respectively 31% of the total working time per day. The utilization rate of the truck remains the same, 65%, for the south loop and has increased to 64% for the north loop. The utilization rate is calculated as the necessary time contributing towards the cargo getting closer to the destination divided by the total operating time. Included in the value-adding time are all processes that contribute towards the cargo coming closer to the destination, which is necessary loading and unloading as well as driving time. Further, the standstill time has been reduced to 45% and 50% respectively.

	South	North
Operating time of the truck (hours)	20,0	18,0
Standstill time (hours)	9,0	9,0
Standstill time of total operating time	**45%**	**50%**
Total charging time (hours)	6,5	5,5
Charging time of total operating time	**33%**	**31%**
Neccesary loading/unloading/swap (hours)	2,0	2,5
Time spent driving each day (hours)	11,0	9,0
Utilization rate	**65%**	**64%**

Table 9: Shows a breakdown of the calculation for standstill time and charging time in relation of total operation time, as well as the utilization rate per day.

Furthermore, the utilization rate for the charging stations in Mariestad has increased to an occupancy of approximately 69% for each day. The total amount of energy charged at Mariestad has also been calculated, which amounts to approximately 10,000 kWh per day.

Usage of the charging station in Mariestad	South	North	Total
Charging time per truck each day in Mariestad (hours)	3	2,5	5,5
Number of trucks	9	9	18
Number of charging stations	3	3	6
Total charging time per station each day (hours)	9	7,5	16,5
Utilization rate of each charging station			**69%**

Table 10: shows key values from calculations of occupancy rate of the chargers in Mariestad.

Total charging time in Mariestad over all stations	49,5	hours
Average energy charged per truck	275	kW
Total energy charged in Mariestad	**9900**	kW

Table 11: Shows how many kW are charged in Mariestad.

4.5 Evaluating feasibility of operating in three shifts

To investigate whether it was theoretically possible to carry out three shifts, a model was designed using excel. This model used a table where parameters such as charging time and unloading time at the depot could be adjusted. By changing these variables, it was analyzed whether three shifts were possible to achieve or not. Driving time cannot be shortened, therefore it was considered a fixed variable.

Firstly, the focus was to investigate what is required to enable three shifts in the northern part. Based on data, it could be concluded that it is possible to only charge for about 75 minutes based on median and maximum consumption and a charging speed of 200 kWh. Based on interviews and data, the loading and unloading of drive shafts usually takes about an hour in Lindesberg and 90 minutes of charging is required. Although, for three shifts to be possible this stop in Lindesberg may take a maximum of 120 minutes, including charging the truck. To reach a 120-minute stop, either the truck needs to be able to switch to a trailer that is already loaded in Lindesberg or charge during loading and unloading to save time and reduce idle time. As well as the stop in Mariestad lasting for only 90 minutes, including a trailer swap and charging, it is possible to achieve 3 shifts. This assumes that there is no queue at the charging station, the trucks keep their compressed schedule and that no charging problems occur in Mariestad or the depot.

Number	Operation	North
1	Depo - Mariestad	135
2	Charging in Mariestad	75
3	Trailer swap in Mariestad	15
4	Mariestad - Depo	135
5	Loading/unloading/trailer swap	30
6	Charging in depo/swap truck	90
7	Buffer	0
	Total time	**480**
	Total work time for the driver (hours)	**6,75**

Table 12: Showing the operating times needed to be able to operate in 3 shifts for the north loop.

The figure below shows that the operating times work to be able to work in three shifts for the north loop. The yellow marked box needs to be 24,00 or under showing that it is possible to do 3 rounds during a 24-hour period.

North

Specification	(1)	(2, 3)	(4)	(5, 6)	(7)	
Operating times (hours)	2,25	1,5	2,25	2	0	

Round 1	Departure Lindesberg	Arriving Mariestad	Depature Mariestad	Arriving Lindesberg	Ready for round 2	Including Buffer
Truck 1	0,00	2,25	3,75	6,00	8,00	8,00
Truck 1	8,00	10,25	11,75	14,00	16,00	16,00
Truck 1	16,00	18,25	19,75	22,00	24,00	24,00

Figure 8: Illustration of the schedule needed to operate in three shifts for the north loop.

