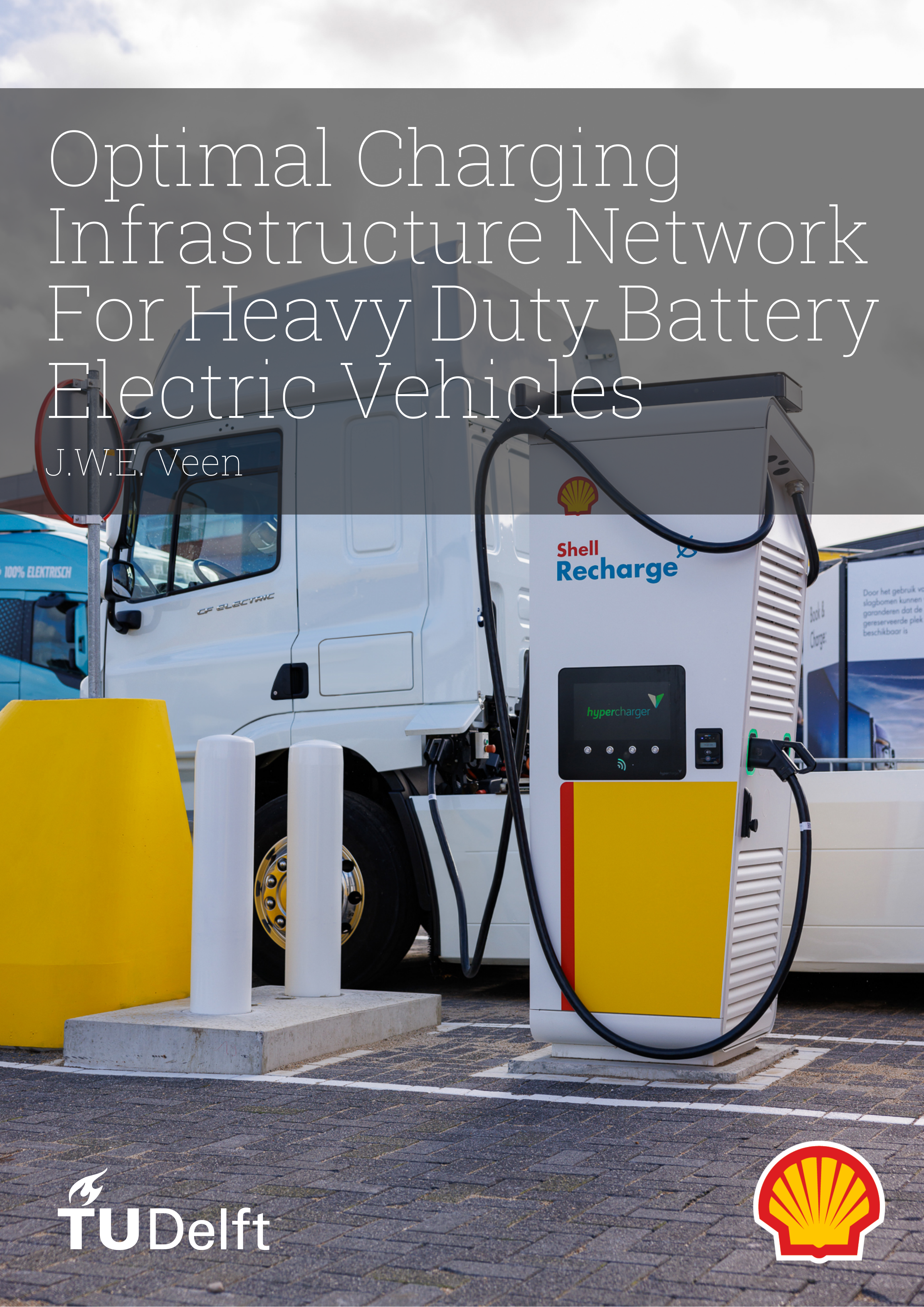
Optimal Charging Infrastructure Network For Heavy Duty Battery Electric Vehicles

J.W.E. Veen



TU Delft

Optimal Charging Infrastructure Network For Heavy Duty Battery Electric Vehicles

by

J.W.E. Veen

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Cover: Shell public charging station Eindhoven acht opening (Credits: Shell)

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TU Delft

Preface

This thesis marks the end of my time at TU Delft, a journey filled with both challenges and triumphs. As I reach this milestone, I have come to deeply appreciate the experiences and opportunities TU Delft has brought into my life.

First and foremost, I am grateful to my professors, Bilge Atasoy and Stefano Fazi, for their support throughout this thesis, with their feedback and willingness to answer all of my questions.

I would also like to extend a large thank you to my supervisors at Shell, Joost Commandeur and Anitha Immaneni, for their guidance during this project. My gratitude also goes to everyone at Shell who made my internship such a rewarding experience. Additionally, I appreciate the fleet owners who participated in the survey and interviews, contributing significantly to this research.

My family has been a constant source of support during my studies and thesis work, and I am deeply thankful for their encouragement. A special thanks to my girlfriend for not only being a great listener and providing support during tough times, but also for challenging me to excel.

As this thesis wraps up my life as a student, I want to thank all my friends who made this journey unforgettable with the fun and unforgettable times. I know most of you won't read this thesis, but if you do, and you make it past this preface, here's a special thanks to you!

J.W.E. Veen
Delft, January 2025

Summary

This thesis aims to design an optimal charging infrastructure network for heavy-duty battery electric vehicles in the Netherlands. This involves determining the distribution of demand between private and public charging and identifying the best locations for public charging facilities based on scenarios evolving over the years to come.

The Current State of HD BEVs and charging infrastructure shows limited market penetration of HD BEVs, with around 1,000 registered in the Netherlands but is expected to increase over the coming years. Existing charging infrastructure includes approximately 125 public locations with around 350 charging points. Private charging is the most cost-effective but faces challenges like high installation costs and limited space.

Analysing the logistics sector reveals that trucks typically cover around 70,000 km annually, with newer trucks averaging 100,000 km. The sector includes city logistics, regional logistics, and long-haul logistics, each with distinct driving patterns and refuelling needs. Most trucks currently refuel at public stations, with some using private refuelling at their facilities.

After interviewing and having a survey send out to fleet owners tot test their preferences. Fleet owners prefer private charging due to lower operational costs and greater control. High initial investment costs, limited space, and grid capacity issues are significant barriers for private charging. Public charging offers flexibility but comes with higher per-kWh costs and potential reliability and availability issues.

A demand distribution estimation model has been developed and allocates charging demand between private and public facilities based on cost efficiency, operational constraints, and fleet owners' preferences. As battery capacity increases, the demand shifts from public to private charging. With a 350 kWh battery, 63% of the demand is met by private charging, 4% by semi-public, and 33% by public charging. This shifts to 82% private, 5% semi-public, and 14% public with a 650 kWh battery.

The developed location model maximizes the captured flow of electric trucks while minimizing installation costs. Constraints include budget limitations, and the range of HD BEVs. Scenarios were developed to test the model under different future conditions, ensuring a robust and cost-effective charging infrastructure which can be found in Figure 7.6.

This research provides a comprehensive framework for developing an optimal charging infrastructure network for HD BEVs in the Netherlands. By understanding the distribution of demand between private and public charging and incorporating relevant constraints into a mathematical model, the study offers valuable insights for energy providers. The findings highlight the importance of strategic planning in charging infrastructure to support the transition to electric transport and reduce greenhouse gas emissions.

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Nomenclature

Abbreviation	Definition
CBS	Centraal Bureau voor de Statistiek (Statistics Netherlands)
DC	Distribution Center
EU	European Union
FCLM	Flow-Capturing Location Model
FRLM	Flow Refuelling Location Model
HD BEV	Heavy Duty Battery Electric Vehicle
HDT	Heavy Duty Truck
IBIS	Integraal Bedrijventerreinen Informatie Systeem (Integrated Business Parks Information System)
km	kilometre
kWh	kiloWatt-hour
MW	MegaWatt
NAL	Nationale Agenda Laadinfrastructuur (National Charging Infrastructure Agenda)
NC-FRLM	Node Capacitated Flow Refuelling Location Model
OD	Origin-Destination
TEN-T	Trans-European Transport Network

1 Introduction

This Chapter will give an introduction to the problem, provide a brief technical and economic perspective on Heavy Duty Battery Electric Vehicles (HD BEV's), and the challenges in designing a charging facility network for HD BEV's, thereafter the research problem and objective will be described an the outline of the this thesis will be given.

The effects of climate change that scientists predicted can already be seen, such as melting glaciers, rising sea level, the loss of sea ice and intense heat waves [1]. Scientists predict that global temperatures will continue to rise due to increases from human emitted green house gases [1]. To address and reduce the impacts of climate change, governments are implementing new regulations. The European Union introduced the European Green Deal which aims to become the first climate neutral continent in the world by 2050 [2]. Emissions from road transport account for 6% of total European green house gas emissions [2]. From all green house gas emissions by road transport around a quarter is emitted by heavy duty trucking (HDT) [3], HDT for example make use of tractor trailer combinations, dump trucks and tanker trucks to transport all sorts of goods over different distances, including city, regional, and long-haul logistics. For this research vehicles of class N3 with a weight over 12 ton will be seen as heavy duty [4]. For city logistics, vehicles are typically involved in short-distance deliveries within urban areas. Regional logistics covers medium-distance transportation between cities or within a specific region. Long-haul logistics, on the other hand, involves transporting goods over long distances, often across national borders. Part of the European Green Deal is reducing the green house gas emissions by HDT, a 45% reduction from 2030, a 65% reduction from 2035 and a 90% reduction from 2040 [3]. These reduction targets bring new challenges and opportunities to all stakeholders involved with HDT such as, truck manufacturers, logistics companies and energy providers. One of the solutions these stakeholders are pursuing to be able to reduce emissions from HDT is transitioning from conventional trucks with internal combustion engines to the use of HD BEV's.

1.1. Current state and challenges

This section will provide a brief technical and economic perspective on HD BEVs, the role of Shell in the eMobility sector as an energy provider, and the challenges in providing a charging facility network for HD BEV's.

1.1.1. HD BEV's

According to Liimatainen, Vliet, and Aplyn [5], the recent developments of battery technology make HD BEV's technically viable and several manufacturers have introduced their first HD BEV's. Research by Nykvist and Olsson [6] shows that, new developments in charging technology makes it possible to use smaller batteries. The ability to utilise smaller batteries is advantageous because it reduces vehicle weight, improves energy efficiency, and lowers production costs. Which makes HD BEV's possibly more competitive in HDT [6]. In the Netherlands there are currently around 1000 registered HD BEV's on the road, this is 0.6 % of the total registered trucks according to the CBS [4]. There are many different HD BEV's manufacturers with different specification for electric trucks. In Table 1.1 an overview is given of the specifications for a HD BEV's used today and build by Mercedes [7].

Table 1.1: Specifications Mercedes eActros 400[7]

Description	**Value [unit]**
Max. power output	400 [kW]
Battery capacity	336 [kWh]
Range	300 [km]
Costs	350.000 [Euro]

With the adaptation of HD BEV's, logistics companies and energy providers are still facing challenges. Currently HD BEV's are limited in their range compared to conventional trucks, which can have a range of over 1000km.

1.1.2. HD BEV's charging facility network

Logistics companies are in need of a good network to charge their trucks and continue their operations smoothly. This is where energy providers come in to play, they want to establish a good network of charging facilities to provide in the supply of energy that matches the demand coming from HD BEV's.Because of the fast pace of developments around charging and the energy supply market energy providers are implementing a learning by doing strategy [8]. This strategy is a combination of research and development, and during the research already deploying in the market. This means that while the charging infrastructure is already being deployed there is still research that needs to be done. Some of the research that still needs to be done regarding charging infrastructure and need a scientific approach for example is:

- Understanding the fleet owners attitude towards the use of HD BEV's and their implications (choosing between depot charging or on-the-go charging, public charging network design, etc.).
- Deploying and testing chargers with capacities of over 1 MW for very fast charging of HD BEV's.

Doing more scientific research on one of these topics can possibly help with the roll-out strategy of energy providers. The design of an optimal network of charging facilities is mentioned in the first research topic that needs a scientific approach. The design of this optimal network depends on the distribution between private and public charging demand in the future and the fleet owners attitude towards the use of HD BEV's and there expected charging behaviour.

1.2. Research Problem

As mentioned in the previous section there is the need for better scientific research for the design of the optimal charging network for HD BEV's in the Netherlands. The main problem is that it is not yet known what demand for charging at public facilities will be as it is expected that most of HD BEV's will charge at private locations. The choices fleet owners will make on charging private or publicly will influence this demand. The first part of the problem is to estimate this demand distribution, as it will serve as a basis for determining the optimal locations, which is the second part of the problem. For the second part in determining the optimal locations from the viewpoint of an energy provider, on the one hand you want to minimise the cost for realising the charging infrastructure, but want to maximise the number of trucks being able to recharge at your facilities. Some constraints in determining the locations could be for example a given budget for installation or the range of HD BEV's. For a problem like this an optimisation model could be developed taking into account these objectives and constraints. In the next chapter a literature review will be conducted to understand the current body of knowledge and be able to develop a scientific approach in solving this problem.

1.3. Research Objective

It has been discussed that there is a problem which requires the development of a charging infrastructure network by energy providers in the Netherlands to support the adoption of HD BEV's by logistics companies, in order to reduce green house gas emissions. However, as mentioned the current strategy for developing a charging facility network needs to be backed by scientific research. The research objective is to determine the demand distribution between private/public charging by considering the charging behaviour of fleet owners. Furthermore, an optimisation model will be developed that determines the optimal locations for public charging facilities, while balancing the objectives of minimising the cost of infrastructure installation and maximising the number of trucks that can recharge at the facilities. The model will need to take into account constraints such as budget limitations and the range of HD BEV's.

1.4. Research Questions

The research problem from section 1.2 serves as a basis for the development of the research question. The question should also attempt to fill the identified research gaps in in chapter 2. The main research question that aims to do both will be:

How can the the distribution of demand between private and public charging be determined and be used to determine the optimal locations in the Netherlands for a heavy duty battery electric vehicle public charging facility network?

To come to an answer of this main research question the following sub-questions have been developed, these will help indicating research activities and a constructive research setup:

1. **What is the current state of charging facilities and HD BEV's in the Netherlands?**
   The purpose of this question is to develop a general understanding of the current state of charging infrastructure and battery electric trucks. It will provide general insight on a technical, economic and geographical perspectives.
2. **What is the current state of the logistics sector, what distances do they drive, where do they drive where do they refuel?**
   The answer to this question will give general understanding of the current state of the logistics sector in the Netherlands, and insights on a technical, economical and geographic perspective
3. **What are the reasons, constraints and needs from fleet owners to install private charging facilities or make use of public charging facilities?**
   This question will provide insights into the technical, economic and subjective choices fleet owners will need to make for their regarding the use of HD BEV's. The insights serve as a basis for the constraints and decisions for the demand distribution model.
4. **How can the reasons, constraints and needs to install private charging facilities or use public charging facilities be translated into the demand distribution between private and public charging facilities for battery electric trucks?**
   The result from this model will determine the distribution between the private and public charging demand. The answer to this question will also be the answer to the first part of the main research question.
5. **What are relevant technical and economic constraints for the location of on-the-go charging facilities for battery electric trucks?**
   The outcomes of this question will provide the constraints to the location model in question 6.
6. **How can these constraints be translated into a mathematical model or scenarios?**
   A mathematical model will need to be developed to give an answer to the second part of this research in determining the locations for on-the-go charging.
7. **How can the modelling results be related to determining the optimal locations for on-the-go charging facilities for battery electric trucks?**
   The results from the developed model should be analysed to gain an understanding in what the optimal locations will be and give a final answer to the main research question.

1.5. Thesis outline

This thesis has the following structure: Chapter 2 presents a comprehensive literature review, focusing on charging infrastructure and strategies, charging demand estimation, and location modelling. Chapter 3 outlines the research methodology, presenting the research framework and different methodologies used for this thesis. Chapter 4 is a case study on the current state of the logistics sector and HD BEVs in the Netherlands, providing insights into truck operations, distances driven, and refuelling patterns and the evolving market. Chapter 5 develops the demand distribution model, integrating theoretical and expert knowledge to estimate the distribution of charging demand between private and public facilities. Chapter 6 optimizes the location of charging facilities, incorporating flow data, grid congestion, and existing infrastructure into a mathematical model. Chapter 7 conducts numerical experiments to test the model under different scenarios, to be able to develop a charging infrastructure network over the coming years. Finally, Chapter 8 concludes the thesis, summarizing the key findings, discussing the implications, and providing recommendations for future research.

2
Literature Review

The methodology for this literature review is based on the guidelines provided by Snyder [9] . This literature review aims to conduct a comprehensive review of articles focusing on HD BEV's, charging infrastructure and strategies, charging distribution between private and public facilities, charging demand estimation and location modelling. It will encompass an exploration of recent literature to identify what are gaps on this topics. The keywords used for the literature search are shown in Table 2.1, with Google Scholar and Scopus selected as the search engines. To enhance the search backward and forward snowballing techniques were employed to find additional relevant literature.

Table 2.1: Keywords used

Section	Keywords
Charging infrastructure and strategies	truck AND charging AND strategies
Distribution private/public demand	charging AND private AND public AND demand
Charging demand estimation	charging AND demand AND estimation
Location Modelling	location AND Modelling

2.1. Charging Infrastructure and Strategies

Providing charging infrastructure for HD BEV's brings complex challenges with many stakeholders involved [10]. These stakeholders range from energy supply markets to those who facilitate the provision of energy to end-users [11]. Challenges that have to be dealt with are for example issues with: sufficient capacity in the local grid, ensuring a stable grid and matching supply-demand [12]. The charging service providers that provide semi-public access chargers, with different kind of services such as fast or smart charging and dynamic pricing, will need to make sure that their placement of chargers correspondents with the needs and preferences of the users [13], it is crucial to understand the behaviour of users to design the charging infrastructure. The reasons for the use of public charging infrastructure underlie in insufficient range, availability and opportunity, and the lack of the ability to charge at the next destination [14]. The charging strategy is what is underlying of the choices and behaviour of users [13]. According to Teoh [15] charging strategies are described very differently in the literature, they may emphasise on technology (fast charging or battery swapping), the location of charging (depot charging, destination charging or on-the-go) and ownership of the charging service (public, semi-public or private). For this literature review the charging strategies based on the location and ownership are of relevance. According to Kin, Hopman, and Quak [16] a distinction can be made between low capacity and high capacity charging and four types of charging stations: home (private), depot (private), road (public), at premises (semi-public). This together has an effect on the type of charging station, the charging moment, costs for electricity and investments. The profile of the mission, vehicle type, battery size and charging infrastructure together relate to the charging strategy [16]. It has been demonstrated that overnight charging at home or at a depot is the most cost-effective strategy, as long as the daily operations will fit within the battery range. It hardly affects the way of operating based on conventional trucks [17]. Kin, Hopman, and Quak [16] states there are several reasons why opportunity charging on the road is not the preferred strategy: electricity costs are higher when charging on-the-go, increase in driver costs because the driver is inactive during charging, potential queuing time when using charging infrastructure [18], challenges of integrating on-the-go charging into daily routes minimising disruptions in operations [18]. The review on literature about charging infrastructure and strategies shows that choosing the right locations for charging service providers is a challenge, and that from a fleet operator perspective it is a challenge to choose a strategy between private and public charging with private charging being the potential preferred option.

2.2. Charging Demand

This section will dive into the literature on two topics of charging demand, the first one being the distribution between private and public charging, the second one about the estimation of charging demand. These are relevant topics to find a research gap that suits the first part of the research problem stated in section 1.2.

2.2.1. Distribution between private and public charging demand

There have been many studies about predicting charging demand for different types of electric vehicles (EVs), such as passenger EVs [19] and electric buses [20], but not a lot of research has been done specifically on HD BEV's. A study by Borlaug, Moniot, Birky, *et al.* [21] made a model to predict the charging behaviour for HD BEV's in the USA. The researchers used telemetics data of around 55.000 trucks to classify them in different operating segments. They modelled two types of charging mid-shift (slow) and on-shift (fast) and three operating segments: local range ≤ 100 miles, regional range 100 miles to 300 miles and long-haul range > 300 miles. They found that with increasing ranges of HD BEV's the charging share of mid-shift charging decreases and off-shift charging increases, where with local operating trucks the share off-shift charging will be around 77%. Borlaug, Moniot, Birky, *et al.* [21] recommends further research on the trade-offs between different network designs, for example comparing a network comprised of highly distributed low-power for off-shift charging or a more centralised network with high-power for mid-shift charging. This recommendation on further research about trade-offs and network design for HD BEV's aligns with the research problem. This shows there are potential gaps in this topic of research. Another study on the distribution between private and public charging in the USA by Kampshoff, Kumar, Peloquin, *et al.* [22] estimates that around 20% of charging will be at public sites. But this study has some shortcomings in not explaining where this 20% is exactly based on and did not focus specifically on HD BEV's. The reviewed literature on demand distribution shows there is a significant gap in research specifically with a focus on HD BEV's. The study by Borlaug, Moniot, Birky, *et al.* [21] did a research on HD BEV's but is focused on the USA, trucks in the USA and the Netherlands have different operation characteristics. Borlaug, Moniot, Birky, *et al.* [21] recommends further research in this area. All this together make it scientifically relevant to do more research on the distribution between private and public charging demand of HD BEV's in the Netherlands.

2.2.2. Charging Demand Estimation

Previous research on estimating EV charging demand often relied on data, such as the number of residents [23], vehicle ownership [24], and the distribution of gas stations [25]. Some studies have considered destinations, noting that EVs, unlike conventional vehicles, are more likely to charge at the end of a trip due to longer charging times [26]. For example, Chen, Kockelman, and Khan [27] used household travel data to estimate parking and charging demand, while others used daily schedules and activities [28] or household surveys [29].

However, most of this research focuses on personal EVs, which typically have smaller batteries and are charged overnight at home or occasionally at public stations. In contrast, HD BEVs require larger batteries and high-power DC fast charging to minimize downtime and meet demanding schedules. This difference in operational characteristics means that existing EV charging demand estimations cannot be directly applied to HD BEVs, highlighting the need for specific research in this area.

2.3. Charging Facility Location Modelling

According to Speth, Plötz, Funke, *et al.* [30] there are two main modelling approaches in determining the locations of charging infrastructure. The first one is a coverage-oriented approach based on distributing charging infrastructure as evenly as possible, which guarantees maximal geographic coverage. The second one is a demand-oriented approach based on the charging demand which results in a higher utilisation of charging facilities. For this research a demand-oriented approach seems more relevant as the objective is to maximise the number of trucks coming to the charging stations from an energy providers perspective. In the literature previous studies on refuelling locations focused on locating facilities with the objective of capturing maximal flow. This approach is known as the flow-capturing location model (FCLM) [31]. The fundamentals of this model are the individual traffic flows through a network. This model has been extended by Kuby and Lim [32] into the flow-refuelling location model (FRLM) taking into account multiple stops, which is necessary for vehicles with a limited range. For The FRLM has then been further developed into the node capacitated flow refuelling location model (NC-FRLM) by NC-FRLM, considering (station) location capacity restrictions [33]. The FRLM has been used by Rose and Neumann [34] to develop a hydrogen refuelling station network in Germany. But has not yet been used to develop a network of charging facilities. The identified gaps include the potential to extend the FRLM by incorporating objectives and constraints related to the costs of installing charging infrastructure, as highlighted in the problem statement, and the specific application of this model for HD BEV's in the context of the Netherlands.

2.4. Conclusion and Discussion on the Literature

The literature review reveals substantial progress in the study of EV charging infrastructure, with extensive research on charging demand estimation and infrastructure placement. However, there is a notable gap in the literature regarding HD BEVs. Due to their distinct operational characteristics, the charging demand models developed for EVs cannot be directly applied to HD BEVs. This highlights the need for further research specifically focused on HD BEVs, particularly in understanding the distribution of private versus public charging demand and its impact on infrastructure development.

Key gaps identified include the lack of studies on HD BEV charging demand. This suggests a critical need for developing new methods or adapting existing ones to accurately estimate HD BEV charging demand, considering fleet owners' preferences for private or public charging locations.

Additionally, existing models for locating charging infrastructure, such as the FRLM, can be extended to better serve energy providers by incorporating objectives and constraints related to installation costs. Applying these models to the geographical context of the Netherlands has not yet been explored.

Addressing these gaps through targeted research will enhance the scientific understanding of HD BEV charging infrastructure and support the development of efficient and cost-effective charging networks. This is particularly crucial for regions like the Netherlands, where strategically placed charging infrastructure could significantly influence the successful adoption of HD BEVs. Developing a research structure that considers user needs to determine demand distribution and combines this with optimal location placement is essential for advancing this field.

3 Methodology and research framework

This section will outline the research methodologies that will be used to give an answer to the research questions in section 1.4. For this research both qualitative and quantitative methodologies will be used. Table 3.1 gives an overview of which methodologies will be used to answer the specific research questions. The coming subsections will describe in detail in which way the different research methodologies will be carried out. In section 3.1 will be explained how all the different methodologies will come together in one research framework. The provided research framework and methodology will be applied to a case study at Shell.

Table 3.1: Overview of methodologies

Question	Methodologies
1. What is the current state of charging facilities and HD BEV's in the Netherlands?	Literature Review, Market Analysis
2.What is the current state of the logistics sector, what distances do they drive, where do they drive where do they refuel?	Literature Review, Expert Interviews, Market Analysis
3. What are the reasons, constraints and needs from fleet owners to install private charging facilities or make use of public charging facilities?	Literature Review, Expert Interviews, Survey
4.How can the reasons, constraints and needs to install private charging facilities or use public charging facilities be translated into the demand distribution between private and public charging facilities for battery electric trucks?	Demand Estimation Method
5. What are relevant technical and economic constraints for the location of on-the-go charging facilities for battery electric trucks?	Literature Review
6. How can these constraints be translated into a mathematical model or scenarios?	Facility Location Model
7. How can the modelling results be related to determining the optimal locations for on-the-go charging facilities for battery electric trucks?	Facility Location Model, Scenario Analysis

3.1. Research Framework

A comprehensive research framework has been established to guide the progression of this study and is shown in Figure 3.1. The initial phase involves developing an understanding to the context of the study through expert interviews, market analysis, and a comprehensive literature review. This theoretical foundation will address sub-questions 1, 2 and 3 providing critical input for the subsequent modelling base and estimation method. In the estimation method, the demand distribution between private and public charging will be determined, addressing sub-question 4. The modelling base will integrate all objectives, decisions, and constraints answering sub-question 5, and will lead to the creation of a mathematical model answering sub-question 6. The location model will then undergo verification and validation. Finally, the optimisation model will be used on different numerical experiments of which the results will be analysed to answer sub-questions 7, ultimately providing a conclusive answer to the main research question.

