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Effective System Solutions for Battery Electric Trucks

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Abstract

One possible step for reducing humans use of fossil fuel due to transportation is to replace diesel trucks with battery electric ones. This thesis focuses on effective system solutions for battery electric trucks but not the ones which can charge while driving on so called electric roads. The *energy distribution diagram* is introduced which makes it easy to visualise the daily energy consumption for the trucks full service life in a compact way. The energy distribution diagram is used to investigate which driving patterns that are suitable for cost effective battery electric trucks and the cost is compared to commercial diesel trucks. These analyses are done both for several simple shapes of the energy distribution as well as for a special case of electrification of long-distance line-haul trucks. An investigation about how to select the total power of a charging station with a given demand of charging is also presented. Finally, the charging needed for trucks, the charger utilization and the problems with queuing at chargers along a highway in Sweden is investigated with an agent-based model based on traffic data.

The results indicates that the utilization of the chargers along the investigated highway could be high and at the same time the system will have good ability to resist queues. Regarding the total power of a charging station, it is found that it is not always optimal to meet the maximum charging demand if the goal is to maximize the net income for the charge point operator.

Further on, the battery electric trucks are, in many cases, found to be competitive to the commercial diesel trucks, especially when there is low variation in the daily energy consumption for the trucks. It is useful to find under what circumstance they may be cheaper, as it will be much easier to transition into battery electric trucks in segments in which the total cost of ownership is reduced. Cost-effective solutions for battery electric trucks are therefore highly important to find, and this thesis explores some of the main factors and trade-offs which influence the effectiveness of the whole system.

Included Publications

This thesis intends to summarize the work done in the following papers

A) Karlsson, J; Grauers, A. "Energy Distribution Diagram used for Cost-Effective Battery Sizing of Electric Trucks". *Energies*, **2023**, *Volume 16, Issue 2*, 779.

B) Karlsson, J; Grauers, A. "Case Study of Cost-Effective Electrification of Long-Distance Line-Haul Trucks". *Energies*, **2023**, *Volume 16, Issue 6*, 2793.

C) Karlsson, J; Grauers, A. "Agent based Investigation of Charger Queues and Utilization of Public Chargers for Electric Long haul Trucks". **2023**, *submitted*.

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2 Introduction

Humans' dependency on oil is problematic since calculations shows that the reserve depletion times is less than 30 years [1] and an continued extensive use of fossil fuel will likely cause severe consequences on the earth climate system [2]. In addition, other downsides of greenhouse gas emissions such as pollution and negative health impacts are expressed in the literature [3]. An attempt to partly solve this grave problem is to use battery electric trucks instead of diesel ones. Hydrogen fuel-cell trucks is also a possible solution but recently published studies favours the battery electric trucks [4][5]. Even though the feasibility of the battery electric trucks seems promising, fuel cells might be better for heavy-duty trucks on extra-long journeys [6]. Still, there is no unambiguous answer to the question which powertrain that result in the lowest total cost of ownership, since it will depend on how the vehicle is used [7]. However, former studies indicates that battery electric trucks could be cost-competitive to the diesel trucks under the right circumstances [8][9][10].

This thesis aims to contribute to the transition by investigate battery electric trucks and their competitiveness relative to conventional diesel trucks. It also aims to provide knowledge of how to make the battery electric trucks as cost effective as possible by for example investigating battery sizing, driving patterns, and charging strategies. Result from the studies included in this thesis agree with past research that states that the cost effectiveness for battery electric vehicles is sensitive to driving patterns [11] and that driving patterns that are relatively uniform has a potential for electrification [12]. However, previous studies have used probability density functions for the daily driven distance for the battery electric vehicles [11][13] but in this thesis the approach is different since the daily energy consumption over the trucks full service life is used instead. The daily energy consumption is visualised in an *energy distribution diagram*, which is introduced in Paper A. Further, the energy distribution diagram is used for cost calculations in Paper B. In a previous study of a commercial electric vehicle, a model for the battery ageing is used to consider the effect of battery ageing due to battery sizing [14]. In the mentioned study it is found that oversizing the battery could lead to a lower total cost of ownership since it reduces the battery ageing. The fact that a larger battery prevents deep battery cycling which reduces battery ageing is clear from other studies as well [15]. Due to the battery ageing and margins to create a robust system it is assumed in Paper A and B that only a share of the battery capacity could be used. In Paper A this share is set to 80% but in Paper B the share depends on how many cycles the battery must perform over its service life. In Paper B, the number of cycles decreases non-linearly with the cycle depth. This results in a larger total lifetime energy throughput for shallower cycles. This can be seen in studies such as [16]. A study of electric truck delivery conclude that battery sizing is essential for maximize profit [17] and it is studied in detail in Paper A and Paper B.

In presenting a systematic review of the cost of battery packs, Nykvist and Nilsson highlight battery price as a crucial parameter for cost-competitive battery electric vehicles [18]. In their article the authors claim (with the support of a previous study [19]), that the price of batteries must fall below 150 $/kWh if battery electric vehicles in general are to compete with internal combustion vehicles. They also show that such a price can be achieved in the near future. In Paper A and B it was shown that, even at a battery cost of 200 €/kWh, many commercial battery electric trucks will be cost-competitive with diesel trucks. This is because commercial trucks have a high utilisation rate compared to private passenger cars. A working Paper by the International Council on Clean Transportation [20] predicts a battery pack cost of 120 \$/kWh in 2030 and an indirect cost multiplier of 36.8% to cover the vehicle manufacturer's warranty and battery-related costs. This gives a cost of 164 \$/kWh, or 149 €/kWh, for the vehicle customer. The estimate used in this thesis, is therefore a conservative estimate for 2030 and may be reached earlier than that. Another study [21] also highlights battery price as a critical parameter: "We also argue that previous findings pointing out that heavy trucks are harder to electrify than lighter trucks are very sensitive to assumptions about the battery cost and battery lifetime". Of course there are many other parameters that could effect the cost effectiveness of the battery electric truck such as the use of grid storage as an example. This possibility has not been investigated in this thesis, but a former study shows that grid storage only seems to have a small benefit for plug-in hybrid vehicles [22]. However, it is worth mentioning that, to be used, battery electric trucks do not necessarily have to be cheaper than diesel ones. They simply must be the most cost-effective way of replacing fossil fuel transport. Cost efficient solutions for battery electric trucks are assumed to accelerate the transition from commercial diesel trucks into battery electric ones and are therefore highly important to find. If they in the long run are cheaper than diesel trucks the transition will become much easier and faster, as profitability is a strong driving force for companies and that force will then help the transition.

Due to the limited range of the battery electric trucks, there is need for charging stations that can supply the trucks with public fast charging, at least for long-haul trucks. As earlier stated in the literature [23], the chargers must have a sufficient utilization to make the installation worthwhile. It is shown in Paper B that the profitability for a charge point operator is based on a sufficiently high utilization factor of the chargers and the lowest required price for fast charging to reach profitable stations is expressed as a function of the charger utilization factor. In a previous study [24] it is expressed that the need for charging infrastructure is highly dependent of the battery size, this is discussed in Paper B as a potential risk for charge point operator since an increase in the battery capacity probably will lead to less demand of public fast charging. Paper B is a case study that investigates the economic consequences for a haulage company that want to make a transition from diesel trucks into battery electric ones. Results from another case study in the literature [25] demonstrate the importance of vehicle-specific examination for the right battery capacity that ideally matches the vehicle's operating profile. This is also clear from the case study in Paper B where alternative battery sizes are discussed for a specific transport task.

In Paper B the approach of building sufficient number of chargers to always fully accommodate the charging demand is questioned, and the total power that maximize the profit for the charge point operator for a given demand is instead investigated. So far, these studies focus on investigating how to make different parts of the system of battery electric trucks and charger stations cost effective. However, it is also of great importance that the system is well functioning, in the sense that one avoids long queues at the charging stations. Of course, it could be hard to achieve this and at the same time keep the charger utilization factor high. A previous study [26] state that the question of how much a chargers can be utilized, without cause queuing at chargers, is a key question when designing charging networks. In Paper C the demand of chargers for battery electric trucks is estimated along one of the main highways (E4) in Sweden, in a possible future scenario where there are equally many battery electric trucks as there are diesel trucks today. Paper B, together with another study [27], discusses advantages with higher charger pricing at rush hours to avoid queuing and increase profit. This was investigated in Paper C with an agent-based model based on data on the flow of trucks along the E4 road [28].

Challenges and Desirable Features of a System of Electric Trucks and Chargers

Many of the results from this thesis are regarding all types of battery electric trucks with stationary charging. However, for medium and long-distance trucks the challenge of electrification is harder compared to local distribution. This is due to that the payload often is higher in case of medium and long-distance transports. Also, the longer transports demand more energy, and thus a larger battery. Both these factors make it difficult to have a battery large enough for a full day's driving. If the trucks do not regularly carry heavy goods the battery can be rather big, but if not the battery can be large the truck has to rely on public fast charging at least once during a workday. So, for many long-distance trucks, a large part of the energy will be charged at public chargers and it is then important that the price for that charging is low. If the public fast chargers are not utilized sufficiently the price for charging will be high. So, a high utilization is desirable, but if the utilization is high that might instead cause problems with queues at fast-charging stations. If there are extensive problems with queues there might be needs for booking systems. But booking systems may not only be a positive thing, as they can also be seen as a potential problem with extra administration and blocked and unused chargers when a truck that has booked a charger is delayed. The system of electric trucks and chargers must also be robust to extreme weather, increased traffic flow and unexpected peaks in the traffic flow.

It will be desirable if the transition to battery electric trucks could be done cost effectively, without unwanted changes to how the trucks operate and no need for booking systems for public fast chargers. The result from this thesis indicates that this can be possible to achieve. Two things that can improve the future system even more, would be if the trucks daily energy consumption and the demand for public charging can be as even as possible. This would further improve the possibility to select cost-effective battery sizes and to achieve high utilization of the public fast chargers.

In this thesis the main mechanisms that make for a cost effective and robust system are explored, but under several simplifications. It would be interesting to add more detailed and precises models, for example regarding battery ageing, loss in payload-capacity and more precise traffic data and see if the main results still hold. If they do, one may assume that the simplifications were accurate, and if they do not, one may question the simplifications. Another, more nuanced way of looking at it is that if changes in assumptions cause dramatic changes in results, then the system itself is sensitive. If so, it will be hard, but still very important, to find good system solutions. If, however, the system itself seems to be insensitive to the assumptions, it will be a lot easier to design a good system provided that one has done the proper investigations in advance.

3 Summary of the Papers

The aim of this research has been to develop better understanding of efficient system solutions for battery electric trucks and their chargers. In Paper A, the cost of electric trucks in general was studied with the aim of finding how the cost could be affected by changing the battery capacity, charging strategy and charger power for different types of driving patterns. Knowledge in this area is important since it can reduce the total cost of ownership for the haulage companies. Then the general work in Paper A, was concretized by investigating a specific long-distance haulage company, in Paper B. The studied case was also a step towards studies on a system level, since the number of public chargers that could provide the trucks with public fast charging was investigated. Studies of this type demonstrates how to apply knowledge about battery electric trucks and their chargers to get cost effective solutions. Further on, in Paper B, the focus was shifted to the charge point operator's perspective. It was investigated how to size the total power for a charging station to maximize the profit for the charge point operator. This question is also of importance since one wants to know how many chargers should be built to meet the demand in a cost-effective way. Finally, in Paper C, the charging needed for trucks along a highway in Sweden was estimated from traffic data. This study was done with the objective to be able to predict the future need for public fast chargers along roads and how to make sure the system is resistant towards queues at charging stations even with unexpected peaks in the traffic flow. The above investigations together build an important part of the knowledge required to find efficient system solutions for battery electric trucks. Below, each article included in this thesis are summarized individually followed by a discussion of the contributions in the coming section.

3.1 Summary of Paper A

Paper A compares the cost for a battery electric truck with the cost for a commercial diesel truck. The most cost-effective battery size and the cost competitiveness is investigated for different driving patterns. The introduced *energy distribution diagram* visualizes the data for the daily energy consumption for all the days in the trucks service life and is used to facilitate the analysis.

3.1.1 Cost of a Battery Electric Truck

Some of the main costs for operating a truck, regardless of whether it is driven by diesel or electricity, are approximately equal for a diesel truck and a battery electric truck. These are the cost for the vehicle, when excluding the battery in the electric case, the cost for maintenance and insurance. Under the assumption that the charging of the trucks is done in a way that does not increase the working hours of the driver, also the salary for the driver remains the same. These costs are therefore ignored when the comparison is made. In this Paper it is also assumed that the electric truck has the same payload capacity as the diesel truck, which is reasonable in many cases, with the main exception being trucks driving a long distance without charging in combination with carrying heavy goods. What differs is that the electric trucks have additional cost for battery, charger and grid connection, and also that the diesel cost is replaced by the cost for electricity. In this Paper the costs are normalised and expressed in Euros per kWh propulsion energy.

The main idea in Paper A is to express the cost for the battery electric truck as a function, which will be called the cost function, and then try to find the battery size which minimizes that function for different ways of using the vehicle. The cost function,

$$f_{BEV} = r_{ch} \cdot C_e + (1 - r_{ch}) \cdot C_{epub} + \frac{C_b \cdot B_c}{E_{tot}} + \frac{C_{charger} \cdot P_{ch}}{E_{tot}} + T \cdot \frac{C_g \cdot P_{ch}}{E_{tot}}, \tag{3.1}$$

where the parameters are given in Table 3.1 and 3.2, sums up the costs per kWh for private charging, public fast charging battery, charger, and grid connection, respectively. The values used in this paper for the cost parameters in Table 3.1 are listed in the column "typical value".

Table 3.1: Notations for the different costs and their assumed values. Please keep in mind that the cost refers to the cost of *propulsion* energy.

Costs	**Notation**	**Typical Value**
Diesel Cost	C_d	0.30 €/kWh
Electricity Cost, Private Charging	C_e	0.08 €/kWh
Electricity Cost, Public Fast Charging	C_{epub}	0.4 €/kWh
Battery Cost	C_b	200 €/kWh
Price of Charger	$C_{charger}$	400 €/kW
Grid Fee	C_g	60 €/kW/year
Service Life of Truck, Charger and Battery	T	7 years
Combined Price of Charger and Grid	$C_{ch} = \frac{C_{charger}}{T} + C_g$	117 €/kW/year

Table 3.2: Notations for parameters.

Parameters	**Notation**
Total Propulsion Energy Consumed Over the Trucks Service Life	E_{tot}
Ratio of Private Charging to the Total Amount of Energy	r_{ch}
Battery Capacity	B_c
Charger Power	P_{ch}

Defining the battery utilization factor, Γ_b, as

$$\Gamma_b := \frac{E_{tot}}{B_c}, \tag{3.2}$$

the battery utilization factor has the dimension-less unit *equivalent full cycles* (EFC) and describes the number of *full* discharge cycles that can deliver the total amount of energy. Also, defining the charger utilization factor, Γ_{ch}, as the total energy delivered divided by the maximum energy that can be delivered by the charger over its service life, i.e.,

$$\Gamma_{ch} := \frac{E_{ch}}{T \cdot P_{ch}}, \tag{3.3}$$

where E_{ch} is the total amount of energy delivered divided by the charger over its service life. This charging utilization factor is therefore a dimensionless scalar ranging from 0 to 100%. By using the notation for the combined price for charger and grid according to Table 3.1 together with $E_{ch} = r_{ch} \cdot E_{tot}$ it is now possible to rewrite the cost function as

$$f_{BEV} = r_{ch} \cdot C_e + (1 - r_{ch}) \cdot C_{epub} + \frac{C_b}{\Gamma_b} + \frac{r_{ch} \cdot C_{ch}}{\Gamma_{ch}}. \tag{3.4}$$

The cost parameters in Table 3.1 will be determined by the market and technology development and the total energy consumed for a vehicle during its service life depends on the transport task for the truck. However, the parameters for the battery capacity, the charger power and the ratio of private charging is of special interest since they will change depending on charging strategy. As seen from Equation 3.4 one should aim to choose the battery capacity and the charging power, so it increases the utilization factors while at the same time public fast charging is avoided, since it decreases r_{ch} and thereby increases the cost. If one can express the relationship between these parameters one may be able to optimise these parameters in order to find the lowest total cost per kWh propulsion. In Paper A it is shown that the relationship depends on the shape of the energy distribution diagram for the truck, which is introduced in the next section.

3.1.2 The Energy Distribution Diagram

The energy that a battery electric truck consumes each day will differ due to for example different transport tasks and weather conditions. The data for the daily energy consumption for a truck can be presented in an energy distribution diagram. At first, consider a trucks daily energy consumption over one week in the left-hand part of Figure 3.1, where the height of each bar on the y-axis represent the energy consumed for that day. Over a truck's service life the number of days are many and if they are sorted with respect to energy consumption, starting at the highest consumption, one obtain a curve which is called the energy distribution diagram (EDD)[1] (see the right-hand part of Figure 3.1). The total number of days during the vehicles service life is N_{tot} and the number of days the vehicle is operated is N_{op}. In this paper $N_{op} = 1750$ which corresponds to a truck that operates five days per week, 50 weeks per year in seven years. It is not a problem that the days are rearranged according to energy consumption since the truck is charged during night and the energy needs of the coming day are therefore independent of consumption the day before. To sort the days according to energy consumption has advantages as it is easier to overview to, for example, read the highest daily energy consumption or to estimate the mean energy consumption. Also, it is easier to approximate the sorted EDD with a mathematical function that is always monotonically decreasing. Notice that it is possible to change to number of trips instead of number of days on the x-axis, for a vehicle which is charged after each trip.

By plotting the useful battery capacity in the EDD it is also possible to determine how many days the battery is too small to run the whole day on one charge. These days the vehicle needs to fast charge during the day. In the paper it is assumed that the fast charging only charges the minimum energy needed to carry out the rest of the days driving. Thus, the energy which needs to be fast charged can

[1]Notice that curve actually should be a discrete number of points but for convenience it is instead seen as continuous curve.

be determined as the red-striped area in the diagram and the energy charged from the home charger corresponds to the blue striped area.

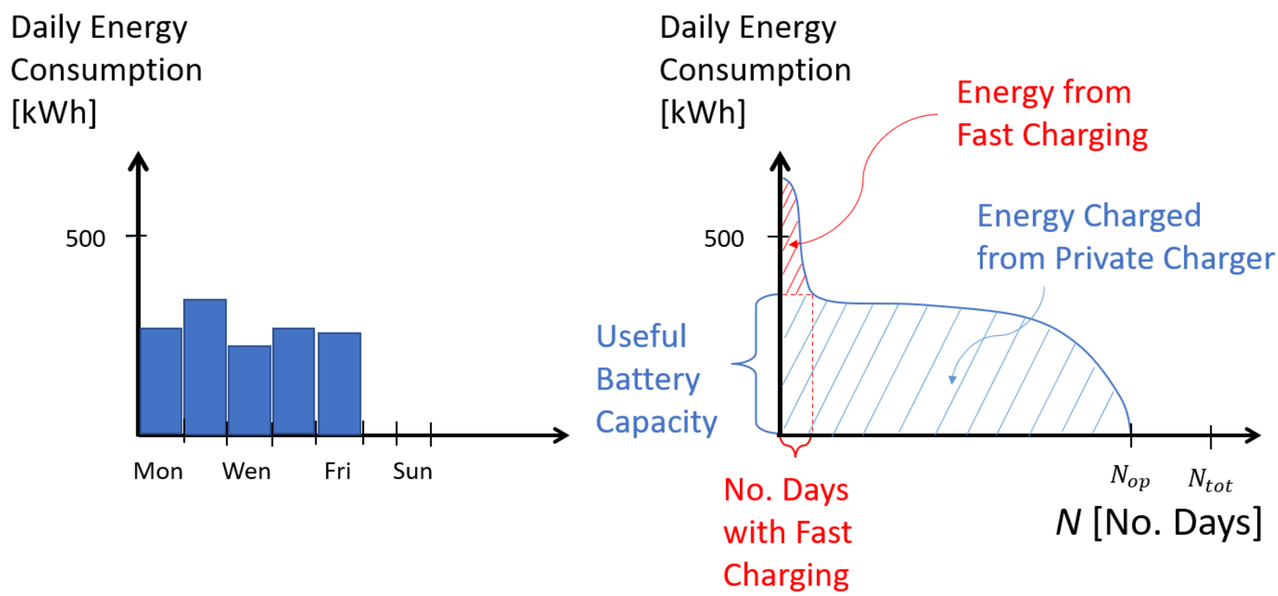

Figure 3.1: The daily consumed energy for five working days to the left and the energy distribution diagram for a truck's full service life to the right. In the right-hand part of the figure the number of days that needs fast charging and the amount of fast charging needed is marked with red for a certain useful battery capacity.

The EDD gives a lot of information for the full service life of a vehicle in a compact way. This information is listed below:

- The total energy consumption is the area under the curve.
- The total number of operation days is where the curve meets the x-axis.
- The mean consumed energy for the days when the truck is used equals the total energy divided by the number of operation days.
- The highest consumed energy is where the curve meets the y-axis.
- The number of days that needs fast charging and the amount of fast charging needed for a particular useful battery capacity.
- The shape of the EDD gives a quick picture of how large the variation in the energy consumption is and how large share of the days that have high, medium or low energy consumption.
- Maybe most important, the EDD connects the useful battery capacity with the parameter r_{ch}, since r_{ch} can be found as the blue striped area divided with the area under the curve (see Figure 3.1).

When considering the right-hand part of Figure 3.1 one may suspect that the optimal charging strategy is strongly influenced by the shape of the EDD. For example, can it be a good idea to select a battery capacity that can handle the majority of the trips but not the thin peak in the EDD? In that case the battery cost is strongly reduced compared to a battery that can handle all the trips but the amount of energy from fast charging is low compared to the total energy. In the coming subsections the studied cases of EDDs are presented among with the results from the paper. All the analysis in the paper was done under the assumptions that the battery capacity and the power of the charger are assumed to be continuous variables in the span from zero to arbitrary high values and that it is possible to charge exactly when it is needed.

3.1.3 Studies of Different Energy Distribution Diagrams

In the paper three different energy distribution diagrams are investigated namely, the rectangular EDD, the triangular EDD and the two-step rectangular EDD defined as below. Let $E(N)$ be the the total amount of energy consumed by a truck day N. That means, $E(N)$ determines the envelope of the EDD and is, therefore, called the energy function. For the rectangular EDD the energy function is expressed as

$$E(N) = E_{max}, \qquad N \in [0, N_{op}], \tag{3.5}$$

where E_{max} is the highest daily energy consumption over the truck's service life. For the triangular EDD the energy function is

$$E(N) = -\frac{E_{max}}{N_{op}} N + E_{max}, \qquad N \in [0, N_{op}]. \tag{3.6}$$

For the two-step rectangular EDD the energy function is written as

$$E(N) = \begin{cases} E_{max}, & N \in [0, M] \\ E_{min}, & N \in (M, N_{op}], \end{cases} \tag{3.7}$$

where E_{min} is the lowest daily consumed energy for the truck and M is the number of days the truck consumes the maximum daily energy E_{max}. Figure 3.2 shows the above mentioned energy distribution diagrams, where the upper left-hand part of the figure shows the rectangular EDD, the upper right-hand part of the figure shows the triangular EDD and the lower middle part of the figure shows the two-step rectangular EDD. The number of days with fast charging, the amount of public fast charging and the energy charge from the private charger are marked in the sub figures for a certain useful battery capacity.

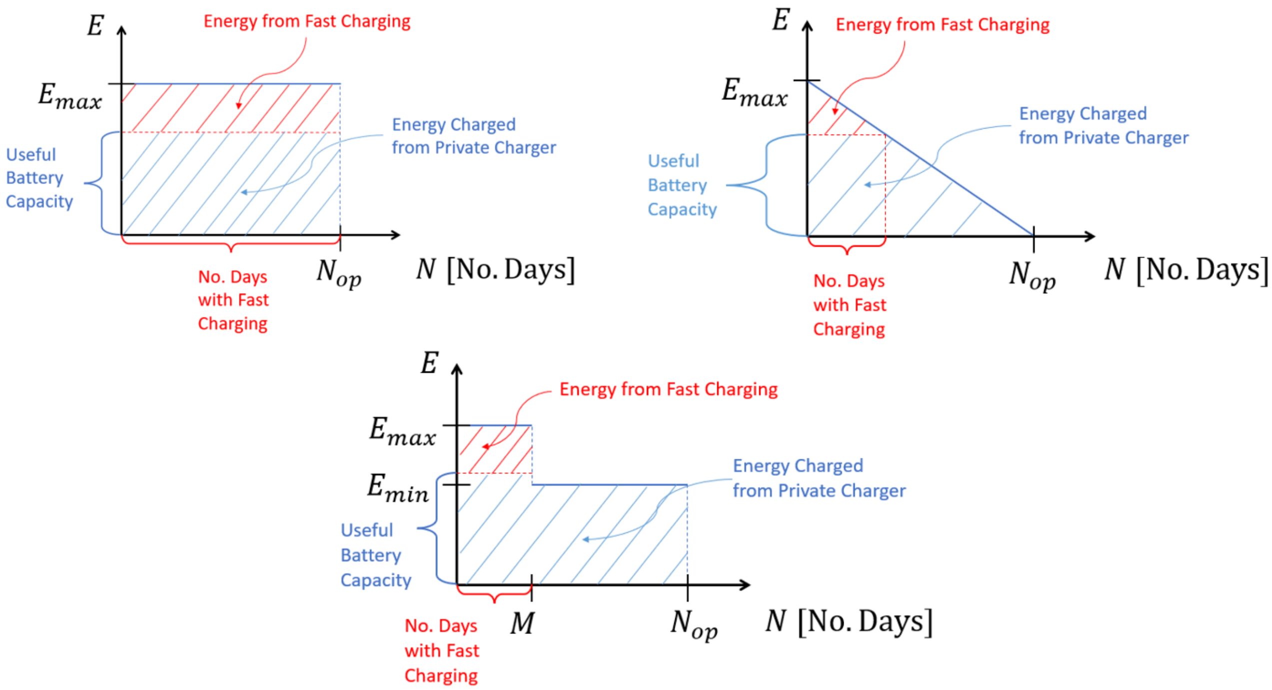

Figure 3.2: Three types of energy distribution diagrams. The upper left-hand part of the figure shows the rectangular EDD, the upper right-hand part of the figure shows the triangular EDD and the lower middle part of the figure shows the two-step rectangular EDD. The number of days with fast charging, the amount of public fast charging and the energy charge from the private charger are marked in the sub figures for a certain useful battery capacity.