For the southern loop, the driving time per shift is 330 minutes and is a variable that cannot be reduced. To be able to operate in three shifts, charging in Mariestad, changing trailers, charging in the depot and loading and unloading the cargo must all take a maximum of 150 minutes per shift. Based on the southern part's average energy consumption from Gothenburg to Mariestad, which is 276 kWh, at least 75 minutes of charging in Mariestad is required. Additionally, a trailer swap that takes about 15 minutes takes place resulting in a total of 90 minutes in Mariestad. This means that there is only 60 minutes left for charging and loading and unloading in Gothenburg. Resulting in the following operating times and schedule.

Number	Operation	South
1	Depo - Mariestad	165
2	Charging in Mariestad	75
3	Trailer swap in Mariestad	15
4	Mariestad - Depo	165
5	Loading/unloading/trailer swap	15
6	Charging in depo/swap truck	30
7	Buffer	15
	Total time	**480**
	Total work time for the driver (hours)	**7,25**

Table 13: Showing the operating times needed to be able to operate in 3 shifts for the south loop.

South

Specification	(1)	(2, 3)	(4)	(5, 6)	(7)	
Operating times (hours)	2,75	1,5	2,75	0,75	0,25	
Round 1	Departure Gothenburg	Arriving Mariestad	Depature Mariestad	Arriving Gothenburg	Ready for round 2	Including Buffer
Truck 1	0,00	2,75	4,25	7,00	7,75	8,00
Truck 1	8,00	10,75	12,25	15,00	15,75	16,00
Truck 1	16,00	18,75	20,25	23,00	23,75	24,00

Figure 9: Illustration of the schedule needed to operate in three shifts for the south loop.

If the southern part were to go to a transshipment point and leave the trailer instead of unloading at the factory or port, 45 minutes would be left for charging the truck for the next round. With a median consumption of 322 kWh from Mariestad to Gothenburg, the truck will need to charge for at least 90 minutes, which means that the truck will not have time to reach full battery level before the scheduled departure. Based on the identified limiting factors, it appears difficult to realize three shifts for one and the same truck in the southern part based on current conditions. However, it is possible to carry out three shifts for truck drivers on the south side if an operator with a larger fleet of vehicles can use more electric trucks, which eliminates waiting time for charging in the depot. For instance, an operator might have four trucks, but only three are always in operation and the trucks follow a rotating schedule.

4.6 Analysis of the theoretical requirements needed to scale up the system

Scaling up a system like this is done in several steps, first focusing on improving efficiency and then on expanding. To investigate the project from the efficiency part, the focus has been on the possibilities for upscaling the technical parts by investigating how much capacity the system has. Here, it will be discussed whether this system is theoretically possible to scale up, which is done by examining whether it meets the requirements described by Simmons et al. (2002).

The pilot does not quite meet the first criteria, credibility, because there is a very limited amount of research in the field that can strengthen this philosophy. This makes it difficult to base the idea on research and thus makes it more difficult to justify the decisions that are made because there are not so many proven studies. The second criteria that the pilot must be observable is partly fulfilled because it is a real project that exists on a small scale and there is the opportunity to make various measurements and the like to examine the results in practice. One disadvantage, however, is that it is a high investment cost to implement many of the changes that require more trucks to be purchased. This means that the changes cannot be tested until they have been thoroughly tested in theory and can thus be difficult to observe fully.

The third criteria, relevance, is fulfilled because electrification of the transport sector is a very relevant topic that strives to minimize climate impact and is a good solution to this problem. The fourth criteria, relative advantage, is partly fulfilled because there are not many similar solutions, which means that this system has great relative strength and the opportunity to be developed further. On the other hand, it is possible for other actors to create a similar system that becomes more efficient, and therefore constant development is required to be sustainable in the long term. It also has relative strength since using electric trucks for long-distance transport is a new area and therefore changes the way of using electric transportation.

The fifth criteria, adoptability, is partly fulfilled because the system is relatively easy to adapt to different volumes. However, it is difficult to adapt to other geographical placements because this is designed to specific distances and placements. Although it is possible to introduce the same idea in other places, then planning is required according to the conditions that exist in that case. The sixth criteria, compatibility, is also partially fulfilled because it is possible to drive the same goods on the same route and it does not affect production. But according to respondents from the interviews more planning and investments is required of haulers to adapt and be able to drive with electric trucks. The last criteria, that the system must be able to be tested is difficult to meet within this thesis since no simulations will be created. However, it is possible to test in simulated environments or in real life and evaluate to the extent it is economically justifiable.