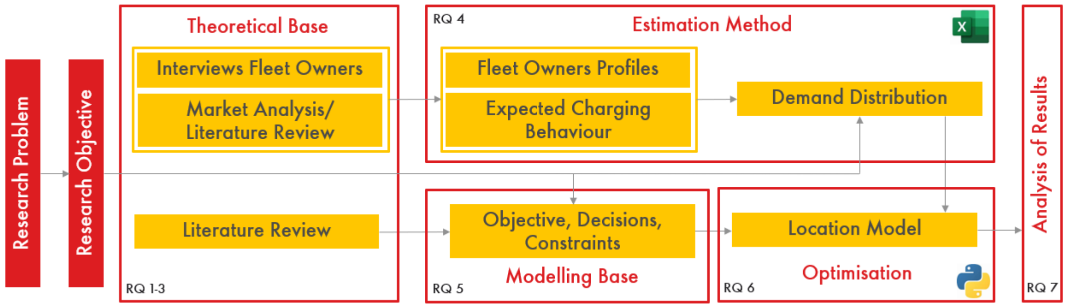

Figure 3.1: Research framework

3.2. Application of the methodology

This methodology and research framework will be used for a real world case study at Shell. Shells Powering Progress strategy aims to become a net-zero emissions energy business by 2050. To achieve this goal part of the strategy is to decarbonise commercial road transport by providing charging facilities for HD BEV's [35]. Shells eMobility team in the Netherlands is researching the opportunities and helping fleet owners in transitioning from the use of fossil-fuel trucks to the use of HD BEV's. With the transition to electric trucking the locations with demand for energy will possibly change. Shell is offering three types of charging options for fleet owners: the eDepot at their own facility (private), charging stations along the road (public) and the ability to charge at the location where the truck is loading and unloading goods eDepot+ (semi-public) [36]. The electricity prices at all these locations will be different. At the fleet owners own facility the electricity prices will most likely be the lowest. This means that for a fleet owner it is most interesting to charge their trucks at their own facility, but in reality this will not always be possible. Constraints such as limited space for installing charging infrastructure at their own facilities, congestion on the electricity grid, or the insufficient range of HD BEVs for daily operations could compel fleet owners to seek charging options at public or semi-public locations.

3.3. Theoretical base

For the theoretical base different methodologies will be used of which a literature review is one. A literature review can be an excellent research methodology for several reasons: identifying gaps in existing research, understanding theories and concepts and enhancing knowledge on specific topics. These are all reasons why a literature has been chosen as one of the methodologies to help answer some of the sub-question, especially the more qualitative ones. For all the literature reviews in this research, the methodology used is as described by Snyder [9]. The theoretical base will also include some insights from experts for which the methodology is explained in subsection 3.4.2. A market analysis will also be conducted to provide valuable insights into the current state and context of the logistics market and the status of HD BEV's in the Netherlands. The findings from this theoretical base are presented in chapter 4. These findings will form the foundation for the rest of the proposed research framework and methodology.

3.4. Demand Distribution Estimation

As concluded from the literature review in chapter 2, existing studies have explored charging demand estimation for EVs. However, due to the distinct operational characteristics of HD BEV's, the charging demand models designed for EVs are not directly applicable to HD BEV's. The before mentioned objective in section 1.3 shows the methodology should include the behaviour of fleet owners. For research on behaviour of choices a discrete choice model could be developed [37]. The downside of a discrete choice model is it often requires a large and detailed dataset to produce reliable estimates. Obtaining such data can be costly and time-consuming, especially if the model needs to account for a wide range of factors and alternatives [38]. This makes this methodology not suitable for this research, considering the available time.

A tailored methodology is developed to this specific problem and research. The methodology will be of a more qualitative approach in determining the fleet owners profiles and expected charging behaviour. Qualitative research methodologies are particularly well-suited for studies where little is known about the subject matter [39] which is the case in this research as seen in chapter 2. The tailored method allows for an in-depth exploration of the perspectives of stakeholders, which is crucial in complex and less-documented sectors such as the transition to the usage of HD BEV's by logistics companies. By using a qualitative approach, the aim is to uncover insights into what works, for who, under what circumstances and why, which are critical in developing effective strategies [40].

The tailored methodology to estimate the demand distribution between private and public charging is based on 4 steps and explained below, Figure 3.2 gives a visual representation of the proposed methodology. The outcomes of this method gives an answer to the first part of the main research question.

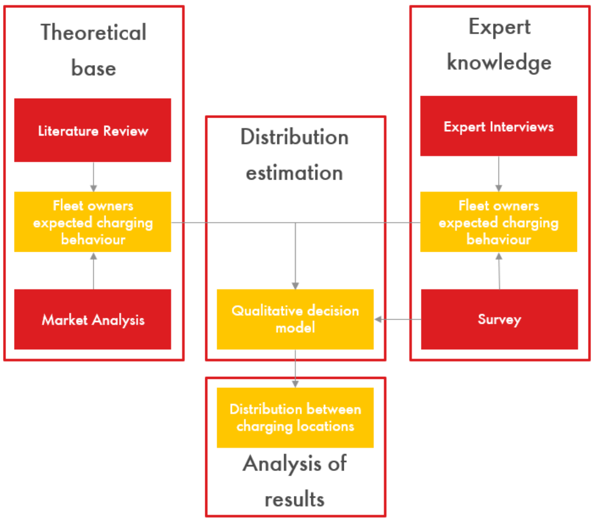

Figure 3.2: Demand distribution estimation method

3.4.1. Theoretical base

To develop a comprehensive understanding of the expected charging behaviour of fleet owners, a theoretical foundation will first be established through literature research and market analysis as explained in section 3.3. This foundation will identify the characteristics, inputs, and factors that influence fleet owners' charging behaviour. Additionally, various fleet owner profiles will be created to provide insights into what their theoretical charging patterns could be. The results to the theoretical base can be found in section 5.1.

3.4.2. Expert knowledge

In parallel with the theoretical base, a practical foundation will be built using expert knowledge. Expert interviews and surveys will be conducted to determine the anticipated charging behaviour of fleet owners and compare these with the theoretical established charging behaviour.

Expert Interviews

Expert interviews are a valuable research methodology for several reasons, as outlined by Von Soest [41]. They provide detailed and nuanced insights that are often not available through other methods, offering deep knowledge and understanding of complex issues, which is crucial for exploring intricate topics. Engaging with experts allows to test and refine assumptions, ask specific questions, and fill in any gaps in their understanding. Additionally, experts often have first-hand experience with decision-making processes, providing valuable insights into how decisions are made and the factors influencing them.

The goal of these interviews is to verify, validate, and extend the theoretical foundation of the characteristics and charging scenarios established with the method for the theoretical base (see section 3.3). To achieve this, a semi-structured format is used, allowing for open discussions on the topic. While the questions guide the direction of the interview, they are flexible enough to gather unexpected information. An interview guide was developed for the expert interviews, following these four steps: utilizing previously acquired knowledge on the topic for example from chapter 4 and section 5.1, formulating a draft of the interview guide, pilot testing the draft, and completing the interview guide [42]. The interview guide covers the main topics of the research and provides a structure to guide the interviews, ensuring data is collected in a consistent manner from each participant [43]. The interview guide used for these semi-structured interviews can be found in Appendix B. All interviews were automatically transcribed using Microsoft Teams/Word to support the analysis of the interviews.

To assess whether the number of interviews conducted is sufficient, we can examine the saturation rate. The concept of saturation was first introduced in qualitative research as "theoretical saturation" by Glaser and Strauss [44], they defined it as the point at which "no additional data are being found whereby the researcher can develop properties of the category". This definition is specifically aimed at the practice of building and testing theoretical models using qualitative data, referring to the point at which the theoretical model being developed stabilizes.

Guest, Namey, and Chen [45] described a method to calculate saturation, which involves determining the base size, run length, and new information threshold. These elements are subjectively determined as the research is qualitative. The base size refers to the number of themes introduced by the initial interviews, while the run length is the number of subsequent interviews examined to see how much new information emerges. These successive runs overlap each other. The new information threshold established for this research is 5%, as there is not enough time to achieve full saturation. The base size is the denominator in the saturation calculation, and the new information from the run is the numerator. The themes are the factors and challenges mentioned that can influence the charging behaviour, the base size will be based on the theoretical characteristics established in the theoretical base.

Survey

To collect data for the model, especially on a topic that has not been extensively researched or lacks existing datasets, conducting a survey is an effective approach. As noted by Roopa and Rani [46], questionnaires are commonly utilised in marketing and social research. A questionnaire consists of a series of questions posed to individuals to gather valuable information on a specific topic. When designed and administered correctly, questionnaires become essential tools for making statements about particular groups or entire populations. The success of a survey heavily depends on the construction of the questionnaire. Crafting appropriate questions, ordering them correctly, using proper scaling, and having a well-designed format can make the survey valuable by accurately reflecting the respondents views and opinions [46].

The survey which will be developed for this research will try to gather data on the inputs and constraints determined and described in subsection 5.1.1, and have some questions to reveal the preference of fleet owners towards certain charging locations. The questions on revealing the choice preference have been based on that of a a stated preference survey [47]. However, as explained before there will not be an actual stated preference survey with a choice model. The construction and justification of chosen question types for the survey can be found in Appendix C. The complete format of the questionnaire can be found in Appendix D.

According to Taherdoost [48], the sample size is a significant feature of any survey in which the goal is to make inferences about a population from a sample. In order to be able to generalize from a sample and avoid errors or biases, an adequate sample size needs to be determined [48]. The sample size can be determined using the following formula:

$$n = \frac{p(100-p)z^2}{E^2} \tag{3.1}$$

Where n is the required sample size, p is the percentage occurrence of a state E is the percentage maximum error and z is the value corresponding to the level of confidence. One issue is how the value of p can be estimated before conducting the survey [48], it is suggested by Bartlett, Kotrlik, and Higgins [49] that 50% should be used as this will result in maximisation of the variance and produce the maximum sample size.

For this research, the population consists of 3,000 fleet owners. To achieve a 95% confidence interval with a population variance of 50% and a margin of error of 5%, the required sample size is 341. Given the time frame of this research, it may not be feasible to obtain 341 respondents. However the survey will provide new insights into a topic which has not been researched in the body of literature as explained in chapter 2

3.4.3. Distribution estimation

The insights from the theoretical base and expert knowledge will be integrated into a qualitative decision model. This model, resembling sort of a decision tree/flow chart, and will predict the expected charging behaviour for each fleet owner. The survey designed to understand fleet owners' behaviour will also collect data inputs for the qualitative decision model. By combining theoretical research with expert insights, a robust qualitative model can be developed. This approach ensures that the model is grounded in both existing literature and practical expertise. The developed model and results are detailed in chapter 5. These distribution results will be utilized in chapter 7 to evaluate the optimal charging infrastructure for HD BEV's.

3.5. Facility Location Modelling

To address the second part of the main research question, a facility location model will be developed with the objective of maximizing the utilization of the charging infrastructure while minimizing installation costs. Based on the literature review, the FRLM by Kuby and Lim [32] appears well-suited for this purpose, as its primary goal is to maximize the flow captured from the network. However, for this research, the model will be extended to include cost minimization as an additional objective. These extra objectives have been established within the earlier step in understanding the theoretical base in the form of the context case study chapter 4.

The location model will require several data inputs, including flow data and cost data related to grid congestion, Shell truck diesel sites, and small industry sites which will al be explained in subsection 3.5.1 these different data sources have been established in the earlier parts of this research methodology.

he model will need to undergo verification and validation. Verification ensures the model meets the developer's intent by incorporating all specified requirements and confirming the final build includes only what is specified, while validation determines if the model effectively fulfills its intended purpose by evaluating the conceptual design's fidelity and comparing the model's outcomes against a suitable reference [50].

To perform the verification and validation, the following steps will be undertaken. For verification running test cases to ensure that the model behaves as expected under different conditions, verifying that it meets the developer's intent. To evaluate and test the model's performance, the problem will also be solved using a greedy algorithm, and the results will be compared to those obtained from the model. For validation a sensitivity analysis will be conducted to test the model's responses to changes in input parameters and see if they align with real-world behaviour [51]. To evaluate and test the model's performance, the problem will also be solved using a greedy algorithm, and the results will be compared to those obtained from the model.

3.5.1. Data

This section will describe all the data gathering for the model and what operations have been done to create the dataset which has been used as an input for the model in this research.

Flow data

One of the datasets used for this research was developed by Speth, Sauter, Plötz, *et al.* [52] and is publicly available for research purposes. The dataset provides comprehensive information on European road freight traffic, including truck flows between 1,675 regions across Europe. It covers road freight flows in tons and vehicle counts, as well as the shortest paths between regions on the European highway network (E-roads). Each entry includes fifteen variables, such as region IDs, path details, distances, and freight and vehicle flows for 2010, 2019, and a forecast for 2030. The data also includes a model of the E-road network and regional information. Initially collected in 2010 through the ETISplus project, which aggregated and calibrated freight volumes using European and national data, the dataset was later updated with Eurostat figures from 2019 and 2030 projections. Dijkstra's algorithm was used to allocate origin-destination volumes to the network, generating synthetic traffic volumes. According to Speth, Sauter, Plötz, *et al.* [52] this dataset can be used for planning future European road infrastructure, such as hydrogen refuelling and electric truck charging stations, making it valuable for research and practical applications. This dataset seems appropriate to use as it contains flow between origin and destination pairs which is needed for the flow refuelling location model. There are some operations needed to construct a usable dataset for the model in this research from the dataset by Speth, Sauter, Plötz, *et al.* [52]. First, the data is filtered to focus on the Netherlands. Then, using the node, edge, and flow data, two origin-destination (OD) matrices are constructed: one representing the distances between nodes and the other capturing the flow between the nodes. All trips with less than 150 km are deleted as it can be expected they do not need to recharge at public locations for a round trip based on the before mentioned findings in this research. This resulted in a OD flow matrix with the a size of 457x457 based on the truck traffic flow of 2019 as it is the most recent flow.

In Figure 3.3 a figure is shown of all nodes and edges within the dataset that will be used as the network for this research.

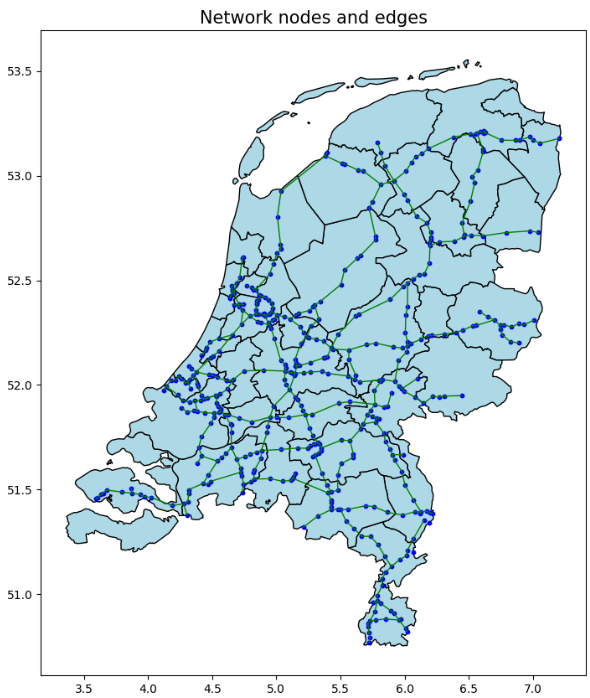

Figure 3.3: The network with all nodes and edges

Grid congestion

To incorporate grid congestion as a cost input for the model, a dataset detailing grid congestion at the node locations is required. The Dutch grid operators have published a map showing congestion at the postal code level. The source data for this map can be downloaded from [53]. The source data contains the following columns that can be used for this research: postal code and off take which has a -1 no information available, 0 no waiting time for new connection and transport capacity available, 1 transport capacity limited but no waiting times yet, 2 area has a waiting time and research to transport capacity, 3 the area has no transport capacity and there is a waiting time. A python script is used that utilises the geopy library Geopy Contributors [54] to retrieve postal codes based on latitude and longitude coordinates. It processes the node data to add a new column containing these postal codes. Subsequently, the congestion data is merged with the node data using the postal code as the key, enabling the integration of grid congestion information into the node dataset.

In Figure 3.4 a figure is shown of all nodes and the corresponding grid congestion where white is 1, yellow is 2, orange is 3, and red is 4.

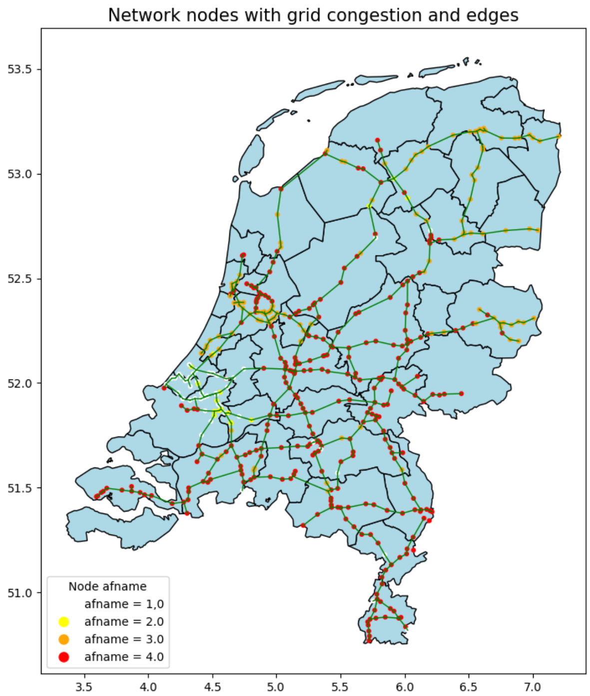

Figure 3.4: The network with all nodes and their corresponding grid congestion color

Current Shell truck diesel sites

Shell has provided a dataset containing all current Shell truck diesel sites along with their corresponding longitude and latitude. These sites do not directly match the coordinates of the nodes in the network used for the model. Shell truck diesel sites within 0.1 degrees of a network node will be assigned to that node. If a Shell truck diesel site is assigned, the node will receive a score of 1, while all other nodes will receive a score of 4. To assign Shell truck diesel sites to nodes, a nearest neighbour algorithm is particularly useful. It efficiently identifies the closest node to each Shell truck diesel site based on geographical coordinates, ensuring optimal connection to the network. This minimises distance, potentially reducing costs and improving service efficiency. By finding the nearest node, the algorithm maintains spatial proximity [55]. The CKD-Tree (Coreset KD-Tree) algorithm is chosen for this task due to its enhanced efficiency [55]. The CKD-Tree maintains high accuracy in nearest neighbour searches, ensuring that std locations are linked to the most appropriate network nodes, thus preserving the network's integrity and performance. The scipy package in Python, from Virtanen, Gommers, Oliphant, *et al.* [56], includes a built-in function for the cKDTree. This function will be utilised to link the Shell truck diesel sites to the nodes in the network. In Figure 3.5 the network with nodes assigned to the Shell truck diesel sites are shown.

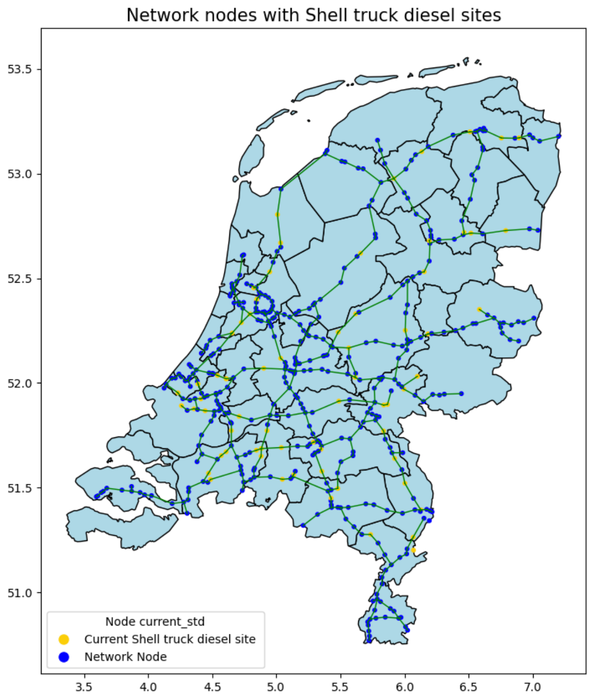

Figure 3.5: Shell truck diesel sites in the network

Small industry locations

For the industry locations in the Netherlands a dataset from IBIS (Integraal Bedrijventerreinen Informatie Systeem) used and updated by the provinces of the Netherlands and open for use for other research [57]. This dataset provides valuable information for this research, including the location of industry sites, parking availability, road accessibility, and size in hectares. The data is filtered to include only entries with the highest score of 'A' in the parking availability and reachability columns, as these factors are crucial for selecting sites for public recharging facilities. To then determine if the industry size is small a plot is shown in Figure 3.6 of the size distribution, together with the 25th percentile and 75th percentile.

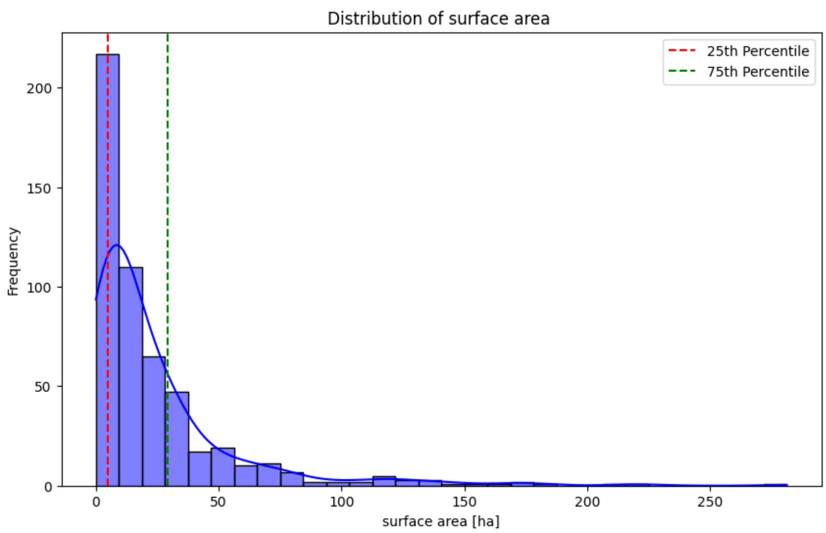

Figure 3.6: Distribution of surface area for industry sites

The 25th percentile will be used as the upper limit for a small industry site, the 25th percentile is 5 ha so every industry site larger will be filtered out of the dataset. Then the locations of the industry sites need to be connected to the nodes in the network, this will be done in the same way was explained in Figure 3.5.1. Where the node containing a small industry site gets a score of 1 and without a small industry site gets a score of 5. InFigure 3.7 a figure is shown of the network with the nodes that contain a small industry site.

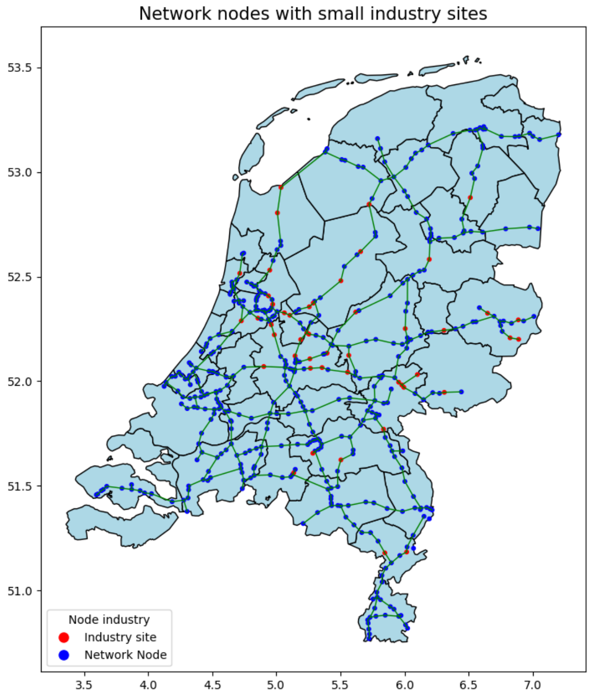

Figure 3.7: Network nodes with a small industry site

Final dataset

As final data input for the model the flow matrix and final node data frame will be used where the node dataframe will have the following columns: Network_Node_ID, Network_Node_X (Longitude), Network_Node_Y (Latitude), Grid_offtake, Current_std, Industry and the Total_Flow through the node. Table 3.2 shows the first 5 rows of the data frame constructed. The values 1 and 4 were chosen for the columns representing current std and industry sites to align them with the range of values used for grid off-take. This consistency simplifies their integration into the model's cost function.

Table 3.2: Dataframe node information

Network_Node_ID	Network_Node_X	Network_Node_Y	Grid_offtake	Current_std	Industry	Total_Flow
196014	4.312540	52.013020	1.0	4	4	329201.00
196068	5.271197	52.280708	3.0	4	4	1195002.00
196061	5.238911	52.231791	4.0	4	1	1195002.00
113445	6.457520	52.707902	3.0	4	4	2909697.00
196637	6.389035	52.686699	3.0	4	4	2909697.00

3.5.2. Greedy algorithm

According to Mestre [58], a greedy algorithm is perhaps the most natural first attempt at solving any optimisation problem. This greedy algorithm can be used as a benchmark to evaluate whether the later developed MILP provides additional value in solving this problem. A straightforward greedy algorithm could involve sorting the dataset by certain columns to maximise the flow while minimising the values for opening a facility. This means prioritizing higher flow values and lower scores for grid offtake, current std, and industry columns.

To achieve this, you can first normalise the values to make sure they are within equal range of each other, within each column and then apply a weighted sorting algorithm. The normalisation is performed using the following formula which is the min-max normalisation method [59]:

$$x_{normalised} = \frac{(x - min)}{(max - min)} \tag{3.2}$$

where x is the original value in the column, min is the minimum value in the column, and max is the maximum value in the column. This normalisation scales all values to a range between 0 and 1, ensuring comparability across different columns.

Once the columns are normalised, a total weighted score is calculated for each row. This score is computed by multiplying each normalised value by its corresponding weight and summing the results:

$$score_{weighted} = \sum_{i=1}^{n} x_{normalised,i} * weight_i \tag{3.3}$$

where n is the number of columns, $x_{normalised,i}$ is the normalized value of the i-th column, and $weight_i$ is the weight assigned to the i-th column. The rows are then sorted based on this total weighted score in ascending order.