By considering Equation 3.1 one realizes that for a fixed set of cost parameters and a certain EDD there are three parameters that could be affected to minimize the cost, namely r_{ch}, B_c and P_{ch}. However, these three are strongly connected. For a certain battery capacity, one finds the cheapest charger by selecting the charger power so it just can charge the whole useful battery capacity over the night. The amount of private charging follows from the shape of the EDD and the choice of the useful battery capacity, see the blue striped areas in the right-hand part of Figure 3.1 and in Figure 3.2, which then gives r_{ch}. This follows from the fact that one does not want to charge with public fast chargers more than necessary for a given battery capacity. So, for a given EDD the most cost effective P_{ch} and r_{ch} can be seen as a function of the battery capacity. Hence, the cost function can now be seen as a function of just one variable, for example B_c, and can then be optimized by methods from calculus in one dimension. Due to battery aging and robustness margins, it is assumed that only a share of the battery capacity, r_{SoC}, can be used. The useful battery capacity, B_{cu}, can then be expressed as

$$B_{cu} = r_{SoC} \cdot B_c, \tag{3.8}$$

where r_{SoC} is set to 80 % in Paper A.

3.1.4 Result and Conclusions

In the study it is found that the rectangular EDD gives gives the lowest value, 0.26 €/kWh, on the cost function compared to all other energy distribution diagrams, for a fixed number of operation days. In this case the electric truck is more cost effective than the commercial diesel truck and the battery should be sized so it can handle the energy need for all the days, without using any public fast charging. In the case with the triangular EDD the electric truck is not competitive with the diesel truck with the price parameters used in the paper. Luckily this shape of EDD is rare for commercial trucks.

In case of a two-step rectangle EDD the electric trucks can, in many cases, compete with diesel trucks. With this EDD the lowest cost is obtained by either having a battery so large that it can handle all the trips without fast charging, or a battery that just can handle the low consuming trips without fast charging. If the days with high consumption are sufficiently many, one should choose the large battery, otherwise the small. In this context sufficiently many are a little less than 1000 days. The EDD best suited for the electric trucks are the ones close to a single rectangle or a rectangle with a thin peak on top. The worst EDD is the ”L”-shaped one, if the peak is not really thin, and the EDD that has a long thin tail.

In the paper a general algorithm for selecting the battery capacity for any EDD is presented. It is also found that a battery electric truck is not competitive to a diesel truck if the number of operating days is less than 1400, regardless of the shape of the EDD. Finally, it is stated that for any EDD, as long as the shape is fixed, the total normalised cost is reduced by increasing the number of operating days while the maximum energy consumed per day does not influence the normalised cost. The analysis is preformed using the introduced energy distribution diagram, which visualizes the needed data for the daily energy consumption for the truck in a compact way.

3.2 Summary of Paper B

In this paper the economic consequences for a haulage company that replaces their line-haul diesel trucks with battery electric trucks is investigated. It is examined how large the batteries of the trucks should be, if the haulage company should use public fast chargers as a complement to their own chargers, as well as if the public fast chargers have a potential to be profitable. Further, the number of chargers needed to avoid queuing at the rest area is investigated, and the potential cost for loss of pay load capacity due to large batteries is estimated. Finally, it is investigated how to select the total charger power of a charging station for a given demand of charging. The analysed case is designed to represent typical line-haul between terminals in a big logistic system, and is strongly inspired by the Swedish haulage company "Tommy Nordbergh Åkeri ab".

3.2.1 The Haulage Company’s Transport Task

In the case study the haulage company has a fleet of commercial diesel trucks and has the ambition to replace all of them by battery electric ones. This paper will investigate the economic consequences of a full electrification with out any changes to how the trucks operate.

The company has two terminals, Terminal A and Terminal B, which are connected with a highway. Terminal A is located in the city Helsingborg at the Swedish west coast and Terminal B in Stockholm, the capitol of Sweden, located on the east coast. Five times per week the following procedure is repeated. Half of the trucks arrive to Terminal A and half of the trucks arrive to Terminal B in early afternoon after some local distribution tasks during the day. Then the trucks stand still for a certain time, T_1, and thereafter leave the terminal and drive towards the other terminal. The trucks leave the terminal, one by one, with a certain time gap, T_{gap}. Midway between the terminals the drivers have a mandatory break of length T_{break} at a rest area. After the break each driver from Terminal A changes truck with a driver from Terminal B and then return to their home terminal. After arrival the trucks stand still for a certain time T_2. Further, let the distance between Terminal A and Terminal B be S, the trucks mean speed be $\overline{v}$, the trucks mean energy consumption per unit distance travelled be $\frac{\Delta E}{\Delta x}$ and the number of trucks starting from *each* terminal be N_{trucks}. During the local distribution tasks, which takes place during the day, each truck drives a distance $S/2$. The notation for the parameters and their values used in this paper are listed in Table 3.3. In addition to driving each weekday during the year, the trucks preform on average 50 extra night trips per year and truck during the weekends. At the rest area a charge-point operator is planning to build public fast chargers, so in addition to the company's private chargers at each terminal the trucks can also be charged at the rest area by the public fast chargers.

Table 3.3: Notations for the different parameters and their value used in this paper.

Parameters	Notation	Value
Time Gap Between Trucks	T_{gap}	7 minutes
Inactive Time for the Trucks in the Afternoon	T_1	2 h
Time for the Break	T_{break}	45 minutes
Inactive Time for the Trucks in the Morning	T_2	4 h
Distance Between the Terminals	S	550 km
Mean Speed of the Trucks	$\overline{v}$	75 km/h
Energy Consumption	$\frac{\Delta E}{\Delta x}$	1.5 kWh/km
Numbers of Trucks Starting from Each Terminal	N_{trucks}	30

3.2.2 Economic Consequences of Electrification for the Haulage Company

Equation 3.4 is used to determine the value of the cost function, with the same parameter values as in the earlier paper, with the exception that r_{SoC} is adopted so that the battery can perform the needed number of charging cycles over the trucks service life. In Paper B the number of possible charging cycles for different r_{SoC} is assumed to be given by the power function $g(r_{SoC}) = a \cdot {r_{SoC}}^b$ where $a \approx 2000$ and $b \approx -1.9$. The cost function expresses the cost for just *one* truck with *one* private charger. However, even if the company has many trucks there is no problem to using the above expression since it is assumed that there are as many private chargers as trucks. The battery electric propulsion cost is then compared to the diesel propulsion cost, which again is taken as 0.30 €/kWh. Since the trucks only preforms two different trips over their whole service life the driving pattern is described by a two-step rectangular EDD. Even if the presumptions are not identical it is reasonable to assume the results from Paper A is valid and the battery should therefore be sized so it either just can manage the low consuming trips without public fast charging or just can handle even the high consuming trips without public fast charging. When the small battery was used the value of the cost function was found to be 0.32 €/kWh which is above the reference value for diesel but when the large battery was used the value of the cost function was 0.24 €/kWh, which is below the reference value for diesel.

In the study the potential cost for losing payload capacity due to the battery is also estimated. It was found that this cost could be quite high, namely 0.11 €/kWh in the case with the small battery and 0.24 €/kWh with the large battery. This is the highest possible cost, and it could also be zero depending on if the goods that is transported is heavy or not. However, since there is a potential large extra cost for having a large battery the haulage company should still be interested in the solution with small battery, if only the public fast charging would be cheaper. Therefore, it is also investigated if the charge point operator could be profitable with a lower price on public fast charging.

3.2.3 The Number of Chargers and the Price for Charging at the Fast Charging Station

The above calculations suggests that the haulage company will size the battery such that there is no need for public fast charging, if the price for the public fast charging is 0.4 €/kWh. It is therefore interesting to investigate if the charge point operator can lower the price. The cost for the charger owner is the cost for the electricity, and the charger and the grid connection. The cost for the charger and the grid connection is assumed to be proportional to the power of the charges and the cost per kWh, f_{ch}, is expressed as

$$f_{ch} = C_e + \frac{C_{ch} \cdot P_{ch} \cdot T}{E_{ch}} = C_e + \frac{C_{ch}}{\Gamma_{ch}}. \tag{3.9}$$

First, one may assume that the company with the trucks will charge fully at the rest area. The drivers have a break of 45 minutes, so one knows that each truck will charge for 45 minutes. So how many chargers are needed? The 30 trucks from each terminal depart with a time gape $T_{gap} = 7$ minutes since the terminal personnel and gates do not have the capacity of sending them off at the same time. The first two truck leaves Terminal A and B at 6 PM, then drive the distance $S/2 = 275$ km to the rest area with the mean speed 75 km/h, and charge for 45 minutes when they arrive at the rest area. The drivers switch truck with the driver from the other terminal and then return home. The number of charging truck as a function of time can be found from a simulation. However, one cannot expect perfect timing, so the trucks are assumed to sometimes be delayed. For the company delays over 15 minutes are very rare. Therefore, each truck is delayed with the delay-magnitude of a random number drawn from a normal distribution with expected value 0 minutes and standard deviation 5 minutes. The left-hand part of Figure 3.3 shows the number of charging trucks at the rest area as a function of time, for one night. As seen from Figure 3.3 the maximum number of chargers needed this day is 15. The right-hand part of Figure 3.3 shows a histogram where the value on the x-axis represent the maximum chargers needed on one day and the height of the bar represent how many days that occurs on a 10-year period[2]. As seen from the histogram in the right-hand part of Figure 3.3 one needs to have 16 chargers at the rest area, with the selected model and parameter settings. The fact that it sometimes is a demand for 17 chargers is not seen as a problem since this happens only twice in a year. The result does *not* change dramatically when one changes the standard deviation with ± 2 minutes.

[2]The trucks operate almost 6 nights per week.

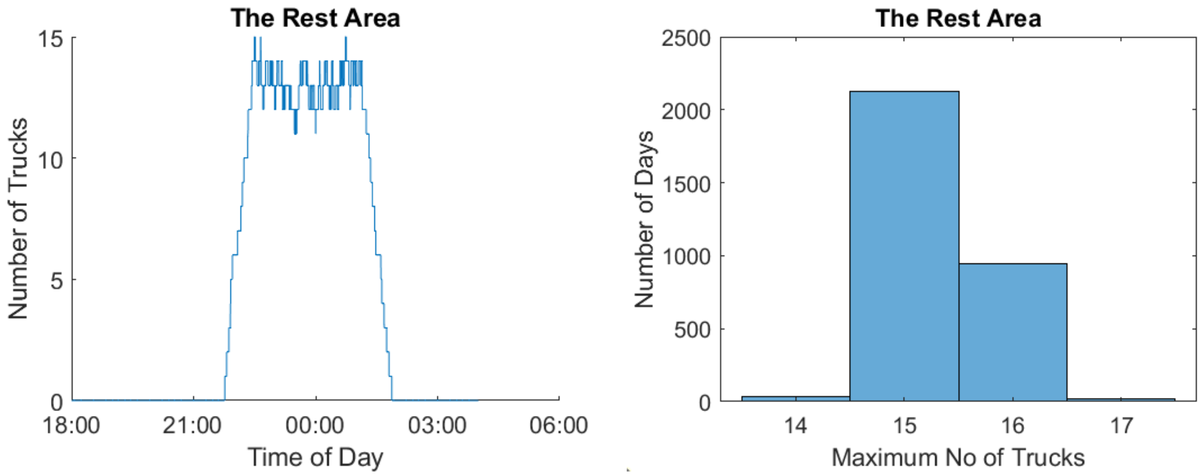

Figure 3.3: The left-hand part of the figure shows the number of charging trucks at the rest area as a function of time for one day. The right-hand part of the figure shows how many days over a 10-year period a special number of chargers is needed.

Each of the 16 chargers must be able to charge the trucks whole useful battery capacity in the time T_{break}. Thus

$$P_{ch} = \frac{B_{cu}}{T_{break}} = \frac{412.5 \text{ kWh}}{0.75 \text{ h}} = 550 \text{ kW}. \tag{3.10}$$

Since the charging need of the trucks is known the charge utilization factor, when only the haulage company uses these chargers, can be calculated with the result

$$\Gamma_{ch} = 10 \ \%. \tag{3.11}$$

So, if the company that installs the chargers have no other customers than the analysed company the cost for the chargers will, according to Equation 3.9, be

$$f_{ch} = 0.21 \text{ €/ kWh}. \tag{3.12}$$

Consequently, it seems to be possible to lower the price from the originally assumed 0.4 €/kWh. So, how low does the price have to be if the haulage company shall consider the small battery and fast charge the whole useful capacity at the rest area? The company will probably select the smaller battery if it is possible to reach an equally low value of the cost function as for the large battery, due to less loss in payload capacity. Thus, one may determine the required price for fast charging by solving the equation

$$f_{BEV} = 0.24 \text{ €/kWh}, \tag{3.13}$$

with the values for the small battery. To proceed

$$C_{epub} = \frac{0.24 \text{ €/kWh} - r_{ch} \cdot C_e - \frac{C_b}{\Gamma_b} - \frac{r_{ch} \cdot C_{ch}}{\Gamma_{ch}}}{1 - r_{ch}} = 0.17 \text{ €/kWh}. \tag{3.14}$$

At first this seems hard to reach since the value is below the cost of the charger owner, according to Equation 3.12 . However, as seen from Equation 3.9 the normalised cost for the charge point operator only depends on the charger utilization factor.

Figure 3.4 shows f_{ch} as a function of Γ_{ch}.

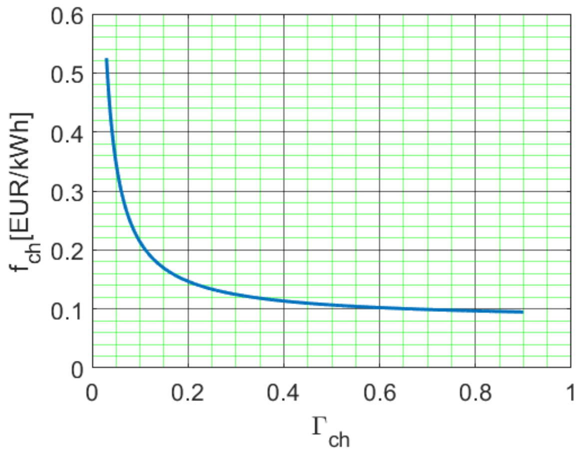

Figure 3.4: The normalised cost f_{ch} as a function of the charger utilization factor, Γ_{ch}.

From the figure one observes that the value of f_{ch} is below 0.17 €/kWh for charger utilization factors of 15% or more. It seems possible to have at least the same use of the chargers during the day by other companies, for example, the lunch break should be a great opportunity to charge. In this case the charger utilization factor will be 20 % which by Equation 3.9 leads to $f_{ch} = 0.15$ €/kWh, allowing some profit also at a price of only 0.17 €/kWh . If one in addition have other customers in the morning, afternoon and evening it might be possible to reach a charger utilization factor of 25 %. Such a utilization factor will lead to $f_{ch} = 0.13$ €/kWh and then the chargers can provide a profit also with as low price as only 0.17 €/kWh.

The haulage company will have a normalized cost for battery electric propulsion of 0.24 €/kWh of which the cost for the private charging is 0.05 €/kWh, the cost for the public fast charging is 0.06 €/kWh, the cost for the battery is 0.06 €/kWh and the cost for the charger and grid is 0.07 €/kWh. The indirect cost for any loss in payload capacity will probably be low with the small battery. The calculations done in this paper strongly indicates that the electric trucks will be more cost efficient than the commercial diesel trucks, for haulage companies with similar driving patterns to the treated company.

3.2.4 Selecting Total Power for a Fast-Charging Station

In the previous section it was found that 16 chargers should be built at the rest area to meet the demand from the haulage company. To meet this whole demand is probably not questionable since the haulage company will be a key customer, charging a large amount of energy almost six days a week. However, one may suspect that the demand at for example lunch time could be quite high since many truck drivers will have a natural break at that time. Then one wants to answer the question, is it cost effective to meet the peak charging demand? If not, how much of the peak demand should one meet? In order to investigate this, it is assumed that the demand for public fast charging can be expressed as how much charger power is demanded for a certain price level. Since there is a discrete number of trucks that wants to charge, it is natural to assume that the charging demand will be a step function of time, as in the left-hand part of Figure 3.5. If the power demand is sorted with respect to magnitude over the chargers service life one ends up with a diagram which we chose to call *the power* *demand distribution*, see the right-hand part of Figure 3.5. Here, $P_1 > P_2 > ... > P_N$ is the power demand during different times according to the figure and $T_1 < T_2 < ... < T_N$. In the right-hand part of the figure the energy that will be delivered by the chargers over their service life is marked in red for the choice $P_{ch} = P_{N-1}$.

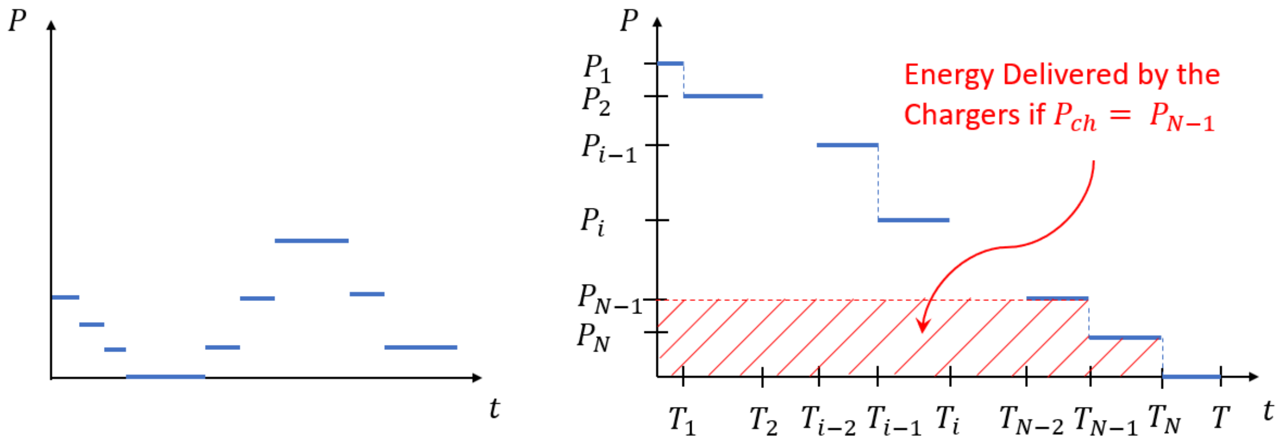

Figure 3.5: The power demand from the chargers as a function of time to the left and the power demand distribution to the right. Notice that the right-hand part schematically shows sorted demand power over the whole service life of the chargers while the left-hand part shows the unsorted demand over a shorter period. In the right-hand part of the figure the energy that will be delivered by the chargers over their service life is marked in red for the choice $P_{ch} = P_{N-1}$.

The demand power, $P = P(t)$, can be expressed as:

$$P = \begin{cases} P_1, & t \in [0, T_1] \\ P_2, & t \in (T_1, T_2] \\ \vdots & \vdots \\ P_{i-1}, & t \in (T_{i-2}, T_{i-1}] \\ P_i, & t \in (T_{i-1}, T_i] \\ \vdots & \vdots \\ P_N, & t \in (T_{N-1}, T_N] \\ 0, & t \in (T_N, T], \end{cases} \tag{3.15}$$

where T_N is the total time that there is demand of using at least one charger and therefore the notation $T_N = T_{use}$ is introduced.

In order to be able to make a clever choice of the total power of the charging station the profit, I, for the charge point operator is now expressed as follows:

$$I = C_{epub} \cdot E_{ch} - C_e \cdot E_{ch} - C_{ch} \cdot T \cdot P_{ch}. \tag{3.16}$$

Note, that in this context, E_{ch} is the total energy delivered by the *charging station* over the chargers service life. P_{ch} is the total power of the chargers, and T is the service life of the chargers. In the above equation the first term on the right-hand side is the total income from the users over the time T, the second term is the total cost for the electricity over the time T and the last term is the total cost for the chargers and the grid connection over the time T. Let:

$$C_{diff} = C_{epub} - C_e \tag{3.17}$$

and Equation 3.16 becomes:

$$I = C_{diff} \cdot E_{ch} - C_{ch} \cdot T \cdot P_{ch}. \tag{3.18}$$

The charge point operator can directly affect two of the parameters in Equation 3.18, namely, C_{diff} by setting the price for charging and P_{ch} by deciding how many and how large chargers to invest in. These choices will indirectly affect the total energy delivered by the chargers, E_{ch}, since the price for public fast charging will affect the demand and the total power of the chargers will limit the capacity to deliver energy from the chargers. It is assumed that a fixed price on public fast charging (i.e., the price does *not* vary with time) results in a given power demand distribution. After calculations, it is found that:

$$\text{The chargers are profitable} \iff \frac{T_{use}}{T} > \frac{C_{ch}}{C_{diff}} \tag{3.19}$$

and if the chargers are profitable one should choose the charger power $P_{ch} = P_k$ where k is the smallest integer in the set $[1, N]$ that fulfills the inequality:

$$\frac{T_k}{T} > \frac{C_{ch}}{C_{diff}} \tag{3.20}$$

to maximise the profit for the charge point operator. It appears that the charger's power only shall meet the full demand if the high power will be used a sufficiently long time. With the different values used in Paper B the peak demand must last for 4% of the charger service life, if the price of public fast-charging is 0.4 €/kWh, to 15% , if the price is 0.17 €/kWh. Worth mentioning is that these calculations aim to maximise the profit for a given demand power distribution with fixed prices of public fast charging but does not include for example effects that one may lose a customer to a competitor who has more available chargers, and one may lose all the charging from that customer, not only the charging at the peak hour.

3.2.5 Discussion and Conclusions

The calculations done in this paper shows that the battery electric trucks have a great potential to be competitive to commercial diesel trucks already with a diesel price of only 1.2 €/liter (excluding VAT). Figure 3.6 compares the different alternatives for the haulage company. In the figure all the numbers are in €/kWh, where the height of the bars represent the total cost for one strategy. The bars for the battery electric trucks are marked with different colors to separate the individual cost according to the legend in the upper right-hand part of the figure. Due to rounding the individual cost for the battery electric truck with the large battery seems to add up to more than the total cost. As stated in the text earlier the haulage company will likely select, by negotiation with the charge point operator, the strategy represented by the fourth bar which will give a lower cost for propulsion energy than the current diesel trucks and less loss in payload capacity when comparing with the strategy with the large battery.

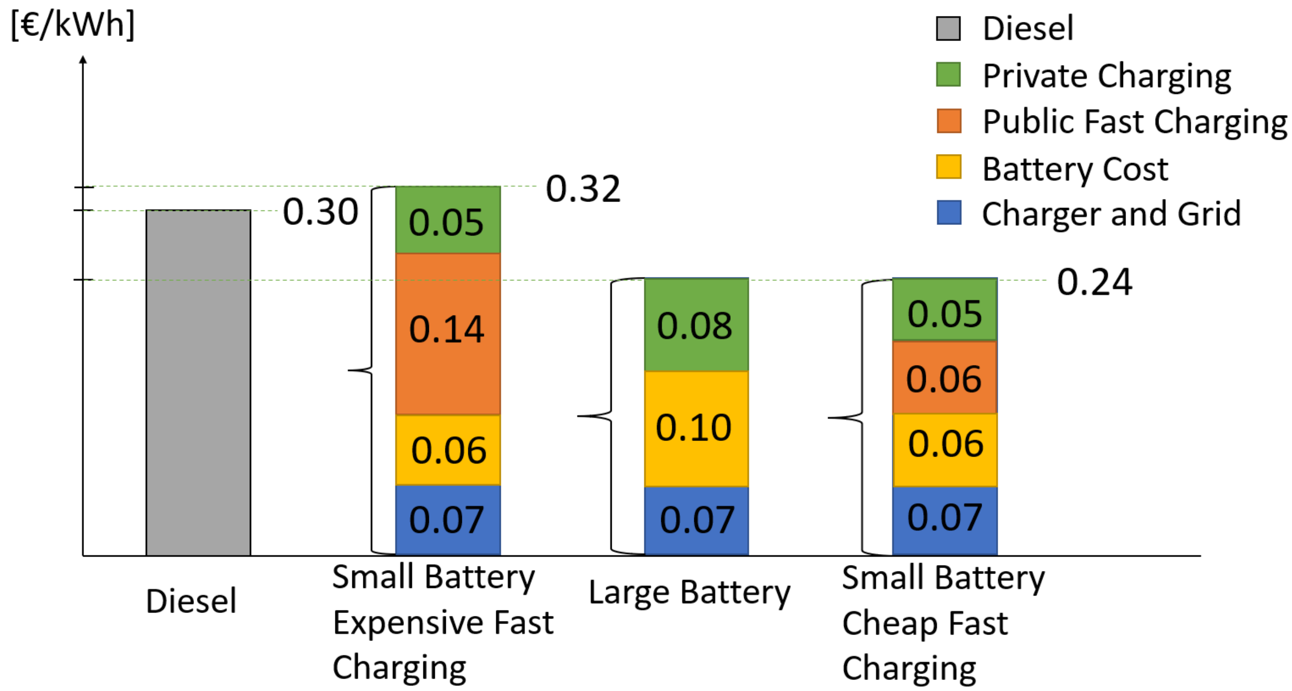

Figure 3.6: The different cost for the alternative strategies for the haulage company. The height of the bars represents the total cost for one strategy. The bars for the battery electric trucks are marked with different colours to disclose the individual cost according to the legend in the upper right-hand part of the figure. All the numbers are in €/kWh. Due to rounding the individual cost for the battery electric truck with the large battery seems to add up to more than the total cost.

In the previous section the price for electricity and public fast charging was assumed to be fixed. However, is it likely that a charge point operator will have fixed prices for their users? Maybe not. In reality the demand for charging power will vary with time as can be shown with a demand power distribution like the one on the left-hand part of Figure 3.7. From such an demand power distribution one observes that for $t \in [0, T_1)$ there is a much greater demand than the charging station can supply, so here the charge point operator have opportunity to increase the price for public fast-charging and still sell the same amount of energy while increasing the profit. It might also be possible to move users from the rush hours to other times by having high price during rush hours and lower price other times, compare the left and right-hand part of the figure. The mean value of the difference in the price for public fast-charging and electricity might even be the same but due to the increase in E_{ch} the total net income will still increase. Again, consider the left-hand part of Figure 3.7 as an illustration. One may argue that time varying pricing will be beneficial for the users as well, since it will make it possible to offer fast charging exactly when it is desirable, for those who really need it and pays for it, and the users that moves their charging to other times will be rewarded with lower prices. How to select the price for public fast charging is a very complex question and will require a thorough investigation on its own. Based on this short analysis we cannot predict charging prices. Still, this analysis shows that a low price seems achievable, and that there are many ways in which the pricing and the hauliers charging strategy may change to increase the charger utilization and thus enable even lower price.