As most of the criteria have been met or is possible to meet with minor changes, this project has the potential to be scaled up in a sustainable way. After taking the mentioned suggestions into consideration, the system will be more efficient and can now move on to expansion. Two suggestions that enable expansion are to start implementing three shifts and find new partners to scale up further. To find partners that fit into the corridor, several conditions need to be met, which 4.7 will analyze further.

4.7 Investigation of the theoretical possibility to have a well working cooperation

For the expansion phase of this work, the collaboration method is one of the methods used, because collaboration is an important part of achieving what is required. The requirements are close cooperation between Volvo as a transport buyer, the suppliers and the haulers. If it develops in the right direction, the chances increase that the pilot project will succeed and be possible to scale up. Developing a close collaboration between companies can be difficult as there are many criteria that should be considered.

One of the most important criteria that Grzybowska et. al (2014) addressed was that the sharing of information should work in a good way. Within this collaboration, information is shared to a limited extent because no company wants to share its competitive advantages, making it difficult to be completely transparent. This leads to that all actors do not receive the same information, which can lead to discussions. But according to the interviews conducted with various actors, the collaboration and information sharing works well. This is largely since the different actors trust each other and work towards the same goal, to create a sustainable transport solution. Combined with the fact that all actors have a great ambition and are willing to cooperate actively to solve challenges that arise are important criteria for a well-functioning collaboration. Actor C mentions that there is a risk that legal problems can arise because different companies drive each other's trailers and thus it becomes a question of who should be responsible for possible problems. But according to Actor C, it has worked very well so far, which is a further sign of strong will, commitment from the actors involved.

The other two criteria, coordination and communication, should also be met. The coordination lies mainly with Volvo as they make the schedule and collect data from the system. But it assumes that all partners agree to it and are allowed to participate and say what they think. Communication is the most important aspect as it lays the foundation for a functioning collaboration. Based on the observations and interviews that have been made, communication between the parties works well in terms of the design of the schedule and events that have needed to be solved along the way. However, all drivers need to receive the same information in terms of charging and other practical parts to work with the same conditions.

The conditions for being able to increase the collaboration further are good, which is a prerequisite for creating smooth flows in a scaled-up version of the green transport corridor. Thus, to be able to scale up this pilot project, more goods going north in the corridor along the E20 are required to cover the imbalance that exists in this direction. The criteria that exist for a load to be possible to drive in this flow, according to conclusions from the interview with actor B, is that it needs to be a trailer. Since it is not economically justifiable to drive palletized goods between distribution terminals because it will be insufficient. The company also needs to have consistent volumes on a relatively large scale to be able to collaborate in the green corridor.

From interviews, it has emerged that there are large volumes going north along E20 that are possible candidates to drive in this corridor. An actor drives over 500 trailers a week along this road and the volumes required to create a balance are about 50 trailers a week. It was confirmed during the observations that there are a lot of trailers transported along E20. There were approximately 40 trailers transported north on E20 during a one-hour period. Which indicates that there are a lot of trailers on the road. About 30% was driven by the mentioned actor which further strengthens the possibility of finding goods for the green corridor.

Another way to increase the volumes and the number of players in the E20 corridor that is highlighted during an interview is the use of duo trailers, where two trailers are connected to the truck. This means that a truck can carry twice as much load at the same time and other companies can connect to increase capacity. This can facilitate scaling of volumes and is approved for running on E20. A limitation of this idea is that it only applies to the Swedish market and not globally. Another possible disadvantage is that energy consumption will increase due to more friction and more weight to pull.

5. Discussion

The following chapter will present a discussion and comparison between the different suggestions. As well as a more in-depth discussion of the benefits and challenges that appear with the optimized schedule and operating in 3 shifts.

5.1 Comparison between the different suggestions

The different suggestions of a schedule results in the following improvements of the utilization rate of the truck and decreased standstill time as well as charging time. This was achieved despite difficulty in reducing time consuming charging stops according to Schiffer (2021). The charging time rate of total operating time is reduced from the original schedule to the optimized schedule for both the south and north loop. Charging times were reduced by 2 percentage points for the south and 7 for the north part. This is a result of findings that indicated that the charging times were too long for both loops, these findings were confirmed by interviews. So, the time for charging was reduced to be more accurate. Although, by reducing the scheduled times for charging an increased risk of delays will appear, therefore 15 minutes are added to the buffer to prevent possible delays.