3.5.3. The model

The flow refuelling location model, needs to be extended with a cost function to minimize total costs. This extension ensures that the model selects locations that maximize the captured flow while minimizing the costs associated with installing infrastructure or preferring certain characteristics. Installation costs can be influenced by factors such as grid congestion, the availability of existing Shell sites, or the presence of small industry locations with public charging potential can be preferred and thus have a lower cost. Therefore, the objective function will have two goals: maximizing the captured flow and minimizing total costs. This approach is chosen over a constraint approach because it allows for a more flexible and balanced optimization of both objectives. By integrating the new parameters directly into the objective function, the model can simultaneously address both goals, providing a more comprehensive solution than if cost minimization were treated as a separate constraint.

For this multi-objective optimization problem, the scalarization method using the weighted sum approach, as developed by Zadeh [60], will be employed. This method combines multiple objectives into a single objective function with different weights assigned to each element. According to Marler and Arora [61], the weighted sum method is straightforward and effective for multi-objective optimization, but it only works for convex problems. Since the model by Kuby and Lim [32] is a linear model and therefor convex, this method is chosen instead of the Pareto optimum, which allocates resources in such a way that improving one objective would worsen another [62].

The ranked sum method [63] will be used to determine the weights, which enables to differentiate the ranks of parameters and through that the weights for different numerical experiments in chapter 7.

The weight parameters can be determined with the following equation [63]:

$$w_i = \frac{2(n + 1 - i)}{n(n + 1)} \tag{3.4}$$

Where w_i is the weight of the specific parameter, i is the rank of that parameter and n is the total number of ranked parameters.

When using the scalarization method, the minimising function should be marked negative, while the maximising function is marked positive [63].

To provide a sense of fairness between each objective function, it is necessary to normalise. The normalisation is performed using the same formula as within the greedy approach [59]:

Notations of the model

In Table 3.3 all Sets, Parameters and Decision Variables of the model are presented.

Table 3.3: Notation of the model

Sets and Indices		
Q	set of all O–D pairs	$q \in Q$
K	set of all potential facility locations	$k \in K$
H	set of all potential facility combinations	$h \in H$
Parameters		
f_q	flow volume on the shortest path between O–D pair q	number of vehicles
a_{hk}	a coefficient equal to 1 if facility k is in combination h and 0 otherwise	{0,1}
b_{qh}	a coefficient equal to 1 if facility combination h can refuel O–D pair q and 0 otherwise	{0,1}
$c1_k$	cost parameter grid	unit of cost
$c2_k$	cost parameter current std	unit of cost
$c3_k$	cost parameter small industry site	unit of cost
B	Budget for installing infrastructure	unit of cost
w_1	weight for maximising flow	
w_2	weight for minimising grid costs	
w_3	weight for minimising current std costs	
w_4	weight for minimising small industry site costs	
Decision Variables		
y_q	1 if f_q is captured, 0 otherwise	{0,1}
x_k	1 if a facility is located at k, 0 otherwise	{0,1}
v_h	1 if all facilities in combination h are open, 0 otherwise	{0,1}

Sets Q and K can be directly derived from the OD matrices, and the parameters f_q, $c1_k$, $c2_k$, $c3_k$ are within the OD matrices or in the node information data frame. However, generating set H and the parameters a_{hk} and b_{qh} requires running an algorithm. This algorithm was originally developed by Kuby and Lim [32] and is shown below:

Step 1: Initializations

1. Generate the shortest path for all origin–destination pairs q. Store the nodes and links of the path.
2. Establish an empty master list of all combinations h.

Step 2: Generate Combinations

1. For each path q, generate all possible combinations h of the nodes on the path capable of refuelling the path.

Step 3: Evaluate Combinations

1. Remove facility combinations that cannot refuel a vehicle on the given path:
   (a) Start at the origin node. Set the remaining fuel range at full or half based on whether there is a facility at the origin.
   (b) Move to the next node, subtract the distance travelled from the remaining fuel range, and check:
      - If the remaining fuel range is less than zero, remove the combination.
      - If the node is the destination and has a refuelling station, keep the combination.
      - If the node is the origin, keep the combination.
      - If the node has a refuelling station, reset the remaining fuel range.

Step 4: Remove Supersets

1. Remove combinations that are supersets of any other remaining combination:
   (a) Sort combinations by the number of nodes in descending order.
   (b) Remove supersets from the list.

Step 5: Record Viable Combinations

1. Record the facilities k in each viable combination h and the viable combinations h for path q. Use coefficients b_{qh} and a_{hk} to store these relationships.

Step 6: Repeat

1. Repeat Steps 2–5 for all paths q.

A key step in the algorithm involves determining which refuelling combinations are feasible for each path. For every path, it generates potential combinations and validates them against the OD matrix, which includes 457 nodes and an average path length of 25. This process is computationally intensive because it initially considers all combinations along a path, even those with 25 possible refuelling points. However, in subsequent steps, the algorithm eliminates super sets of combinations when they are unnecessary. For instance, if a path is 400 km long and a vehicle's range is 300 km, refuelling at all 25 nodes would allow it to reach its destination. Yet, it could also complete the trip with only 2 refuelling points, forming a smaller combination. Thus, recording all combinations initially and then removing the supersets is redundant. Given that, in this dataset, the maximum path length is 400 km and the minimum vehicle range is 350 km, only combinations of up to 2 nodes need to be considered for the round trip and even when the vehicle starts with half a range. This significantly accelerates the process of generating set H and the parameters a_{hk} and b_{qh}. This algorithm has been run for ranges of 350, 400, 500, 600, 700 and 800 km to be able to develop a solution over the coming years in chapter 7.

Model formulation

The modelling objectives of maximising flow and minimising costs are defined below:

Flow maximisation:

$$f_1(x) = \sum_{q \in Q} f_{q,normalised} y_q \tag{3.5}$$

Cost minimisation:

$$f_2(x) = \sum_{k \in K} c1_{k,normalised} x_k \tag{3.6}$$

$$f_3(x) = \sum_{k \in K} c2_{k,normalised} x_k \tag{3.7}$$

$$f_4(x) = \sum_{k \in K} c3_{k,normalised} x_k \tag{3.8}$$

$$F(x) = w_1 f_1(x) - w_2 f_2(x) - w_3 f_3(x) - w_4 f_4(x) \tag{3.9}$$

where $F(x)$ is the fitness function, $f_1(x)$, $f_2(x)$, $f_3(x)$, $f_4(x)$ are objective functions 1, 2, 3, 4 and w_1, w_2, w_3, w_4 are the weights for the respective objective functions.

Objective function:

$$\max Z = F(x) \tag{3.10}$$

Subject to:

$$\sum_{h \in H} b_{qh} v_h \geq y_q \quad \forall q \in Q \tag{3.11}$$

$$a_{hk} x_k \geq v_h \quad \forall h \in H \tag{3.12}$$

$$\sum_{k \in K} (c1_k + c2_k + c3_k) \, x_k \leq B \tag{3.13}$$

$$x_k, v_h, y_q \in 0, 1 \quad \forall k, h, q \tag{3.14}$$

Equation 3.10 is the objective function that maximises the total flow that can be refuelled while minimising the opening costs with the selected facilities. Equation 3.11 ensures that for each path q, at least one eligible combination of facilities h is open to allow refuelling on that path. Equation 3.12 ensures that v_h is zero unless all facilities in the combination h are open. Equation 3.13 ensures that the total cost of the opened facilities does not exceed the budget B. Equation 3.14 specifies that the decision variables x_k, v_h, and y_q are binary, meaning they can only take values of 0 or 1.

4 Context Case Study

This chapter will explore the current state and future market predictions for HD BEV's, charging infrastructure, and the logistics sector in the Netherlands. The goal is to answer the first two sub-questions: What is the current state of the logistics sector, what distances do they drive, where do they drive where do they refuel? What is the current state of charging facilities and HD BEV's in the Netherlands? Firstly, section 4.1 will examine the current state of the logistics sector including the locations from where trucks operate, where trucks drive and what distances trucks drive. Secondly, section 4.2 will provide an overview of the current HD BEV's available and penetration of the market and anticipated developments in the coming years, and an overview of the current state of the charging infrastructure for HD BEV's.

4.1. The logistics and transport sector

The transport and logistics sector is of great importance to the Dutch economy according to the CBS [4]. In 2022, the contribution of the transportation and storage industry to the Dutch economy was 4.5 percent. By the end of 2022, the sector had nearly 60 thousand companies. Of all transport companies, 88 percent are active in land transport, such as freight transport, moving services, and taxi services [4].Approximately 15% of truck transport in the Netherlands is carried out by foreign trucks, while 85% is handled by trucks registered in the Netherlands [4]. For this research, it is crucial to develop a better understanding of the logistics sector in the Netherlands. This section will provide insights into the locations where trucks are based, since most HD BEV's are expected to charge at private facilities this is essential to know. Understanding where they operate is important for determining the locations of public charging stations. Assessing how far they will travel is necessary to estimate their total energy demand and evaluate whether the range of HD BEV's is sufficient.

4.1.1. Where are trucks based?

Understanding where trucks are based will provide insights into where HD BEV's are likely to charge at private locations and identify the key areas where significant truck traffic will originate or terminate. A dataset from CBS [4] is available with all registered trucks per postal code. Figure 4.1 shows a heat map of all the registered trucks and their registered location. This can give some understanding of where trucks are based. However some companies centralise truck registration at their headquarters, even though they operate multiple facilities. While the resulting heat map does not provide precise truck resting places, it does offer some insights on where trucks might be based.

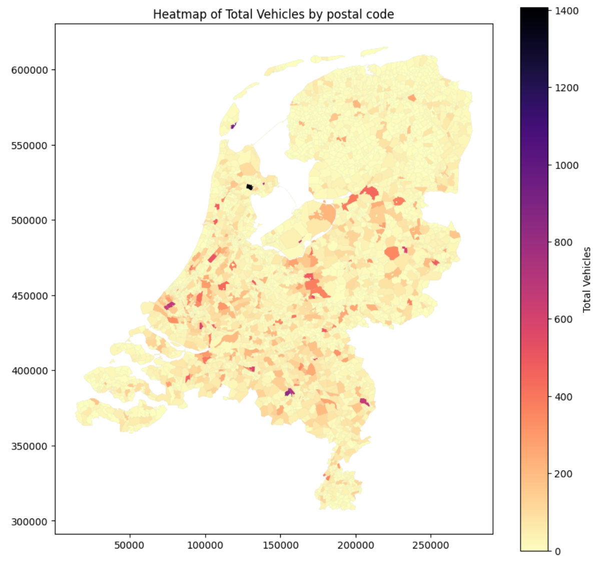

Figure 4.1: Registered trucks per postal code

An overview of the 5 postal codes with the most registered trucks is shown in Table 4.1. Google Maps [64] was utilised to examine these postal codes in more detail, aiming to understand why a significant number of trucks are registered there. The location with the most registered trucks is Wognum, the large logistics and transport company Simon Loos has its headquarters here so it makes sense that this place has the most registered trucks. It is remarkable that the postal code with the second most registered trucks is Oudeschild on the isle of Texel which is not directly connected by road to the mainland of the Netherlands. However, in Oudeschild is the headquarters of AB Texel which is a large logistics company. This again shows that this heat map gives some insight but not detailed on the real resting places of the trucks. The third an fifth postal codes lie within the city of Eindhoven, one contains the airport area and the other one an industry site full of large size distribution centres. The number 4 is in Zwaagdijk where the large retailer Action has its headquarters. So except for the trucks registered on the isle of Texel it can be assumed that at the other locations there will be a lot of truck activity.

Table 4.1: Top 5 postal codes with most registered trucks

Postal Code	City	Province	# Trucks
1678	Wognum	North-Holland	1408
1792	Oudeschild	North-Holland	932
5657	Eindhoven	Brabant	841
1681	Zwaagdijk	North-Holland	744
5651	Eindhoven	Brabant	718

XXL distribution centres (DC), which have a surface area of over 40,000 m² could also serve as potential locations for trucks to be based [65]. In the Netherlands there are in total 137 XXL distribution centres of which more than half of them are in the same 4 COROP regions. These COROP regions are: Groot-Rijnmond, Noord-Limburg, Midden-Noord-Brabant and West-Noord-Brabant [65]

Another location where trucks possibly will be based or orginate or destinate from are industry sites within the Netherlands, as these are the places where goods are produced. In Figure 4.2 a figure is shown with all areas in the Netherlands marked as industrial site [57]. It can be seen that some areas have larger industrial sites than other area within the Netherlands.

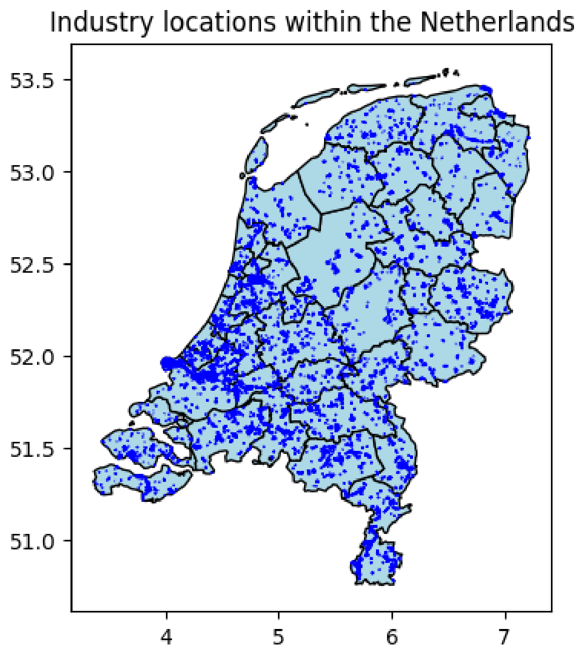

Figure 4.2: Industry locations in the Netherlands

4.1.2. Where do trucks drive?

Since this research aims to determine the optimal locations for public charging facilities, it is essential to understand where and how much trucks travel. As mentioned in subsection 4.1.1 there are so called XXL distribution centres which are potential locations where trucks originate and are destined. In Figure 4.3 these regions have been highlighted in light blue. In the same figure the truck flows from the dataset which has been explained in **??** are shown. In Figure 4.3 can be seen that around Eindhoven there is a lot of truck traffic which coincides with the registered trucks over there. The other places where a lot of truck traffic can be seen is between the COROP regions which have been highlighted in light blue which have the largest part of XXL Distribution centres as mentioned before. The truck flow also occurs on the EU's Trans-European Transport Network (TEN-T) [66], which plays a crucial role in facilitating efficient transportation of people and goods, supporting access to employment and services, and promoting trade and economic growth. The TEN-T framework also serves as a foundation for regulations on the establishment of recharging stations [66]. According to those regulations, from 2030 onwards, there must be a recharging facility with a minimum power output of 350 kW every 60 km along the TEN-T network.

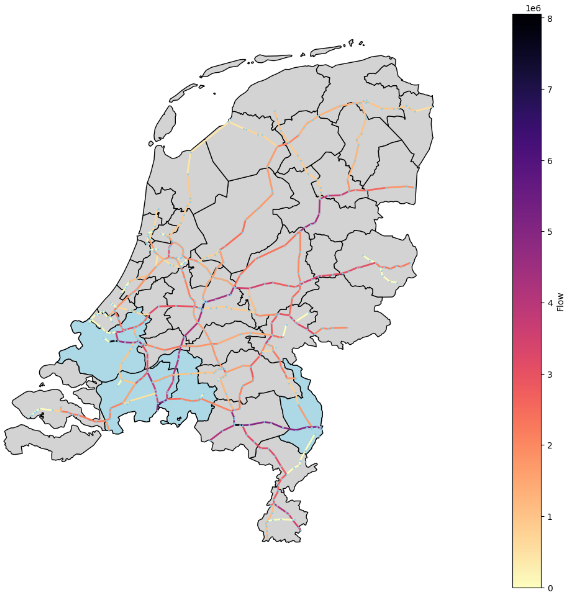

Figure 4.3: Yearly truck traffic flow 2019

4.1.3. How far do trucks drive?

For this research it is important to know how far trucks drive, as the range of HD BEV's is a potential constraint in their operation, this range together with the distance a truck drives also influences where it needs to recharge. According to CBS [4], trucks in the Netherlands typically travel around 70,000 km annually, averaging about 270 km per day, assuming they primarily operate on working days. Newer trucks tend to cover more distance, averaging approximately 100,000 km annually, or 385 km per day during their first three years [4]. In Figure 4.4 a figure is plotted with a statistic from the CBS [4]. This figure shows a bar plot of all transported goods in weight by distance class. It can be seen that almost 90% of transported goods do travel less then 300 kilometres. With the current range of HD BEV's a rough assumption can be made that 90% of trucks will be able to do this on one charge. However, this assumption has flaws in that this statistics also contain transportation of goods by vans and car trailers. Furthermore do trucks sometimes drive empty legs after delivering their goods which means they transport no weight over the way back.

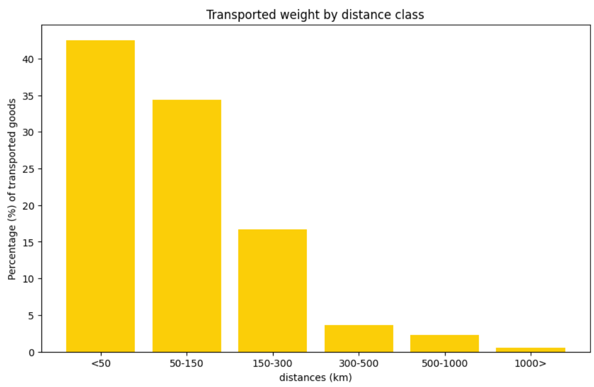

Figure 4.4: Transported weight by distance class

4.1.4. Operational types

The previous section on truck travel distances offers a general overview of how far trucks typically drive. However, logistics companies differ in their operations, with distinct categories such as city, regional, and long-haul transport. Each of these has unique driving patterns, operational constraints, and requirements. Understanding these different operational types is vital for this research, as they significantly influence driving distances and needs, which in turn affects the demand for private versus public charging infrastructure.

City
City logistics often represent the final stage of the logistics process, where for example goods are transported from a DC to a supermarket or store located in a city centre, by a HD BEV. These operations generally involve driving distances of up to 200 km per day [67]. Over the coming years, an increasing number of zero-emission zones will be implemented, with 20 city centres in the Netherlands introducing such zones by 2025 [68]. In the years following, additional zero-emission zones are expected [68]. Only zero-emission vehicles, such as HD BEVs, will be permitted to operate within these zones. City logistics routes often involve multiple stops [69], where limited space for charging infrastructure is a common issue. As a result, private charging at fleet owners facilities is likely to become a more attractive option for these operations.

Regional
In regional logistics goods are often transported between different DC, over distances of up to 400 km a day [67]. Unlike city logistics, these operations typically require fewer stops at public locations, reducing the need for public charging infrastructure. According to experts from the industry, the space available at DCs provides an ideal opportunity for HD BEVs to charge during loading and unloading activities. As a result, these vehicles can possible rely on private charging facilities at DCs and potentially on semi-public locations at their destination to fulfil their energy demand.

Long-Haul International
Long-haul logistics are often associated with international transport, which involve transporting goods over distances of up to 1,000 km a day [67]. These operations typically include extended routes that require drivers to take regular mandatory rest breaks and overnight stops at public locations. Due to the nature of these long journeys, vehicles in long-haul logistics are likely to rely on public charging infrastructure to meet most of their energy demands.

4.1.5. How do trucks currently refuel?

Currently conventional diesel trucks can also choose between refuelling at public sites or at a private refuelling location. After speaking to some experts within the field it can be said that trucks primarily refuel at public stations, where facilities are designed for the needs of heavy duty vehicles. However, some trucking companies opt for home base fuelling by installing private fuel tanks at their facilities. While this option offers more control over fuel costs and flexibility, it requires obtaining proper permits and complying with environmental and safety regulations. Companies must ensure the installation meets legal standards, with regular inspections and maintenance to prevent leaks or contamination. Though it involves an upfront investment, home base fuelling can be a cost-effective solution for fleets that return to a central hub regularly. Currently around 5% of the customers of Shell use a home base refuelling station.

4.2. HD BEV's Market Analysis

For this research, it is crucial to understand both the current state and future projections of the HD BEV's market. This involves examining the technical and economic specifications of HD BEV's that are currently available and those expected to enter the market in the near future. The specifications of HD BEV's in subsection 4.2.1 will give insights on potential constraints and inputs, such as limited range, costs, and energy consumption. Additionally, subsection 4.2.2 will give an understanding on the current market penetration of HD BEV's, along with forecasts for the future. Analysing current usage trends and future predictions will provide a foundation for assessing the charging demand and flow of HD BEV's in the coming years.

4.2.1. HD BEV's specifications

This subsection will provide insights in the technical and economical specification of HD BEV's currently available or coming in the near future. These will be compared to the specification of conventional trucks to give an insight in what could be potential constraints to the usage of HD BEV's. In Table 4.2

an overview is given based on the current specification for HD BEV's and a conventional truck all build by Mercedes [7]. This manufacturer was selected because they currently offer a HD BEV, are developing a more advanced HD BEV that will be available soon, and also have a similar diesel truck in their product lineup, which results in a good comparison.

Table 4.2: Truck Specs [7]

HD BEV			Diesel Truck	
	Current	Near Future		
Battery capacity	400 [kWh]	600 [kWh]	Fuel Capacity	400 [l]
Energy usage	1,3 [kWh]	1,3 [kWh]	Fuel usage	28,6 [l/100 km]
Range	300 [km]	460 [km]	Range	1400 [km]
Price	350.000 [euro]	500.000 [euro]	Price	130.000 [euro]

It can be seen that the current HD BEV and near Future HD BEV have a range which is far less then the range of a conventional diesel truck. But as explained in subsection 4.1.3 trucks on average do not drive more then 385 km a day so with the HD BEV coming in the near future this should be no problem. The price of the HD BEV's is higher, but fleet owners will probably use the total cost of ownership (TCO) for trucks, according to industry experts, which includes the purchase price, financing, fuel, maintenance, insurance, depreciation, taxes, and operational costs [70]. The TCO for HD BEV's is nearing parity with that of diesel trucks.

4.2.2. HD BEV's market penetration

Understanding how the adoption of HD BEV's will unfold in the coming years is crucial for developing the location model. Market penetration data can be used to estimate how many of the known truck flows will be made up of HD BEV's. In the Netherlands there are currently around 1000 registered HD BEV's on the road, this is 0.6 % of the total registered trucks according to the CBS [4]. More and more fleet owners are exploring the possibilities to renew their current fleet with trucks, as they need to reduce their emissions. It is expected that the number of HD BEV's registered in the Netherlands will increase drastically the coming years, in 2035 70% of all new sold trucks in Europe will be battery electric [71].

4.2.3. HD BEV's charging infrastructure

Part of the objective of this research is to determine the demand distribution between public, semi-public, and private charging. This section will provide an understanding of these three types of charging locations and outline the current state of each. First will be explained a bit about the available charging hardware and their economic and technical specifications. Afterwards the three different charging locations will be explained.

Chargers

There is a wide variety of chargers on the market, differing in price, charging speed, and potential use cases. Based on Bernard, Tankou, Cui, *et al.* [72] an overview of the most commonly available chargers and their intended applications is shown in Table 4.3. The charging times are calculated for a truck with a 400 kWh battery, based on a state of charge from 20% to 80%.

Table 4.3: Charger types [72]

Power Output [kW]	Charging time [Hours]	Installation costs [Euro]	Use Case
DC Charging CCS			
50	5	45.000	Overnight Depot/ Truck parking
150	1,5	90.000	Overnight Depot/ Truck parking
350	0.75	250.000	Opportunity Fast Charging Destination/ On-the-go
DC Charging MCS			
>1000	<0.5	>500.000	Opportunity Ultra Fast Charging Destination/ On-the-go

Public charging

Public charging facilities are accessible to everyone and are typically located in convenient, high-traffic areas. Common locations for these charging stations include parking lots, rest stops, and other public spaces where trucks naturally spend time, ensuring that charging is convenient and integrated into daily routines. Presently, there are approximately 125 public locations equipped with around 350 charging points that can facilitate HD BEV's [73]. The charging locations are spread out all across the Netherlands. However, a notable limitation is that not all of these locations are suited for use by tractor-trailer combinations, which are the primary configuration for heavy-duty trucking operations. The available charging points vary significantly in their power output, ranging from 100 kW to 350 kW. This range in power levels directly impacts the charging duration as explained in the previous section and can be seen in Table 4.3. For public charging facilities fast chargers are more convenient, as is expected they will more likely be used by trucks that are on a trip. The projected expansion of HD BEV's usage necessitates a substantial increase in the number of charging points. By 2030, it is estimated that the Netherlands will require around 3,400 public charging points to adequately support the expected growth in the HD BEV's fleet [74]. The current price for charging at a public facility lies around 0,60 euro per kWh.

Semi-public charging

Semi-public charging stations are located on private properties but are accessible to the public under certain conditions. These stations might be available for public use during specific hours or for particular groups, such as business partners or delivery services. For instance, a warehouse or distribution centre might have semi-public chargers that are available to truck drivers while they are loading or unloading goods, which can also be referred to as destination charging. This arrangement allows for efficient use of the charging infrastructure by aligning charging opportunities with other business activities, making it a convenient option for both the property owner and the users. After speaking to some industyr experts it has been found that semi-public charging infrastructure is currently not really available due to challenges related to regulations and contractual agreements.

Private charging

Private charging locations are exclusively available for use by specific individuals or groups, typically the property owners or designated users. These chargers are not open to the general public and are usually installed at private businesses or fleet facilities. The primary users of private charging stations are companies that maintain their own fleet of HD BEV's. Because these chargers are privately owned, access is controlled by the owner, ensuring that only authorised users can charge their vehicles. The cost per kWh at these private facilities is approximately 0.20 euros, significantly cheaper than public charging stations. However, installing private chargers comes with several challenges. According to Nationale Agenda Laadinfrastructuur (NAL) [75] fleet owners must evaluate their energy requirements, choose from various chargers with differing speeds and costs as seen in Table 4.3, obtain the necessary grid connection, which is an increasingly difficult task due to current grid congestion, and ensure they have the financial means to make the investment. Despite these challenges, private charging is expected to be used for the majority of the electricity demand for HD BEV's [76].