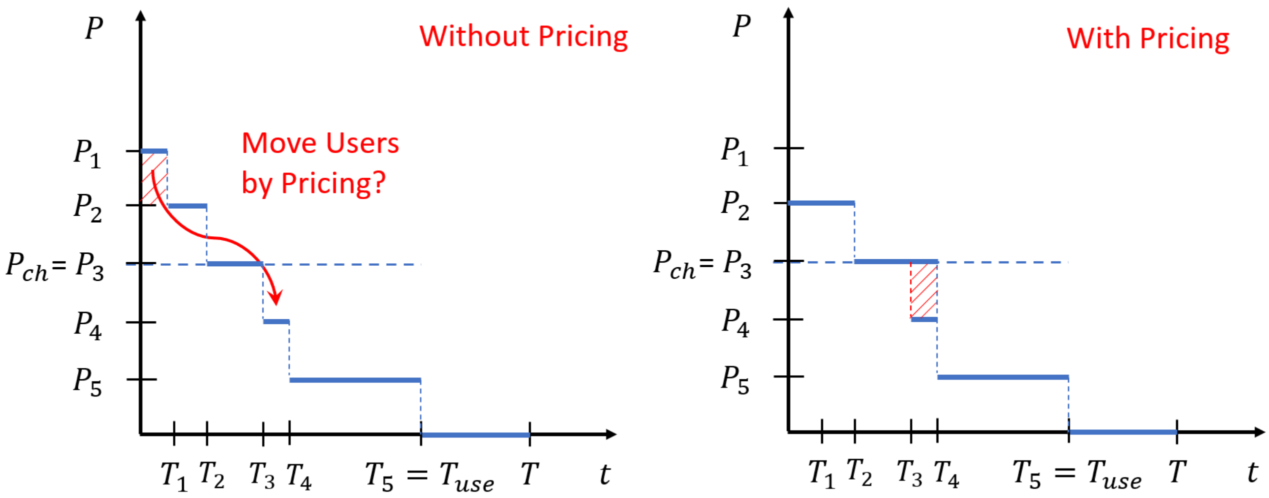

Figure 3.7: Example of charging power demand distribution. Left-hand part shows the original demand, and right-hand shows a more even demand if the price is adjusted to reflect the demand. Thus, time varying pricing may lead to a higher charger utilization.

Based on the above analysis one may draw the following conclusions for the type of Long-Haul trucks investigated in this paper.

• The battery electric trucks with driving pattern that are similar to the haulage company studied in this paper seems to be more cost-effective than today's diesel trucks. A reason for the competitiveness of the electric trucks is that they have a high battery utilization, and that they can be charged on mandatory breaks.

• The study indicates that the main uncertain factors, for knowing what charging strategy to use, are the pricing of public charging, and the density of the goods.

• The choice of battery capacity is strongly influenced by the price for public fast charging. For the case studied in this paper, the price for fast-charging has to be 0.17 €/kWh if the haulier should go for the small battery instead of the large battery. The size of the battery could have a large impact on the total cost of ownership.

• The cost per kWh for public fast-charging drops significantly with increasing charger utilisation. To be able to offer fast-charging for a low price, such as 0.17 €/kWh, and still make some profit, the charger utilisation factor has to be about 20% or higher.

The ratio $\frac{C_{ch}}{C_{diff}}$, where C_{ch} is the combined cost for the charger and grid, and C_{diff} is the difference between the price for public fast charging and the price for the electricity, turns out to be an important parameter when analysing the profit for a charge point operator. This is intuitive since the profit increases with C_{diff} but decreases with C_{ch}. With the values used in Paper B the ratio is in the interval 4% - 15%. This span in required utilization is caused by the uncertainty in the price for public fast charging.

• For fixed price of public fast-charging, a charge point operator has the possibility to be profitable, if and only if there is a demand of charging, which expressed as share of the chargers service life, equals or exceeds $\frac{C_{ch}}{C_{diff}}$.

• For fixed price of public fast charging, the charge point operator shall not meet the maximum demand of charging in order to maximise the profit, with the only exception when the share of the time for the maximum demand at least equals $\frac{C_{ch}}{C_{diff}}$ of the chargers service life.

• If the chargers have the possibility to be profitable for a given power demand distribution, the profit for the charge point operator, at a fixed price, can be maximised according to the procedure presented in Section 3.2.4.

3.3 Summary of Paper C

Paper C aims to investigate the charging need, the utilization of the public fast chargers and the potential problems with queues at charging stations along the highway between the Swedish cities Helsingborg on the west coast and the capital Stockholm on the east coast, if all the trucks that are driving on that road today were battery electric. The system is investigated by an agent-based model where the traffic flow is intended to be representative for a typical day. The main part of the highway between Helsingborg and Stockholm is called E4 and a minor part is called E20. The road is 553 km long and marked with blue in the map, see Figure 3.8.

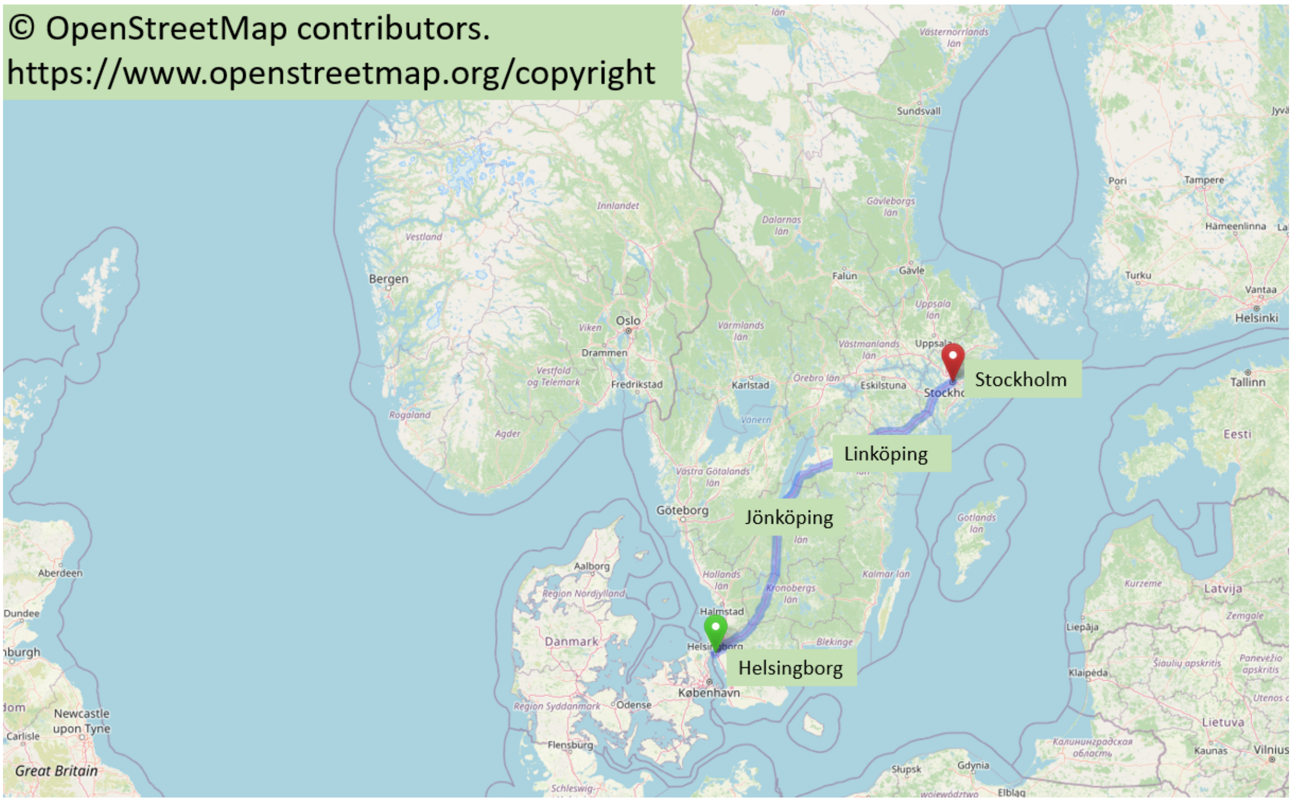

Figure 3.8: The highway between Helsingborg and Stockholm marked with blue.

3.3.1 The Traffic Flow

In the study it is assumed that trucks can only enter or leave the highway where roads with considerable traffic flow of trucks connects to the highway. Since the cities Mjölby, Linköping and Norrköping are quite close to each other they are seen as one city located in Linköping. The road is divided in to three sections, where Section 1 starts at Helsingborg and ends at Jönköping, Section 2 starts at Jönköping and ends at Linköping and Section 3 starts at Linköping and ends at Södertälje/Stockholm, which is considered as one city located in Stockholm. Data on the truck flow has been available at the communities Ljungby, Gränna and Tystberga which are located in Section 1, 2 and 3 respectively. In Table 3.4, the distances from Helsingborg to the cities and communities are listed, and the traffic flows are shown in Figure 3.9. In the figure the traffic flows are expressed in trucks per day, which has been averaged over a year. Trucks without trailer are excluded since they probably do not travel long distances and therefore do not use public fast charging. The outward direction is defined from Helsingborg to Stockholm according to Figure 3.9. The black arrows represent the flows along the way and the red arrows shows the flow of trucks that enter or leave the highway.

Table 3.4: Distance from Helsingborg to the cities and communities.

City/Community	Position [km]
Helsingborg	0
Ljungby	134
Jönköping	228
Gränna	265
Mjölby/Linköping/Norrköping	355
Tystberga	470
Södertälje/Stockholm	553

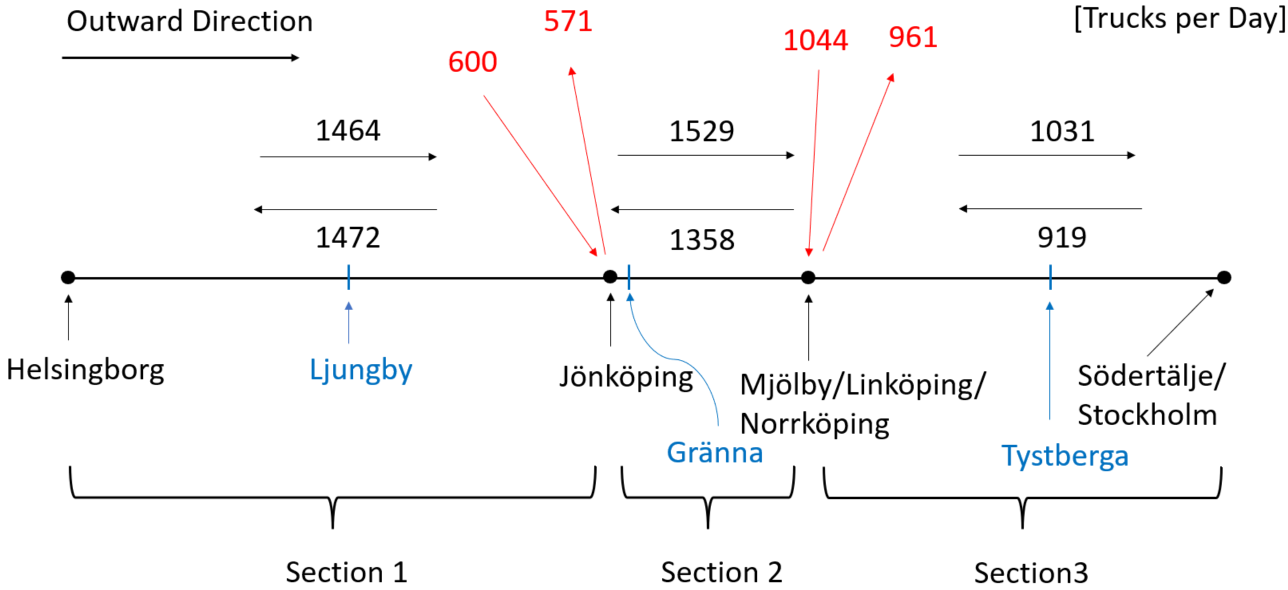

Figure 3.9: The traffic flows along the studied road are indicated by with black arrows and the traffic flows that connect or leave the road are indicated by red arrows. The flows are given in trucks per day. The outward direction is defined from Helsingborg to Stockholm and indicated by a black arrow in the figure.

Based on the data in Figure 3.9 the truck flows between the different cities are constructed, with the aim of representing a typical day. The flows are shown in Table 3.5 and agrees with the total flows along the highway (the black arrows) presented in Figure 3.9.

Table 3.5: The origin and destinations for the trucks.

Start (No. trucks)	Destination (No. trucks)			
	Helsingborg	**Jönköping**	**Linköping**	**Stockholm**
Helsingborg 1464	-	381	520	563
Jönköping 909	463	-	221	225
Linköping 1063	621	199	-	243
Stockholm 919	388	150	381	-

For some days traffic-flow data, expressed as trucks per hour, was available each hour. The departure time of the trucks in the simulation was selected randomly according to a distribution to resemble the actual time variation in the data. The result can be seen in Figure 3.10. The model flows, expressed as share of the daily flows, shown in the figure are the flows when the trucks do not stop and charge. However, since many of the trucks will charge the traffic flow in the simulations will not be exactly the same.

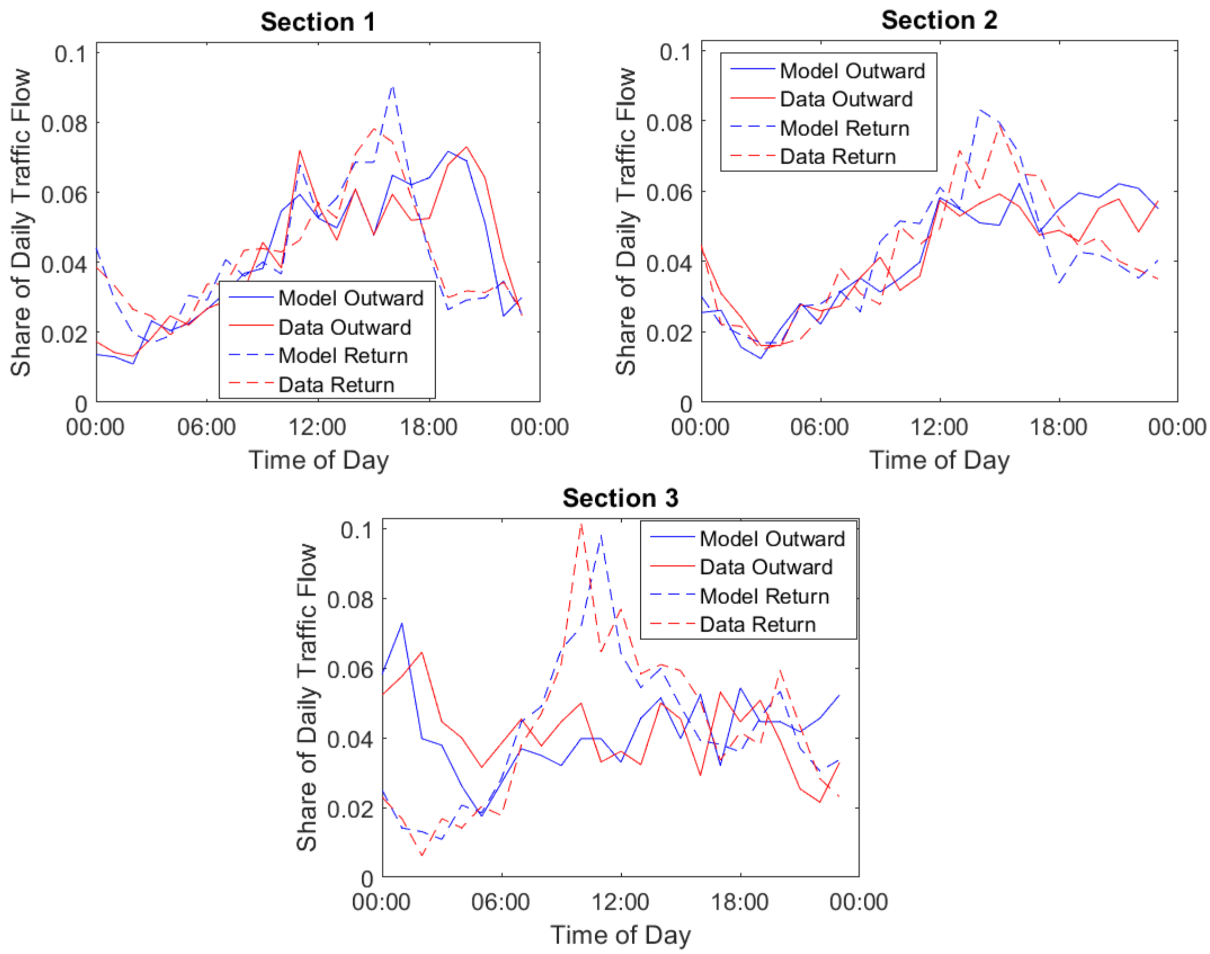

Figure 3.10: The share of the daily traffic flow for each section in the outward (solid) and return (dashed) direction. The red curves corresponds to the data and the blue curves correspond to the flow that the model would arise if the trucks always drive at constant speed $v = 75$ km/h without charging.

The initial value of the battery SoC is drawn from a uniform random distribution on the interval [50%, 100%], and the required SoC at the destination is drawn from a uniform random distribution on the interval [0%, 40%].

3.3.2 Assumptions

All the trucks in the simulation have a useful battery capacity of $B_{cu} = 500$ kWh, a speed of $v = 75$ km/h and have an energy consumption of $\frac{\Delta E}{\Delta x} = 1.5$ kWh/km. To have good initial conditions the model is run for two days. The first day starts with no trucks on the road and empty charging stations, and with the same prices for charging and truck flows as for the typical day. The second day therefore starts with some trucks already on the road and some using the charging stations. In the analysis it is the results from the second day that is used. Each truck in the simulation has a starting position and a destination in either Helsingborg, Jönköping, Linköping, or Stockholm. Each truck enters the highway at a certain time, with a certain SoC and an individual requirement on the SoC at the destination. However, none of the trucks are entering the highway with less than 50% SoC and no truck must have more than 40% SoC when they exit the highway.

In reality, there are laws that regulate how long the drivers are allowed to drive. For example, the drivers must take a break after at least 4.5 hours of driving. This constraint is not explicitly used in the simulations, but the trucks cannot run for more than 4.5 hours without charging, inferring this constraint is fulfilled anyway. Also, the fact that the driver must take breaks under some conditions might affect where and when they choose to charge, but the total charging need will not be affected.

There are charging stations along the road, and the number of charging stations, their position, and the number of chargers at each station varies from simulation to simulation. The price for charging depends on the station and the time but have been set to the same value in almost all simulations. In all simulations there will be at least three charging stations along the way and these three will be uniformly distributed along the highway. All the chargers are assumed to have a power $P = 700$ kW. Further, it is assumed that this power can be used for all trucks regardless of the SoC. This implies that a truck will charge the whole useful capacity in 43 minutes.

The Behavior of the Trucks

In the simulation each truck, i.e., each agent, will act according to the following rules:

A) The trucks only charge when they need it to complete their mission, and only what is needed to have the required SoC at their destination.

B) The trucks will not charge more times than necessary. This will together with the assumptions that were presented earlier imply that none of the trucks will charge more than twice. The assumptions also prevent a truck from reaching zero SoC before it reaches a charging station.

C) If a truck needs to charge twice, it will charge full, the first time it charges.

D) A truck arriving to charge at a charging station, will continue to the next charging station if there are too many trucks queuing and if it has the possibility to reach another charging station. The queue is judged to be too long if the fraction of queuing trucks divided by the stations total number of chargers is greater than the parameter $r_{queuing}$.

E) Trucks that have possibility to select between stations while following the rules above, will choose to charge at the lowest cost. Trucks that are charging twice minimize the cost for the first charge. If the price between two stations are equal the truck selects the nearest station.

3.3.3 Results and Conclusions

The main results from this paper are summarized in the following conclusions.

• A future system of battery electric trucks and public fast chargers along the highway between Helsingborg and Stockholm seems to function very well. Due to the relatively uniform traffic flow of the trucks the simulations point to a system with low prices on public fast charging, profitable charging stations, high charger utilization and few problems with queues at the charging stations. The system will also be robust towards an increase in the traffic flow or an unusual peak in the traffic flow.

• It is estimated that there is a need for 140 chargers with the power of 900 kW along the highway between Helsingborg and Stockholm for a full electrification of the current long-haul truck fleet. The 900 kW chargers will be able to deliver the average power of 700 kW as the ones in the simulations.

•The system charger utilization factor is estimated to be 30% which should be considered as a high value for a system with small problems with queuing.

• The study indicates that a system with a fixed number of chargers resists queues better if there are a few charging stations with many chargers rather than many charging stations with few chargers.

•Simulation shows that time-varying pricing could lead to queuing deterioration on a system level, even if it improves the queuing locally in the system.

• The truck's unwillingness to queue is an important property and leads to less queuing at the system level.

4 Contributions

In this section this thesis' contributions to the field of battery electric trucks are discussed. The EDD is a useful tool when studying systems of battery electric trucks and public fast chargers and can be used for example to size the battery and deciding charging strategy. The EDD summarizes a lot of information about how the vehicle is used over its service life in a compact format. Further, the calculations shows that battery electric trucks are competitive to commercial diesel trucks in many cases. Hopefully, this work has improved the knowledge of how to size the battery and select charging strategy in order to achieve cost effective and competitive battery trucks. It is important to highlight, even if it might feel simple and intuitive, that high utilization of the batteries and the chargers is crucial to reach cost effective system solutions. There are often many different parameters that affects the cost effectiveness, but in the end, the utilization factor can summarize the combined effect of most of them in just one number. For example, a large battery is more expensive but results in a smaller cycle depth, which reduces battery ageing. These two aspects are in conflict but together they give a utilization of the battery, and it is the utilization which in the end determines the battery cost per kWh. The battery size that gives the largest utilization in the previous mentioned example is the most cost effective one, when considering this particular trade off.

Still, finding the best solution to the real future system of battery electric trucks and public fast chargers is far from simple. The system is complex and the trade-offs between, for example, a large and expensive battery and less need for expensive fast charging, contra a small and cheap battery and need for more of the expensive fast charging but less loss in pay-load capacity, is hard. The tools and methods presented in this thesis facilitates decisions regarding this trade-off and hopefully give a better understanding of which factors that are important in certain use-cases, and which are not.

There are reasons to expect that fast charging will be expensive, but will that be the case for long-haul trucks? Results from this work indicate that the charger utilization may be high along one big highway in Sweden, and that makes it possible to achieve a low cost per kilowatt-hour for fast chargers. However, then a second question arises; will the high charger utilization result in large problems with queuing? In the studied case the answer to that question seems to be no, but this was just for *one* highway. However, by proper changes the same method could be used to study other roads as well, so this thesis provides a method for examining the charger need, charger utilization, and the charger queues along any roads.

Of course, there are uncertainties, for example in the price for public fast charging. It is hard for the vehicle owners to select battery capacity and charging strategy with uncertainties in the price for public fast charging, but it is also hard to set precise prices on public fast charging without knowing how much the chargers will be used, which in turn depends on the truck's charging strategies. This creates a challenge, as initial high prices for fast charging may lead to truck owners selecting charging strategies which result in low utilization of chargers, and therefore lock the system in a state of unnecessarily high prices. Once in this state, the expectation of high prices may prevent a high utilization of chargers and low prices to materialize, even if it is possible.

Further, the investments can be risky if another part changes their strategy. If, for example, truck owners start to buy larger batteries the need for public fast charging can be reduced, which is bad for the charge point operator. Or, if the truck owners have selected small batteries, a rise in the cost for public fast charging can be problematic for them, still they have no option but to continue to use the public chargers as their small batteries do not allow them to skip fast charging. However, these problems probably decrease with time, since the more numerous battery electric trucks and other battery electric vehicles become, the easier will it be to have high charger utilization, which can lead to lower prices for public fast charging. This can create a positive spiral of lower prices and growing utilization of public chargers. In addition, with growing market shares of electric trucks the price picture will probably change in favour of the battery electric trucks due to growing production volumes and technology development. Even if the reference price for diesel used in this thesis is intentionally low, the current high diesel price also favours the battery electric trucks. It is also important to clarify that in the long run it is desirable, but not required, that the battery electric trucks are more cost effective than the diesel trucks. To be the main solution for the future transport system, they only have to be the cheapest alternative to replace transports that use fossil fuel.

We also show that the cost for losing pay-load capacity due to a large battery could be high, but often it may as well be zero. It depends on the goods the truck transport and their charging strategy. This means that trucks that have similar driving patterns might have completely different battery capacity and charging strategies only depending on which type of goods they transport.

To summarize, this thesis does not prove that battery electric trucks with stationary charging is the future solution, but it presents several methods to analyse cost effective battery electric truck solutions. The case studies made with these methods show that it is likely that the cost of operation for battery electric trucks may become lower than for diesel trucks in many cases. Besides the driving pattern, the potential loss in pay-load capacity together with the price for public fast charging are the key factors when selecting battery capacity and charging strategy.

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Article

Energy Distribution Diagram Used for Cost-Effective Battery Sizing of Electric Trucks

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Abstract: One possible step for reducing humans' use of fossil fuel due to transport tasks is to replace diesel trucks with battery electric ones. This paper introduces the *energy distribution diagram*, which makes it easy to visualise the trucks' daily energy consumption over their full service life. The energy distribution is used to investigate which driving patterns are suitable for cost-effective battery electric trucks when compared to commercial diesel trucks. It is shown that the battery capacity that results in the lowest cost per kilowatt-hour propulsion energy depends on the driving pattern, and an algorithm for selecting the most cost-effective capacity is presented. In many instances, it was found that battery electric trucks competed favourably with diesel trucks, especially when the trucks had low variations in daily energy consumption. It is beneficial to determine the circumstances under which they may be cheaper, as this will facilitate the transition to battery electric trucks in segments with a reduced overall cost of ownership.

Keywords: battery electric vehicle; battery electric trucks; battery sizing; charging strategy; cost-efficient

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1. Introduction

Society's dependence on oil is problematic, since calculations show the reserve depletion times are less than 30 years [1] and continued extensive use of fossil fuel will likely have severe consequences for the Earth's climate system [2]. Other downsides of greenhouse gas emissions, such as pollution and negative health impacts, are also expressed in the literature [3]. An attempt to partly solve this grave problem is to use battery electric trucks instead of diesel ones. Another possible solution is using hydrogen trucks, but recently published studies favour the battery electric type [4,5]. Yet another study declares the promising feasibility of the battery electric trucks, but notes that fuel cells might be better for heavy-duty trucks on extra-long journeys [6]. This paper aims to contribute to the transition from diesel to battery electric trucks. It will do so by introducing a method to help obtain the various important results needed to design cost-effective charging strategies and battery and charger sizes. Cost-efficient solutions for battery electric trucks are vital, as it is assumed they will accelerate the transition from diesel to battery electric trucks. In presenting a systematic review of the cost of battery packs, Nykvist and Nilsson highlight battery price as a crucial parameter for cost-competitive battery electric vehicles [7]. In their article the authors claim (with the support of a previous study [8]), that the price of batteries must fall below 150 $/kWh if battery electric vehicles in general are to compete with internal combustion vehicles. They also show that such a price can be achieved in the near future. The present paper introduces a method facilitating cost comparisons, taking vehicle usage patterns into account. It will be shown that, even at a battery cost of 200 €/kWh, many commercial battery electric trucks will be cost-competitive with diesel trucks. This is because commercial trucks have a high utilisation rate compared to private passenger cars. However, it is worth mentioning that, to be used, battery electric trucks do not necessarily have to be cheaper than diesel ones. They simply have to be the most cost-effective way of replacing fossil fuel transport.