From the original to the optimized schedule the standstill time remains the same for the south loop, a standstill rate of 45%. Due to longer operating times and an additional buffer to prevent delays this value remains the same. Although, for the north loop the standstill time was reduced by 5 percentage points.

When comparing 3 shifts and the optimized schedule for 2 shifts a decrease of standstill and charging times occurred for both loops. For the south loop a decrease of 14 and 11 percentage points respectively, resulting in a standstill rate of 31% and a charging rate of 22%. These values are a result of the solutions mentioned in 4.5, for example a swap of trucks and a transshipment point. For the northern part there was a decrease from 50% to 44% for the standstill time of total operating time. This was because of the possibility to charge at the same time as loading the trailer or swapping trailers in Lindesberg. Additionally, there was an increase in the charging time from 31% to 34%, since the charging times remained the same and the operating time was decreased.

The utilization rate of the truck has increased from 65% to 75% for the south loop and from 64% to 66% for the north loop, because of the introduction of 3 shifts. Since it is calculated as the value-adding time divided by total operating time. By introducing 3 shifts the same number of trailers that can be driven with 9 trucks operating in 2 shifts can be driven by 6 trucks operating in 3 shifts. Since 3 shifts can transport the same amount of goods with less trucks, the investment cost will be lower. As Gillström (2024) mentions the higher investment cost of electric trucks will be more noticeable when the number of trucks can be decreased. Furthermore, Gao et al. (2017) mentions that electric trucks can be more cost efficient to operate assuming they are utilized at a higher rate, which 3 shifts enables.

South loop	Original schedule	Optimized schedule	3 shift
Standstill time of total operating time	45%	45%	31%
Charging time of total operating time	35%	33%	22%
Utilization rate of the truck	65%	65%	75%
North loop			
Standstill time of total operating time	55%	50%	44%
Charging time of total operating time	38%	31%	34%
Utilization rate of the truck	58%	64%	66%

Table 14: Summary of the standstill time rate, charging time rate and the utilization rate.

The improvements in the above values are a result of shorter charging times. The times are decided based on interviews and data collected from the trucks. The charging times for 3 shifts are too short due to a lack of time since the driving times could not change. For that reason, the earlier solutions mentioned are needed which means that a swap of trucks for the south part is made that can take a maximum of 30 minutes. Additionally, the utilization rate of three shifts in the south loop is calculated assuming that all trucks are used as much as before. But since the charging time does not cover the need for charging it results in more trucks, or a faster charging time will be needed.

Charging times	(minutes)		
South loop	Original schedule	Optimized schedule	3 shift
Mariestad	105	90	75
Depo	105	90	30
Support		15	
North loop			
Mariestad	105	75	75
Depo	120	90	90

Table 15: Summary of the charging times in the three different schedules.

Since the working hours spent driving will decrease for every driver operating in 3 shifts. It could be extended by loading and unloading the trailer for the next round resulting in shorter standstill time for the truck. But it will mean that more trailers will be needed resulting in higher costs and lower utilization of them.

5.2 Schedule optimization in practice: opportunities and limitations

For the optimized schedule the charging time has been reduced in Mariestad for both the northern and southern parts, which entails an increased risk of delays or too short a range. An attempt has been made to reduce this risk through analysis of the trucks' energy consumption. Moreover, the measured maximum consumption has been considered to provide a buffer. This schedule is based upon charging the trucks to the greatest extent possible at the haulage companies own depots to reduce charging costs and uncertainty with a public charging station. Gillström et al., (2024) highlight this as two advantages of charging in the haulage company's own depot.

A risk with the current arrangement is whether other haulers start charging at the charging station in Mariestad or if electric cars find their way to the charging station. As previous research highlights, limited availability and queues at public charging stations pose a challenge for electric trucks (Gillström et al., 2024). This can result in waiting times and delays, hence a buffer is needed when charging to reduce the impact on the schedule. The northern part has a time buffer of 10-15 minutes and does not need to charge to 100% if the temperature and weather conditions are favorable. It is enough for them to charge the battery to between 85-90%. The southern part does not have the same opportunity to reduce its charging, as the journey requires almost 100% battery level from Mariestad to Gothenburg. What can be done is to charge 90% and support charge along the way if necessary.