4.3. Conclusion Context Case Study

This conclusion will provide an answer to the first two sub-questions and will provide a general understanding and insights on the technical, economical and geographical perspectives regarding HD BEV's, charging facilities and the logistics sector in the Netherlands.

What is the current state of the logistics sector, what distances do they drive, where do they drive where do they refuel?

The distribution of trucks across the country provides some insight in where they might be charging overnight, and where trucks will originate from and what their destination could be. While truck registration data gives an overview of where vehicles are likely to be based, it does not always reflect the precise locations where trucks are stationed overnight or during idle periods. The locations of industry sites in the Netherlands can also be interesting as trucks are likely to originate and destinate at these locations, and will potentially serve their overnight or in between trip idling time, leading to an opportunity to recharge.

Truck traffic flow data indicates significant activity around major logistics hubs, particularly in regions with large XXL distribution centres and along the Trans-European Transport Network (TEN-T). The concentration of truck traffic in these areas aligns with the locations of registered trucks, especially around Eindhoven and the COROP regions Groot-Rijnmond and West-Noord-Brabant. These regions are critical for the planning of public charging infrastructure, as they are likely to experience heavy truck traffic and potentially higher demand for energy.

In terms of distance travelled, trucks in the Netherlands typically cover around 70,000 km annually, with newer vehicles averaging approximately 100,000 km per year. This translates to daily driving distances of 270 km for the average truck and up to 385 km for newer models. Notably, nearly 90 percent of transported goods travel less than 300 km, suggesting that a significant proportion of truck journeys could potentially be completed on a single charge by the current HD BEVs specifications. The operational types within the logistics sector are city, regional, and long-haul and define the the operation needs. City logistics, characterised by shorter routes and frequent stops, are likely to benefit from private charging facilities due to space constraints in urban areas. Regional logistics, involving medium distances between distribution centres, can potentially leverage private or semi-public charging during loading and unloading activities. Long-haul logistics, with extended routes and mandatory rest periods, will potentially depend more heavily on public charging infrastructure to meet their energy requirements.

In conclusion, the current state of the logistics sector in the Netherlands is marked by a strong dependence on road transport, with a clear need to strategically develop both private and public charging infrastructure to support the transition to HD BEVs. Understanding where trucks are based, the distances they drive, and other operational needs and constraints is essential for optimising the deployment of charging facilities, ensuring that the logistics network remains efficient and sustainable in the years to come.

What is the current state of charging facilities and HD BEV's in the Netherlands?
As of now, the market penetration of HD BEVs is limited, with around 1,000 registered HD BEVs on Dutch roads, accounting for only 0.6% of the total truck fleet. However, this number is expected to rise sharply as more fleet owners seek to reduce emissions and comply with stricter environmental standards. By 2035, it is anticipated that 70% of all new trucks sold in Europe will be battery electric, underscoring the critical need for a robust charging infrastructure.

In terms of specifications, current HD BEVs, such as those offered by Mercedes, have a range of around 300 km, with near-future models expected to achieve up to 460 km. While this range is considerably less than that of conventional diesel trucks, which can cover up to 1,400 km on a full tank, it is sufficient for many typical daily operations, as most trucks in the Netherlands do not drive more than 385 km per day. However, the higher purchase price of HD BEVs remains a potential barrier, although fleet owners are likely to consider the TCO when making purchasing decisions, which includes factors such as maintenance, fuel costs, and depreciation.

The charging infrastructure for HD BEVs in the Netherlands is still developing but is expected to grow significantly to meet future demand. Currently, there are approximately 125 public charging locations equipped with around 350 charging points capable of serving HD BEVs. These charging stations are dispersed throughout the country, but not all are suitable for larger vehicle configurations, such as tractor-trailer combinations. The power output of these public chargers varies, with options ranging from 100 kW to 350 kW, which directly affects charging times. In addition to public charging, semi-public and private charging facilities play an essential role in the overall infrastructure landscape. Semi-public chargers, which will be located at warehouses or distribution centres, allow for destination charging during loading and unloading operations. These chargers provide flexibility and convenience by aligning charging opportunities with business activities, although their availability to currently is limited. Private charging facilities, on the other hand, are typically owned by companies with their own fleets of HD BEVs. These chargers offer the lowest cost per kWh, around 0.20 euros, compared to public facilities, which charge approximately 0.60 euros per kWh. However, installing private chargers involves significant technical and financial challenges, such as securing the necessary grid connections.

In conclusion, while the current state of HD BEVs and charging facilities in the Netherlands is still evolving, the foundation is being laid for a substantial expansion in the near future. As HD BEV adoption increases, the development of a comprehensive and accessible charging infrastructure will be crucial to support the growing demand and ensure the integration of these vehicles into the logistics sector leading to less emissions.

5 Demand distribution estimation

This chapter will present the results derived from theoretical and expert knowledge, which will form the basis for the qualitative model. This qualitative model will utilize data gathered through surveys and interviews as input. The final section of this chapter will provide the results on demand distribution based on this model. These results correspond to the methodology explained in section 3.4

5.1. Theoretical base

To gain a comprehensive understanding of the needs and constraints of fleet owners, this section will first focus on researching these factors trough a literature review. By analysing the specific needs and operational constraints that fleet owners face, key insights into their charging behaviour can be identified. The current assumption based on the previous chapter is that fleet owners will primarily aim to charge 100% of their fleet at their private facilities, given the likely lower costs for charging at these locations including investments, maintenance and electricity prices. However, depending on the specific needs and constraints identified, such as operating larger distances beyond the range of a HD BEV, a portion of this demand may need to be supplied at public or semi-public facilities during operations. Based on the findings from this theoretical research, different fleet owner profiles will be developed, each reflecting a different type of fleet owner based on the determined characteristics. These profiles will then be used to analyse what characteristic could be used as a constraint for charging at private locations. The profiles will also give insights in what characteristics will be possible to use as an input for the charging demand.

5.1.1. Fleet owners characteristics

This section will provide a comprehensive analysis of the characteristics of fleet owners that can be utilised to assess their energy demand, as well as their constraints in fulfilling this demand at their private facilities. By identifying and understanding these characteristics, it will be possible to develop the fleet profiles and charging scenarios. As mentioned before that the current assumption is that fleet owners will try to charge their trucks most of the time at private locations. It seems relevant to explore the factors involved in the installation of private infrastructure. According to Andersen, Bach, and Teoh [77], fleet owners need to follow three key steps to establish private charging infrastructure: first, determine the energy demand by evaluating truck characteristics and their operational profiles; second, calculate the necessary number of charging points at the depot; and third, assess the depot's grid connection capacity and available space. The three steps mentioned will serve as a base in identifying factors and characteristics influencing the choice of fleet owners. Another study by Bae, Rindt, Mitra, *et al.* [78] on the decisions made by fleet owners regarding the installation of compressed natural gas fuelling infrastructure found that HDT fleet operators' were influenced by several motivators and barriers. These motivators and barriers can also be applied to this study, as it to some extend it is similar to installing private charging infrastructure. Key motivators found by Bae, Rindt, Mitra, *et al.* [78] for constructing on-site facilities included dissatisfaction with off-site fuelling due to higher fuel prices, travel and wait times, labour costs, and scheduling complexities. Larger fleets (20+ vehicles) were more likely to build on-site facilities. Barriers to constructing on-site facilities included high construction costs, complexities with utilities, maintenance challenges, and limited space. Financial incentives were identified as a facilitator for building on-site infrastructure. Both on-site and off-site users shared concerns about fuel security and the limited availability of off-site fuelling infrastructure.

The following categories have been identified to analyse factors influencing charging behaviour: fleet size, operation, origin location, destination location and other more subjective factors. Fleet size and operation will help with determining energy demand, with operation also highlighting potential constraints in fulfilling all demand at private locations, such as home to home trips exceeding the vehicle's range. Origin location will focus on depot related factors, such as space limitations that may affect private charging. Destination location will examine truck stopping location and consider potential constraints or opportunities for semi-public charging at those locations. In the following sub-sections, these categories will be further examined in terms of the characteristics within each. These characteristics will be analysed to determine whether they can serve as an input, a constraint, or a factor contributing to a general understanding of expected charging behaviour.

Fleet Size

In this category, the following three characteristics have been identified as potentially useful for determining charging behaviour:

- **Number of box-trucks:** this characteristic can be used as a input parameter in determining the total energy demand of a fleet owner together with the daily distance driven and the energy consumption of a HD BEV [77].
- **Number of tractors before trailers:** this characteristic can be used as a input parameter in determining the total energy demand of a fleet owner together with the daily distance driven and the energy consumption of a HD BEV. [77]
- **Number of HD BEVs:** this factor can help with understanding if a fleet owner already has some experience in the usage of HD BEVs.

Operation

In this category, the following factors have been identified as potentially useful for determining charging behaviour:

- **Operation Type:** can serve to get a general understanding in what kind of operations the fleet owner is involved: city logistics, regional transport or long-haul transport. In subsection 4.1.4 these operational types have been explained and in which way they may influence charging behaviour.
- **Daily kilometres driven:** This will help as an input in determining the total energy demand together with number of trucks and energy consumption [77]. It can also be used to determine if the range of a HD BEV is sufficient enough for the daily operation.
- **Number of trips per day:** A trip is a route of a truck that leaves it depot and comes back to a depot of the company. This can serve as an input for the private demand. If a truck is making multiple trips a day this could lead to recharging at the depot in between trips and thus not using public infrastructure.
- **Mandatory driver breaks:** By law truck drivers will have mandatory stopping breaks. In the Netherlands a driver needs to have a mandatory stopping break of 45 minutes every 4,5 hours [79]. This mandatory break could be used for charging of a HD BEV and as the driver is on the road this probably will be at a public location, but if a driver serves its breaks at the company depot the truck could potentially recharge at the private facility.

Origin Location

In this category, the following factors have been identified as potentially useful for determining charging behaviour:

- **Home to home kilometres:** This can serve as an input/constraint for the model, as it is possible that a trip is within range of the HD BEV. This could lead to recharging at at private depot instead of needing to recharging at a public location.
- **Overnight idling time at depot:** With this characteristic can be determined if it is possible to charge a HD BEV in the time it is at the depot overnight [77]. It could possibly be a constraint for not charging at a private location if the resting time at a depot is not sufficient for fully charging the battery. It is also important to determine whether all trucks are resting at the depot simultaneously.
- **Between trip idling time:** This is the same as with overnight idling time, it could be a constraint or opportunity to be able to charge within the idling time between trips at the depot. [77]
- **Public charger nearby:** When a public charger is available near the depot of a fleet owner, the fleet owner may choose to use this one instead of installing private chargers.
- **Available space for private chargers:** The space that is available for private chargers can be a constraint in the usage of private charging [77]. Insight from fleet owners after testing HD BEVs researched by UK Government [80] also revealed that available space is seen as a potential constraint by fleet owners. There is also the consideration within this factor of the desire to utilise the available space for chargers.
- **Available grid connection:** The grid connection that is available can be a constraint in the usage of private charging [77]. Insight from fleet owners after testing HD BEVs researched by UK Government [80] also revealed that there are concerns about available grid connections

Destination Location

In this category, the following two characteristics have been identified as potentially useful for determining charging behaviour:

- **Number of stops per trip:** Stops can serve as an opportunity to charge publicly or semi-publicly, for instance when a truck is loading/unloading it goods at a DC it can possible recharge. This can give a general insight of the operation and the choice to maybe recharge at every stop which also takes demand from private charging.
- **Average stopping time:** This is the same as overnight idling time and in between trip idling time. The time the truck is standing still will influence the amount of kWh it is able to recharge. [77]
- **Distance driven between stops:** Same reason as with home to home trips.
- **Public charger nearby:** When a public charger is available near the destination location, the fleet owner may choose to use this one when there is no charger available at the exact destination.
- **Private charger available:** When a private charge is available at the destination such as a DC, it may be possible to use it which will then be semi-public demand.

Other Factors

The previous four categories highlight the more technical reasons that could be used as input for demand or constrain fleet owners from charging at private facilities. However, fleet owners might also have some other reasons for choosing public over private charging. These other factors have been established by talking to experts within the field of eMobility and electrifying fleets, and from the study by Bae, Rindt, Mitra, *et al.* [78] on fleet owners decisions regarding compressed natural gas fuelling infrastructure, it is important to analyse the parallels with the installation of charging infrastructure. Both involve similar decision-making processes, including considerations such as cost, space utilization, and long-term operational benefits.

- **Investment costs:** This includes the initial expenses for setting up private charging stations, such as purchasing chargers, upgrading electrical systems, and possibly installing renewable energy sources like solar panels. These costs can be substantial but are a one-time investment. However, these costs could lead to fleet owners choosing for public over private charging, as these require a significant amount of initial capital.
- **Cost Delta:** This refers to the cost comparison between kWh prices for using private charging facilities versus public ones. Private charging might have lower per-kWh costs, but public charging can be more expensive per use. However, public charging eliminates the need for upfront

infrastructure investment. The height of this cost delta could influence the choice for charging privately.

- **Location ownership:** If the fleet owner owns the depot, they have more control over the installation and maintenance of private charging infrastructure. If the depot is rented or leased, there might be restrictions or additional negotiations required with the property owner. This could lead to using public charging infrastructure.
- **Moving out:** If the business is considering relocating, investing in private charging infrastructure might not be practical. Public charging facilities offer more flexibility in such scenarios, as they are not tied to a specific location.
- **Flexibility:** This is a factor related to the flexibility of their operations. With private infrastructure, fleet owners gain more control over their charging schedules. In contrast, public charging facilities offer flexibility in terms of location, allowing them to charge at various sites and align charging with their operational needs in that way.
- **Fleet transitions:** The factor of fleet transitions can give some insight in if a fleet owner will first charge publicly and later on privately or vice versa.
- **Driver factors:** It could be that fleet owners take into account that their drivers will have brakes at certain locations at which then a recharge can be done.

5.1.2. Fleet owners profiles with charging scenarios

Based on the earlier explained operational types in the logistics sector in subsection 4.1.4 and the factors provided in subsection 5.1.1 fleet owner profiles together with their expected theoretical charging behaviour will be developed. The profiles and theoretical behaviour will later be used together with the expert knowledge in developing the qualitative distribution model. These profiles and charging behaviour are also based on the current range of 300 kilometres of a HD BEV as explained in subsection 4.2.1. In Appendix A a complete overview of the developed theoretical charging behaviour can be found. For city logistics, fleet owners with ample space and chargers, like profile C1, can rely entirely on private charging, while those facing space limitations, such as profile C2, will need to make use of public charging. In regional operations, profile R1 can meet most of the charging needs at private facilities but may require additional charging at customer locations or during trips. Fleet owners profile R2, however, relies more heavily on public charging due to the longer distances and the constraints of having charging infrastructure at construction sites. For long-haul operations, profile LH1 utilises a combination of private, public, and semi-public charging options, enabled by dedicated routes and planned stops, while profile LH2, with varying routes and insufficient grid connections, depends entirely on public charging.

5.1.3. Conclusion on theoretical charging behaviour

In conclusion, the theoretical charging behaviour of the various fleet owner profiles is influenced by operational types, infrastructure availability, and driving distances and this will lead to different strategies. These varied charging strategies show that it is not feasible to apply a single charging profile to all fleet owners in the logistics sector, as their operations differ significantly. The theoretical charging behaviour presented here is based on the assumption that fleet owners will prioritize the most cost-effective option, with private charging generally being cheaper than public charging. This assumption, with the cost factor as a key motivator, will be further validated and explored in the expert knowledge chapter.

5.2. Expert knowledge

Before developing a qualitative model based on theoretical characteristics and charging scenarios, it's essential to research the real-world preferences of fleet owners. This section will present the results on the expert knowledge methodology from subsection 3.4.2

5.2.1. Interview results

All interview transcriptions were summarized and analysed to extract key learnings and insights that should be integrated into the distribution model and can can be found in **??**.

First it is necessary to see if the amount of interviews got to the saturation threshold. Table 5.1 present the amount of new themes emerging in every interview. The base amount of themes is determined by the theoretical base.

Table 5.1: New themes

	Theoretical base	Interview 1	Interview 2	Interview 3	Interview 4	Interview 5
New factors and challenges	25	4	1	1	1	0

Table 5.2 presents the calculated saturation for each run, where run one includes interviews 1 and 2, run two includes interviews 2 and 3, and so forth. After the fourth run, the saturation falls below the 5% threshold. This indicates that the five interviews conducted were sufficient to achieve a solid qualitative understanding of the factors influencing the charging behaviour of fleet owners.

Table 5.2: Saturation Calculation

	Base	Run	1	2	3	4
New themes	25		5	2	2	1
Saturation			20%	8%	8%	4%

The interviews with fleet owners provide valuable insights into their charging behaviours, preferences, and challenges related to charging HD BEVs. Across all interviews, cost consistently emerged as a primary factor in charging decisions. The expense of installing private chargers, particularly due to infrastructure upgrades, can be high, prompting some fleet owners to explore public charging options despite higher per-kWh costs. For others, the ability to manage costs through private charging infrastructure is preferable, especially when electricity rates are lower compared to public stations. Flexibility is another critical factor, particularly for fleet owners with tight schedules or diverse routes. Public charging offers some flexibility due to its potential widespread availability, but concerns were raised about the availability of public stations, particularly during peak times. In contrast, private charging provides more control but is often constrained by limitations in physical space and grid capacity.

Several challenges were identified, particularly in relation to space and grid capacity. Many fleet owners pointed out the lack of space for installing private chargers, limiting the scalability of private charging infrastructure. Additionally, limited grid connections can hinder the simultaneous charging of multiple vehicles at private facilities. Public infrastructure reliability also raised concerns, with public charging stations seen as potentially overcrowded at peak times. This is a key issue for fleet owners who need to charge during mandatory breaks or overnight at these public facilities. Ensuring the reliability and uptime of charging equipment is crucial, as any downtime can significantly impact operations. Most of the challenges identified regarding the use of private infrastructure are technical in nature and are possible to be resolved in the future.

Most fleet owners expressed an interest in expanding their electric fleets and adopting a hybrid approach to charging, combining private, public, and semi-public infrastructure. For long-haul operations, public charging is expected to play a larger role due to the long distances and fewer opportunities to return to the home base for charging. For more localised operations, private charging remains the preferred option due to cost savings, better control over scheduling, and the reliability of the equipment. There was also interest in semi-public charging at customer locations, particularly during loading and unloading times. This would provide a balance between control and flexibility, enabling fleet owners to charge vehicles without disrupting operations. Additionally, when charging at third-party locations, it is essential to have a clear contract outlining responsibilities in case of any malfunctions or issues.

The interviews confirm that no single charging solution fits all fleet owners due to differences in operations, vehicle types, and geographic locations. However, each fleet owner seeks to balance cost, control, operational efficiency, and the trustworthiness of equipment while managing the challenges of both private and public charging infrastructure. The interviews also indicate that fleet owners' charging preferences align with the established theoretical charging behaviour.

In Table 5.3 an overview is given of the key learnings from the interviews with fleet owners.

Table 5.3: Overview of Key Learnings from Fleet Owners

	Key Factors Influencing Charging Behaviour	Challenges Faced	Future Plans	Preferred Charging Setup
Fleet Owner 1	Cost, flexibility, operational efficiency, control	High installation costs for private chargers, space constraints	Expand electric fleet, hybrid charging approach	Hybrid setup: private, public, and semi-public charging
Fleet Owner 2	Cost, space and grid congestion, security of location	Space limitations, grid capacity, electricity cost	Expand electric vehicle operations, address space and grid limitations	Private charging preferred
Fleet Owner 3	Cost, flexibility, operational efficiency	High installation costs, space and network capacity	Expand fleet, consider public charging, explore semi-public charging	Private charging preferred, semi-public charging at customer locations under consideration
Fleet Owner 4	Cost, flexibility, operational efficiency, control	Lack of electric vehicles currently, reliability of public charging	Electrify specific routes when feasible, use public infrastructure	Public charging preferred, potential use of private and semi-public charging
Fleet Owner 5	Control, cost, operational efficiency, trustworthiness of equipment	High installation costs for private chargers, reliability issues with public charging	Use private charging setups at own facility, semi-public options at customer locations, public only for emergencies	Private charging preferred, semi-public charging at customer locations, public charging for emergencies

5.2.2. Survey results

All results from the questions used to gather input for the distribution model will be presented in subsection 5.3.2. This subsection will detail the findings regarding preferences for charging at private or public locations. The survey ultimately had 10 respondents, with fleet sizes ranging from 45 to 670 trucks. Although the number of respondents does not meet the required sample size as discussed in subsection 3.4.2, the total number of trucks they represent, 2,092, is a substantial number but not statistically significant, as they are not individual independent trucks. The sample includes small, medium-sized, and large companies, as well as businesses operating in various sectors such as city logistics, regional logistics, and long-haul operations. While the results can provide some insights, they should be interpreted with caution due to the limited number of respondents, making it challenging to generalize the findings to the entire population.

Results to more general questions

In this sub subsection the results to the more general questions in the survey are presented. 50% of the respondents currently operate battery electric vehicles within their fleet. Of all respondents, 44% have operations in regional logistics, 31% in long-haul logistics, 13% in city logistics, and 13% in other types of transport (such as garbage trucks and delivery of building materials). Regarding where their drivers take mandatory breaks: 20% do so at their own depot, 40% at public locations, 20% at destination locations, and 20% at other locations, with the specific choice depending on planning. Additionally, 90% of respondents indicated they would recharge their trucks during these mandatory breaks, although this depends on planning and the cost of charging at the location. The use of charging during mandatory breaks could have an upside potential to the usage of public charging as a significant amount of the fleet owners serve the breaks at public locations. While 30% of companies have sufficient physical space at their depot, the rest are constrained by space. None of the respondents would use all their available space to install chargers. When asked about using destination charging at customers' locations, most respondents answered they would use it, as long as it is available, but noted that this again depends on price and planning. Other factors mentioned as possible influencing the choice for charging at private locations were the ownership of the depot location and the extension of the fleet in the future.

Results to scenario questions

In this sub subsection the results to the scenario stated preference like questions are presented. The full scenario explanations can be found in Appendix D.

Scenario 1:
10 HD BEVs driving 100,000 km a year, private kWh price 20 cents, public kWh price 60 cents.

- Private charging yearly costs including depreciation: 315,000 euro, capital needed for installation 550,000 euro
- Public charging yearly costs: 780,000, no capital needed

Of all respondents 90% opted for private charging in this situation.

Scenario 2:
25 HD BEVs driving 50,000 km a year, private kWh price 20 cents, public kWh price 40 cents.

- Private charging yearly costs including depreciation: 417,500 euro, capital needed for installation 925,000 euro
- Public charging yearly costs: 650,000, no capital needed

Of all respondents 80% opted for private charging in this situation.

Scenario 3:
10 HD BEVs driving 100,000 km a year, private kWh price 20 cents, public kWh price 30 cents.

- Private charging yearly costs including depreciation: 315,000 euro, capital needed for installation 550,000 euro
- Public charging yearly costs: 390,000, no capital needed

Of all respondents 70% opted for private charging in this situation.

Scenario 4:
10 HD BEVs driving 100,000 km a year, private kWh price 30 cents, public kWh price 20 cents.

- Private charging yearly costs including depreciation: 445,000 euro, capital needed for installation 550,000 euro
- Public charging yearly costs: 390,000, no capital needed

Of all respondents 60% opted for private charging in this situation.

Scenario 5:
maintenance costs and availability.

- Private charging: fully responsible for maintenance and costs, availability 24/7 without waiting times.
- Public charging: no maintenance responsibility or costs, availability might be lower during peak times, resulting in waiting time.

Of all respondents 90% opted for private charging in this situation.

Scenario 6:
maintenance costs and availability.

- Private charging: fully responsible for maintenance and costs, availability 24/7 but during maintenance not available.
- Public charging: no maintenance responsibility or costs, availability based on bookable time slots.

Of all respondents 70% opted for private charging in this situation.

Scenario 7:
kWh price versus availability.

- Private charging: 20 cents per kWh, availability 24/7 without waiting times.
- Public charging: 45 cents per kWh, unpredictable availability possible waiting times.

Of all respondents 100% opted for private charging in this situation.

Scenario 8:
kWh price versus availability.

- Private charging: 35 cents per kWh, availability 24/7 without waiting times, fully control over charging planning.
- Public charging: 25 cents per kWh, unpredictable availability possible waiting times.

Of all respondents 60% opted for private charging in this situation.

Based on these results, it shows that a significant majority of respondents prefer private charging across various scenarios, primarily due to the control over costs, availability, and planning it offers. Even when public charging is less expensive, the predictability and convenience of private charging make it the favoured option for many. These insights suggest that while private charging is generally preferred, the decision ultimately depends on a balance of cost, convenience, and operational flexibility.

5.2.3. Conclusion on expert knowledge

In conclusion, the research reveals that fleet owners face several constraints when it comes to charging their HD BEVs. Key challenges include the high costs associated with installing private chargers, limited physical space at depots, and grid capacity issues that can hinder the simultaneous charging of multiple vehicles. Despite these constraints, a significant majority of respondents prefer private charging due to the control it offers over costs, availability, and scheduling. Overall, the preference for private charging is strong, but it is constraint by practical considerations such as installation costs and space limitations. Some fleet owners are interested in a hybrid approach that combines private, public, and semi-public charging infrastructure to balance cost, convenience, and operational efficiency. This strategy might help mitigating the constraints associated with each charging method, ensuring a more reliable and flexible charging solution for their diverse operational needs. Overall the results from the expert knowledge do align with the established theoretical base of charging behaviour.

5.3. Distribution Method

This section will present the developed qualitative distribution model, the inputs of the model and the results coming out of the model.

5.3.1. Development of the flow chart

Based on the theoretical framework for charging behaviour and expert knowledge, it can be said that fleet prioritize cost and control, while operating within their constraints. This leads to the assumption in the distribution model that fleet owners will opt for cost-effective and controllable options first. Consequently, fleet owners are expected to prefer private charging over semi-public charging, and semi-public charging over public charging. However, these preferences are subject to limitations imposed by their operational behaviour. The factors limiting this behaviour are detailed in subsection 5.1.1. To model this behaviour, a qualitative Excel model has been developed. This model uses specific decision rules, structured as a decision tree or flow chart, to allocate the total energy demand of a fleet owner, based on their preference for private charging, followed by semi-public and public charging, while considering operational and other constraints.