Previous research gives an example of the cost-competitiveness of battery electric against commercial diesel trucks [9] and states that the cost-effectiveness of battery electric vehicles is sensitive to driving patterns [10]. It is subsequently established that relatively uniform driving patterns are favourable to electrification [11]. This paper further investigates the cost-effectiveness of battery electric trucks across a wide variety of driving patterns. Previous studies have used probability density functions for the daily driven distance of battery electric vehicles [10,12]. This paper takes a different approach, basing its analysis on the daily energy consumption of all operating days in a vehicle's service life. The daily energy consumption in a battery electric truck's service life is visualised in an *energy distribution diagram*. The energy distribution includes more information than a probability distribution for the daily distance travelled, but generally allows for similar types of analysis. However, we suggest that the energy distribution diagram is more of a practical tool as it can visualise the information needed to perform the analysis more directly. Moreover, analysing the daily consumed *energy* instead of the daily *distance travelled* has the advantage that the outcome can also be useful for battery electric vehicles that do not use all their energy to move; an excavator, for example.

In a previous study of a commercial electric vehicle, a battery-ageing model is used to consider the effects of ageing due to battery size [13]. That study found that an oversized battery could lead to a lower total cost of ownership because it reduced battery ageing. The fact that larger batteries prevent deep battery cycles and thus reduce battery ageing is also stated in another study [14]. Due to the battery ageing and safety margins, this paper assumes that a maximum of 80% of nominal battery capacity can be used. Using vehicle batteries as a means of grid energy storage can reduce the total cost of battery electric vehicles, but this is not included in this paper. This theme has been analysed in such works as [15], which finds that grid storage has only limited value for plug-in hybrids.

A study of electric delivery trucks concluded that battery sizing is essential for maximising profit [16]. However, there is no unambiguous answer to the question of which power train results in the lowest total cost of ownership, as this will depend on how the vehicle is used [17]. This paper investigates cost-efficient battery sizing for different driving patterns with the aim of finding when battery electric trucks are competitive to diesel trucks. From the work done in this paper, it is clear that the energy distribution diagram is a useful tool for determining the most cost-effective battery capacity. The study also indicates that battery electric trucks are competitive with diesel trucks in many different driving patterns. This paper focuses on battery electric trucks, but its analysis is general and can easily be applied to other types of battery electric vehicles by making the right changes to the parameters.

2. Designing Electromobility Systems Using Energy Distribution Diagrams

Finding the best system design for battery electric vehicles is a very complex issue, as many compromises can only be made on a high system level. What may be an improvement in one part of the system (such as a cheaper truck) may lead to drawbacks in a completely different part (such as reduced reliability in the logistics chain). It is, therefore, not possible to build the most cost-effective system by designing all its parts to meet fixed specifications at minimum cost. Because one needs to make such system-level compromises, evaluating which system is the best must be done on a transport system level. This requires domain experts from many different areas to cooperate on finding the best system trade-offs.

However, since the investigated system is so big, with so many different aspects to consider, it will be impossible to carry out a cross-disciplinary system analysis that includes the full complexity of each subsystem. Rather, there is a need to find which aspects of a subsystem are critical to the way the rest of the system is designed and which are not. For the system-level analysis, one must try and find simplified models which can be understood by experts from different domains. They can then link these models to their own domain expertise and draw conclusions that transcend their specialist domain.

The energy distribution diagram (EDD) is such a tool. It aims to explain important mechanisms linking the usage pattern of a specific vehicle to battery size, charging strategy and total cost of owning the vehicle. Using the EDD, it is possible to understand many important design decisions from the vehicle owner's perspective. By itself, the EDD cannot tell us what the overall optimal system design is, but it will provide key information to help make system trade-offs. This paper introduces the energy distribution diagram and explains how it can be used to determine several important values. The EDD is also used to find cost-effective battery sizing for some different usage patterns. Note that, in this paper, the analysis is made purely from a vehicle perspective. Thus, what this paper finds to be the cost-effective solution it is not necessarily the same as the optimal solution for the whole system. However, the results still show several very important aspects of battery sizing and these will also be important for the system level.

3. Cost of a Battery Electric Truck

In this analysis, some of the main costs of operating a truck have been assumed to be equal for diesel and battery electric trucks and have thus been omitted from the cost comparisons. This is not because of any limitations when using the EDD to size batteries and estimate charging costs. Rather, the simplification has been made to focus this paper on how the EDD can be used to analyse the effect of varying driving patterns. Costs which this analysis assumes to be equal for both battery and diesel trucks are: the cost of the vehicle (excluding the battery in the electric case), the second-hand value of the vehicle and the cost of maintenance and insurance. Naturally, differences in these costs can influence the cost comparison to some extent. However, it is unclear whether their combined effect will favour electric trucks or diesel ones.

Assuming that trucks are charged during existing driver breaks, the charging will not increase the working hours of the driver. Thus, the driver's salary also remains the same. Should the charging not be done during driver breaks, the EDD can also provide the number of charging instances and the amount of energy charged from different type of chargers. This makes it possible to estimate the time required for charging and thus any extra driver salary.

Furthermore, this paper assumes that an electric truck can carry the same goods as a diesel truck. This will be true if the goods are not heavy or the driving distance is short (resulting in a small battery). This is the case for most local and regional, as well as some long-haul trucks. So, for them, the results of this analysis are accurate. The main exception is trucks that are driven long distances without charging, in combination with carrying heavy goods. For these, there will be a need to estimate the cost of the reduced payload, and the optimal battery size may be smaller than suggested in this paper.

In this analysis, some costs differ between electric and diesel trucks. These include the fact electric trucks have additional costs for batteries, chargers and grid connection. Additionally, the cost of diesel is replaced with the cost of electricity. In this paper, the costs are normalised and expressed in EUR per kWh of propulsion energy. Whenever the word *energy* appears in this paper, it stand for *propulsion* energy. The fuel cost for diesel trucks is estimated at 0.30 €/kWh. This cost is based on a diesel price of 1.2 €/L (excl. VAT) and a high powertrain efficiency of 40%. This cost estimate is low, especially given the recent surge in diesel prices. However, the calculations were made before the strong diesel price increases of 2021 and 2022 and it is not impossible that the current diesel price may only be temporary. Moreover, the authors wanted to be sure that the reference value of diesel was not too high. Based on this price picture, if it can be shown that electric trucks are competitive, then the conclusions should be quite reliable. Thus, for electric trucks to be cost-competitive, the cost of the electricity, battery, grid and charger should not total more than 0.30 €/kWh. A realistic electricity price, excluding grid tariffs, is 0.08 €/kWh when using a privately owned charger. The price of using a public fast charger is uncertain, but around 0.4 €/kWh. The estimated average charge and discharge losses and efficiency of the electric powertrain have been indirectly included, as an increase in the price of the electricity per kWh of propulsion energy. This is similar to the way in which the average efficiency of the diesel powertrain has been included in the cost of diesel. The cost of a complete battery system is set at 200 €/kWh and the battery is assumed to last as long as the truck. In this analysis, the economic life is assumed to be seven years. The price of a charger increases with its power and is about 400 €/kW, the annual grid fee can vary but is around 60 €/kW/year. Even the charger is assumed to have a service life of only seven years, due to the rapid development of the charging technology.

To make the analysis more general, variables for the different costs and their assumed values are introduced in Table 1. To make the following equations more readable, a combined parameter for the price of the charger and grid has also been introduced in the table. The combined parameter can be seen as the total cost for the charger depreciation and annual grid fee. This generalisation is advantageous, as the parameter values will probably change with time.

Table 1. Notations for the different costs and their assumed values. Please keep in mind that the cost refers to the cost of *propulsion* energy.

Costs	Notation	Typical Value
Diesel Cost	C_d	0.30 €/kWh
Electricity Cost, Private Charging	C_e	0.08 €/kWh
Electricity Cost, Public Fast Charging	C_{epub}	0.4 €/kWh
Battery Cost	C_b	200 €/kWh
Price of Charger	$C_{charger}$	400 €/kW
Grid Fee	C_g	60 €/kW/year
Service Life of Truck, Charger and Battery	T	7 years
Combined Price of Charger and Grid	$C_{ch} = \frac{C_{charger}}{T} + C_g$	117 €/kW/year

To calculate the cost of operating a truck, one only needs to know a few parameter values for how that truck is used and charged. These include the amount of propulsion energy consumed over the vehicle's service life, E_{tot} (which applies to both diesel and electric trucks). For the electric trucks, one also needs to know the ratio r_{ch}, which is the energy derived from the truck owner's private charger, divided by the total amount of energy (E_{tot}). The cost will also be influenced by the battery capacity B_c and power of the private charger P_{ch}. These parameters are summarised in Table 2.

Table 2. Notations for parameters.

Parameters	Notation
Total Propulsion Energy Consumed Over the Trucks Service Life	E_{tot}
Ratio of Private Charging to the Total Amount of Energy	r_{ch}
Battery Capacity	B_c
Charger Power	P_{ch}

One aim of this paper is to find solutions for battery electric trucks so that they are cost-competitive with commercial diesel trucks. This means that the total cost for the electric truck should be less than or equal to the cost for a diesel truck. In other words, the sum of the cost per kWh for:

- Energy from private charging;
- Energy from public charging;

- Battery;
- Charger;
- Grid fees;

should be less than or equal to the cost per kWh for diesel. Thus, the following inequality should be satisfied:

$$r_{ch} \cdot C_e + (1 - r_{ch}) \cdot C_{epub} + \frac{C_b \cdot B_c}{E_{tot}} + \frac{C_{charger} \cdot P_{ch}}{E_{tot}} + T \cdot \frac{C_g \cdot P_{ch}}{E_{tot}} \leq C_d. \tag{1}$$

To make the discussion and calculations clearer, the left-hand side of inequality (1) is expressed as a cost function, f_{BEV}, according to:

$$\begin{aligned} f_{BEV} &= r_{ch} \cdot C_e + (1 - r_{ch}) \cdot C_{epub} + \frac{C_b \cdot B_c}{E_{tot}} + \frac{C_{charger} \cdot P_{ch}}{E_{tot}} + T \cdot \frac{C_g \cdot P_{ch}}{E_{tot}} \\ &= r_{ch} \cdot C_e + (1 - r_{ch}) \cdot C_{epub} + \frac{C_b}{\frac{E_{tot}}{B_c}} + \frac{T \cdot P_{ch}}{E_{tot}} \left(\frac{C_{charger}}{T} + C_g \right). \end{aligned} \tag{2}$$

Defining the battery utilisation factor, Γ_b, as:

$$\Gamma_b := \frac{E_{tot}}{B_c}, \tag{3}$$

the battery utilisation factor has the dimensionless unit *equivalent full cycles* and describes the number of *full* discharge cycles that can deliver the total amount of energy consumed. Additionally, the charger utilisation factor Γ_{ch} is defined as the total energy delivered by the charger over its service life divided by the maximum possible amount of energy that *can* be delivered from the charger over its service life. The charger utilisation factor is, therefore, a dimensionless scalar with possible values from 0% to 100%. Thus:

$$\Gamma_{ch} := \frac{E_{ch}}{T \cdot P_{ch}}, \tag{4}$$

where E_{ch} is the total amount of energy delivered by the charger over its service life. By using the notation for the combined prices for charger and grid according to Table 1 together with $E_{ch} = r_{ch} \cdot E_{tot}$ it is now possible to express the cost function as:

$$f_{BEV} = r_{ch} \cdot C_e + (1 - r_{ch}) \cdot C_{epub} + \frac{C_b}{\Gamma_b} + \frac{r_{ch} \cdot C_{ch}}{\Gamma_{ch}}. \tag{5}$$

The cost parameters in Table 1 will be determined by the market and technology development, while the total energy consumed for a vehicle during its service life will depend on the truck's transport task. However, the parameters for battery capacity, charger power and ratio of private charging are of special interest, as they will change depending on the charging strategy. As seen from Equation (5), one should aim to choose the battery capacity and charging power so that they increase the utilisation factors, but simultaneously avoid too much public fast-charging, which decreases r_{ch} and therefore increases the cost. If the relationship between these parameters can be expressed, it may be possible to optimise these parameters and determine the lowest total cost per propulsion kWh. This paper will show that the relationship depends on the shape of the energy distribution diagram for the truck. This will be introduced in the next section.

4. The Energy Distribution Diagram

A truck's daily energy consumption will differ each day due to such things as varying transport tasks and weather conditions. The daily energy consumption data for a truck can be presented in an energy distribution diagram. Consider a truck's daily energy consumption over a week, as shown in the left-hand part of Figure 1. The length of each bar on the y-axis represents the energy consumed for that day. A truck's service life consists of many days and, if these are sorted according to energy consumption, starting with the highest figure, a curve is derived. This is called an energy distribution diagram (note that the curve should actually be a discrete number of points, but for convenience, it appears as a continuous curve), see the right-hand part of Figure 1. The total number of days in the vehicle's service life is N_{tot}, and the number of days the vehicle is operational is N_{op}. Rearranging the days according to energy consumption does not pose a problem, since the truck is charged at night and thus the energy needs of the coming day are independent of the previous day's consumption. Sorting the days by energy consumption has advantages. For example, it is easier to read the highest daily energy consumption, or estimate the mean energy consumption. It is also possible to approximate the sorted EDD using a monotonically decreasing mathematical function. Note that for vehicles that are charged after each trip, it is possible to change the x-axis to show the number of trips rather than the number of days.

By plotting the useful battery capacity in the EDD, the number of days can be determined for which the battery is too small to run an entire day on a single charge. On these days, the vehicle will need to fast charge during the day. Assuming that fast charging only adds the minimum energy needed to carry out the rest of the day's driving, the energy which needs to be fast charged can be determined as the red-striped area in the diagram.

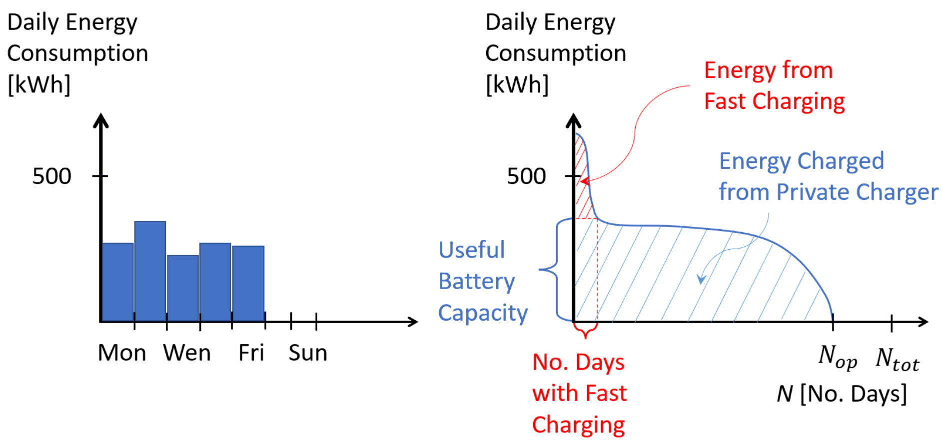


Figure 1. The daily energy consumption for five working days appears on the left and the energy distribution diagram for a truck's full service life is on the right. In the right-hand part of the figure, the number of days that needs fast charging and the amount of fast charging needed are marked in red, while the energy from private chargers for a given useful battery capacity is marked with blue.

The EDD gives a lot of concentrated information on the full service life of a vehicle. This information is listed below:

- The total energy consumption is the area under the curve.
- The total number of operational days is found from the curve's intersection with the x-axis.
- The mean consumed energy for the days when the truck is used equals the total energy divided by the number of operational days.
- The highest consumed energy can be read off from the curve's intersection with the y-axis.
- The number of days that need fast charging and the amount of fast charging needed for a particular useful battery capacity.
- The shape of the EDD gives a quick picture of the size of the variation in daily energy consumption and the respective share of days with high, medium or low energy consumption.

When considering the right-hand part of Figure 1, it may look as though the optimal charging strategy is strongly influenced by the shape of the EDD. For example, can it be a good idea to select a battery capacity that can handle the majority of the trips, but not the slender EDD peak? In that case the battery cost is greatly reduced compared to a battery that can handle all the trips, while only requiring a small amount of public fast charging. Subsequent sections will investigate the most cost-efficient charging strategy for different shapes of EDD, with the aim of finding which EDD shapes give cost-efficient solutions for battery electric trucks. All the analysis is made under the assumption that the battery capacity and power of the charger are continuous variables (spanning from zero to arbitrary high values) and that charging is possible exactly when needed.

5. A Rectangular Energy Distribution Diagram

This section investigates a rectangular EDD, which represents a truck using the same amount of energy each day during its whole service life. Of course real trucks never consume exactly the same energy each day, but it is rather common that trucks are used in very similar ways most days. So, although an extreme case, the rectangular EDD is interesting to study.

Let $E(N)$ be the total amount of energy consumed by a truck during day N, i.e., $E(N)$ describes the EDD's envelope and is, therefore, called the "energy function". Let the highest energy consumption for a day be E_{max}. Thus, the energy function for a rectangular EDD is given by:

$$E(N) = E_{max}, \qquad N \in [0, N_{op}], \tag{6}$$

where N_{op} is the number of operational days for the truck. This energy function gives a rectangular EDD, see Figure 2.

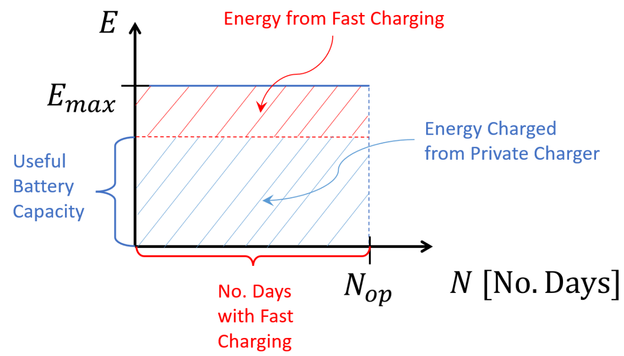


Figure 2. A rectangular EDD. In the figure, the number of days that need fast charging and the amount of fast charging needed is marked in red. The energy delivered by private chargers for a given useful battery capacity is marked in blue.

The most cost-effective battery capacity, charger power and the share of public fast charging will now be determined. Due to battery ageing and safety margins, it is assumed that only a share of the battery capacity, r_{SoC}, can be used. This paper assumes that up to 80% of the battery capacity may be used and therefore:

$$r_{SoC} = 0.8. \tag{7}$$

Thus, at the start of a day, the available energy charged during the night is $r_{SoC} \cdot B_c$. The rest, up to E_{max}, must be charged at public fast chargers. By dividing the energy charged using the home charger over the truck's service life by the total energy it uses over its service life, the result is:

$$r_{ch} = \frac{r_{SoC} \cdot B_c}{E_{max}} \tag{8}$$

or equivalent:

$$B_c = \frac{E_{max} \cdot r_{ch}}{r_{SoC}} \tag{9}$$

for a rectangular EDD. From the definition of the battery utilisation factor, one obtain:

$$\Gamma_b = \frac{E_{tot}}{B_c} = \frac{r_{SoC} \cdot E_{tot}}{E_{max} \cdot r_{ch}}. \tag{10}$$

As one want the cheapest possible charger that can charge the maximum daily energy consumption in one night, the charger power should be:

$$P_{ch} = \frac{r_{SoC} \cdot B_c}{T_{ch}}, \tag{11}$$

where T_{ch} is the time for which the charger can be used every night (the charger runs on full power). The charger utilisation factor can now be expressed as:

$$\Gamma_{ch} = \frac{E_{ch}}{P_{ch} \cdot T} = \frac{r_{ch} \cdot E_{tot}}{P_{ch} \cdot T} = \frac{r_{ch} \cdot E_{tot}}{\frac{r_{SoC} \cdot B_c}{T_{ch}} \cdot T} = \frac{N_{op} \cdot T_{ch}}{T}, \tag{12}$$

where the last equality is obtained by Equation (8) and the fact that $\frac{E_{tot}}{E_{max}} = N_{op}$ for a rectangular EDD. Using the above equations in Equation (5) produces the following expression of cost function:

$$\begin{aligned} f_{BEV} &= r_{ch} \cdot C_e + (1 - r_{ch}) \cdot C_{epub} + \frac{C_b}{\frac{r_{SoC} \cdot E_{tot}}{E_{max} \cdot r_{ch}}} + \frac{r_{ch} \cdot C_{ch}}{\frac{N_{op} \cdot T_{ch}}{T}} \\ &= r_{ch} \cdot C_e + (1 - r_{ch}) \cdot C_{epub} + \frac{C_b \cdot r_{ch}}{r_{SoC} \cdot N_{op}} + \frac{T \cdot C_{ch} \cdot r_{ch}}{N_{op} \cdot T_{ch}}. \end{aligned} \tag{13}$$

The cost function is now expressed as a function solely of the variable r_{ch}. Thus, the derivative of $f = f(r_{ch})$ is studied in order to find the lowest cost:

$$\frac{df_{BEV}}{dr_{ch}} = C_e - C_{epub} + \frac{C_b}{r_{SoC} \cdot N_{op}} + \frac{T \cdot C_{ch}}{N_{op} \cdot T_{ch}}. \tag{14}$$

By assuming that $T_{ch} = 14$ h, $N_{op} = 1750$ (corresponds to 5 days per week, 50 weeks per year over 7 years) and inserting the parameter values from Table 1 one obtains:

$$\frac{df_{BEV}}{dr_{ch}} < 0, \tag{15}$$

which implies that the lowest cost per kWh has been obtained for the highest possible value of r_{ch} which is $r_{ch} = 1$. Inserting $r_{ch} = 1$ in Equation (13) with the same parameter values as previously produces:

$$f_{BEV}(1) = 0.26 \text{ €/kWh} < C_d. \tag{16}$$

In this case, the cost for the battery is the largest proportion; 0.14 €/kWh compared to the other costs (cost of electricity from home charging, 0.08 €/kWh, cost of public fast charging, 0 €/kWh and cost of the charger and grid, 0.03 €/kWh). (Due to rounding, the individual costs do not seem to add up to the total cost). Since $r_{ch} = 1$ corresponds to charging all the energy at home, it may be concluded that, with the EDD as a rectangle, the most cost-efficient charging strategy is *night charge only* and that the battery should be sized so that $r_{SoC} \cdot B_c = E_{max}$. In this case, an electric truck will be more cost-efficient than today's commercial diesel trucks. Note that the total cost is the same, irrespective of the highest energy consumption for a day, but that it reduces if the total number of operational days is increased. Additionally, note that with $r_{ch} = 1$, Equation (10) now gives $\Gamma_b = r_{SoC} \cdot N_{op}$ since $N_{op} = \frac{E_{tot}}{E_{max}}$ for a rectangular EDD. This is intuitive, since all the useful capacity is used exactly once every day.

6. A Triangular Energy Distribution Diagram

The previous section showed that the charging strategy *night charge only* was cost-efficient when the EDD was rectangular. A triangular EDD will now be similarly investigated. A triangular EDD represents a truck, which uses different amount of energy each day, between zero and a maximum value E_{max} and all the levels of daily energy consumption are equally common. This is an unusual way of using a truck, but is interesting to study as it results in a more difficult trade-off when selecting battery capacity. The triangular energy function can be expressed as:

$$E(N) = -\frac{E_{max}}{N_{op}} N + E_{max}, \qquad N \in [0, N_{op}]. \tag{17}$$

The energy function is illustrated in Figure 3. In the figure, the available energy stored in a full battery is marked in blue on the y-axis and the number of days charging with a public fast charger is marked in a red N_{ch} on the x-axis.

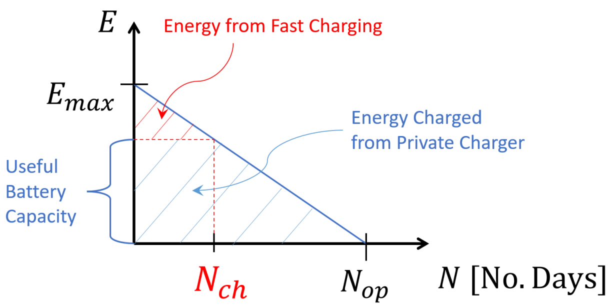


Figure 3. A triangular EDD. The available energy stored in a full battery is marked on the y-axis in blue and the number of days charging with a public fast charger is marked as N_{ch} in red on the x-axis. The amount of fast charging needed is marked in red and the energy delivered by private chargers is marked in blue for a given useful battery capacity.