An additional risk is that the chargers malfunction, which emerge from interviews and observations that it occurs. In case of a problem, the driver needs to contact the charging station owner and report a fault, which leads to a restart of the charging station, which can take up to 15-20 minutes. This increases "ideal time" and "standstill time", which is counted as non-value-creating activity that haulers therefore try to eliminate (Gillström et al., 2024). To reduce this risk, it is important that drivers report faults immediately when the charger is not working and quickly choose a working charger while the charger is being restarted. Similarly, the buffers between each charging pair can be utilized.

When calculating the schedule, the maximum consumption from the collected data has been considered to ensure that they are able to reach the destination on time. However, it should be noted that the scheme has not yet been tested in more demanding winter conditions since the winter of 2025 has been mild. The coldest day, according to the data collected from the E20 corridor, is around -5 °C. As snow increases friction and has an unfavorable ambient temperature, the truck's range will be reduced (Singh & Kumar, 2024). This implies some uncertainty about its actual robustness in such circumstances.

To reduce the risk of errors and ensure that the schedule is followed, it is recommended that Volvo clearly informs all players about the applicable procedures, especially highlighting the points described above. A potential source of error that has been identified is handling errors, such as several vehicles being charged at the same station or the charging cable being connected incorrectly. This has not yet been investigated in detail due to lack of time.

5.3 Discussion about three shift operation

From the results in 5.3 it appeared that for the Northern Loop to be able to run three shifts with its 6 electric trucks, the charging and loading time need to be reduced in

Lindesberg. Two suggestions that were highlighted in the results to reduce this time are if charging can take place when loading and unloading. Secondly, if a trailer is already loaded when the truck arrives at Lindesberg, and a swap of trailer is made to then charge afterwards. If the proposal for charging when loading is chosen it will enable three shifts for the trucks, which Gillström (2024) and Engdahl (2023) mention as way to optimize the charging. This will increase the utilization rate, but this proposal requires charging infrastructure expansions, which take time and require high investments.

The advantage of having a trailer already loaded is that it enables three shifts for the northern part without major infrastructure costs. This will result in a higher utilization rate of the electric trucks, which is needed since electric trucks are more expensive to purchase (Gillström, 2024). To make this proposal possible the driver cannot carry out loading and unloading of the truck, it must be carried out by, for instance, someone in the factory in Lindesberg.

As the results show, it is not possible to achieve three shifts with existing trucks in the southern loop. But for three shifts to work for the entire E20 corridor, a haulage company with a large fleet of vehicles is needed. Actor C highlighted this as a possible solution and an actor who could make this possible. The downside of this proposal is that it does not result in a three-shift operation for the trucks, which Volvo aims to achieve. Instead, it leads to a two-shift schedule for the trucks, while maintaining a three-shift schedule for the southern drivers. In addition, a safe dropping point needs to be established in Gothenburg where trailers can be dropped and picked up to save time from driving time and time from loading and unloading. This solution can save up to 1 hour for the south corridor per shift.

In addition, it was investigated to move the trailer swap point to another city with already expanded charging infrastructure. This is to see if it could be possible to work three shifts if both sides drove about the same distance instead of the current schedule where the southern part drives 30 km further. Skara was observed to be a city with a truck charging station located along the E20 with 4 poles and an output of 400 kW. When checking the stall, it was found that three shifts were possible for the southern loop, but not for the northern. But it would only result in the north loop having to drive 190 kilometers and the southern part 155 kilometers which would result in a useless switch of driving distance between the loops. For this reason, it was found that it was not a good idea from a three-shift perspective, but that the charging station could be a possible candidate for replacement if there were continued problems with the charging stations in Mariestad or if a lower charging cost could be negotiated there.

One way to enable continuous three-shift operation is to use four trucks, with three in service at a time, while trucks and drivers rotate according to a rolling schedule. This would possibly make three shifts theoretically possible. However, such a schedule would be more complicated and require one more truck for every 3 trucks to be operated for the southern part. This would result in a higher investment cost in the form of another electric truck. Furthermore, the purchase price of an electric truck is higher according to Gillström (2024) and it emerged from interviews that it could be almost twice as expensive. More detailed calculations of the total cost of ownership (TCO) and an assessment of revenue for the proposed alternative should be studied further. Due to lack of time, this has not have been analyzed more deeply in this study. It is recommended that future research examine the economic implications of this proposal in more detail.