The model begins by calculating the total energy demand based on the number of trucks and the total kilometres driven. It assumes that each truck leaves the depot with a full state of charge whenever possible. Trucks will charge whenever necessary and feasible. The primary constraints for meeting this demand are based on the total kilometres driven, whether for home-to-home routes or stop-to-stop routes. When the kilometres driven exceed the truck's range, charging becomes necessary. Following this, other constraints are considered, such as the availability of space for chargers at private locations and sufficient time for recharging during stops. The flow chart does not explicitly account for the opportunity to charge during mandatory breaks. However, as noted in the previous section, this could potentially increase public charging. Given the operational constraints outlined in the flow chart, it is assumed that charging occurs at the most convenient times. It is assumed that driver breaks coincide with these moments, as companies aim to avoid unnecessary downtime for their trucks.

In Figure 5.1 the flow chart for the decisions in charging at private, public and semi-public are shown with the calculation for the amount of demand at these charging locations.

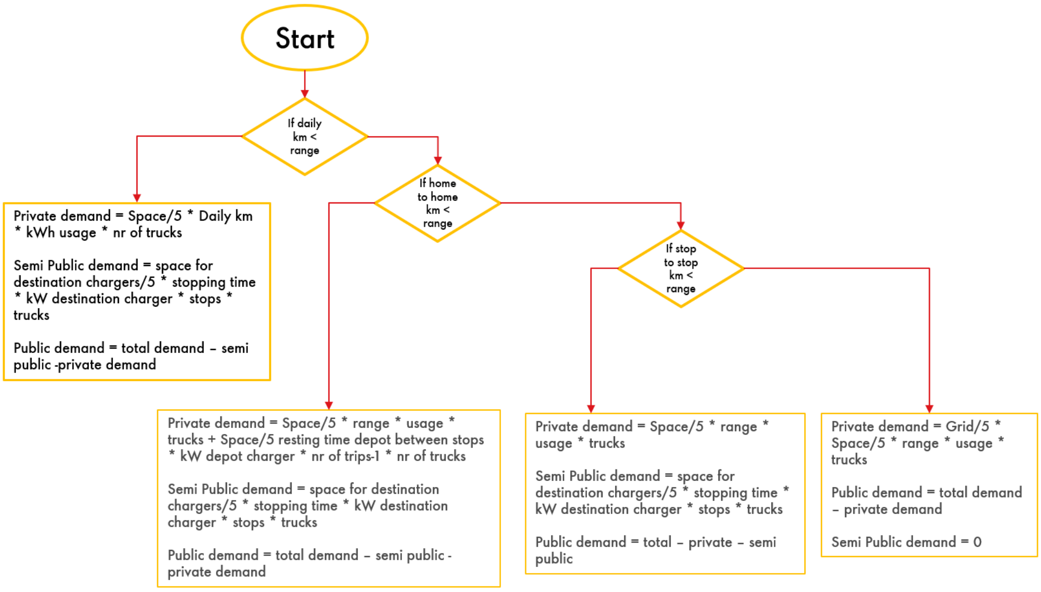

Figure 5.1: Flow chart for decision making demand model

5.3.2. Model input

The input for the model has been retrieved with the survey, from the interviews or data available form Shell on some of their customers. All inputs can be seen in **??**, the needed inputs were based on the theoretical charging behaviour and asked in the survey or interviews. The model can also take the battery capacity of the vehicles as an input. For this research is chosen to use three inputs 350 kWh, 500 kWh and 650 kWh. As they represent the batteries in HD BEVs getting larger over the coming years.

5.3.3. Model results

This subsection will present the results of the demand model on the three different battery size cases. In Table 5.4 are the results of the model given for a battery size of 350 kWh. It shows that potentially 63% of charging will be private, 4% will be semi-public and 33% will be public. The demand for private charging in this case is mostly constraint by the limited range of the vehicle to return to the home base.

Table 5.4: Results of demand model 350 kWh

Fleet owner	Total demand [kWh]	Private demand [kWh]	Semi-public demand [kWh]	Public demand [kWh]	% Private	% Semi-public	% Public
1	178750	38500	16500	123750	21.5%	9.2%	69.2%
2	161200	43400	0	117800	26.9%	0.0%	73.1%
3	87100	34840	13400	38860	40.0%	15.4%	44.6%
4	18200	18200	0	0	100.0%	0.0%	0.0%
5	65000	35000	1500	28500	53.8%	2.3%	43.8%
6	65000	35000	8000	22000	53.8%	12.3%	33.8%
7	110500	47600	5100	57800	43.1%	4.6%	52.3%
8	58500	31500	0	27000	53.8%	0.0%	46.2%
9	17550	9450	3600	4500	53.8%	20.5%	25.6%
10	468000	468000	0	0	100.0%	0.0%	0.0%
11	31200	26400	1600	3200	84.6%	5.1%	10.3%
12	50700	36400	2600	11700	71.8%	5.1%	23.1%
13	36270	26040	1162.5	9067.5	71.8%	3.2%	25.0%
Total	**1347970**	**850330**	**53462.5**	**444177.5**	**63%**	**4%**	**33%**

In Table 5.5, the results for a battery size of 500 kWh are presented. It indicates that the proportion of private demand is higher at 76%, while the proportion of public charging decreases to 20% compared to the 350 kWh battery scenario.

Table 5.5: Results of demand model 500 kWh

Fleet owner	Total demand [kWh]	Private demand [kWh]	Semi-public demand [kWh]	Public demand [kWh]	% Private	% Semi-public	% Public
1	178750	116875	16500	45375	65.4%	9.2%	25.4%
2	161200	62000	0	99200	38.5%	0.0%	61.5%
3	87100	34840	13400	38860	40.0%	15.4%	44.6%
4	18200	18200	0	0	100.0%	0.0%	0.0%
5	65000	50000	1500	13500	76.9%	2.3%	20.8%
6	65000	50000	8000	7000	76.9%	12.3%	10.8%
7	110500	68000	5100	37400	61.5%	4.6%	33.8%
8	58500	45000	13500	0	76.9%	23.1%	0.0%
9	17550	10530	3600	3420	60.0%	20.5%	19.5%
10	468000	468000	0	0	100.0%	0.0%	0.0%
11	31200	24960	1600	4640	80.0%	5.1%	14.9%
12	50700	40560	2600	7540	80.0%	5.1%	14.9%
13	36270	29016	1162.5	6091.5	80.0%	3.2%	16.8%
Total	**1347970**	**1017981**	**66962.5**	**263026.5**	**76%**	**5%**	**20%**

In Table 5.6, the results for a battery size of 650 kWh are presented. It indicates that the proportion of private demand is higher at 82%, while the proportion of public charging decreases to 14% compared to the 500 kWh battery scenario.

Table 5.6: Results of demand model 650 kWh

Fleet owner	Total demand [kWh]	Private demand [kWh]	Semi-public demand [kWh]	Public demand [kWh]	% Private	% Semi-public	% Public
1	178750	133375	16500	28875	74.6%	9.2%	16.2%
2	161200	64480	18600	78120	40.0%	11.5%	48.5%
3	87100	34840	13400	38860	40.0%	15.4%	44.6%
4	18200	18200	0	0	100.0%	0.0%	0.0%
5	65000	65000	0	0	100.0%	0.0%	0.0%
6	65000	65000	0	0	100.0%	0.0%	0.0%
7	110500	88400	5100	17000	80.0%	4.6%	15.4%
8	58500	58500	0	0	100.0%	0.0%	0.0%
9	17550	10530	3600	3420	60.0%	20.5%	19.5%
10	468000	468000	0	0	100.0%	0.0%	0.0%
11	31200	24960	1600	4640	80.0%	5.1%	14.9%
12	50700	40560	2600	7540	80.0%	5.1%	14.9%
13	36270	29016	1162.5	6091.5	80.0%	3.2%	16.8%
Total	**1347970**	**1100861**	**62562.5**	**184546.5**	**82%**	**5%**	**14%**

As battery size increases, the demand shifts from public charging to private charging. This aligns with expectations from interviews, surveys, and theoretical foundations. Fleet owners prefer private charging due to its potentially lower cost and greater control. Public charging is only utilised when operational constraints necessitate it. It can be observed that the percentage of private charging is eventually constrained to percentages such as multiples of 20%. This is potentially due to the survey asking for available physical space on a scale of 1-5. In the future, this question may need to be asked differently to obtain a more accurate distribution. However, for the purpose of this study, it provides insight into how fleet owners are constrained and how this develops over time.

5.4. Conclusion Demand Estimation

Concluding this chapter, research questions 3 and 4 can be answered.

What are the reasons, constraints, and needs for Installing Private or Using Public Charging Facilities?

Fleet owners face a variety of technical, economic, and subjective factors when deciding whether to install private charging facilities or use public charging facilities. The primary reasons for preferring private charging include lower operational costs, greater control over charging schedules, and enhanced operational efficiency as result. Private charging allows fleet owners to avoid the higher per-kWh costs associated with public charging and reduces dependency on the availability and reliability of public infrastructure.

However, several constraints limit the feasibility of private charging. High initial investment costs for installing private chargers, limited physical space at depots and grid capacity issues can restrict the number of chargers that can be installed and used simultaneously. These constraints can leead to fleet owners to consider public charging as an option.

Some fleet owners also express a need for flexibility in their operations. Public charging offers this flexibility, especially for long-haul operations where returning to the depot for charging is not feasible. Public charging is also seen as a necessary backup when private charging infrastructure is insufficient or unavailable due to space or grid limitations.

How can the reasons, constraints, and needs be translated into Demand Distribution model?

The reasons, constraints, and needs identified for installing private charging facilities or using public charging facilities can be translated into a demand distribution model that allocates charging demand between private and public facilities. This model considers the following factors:

- **Cost Efficiency**: Fleet owners prioritize private charging due to its lower cost per kWh compared to public charging. The model assumes that fleet owners will maximise the use of private charging until constrained by space or grid capacity.
- **Operational Constraints**: The model incorporates constraints such as the range of HD BEVs and the availability of space for chargers. When these constraints limit private charging, the model shifts the demand to public charging facilities.
- **Flexibility and Control**: The preference for private charging is driven by the need for control over charging schedules and operational efficiency. However, the model accounts for the necessity of public charging in scenarios where operational flexibility is required due to operational constraints while using HD BEVs.
- **Survey and Interview Insights**: Data from surveys and interviews with fleet owners provide support for the model's assumptions. Fleet owners' preferences and constraints, as revealed through these methods, are integrated into the model to ensure it reflects real-world decision-making processes. The survey and interviews also generated the data needed to use in the model.

The demand distribution model reveals the following allocation of charging demand between private and public facilities:

Table 5.7: Demand Distribution for Different Battery Scenarios

Battery Scenario	Private Demand	Semi-Public Demand	Public Demand
350 kWh	63%	4%	33%
500 kWh	76%	5%	20%
650 kWh	82%	5%	14%

These results show that private demand is the preferred option, but it is constrained by operational and depot location characteristics. However, as battery sizes increase, the demand shifts from public to private charging, as the operational constraints become less restrictive. This aligns with expectations from interviews, surveys, and theoretical foundations. Fleet owners prefer private charging due to its potentially lower cost and greater control. Public charging is only utilised when operational constraints necessitate it. The demand distribution model effectively translates the reasons, constraints, and needs of fleet owners into a practical framework for allocating charging demand between private and public facilities.

To obtain more accurate results, a larger survey should be conducted, as this research was limited by time and did not achieve statistical significance. Some questions, such as those regarding available physical space, could be asked differently, as the private demand is currently constrained by multiples of 20%. However, a solid framework for researching the distribution of demand has been established, and the outcomes and framework can serve as a basis for further research on this topic.

6

Location modelling results

This chapter will present the solution to the greedy algorithm and the solution to the model, as well as verify and validate the model for determining the optimal locations of charging infrastructure. The used model and greedy approach together with the explanation of the data sources can be found in chapter 3. This chapter will eventually answer research questions 5 and 6.

6.1. Greedy algorithm results

The developed greedy algorithm in subsection 3.5.2 will be used to obtain three different results. First the top 5 locations will be determined with all weights assigned equally to 0.25. In Table 6.1 the solution is shown. It can be seen that the total costs for the three cost columns is **28** and the total flow that passes these locations yearly is **8354878.75**. In Figure 6.1 a figure of the chosen locations is shown.

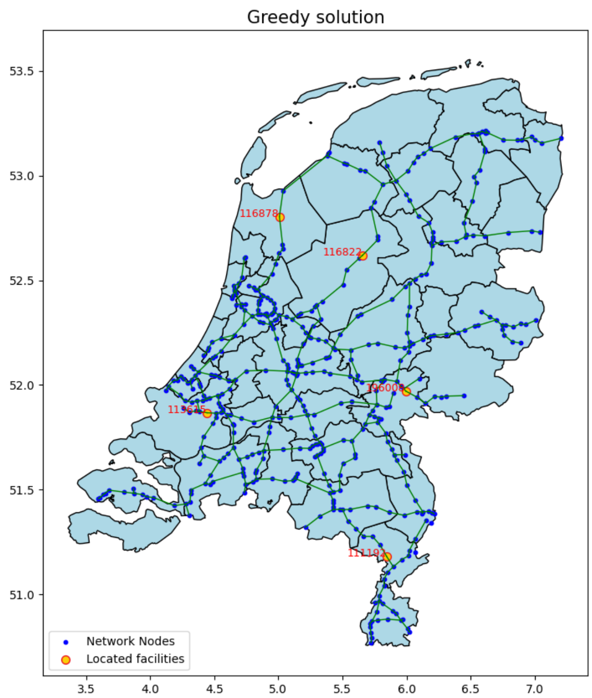

Figure 6.1: Greedy solution 5 locations equal weights

Table 6.1: Top 5 locations greedy algorithm

Network_Node_ID	Network_Node_X	Network_Node_Y	Grid_offtake	Current_std	Industry	Total_Flow
116822	5.657752	52.619594	3.0	1	1	1306349.00
116878	5.008787	52.804469	3.0	1	1	278418.00
111192	5.846700	51.179100	1.0	4	1	2305745.00
196008	5.994942	51.970424	4.0	1	1	2248331.00
113615	4.444600	51.867100	1.0	1	4	2216033.00
Total			**12.0**	**8**	**8**	**8354876.00**

In the second solution the top 10 locations will be determined while assigned equal weights. It can be seen in Table 6.2 that the total costs for the three cost columns is **58** and the total flow that passes these locations yearly is **16551976.00**. In Figure 6.2 a figure of the chosen locations is shown.

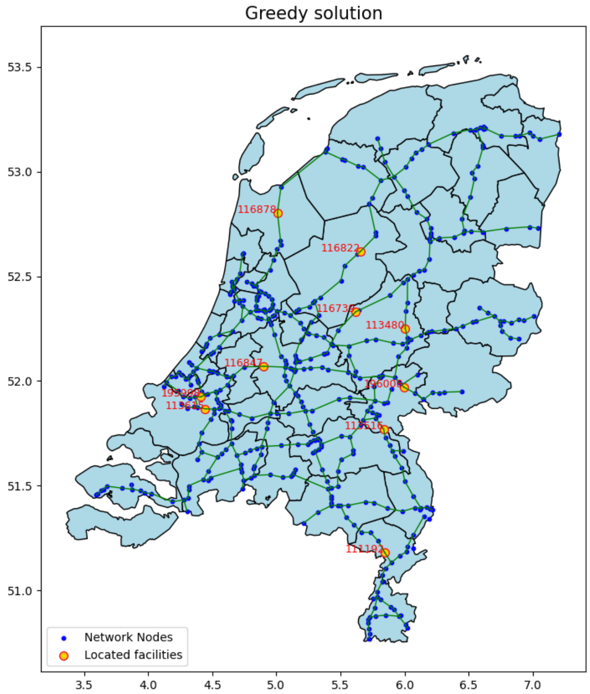

Figure 6.2: Greedy solution 10 locations equal weights

Table 6.2: Top 10 locations greedy algorithm

Network_Node_ID	Network_Node_X	Network_Node_Y	Grid_offtake	Current_std	Industry	Total_Flow
116822	5.657752	52.619594	3.0	1	1	1306349.00
116878	5.008787	52.804469	3.0	1	1	278418.00
111192	5.846700	51.179100	1.0	4	1	2305745.00
196008	5.994942	51.970424	4.0	1	1	2248331.00
113615	4.444600	51.867100	1.0	1	4	2216033.00
116739	5.619100	52.330300	4.0	1	4	2202436.00
113516	5.836800	51.770500	4.0	1	1	1844792.00
116847	4.902239	52.069980	4.0	4	1	1700074.00
195998	4.411253	51.923868	1.0	1	4	1319138.00
113480	6.005700	52.251200	4.0	1	1	1130656.00
Total			**29.0**	**13**	**16**	**16551976.00**

The third solution uses the weights based on the ranked approach, as explained in subsection 3.5.3, to benchmark the ranked weights approach. With the ranks in the following order rank 1: flow, rank 2: grid, rank 3: current std, rank 4: industry locations. It can be seen in Table 6.3 that the total costs for the three cost columns is **33** and the total flow that passes these locations yearly is **11586842.00**. In Figure 6.3 a figure of the chosen locations is shown.

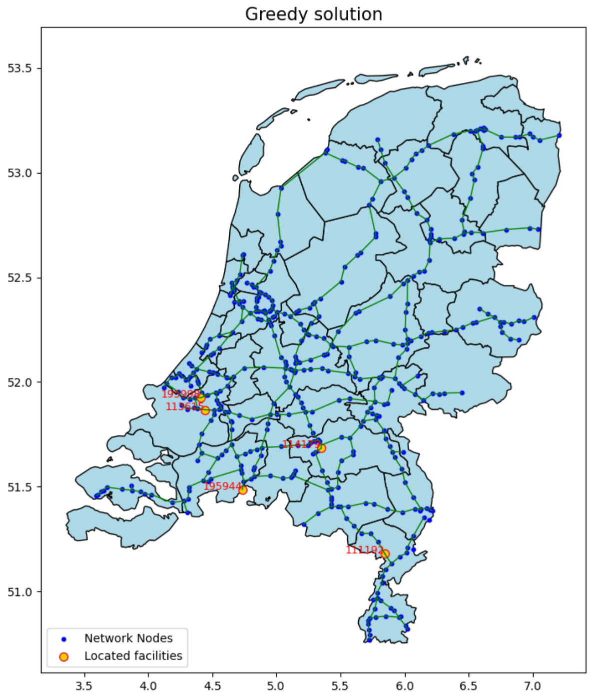

Figure 6.3: Greedy solution 5 locations ranked weights

Table 6.3: Top 5 locations greedy algorithm ranked weights

Network_Node_ID	Network_Node_X	Network_Node_Y	Grid_offtake	Current_std	Industry	Total_Flow
113615	4.444600	51.867100	1.0	1	4	2216033.00
195944	4.735079	51.486016	1.0	4	4	4902582.00
195998	4.411253	51.923868	1.0	1	4	1319138.00
114179	5.348896	51.683377	1.0	1	4	843342.00
111192	5.846700	51.179100	1.0	4	1	2305745.00
Total			**5.0**	**11**	**17**	**11586842.00**

The three different solutions demonstrate that achieving a higher amount of flow in the solution involves incurring higher costs. The ranked solution indicates that with only slightly more cost units than the equal weights top 5 solution, a significantly larger amount of flow is captured. This suggests that the greedy algorithm can provide a solution where, if flow is ranked higher, it can capture more flow without substantially increasing the cost.

6.2. Location model results

This section will present the results of the model, starting with verification and then moving on to validation. It will assess whether the model performs better than the greedy algorithm benchmark and behaves as intended.

6.2.1. Model verification

To verify the model, it will be compared to the greedy algorithm described in section 6.1. The inputs for the model will be aligned with those used in the greedy algorithm, with all objective function weights set to 0.25. The budget will be set at 28, matching the total cost of the greedy solution with 5 locations. Figure 6.4 shows the chosen locations obtained from the model.

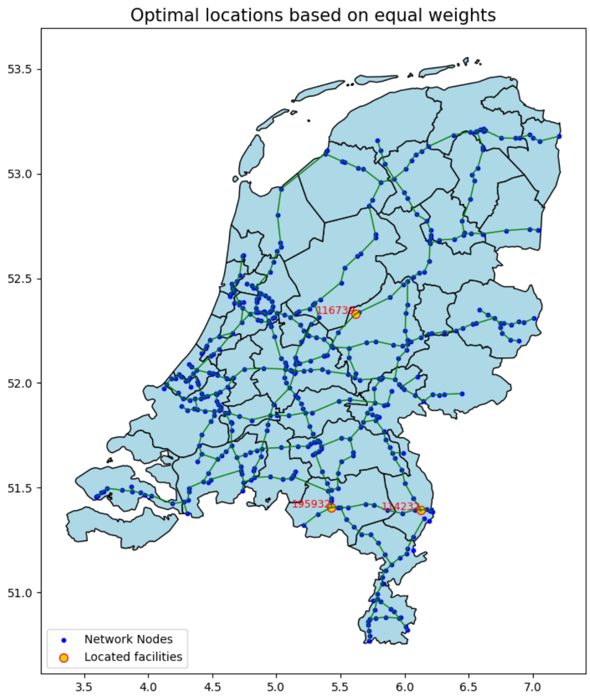

Figure 6.4: Model test solution

The results presented in Table 6.4 demonstrate that the model captures a significantly higher flow of **13,208,572.0** units compared to **8,354,876.00** units achieved by the greedy solution. Additionally, the total cost of **27** units is **1** unit lower than that of the greedy solution. This test indicates that the model provides a better solution.

Table 6.4: Test solution with equal weights and budget 28

Network_Node_ID	Network_Node_X	Network_Node_Y	Grid_offtake	Current_std	Industry	Total_Flow
195932	5.431533	51.405376	4.0	4	4	6235060.0
116739	5.619100	52.330300	4.0	1	1	2202436.0
114232	6.128000	51.393200	4.0	1	4	4771076.0
Total			**12.0**	**6**	**9**	**13208572.0**

The budget is thereafter set at 58, matching the total cost of the greedy solution with 10 locations. Figure 6.5 shows the chosen locations obtained from the model. The results presented in Table 6.5 demonstrate that the model captures a significantly higher flow of **25407938.0** units compared to **16551976.00** units achieved by the greedy solution. Additionally, the total cost of **53** units is **5** units lower than that of the greedy solution. This test indicates that the model provides a better solution also in this case.

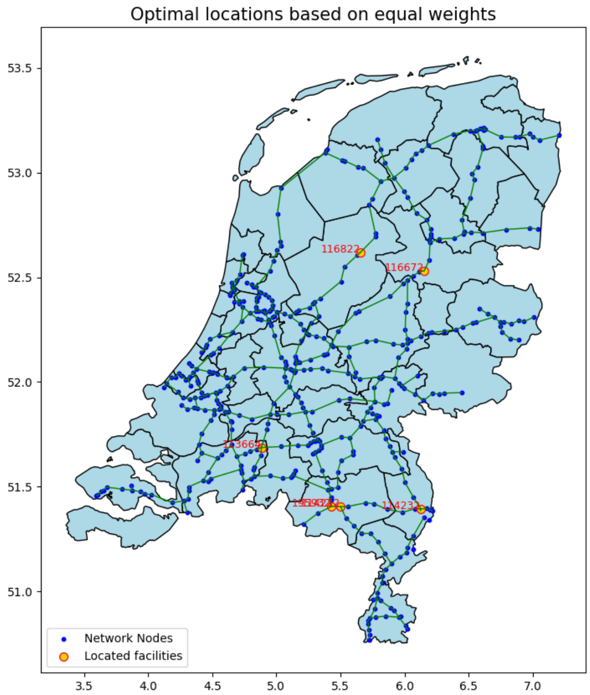

Figure 6.5: Model test solution with equal weights and budget 58

Table 6.5: Test solution with equal weights and budget 58

Network_Node_ID	Network_Node_X	Network_Node_Y	Grid_offtake	Current_std	Industry	Total_Flow
195932	5.431533	51.405376	4.0	4	4	6235060.0
116739	5.619100	52.330300	4.0	1	1	2202436.0
114232	6.128000	51.393200	4.0	1	4	2305745.0
114212	5.501600	51.404100	4.0	4	4	6235060.0
113664	4.883500	51.686400	4.0	1	4	3527300.0
116822	5.657752	52.619594	3.0	1	1	1306349.0
Total			**23.0**	**12**	**18**	**25407938.0**

The budget is thereafter set at 33, matching the total cost of the greedy solution with ranked weights and 5 locations. With the ranks in the following order rank 1: flow, rank 2: grid, rank 3: current std, rank 4: industry locations. Figure 6.6 shows the chosen locations obtained from the model. The results presented in Table 6.6 demonstrate that the model captures a higher flow of **15780956.0** units compared to **11586842.00** units achieved by the greedy solution. Additionally, the total cost of **33** units which is equal to the greedy solution. This test shows that the model also performs better with the ranked weights and is able to capture more flow with the same budget.

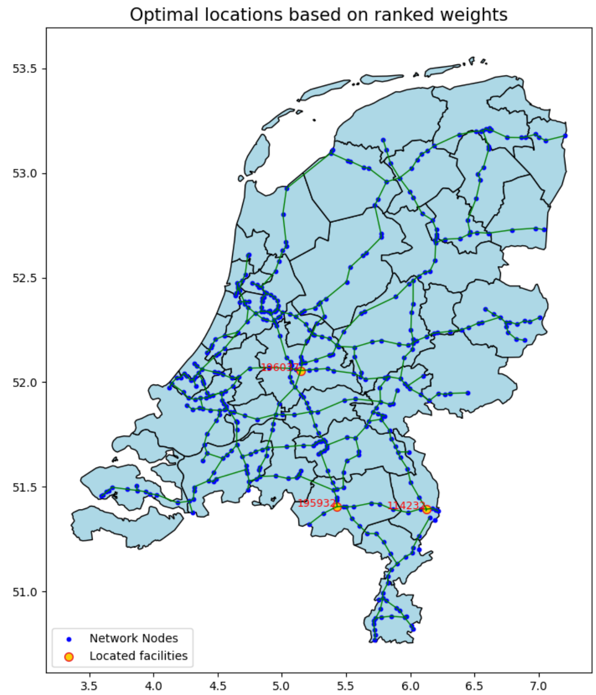

Figure 6.6: Model test solution with ranked weights and budget 33

Table 6.6: Test solution with ranked weights and budget 33

Network_Node_ID	Network_Node_X	Network_Node_Y	Grid_offtake	Current_std	Industry	Total_Flow
196037	5.144816	52.055205	4.0	4	4	4774820.0
195932	5.431533	51.405376	4.0	4	4	6235060.0
114232	6.128000	51.393200	4.0	1	4	4771076.0
Total			**12.0**	**9**	**12**	**15780956.0**

Overall, these results indicate that the model provides a superior solution by capturing more flow at lower or equivalent costs compared to the greedy solution in all different test cases. This verifies the effectiveness of the model in optimizing the locations for charging infrastructure.