The aim is to find the battery capacity that gives the lowest value on the cost function. Therefore, the cost function will be expressed solely as a function of battery capacity and the parameters. The mathematical steps follow below. Figure 3 makes it apparent that the amount of energy to be charged by public chargers corresponds to the area of the small upper triangle of height $E_{max} - r_{SoC} \cdot B_c$ and base N_{ch}, with the rest charged at night using a private charger. Thus:

$$r_{ch} = \frac{\frac{E_{max} \cdot N_{op}}{2} - \frac{(E_{max} - r_{SoC} \cdot B_c) \cdot N_{ch}}{2}}{\frac{E_{max} \cdot N_{op}}{2}} = 1 - \frac{(E_{max} - r_{SoC} \cdot B_c) \cdot N_{ch}}{E_{max} \cdot N_{op}}. \tag{18}$$

To eliminate N_{ch}, Equation (17) and Figure 3 can be used, thus:

$$-\frac{E_{max}}{N_{op}} \cdot N_{ch} + E_{max} = r_{SoC} \cdot B_c \iff N_{ch} = \frac{(E_{max} - r_{SoC} \cdot B_c) \cdot N_{op}}{E_{max}} \tag{19}$$

This gives:

$$r_{ch} = 1 - \frac{(E_{max} - r_{SoC} \cdot B_c) \cdot \frac{(E_{max} - r_{SoC} \cdot B_c) \cdot N_{op}}{E_{max}}}{E_{max} \cdot N_{op}} = 1 - \left(1 - \frac{r_{SoC} \cdot B_c}{E_{max}}\right)^2. \tag{20}$$

Again, the definition of the battery utilisation factor is:

$$\Gamma_b = \frac{E_{tot}}{B_c} \tag{21}$$

and for the triangular EDD, the charger utilisation factor becomes:

$$\Gamma_{ch} = \frac{E_{ch}}{P_{ch} \cdot T} = \frac{r_{ch} \cdot E_{tot}}{P_{ch} \cdot T} = \frac{r_{ch} \cdot \frac{E_{max} \cdot N_{op}}{2}}{\frac{r_{SoC} \cdot B_c}{T_{ch}} \cdot T} = \frac{r_{ch}}{\frac{r_{SoC} \cdot B_c}{E_{max}} \cdot \frac{2 \cdot T}{N_{op} \cdot T_{ch}}}. \tag{22}$$

By inserting Equations (20)–(22) in Equation (5), one obtains:

$$\begin{aligned} f_{BEV} &= \left(1 - \left(1 - \frac{r_{SoC} \cdot B_c}{E_{max}}\right)^2\right) \cdot C_e + \left(1 - \left[1 - \left(1 - \frac{r_{SoC} \cdot B_c}{E_{max}}\right)^2\right]\right) \cdot C_{epub} \\ &\quad + \frac{C_b \cdot B_c}{E_{tot}} + \frac{r_{ch}}{\frac{r_{ch}}{\frac{r_{SoC} \cdot B_c}{E_{max}} \cdot \frac{2 \cdot T}{N_{op} \cdot T_{ch}}}} \cdot C_{ch} \\ &= \left(1 - \left(1 - \frac{r_{SoC} \cdot B_c}{E_{max}}\right)^2\right) \cdot C_e + \left(1 - \frac{r_{SoC} \cdot B_c}{E_{max}}\right)^2 \cdot C_{epub} \\ &\quad + \frac{C_b}{r_{SoC} \cdot \frac{N_{op}}{2}} \cdot \frac{r_{SoC} \cdot B_c}{E_{max}} + \frac{r_{SoC} \cdot B_c}{E_{max}} \cdot \frac{2 \cdot T}{N_{op} \cdot T_{ch}} \cdot C_{ch}. \end{aligned} \tag{23}$$

For a clearer view, the substitution:

$$x = \frac{r_{SoC} \cdot B_c}{E_{max}}, \qquad x \in [0, 1] \tag{24}$$

is made. This gives:

$$\begin{aligned} f_{BEV} &= \left(1 - (1 - x)^2\right) \cdot C_e + (1 - x)^2 \cdot C_{epub} + \frac{C_b}{r_{SoC} \cdot \frac{N_{op}}{2}} \cdot x + \frac{2 \cdot T}{N_{op} \cdot T_{ch}} \cdot C_{ch} \cdot x \\ &= (C_{epub} - C_e) \cdot x^2 + \left(2 \cdot C_e - 2 \cdot C_{epub} + \frac{C_b}{r_{SoC} \cdot \frac{N_{op}}{2}} + \frac{2 \cdot T}{N_{op} \cdot T_{ch}} \cdot C_{ch}\right) \cdot x + C_{epub}. \end{aligned} \tag{25}$$

Note that $x = 0$ corresponds to $B_c = 0$, which is not possible in reality. From the known properties of quadratic functions, one knows that the cost function has a global minimum for x, so that:

$$\frac{d f_{BEV}}{dx} = 0. \tag{26}$$

One must therefore solve the equation:

$$2 \cdot (C_{epub} - C_e) \cdot x + 2 \cdot C_e - 2 \cdot C_{epub} + \frac{C_b}{r_{SoC} \cdot \frac{N_{op}}{2}} + \frac{2 \cdot T}{N_{op} \cdot T_{ch}} \cdot C_{ch} = 0 \tag{27}$$

which is equivalent to:

$$x = -\frac{2 \cdot C_e - 2 \cdot C_{epub} + \frac{C_b}{r_{SoC} \cdot \frac{N_{op}}{2}} + \frac{2 \cdot T}{N_{op} \cdot T_{ch}} \cdot C_{ch}}{2 \cdot (C_{epub} - C_e)}. \tag{28}$$

By inserting parameter values from Table 1, $N_{op} = 1750$ and $T_{ch} = 14$ h one obtain:

$$x = 0.45 \in [0, 1] \tag{29}$$

and the corresponding minimum cost:

$$\min(f_{BEV}) = 0.34\ \text{€/kWh} > C_d. \tag{30}$$

By computing r_{ch} and the utilisation factors, the individual costs can be worked out using Equation (5) (be careful with the units). It becomes apparent that the battery still represents the largest cost, 0.13 €/kWh, closely followed by the cost of public fast charging, 0.12 €/kWh, and that the price for home charging is 0.06 €/kWh. The smallest cost is the charger and grid, at 0.03 €/kWh.

So, if the EDD is triangular, an electric truck has a higher cost per propulsion kWh compared with that of a diesel truck. The battery capacity should be selected so that the useful battery capacity equals 45% of the maximum daily energy consumption. In that case, the cost per propulsion kWh of the electric truck is a little higher than for the diesel truck. Note that (as with the rectangular EDD) the number of operational days influence the result, while the daily maximum consumed energy does not.

A battery sized so that the useful battery capacity equals 45% of the maximum daily energy consumption implies that the truck must charge with public fast chargers on 55% of the days and that it must fast charge twice during the same day on 10% of the days. This is illustrated in Figure 4.

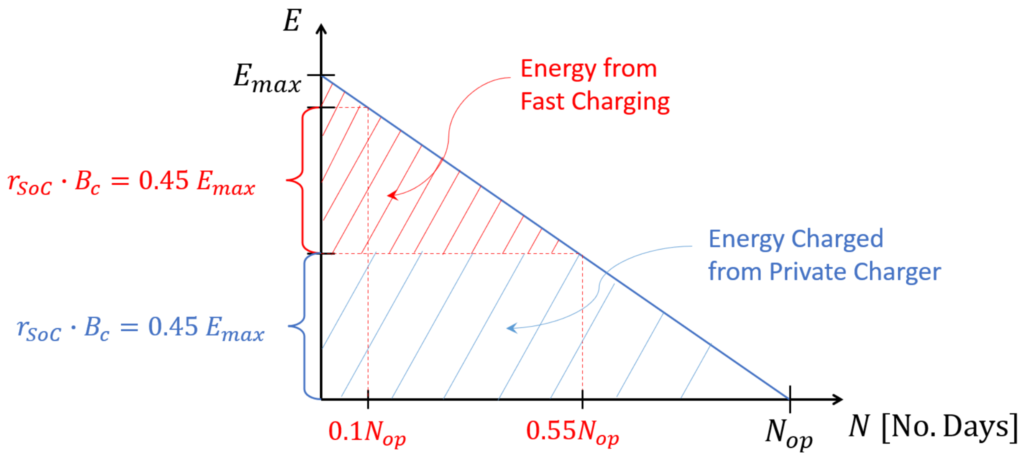


Figure 4. The charging strategy for a triangular EDD with $N_{op} = 1750$. The figure illustrates that fast charging must take place on 55% of the days and that there must be fast charging twice on 10% of the days.

Although this is the most cost-efficient charging strategy, it can lead to inconvenience and operational reliability problems. Luckily, for real commercial trucks, a triangular EDD is rare.

7. A Two-Step Rectangular Energy Distribution Diagram

Imagine an EDD with a thin peak, like the one in the right-hand part of Figure 1. In this case, one might surmise that it will be cost-efficient to size the battery to handle most trips, but not those with the highest energy consumption. Naturally, this strategy will require public fast charging. However, it allows a smaller, cheaper battery. This section will explore how thin the peak must be before it is cost-effective to use fast charging to handle peak demand rather than sizing the battery to fit the peak. To investigate this, a two-step rectangular EDD is analysed. Such an EDD would correspond to a truck being used for two different tasks, different days. Each task consumes exactly the same energy all times it is performed, but the two tasks consumes different energy than each other. Additionally, the number of days which the two tasks are performed can vary. The two-step rectangular EDD appears in Figure 5 and the corresponding energy function can be expressed as:

$$E(N) = \begin{cases} E_{max}, & N \in [0, M] \\ E_{min}, & N \in (M, N_{op}], \end{cases} \quad (31)$$

where E_{min} is the lowest daily energy consumption for the truck and M is the number of days the truck consumes the maximum daily energy E_{max}.

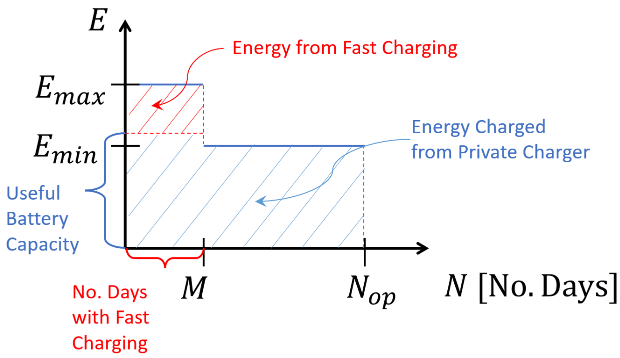


Figure 5. A two-step rectangular EDD. In the figure, the number of days requiring fast charging and the amount of fast charging needed is marked in red, while the energy delivered by private chargers is marked in blue for a given useful battery capacity.

Since the energy function is discontinuous at $N = M$, the calculations needed to determine the most cost-efficient battery capacity are made in two steps. Firstly, it is assumed that $r_{SoC} \cdot B_c \leq E_{min}$, which leads to:

$$r_{ch} = \frac{r_{SoC} \cdot B_c \cdot N_{op}}{E_{tot}} \tag{32}$$

and the battery utilisation factor becomes:

$$\Gamma_b = \frac{E_{tot}}{B_c} = \frac{r_{SoC} \cdot N_{op}}{r_{ch}} \tag{33}$$

with the charger utilisation factor:

$$\Gamma_{ch} = \frac{E_{ch}}{P_{ch} \cdot T} = \frac{r_{ch} \cdot E_{tot}}{P_{ch} \cdot T} = \frac{r_{ch} \cdot E_{tot}}{\frac{r_{SoC} \cdot B_c}{T_{ch}} \cdot T} = \frac{N_{op} \cdot T_{ch}}{T}. \tag{34}$$

By inserting the expressions of the utilisation factors into Equation (5) one obtain:

$$f_{BEV} = r_{ch} \cdot C_e + (1 - r_{ch}) \cdot C_{epub} + \frac{C_b}{r_{SoC} \cdot N_{op}} \cdot r_{ch} + \frac{r_{ch} \cdot T}{N_{op} \cdot T_{ch}} \cdot C_{ch}, \tag{35}$$

which is the same equation as Equation (13). One thus obtains the lowest value on f_{BEV} again by taking the highest possible value on r_{ch} which, in this case, is $r_{ch} = \frac{E_{min} \cdot N_{op}}{E_{tot}}$. One concludes that the battery should be sized to handle the low-energy-consumption trips without day charging. The results may seem intuitive after studying the rectangular EDD.

Secondly, consider the case when $r_{SoC} \cdot B_c > E_{min}$. This means that:

$$r_{ch} = \frac{E_{min} \cdot N_{op} + (r_{SoC} \cdot B_c - E_{min}) \cdot M}{E_{tot}}. \tag{36}$$

The charger utilisation factor becomes:

$$\Gamma_{ch} = \frac{E_{ch}}{P_{ch} \cdot T} = \frac{r_{ch} \cdot E_{tot}}{P_{ch} \cdot T} = \frac{r_{ch} \cdot E_{tot}}{\frac{r_{SoC} \cdot B_c}{T_{ch}} \cdot T} = \frac{r_{ch} \cdot E_{tot} \cdot T_{ch}}{r_{SoC} \cdot B_c \cdot T}. \tag{37}$$

Inserting this charger utilization factor and the definition of the battery utilisation factor into Equation (5), the cost function becomes:

$$f_{BEV} = r_{ch} \cdot C_e + (1 - r_{ch}) \cdot C_{epub} + \frac{C_b \cdot B_c}{E_{tot}} + \frac{r_{SoC} \cdot B_c \cdot T}{E_{tot} \cdot T_{ch}} \cdot C_{ch}. \tag{38}$$

Equation (36) gives:

$$\frac{dr_{ch}}{dB_c} = \frac{r_{SoC} \cdot M}{E_{tot}} \tag{39}$$

and therefore:

$$\begin{aligned}\frac{df_{BEV}}{dB_c} &= \frac{r_{SoC} \cdot M}{E_{tot}} \cdot C_e - \frac{r_{SoC} \cdot M}{E_{tot}} \cdot C_{epub} + \frac{C_b}{E_{tot}} + \frac{r_{SoC} \cdot T}{E_{tot} \cdot T_{ch}} \cdot C_{ch} \\ &= \frac{r_{SoC}}{E_{tot}} \left(\frac{C_b}{r_{SoC}} + \frac{T}{T_{ch}} \cdot C_{ch} - (C_{epub} - C_e) \cdot M \right).\end{aligned} \tag{40}$$

It appears that the sign of the derivative depends on the parameter M. One can see that:

$$M > \frac{\frac{C_b}{r_{SoC}} + \frac{T}{T_{ch}} \cdot C_{ch}}{C_{epub} - C_e} \iff \frac{df_{BEV}}{dB_c} < 0 \tag{41}$$

and by inserting the same values as before, one obtains:

$$M > 964 \iff \frac{df_{BEV}}{dB_c} < 0. \tag{42}$$

This means that it becomes cost-efficient to have a smaller battery, one that can handle only the energy needs of low-consumption days, if there are fewer than or equal to 964 days of high energy consumption. The remaining days require fast charging. In other words, it is cost-effective to have a battery that can handle all trips using *night charge only* if the number of high-consumption days is greater than 964 (note that this is valid for the parameter values selected in this paper). The results confirm the intuition that when an EDD has a peak, it is cost-efficient to have a smaller battery and fast charge the remaining days, but only if the peak is sufficiently thin.

It is now clear how the battery should be sized, but is this electric truck competitive compared to a diesel truck? To investigate this, the cost function is expressed as a function of two variables as follows. Firstly, consider the case when $M \leq 964$, which implies that the smaller battery should be chosen. Thus, $r_{SoC} \cdot B_c = E_{min}$, which gives:

$$r_{ch} = \frac{E_{min} \cdot N_{op}}{E_{tot}} = \frac{E_{min} \cdot N_{op}}{E_{min} \cdot N_{op} + M \cdot (E_{max} - E_{min})} = \frac{r \cdot N_{op}}{r \cdot N_{op} + M \cdot (1 - r)} \tag{43}$$

where $r = \frac{E_{min}}{E_{max}} \in [0, 1]$. Inserting Equations (33) and (34) into Equation (5) gives:

$$f_{BEV}(M, r) = r_{ch} \cdot C_e + (1 - r_{ch}) \cdot C_{epub} + r_{ch} \cdot \frac{C_b}{r_{SoC} \cdot N_{op}} + r_{ch} \cdot \frac{T}{N_{op} \cdot T_{ch}} \cdot C_{ch}. \tag{44}$$

Note that $f_{BEV} = f_{BEV}(M, r)$ since $r_{ch} = r_{ch}(M, r)$.

Secondly, consider the case when $M > 964$ and thus $r_{SoC} \cdot B_c = E_{max}$, which gives $r_{ch} = 1$, and by Equation (5) one obtains:

$$f_{BEV} = C_e + \frac{C_b}{\Gamma_b} + \frac{1}{\Gamma_{ch}} \cdot C_{ch}. \tag{45}$$

The battery utilisation factor then becomes:

$$\Gamma_b = \frac{E_{tot}}{B_c} = \frac{r_{SoC} \cdot E_{tot}}{E_{max}} = \frac{r_{SoC} \cdot (E_{min} \cdot N_{op} + M \cdot (E_{max} - E_{min}))}{E_{max}} = r_{SoC} \cdot (r \cdot N_{op} + M \cdot (1 - r)) \tag{46}$$

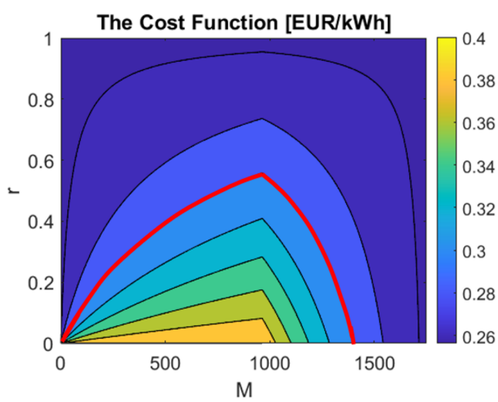
and the charger utilisation factor is obtained from Equation (37):

$$\Gamma_{ch} = \frac{r_{ch} \cdot E_{tot} \cdot T_{ch}}{r_{SoC} \cdot B_c \cdot T} = \frac{(E_{min} \cdot N_{op} + M \cdot (E_{max} - E_{min})) \cdot T_{ch}}{E_{max} \cdot T} = \frac{(r \cdot N_{op} + M \cdot (1 - r)) \cdot T_{ch}}{T}. \tag{47}$$

The above expressions of the utilisation factors give:

$$f_{BEV}(M, r) = C_e + \frac{C_b}{r_{SoC} \cdot (r \cdot N_{op} + M \cdot (1 - r))} + \frac{T}{(r \cdot N_{op} + M \cdot (1 - r)) \cdot T_{ch}} \cdot C_{ch}. \tag{48}$$

Equations (44) and (48) allow the cost function to be visualised. This is shown in the left-hand part of Figure 6, in which the electric truck is more costly than the diesel truck between the red curve and the M-axis. So, for which type of two-step rectangle EDD is the electric truck competitive with the diesel truck? According to the left-hand part of Figure 6, it is often possible to compete with diesel, but this becomes hard when the EDD is L-shaped. In this case, the spike must be really thin if the cost is not to be too high according to the lower left-hand part of Figure 6. It is also problematic when none of the sides of any rectangle are thin (see centre of left-hand part of Figure 6). Finally, it is problematic when none of the sides of the left-hand rectangle are thin, but the height of the right-hand rectangle is small (like a thin tail). See the lower centre of the left-hand part of Figure 6. The right-hand part of Figure 6 shows how the shape of the two rectangle EDDs depend on M and r. For the shapes of the EDD inside the area enclosed by the red curve and the M-axis, it is hard to compete with the diesel trucks. Note that this area should *not* be seen as *absolutely* fixed, especially not those parts close to the red curve, since the area depends on the values of many estimated parameters. The vertical, dashed black line, $M = 964$, in the right-hand part of Figure 6 shows how to select battery capacity. On or to the left of the black dashed line, the smaller battery should be selected and, to the right of it, the larger battery.



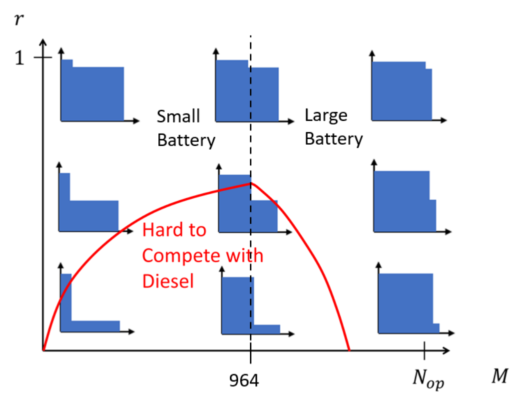


Figure 6. The cost function as a function of M and r in the left-hand part of the figure. The battery electric trucks are more expensive than the commercial diesel ones in the area enclosed by the red curve and the M-axis. The right-hand part of the figure shows how the shape of the EDD depends on the parameters M and r. If there is an EDD on or to the left of the dashed vertical black line, the smaller battery is the most cost-efficient and, to the right of it, the larger battery.

As seen from Figure 6, the cases when EDDs tend to be a rectangle, or a rectangle with a thin spike are *best* suited to battery electric trucks. Note that the same cost function value (0.26 €/kWh) is obtained when the two rectangles tend towards forming a single rectangle, as obtained for the rectangular EDD. The cases when the EDD is L-shaped with a *really* thin spike or when none of the sides of any rectangle are thin show when the electric trucks *could* compete with diesel trucks. As a rough guide, the closer one gets to the point $(M = 750, r = 0)$, the harder it is for electric trucks to be competitive, compared with the left-hand part of Figure 6.

From the left-hand part of Figure 6 and the studies of the rectangular EDD, the expectation might be for the rectangular EDD to give the lowest cost per propulsion kWh compared to *any* EDD for a fixed number of operational days. There now follows a series of arguments showing that a rectangular EDD gives the lowest cost function value.

Take a non-rectangular EDD. The analysis starts by considering the unrealistic case of the battery capacity being zero. The cost function then has the value of $C_{epub} = 0.4$ €/kWh $> f_{BEV}^{rec}$, where $f_{BEV}^{rec} = 0.26$ €/kWh is the cost function value when the EDD is rectangular. To try to find a lower cost function value, the battery capacity is increased and, if an EDD is found that is better than the rectangular one, the cost function must begin to drop at some point as battery capacity increases. That being the case, the cost drops because the benefit of charging the majority of the total energy with a home charger rather than a fast public one exceeds the increasing costs of battery, charger, and grid. The required power for the charger is directly proportional to the battery capacity. This means that the extra cost for the battery, charger and grid is the same for *any* EDD (even the rectangular one) when increasing the battery capacity by a given step according to Equation (2), while the increase in energy that can be moved from public fast charging to home charging is greatest when the EDD is rectangular. Since this maximum decrease in the cost function continues right up until the battery capacity reaches the highest possible value (assuming the battery size is no larger than it needs to manage the trip at the highest daily level of energy consumption), the rectangular EDD must be the most cost-efficient EDD provided the number of operational days is fixed. Or, more simply and less stringently, when the battery size increases, the extra cost of the battery, charger and grid increases equally, independently of the shape of the EDD. However, the most energy will be moved from public fast charging to home charging if the EDD is rectangular. Thus, a rectangular EDD will result in the lowest cost function provided the number of operational days is fixed.

8. Importance of the Number of Operational Days

So far, the number of operational days has been fixed at 1750. However, from the equations, it is apparent that the number of operational days often influences the result. Naturally, if the number of operational days is too low, this makes it impossible for battery electric trucks to compete with commercial diesel trucks because the utilisation factors will be very low. Thus, it is interesting to investigate the lowest necessary number of operational days for battery electric trucks to be competitive. Since the aim is to find a lower bound for the number of operational days, the most preferable EDD is used—the rectangular one. Firstly, from Equation (14), it is clear that:

$$\frac{df_{BEV}}{dr_{ch}} < 0 \iff N_{op} > \frac{\frac{C_b}{r_{SoC}} + \frac{T \cdot C_{ch}}{T_{ch}}}{C_{epub} - C_e} \tag{49}$$

for a rectangular EDD and by inserting the previous values, one obtains:

$$\frac{df_{BEV}}{dr_{ch}} < 0 \iff N_{op} > 964. \tag{50}$$

Note the similarity with Equations (41) and (42). This means that, if the number of operational days is 964 or less, the lowest value of r_{ch}, i.e., $r_{ch} = 0$, should be chosen. This gives the lowest cost function value, which would be $C_{epub} = 0.4$ €/kWh. So, in this case, the battery electric truck is not competitive. Furthermore, in this context, $r_{ch} = 0$ corresponds to having a battery capacity of zero kWh, something which is not possible in reality. Thus, one now knows that the number of operational days must be greater than 964, which implies that $r_{ch} = 1$.

Secondly, the minimum number of operational days will be determined by solving the inequality:

$$f_{BEV}(N_{op}) \leq C_d. \tag{51}$$

Equation (13) with $r_{ch} = 1$ gives:

$$N_{op} \geq \frac{\frac{C_b}{r_{SoC}} + \frac{T \cdot C_{ch}}{T_{ch}}}{C_d - C_e} \tag{52}$$

and by inserting the typical values, one obtains:

$$N_{op} \geq 1402. \tag{53}$$

This means that the number of operational days must be at least 1400 if a battery electric truck is to compete with diesel trucks. This corresponds to approximately five-and-a-half years if the truck is used every weekday. This is exceeded in most commercial trucks.

9. An Algorithm for Sizing the Battery of a General EDD

So far, the most cost-efficient battery size has been determined for a few specific EDD shapes. These cases approximate most of the possible EDDs and give insights as to which EDD shapes are best suited to electric trucks. However, for a specific EDD, it may be necessary to determine the most cost-efficient battery size of *that particular* EDD rather than just the best battery size for an approximation of it.

As mentioned earlier, three parameters can change when the charging strategy is changed. These are: B_c, r_{ch} and P_{ch}. This is apparent from Equation (2). However, based on the analysis so far, it is apparent that the three parameters are strongly connected. Since the aim is to use the home charger as much as possible for a given battery capacity and to have a charger powerful enough to supply the full capacity in one night (but no more than that), the choice of B_c directly determines r_{ch} and P_{ch}. Thus, a battery capacity may be chosen which determines r_{ch} and P_{ch} and the corresponding cost function value. By systematically testing enough battery capacity values, the most cost-efficient battery capacity can be selected. The most cost-efficient battery capacity will depend on the energy function. This insight allows us to establish an algorithm to determine the most cost-efficient battery capacity for an EDD of arbitrary energy function $E(N)$. The algorithm follows below.

Algorithm Description

1. Choose a sufficiently small battery capacity value, such as B_{c1}.
2. Compute the total energy, $E_{tot} = \int_0^{N_{op}} E(N)dN$.
3. Find the smallest N_1 so that $r_{SoC} \cdot B_{c1} = E(N_1)$. The number of days needed to fast charge is N_1.
4. Compute
   (a) $r_{ch} = \frac{r_{SoC} \cdot B_{c1} \cdot N_1 + \int_{N_1}^{N_{op}} E(N)dN}{E_{tot}}$,
   (b) $\Gamma_b = \frac{E_{tot}}{B_{c1}}$
   and
   (c) $\Gamma_{ch} = \frac{r_{ch} \cdot E_{tot}}{\frac{r_{SoC} \cdot B_{c1}}{T_{ch}} \cdot T}$.
5. Compute $f_{BEV1} = f(B_{c1})$ from Equation (5).
6. Set $B_{c2} = B_{c1} + \Delta B_c$, ΔB_c should be sufficiently small.

7. Repeat steps 3–6 but increase each index by one until $r_{SoC} \cdot B_{c(n+1)} > E_{max}$, then set $r_{SoC} \cdot B_{c(n+1)} = E_{max}$, repeat steps 3–5 and then jump to step 8.
8. One now have the cost per kWh of useful energy expressed as a function of battery capacity. Select the battery capacity that gives the lowest cost.

10. Conclusions

This paper demonstrates that an energy distribution diagram is an effective tool for describing the usage pattern of a vehicle and making it easy to analyse the cost-effectiveness of battery electric vehicles. An algorithm has been presented for determining a cost-effective battery size, charger power and amount of public charging using just the EDD and some cost parameters. This paper focuses on battery electric trucks, but the method could also be used for other battery electric vehicles by making appropriate changes to the parameter values.

How Usage Pattern Influences the Cost-Effectiveness of Battery Electric Vehicles

A rectangular EDD (with no variation in daily energy consumption) gives the lowest cost per kWh propulsion energy compared to all other possible EDDs, for a fixed number of operational days. This is due to making the greatest use of private chargers and no need for fast charging without having an unnecessarily large battery. In this case, night charging only will be the most cost-effective charging strategy. When an EDD is rectangular and has 1750 operating days, an electric truck clearly competes with a diesel truck. However, given the assumed cost parameters, if the number of operational days is fewer than 1400, the diesel truck will cost less.