If the above proposals were to be implemented three shifts would be possible. However, the schedule would be strictly compressed and hardly have any buffer for possible disruptions. If there were to be any delays or problems with the charging post, it would result in the schedule failing. Singh & Kumar (2024) also highlights external factors such as weather that reduces the range, which in turn will lead to the need for support charging and possible delays. Two factors that would potentially reduce these risks and increase the possibility of maintaining a robust three-shift schedule are increased range and higher charging power. These technical solutions are outside the boundaries of this study and are not discussed further, although it is worth noting their potential importance for future implementation of three-shifts.

A challenge with three shifts that was highlighted was that haulers may have leased their electric trucks and at a certain kilometer breakpoint, the trucks become much more expensive to drive due to a large increase in service agreements. This is something Volvo might need to help the haulers to better integrate them into the E20 corridor and be able to drive three shifts without too high costs. This is to make it profitable for all parties and enable three shifts.

6. Conclusion

The purpose of this thesis was to analyze, optimize and scale up this green transport corridor and thereby address the research gap. We have been focusing on how to increase the utilization rate with the introduction of electric trucks in the transport corridor. Furthermore, how cooperation between Volvo and other companies could increase the utilization rate without extensive infrastructure expansion.

Based on the purpose of the study the following conclusion has been drawn from this thesis. The maximum number of trucks that can operate in the green transport corridor using two shifts is 9 trucks in each loop. It is an increase of 6 electric trucks on each side from the current 3 trucks operating and no major infrastructure expansions are needed. This will result in a higher utilization of the chargers in Mariestad and more electric trucks operating in the corridor. To implement 3 shifts some actions are needed, for the south loop the charging in the depo must be removed by swapping to a fully charged truck for the next shift. There must be a trailer yard so the trailer could be swapped and thereby saving time by reducing the idle time for loading and unloading in the corridor. For the north loop there must be a possibility to charge the truck while loading and unloading the cargo or that the trailer is already loaded to reduce the standstill time. Introducing three shifts will increase the utilization rate of the trucks.

The pilot project meets the most crucial criteria to be possible to efficiently scale up, which is a requirement for a scale up process. Further, the horizontal collaboration has a foundation to be successful and it is important to work on the key factors for the collaboration to keep evolving in the right direction. The prerequisite for a company to be able to become a collaborator is that they need to have cargo transported through trailers in a steady and relatively large flow.

For future research it is possible to investigate possible sources of error and try to isolate them to determine which factors have the most impact on the system and are most crucial. Further, the possibility of relocating the swapping point to a place that is more centered could be researched further. This will enable operating in three shifts to a larger extent. Additionally, to research what possibilities the use of connected trailers (two trailers driven with one truck) would mean, how it would increase the utilization and the increase possibility of collaboration. Furthermore, it would be possible to look further into cost analyses of how different solutions would impact the costs and investments. Lastly, it would be suitable to investigate how the schedule and results will be affected by new models of trucks with faster charging times and longer range.

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Appendix 1 Interview questions

- What are the possibilities for charging in the depot?
- How long does it take to charge the truck, and how does it affect working hours and route planning?
- What changes have been needed to adapt to electric transportation?
- Are there any driving tasks that have become easier or more difficult with electric driving?
- Have there ever been problems with insufficient range during a working day? What was the consequence of this?
- Has the shift to BEV trucks led to more delays than before? What are the consequences?
- What are the main challenges of using electric trucks, and what advantages do you see compared to fossil fuel vehicles?
- How do charging times affect your hold times and delivery accuracy?
- What are the main challenges of using electric truck, and what advantages do you see compared to fossil fuel vehicles?
- Has the shift to electric trucks led to more delays than before? What are the consequences?
- Have there ever been problems with insufficient range during a working day? How did you address this and what the consequences of this?
- Are there any driving tasks that have become easier or more difficult with electric driving?
- What changes have been made to adapt to electric transportation?
- How long does I take to charge the truck, and how does this affect working hours and route planning?
- What are the possibilities for charging in depo?
- Is there any operator that carries out transports north along the E20 in larger volumes?

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