6.2.2. Model validation

To thoroughly evaluate the robustness and performance of the model, a sensitivity analysis will be conducted on both the flow parameter and the cost parameters. This analysis aims to understand how variations in these parameters affect the model's outcomes [81]. For this sensitivity analysis a one at a time approach will be used, with this method a sensitivity ranking can be obtained quickly by increasing or decreasing each parameter by a given percentage while leaving all others constant, and quantifying the change in model output [81].

Cost parameters

The cost parameters will be systematically varied by increasing and decreasing them by 10%. This approach helps in assessing the model's sensitivity to changes in costs, which is crucial given the budget constraint. Specifically, the following steps will be taken:

1. Baseline Costs: The model will first be run with the original cost parameters to establish a baseline performance.
2. Increased Costs: The costs will be increased by 10%, and the model will be re-evaluated to observe the impact on the total flow captured and the selection of facilities.
3. Decreased Costs: Similarly, the costs will be decreased by 10%, and the model will be run again to compare the results with the baseline and increased cost scenarios.

The given budget for the model is set at 28 units, which is the same as in the greedy solution and the test case. The sensitivity analysis results, as shown in Table 6.7, indicate the following: With the original cost parameters, the model opens 3 facilities, incurs a total cost of 27 units, and captures a total flow of 13,311,882.00 units. Decreased Costs (Sensitivity 0.9): the model still opens 3 facilities and incurs a total cost of 27 units, but captures a higher total flow of 14,533,436.00 units. This shows that the model can utilise the budget more effectively when costs are lower. Increased Costs (Sensitivity 1.1): the model can only afford to open 2 facilities within the budget, leading to a slightly lower total cost of 26.4 units and a reduced total flow captured of 12,470,120.00 units. This demonstrates the impact of higher costs on the model's ability to capture flow within the budget constraint.

Table 6.7: Cost Sensitivity Analysis

Sensitivity	Number of Opened Facilities	Total Costs	Total Flow Captured
0.9	3	27	14,529,429.00
1	3	27	13,208,572.0
1.1	2	26.4	11,887,715.00

These results highlight the impact of cost variations on the model's performance. The model adheres to the budget constraint in all scenarios, but the number of facilities opened and the total flow captured vary with changes in costs. The sensitivity analysis demonstrates that the model is robust under varying cost conditions. It consistently adapts to changes in costs by adjusting the number of facilities opened and the total flow captured, while still operating within the given budget constraint. This robustness ensures that the model can provide reliable and effective solutions even when faced with fluctuations in cost parameters.

Flow parameter

For the flow parameter the same structured sensitivity analysis will be done increasing and decreasing the values by 10

The given budget for the model is set at 28 units, which is the same as in the greedy solution and the test case. The sensitivity analysis results, as shown in Table 6.8, indicate the following: With the original flow parameters, the model opens 3 facilities, incurs a total cost of 27 units, and captures a total flow of 13,311,882.00 units. Decreased Flow (Sensitivity 0.9): the model still opens 3 facilities and incurs a total cost of 27 units, but captures a lower total flow of 11,820,494.00 units. This shows that the model's performance decreases with lower flow values. Increased Flow (Sensitivity 1.1): the model opens 3 facilities, incurs a total cost of 27 units, and captures a higher total flow of 14,447,270.00 units. This demonstrates the model's ability to capture more flow when the flow is increasing.

Table 6.8: Flow Sensitivity Analysis

Sensitivity	Number of Opened Facilities	Total Costs	Total Flow Captured
0.9	3	27	11,887,715.00
1	3	27	13,208,572.0
1.1	3	27	14,529,429.00

These results highlight the impact of flow variations on the model's performance. The model adheres to the budget constraint in all scenarios, but the total flow captured varies with changes in flow values. The sensitivity analysis demonstrates that the model is robust under varying flow conditions. It consistently adapts to changes in flow by adjusting the total flow captured, while still operating within the given budget constraint.

Weight parameters

This section will provide a sensitivity analysis on the weight parameters. By establishing a base scenario and then systematically changing the weight parameters by decreasing or increasing them by 0.1 while maintaining a total weighted sum of 1.

Table 6.9: Sensitivity Analysis on Weight Parameters

Scenario	Weights [w_1, w_2, w_3, w_4]	Total Cost	Total Flow	Number of Facilities
Base Scenario	[0.25, 0.25, 0.25, 0.25]	27	13,208,572.0	3
Scenario 1	[0.15, 0.2833, 0.2833, 0.2833]	11	3,612,095.0	2
Scenario 2	[0.35, 0.2167, 0.2167, 0.2167]	27	13,208,572.0	3
Scenario 3	[0.2833, 0.15, 0.2833, 0.2833]	27	13,208,572.0	3
Scenario 4	[0.2167, 0.35, 0.2167, 0.2167]	27	11,851,642.0	3
Scenario 5	[0.2833, 0.2833, 0.15, 0.2833]	28	11,716,263.0	4
Scenario 6	[0.2167, 0.2167, 0.35, 0.2167]	26	11,631,469.0	3
Scenario 7	[0.2833, 0.2833, 0.2833, 0.15]	27	13,222,169.0	4
Scenario 8	[0.2167, 0.2167, 0.2167, 0.35]	28	11,716,263.0	4

The impact on total cost varies across different scenarios. In Scenario 1, lowering the weight for flow maximization to 0.15 and increasing the weights for cost minimization to 0.2833 significantly reduced the total cost to 11 and the number of facilities to 2, indicating a strong focus on cost minimization. In Scenarios 2, 3, 4, 6, and 7, the total cost remained stable around 26-27, showing the model's robustness to weight changes within this range. In contrast, Scenarios 5 and 8 saw the total cost increase slightly to 28, suggesting that higher weights for specific cost components can lead to marginally higher costs.

The impact on total flow also shows notable differences. In Scenario 1, the total flow dropped significantly to 3,612,095.0, highlighting the trade-off between cost minimization and flow maximization. In Scenarios 2 and 3, the total flow remained unchanged at 13,208,572.0, indicating that changes in weights for flow maximization or cost components do not significantly impact the flow. Scenarios 4, 5, 6, and 8 saw the total flow decrease to around 11,716,263.0 - 11,851,642.0, showing that higher weights for cost minimization can reduce the flow captured. Scenario 7, however, saw a slight increase in total flow to 13,222,169.0, suggesting that balanced increases in weights for cost minimization do not drastically affect the flow.

The number of facilities also varied across scenarios. In Scenario 1, the number of facilities decreased to 2, reflecting the model's focus on minimizing costs. In Scenarios 2, 3, 4, and 6, the number of facilities remained at 3, indicating stability in the model's performance. In Scenarios 5, 7, and 8, the number of facilities increased to 4, showing that higher weights for specific cost components can lead to opening more facilities.

The sensitivity analysis on the weights reveals that the model is robust to small changes in weights but shows significant variations in total cost and flow when weights are adjusted more substantially. Decreasing the weight for flow maximization and increasing the weights for cost minimization can lead to lower costs but also significantly reduce the total flow captured. Conversely, increasing the weight for flow maximization does not lead to more flow, possibly due to the budget constraint. This behaviour aligns with the expected trade-offs between cost minimization and flow maximization, as well as the impact of weight adjustments on total cost, flow, and the number of facilities.

6.3. Conclusion Location Model

In this thesis, a comprehensive location model has been developed for the optimal placement of on-the-go charging facilities for HD BEVs. The model integrates various data inputs, including flow data, grid congestion, current Shell truck diesel sites, and small industry locations, to ensure a robust and practical solution. In this conclusive section research questions 5 and 6 can be answered.

What are relevant technical and economic constraints for the location of on-the-go charging facilities for battery electric trucks?
The relevant technical and economic constraints for the location of on-the-go charging facilities include:

- **Grid Congestion**: The availability and capacity of the electrical grid at potential charging locations are critical. Areas with high grid congestion may face challenges and higher costs for infrastructure upgrades, making them less suitable for new charging facilities.
- **Proximity to Existing Infrastructure**: Locations near existing Shell truck diesel sites or small industry sites with high accessibility and parking availability are preferred. These sites can leverage existing infrastructure, reducing the need for extensive new installations.
- **Flow Data**: The volume of truck traffic and the flow of goods between regions are essential for determining the demand for charging facilities. High-traffic routes are prioritized to maximise the utilization of the charging infrastructure.
- **Range of HD BEVs**: The driving range of HD BEVs is a crucial factor. Charging facilities need to be strategically placed within the range limits to ensure that trucks can complete their routes without running out of power.

How can these constraints be translated into a mathematical model or scenarios? To address these constraints, a mathematical model is developed that incorporates the following elements:

- **Objective Function**: The model aims to maximise the captured flow of electric trucks while minimising the total costs associated with installing the charging facilities. This dual objective ensures that the selected locations are both economically viable and meet the demand.
- **Constraints**: The model includes constraints for budget limitations, and the range of HD BEVs. These constraints ensure that the selected locations are feasible, cost-effective, and within the operational range of the vehicles.

To ensure the reliability and effectiveness of the model, verification and validation processes were conducted:

- **Verification**: The model's performance was evaluated against a greedy algorithm, and the results demonstrated that the model consistently outperformed the greedy solution. It captured more flow at lower or equivalent costs across all test cases, confirming its effectiveness in optimizing the locations for charging infrastructure.
- **Validation**: A sensitivity analysis was performed on both the flow and cost parameters to assess the model's robustness. The analysis involved varying these parameters by $\pm 10\%$ and observing the impact on the model's outcomes. The results showed that the model consistently adhered to the budget constraint and adapted to changes in costs and flow, demonstrating its robustness under varying conditions. The sensitivity analysis on the weights showed that the model is robust to small changes in weights but exhibits significant variations in total cost and flow when weights are adjusted more substantially. Reducing the weight for flow maximization and increasing the weights for cost minimization can lead to lower costs but also significantly reduce the total flow captured. Conversely, increasing the weight for flow maximization does not result in more flow, possibly due to the budget constraint. This behaviour does align with the expected trade-offs between cost minimization and flow maximization, as well as the impact of weight adjustments on total cost, flow, and the number of facilities. So the model is robust for determining the optimal locations.

7

Numerical experiments to determine the optimal charging locations

For the case study on developing the optimal charging infrastructure network for (HD BEVs, a scenario analysis will be conducted using the model. Scenarios are employed in decision-making and strategic planning. They enable the development of options and indicators for action [82]. Additionally, scenarios facilitate the evaluation of decision-making processes, actions, and strategies. Typically, multiple alternative scenarios are compared to illustrate different future developments and to assess the consequences of various decisions against a virtual backdrop. This approach helps test the reliability, robustness, and effectiveness of decisions [82]. According to Kosow and Gaßner [82], scenarios are defined as possible future situations, or conceptual futures, which include the paths of development that may lead to those situations. Therefore, the scenarios aim to provide insights into the development of the optimal charging network over the coming years.These scenarios are developed based on the knowledge gained during this research, current conditions, expert insights, market predictions, and findings from earlier stages of the study.

7.1. Scenario 1: Grid congestion and limited adoption of HD BEVs

Grid congestion significantly limits the power available for new charging stations. Shell chooses to build chargers at its own locations due to their established infrastructure and reliability. The adoption rate of HD BEVs remains low, indicating the market is still in its early stages. Public charging is preferred because the investment for private depot charging is substantial. Companies are exploring the use of HD BEVs, but range limitations necessitate public charging to fulfil operations, affecting the turn-in ratio. Smaller trucking companies have not yet transitioned to HD BEVs due to higher costs, making smaller industry sites less appealing. Equation 3.4.

Table 7.1: Model Input scenario 1

Parameter	**Value**
Flow weight	Rank 1
Grid weight	Rank 2
Current Std weight	Rank 3
Industry Sites Weight	0
Budget	10
Range of HD BEV	350 km

Figure 7.1 and Table 7.2 show that the model picked 4 locations with a total potential yearly traffic flow passing by of 7711607.00 trucks.

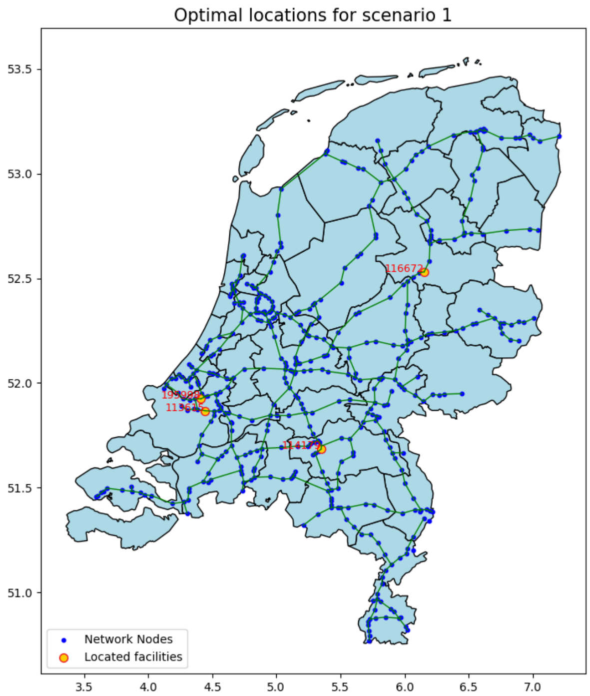

Figure 7.1: Results for scenario 1

Table 7.2: Solution scenario 1

Network_Node_ID	Network_Node_X	Network_Node_Y	Grid_offtake	Current_std	Total_Flow
195998	4.411253	51.923868	1.0	1	1319138.00
116672	6.153900	52.531200	3.0	1	3333092.00
114179	5.348896	51.683377	1.0	1	843342.00
113615	4.444600	51.867100	1.0	1	2216033.00
Total			**6**	**4**	**7711607.00**

7.2. Scenario 2: Moderate HD BEV Adoption with Grid Congestion

Grid congestion remains an issue, though less severe than in scenario 1. Some Shell sites have been selected, but they are still favoured over other locations. The adoption of heavy-duty BEVs by smaller companies is increasing, making small industrial sites somewhat appealing. As the market for HD BEVs grows and their range improves, depot charging is becoming more relevant for larger companies affecting the turn in ratio.

Table 7.3: Model Input scenario 2

Parameter	Value
Flow weight	Rank 1
Grid weight	Rank 2
Current Std weight	Rank 3
Industry Sites Weight	Rank 4
Budget	40
Range of HD BEV	400 km

Figure 7.2 and Table 7.4 show that the model picked 4 locations with a total potential yearly traffic flow passing by of 17866529.00 trucks.

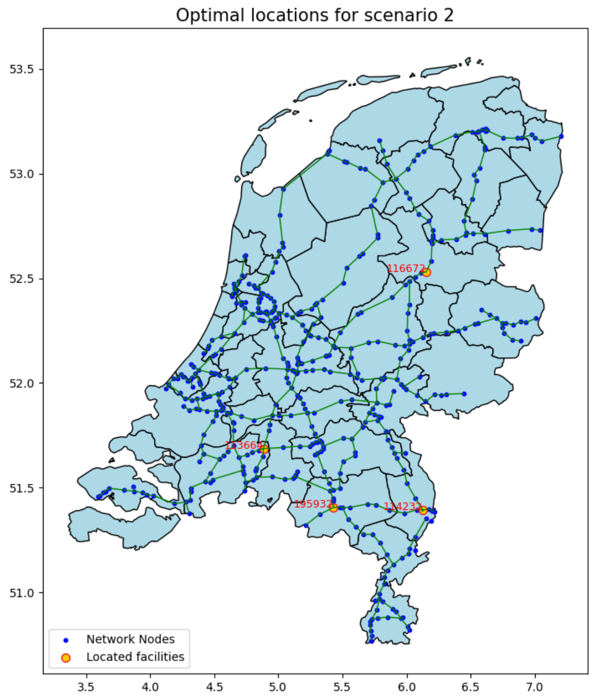

Figure 7.2: Results for scenario 2

Table 7.4: Solution scenario 2

Network_Node_ID	Network_Node_X	Network_Node_Y	Grid_offtake	Current_std	Industry	Total_Flow
195932	5.431533	51.405376	4.0	4	4	6235060.00
116672	6.153900	52.531200	3.0	1	4	3333092.00
114232	6.128000	51.393200	4.0	1	4	4771076.00
113664	4.883500	51.686400	4.0	1	4	3527300.00
Total			**15**	**7**	**16**	**17866529.00**

7.3. Scenario 2a:

Compared to scenario 2, the budget is doubled to 80 for scenario 2a while the other inputs remain the same, allowing for more investments in locations due to the rising heavy-duty BEV market.

Figure 7.3 and Table 7.5 show that the model picked 4 locations with a total potential yearly traffic flow passing by of 35995025.00 trucks.

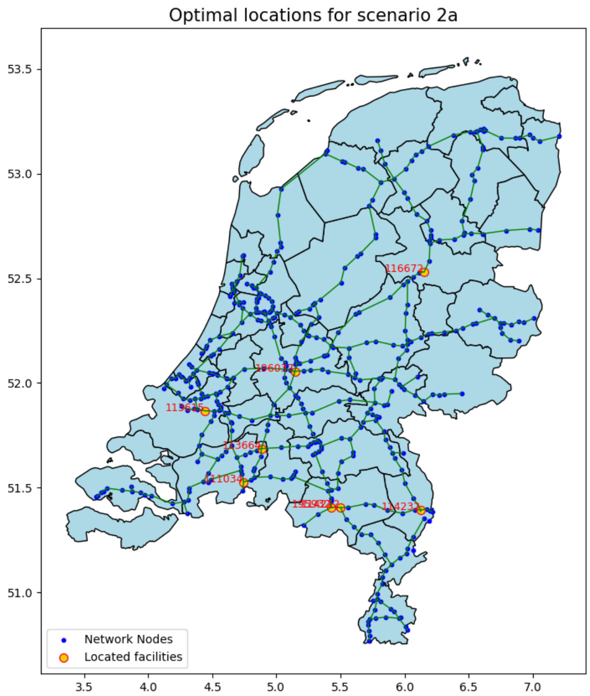

Figure 7.3: Results for scenario 2a

Table 7.5: Solution scenario 2a

Network_Node_ID	Network_Node_X	Network_Node_Y	Grid_offtake	Current_std	Industry	Total_Flow
196037	5.144816	52.055205	4.0	4	4	4774820.00
195932	5.431533	51.405376	4.0	4	4	6235060.00
116672	6.153900	52.531200	3.0	1	4	3333092.00
114232	6.128000	51.393200	4.0	1	4	4771076.00
114212	5.501600	51.404100	4.0	4	4	6235060.00
113664	4.883500	51.686400	4.0	1	4	3527300.00
111034	4.745600	51.526500	4.0	4	4	4902582.00
113615	4.444600	51.867100	1.0	1	4	2216033.00 5
Total			**28**	**20**	**32**	**35995025.00**

7.4. Scenario 3: Increased HD BEV Adoption with Reduced Grid Congestion

In scenario 3, grid congestion is no longer an issue, which significantly improves the feasibility of various locations. Shell truck sites are still preferred due to their strategic advantages, but small industrial sites are also becoming increasingly attractive. This shift is driven by the growing adoption of HD BEVs by smaller companies, which find these sites suitable for their operations. Additionally, as the range of HD BEVs continues to improve, this will influence the turn in ratio to public charging facilities.

Table 7.6: Model Input scenario 3

Parameter	Value
Flow weight	Rank 1
Current Std weight	Rank 2
Industry weight	Rank 3
Grid offtake weight	0
Budget	20
Range of HD BEV	500 km

Figure 7.4 and Table 7.7 show that the model picked 4 locations with a total potential yearly traffic flow passing by of 17600360.00 trucks.

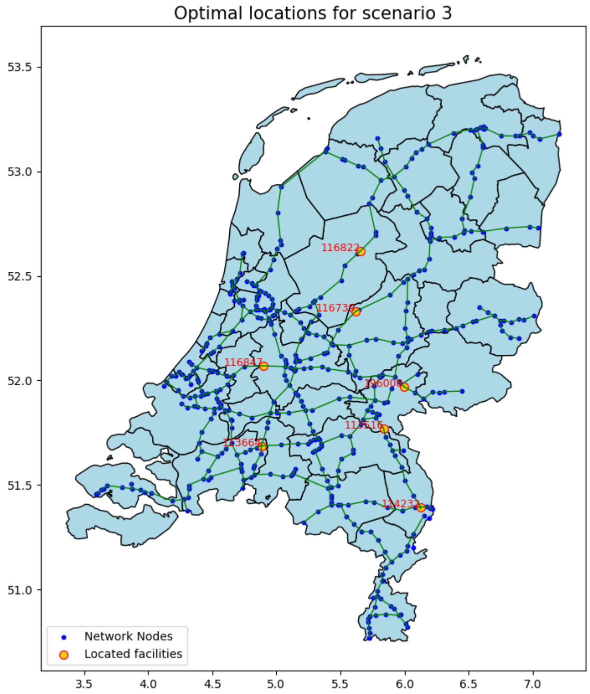

Figure 7.4: Results for scenario 3

Table 7.7: Solution scenario 3

Network_Node_ID	Network_Node_X	Network_Node_Y	Current_std	Industry	Total_Flow
196008	5.994942	51.970424	1	1	2248331.00
116847	4.902239	52.069980	1	1	1700074.00
116739	5.619100	52.330300	1	1	2202436.00
114232	6.128000	51.393200	1	4	4771076.00
113664	4.883500	51.686400	1	4	3527300.00
113516	5.836800	51.770500	1	1	1844792.00
116822	5.657752	52.619594	1	1	1306349.00
Total			**7**	**13**	**17600360.00**

7.5. Scenario 4: High HD BEV Adoption with Extensive Depot Charging

In scenario 4, there is no grid congestion, which greatly enhances the feasibility of various locations. Shell sites have already been built, providing a solid foundation for further development. The focus has shifted towards small industrial locations, which are becoming increasingly attractive due to the growing interest from smaller companies adopting HD BEVs. These companies might not have the capital to invest in private infrastructure making it interesting locations for public facilities. Most large companies have installed private infrastructure and with a large range for HD BEVs they will only use public infrastructure in emergency cases.

Table 7.8: Model Input scenario 4

Parameter	Value
Flow weight	Rank 1
Industry weight	Rank 2
Current std weight	0
Grid offtake weight	0
Budget	20
Range of HD BEV	700 km

Figure 7.5 and Table 7.9 show that the model picked 4 locations with a total potential yearly traffic flow passing by of 24921245.00 trucks.

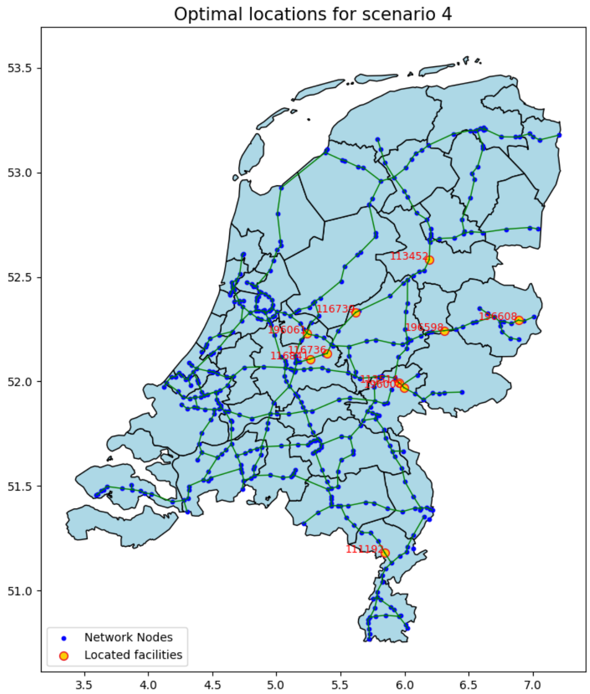

Figure 7.5: Results for scenario 4

Table 7.9: Solution scenario 4

Network_Node_ID	Network_Node_X	Network_Node_Y	Industry	Total_Flow
196608	6.887683	52.292997	1	2222938.00
196598	6.308132	52.242724	1	2281253.00
196061	5.238911	52.231791	1	1195002.00
196008	5.994942	51.970424	1	2248331.00
116841	5.262100	52.106800	1	3442057.00
116739	5.619100	52.330300	1	2202436.00
116736	5.396324	52.133879	1	3442057.00
113514	5.954400	51.995000	1	2248331.00
111192	5.846700	51.179100	1	2305745.00
113452	6.193200	52.582300	1	3333092.00
Total			**10**	**24921245.00**

7.6. Overlapping locations

From an energy provider's perspective, it's crucial to build assets that retain their value across various scenarios, minimising the risk of stranded assets. To achieve this, a table has been created listing all locations that appear in at least two scenarios. As these scenarios are developed over time, it is most strategic to construct the facilities in the order presented in Table 7.10. Figure 7.6 illustrates that this approach will result in a well-distributed network throughout the Netherlands.

Table 7.10: Network Node IDs in Different Scenarios

Network_Node_ID	Scenario 1	Scenario 2	Scenario 2a	Scenario 3	Scenario 4
116672	✓	✓	✓		
113615	✓		✓		
195932		✓	✓		
114232		✓	✓	✓	
113664		✓	✓	✓	
196008				✓	✓
116739				✓	✓

Figure 7.6 and Table 7.11 show that the model picked 4 locations with a total potential yearly traffic flow passing by of 24533328.00 trucks.

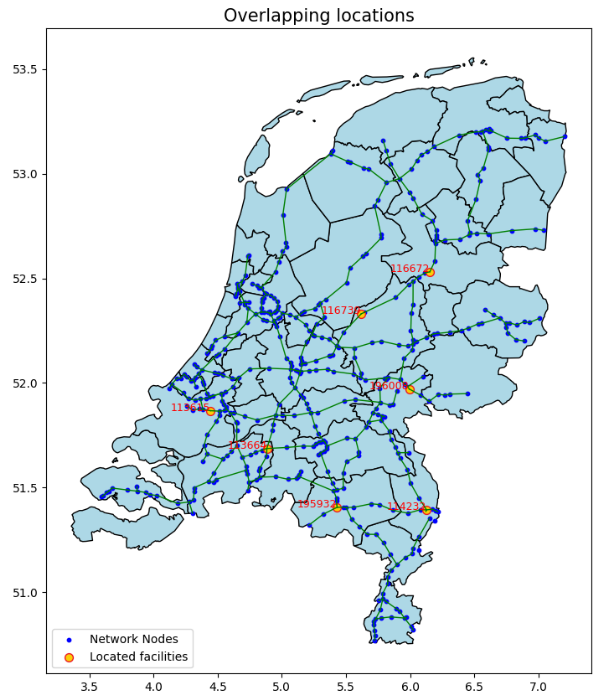

Figure 7.6: Overlapping results

Table 7.11: Overlapping Nodes

Network_Node_ID	Network_Node_X	Network_Node_Y	Grid_offtake	Current_std	Industry	Total_Flow
116672	6.153900	52.531200	3.0	1	4	3333092.00
113615	4.444600	51.867100	1.0	1	4	2216033.00
195932	5.431533	51.405376	4.0	4	4	6235060.00
114232	6.128000	51.393200	4.0	1	4	4771076.00
113664	4.883500	51.686400	4.0	1	4	3527300.00
196008	5.994942	51.970424	4.0	1	1	2248331.00
116739	5.619100	52.330300	4.0	1	1	2202436.00
Total			**24**	**10**	**22**	**24533328.00**

7.7. Conclusion on numerical experiments

This conclusive section on the numerical experiments with different scenarios will provide an answer to the last sub-question of this research.