A triangular EDD leads to a higher total cost than a rectangular one. This is because there is no battery size which can lead to a high level of battery utilisation without also requiring a lot of public fast charging—and vice versa.

In the case of a two-step rectangular EDD, in many of the cases electric trucks can compete with diesel ones. With this EDD, the lowest cost is obtained either by having a battery so large that it can handle all trips without fast charging, or one that can handle solely the low-consumption trips without fast charging. If there are sufficiently many high-consumption days, the large battery should be chosen; otherwise, the choice should be the small one. In this context, "sufficient" means just under 1000 days. The EDDs best suited to electric trucks are those close to a single rectangle, or a rectangle with a thin peak on top. The worst EDDs are L-shaped ones (if their peak is not really thin) and EDDs with a long, thin tail.

For any EDD, provided the shape is fixed, the total cost is reduced by increasing the number of operational days while the maximum daily energy consumption is not influencing the cost.

These conclusions are drawn under the following assumptions:

1. Battery capacity and charger power are continuously variable, from zero to arbitrary high values.
2. Charging is always possible, precisely when needed.
3. Charging is done on planned breaks and requires no extra time.
4. A battery electric truck has the same payload capacity as a diesel truck.
5. Parameter values are selected according to Table 1, the vehicle is operated for 1750 days, the home charger can be used for up to 14 hours per night and there is 80% of the battery capacity available.

Some of these assumptions are not always true for real trucks. However, the results still allow an increased understanding of how cost-efficiency and charging strategy depend on how a vehicle is used. Typically, the assumptions are reasonable for local trucks and most regional trucks, if they are not carrying very heavy goods or driving very long daily distances. These assumptions favour the battery electric trucks over diesel trucks. However, it should be borne in mind that the price picture will likely change to favour electric trucks as the production volume increases. Additionally, the assumed fuel cost for diesel trucks is intentionally low. Even without these assumptions, the EDD is still a useful tool for determining the cost-effectiveness of battery electric trucks.

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Abbreviations

The following abbreviations are used in this manuscript:

EDD	Energy distribution diagram

Nomenclature

B_c	Battery capacity [kWh]
C_b	Battery cost [€/kWh]
C_{ch}	Combined price for charger and grid [€/kW/year]
$C_{charger}$	Price of charger [€/kW]
C_d	Diesel cost [€/kWh]
C_e	Electricity cost, private charging [€/kWh]
C_{epub}	Electricity cost, public fast charging [€/kWh]
C_g	Grid fee [€/kW/year]
E	Energy function [kWh]
E_{max}	Highest daily energy consumption in the truck's service life [kWh]
E_{min}	Lowest daily energy consumption in the truck's service life [kWh]
E_{tot}	Total propulsion energy consumed over the truck's Service life [kWh]
f_{BEV}	Cost function [€/kWh]
f_{BEV}^{rec}	Lowest value of the cost functions when the EDD is rectangular [€/kWh]
Γ_b	Battery utilisation factor [equivalent full cycles]
Γ_{ch}	Charger utilisation factor [−]
M	No. of high energy consumption days for a two-step rectangular EDD [−]
N_{ch}	Number of fast charging days [−]
N_{op}	Number of operational days [−]
N_{tot}	Number of days in the truck's service life [−]
P_{ch}	Charger power [kW]
r_{ch}	Ratio of private charging to total amount of energy [−]
r_{SoC}	Share of battery capacity that could be used [−]
T	Service life of truck, charger and battery [year]
T_{ch}	Available time for charging during night [hours]

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Case Study of Cost-Effective Electrification of Long-Distance Line-Haul Trucks

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Abstract: This paper investigates the economic consequences of a haulage company replacing its line-haul diesel trucks with battery-electric ones. It also examines how large truck batteries should be, whether the haulage companies should use public fast chargers to complement their own, and whether public fast chargers have the potential to be profitable. The potential extra cost of losing payload capacity is estimated and there is an investigation of whether a charge-point operator should meet the peak demand for charging. The case under analysis is designed to represent a typical line-haul service between terminals in a major logistics system, with the finding that, in this case, a transition to battery-electric trucks seems cost effective for the company. Moreover, it is advisable for the company to use public fast chargers and these will likely become profitable given that the utilisation factor of the investigated public fast chargers may realistically exceed 20%.

Keywords: battery electric truck; battery electric vehicle; cost effective; battery sizing; charging strategy; payload capacity; charge-point operator; long-haul truck

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1. Introduction

The use of fossil fuels has severe drawbacks: the oil depletion time is less than 30 years [1], the Earth's climate system is likely affected [2], and negative health impacts are discussed in the literature [3]. Part of the solution is to avoid running trucks on fossil fuels. Possible alternatives are hydrogen or battery-electric trucks but recently published studies favour the battery-electric option [4,5]. Although the feasibility of battery-electric trucks seems promising, fuel cells might be better for heavy-duty trucks on extra-long journeys [6]. Still, there is no unambiguous answer to the question of which powertrain would result in the lowest overall cost of ownership, as this will depend on how the vehicle is used [7].

A previous study indicated that battery-electric trucks have the potential to be competitive with diesel trucks under the right circumstances [8]. The present study concretises the work conducted in [8] by applying the theory to a specific line-haul case involving a common type of transport. This paper's study case investigates the economic consequences of a haulage company replacing its diesel trucks with battery-electric ones. The aforementioned study focused solely on the vehicle owner's perspective but this study also focuses on the charge-point operator. The present study also further expands on the previous one by estimating the potential cost of losing payload capacity due to having a large battery, which was not discussed in [8]. Furthermore, the present study does not assume that 80% of the battery capacity can be used. Rather, it varies the useful state-of-charge range to include battery ageing and safety margins in the battery sizing. Other studies have also shown the competitiveness of battery-electric trucks compared to diesel trucks under the right conditions [9–11]. When reading the present paper, it is important to remember that the cost effectiveness of battery electric vehicles is sensitive to driving patterns [8,12]. In addition, relatively uniform driving patterns show good potential for electrification [8,13]. Thus, the results of the present study might have been different had a different case been chosen.

The literature indicates that over-sizing the battery could lower the total cost of ownership, as it can reduce battery ageing [14]. A larger battery prevents deep battery cycles, which reduces battery ageing. This is also stated in another study [15]. Due to the battery ageing and safety margins, this paper assumes that only a share of the battery capacity could be used. This share would depend on the number of cycles that the battery is required to perform. A previous study concerning battery-electric truck deliveries concluded that battery sizing is essential for maximising profit [16]. The present paper also discusses battery sizing, which can reduce the total cost of ownership. Vehicle batteries could be used for grid-energy storage, which can also reduce the total cost of battery-electric trucks. However, this topic has not been included in this paper for two reasons. Firstly, the electric trucks in the studied case are used extensively, with very little inactive time to act as grid storage. Secondly, a previous study showed that grid storage only has limited value for plug-in hybrids [17].

In a previous study, the battery price was highlighted as a crucial parameter for cost-competitive battery-electric vehicles [18]. Supported by an earlier study [19], the authors of [18] claimed that the price of batteries must fall below 150 USD/kWh (140 EUR/kWh) if battery-electric vehicles, in general, are to compete with internal combustion vehicles. The same authors also showed that this price is realistic for the near future. For the case studied in this paper, battery-electric trucks are competitive with a battery price set at 200 EUR/kWh (this price is reasonable according to Appendix D). This is because trucks have a higher utilisation rate compared to private passenger cars.

So far, the electrification of heavy trucks has occurred in sectors that are the easiest to electrify, such as local and regional distribution. However, due to the limited driving range of battery-electric trucks, the long-distance truck sector is more difficult to electrify. This paper studies one type of long-distance transport: line haul between terminals in a major logistics system. To further investigate the competitiveness aspect, this paper examines the economic consequences of a haulage company replacing its diesel trucks with battery-electric ones, along with the profitability of the public fast chargers used by the company. The studied line-haul case is strongly inspired by a Swedish haulage company, Tommy Nordbergh Åkeri AB. The results and calculations in this paper are not entirely general, as they are based on a specific case. However, with proper changes to the conditions and values of the parameters, the same method can be used to evaluate cost efficiency for other companies. Furthermore, this type of example gives an idea of when battery-electric trucks are cost effective. The first part of this paper focuses on the haulage company's perspective. Later, the focus shifts to the owner of the public fast chargers. This is followed by a discussion from a system perspective. This paper finds that the transition to battery-electric trucks appears to be cost efficient for the haulage company studied in the use case.

2. The Haulage Company's Transport Task

Suppose that a haulage company has a fleet of diesel trucks and wants to change them all to battery-electric trucks. This paper investigates the economic consequences of full electrification, with no changes to how the trucks operate.

The company has two terminals, A and B, which are connected by a highway. Terminal A is located in Helsingborg on Sweden's west coast and Terminal B is located in Stockholm, Sweden's capital located on the east coast (see Figure 1). From the map, it is clear that this type of transport distance is sufficient to reach many cities in Europe from the closest harbour. Five times a week, the following procedure is repeated. Half of the trucks arrive at Terminal A and half arrive at Terminal B in the afternoon, following some local distribution tasks during the day. The trucks are then idle for a certain time, T_1. At 6 PM, the first truck leaves the terminal and drives towards the other terminal. Thereafter, the other trucks leave the terminal one by one at a given interval, T_{gap}. Midway between the terminals, the drivers take a break, T_{break}, at a rest area. This break is compulsory under the Driving and Resting time Rules and must be at least 45 min. After the break, the driver from Terminal A swaps trucks with the driver from Terminal B and the drivers then return to their original terminals. After arriving at their destination terminals, the trucks stand idle for a certain period of time, T_2. Let the following values also apply: the distance between Terminals A and B—S; the mean speed of the trucks—$\overline{v}$; the trucks' mean energy consumption per unit of distance travelled—$\frac{\Delta E}{\Delta x}$; and the number of trucks leaving from each terminal—N_{trucks}. For clarity, the charge losses are not explicitly modelled in this paper but their cost can be included in the price of electricity. The battery discharge losses and efficiency of the powertrain are also not explicitly modelled but are included in the trucks' energy consumption. During the local distribution tasks that take place during the daytime, each truck has driven a distance, $S/2$. This paper's notation for the parameters and their values is listed in Table 1. In addition to driving each weekday during the year, each truck performs, on average, 50 extra night trips per year on the weekends. At the rest area, a charge-point operator has a public fast-charging station for trucks. So, in addition to the company's private chargers at each terminal, the trucks can also be charged at the rest area using public fast chargers.

Figure 1. The assumed 550 km transport route is plotted on a map of Europe as a reference.

Table 1. Notations for the different parameters and their values used in this paper.

Parameters	Notation	Value
Departure time of the first truck	–	6 PM
Time gap between trucks	T_{gap}	7 min
Inactive time for the trucks in the afternoon	T_1	2 h
Time for the break	T_{break}	45 min
Inactive time for the trucks in the morning	T_2	4 h
Distance between the terminals	S	550 km
Mean speed of the trucks	$\overline{v}$	75 km/h
Energy consumption	$\frac{\Delta E}{\Delta x}$	1.5 kWh/km
Numbers of trucks leaving from each terminal	N_{trucks}	30

This paper investigates whether it is economical to use battery-electric trucks for the studied type of line haul and, if so, how the system should be designed. More specifically, this paper attempts to answer the following questions:

1. What are the economic consequences for the company to change from diesel trucks to battery-electric ones?

2. What power should the company's private chargers have?
3. What is the maximum extra cost of the reduced payload capacity due to heavy batteries?
4. How many public fast chargers must be installed at the rest area by the charge-point operator and what should their power capacity be to meet the demand from the haulage company?
5. Can the charge-point operator at the rest area expect a profit from the chargers if the stated company is their only user?
6. Should a charge-point operator always meet the demands of its users? If not, how should the total power be selected?

3. Economic Consequences of Electrification for the Haulage Company

Many of the trucks' main costs would remain approximately the same if the company replaced its diesel trucks with battery-electric ones. This includes the cost of maintenance and insurance, as well as the cost of the vehicle (excluding the battery in the case of electric trucks). Drivers' salaries would also remain the same if charging took place during planned breaks. In addition, it is assumed that the second-hand value of the trucks would be comparable. The main differences would be the cost of diesel compared to the cost of electricity, as well as the cost of the battery, the grid connection, and the charger. In this paper, the costs are normalised and expressed in EUR per propulsion kilowatt-hour. The costs that would remain the same after the transition to battery-electric trucks are ignored since the company is interested in how the expenditure *changes*. In a recently published study [8], a cost function, f_{BEV}, for the battery-electric truck is presented as follows:

$$f_{BEV} = r_{ch} \cdot C_e + (1 - r_{ch}) \cdot C_{epub} + \frac{C_b}{\Gamma_b} + \frac{r_{ch} \cdot C_{ch}}{\Gamma_{ch}}, \tag{1}$$

where Γ_b is the battery utilisation factor and Γ_{ch} is the charger utilisation factor. The cost parameters in the above equation are defined in Table 2. The parameter r_{ch} is the ratio of the energy from private charging to the total amount of energy that is consumed by the truck over its service life. The table shows the parameter values used in this paper. These values are the same as those used in a previous study [8]. The first term describes the cost of electricity when charging with a private charger; the second term gives the cost of public fast charging; the third term expresses the battery cost; and the last term gives the combined cost of the charger and grid connection. The battery utilisation factor is defined as the total energy consumed by the battery over its service life divided by the battery capacity. The battery utilisation factor uses the dimensionless unit, the *equivalent full cycle* (EFC). The charger utilisation factor is defined as the total energy delivered by the charger over its service life divided by the maximum energy that it *can* deliver over its service life. Thus, the charger utilisation factor is a dimensionless scalar from 0% to 100%.

Table 2. Cost parameters and their values used in this study.

Parameters	Notation	Typical Value
Electricity Cost, Private Charging	C_e	0.08 EUR/kWh
Total Cost, Public Fast Charging	C_{epub}	0.4 EUR/kWh
Battery Cost	C_b	200 EUR/kWh
Service Life of Truck, Charger, and Battery	T	7 years
Combined Price for Charger and Grid	C_{ch}	117 EUR/kW/year

The cost function expresses the cost of *one* truck with *one* private charger. However, even if the company has many trucks, the above expression can still be used, as it is assumed that there are as many private chargers as trucks. The battery-electric propulsion cost (f_{BEV}) should be compared to the diesel propulsion cost, C_d, which is taken as 0.30 EUR/kWh, as in the above-mentioned study [8]. This corresponds to a diesel price of only 1.2 EUR/litre (excluding VAT) and a high power-train efficiency of 40%. The value of the diesel price is uncertain and most likely a bit too low, especially with the recent surge in diesel prices. However, it is possible that the current diesel price is only temporary. Furthermore, it is necessary to ensure that the reference value for diesel is not too high. If electric trucks can be shown to be competitive at the stated diesel price, then there is more certainty about this paper's conclusions. To calculate the cost function value, it is necessary to find the values of r_{ch} and the utilisation factors. These parameters depend on the charging strategy, as shown below.

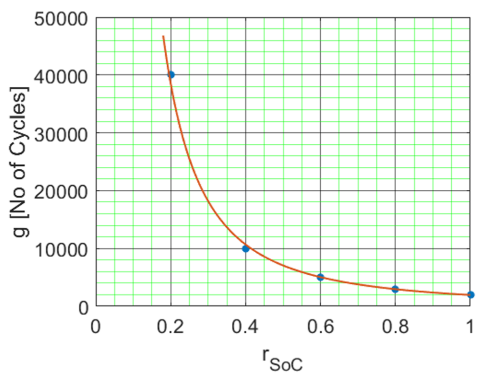
This case study assumes that the vehicle will have the same energy consumption throughout its service life. This allows the battery to be sized solely for this specific type of use. Due to battery ageing and safety margins, it is assumed that only a share of the battery capacity will be used. Let this share be r_{SoC} and the useful capacity B_{cu}. This can be expressed as:

$$B_{cu} = r_{SoC} \cdot B_c, \tag{2}$$

where B_c is the battery capacity. The number of possible charging cycles for a modern lithium battery is assumed to depend on r_{SoC} according to the table in Figure 2a. The exact number of lifetime cycles varies for different types of Li-ion cells but the general trends are the same, that is, the number of cycles increases faster than the decrease in cycle depth, resulting in a total life–energy throughput. This can be seen in studies such as [20]. The numbers used here are selected based on the tests and data sheets for several different Li-ion cells. The cycle life of the battery depends on many factors, for example, the temperature. It is assumed that the battery management system will keep the temperature in the allowed temperature range.

r_{SoC}	**No. Possible Charging Cycles**
0.2	40,000
0.4	10,000
0.6	5000
0.8	3000
1	2000

(**a**)



(**b**)

Figure 2. (**a**) The number of possible charging cycles for a modern lithium battery depending on the parameter r_{SoC}. (**b**) A power function $g(r_{SoC})$ is fitted to the table values and is indicated with blue dots.

So, how many cycles are needed during the battery's service life? The battery must be able to cover the distance $S/2$ without being charged. However, if the battery is too heavy, there is a risk of losing payload capacity. Therefore, a company's primary aim is to size the battery so that it just can handle the distance $S/2$ without charging. This means that the entire useful capacity must be charged at a rest area each day the truck is operating. Thus, each truck performs three charging cycles each weekday for seven years (the lifetime value of the battery according to Table 2), plus two extra charging cycles on the weekends 50 times per year. Thus, the number of charging cycles in the battery's service life, N_{cc}, can be determined as follows:

$$\begin{aligned} N_{cc} &= 3 \text{ cycles/day} \cdot 5 \text{ days/week} \cdot 52 \text{ weeks/year} \cdot 7 \text{ years} \\ &\quad + 2 \text{ cycles/day} \cdot 50 \text{ days/year} \cdot 7 \text{ year} = 6160 \text{ cycles.} \end{aligned} \tag{3}$$

Since the value did not match the table values in Figure 2a, a power function $g(r_{SoC}) = a \cdot r_{SoC}{}^{b}$ is fitted to the table values with the result $a = 1957.4$ and $b = -1.85127$ (see the red curve in Figure 2b). By solving the equation $g(r_{Soc}) = 6160$, we obtain the root:

$$r_{SoC} = 0.5383. \tag{4}$$

The required useful battery capacity is given by:

$$B_{cu} = \frac{\Delta E}{\Delta S} \cdot \frac{S}{2} = 412.5\ \text{kWh}. \tag{5}$$

This results in a battery capacity of:

$$B_c = \frac{B_{cu}}{r_{SoC}} = 766.3\ \text{kWh}. \tag{6}$$

The battery utilisation factor can now be calculated:

$$\Gamma_b = \frac{N_{cc} \cdot B_{cu}}{B_c} = 3316\ \text{EFC}, \tag{7}$$

which is a high value and results in a low battery cost. The reason for this high value is that the truck is driven in two shifts and often performs three charge and discharge cycles per day.

Since the price of the chargers and grid increases with the charger power, P_{ch}, private chargers should be as low-powered as possible. However, the charger must still be able to charge the useful capacity in the time T_1 and T_2 and, therefore:

$$P_{ch} = \frac{B_{cu}}{\min(T_1, T_2)} = 206.3\ \text{kW}. \tag{8}$$

In real life, there may be reasons to oversize the chargers slightly but this is not discussed here. From the definition of the charger utilisation factor, one obtains

$$\Gamma_{ch} = \frac{E_{ch}}{P_{ch} \cdot T}, \tag{9}$$

where E_{ch} is the total amount of energy delivered by the private charger over its service life. For the weekdays, the private charger must deliver enough energy for two cycles each day. For each of the weekend trips, the private charger must deliver enough energy for one cycle. This is because the battery's entire useful capacity will be charged at the rest area each day the truck is operating. Each cycle demands energy of $B_{cu} = 412.5$ kWh. Thus, the energy delivered by the private charger is given by:

$$\begin{aligned} E_{ch} = {} & 2\ \text{cycles/day} \cdot 5\ \text{days/week} \cdot 52\ \text{weeks/year} \cdot 7\ \text{years} \cdot 412.5\ \text{kWh/cycle} \\ & + 50\ \text{cycles/year} \cdot 7\ \text{years} \cdot 412.5\ \text{kWh/cycle} = 1.646 \cdot 10^6\ \text{kWh}. \end{aligned} \tag{10}$$

which gives:

$$\Gamma_{ch} = 13.01\%. \tag{11}$$

So far, the utilisation factors for the private chargers and batteries have been determined. It is now necessary to determine the value of r_{ch} to find the cost of battery-electric propulsion using Equation (1). Over its service life, a truck performs one day trip and one night trip every weekday for seven years. So, each weekday involves charging the entire useful capacity three times. The truck also performs 50 extra night trips per year, with each night trip resulting in the entire useful battery capacity being charged twice. Thus, the total energy consumed over a truck's service life is given as:

$$\begin{aligned} E_{tot} &= 3 \text{ cycles/day} \cdot 5 \text{ days/week} \cdot 52 \text{ weeks/year} \cdot 7 \text{ years} \cdot 412.5 \text{ kWh/cycle} \\ &+ 2 \text{ cycles/day} \cdot 50 \text{ days/year} \cdot 7 \text{ years} \cdot 412.5 \text{ kWh/cycle} = 2.541 \cdot 10^6 \text{ kWh}. \end{aligned} \tag{12}$$

Since r_{ch} is the energy charged using a private charger divided by the total energy consumed over the truck's service life, the result is:

$$r_{ch} = \frac{E_{ch}}{E_{tot}} = 0.6478. \tag{13}$$

Using this value, the values for the utilisation factors, and the values from Table 2 in Equation (1), the following cost-function value is obtained:

$$f_{BEV} = 0.32 \text{ EUR/kWh}. \tag{14}$$

By evaluating each term in Equation (1), the price of energy from private charging is 0.05 EUR/kWh, the price for public fast charging is 0.14 EUR/kWh, the battery price is 0.06 EUR/kWh, and the price of the private charger and grid is 0.07 EUR/kWh. Notice that these individual costs are now normalised per the *total energy* consumption and not the amount of energy from the respective chargers themselves. This means that fast charging that costs 0.4 EUR/kWh will cost 0.14 EUR/total kWh since only 35% of the total energy comes from fast charging.

Thus, these particular electric trucks have proven to be slightly more expensive than diesel trucks. The savings will be negative and the annual value is:

$$\text{BEV savings} = \frac{(C_d - f_{BEV}) \cdot N_{cc} \cdot B_{cu} \cdot 2N_{trucks}}{T} = -440{,}000 \text{ EUR/year}. \tag{15}$$

Since the above calculations indicate extra costs for the company, a more cost-efficient charging strategy should be used. In considering the above individual costs, it becomes apparent that the cost of public fast charging is by far the greatest. Is it possible to reduce this cost? Yes, if the trucks have batteries large enough to handle long night trips with less reliance on public fast charging. Even so, this will increase other costs such as the cost of a large battery. If all the day trips are viewed as one type of trip consuming energy B_{cu} and all the night trips as another type of trip consuming energy $2 \cdot B_{cu}$, the energy consumption for the trips can be presented in an *energy distribution diagram*, similar to that introduced in [8]. There are five daytime trips each week for seven years, resulting in 1820 day trips in a truck's service life and equally as many night trips during the week. However, an additional 50 night trips per year equates to 2170 night trips in a truck's service life. The energy distribution diagram for each truck is shown in Figure 3 and it is a "two-step rectangular" type [8].

It was shown in [8] that for a two-step rectangular energy distribution diagram, the lowest cost-function value is obtained either when the battery can handle the energy needs for the low-energy-consumption trips *or* when the battery is sufficiently large to handle the complete energy needs of all trips without being charged. A certain level of care must be exercised since the prerequisites of that analysis are not in complete agreement with those of this study. Nevertheless, the special case of a battery that can handle high-consumption trips still warrants investigation.

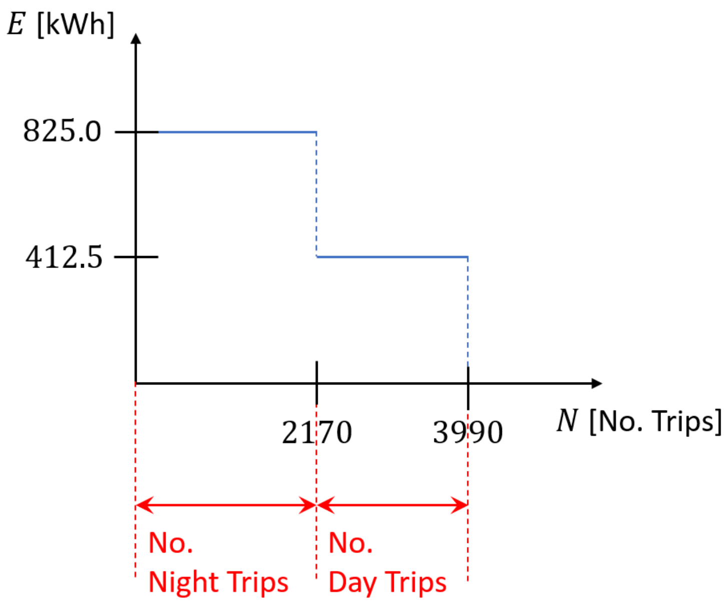


Figure 3. The energy distribution diagram for each truck.

For a large battery, the useful capacity must be able to handle an entire night trip without charging. Thus,

$$B_{cu} = \frac{\Delta E}{\Delta S} \cdot S = 825.0 \text{ kWh}. \tag{16}$$

The power of the charger must be considered, as it needs to meet the charging demand for a battery's entire useful capacity in time T_2 and half that capacity in time T_1. Again, this yields a charger power of:

$$P_{ch} = 206.3 \text{ kW}. \tag{17}$$

So, what value is reasonable for r_{SoC}? As seen in the energy distribution diagram in Figure 3, the battery must now perform 3990 cycles during its service life. Furthermore, 1820 of these will be half cycles. Thus, r_{SoC} may be set so that the battery can survive 3990 major cycles. This also gives an even better safety margin compared to the small battery. By solving the equation $g(r_{Soc}) = 3990$, the following root is obtained:

$$r_{SoC} = 0.6807. \tag{18}$$

This results in a battery capacity of:

$$B_c = \frac{B_{cu}}{r_{SoC}} = 1212 \text{ kWh}. \tag{19}$$

The battery utilisation factor is given by the total energy consumed by a truck over its service life divided by the battery capacity. The total energy consumed is obtained from the area under the curve in the energy distribution diagram in Figure 3. Thus,

$$\Gamma_b = \frac{(825.0 \text{ kWh} \cdot 2170 + 412.5 \text{ kWh} \cdot (3990 - 2170))}{1212 \text{ kWh}} = 2097 \text{ EFC}. \tag{20}$$

As expected, a lower value for the battery utilisation factor is obtained compared to a small battery. The result is a rising battery cost. The charger utilisation factor is defined as follows:

$$\Gamma_{ch} = \frac{E_{ch}}{P_{ch} \cdot T} = 20.09 \text{ \%}, \tag{21}$$

In this case, E_{ch} is all the energy consumed by the truck in its service life, as all the energy comes from a private charger. This also implies that $r_{ch} = 1$. The charger utilisation factor increases compared to a small battery. This is reasonable since the chargers (which have the same power) deliver more energy over their service life. By inserting the values of the utilisation factors r_{ch} and the values from Table 2 into Equation (1), we obtain:

$$f_{BEV} = 0.24 \text{ EUR/kWh}. \tag{22}$$

The largest cost is that of the battery, 0.10 EUR/kWh, followed by the cost of the energy from the private charger, 0.08 EUR/kWh; the cost of the private charger and grid, 0.07 EUR/kWh; and the cost of public fast charging 0 EUR/kWh. Due to rounding, the individual cost appears to total more than the overall cost. This charging strategy appears promising and the company's savings can now be calculated:

$$\text{BEV savings} = \frac{(C_d - f_{BEV}) \cdot E_{tot} \cdot 2N_{trucks}}{T} = 1{,}300{,}000 \text{ EUR/year}, \tag{23}$$

where E_{tot} is the total energy consumed by one truck over its service life. This is obtained from the area under the curve in the energy distribution diagram.