How can the modelling results be related to determining the optimal locations for on-the go charging facilities for battery electric trucks?

The numerical experiments across various scenarios reveal that while the optimal locations for on-the-go charging facilities for HD BEVs may differ, certain locations overlap. These overlapping locations are strategically distributed to create a robust and reliable charging network, minimising the risk of stranded assets. By applying different weights to the inputs of the objective function and considering varying adoption rates and turn-in ratios over the years, this strategic approach ensures that the charging network can adapt to future developments and effectively meet the evolving needs of the fast changing landscape of HD BEVs.

8 Conclusion & Discussion

8.1. Conclusion

This research aimed to determine the optimal locations for public charging facilities for heavy-duty battery electric vehicles in the Netherlands by understanding the distribution of demand between private and public charging. The study addressed several research questions, which are answered below and will lead to a final answer on the main research question:

1. What is the current state of charging facilities and HD BEVs in the Netherlands?
While the current state of HD BEVs and charging facilities in the Netherlands is evolving fast, currently there are around 1,000 HD BEVs on Dutch roads, representing only 0.6% of the total truck fleet. However, this number is expected to rise sharply as fleet owners aim to reduce emissions and comply with stricter environmental standards. By 2035, it is anticipated that 70% of all new trucks sold in Europe will be battery electric, highlighting the urgent need for a robust charging infrastructure network.

The existing HD BEVs, such as those from Mercedes, have a range of about 300 km, with future models expected to reach up to 460 km. The higher purchase price of HD BEVs remains a barrier, but fleet owners are likely to consider the total cost of ownership, including maintenance, fuel costs, and depreciation, in their purchasing decisions. The total cost of ownership is approaching parity with diesel trucks.

The charging infrastructure is still developing but is expected to grow significantly. Currently, there are approximately 125 public charging locations with around 350 charging points for HD BEVs. These stations are spread across the country, but not all are suitable for larger vehicle configurations such as tractor trailer combinations. The power output of these chargers varies from 100 kW to 350 kW, which affect charging times. Semi-public and private charging facilities also play a crucial role. Semi-public chargers at warehouses or distribution centres provide convenient charging during loading and unloading, while private chargers, typically owned by companies with their own fleets, offer the lower cost per kWh but involve installation challenges such as grid congestion.

2. What is the current state of the logistics sector, what distances do they drive, where do they drive, and where do they refuel?
The logistics sector in the Netherlands is reliant on road transport, with trucks typically covering around 70,000 km annually, and newer vehicles averaging up to 100,000 km per year. Major logistics hubs, particularly around Eindhoven and the COROP regions Groot-Rijnmond and West-Noord-Brabant, experience significant truck traffic.

Most truck journeys are under 300 km, making them suitable for current HD BEV specifications. The sector's operational needs vary: city logistics, characterized by shorter routes and frequent stops, benefit from private charging facilities due to space constraints in urban areas; regional logistics, involving medium distances between distribution centres, can leverage private or semi-public charging during loading and unloading activities; and long-haul logistics, with extended routes and mandatory rest periods, will depend more heavily on public charging infrastructure to meet their energy requirements.

Understanding where trucks are based, the distances they drive, and their operational needs is essential for optimizing the deployment of charging facilities. This strategic development of both private and public charging infrastructure is crucial to support the transition to HD BEVs and ensure that the logistics network remains efficient and sustainable in the years to come.

3. What are the reasons, constraints, and needs from fleet owners to install private charging facilities or make use of public charging facilities?
Fleet owners consider a range of technical, economic, and subjective factors when deciding between installing private charging facilities and using public charging facilities. The main reasons for preferring private charging include lower operational costs, greater control over charging schedules, and improved operational efficiency. Private charging helps fleet owners avoid the higher per-kWh costs of public charging and reduces reliance on the availability and reliability of public infrastructure.

However, several constraints can limit the feasibility of private charging. These include high initial investment costs for installation, limited physical space at depots, and grid capacity issues that can restrict the number of chargers that can be installed and used simultaneously. These constraints may lead fleet owners to consider public charging as a viable alternative.

Additionally, some fleet owners need flexibility in their operations. Public charging provides this flexibility, especially for long-haul operations where returning to the depot for charging is not practical. Public charging is also viewed as a necessary backup when private charging infrastructure is insufficient or unavailable due to space or grid limitations.

4. How can the reasons, constraints, and needs to install private charging facilities or use public charging facilities be translated into the demand distribution model
The reasons, constraints, and needs identified for installing private charging facilities or using public charging facilities can be translated into a demand distribution model that allocates charging demand between private and public facilities. This model considers several key factors: Fleet owners prioritize private charging due to its lower cost per kWh compared to public charging. The model assumes that fleet owners will maximise the use of private charging until they are constrained by space or grid capacity. Operational constraints, such as the range of HD BEVs and the availability of space for chargers, are also incorporated into the model. When these constraints limit private charging, the model shifts the demand to public charging facilities.

The preference for private charging is driven by the need for control over charging schedules and operational efficiency. However, the model accounts for the necessity of public charging in scenarios where operational flexibility is required, such as long-haul operations where returning to the depot for charging is not practical. Public charging is also seen as a necessary backup when private charging infrastructure is insufficient or unavailable due to space or grid limitations.

Data from surveys and interviews with fleet owners support the model's assumptions. Fleet owners' preferences and constraints, as revealed through these methods, are integrated into the model to ensure it reflects real-world decision-making processes. The survey and interviews also provide the data needed to use in the model.

The demand distribution model reveals that private charging is the preferred option, but it is constrained by operational and depot location characteristics. As battery sizes increase, the demand shifts from public to private charging, as the operational constraints become less restrictive. This aligns with expectations from interviews, surveys, and theoretical foundations. Fleet owners prefer private charging due to its potentially lower cost and greater control. Public charging is only utilised when operational constraints necessitate it.

5. What are relevant technical and economic constraints for the location of on-the-go charging facilities for battery electric trucks?
The relevant technical and economic constraints for the location of on-the-go charging facilities for HD BEVs include several key factors. Grid congestion is a significant consideration, as the availability and capacity of the electrical grid at potential charging locations are crucial. Areas with high grid congestion may face challenges and incur higher costs for infrastructure upgrades, making them less suitable for new charging facilities.

Proximity to existing infrastructure is also important. Locations near existing Shell truck diesel sites or small industry sites with high accessibility and ample parking are preferred. These sites can leverage existing infrastructure, reducing the need for extensive new installations and thereby lowering costs.

Flow data, which includes the volume of truck traffic between regions, is essential for determining the demand for charging facilities. High-traffic routes are prioritized to maximise the utilisation of the charging infrastructure, ensuring that the facilities are placed where they are most needed.

The driving range of HD BEVs is another critical factor. Charging facilities need to be strategically placed within the range limits of these vehicles to ensure that trucks can complete their routes without running out of power. This requires careful planning to ensure that charging stations are available at appropriate intervals along major routes.

By considering these constraints, planners can optimise the placement of charging facilities to support the efficient and effective operation of HD BEVs, ensuring that the infrastructure meets both current and future demands.

6. How can these constraints be translated into a mathematical model or scenarios?
The mentioned constraints can be translated into a mathematical model by focusing on the objective function and incorporating relevant constraints. The objective function aims to maximise the captured flow of HD BEVs while minimising the total costs associated with installing the charging facilities. This dual objective ensures that the selected locations are both economically viable and meet the demand.

The model includes constraints such as budget limitations and the range of HD BEVs. These constraints ensure that the selected locations are feasible, cost-effective, and within the operational range of the vehicles.

To ensure the reliability and effectiveness of the model, verification and validation processes are conducted. Verification involved comparing the model to a greedy algorithm to evaluate its performance. The results demonstrate that the model captures a significantly higher flow and achieves better cost efficiency than the greedy solution. A sensitivity analysis was conducted on both flow and cost parameters to evaluate the model's robustness. By varying these parameters by $\pm 10\%$, the impact on the model's outcomes was observed. The results indicated that the model consistently adhered to the budget constraint and adapted well to changes in costs and flow, demonstrating robustness under varying conditions. The sensitivity analysis on the weights revealed that the model is stable with small changes in weights but shows significant variations in total cost and flow with larger weight adjustments. Reducing the weight for flow maximization and increasing the weight for cost minimization can lead to lower costs but also significantly reduce the total flow captured. Conversely, increasing the weight for flow maximization does not result in more flow, likely due to the budget constraint. This behaviour aligns with the expected trade-offs between cost minimization and flow maximization, as well as the impact of weight adjustments on total cost, flow, and the number of facilities. Overall, the model is robust for determining the optimal locations.

By integrating these technical and economic constraints into the mathematical model and validating its performance through verification and sensitivity analysis, the most suitable locations for on-the-go charging facilities for HD BEVs can be identified by using the model on different scenarios. This approach ensures that the charging network is both efficient and adaptable to future developments.

7. How can the modelling results be related to determining the optimal locations for on-the-go charging facilities for battery electric trucks?
The numerical experiments across various scenarios reveal that while the optimal locations for on-the-go charging facilities for HD BEVs may differ, certain locations overlap. These overlapping locations can create a robust and reliable charging network, minimisng the risk of stranded assets. By applying different weights to the inputs of the objective function and considering varying adoption rates and turn-in ratios over the years, this strategic approach ensures that the charging network can adapt to future developments and effectively meet the evolving needs of the changing landscape of HD BEVs.

How can the distribution of demand between private and public charging be determined and be used to determine the optimal locations in the Netherlands for a heavy-duty battery electric vehicle public charging facility network?

The distribution of demand between private and public charging can be determined by analysing the preferences and constraints of fleet owners, as well as the operational characteristics of their fleets. This involves understanding the factors that influence the choice between private, semi-public, and public charging, such as cost, flexibility, operational efficiency, and control.

A qualitative model has been created to allocate demand across public, semi-public, and private charging infrastructure. This model uses a decision flow chart that considers the operational characteristics and constraints of the fleet owner. It prioritises lower costs and greater control over charging, thus favouring private charging over public charging whenever possible.

A mathematical model that optimised the placement of public charging facilities has been developed. The model aims to maximise the captured flow of HD BEVs while minimising the total costs associated with installing the charging facilities. It includes inputs for flow, grid capacity and proximity to existing infrastructure. And is constraints by the budget and the range of the HD BEVs.

Scenarios were developed to test the model under different future conditions, such as varying levels of HD BEV adoption and grid congestion. These scenarios were used to identify robust locations for public charging facilities that remain valuable across different future developments. This approach ensures that the charging infrastructure network is both efficient and cost-effective, supporting the transition to heavy-duty battery electric vehicles in the Netherlands.

In conclusion, this research provides a comprehensive framework for developing an optimal charging infrastructure network for HD BEVs in the Netherlands. By understanding the distribution of demand between private and public charging, considering the needs and constraints of fleet owners, and incorporating relevant constraints into a mathematical location model, this study offers valuable insights for energy providers. This work paves the way for the future of refuelling, ensuring an efficient and sustainable approach to meeting the energy needs of the logistic sector.

8.2. Discussion

This section will outline the implications, limitations, and recommendations of this research.

Implications of the Research

The findings of this research have significant practical implications for the development of charging infrastructure for HD BEVs. By identifying optimal locations for public charging facilities, energy providers like Shell can strategically invest in infrastructure that maximises utility and minimises costs for opening facilities. This approach ensures that the charging network supports the growing adoption of HD BEVs, facilitating a smoother transition to electric transport and contributing to the reduction of greenhouse gas emissions. Additionally, the insights into fleet owners' preferences and constraints reveal how they might behave, contributing to the estimation of the distribution between private and public charging demand, which is essential to know for Shells roll out strategy. This research can be viewed as a pilot study, providing a comprehensive framework for future studies on the distribution of demand between private and public charging facilities.

This research contributes to the existing body of knowledge on electric vehicle infrastructure by addressing the specific needs and challenges of HD BEVs, a relatively less explored area. The study extends the application of the Flow Refuelling Location Model by incorporating cost minimisation for factors such as grid congestion and existing infrastructure. This approach provides a more comprehensive framework for future studies on electric vehicle infrastructure planning. Furthermore, the qualitative insights into fleet owners' decision-making processes enrich the literature on the behavioural aspects of adopting new technologies in the logistics sector. The framework presented in this thesis can be adapted for various applications in other research where modelling is combined with understanding customer or user behaviour. While this thesis focused on fleet owners and the spatial modelling of a charging network, the same approach can be applied to other contexts. For example, it could be used to analyse consumer behaviour in retail environments and to optimise the layout of a grocery store.

Limitations of the Research

Despite its contributions, this research has several limitations. Firstly, the demand distribution model relies on survey data, which may not fully capture the diversity of fleet operations and preferences. The limited number of survey respondents and the potential for response bias could affect the generalisability of the findings. Some of the questions asked, such as those regarding the physical space available, should be revised. With the scaled question, the distribution method ultimately allocated private charging in increments of 20%. Secondly, the model's assumptions about the availability and cost of grid connections, as well as the feasibility of installing private charging infrastructure, may not hold true in all contexts. Additionally, the scenarios developed for the optimisation location model are based on current market predictions and may not accurately reflect future developments in technology and policy. Finally, the research focuses on the Netherlands, and the findings may not be directly applicable to other regions with different logistical, regulatory, and infrastructural contexts.

Recommendations for Future Research
Future research should aim to address these limitations by expanding the scope and scale of data collection. Conducting larger-scale surveys and including a more diverse range of fleet operators can provide a more comprehensive understanding of charging preferences and constraints. Additionally, longitudinal studies that track changes in fleet operations and charging behaviour over time would offer valuable insights into the evolving needs of the logistics sector. Researchers should also explore the impact of emerging technologies, such as ultra-fast charging, on the optimal design of charging infrastructure. Comparative studies across different regions and regulatory environments can help identify adaptable strategies for various regions, while the framework from this research can be used. By addressing these areas, future research can build on the foundations laid by this study, contributing to the development of robust and efficient charging networks for HD BEVs and supporting the broader transition to sustainable transport.

References

[1] NASA, *The Effects of climate change*, 2021.

[2] European Commission, *European Green Deal*, 2020.

[3] European Commission, *Reducing CO□ emissions from heavy-duty vehicles*, 2024.

[4] CBS, *Central Bureau for Statistics the Netherlands*, 2024.

[5] H. Liimatainen, O. van Vliet, and D. Aplyn, "The potential of electric trucks – An international commodity-level analysis," *Applied Energy*, vol. 236, pp. 804–814, Feb. 2019, ISSN: 03062619. DOI: `10.1016/j.apenergy.2018.12.017`.

[6] B. Nykvist and O. Olsson, "The feasibility of heavy battery electric trucks," *Joule*, vol. 5, no. 4, pp. 901–913, Apr. 2021, ISSN: 25424351. DOI: `10.1016/j.joule.2021.03.007`.

[7] Mercedes, *Mercedes Benz Trucks*, 2024.

[8] H. W. Reese, "The learning-by-doing principle.," *Behavioral Development Bulletin*, vol. 17, no. 1, pp. 1–19, 2011, ISSN: 1942-0722(Electronic). DOI: `10.1037/h0100597`.

[9] H. Snyder, "Literature review as a research methodology: An overview and guidelines," *Journal of Business Research*, vol. 104, pp. 333–339, Nov. 2019, ISSN: 01482963. DOI: `10.1016/j.jbusres.2019.07.039`.

[10] W. Leal and F. R. Kotter, "Green Energy and Technology E-Mobility in Europe Trends and Good Practice," Tech. Rep., 2015. [Online]. Available: `http://www.springer.com/series/8059`.

[11] T. G. San Román, I. Momber, M. R. Abbad, and Á. Sánchez Miralles, "Regulatory framework and business models for charging plug-in electric vehicles: Infrastructure, agents, and commercial relationships," *Energy Policy*, vol. 39, no. 10, pp. 6360–6375, Oct. 2011, ISSN: 03014215. DOI: `10.1016/j.enpol.2011.07.037`.

[12] D. B. Richardson, *Electric vehicles and the electric grid: A review of modeling approaches, Impacts, and renewable energy integration*, 2013. DOI: `10.1016/j.rser.2012.11.042`.

[13] N. Daina, A. Sivakumar, and J. W. Polak, "Electric vehicle charging choices: Modelling and implications for smart charging services," *Transportation Research Part C: Emerging Technologies*, vol. 81, pp. 36–56, Aug. 2017, ISSN: 0968090X. DOI: `10.1016/j.trc.2017.05.006`.

[14] R. Wolbertus and R. Van den Hoed, "Electric vehicle fast charging needs in cities and along corridors," *World Electric Vehicle Journal*, vol. 10, no. 2, Jun. 2019, ISSN: 20326653. DOI: `10.3390/wevj10020045`.

[15] T. Teoh, "Electric vehicle charging strategies for Urban freight transport: concept and typology," *Transport Reviews*, vol. 42, no. 2, pp. 157–180, 2022, ISSN: 14645327. DOI: `10.1080/01441647.2021.1950233`.

[16] B. Kin, M. Hopman, and H. Quak, "Different charging strategies for electric vehicle fleets in urban freight transport," *Sustainability (Switzerland)*, vol. 13, no. 23, Dec. 2021, ISSN: 20711050. DOI: `10.3390/su132313080`.

[17] T. S. Logistics, "Charging infrastructure for electric vehicles in urban logistics," *Top Sector Logistics: Amsterdam, The Netherlands*, 2019.

[18] E. Morganti and M. Browne, "Technical and operational obstacles to the adoption of electric vans in France and the UK: An operator perspective," *Transport Policy*, vol. 63, pp. 90–97, Apr. 2018, ISSN: 1879310X. DOI: `10.1016/j.tranpol.2017.12.010`.

[19] S. Wang, Z. Y. Dong, F. Luo, K. Meng, and Y. Zhang, "Stochastic Collaborative Planning of Electric Vehicle Charging Stations and Power Distribution System," *IEEE Transactions on Industrial Informatics*, vol. 14, no. 1, pp. 321–331, 2018. DOI: `10.1109/TII.2017.2662711`.

[20] H. Hu, B. Du, W. Liu, and P. Perez, “A joint optimisation model for charger locating and electric bus charging scheduling considering opportunity fast charging and uncertainties,” *Transportation Research Part C: Emerging Technologies*, vol. 141, Aug. 2022, ISSN: 0968090X. DOI: 10.1016/j.trc.2022.103732.

[21] B. Borlaug, M. Moniot, A. Birky, M. Alexander, and M. Muratori, “Charging needs for electric semi-trailer trucks,” *Renewable and Sustainable Energy Transition*, vol. 2, Aug. 2022, ISSN: 2667095X. DOI: 10.1016/j.rset.2022.100038.

[22] P. Kampshoff, A. Kumar, S. Peloquin, and S. Sahdev, “Building the electric-vehicle charging infrastructure America needs,” Tech. Rep., 2022.

[23] K. Lingfeng, L. Zifa, and Z. Huan, “Modeling Algorithm of Charging Station Planning for Regional Electric Vehicle,” *Modern Electric Power*, vol. 27, no. 4, pp. 44–48, 2010, ISSN: 1007-2322. [Online]. Available: http://xddl.ncepujournal.com/en/article/id/106.

[24] P. Sadeghi-Barzani, A. Rajabi-Ghahnavieh, and H. Kazemi-Karegar, “Optimal fast charging station placing and sizing,” *Applied Energy*, vol. 125, pp. 289–299, Jul. 2014, ISSN: 03062619. DOI: 10.1016/j.apenergy.2014.03.077.

[25] J. Liu, “Electric vehicle charging infrastructure assignment and power grid impacts assessment in Beijing,” *Energy Policy*, vol. 51, pp. 544–557, Dec. 2012, ISSN: 03014215. DOI: 10.1016/j.enpol.2012.08.074.

[26] L. Pan, E. Yao, Y. Yang, and R. Zhang, “A location model for electric vehicle (EV) public charging stations based on drivers’ existing activities,” *Sustainable Cities and Society*, vol. 59, Aug. 2020, ISSN: 22106707. DOI: 10.1016/j.scs.2020.102192.

[27] T. D. Chen, K. M. Kockelman, and M. Khan, “Locating Electric Vehicle Charging Stations: Parking-Based Assignment Method for Seattle, Washington,” *Transportation Research Record*, vol. 2385, no. 1, pp. 28–36, 2013. DOI: 10.3141/2385-04. [Online]. Available: https://doi.org/10.3141/2385-04.

[28] M. R. Mozafar, M. H. Moradi, and M. H. Amini, “A simultaneous approach for optimal allocation of renewable energy sources and electric vehicle charging stations in smart grids based on improved GA-PSO algorithm,” *Sustainable Cities and Society*, vol. 32, pp. 627–637, Jul. 2017, ISSN: 22106707. DOI: 10.1016/j.scs.2017.05.007.

[29] M. Andrews, M. K. Do˘ Gru, J. D. Hobby, Y. Jin, and G. H. Tucci, “Modeling and Optimization for Electric Vehicle Charging Infrastructure,” Tech. Rep.

[30] D. Speth, P. Plötz, S. Funke, and E. Vallarella, “Public fast charging infrastructure for battery electric trucks—a model-based network for Germany,” *Environmental Research: Infrastructure and Sustainability*, vol. 2, no. 2, Jun. 2022, ISSN: 26344505. DOI: 10.1088/2634-4505/ac6442.

[31] M. J. Hodgson, “A Flow□Capturing Location□Allocation Model,” *Geographical Analysis*, vol. 22, no. 3, pp. 270–279, 1990, ISSN: 15384632. DOI: 10.1111/j.1538-4632.1990.tb00210.x.

[32] M. Kuby and S. Lim, “The flow-refueling location problem for alternative-fuel vehicles,” *Socio-Economic Planning Sciences*, vol. 39, no. 2, pp. 125–145, Jun. 2005, ISSN: 00380121. DOI: 10.1016/j.seps.2004.03.001.

[33] P. Kluschke, R. Nugroho, T. Gnann, P. Plötz, M. Wietschel, and M. Reuter-Oppermann, “Optimal development of alternative fuel station networks considering node capacity restrictions,” *Transportation Research Part D: Transport and Environment*, vol. 78, Jan. 2020, ISSN: 13619209. DOI: 10.1016/j.trd.2019.11.018.

[34] P. K. Rose and F. Neumann, “Hydrogen refueling station networks for heavy-duty vehicles in future power systems,” *Transportation Research Part D: Transport and Environment*, vol. 83, Jun. 2020, ISSN: 13619209. DOI: 10.1016/j.trd.2020.102358.

[35] Shell, *Fleet Decarbonisation*, 2024.

[36] Shell, *Depot charging solutions*, 2024.

[37] M. Ben-Akiva, D. Mcfadden, M. Abe, *et al.*, “Modeling Methods for Discrete Choice Analysis,” Tech. Rep., 1997, pp. 273–286.

[38] C. Bann, "An overview of valuation techniques: advantages and limitations A P R I L-J U N E 2 0 0 2 An overview of valuation techniques: Advantages and limitations," Tech. Rep. [Online]. Available: https://www.researchgate.net/publication/228583882.

[39] P. D. Bachiochi and S. P. Weiner, "Qualitative data collection and analysis.," in *Handbook of research methods in industrial and organizational psychology.* Ser. Blackwell handbooks of research methods in psychology. Malden: Blackwell Publishing, 2002, pp. 161–183, ISBN: 0-631-22259-6 (Hardcover).

[40] L. Choy, "The Strengths and Weaknesses of Research Methodology: Comparison and Complimentary between Qualitative and Quantitative Approaches," *IOSR Journal of Humanities and Social Science*, vol. 19, pp. 99–104, Jan. 2014. DOI: 10.9790/0837-194399104.

[41] C. Von Soest, "Why Do We Speak to Experts? Reviving the Strength of the Expert Interview Method," *Perspectives on Politics*, vol. 21, no. 1, pp. 277–287, Mar. 2023, ISSN: 15375927. DOI: 10.1017/S1537592722001116.

[42] N. Naz, F. Gulab, and N. Aslam, "Development of Qualitative Semi-Structured Interview Guide for Case Study Research," *Competitive Social Sciences Research Journal (CSSRJ)*, vol. 3, no. 2, pp. 42–52, 2022, ISSN: 2708-9037. [Online]. Available: www.cssrjournal.com.

[43] I. Holloway, *Qualitative Research in Health Care*. McGraw-Hill Education, Jan. 2005, pp. -1, ISBN: 0335225799. DOI: doi:10.1036/9780335225798. [Online]. Available: https://www.mhebooklibrary.com/doi/book/10.1036/9780335225798.

[44] B. G. Glaser and A. L. Strauss, *The Discovery of Grounded Theory*. Routledge, Jul. 1967, ISBN: 9780203793206. DOI: 10.4324/9780203793206.

[45] G. Guest, E. Namey, and M. Chen, "A simple method to assess and report thematic saturation in qualitative research," *PLoS ONE*, vol. 15, no. 5, May 2020, ISSN: 19326203. DOI: 10.1371/journal.pone.0232076.

[46] S. Roopa and M. Rani, "Questionnaire Designing for a Survey," *The Journal of Indian Orthodontic Society*, vol. 46, pp. 273–277, Oct. 2012, ISSN: 03015742. DOI: 10.5005/jp-journals-10021-1104.

[47] D. A. Hensher, "Stated preference analysis of travel choices: the state of practice," Tech. Rep., 1994, pp. 107–133.

[48] H. Taherdoost, "Determining Sample Size; How to Calculate Survey Sample Size," Tech. Rep., 2018. [Online]. Available: https://ssrn.com/abstract=3224205http://www.ahooraltd.comhttp://www.hamta.org.

[49] J. E. Bartlett, J. W. Kotrlik, and C. C. Higgins, "Organizational Research: Determining Organizational Research: Determining Appropriate Sample Size in Survey Research Appropriate Sample Size in Survey Research," Tech. Rep. 1, 2001.

[50] D. K. Pace, "M Modeling and Simulation Verifi cation and Validation Challenges," Tech. Rep. 2, 2004.

[51] L. G. Birta, R. E. Crosbie, T. Jakeman, *et al.*, "Simulation Foundations, Methods and Applications Series Editor," Tech. Rep. [Online]. Available: http://www.springer.com/series/10128.

[52] D. Speth, V. Sauter, P. Plötz, and T. Signer, "Synthetic European road freight transport flow data," *Data in Brief*, vol. 40, Feb. 2022, ISSN: 23523409. DOI: 10.1016/j.dib.2021.107786.

[53] Netbeheer Nederland, *Capaciteitskaart*, 2024.

[54] Geopy Contributors, *geopy: Geocoding library for Python*, 2024.

[55] Y. Narasimhulu, A. Suthar, R. Pasunuri, and C. Venkaiah, "CKD-TREE: AN IMPROVED KD-TREE CONSTRUCTION ALGORITHM," Tech. Rep., 2021. [Online]. Available: http://cse.mrec.ac.in/StaffDetails?FacultyId=3072.

[56] P. Virtanen, R. Gommers, T. E. Oliphant, *et al.*, "SciPy 1.0: fundamental algorithms for scientific computing in Python," *Nature Methods*, vol. 17, no. 3, pp. 261–272, Mar. 2020, ISSN: 1548-7091. DOI: 10.1038/s41592-019-0686-2.

[57] Government of the Netherlands, *IBIS*, 2024.

[58] J. Mestre, “LNCS 4168 - Greedy in Approximation Algorithms,” Tech. Rep., 2006.

[59] S. Gopal, K. Patro, and K. Kumar Sahu, “Normalization: A Preprocessing Stage,” Tech. Rep., 2015. [Online]. Available: www.kiplinger.com,.

[60] L. Zadeh, “Optimality and non-scalar-valued performance criteria,” *IEEE Transactions on Automatic Control*, vol. 8, no. 1, pp. 59–60, Jan. 1963, ISSN: 0018-9286. DOI: 10.1109/TAC.1963.1105511.

[61] R. T. Marler and J. S. Arora, “The weighted sum method for multi-objective optimization: New insights,” *Structural and Multidisciplinary Optimization*, vol. 41, no. 6, pp. 853–862, Jun. 2010, ISSN: 1615147X. DOI: 10.1007/s00158-009-0460-7.

[62] M. Ehrgott, “Vilfredo Pareto and Multi-objective Optimization,” Tech. Rep. [Online]. Available: http://en.wikipedia..

[63] N. Gunantara, “A review of multi-objective optimization: Methods and its applications,” *Cogent Engineering*, vol. 5, no. 1, pp. 1–16, Jan. 2018, ISSN: 23311916. DOI: 10.1080/23311916.2018.1502242.

[64] Google, *Google maps*, 2024.

[65] R. Buck, *De groei van megadistributiecentra zet door.* 2022.

[66] European Commision, *Trans-European Transport Network (TEN-T)*, 2024.

[67] A. Phadke, A. Khandekar, and A. Abhyankar, “Lawrence Berkeley National Laboratory LBL Publications Title Why Regional and Long-Haul Trucks are Primed for Electrification Now Publication Date,” Tech. Rep. [Online]. Available: https://escholarship.org/uc/item/3kj8s12f.

[68] Zero Emissie Stadslogistiek, *Waar komen de ze zones*, 2024.

[69] J.-P. Rodrigue, *The Geography of Transport Systems*, 6th. London: Routledge, Mar. 2024, ISBN: 9781003343196. DOI: 10.4324/9781003343196.

[70] H. Basma and F. Rodríguez, “A total cost of ownership comparison of truck decarbonization pathways in Europe,” Tech. Rep., 2023. [Online]. Available: www.theicct.org.

[71] PwC, *Decarbonisation: Mapping the route to sustainable trucking*, Dec. 2022.

[72] M. R. Bernard, A. Tankou, H. Cui, and P.-L. Ragon, “CHARGING SOLUTIONS FOR BATTERY-ELECTRIC TRUCKS,” Tech. Rep., 2022. [Online]. Available: www.theicct.orgcommunications@theicct.org.

[73] Bleukens, *Op zoek naar een laadpunt voor elektrische trucks? Bekijk de kaart*, 2024.

[74] ACEA, *Truck charging points needed in Europe by 2025 and 2030, per country*, May 2021.

[75] Nationale Agenda Laadinfrastructuur (NAL), “Een praktische checklist voor laadinfrastructuur voor elektrische vrachtwagens Handreiking depotladen,” Tech. Rep.

[76] R. Noordijk, R. Nazir, and van Rookhuijzen, “Truckers komen op stroom,” Elaadnl, Tech. Rep., 2020.

[77] J. ; Andersen, P. Bach, and ; Teoh, “General rights Guidelines-Charging Infrastructure for Truck Depots,” Tech. Rep., 2024. [Online]. Available: https://windenergy.dtu.dk/english.

[78] Y. Bae, C. R. Rindt, S. K. Mitra, and S. G. Ritchie, “Fleet Operator Perspectives on Heavy-duty Vehicle Alternative Fueling Infrastructure,” *Transportation Research Record*, vol. 2678, no. 1, pp. 490–506, Jan. 2024, ISSN: 21694052. DOI: 10.1177/03611981231171150.

[79] Rijksoverheid, *Wat is er wettelijk geregeld voor de rijtijden en rusttijden bij wegvervoer?* 2024.

[80] UK Government, “BETT-Battery Electric Truck Trial-Final Report BETT-Battery Electric Truck Trial Final Report,” Tech. Rep., 2024. [Online]. Available: https://bett.cenex.co.uk.

[81] D. M. Hamby, “A REVIEW OF TECHNIQUES FOR PARAMETER SENSITIVITY ANALYSIS O F E N V I R O N M E N T A L M O D E L S,” Tech. Rep.

[82] H. ; Kosow and R. Gaßner, “www.ssoar.info Methods of Future and Scenario Analysis: Overview, Assessment, and Selection Criteria Zur Verfügung gestellt in Kooperation mit / provided in cooperation with,” Tech. Rep. [Online]. Available: www.ssoar.info.

A

Fleet owner profiles

A.1. City logistics

In Table A.1 an overview is given of two fleet owner profiles that could fit in the city logistics operation type. For fleet owners with profile C1, it can be expected that they will meet 100% of their charging demand at their private depot, as there are no limitations preventing them from doing so. On the other hand, for fleet owners with profile C2, it's anticipated they will partially rely on public charging. This is due to a space constraint at their own facility, highlighted in red, limiting the availability of chargers. But there is a public charger available near their origin location which they could use to charge some of the trucks before returning to the depot.

Table A.1: City logistics profiles

Nr	Characteristics	Profile C1	Profile C2
1	**Fleet size**		
1.1	Number of box-trucks	25	50
1.2	Number of tractors	40	0
1.3	Number of HD BEV	5	10
2	**Operation**		
2.1	Operation Type	Supermarket delivery: depot -> supermarket -> depot	Multi-shop supply: depot -> shop -> …-> shop -> depot
2.2	Daily kilometres driven	150	200
2.3	Number of trips per day	3	1
2.4	Mandatory breaks	Served at depot	Served at depot
3	**Origin location**		
3.1	Home to home kilometres	50	80
3.2	Overnight idling time at depot	8h	8h overnight
3.3	Between trip idling time	30 minutes	0 minutes
3.4	Public charger nearby	No	Yes
3.5	Available space for private chargers	65 chargers	40 chargers
3.6	Available grid connection	Available	Available
4	**Destination location**		
4.1	Number of stops per trip	1	3
4.2	Average stopping time	30 minutes	30 minutes
4.3	Distance driven between stops	25	50 km
4.4	Public charger nearby	No	No
4.5	Private chargers available	No	No

A.2. Regional

In Table A.2, an overview of two fleet owner profiles that could align with regional operations is presented. For fleet owner profile R1, it is possible to meet most of their charging needs at the private facility, as there is sufficient time and available space to fully charge overnight. However, the daily distance travelled exceeds the truck's range, as highlighted in red, which limits the ability to rely solely on overnight charging. The fleet owner can either recharge at the private facility during in-between trip idling time or at customer locations during stops. This presents a trade-off in terms of charging costs. Charging at the private facility may be more cost-effective, but the limited idling time offers minimal opportunity for recharging. On the other hand, at customer locations, the longer stopping time, combined with mandatory breaks, provides a better opportunity to charge. This trade-off between using semi-public or private charging infrastructure will be explored further in the interviews and survey sections. However, this theoretical profile demonstrates that exceeding the truck's range doesn't necessarily require the use of public charging infrastructure, as the home-to-home and stop distances are within range, and other charging options are available along the way. For profile R2, the entire operation exceeds the truck's range, as indicated in red by both the daily distance travelled and the home-to-home distance. While the fleet owner primarily relies on charging at their private facility, with sufficient space for chargers, additional charging will be necessary during operations. Since construction sites are unlikely to have charging infrastructure available, but the driver takes mandatory breaks at a public location with a charger available, it is likely that this supplementary charging will occur at a public facility.

Table A.2: Regional profiles

Nr	Characteristics	Profile R1	Profile R2
1	**Fleet size**		
1.1	Number of box-trucks	5	15
1.2	Number of tractors	70	0
1.3	Number of HD BEV	0	0
2	**Operation**		
2.1	Operation Type	DC to DC transport: depot -> customer depot -> depot	Factory to build site: factory depot -> build site -> factory depot
2.2	Daily kilometres driven	400	400
2.3	Number of trips per day	2	1
2.4	Mandatory breaks	Served at customer	Served at public location
3	**Origin location**		
3.1	Home to home kilometres	200	400
3.2	Overnight idling time at depot	8h	8h overnight
3.3	Between trip idling time	15 minutes	0 minutes
3.4	Public charger nearby	No	No
3.5	Available space for private chargers	75 chargers	15
3.6	Available grid connection	Available	Available
4	**Destination location**		
4.1	Number of stops per trip	1	1
4.2	Average stopping time	45 minutes	30 minutes
4.3	Distance driven between stops	100	200 km
4.4	Public charger nearby	No	Yes
4.5	Private chargers available	Yes	No

A.3. Long Haul

In Table A.3, an overview of two fleet owner profiles suited to long-haul operations is provided. For fleet owners under profile LH1, the nature of the operation ensures that not all trucks are at the depot simultaneously, which means the lower number of chargers compared to the fleet size is not a constraint. As a result, the trucks can be fully charged at the depot before starting their routes. However, given the long-distance nature of these routes and the insufficient driving range to reach the destination, as highlighted in red, public charging will be necessary during mandatory breaks. This can be easily managed, as the routes are fixed, and a known charger can be incorporated into the planning. Additionally, trucks can recharge at the destination during overnight rest, allowing them to begin their return journey fully charged. As a result, this fleet owner will utilise a combination of private, public, and semi-public charging facilities. In contrast, fleet owners with profile LH2 follow different routes for each long-distance trip. Since the trucks operate beyond their range, public charging is already essential for some part of their demand. Although there is space for chargers at the fleet owner's depot, they are unable to secure a sufficient power grid connection, as indicated in red. As a result, this fleet owner relies entirely on public charging infrastructure.

Table A.3: Long Haul

Nr	Characteristics	Profile LH1	Profile LH2
1	**Fleet size**		
1.1	Number of box-trucks	0	0
1.2	Number of tractors	100	10 with crane
1.3	Number of HD BEV	0	0
2	**Operation**		
2.1	Operation Type	Dedicated routes: depot -> customer depot -> depot	Specialised transport unique every time
2.2	Daily kilometres driven	700	600
2.3	Number of trips per day	1	1
2.4	Mandatory breaks	Served at public locations	Served at public location
3	**Origin location**		
3.1	Home to home kilometres	> 1000	> 1000
3.2	Overnight idling time at depot	8h	8h
3.3	Between trip idling time	0	0 minutes
3.4	Public charger nearby	No	No
3.5	Available space for private chargers	30 chargers	10 chargers
3.6	Available grid connection	Available	Not available
4	**Destination location**		
4.1	Number of stops per trip	1	1
4.2	Average stopping time	8h	2h
4.3	Distance driven between stops	700	200
4.4	Public charger nearby	No	Yes
4.5	Private chargers available	Yes	No

B
Interview guide

This appendix shows the interview guide that has been used for the semi-structured interviews with fleet owners.

- **General Questions:**
  1. What is the name of your company?
  2. In what industry/ what type of transport is your company active?
  3. What is your role within the company?
- **Fleet:**
  1. What is the number of box trucks within your fleet?
  2. What is the number of tractors before trailers within your fleet?
  3. Do you currently operate HD BEVs? If yes, ask how many?
- **Operation:**
  1. Can you shortly explain how the operation of your fleet works? Especially focused on the amount of km driven, how many stops there are made, at what kind of locations are these stops, how long are these stops, how many trip, what is currently the refuelling strategy, etc.?
- **Considerations for choosing charging locations:**
  1. What factors do influence your choice between public, semi-public and private charging locations?
  2. Which of these factors are most important to you?
  3. Did you ever consider to install a home base diesel tank? If yes, how is the choice made there comparable to choosing for private chargers?

C

Survey construction

The survey has been designed following the guidelines for developing a questionnaire by Roopa and Rani [46]. The questions are intended to collect information on the specified inputs and constraints for the model as outlined in subsection 5.1.1 and learned from **??**. This explanation will revisit all the characteristics and explain what type of question would be suitable to gain information on the topic.

General Information:
In addition to the questions used to gather data for the model, general questions about the respondents and their respective companies should be included.

- **Company Name:** Open-ended question. This format allows flexibility in capturing a wide range of company names, which can differ in structure and length. An open-ended format accommodates all types of company names without limitation.
- **Respondent's Role:** Open-ended question. Job roles can vary significantly in title and scope. An open-ended question allows respondents to provide detailed descriptions of their roles, reflecting the diversity of functions within different companies.

Fleet Size:

- **Number of Box Trucks:** Open-ended question. This allows respondents to provide an exact number, which is important because fleet sizes can vary greatly across companies.
- **Number of Tractors for Trailers:** Open-ended question. This allows respondents to provide an exact number, ensuring accuracy in reporting fleet sizes, which differ across companies.
- **Number of HD BEVs:** Initially, a Yes/No question asking whether the fleet owner currently operates HD BEVs. If the answer is yes, a follow-up open-ended question should ask for the precise number, which is crucial for analysing electrification levels without restricting responses.

Operation:

- **Operation Type:** Multiple-choice question. Fleet owners should select the operational type that best describes their company. Categories may include city logistics, regional logistics, and long-haul transport. Multiple selections should be allowed, as some companies may operate across different categories. Additionally, an ”Other” option should be available for flexibility.
- **Daily Kilometres Driven:** Multiple-choice question. Most fleet owners may not know the exact number of kilometres their trucks drive. Providing categories with distance ranges simplifies the response process and still serves the research needs in determining their total daily demand for energy from one of the options they choose.
- **Number of Trips per Day:** First, a Yes/No question should ask whether trucks complete multiple trips in one day. If yes, a follow-up multiple-choice question on the number of trips should be provided.

- **Mandatory Driver Breaks:** A factual Yes/No question to determine whether regulatory driver breaks affect operations. A follow-up question should ask if these breaks can be used for charging with an open ended question to provide the reasoning behind their answer.

Origin Location:

- **Home-to-Home Distance:** Multiple-choice question. Fleet owners may not have precise data on how many kilometres their trucks cover between home bases. Providing distance ranges simplifies the process while ensuring that the responses still align with the research objectives.
- **Overnight Idling Time:** Multiple-choice question. Since fleet owners may not know the exact number of hours trucks are idling overnight, categories with time ranges simplify this response. For this research, precise values are unnecessary; ranges will suffice in determining if the overnight idling time is sufficient enough for a full charge.
- **Between-Trip Idling Time:** Multiple-choice question. Fleet owners may not know the exact idling time between trips, which can also vary. Using time ranges makes responding easier while providing sufficient data for the study as this is the same reason with the overnight idling time.
- **Public Charger Availability Nearby:** Multiple-choice question. Predefined options such as Yes/No allow for quick and easy responses. The type of charger and its distance should be mentioned for consistency in the answers from the different respondents as they have the same perspective on the definition of nearby and the type of charger.
- **Available Space for Private Chargers:** Scaled question. Space availability can be subjective. A scaled question lets respondents indicate degrees of space availability, providing a nuanced understanding beyond a simple Yes/No answer. There should also a scaled question be included that gathers information on the fleet owners perspective of the willingnes to use the available space for chargers.
- **Available Grid Connection:** Multiple-choice question if they know the cappacity of their current grid connection. If yes, there will be a follow up answer asking for the capacity in kW of the grid connection

Destination Location:

- **Number of Stops:** Multiple-choice question. Fleet owners may not know the exact number of stops per trip, as this can vary by day and operation. Categories with ranges simplify responses while still meeting research requirements.
- **Average Stop Time:** Multiple-choice question. The exact duration of stop times may not be readily available to fleet owners, and this can vary. Providing time ranges makes it easier to respond while offering the necessary information for this research.
- **Distance Between Stops:** Multiple-choice question. Fleet owners may not have detailed data on how far their trucks travel between stops. By offering categories with distance ranges, the question becomes more manageable and still aligns with the research objectives to gather information if the distance between stops is within the range of a vehicle.
- **Public Charger Availability Nearby:** Multiple-choice question. Similar to the origin location, this question can have predefined answers such as Yes/No. Including details on charger type and distance ensures consistency as the viewpoint on distance and output is the same for every respondent.
- **Private Charger Availability:** Scaled question. The fleet owners should make an estimation in if it is likely that they can use charging at destination locations, so a scaled question captures varying degrees of availability, offering more detail than a Yes/No question. A follow up question can provide an explanation on the usage of charging infrastructure at destinations

Other Factors:
For the other factors, the survey should provide insights into participants preferences. As explained in the relevant chapter, these questions will follow a stated preference format. The results can offer valuable information about their preferences and the trade-off they make regarding the key factors identified as influential in their charging choices from the theoretical base and interviews.

D

Survey format

This appendix shows the format of the developed survey based on the construction explanation in Appendix C.

The Perspective of Fleet Managers on Charging Heavy Electric Vehicles

Dear respondent,

This questionnaire aims to gain better insights into the preferences of fleet managers when choosing between the use of private, semi-public, or public charging infrastructure for heavy battery-electric vehicles. Your answers will contribute to a larger research project aimed at identifying the best locations for public charging stations in the Netherlands. By participating, you help Shell develop a robust network of charging infrastructure for heavy electric vehicles and support the transition to battery-electric transport. If you cannot answer a question or cannot provide an answer due to confidentiality reasons, please leave the question unanswered. Thank you very much for your time and contribution to this research. Your help is greatly appreciated.
Private Charging Infrastructure: Located at the company's site and can only be used by the company's vehicles.
Semi-Public Charging Infrastructure: Located on private property but can be used by others under certain conditions. For example, when a company delivers goods to a customer, and the customer allows the delivery vehicle to charge at their infrastructure.
Public Charging Infrastructure: Accessible to everyone and located at convenient locations

General Information

1. What is the name of your company?

2. What is your role within the company?

Fleet

3. What is the number of trucks in your fleet?

4. What is the number of trailers in your fleet?

5. Do you already have battery-electric variants of trucks or trailers in your fleet?
   Yes/No

6. If Yes:
   What is the number of battery-electric heavy vehicles in your fleet?

Operation

7. Which type of operation best fits your company?
    - City logistics
    - Regional logistics
    - Long-distance transport
    - Other

8. What is the average distance a vehicle in your fleet travels on an operational day?
    - 0-100km
    - 100-200km
    - 200-300km
    - 300-400km
    - 400-500km
    - 500-600km
    - over 600km
    - Not possible to answer this question

9. Do your vehicles make multiple trips in a day?
    - Yes
    - No
    - Not possible to answer this question

10. How many trips do your vehicles make on average per day?
    - 2-3
    - 4-5
    - 6-7
    - More than 7

11. What is the average distance traveled for a home-to-home trip?
    - 0-50km
    - 50-100km
    - 100-150km
    - 150-200km
    - 250-300km
    - 300-400km
    - 400-500km
    - over 500km
    - Not possible to answer this question

12. At which locations do your drivers take mandatory breaks?
    - Own depot

- Public locations
- Destination locations
- Other

13. Would you charge your trucks during mandatory breaks?
    - Yes
    - No

14. Can you briefly explain your answer to question 13?

Origin Location

15. What is the average time your vehicles are stationary between two operational days?
    - Less than 4 hours
    - 4-6 hours
    - 6-8 hours
    - More than 8 hours

16. What is the average time your vehicle is stationary at your own depot between two trips?
    - Less than 15 minutes
    - 15-30 minutes
    - 30-45 minutes
    - 45-60 minutes
    - More than 60 minutes

17. Is there currently a public charger with a minimum output of 150kW available within a range of 10 km from your depot?
    - Yes
    - No

18. How much space do you have available at your depot for installing private charging infrastructure?
    - 1 = no space available
    - 2
    - 3
    - 4
    - 5 = more than enough space available

19. How much of the available space would you like to use for installing private charging infrastructure?
    - 1 = do not want to allocate any space for chargers
    - 2
    - 3
    - 4
    - 5 = would use all available space for chargers

20. Do you know your current grid connection in kW?
    - Yes
    - No

21. What is the value of your grid connection in kW?

Destination Locations

22. How many stops do your vehicles make on average during a trip?
    - 1-2
    - 3-4
    - 5-6
    - 6-8
    - More than 8

23. What is the average stop time during stops?
    - Less than 15 minutes
    - 15-30 minutes
    - 30-45 minutes
    - 45-60 minutes
    - More than 60 minutes

24. What is the average driving distance between two stops?
    - 0-50km
    - 50-100km
    - 100-150km
    - 150-200km
    - 250-300km
    - 300-400km
    - 400-500km
    - over 500km
    - Not possible to answer this question

25. Is there currently a public charger with a minimum output of 150kW within a range of 10km from your destination locations?
    - Yes
    - No

26. Is it likely that you will be able to use charging infrastructure present at destination locations in the future?
    - 1 = not likely
    - 2
    - 3
    - 4

- 5 = very likely

27. Would you use charging infrastructure at destination locations if available? Please briefly explain your answer.

Scenarios

28. You have a fleet of 10 eTrucks that each drive 100,000 km per year and are considering two charging options with different investment costs and electricity rates. A kWh at your private location costs €0.20 and at a public location €0.60.

    Private Charging Station:

    - Required capital for investment: €550,000
    - Total annual costs including depreciation of investment and electricity: €315,000

    Public Charging Station:

    - Required capital for investment: €0
    - Total annual costs: €780,000

    Considering the differences in costs, which option would you choose for your fleet, taking into account that private charging requires immediate capital investment?

    - Private charging
    - Public charging

29. You have a fleet of 25 eTrucks that each drive 50,000 km per year and are considering two charging options with different investment costs and electricity rates. A kWh at your private location costs €0.20 and at a public location €0.40.

    Private Charging Station:

    - Required capital for investment: €925,000
    - Total annual costs including depreciation of investment and electricity: €417,500

    Public Charging Station:

    - Required capital for investment: €0
    - Total annual costs: €650,000

    Considering the differences in costs, which option would you choose for your fleet, taking into account that private charging requires immediate capital investment?

    - Private charging
    - Public charging

30. You have a fleet of 10 eTrucks that each drive 100,000 km per year and are considering two charging options with different investment costs and electricity rates. A kWh at your private location costs €0.20 and at a public location €0.30.

    Private Charging Station:

    - Required capital for investment: €550,000
    - Total annual costs including depreciation of investment and electricity: €315,000

    Public Charging Station:

- Required capital for investment: €0
- Total annual costs: €390,000

Considering the differences in costs, which option would you choose for your fleet, taking into account that private charging requires immediate capital investment?

- Private charging
- Public charging

31. You have a fleet of 10 eTrucks that each drive 100,000 km per year and are considering two charging options with different investment costs and electricity rates. A kWh at your private location costs €0.30 and at a public location €0.30.

Private Charging Station:

- Required capital for investment: €550,000
- Total annual costs including depreciation of investment and electricity: €445,000

Public Charging Station:

- Required capital for investment: €0
- Total annual costs: €390,000

Considering the differences in costs, which option would you choose for your fleet, taking into account that private charging requires immediate capital investment?

- Private charging
- Public charging

32. You are considering charging options for a fleet of eTrucks. You want to weigh the costs of maintenance against the availability of charging facilities:

Private Charging Station:

- Maintenance: Full responsibility for maintenance and repairs and associated costs.
- Availability: 24/7 access, no waiting times.

Public Charging Station:

- Maintenance: No maintenance costs.
- Availability: Access to public fast chargers, but busy during peak times.

Which option would you choose, considering the differences in maintenance responsibilities and the availability of charging facilities?

- Private charging
- Public charging

33. You are considering charging options for a fleet of 15 eTrucks. You want to weigh the responsibilities of maintenance against the availability of charging facilities:

Private Charging Station:

- Maintenance: Full responsibility for maintenance and repairs.
- Availability: 24/7 access, but maintenance can lead to temporary closure.

Public Charging Station:

- Maintenance: No maintenance costs.

- Availability: Access to public fast chargers where a time slot can be reserved in advance, thus no waiting time.

Which option would you choose, considering the differences in maintenance responsibilities and the availability of charging facilities?

- Private charging
- Public charging

34. You are weighing the costs per kWh against the availability of the charging infrastructure:

Private Charging Station:

- Cost per kWh: €0.20
- Availability: 24/7 access, no waiting times, full control over charging schedule.

Public Charging Station:

- Cost per kWh: €0.45
- Availability: Unpredictable availability, possible waiting times during peak hours, but freely accessible outside peak hours.

Which option would you choose, considering the differences in costs per kWh and the availability of charging facilities?

- Private charging
- Public charging

35. You are weighing the costs per kWh against the availability of the charging infrastructure:

Private Charging Station:

- Cost per kWh: €0.35
- Availability: 24/7 access, no waiting times, full control over charging schedule.

Public Charging Station:

- Cost per kWh: €0.25
- Availability: Unpredictable availability, possible waiting times during peak hours, but freely accessible outside peak hours.

Which option would you choose, considering the differences in costs per kWh and the availability of charging facilities?

- Private charging
- Public charging