Firstly, the calculations show that under these circumstances, battery-electric trucks are competitive compared to diesel trucks. Secondly, it shows that the choice of battery capacity could have a major impact on the cost effectiveness of battery-electric trucks. Although the cost of the battery is large, the overall cost of ownership may be lowered by selecting a large battery, as the price of public fast charging may also be high. The trade-off between battery size and the share of public fast charging may be fairly simple to handle if the price picture and charging opportunities are known. However, there are more trade-offs to consider such as the trade-off between reduced costs and any losses in payload capacity. The potential cost of losing payload capacity is estimated in the next section.

4. Cost of Losing Payload Capacity

Since the calculations indicate that a large battery is cost effective, this section aims to estimate the cost of losing payload capacity. Note that the *maximum* extra cost calculated below is only valid *if* the trucks *always* carry the maximum weight. However, for most trucks, this is not the case. Even with large batteries, there are seldom any extra costs. It is often the volume of the truck that limits the payload and the truck may not even be full.

For batteries weighing up to 1.5 tonnes, it is assumed that there is no loss in payload capacity, whereas for heavier batteries, the loss of payload capacity equals the weight of the battery minus 1.5 tonnes (see Appendix A for more details). For increased readability and generality, let $m_0 = 1.5$ tonnes. The total cost of operation, C_{drive}, for a truck weighing 40 tonnes is about 0.9 EUR/kWh (see Appendix B for more details) and it has a payload capacity, m_{pl}, of 27 tonnes (see Appendix A). The battery capacity per ton, $B_{c/m}$, is 170 kWh/tonne (see Appendix C), which leads to a reduced payload capacity, m_{rpl}, of

$$m_{rpl} = \frac{B_c}{B_{c/m}} - m_0. \tag{24}$$

The reduction in the maximum payload is 3.0 tonnes for a small battery and 5.6 tonnes for a big battery. The new payload capacity, m_{npl}, is given by

$$m_{npl} = m_{pl} - m_{rpl}. \tag{25}$$

The ratio of the new required number of trucks to the number of trucks when there was no loss of payload capacity, r_t, can now be expressed as

$$r_t = \frac{m_{pl}}{m_{npl}}. \tag{26}$$

Finally, the maximum *extra* cost of losing payload capacity, C_{pl}^{max}, becomes

$$C_{pl}^{max} = C_{drive} \cdot r_t - C_{drive}, \tag{27}$$

and with the values for the small and large batteries, one obtains

$$\text{Small Battery:} \quad C_{pl}^{max} = 0.11 \text{ EUR/kWh}. \tag{28}$$

and

$$\text{Large Battery:} \quad C_{pl}^{max} = 0.24 \text{ EUR/kWh}. \tag{29}$$

Due to this potentially high indirect cost of large batteries, the company would likely prefer the small battery solution, provided that the price of public fast charging is low enough. Thus, the cost of a reduced payload will be high if the goods being transported are high-density items such as stone slabs. Equally, it might as well be zero if the goods being transported are low-density items such as bundles of tulips. Therefore, it can be concluded that due solely to the payload density, battery sizing may sometimes vary among trucks being driven on identical routes.

5. Number of Chargers and Price of Charging at the Fast Charging Station

The above calculations suggest that the haulage company would want its batteries to be sized to eliminate the need for public fast charging if the price of public fast charging is 0.4 EUR/kWh. Thus, it would be interesting to investigate whether the charge-point operator planning to install chargers in the rest area could lower their prices. The charger owner's costs comprise the costs of the electricity, chargers, and grid connection. As mentioned earlier, the costs of the charger and the grid are assumed to be proportional to the charge power and cost per kWh, f_{ch}, and can be expressed as

$$f_{ch} = C_e + \frac{C_{ch} \cdot P_{ch} \cdot T}{E_{ch}} = C_e + \frac{C_{ch}}{\Gamma_{ch}}. \tag{30}$$

Firstly, one may assume that the haulage company would fully charge its trucks at the rest area. The drivers have a 45-min break and this is the time each truck has for charging. So, how many chargers would be needed? Thirty trucks depart from each terminal at intervals of $T_{gap} = 7$ min, as the terminal and gate personnel do not have the capacity to send them off simultaneously. If the first two trucks leave Terminals A and B at 6 PM and then drive the $S/2 = 275$ km to the rest area at a mean speed of 75 km/h and charge for 45 min upon arrival, the number of charging trucks (as a function of time) can be determined through simulations. The results are presented in Figure 4.

When considering Figure 4, it may appear that 14 chargers would be sufficient. However, the results demand perfect timing with no delays. Therefore, it would be interesting to see what would happen if the trucks were delayed. The company claims that delays over 15 min are very rare. Thus, a new simulation was run in which it was possible to delay the trucks. For each truck, the delay was set as the magnitude of a random number drawn from a normal distribution with the expected value of zero minutes and a standard deviation of five minutes. Figure 5a shows the number of trucks charging for one night at the rest area as a function of time when the trucks are delayed. As seen in Figure 5a, the maximum number of chargers needed on this day was 15. It appears that the delay can increase the number of chargers needed to avoid queuing and further delays. Figure 5b shows a histogram in which the x-axis value represents the maximum number of chargers needed on one day and the height of the bar represents the number of such days that occur in a 10-year period (the trucks operate almost six nights per week). As seen in the histogram, for the selected model and parameter settings, 16 chargers are needed at the rest area. The fact that there is sometimes a demand for 17 chargers is not considered a problem, as this only happens twice a year. The results do *not* change significantly when the standard deviation is changed by ± 2 min.

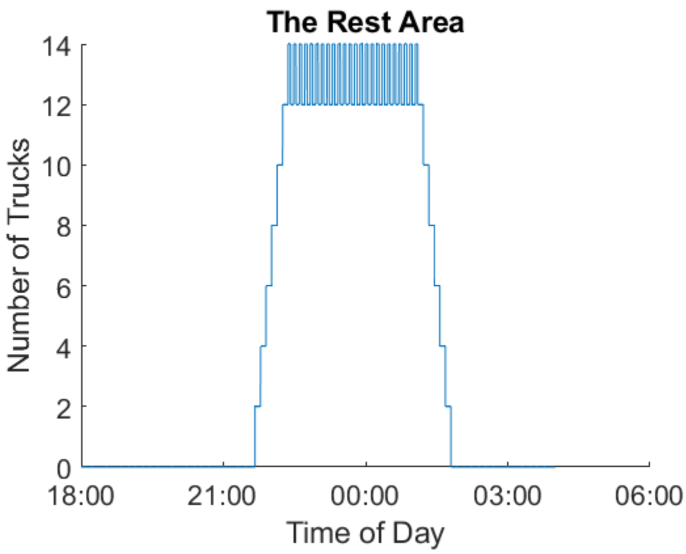
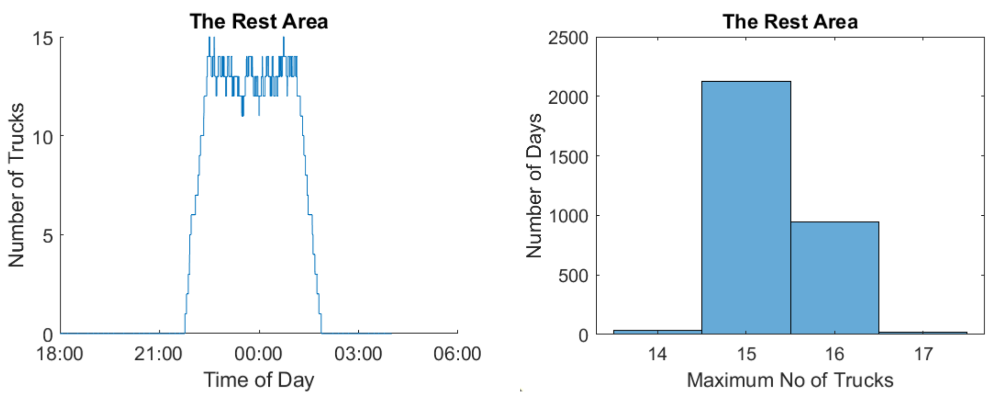


Figure 4. Number of charging trucks at the rest area at different times.



(**a**) (**b**)

Figure 5. (**a**) The number of charging trucks at the rest area at different times for a day when the trucks are delayed. (**b**) Number of days over a 10-year period when a specific number of chargers is needed.

The conclusion is that the number of chargers, N_{ch}, that should be installed at the rest area is

$$N_{ch} = 16. \tag{31}$$

Each charger must be able to charge a truck's entire useful capacity in time T_{break}. Thus,

$$P_{ch} = \frac{B_{cu}}{T_{break}} = \frac{412.5 \text{ kWh}}{0.75 \text{ h}} = 550 \text{ kW}. \tag{32}$$

Since the trucks charge their entire useful capacity five times per week for seven years, with 50 extra charges per year on the weekends, the chargers will deliver the following energy over their service life:

$$\begin{aligned} E_{ch} = 2N_{trucks} \cdot B_{cu} \cdot 7 \text{ years} \cdot (5 \text{ weeks}^{-1} \cdot 52 \text{ weeks/years} + 50 \text{ year}^{-1}) \\ = 5.371 \cdot 10^7 \text{ kWh}. \end{aligned} \tag{33}$$

and the charger utilisation factor becomes

$$\Gamma_{ch} = \frac{E_{ch}}{N_{ch} \cdot P_{ch} \cdot T} = 9.953 \text{ \%}. \tag{34}$$

So, if the charge-point operator has no customers other than the haulage company being studied, the cost of the chargers, according to Equation (30), will be

$$f_{ch} = 0.21 \text{ EUR/ kWh}. \tag{35}$$

It seems possible to lower the price from the originally intended 0.4 EUR/kWh. So, how low must the price be for the haulage company to consider using small batteries and fast charging for their entire useful capacity at a rest area? The company would probably select the smaller battery if it can achieve an equally low cost as large batteries, as increasing the payload capacity also offers gains. Thus, the required fast-charging price may be determined by solving the equation:

$$f_{BEV} = 0.24 \text{ EUR/kWh}, \tag{36}$$

using the values for the small batteries, as follows:

$$C_{epub} = \frac{0.24 \text{ EUR/kWh} - r_{ch} \cdot C_e - \frac{C_b}{\Gamma_b} - \frac{r_{ch} \cdot C_{ch}}{\Gamma_{ch}}}{1 - r_{ch}} = 0.17 \text{ EUR/kWh}. \tag{37}$$

Initially, this seems hard to achieve, as this value is below cost when the studied haulage company is the only user, as determined by Equation (35). However, as seen from Equation (30), the normalised cost to the charge-point operator strongly depends on the charger utilisation factor. Figure 6 shows f_{ch} as a function of Γ_{ch}.

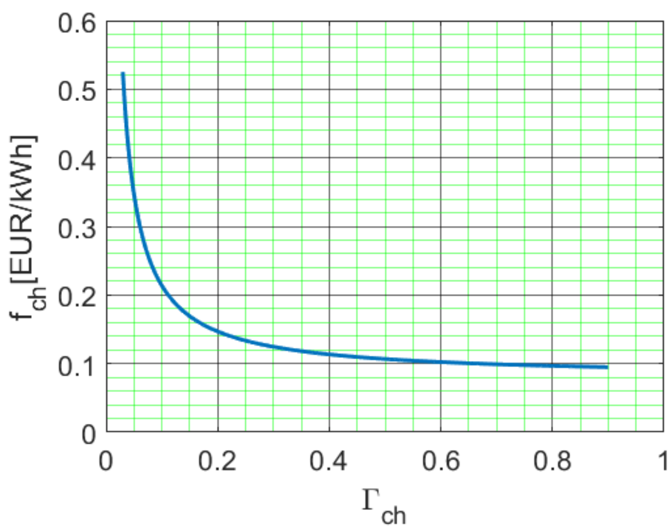


Figure 6. The normalised cost f_{ch} as a function of Γ_{ch}.

In Figure 6, it can be seen that the value of f_{ch} drops quickly for low and increasing values of the charger utilisation factor. Thus, it might be possible to have both profitable charging stations and cheap fast charging if the utilisation factor is sufficiently large. Based on the figure, it seems that roughly 20% or more should be considered "large". The figure shows that f_{ch} is a little below 0.17 EUR/kWh for higher charger utilisation factors. The treated haulage company occupies the chargers for less than four hours, which corresponds to 17% of the day. Since brief investigations from the available data [21] of the road midway between Helsingborg and Stockholm indicates that the traffic flow of heavy vehicles with trailers is quite even over the day, it should be possible to find other haulage companies with complementary driving patterns to the studied one. Consequently, it seems very likely that at least the same level of use of the chargers is possible by other companies during the remaining 83% of the day. Thus, we claim that the charger utilisation could be at least 20%, and Equation (30) then yields a cost of $f_{ch} = 0.15$ EUR/kWh. This could be low enough to be profitable. If, for example, a charger utilisation of 25% is reached, it would lead to

$f_{ch} = 0.13$ EUR/kWh, at which point the chargers appear profitable. However, even if we think it is realistic to reach a charger utilisation of at least 20%, it is important to clarify that the following paragraph relies on the assumption that the public chargers could reach a utilisation rate of at least 20%.

So, if the public fast chargers are utilised sufficiently, the haulage company will have a normalised cost for battery electric propulsion of 0.24 EUR/kWh, of which the cost for private charging is 0.05 EUR/kWh, the cost of the public fast charging is 0.06 EUR/kWh, the cost of the battery is 0.06 EUR/kWh, and the cost of the charger and grid is 0.07 EUR/kWh. The indirect cost of any loss of payload capacity would likely be low. The calculations presented in this paper strongly indicate that electric trucks would be more cost efficient than diesel trucks for haulage companies that have similar driving patterns to the company studied here and do not regularly carry heavy goods. Note that this might not be the case for haulage companies with driving patterns that deviate significantly from those in this paper, as the cost effectiveness of battery-electric trucks is heavily dependent on driving patterns [8]. However, the method presented in this paper can be used to evaluate the economic consequences for haulage companies that use other driving patterns. A more detailed description of the selection of a cost-effective battery size for different energy distribution diagrams was presented in [8].

If, however, the charge-point operator cannot offer public fast charging at a sufficiently low price due to problems related to reaching a high charger utilisation, the haulage company should go with the large battery, even if this scenario seems unlikely to the authors. In the worst-case scenario, when fast charging is expensive *and* the company regularly carries heavy goods, diesel trucks might be the most cost effective out of the analysed solutions.

It is also worth mentioning that since the studied haulage company uses almost 10% of the chargers' capacity, it may want to consider buying its own fast chargers and then selling charging services to others when the chargers are idle.

6. Selecting Total Power for a Fast-Charging Station

The previous section showed that to meet the demands of the haulage company, 16 chargers should be installed in the rest area. Fully meeting this demand is probably a given. The haulage company would be a key customer and charge a large amount of energy six days a week. However, the demand, for example, at lunchtime would likely be quite high, as many drivers probably have a scheduled break at that time. It then becomes a matter of whether it is cost effective to meet the peak demand for charging. If not, how much of the peak demand should be met? To investigate this, it was assumed that the time-variable demand for public fast charging could be estimated for a given fixed price level. In other words, the selected price does not vary over time. Since there is a discrete number of trucks needing to charge, it is natural to assume that the power demand for charging will be a step function of time, as in Figure 7a. If the power demand is arranged by magnitude over the service life of the chargers, the result is a diagram that we call *the power demand distribution* (see Figure 7b), where $P_1 > P_2 > ... > P_N$ represents the power demands of different durations according to the figure and $T_1 < T_2 < ... < T_N$. On the right-hand side of the figure, the red, striped area represents the energy that would be delivered by the chargers over their service lives for the selection $P_{ch} = P_{N-1}$.

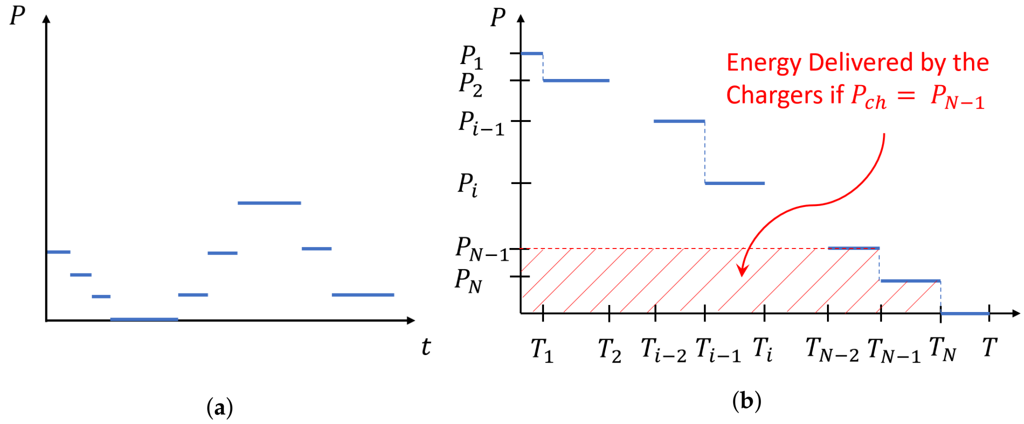


Figure 7. (**a**) The power demand from the chargers as a function of time. (**b**) The power demand distribution. Notice that the right-hand side shows the schematically sorted power demand over the entire service life of the chargers, whereas the left-hand side shows the unsorted demand over a shorter period.

The power demand , $P = P(t)$, can be expressed as

$$P = \begin{cases} P_1, & t \in [0, T_1] \\ P_2, & t \in (T_1, T_2] \\ \vdots & \vdots \\ P_{i-1}, & t \in (T_{i-2}, T_{i-1}] \\ P_i, & t \in (T_{i-1}, T_i] \\ \vdots & \vdots \\ P_N, & t \in (T_{N-1}, T_N] \\ 0, & t \in (T_N, T], \end{cases} \tag{38}$$

where T_N is the total duration in which there is a demand to use at least one charger. Thus, the notation $T_N = T_{use}$ is introduced.

To choose the total power of the charging station wisely, the profit, I, for the charge-point operator is now expressed as follows:

$$I = C_{epub} \cdot E_{ch} - C_e \cdot E_{ch} - C_{ch} \cdot T \cdot P_{ch}. \tag{39}$$

Note, that in this context, E_{ch} is the total energy delivered by the *charging station* over the service life of the chargers, P_{ch} is the total power of the charging station, and T is the service life of the chargers. In the above equation, the first term on the right-hand side is the total income of users over time T, the second term is the total cost of the electricity over time T, and the last term is the total cost of the chargers and the grid connection over time T. Let

$$C_{diff} = C_{epub} - C_e \tag{40}$$

and Equation (39) becomes

$$I = C_{diff} \cdot E_{ch} - C_{ch} \cdot T \cdot P_{ch}. \tag{41}$$

The charge-point operator can directly affect two of the parameters in Equation (41), namely C_{diff} by setting the price for public fast charging and P_{ch} by determining the total power of the chargers when investing in them. These choices will indirectly affect the total energy delivered by the chargers, E_{ch}. This is because the price for public fast charging will affect demand and the total power of the chargers will limit their capacity to deliver energy. Now, we investigate when the chargers are profitable and how to select their total power (number of chargers) and thus maximise the profits for the charge-point operator. Assume that a given fixed price level has resulted in a power demand distribution. From this distribution, the aim is to find the total power of the charging station, P_{ch}, to maximise the profits for the charge-point operator. Since the charge-point operator selects the number of chargers, it may be assumed that $P_{ch} = P_i$, where $i \in \{N+1, N, N-1, ..., 2, 1\}$. The case when $P_{N+1} = 0$ corresponds to there being no chargers at all, whereas $P_{ch} = P_1$ corresponds to the peak charging demand being met.

The energy delivered by the chargers over their service life is now limited by the values of $P(t)$ and $P_{ch} = P_n$. Thus, it is now clear that E_{ch} depends on n according to

$$E_{ch}(n) = \int_0^T \min(P_n, P(t))dt = \sum_{j=n}^{N} T_j(P_j - P_{j+1}), \tag{42}$$

which can be compared to the right-hand side of Figure 7b, with $n = N-1$. Now, $E_{ch}(n)$ can be inserted into Equation (41) to determine the profits, giving

$$I(n) = C_{diff} \cdot \left(\sum_{j=n}^{N} T_j(P_j - P_{j+1}) \right) - C_{ch} \cdot T \cdot P_n. \tag{43}$$

An adequate criterion for a profitable charger station is

$$I(N) > 0, \tag{44}$$

which means that

$$C_{diff} \cdot T_N \cdot (P_N - P_{N+1}) - C_{ch} \cdot T \cdot P_N > 0. \tag{45}$$

Since $P_{N+1} = 0$, $T_N = T_{use}$ and $P_N > 0$, we can write

$$\frac{T_{use}}{T} > \frac{C_{ch}}{C_{diff}}. \tag{46}$$

If the above inequality is satisfied, the chargers will be profitable when $P_{ch} = P_N$. If the inequality is satisfied, how can the chargers be even more profitable when $P_{ch} = P_{N-1}$? To investigate this, let us assume that the chargers are profitable for $P_{ch} = P_n$. Will the profits I then be larger if $P_{ch} = P_{n-1}$ is used? The answer is yes, if, and only if, the increase in the first term is larger than the increase in the second term in Equation (41). Thus, the profits when $P_{ch} = P_{n-1}$ increase compared to the profits when $P_{ch} = P_n$ if, and only if,

$$C_{diff} \cdot T_{n-1} \cdot (P_{n-1} - P_n) > C_{ch} \cdot T \cdot (P_{n-1} - P_n). \tag{47}$$

Since $P_{n-1} - P_n > 0$, this is equivalent to

$$\frac{T_{n-1}}{T} > \frac{C_{ch}}{C_{diff}}. \tag{48}$$

However, if the inequality is *not* satisfied, the income will decrease if P_{ch} is allowed to assume even higher values than P_{n-1}, for example, P_q, where $q < n-1$, since the same procedure would lead to increased profits when $P_{ch} = P_q$ compared to the profits when $P_{ch} = P_n$ if, and only if,

$$C_{diff} \cdot T_q \cdot (P_q - P_n) > C_{ch} \cdot T \cdot (P_q - P_n). \tag{49}$$

As before, since $P_q - P_n > 0$, this is equivalent to

$$\frac{T_q}{T} > \frac{C_{ch}}{C_{diff}}. \tag{50}$$

However, since the inequality Equation (48) was not satisfied, will this one will also not be satisfied, as $T_q < T_{n-1}$. Thus, the above calculations and mathematical induction allow us to conclude that

$$\text{the chargers are profitable} \iff \frac{T_{use}}{T} > \frac{C_{ch}}{C_{diff}}, \tag{51}$$

and to maximise the profits for the charge-point operator (and assuming the chargers are profitable), the charger power $P_{ch} = P_k$ should be chosen such that

$$\frac{T_k}{T} > \frac{C_{ch}}{C_{diff}}, \tag{52}$$

where k is the smallest integer in the set $[1, N]$ that fulfils the inequality. It appears that the power of the chargers would only meet the full demand if the highest power is used for a sufficiently long time. With the different values used in this paper, the peak demand must last for 4% of the service life of the chargers if the price of public fast charging is 0.4 EUR/kWh or 15% if the price is 0.17 EUR/kWh. It is worth mentioning that the sole aim of this calculation is to maximise the profits for a given power demand distribution when public fast-charging prices are fixed. However, it does not consider effects such as losing a customer to a competitor with more chargers available or the loss of all charging undertaken by that customer, not just the peak-time charging.

7. Discussion

This paper shows that long-haul battery-electric trucks can compete with diesel trucks, even if the price of diesel fuel is only 1.2 EUR/litre (excluding VAT), and even more so if the price of diesel fuel stays at the current high level of 1.8 EUR/litre. However, what makes the problem complex is the difficulty of determining the battery capacity and charging strategy if there is significant price uncertainty in public fast charging. At the same time, it is hard to set public fast-charging prices without knowing how much the chargers will be used. Additionally, the investment made by one party can be risky if the other party changes its strategy. For example, if a haulier starts buying larger batteries, the need for public fast charging may greatly diminish, which is bad for the charge-point operator. Similarly, if the haulier has chosen small batteries, a price rise in public fast charging will be problematic. However, what benefits the transition from diesel trucks to battery-electric trucks is that these problems will likely decrease over time. This is because charging in the long run will be a very competitive business with few entry barriers. However, during a rapid transition, the competition may be weaker since there are some additional entry barriers such as high investment risks during a turbulent industry transition, a temporary lack of available grid capacity, and long installation waiting times. However, the more common battery electric trucks and vehicles become, the easier it will be to achieve high charger utilisation factors and thus lower public fast-charging prices. Furthermore, the price picture will probably change in favour of battery-electric trucks due to increased production volumes and technological advancements. Figure 8 compares the costs of the main alternatives for the studied haulage company. In the figure, all the values are in EUR/kWh and the bar height represents the total cost of a given strategy. The indirect cost of a reduced payload is not included, as this depends on the type of goods being transported. This can vary from zero to the values estimated in this paper. (The individual costs of the battery-electric truck with a large battery seem to add up to more than the total cost, but this is due to rounding.) As stated earlier, the haulier is likely to select the strategy represented by the fourth bar. Provided a low price for fast charging can be secured, this will make the cost of propulsion energy lower than the cost of current diesel trucks. Additionally, there will be less of a reduction in the payload capacity compared to the large battery strategy.

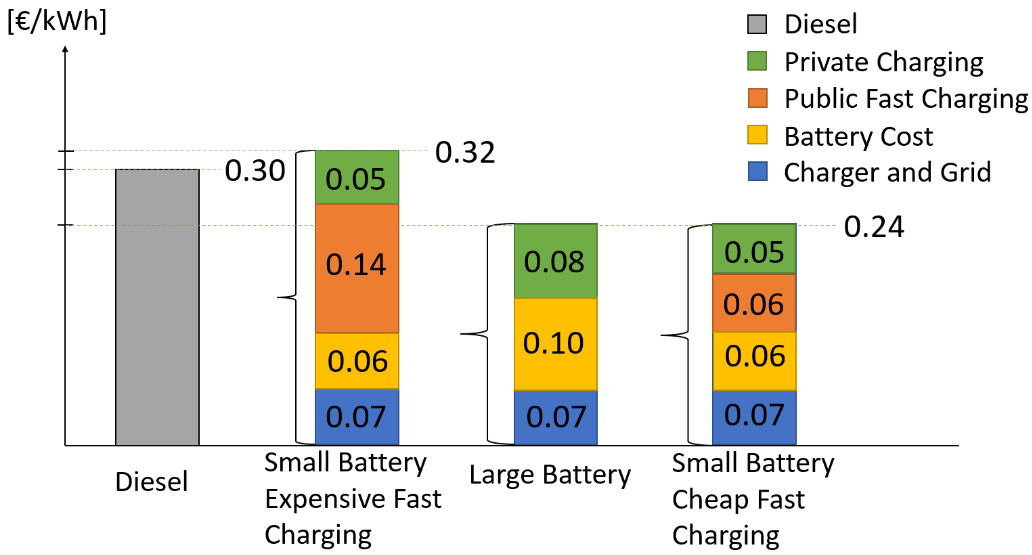


Figure 8. Cost of alternative strategies for the studied haulage company, in EUR/kWh. (The individual costs of the battery electric truck with a large battery seem to add up to more than the total cost, but this is due to rounding).

In the previous section, the price of electricity and public fast charging was assumed to be fixed. However, is it likely that a charge-point operator will have a fixed price for their users? Maybe not. In reality, the demand for charging power will vary over time, which can be demonstrated using a demand power distribution such as the one in Figure 9a. This illustrates that for $t \in [0, T_1)$, there is a much greater demand than the charging station can supply. This means that the charge-point operator has an opportunity to increase the price of public fast charging and still sells the same amount of energy but increases the profits. It may also be possible to move users from rush hour to other times by setting a higher price during rush hour and a lower price at other times (see Figure 9a,b). The mean value of the difference in price for public fast charging and electricity may even be the same but, due to the increase in E_{ch}, the profits will still increase. Again, consider Figure 9 as an example. It may be argued that time-variable pricing will also benefit users, as it allows fast charging to be offered exactly when it is needed by those who really need it and can pay for it. It also means that users who move to other charging times will be rewarded with lower prices. How to select a price for public fast charging is a very complex question and requires a thorough investigation of its own. It is not possible to predict charging prices based on this brief analysis. Still, this analysis shows that a low price seems achievable. It also highlights the many ways in which pricing and the haulier's charging strategy can be changed to increase charger utilisation and facilitate even lower prices.

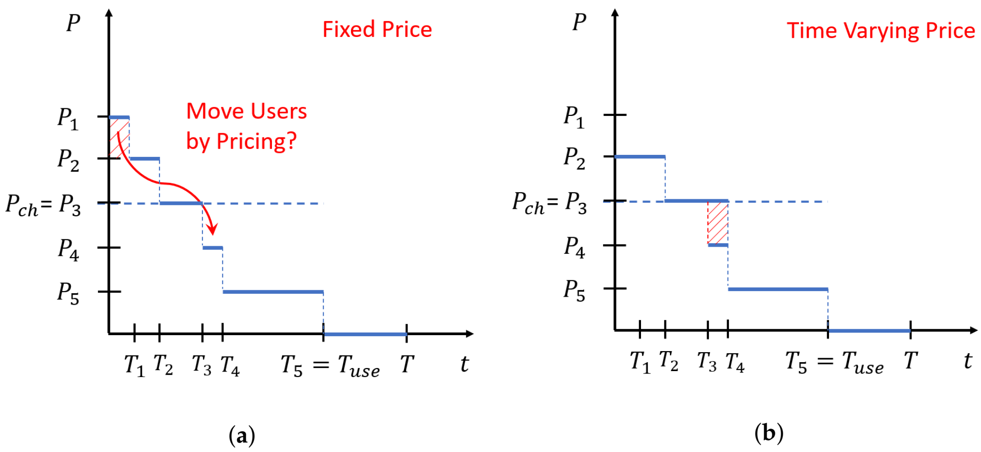


Figure 9. Example of charging power demand distribution. (**a**) The original demand. (**b**) A more even demand, with the price adjusted to reflect the demand. Thus, time-variable pricing may lead to greater charger utilisation.

8. Conclusions

Based on the above analysis, the following conclusions can be drawn for the type of long-haul trucks studied in this paper.

- Battery-electric trucks with driving patterns similar to those of the haulage company studied in this paper appear to be more cost effective than today's diesel trucks, at least if they do not regularly carry heavy goods. One reason for the competitiveness of electric line-haul trucks is that they have a high level of battery utilisation and can be charged during mandatory breaks.
- The study indicates that the main uncertainty factors (in terms of knowing what charging strategy to use) are the price of public charging and the density of the goods.
- The choice of battery capacity is strongly influenced by the price of public fast charging. For the case studied in this paper, the price of fast charging has to be 0.17 EUR/kWh if the haulier chooses the small battery rather than the large one. The size of the battery could have a significant impact on the total cost of ownership.
- The cost per kWh for public fast charging drops significantly as charger utilisation increases. A charger utilisation factor of approximately 20–25% should be sufficient to offer fast charging at a low price such as 0.17 EUR/kWh.
- The ratio $\frac{C_{ch}}{C_{diff}}$ is an important parameter when analysing the profits of a charge-point operator, where C_{ch} is the combined cost parameter of the charger and grid and C_{diff} is the difference between the price of public fast charging and the price of electricity. This is intuitive since the profits increase with C_{diff} but decrease with C_{ch}. With the values used in this paper, the ratio ranges from 4 to 15%. This range is caused by the price uncertainty of public fast charging.
- For public fast charging at fixed prices, a charge-point operator can only be profitable if, and only if, the demand for charging (expressed as a share of the service life of the chargers) exceeds $\frac{C_{ch}}{C_{diff}}$.
- For public fast charging at fixed prices, the charge-point operator cannot meet the peak demand for charging in order to maximise profits. The only exception to this is when the share of the peak-time demand equals at least $\frac{C_{ch}}{C_{diff}}$ of the service life of the chargers.
- If the chargers can be profitable for a given demand power distribution, the profits of the charge-point operator (at a fixed price) can be maximised according to the procedure described in Section 6.

9. Future Work

This paper shows that cheap public fast charging is possible if the charger utilisation is high. Naturally, a high level of charger utilisation can lead to extensive problems with queuing at charger stations. Thus, an important question for future research is whether high levels of charger utilisation can be achieved while also having high levels of charger availability at fast-charging stations.

This paper also shows that the indirect cost of a reduced payload can vary from zero to very high values. This indicates that different types of transport on the same route can select different charging strategies or favour, for example, hydrogen fuel-cell powertrains. It will be crucial to investigate which types of transport are likely to use the different solutions.

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Abbreviations

The following abbreviations were used in this manuscript:

BEV	Battery-electric vehicle
EFC	Equivalent full cycle

Nomenclature

B_c	Battery capacity (kWh)
$B_{c/m}$	Battery capacity per tonne (kWh/ton)
B_{cu}	Useful battery capacity (kWh)
C_b	Battery cost (EUR/kWh)
C_{ch}	Combined price for charger and grid (EUR/kW/year)
C_d	Diesel cost (EUR/kWh)
C_{diff}	Difference in price between public fast charging and electricity (EUR/kWh)
C_{drive}	Cost of driving a 40-tonne truck (EUR/kWh)
C_e	Electricity cost, private charging (EUR/kWh)
C_{epub}	Electricity cost, public fast charging (EUR/kWh)
C_{pl}^{max}	The maximum extra cost of losing payload capacity (EUR/kWh)
$\frac{\Delta E}{\Delta x}$	The trucks' energy consumption (kWh/km)
E_{ch}	The total energy delivered over the service life of the chargers (kWh)
E_{tot}	Total propulsion energy consumed over a truck's service life (kWh)
f_{BEV}	Cost function for the trucks (EUR/kWh)
f_{ch}	Cost function for the fast chargers (EUR/kWh)
$g(r_{SoC})$	Number of possible charging cycles for the battery (—)
Γ_b	Battery utilisation factor (equivalent full cycles)
Γ_{ch}	Charger utilisation factor (—)
I	The profit for the charge-point operator over time T (EUR)
m_0	Battery weight limit for loss of payload (tonne)

m_{npl}	New payload capacity (tonne)
m_{pl}	Payload capacity for a 40-tonne truck (tonne)
m_{rpl}	Reduced payload capacity (tonne)
N_{cc}	Number of charging cycles in the battery's service life (—)
N_{ch}	Number of chargers in the rest area (—)
N_{trucks}	Number of trucks leaving from each terminal (—)
P_{ch}	Charger power (kW)
$P_(t)$	Demand power (kW)
r_{ch}	Ratio of private charging to the total amount of energy (—)
r_{SoC}	Share of battery capacity that could be used (—)
r_t	Ratio of the number of new trucks to the number when there was no loss of payload capacity (—)
S	Distance between terminals (km)
T	Service life of truck, charger, and battery (year)
T_1	Idle time for the trucks in the afternoon (hours)
T_2	Idle time for the trucks in the morning (hours)
T_{break}	Duration of the drivers' breaks (minutes)
T_{drive}	Annual driving time for the trucks (hours)
T_{gap}	Time interval between trucks (minutes)
T_{use}	Time when there is demand for at least one charge (years)
$\overline{v}$	Mean speed of the trucks (km/h)

Appendix A

This appendix estimates the payload of a diesel semi-truck and then estimates the weight difference between an electric and a diesel truck to find out how much the maximum payload is reduced by the battery weight.

A conventional diesel 4 × 2 tractor weighs about 6.5 tonnes [22] and an empty semi-trailer also weighs 6.5 tonnes [23]. Since the maximum gross weight is 40 tonnes, the diesel semi-truck can have a maximum payload of 27 tonnes.

The weight difference between a diesel powertrain and an electric powertrain can be estimated based on the weight of the main powertrain components.

Diesel powertrain components:	
Engine with fluids (Volvo D13) [24]	1182 kg
Gearbox with oil (Volvo I-shift AT2812 with crawler gears) [25]	339 kg
Diesel tank (600 l diesel + 40 kg tank)	550 kg
Ad-blue tank (50 l @ 1.09 kg/L)	55 kg
Exhaust after-treatment system (not included)	-
Total Weight	2.1 tonnes

Electric powertrain components (excl. battery):	
Electric motor—325 kW continuous power (436 hp)	425 kg
(based on DANA HD HV3500-9p [26], but 125% bigger)	
2-speed Gearbox for electric motor	150 kg
(estimated from picture of gearbox for Volvo VNR electric)	
Power electronic inverter	
(based on DANA TM4 CO300 [26], but 140% bigger	50 kg
Total Weight	0.6 tonnes

The diesel powertrain weighs 1.5 tonnes more than the electric powertrain, excluding the battery. Therefore, the payload is reduced if the battery weight exceeds 1.5 tonnes.

Appendix B

The cost of reducing the payload capacity can be estimated if one assumes that the reduced payload results in needing more trucks to transport goods. For example, if the truck can only carry 90% of the load, there will be a need for 1/90% = 111% of the original number of trucks to transport the same amount of goods.

The total cost to operate a truck is estimated to be 90 EUR/h, including the salary, vehicle depreciation, maintenance, insurance, and fuel cost. Since the truck consumes about 100 kW, on average, while driving, the specific total cost translates into 0.9 EUR/kWh. If 11% more trucks are needed, it would correspond to an indirect cost of 11% $\cdot$ 0.9 EUR/kWh = 0.1 EUR/kWh.

Appendix C

A complete battery pack, including, for example, the housing, battery management system, cooling, and heating, is assumed to have an energy density of 170 Wh per kg of total pack weight.

This is very similar to a new electric car such as a VW ID.4, which has a nominal capacity of 82 kWh and a battery pack weight of 489 kg [27], resulting in 168 Wh/kg.

Volvo trucks do not provide exact specifications for their battery modules but their 90 kWh module is said to weigh about 500 kg [28], which would correspond to 180 Wh/kg.

Appendix D

A working paper by the International Council on Clean Transportation [29] predicts a battery pack cost of 120 USD/kWh in 2030 and an indirect cost multiplier of 36.8% to cover the warranty- and battery-related costs of the vehicle manufacturer. This results in a cost of 164 USD/kWh, or 155 EUR/kWh, to the vehicle customer. The estimate used in this paper, that is, 200 EUR/kWh, is thus a conservative estimate for 2030 and may be reached earlier than this.

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Article

Agent-based Investigation of Charger Queues and Utilization of Public Chargers for Electric Long-haul Trucks (Submitted)

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Abstract: This paper investigates the charging needs and charger utilisation of a system of battery electric trucks and their public fast chargers, along the highway between the Swedish cities of Helsingborg and Stockholm, in a possible future scenario in which all trucks are battery electric. The system is investigated via an agent-based model which simulates a typical day with current levels of truck traffic on the road. The traffic flow is based on hourly truck flow data during a day and the annual flow of trucks. The findings indicate major potential for a well-functioning system of public chargers for trucks, with high utilisation, few queuing problems at charging stations, cheap public fast charging and a robust response to queues caused by peaks or increases in the traffic flow. The number of 900 kW chargers along the road needed to achieve this has been estimated at 140 and the utilisation factor for the chargers is predicted to be 30%.

Keywords: battery electric truck; battery electric vehicle; charger utilisation; charging station; charge point operator; long-haul truck; agent-based model

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1. Introduction

The combustion of fossil fuels has severe disadvantages. The oil depletion time is less than 30 years [1], the earth's climate system has likely been affected [2] and negative health impacts are expressed in the literature [3]. Part of the solution is to stop running trucks on fossil fuels. Several studies have concluded that battery electric trucks could become a cost-efficient, fossil-free alternative to today's commercial diesel trucks [4][5][6][7][8]. However, it is important to bear in mind that the cost-effectiveness of battery electric trucks is sensitive to driving patterns [4][9] and that relatively uniform driving patterns are best suited to electrification [4][10]. Another possible solution is hydrogen trucks but recently published studies favour battery electric ones [11][12]. The feasibility of battery electric trucks seems promising but fuel cells might be better for heavy-duty trucks on extra long journeys [13]. Thus, there is no unambiguous answer to the question of which power train results in the lowest total cost of ownership; this will depend on how the vehicle is used [14]. The literature also highlights other important factors for cost-effective battery electric vehicles, such as the battery price [15][16] and size [4][17]. Moreover, the price of public fast charging could strongly impact the cost-effectiveness, battery sizing and charging strategy [5]. The charger utilisation must be high enough for the installation to be worthwhile [18] and is a prerequisite for cheap public fast charging [5]. Some advantages of increased fees during rush hours were presented in a previous study [19], including a better meeting of demand, avoiding queues and increased profit. But is it possible to achieve high charger utilisation and simultaneously high charger availability? This question was highlighted as important to future research in a recently published study [5] and will be investigated in the present one.

This paper aims to investigate the charging need, the utilisation of public fast chargers and the potential queuing problems at charging stations along the highway between the Swedish cities of Helsingborg and Stockholm, if all trucks currently driving on that road were battery electric. Helsingborg is located on Sweden's west coast, while Stockholm (the capital) is located on the east coast. The two cities are connected by the E4 highway and the distance between them is given as 553 km by Google Maps, with the E4 shown as a wavy blue line on the map in Figure 1. The investigations were made using an agent-based model in which each truck counts as one agent. Each truck will have a starting location with a set departure time and state of charge (SoC), plus a set destination with a required SoC upon reaching it. However, the agents will choose where to charge according to a set of rules. This paper focuses on analysing long-haul trucks and is only them we mean when referring to "traffic flow". Where the trucks start and stop, when they start and how many there are has been derived from data from the Swedish Transport Administration [20]. The aim is for this traffic flow to approximate the traffic flow for a typical weekday. The data, the traffic flow produced and the agent-based model will be presented in detail in subsequent sections. An agent-based model was used because it is hard to determine the outcome on a system level from a macroscopic model but much easier to set up reasonable rules for each truck. The agent-based model provides an opportunity to obtain macroscopic results and draw system conclusions just by designing rules on the microscopic level.

The main results of this paper are that the future system of electric trucks and charging stations along the studied road apparently has the potential to charge all the trucks with a high charger utilisation rate, few problems with queuing and robustness concerning increased traffic flow or unexpected peaks.

Figure 1. The highway between Helsingborg and Stockholm marked with blue, the map is from openstreetmaps.org.

2. Traffic Flow Used for the Simulations

2.1. Traffic Flow for a Typical Day

To investigate the charging trucks, a traffic flow was created between Helsingborg and Stockholm. The aim was to represent the flow of long-haul trucks on a typical weekday. It was assumed that trucks can only enter or leave the road at points where the larger roads intersect with the road being investigated, i.e. at Helsingborg, Jönköping, Mjölby, Linköping, Norrköping, Södertälje and Stockholm. Since some of these cities are geographically close to each other, Mjölby, Linköping and Norrköping were regarded as one city located at Linköping, while Södertälje and Stockholm are seen as one city located at Stockholm, see the black dots in Figure 2. Thus, one may regard the road as being divided into three sections: Section 1 between Helsingborg and Jönköping, Section 2 between Jönköping and Linköping and Section 3 between Linköping and Stockholm, again see Figure 2. The traffic flow was created with respect to data from Trafikverket (the Swedish Transport Administration) [20] and the method is presented in Appendix A. The measurement points for the data were at the minor municipalities of Ljungby (Section 1), Gränna (Section 2) and Tystberga (Section 3). If the origin of the one-dimensional highway described above is placed at Helsingborg, the locations of the important cities and measurement stations can be found using Google Maps, see Table 1.

Table 1. Location of the cities and measurement stations.

City/measurement station	Location [km]
Helsingborg	0
Ljungby	134
Jönköping	228
Gränna	265
Linköping	355
Tystberga	470
Södertälje/Stockholm	553

The number of trucks starting at each city and their destination used for the simulations are shown in Table 2. Note that all 4,355 trucks (the sum of the left-hand column in the table) depart on a typical day. The rationale for this set-up is explained in Appendix A.

Table 2. Setup for the traffic flow.

Start city, no. Trucks	Destination Helsingborg, no. trucks	Destination Jönköping, no. trucks	Destination Linköping, no. trucks	Destination Stockholm, no. trucks
Helsingborg, 1464	-	381	520	563
Jönköping, 909	463	-	221	225
Linköping, 1063	621	199	-	243
Stockholm, 919	388	150	381	-

This will result in a traffic flow according to Figure 2, which is consistent with the data used.

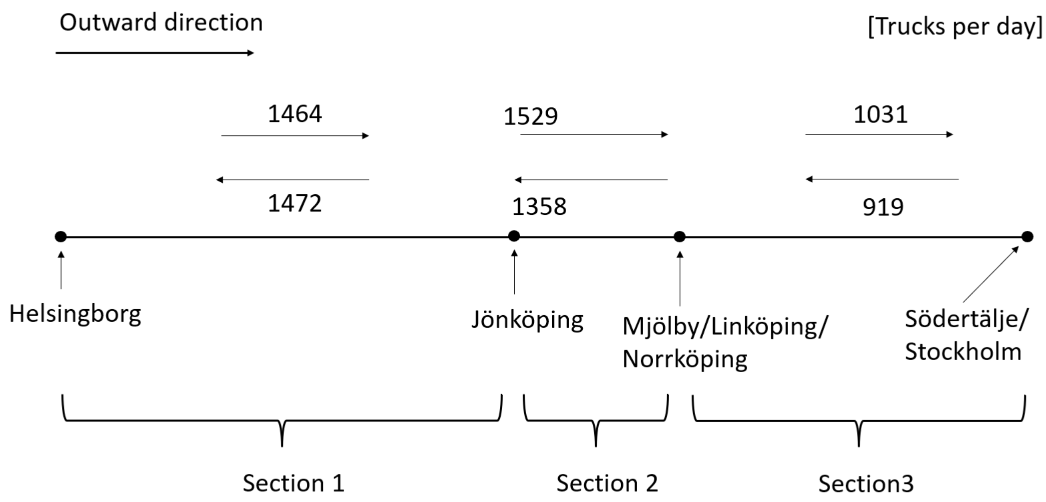
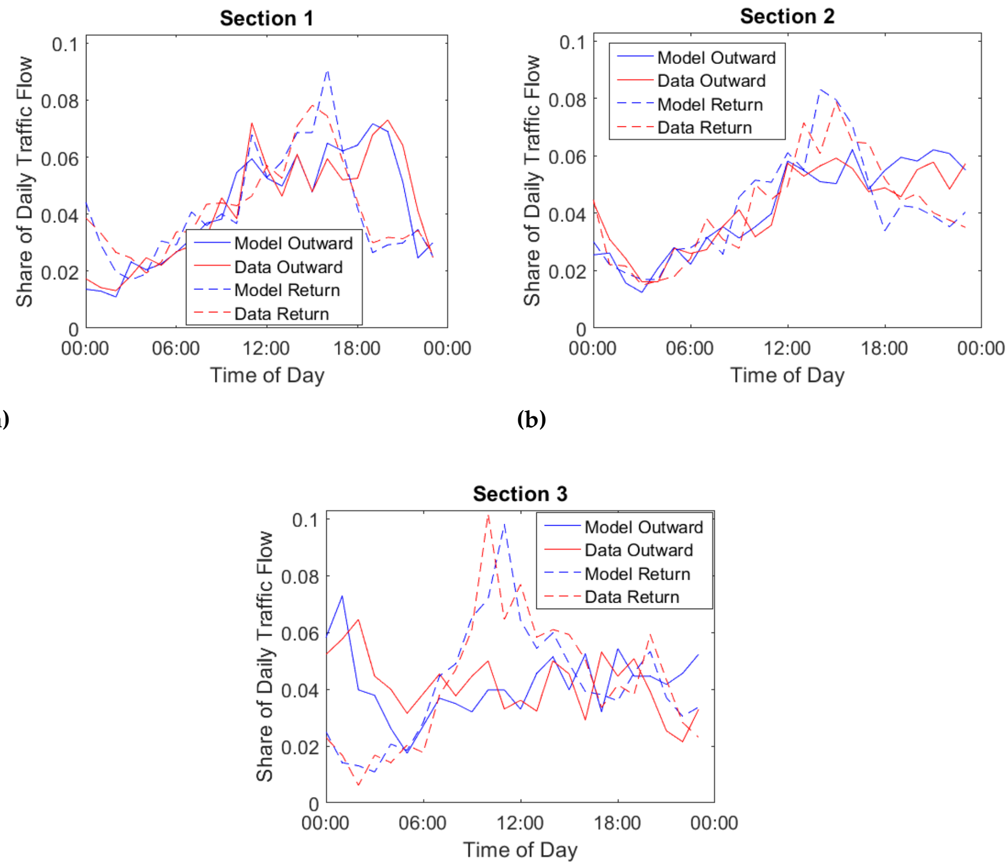


Figure 2. Traffic flow along the studied road for a typical day.

2.2. Time Variations of the Traffic Flow during a Typical Day

To create reasonable departure times for the trucks, available data [20] has been used for six days of traffic flow at the three sections. For these days, the hourly traffic flow is available during the course of a day. Unfortunately, data for the same day was not available for all the locations. However, for the analysis in this paper, it is assumed that this may be taken as reflecting just one day. The red curves in Figure 3 show the data that was used. This data is normalised to show the share of daily traffic flow as a function of time. Figure 3a shows the data for Section 1, Figure 3b shows the data for Section 2 and Figure 3c shows the data for Section 3.

Based on this data, minute-precise departure times were created for the trucks. The blue curves in Figure 3 correspond to the flow that would arise in the model if the departure time was rounded to hours and the trucks travelled at a constant speed $v = 75$ km/h. Note that the actual flows in the simulations will deviate from the blue curves due to breaks for charging and possible queuing at charging stations. A more detailed description of the method is given in Appendix A.



(a) **(b)** **(c)**

Figure 3. The share of daily traffic flow for each section in the outward and return directions. The blue curves correspond to the flow that would arise in the model if the trucks only drove at a constant speed $v = 75$ km/h without charging. (**a**) The flow in Section 1. (**b**) The flow in Section 2. (**c**) The flow in Section 3.

The number of trucks starting at each city, plus their destination and departure times are now set. The only remaining data for the simulation is the state of charge (SoC) when the trucks set out and the SoC they should have at their destinations. In this paper, all state-of-charge values in per cent refer to the *usable* state-of-charge window, and not the actual percentage of the batteries' total capacity. The starting SoC is drawn from a uniform random distribution in the interval [50%, 100%] and the required SoC at the destination is drawn from a uniform random distribution in the interval [0%, 40%]. This set-up is hopefully representative of a typical weekday on the road. However, it is important to bear in mind that it is only an estimate and that, good or bad, real traffic will differ from this set-up. There will probably be some days with more traffic and some with less. The traffic flow will likely vary more at some times and less at others. This will influence the results of the simulations and is also investigated and discussed in this paper.

3. Description of the agent-based model

3.1. Assumptions

The model tries to predict how battery electric trucks will charge on the highway between Helsingborg on Sweden's west coast and Stockholm on its east cost. However, the problem only considers one road and does not consider the full road network. This is necessary and reasonable in order to keep the scope of the problem reasonable and to expend a sensible amount of work investigating it. Limiting the problem also makes it easier to explore basic behaviour. The road has a length of $S = 553$ km. All the trucks in the simulation have a useful battery capacity of $B_{cu} = 500$ kWh, a speed of $v = 75$ km/h and an energy consumption of $\frac{\Delta E}{\Delta x} = 1.5$ kWh/km. To ensure good initial conditions, the model is run through a typical day twice, starting with empty charging stations. The results presented are from the second of the two days. The prices for charging are the same for the two days and for the day after the second day (some of the trucks will decide whether to charge at the end of the typical day or at the beginning of the next day). Each truck in the simulation has a starting location and a destination in Helsingborg, Jönköping, Linköping or Stockholm. Each truck enters the highway at a certain time with a certain SoC and has an individual SoC requirement at its destination. However, none of the trucks enter the highway with less than 50% SoC and no truck has to have more than 40% remaining SoC when it exits the highway. The aim is to represent a typical weekday; the traffic flow used in the simulation was presented in the previous section.

In reality, there are laws controlling how long drivers can drive. For example, drivers must take a break after no more than 4.5 hours of driving. This constraint is not implemented in the model but, with the selected battery size, the truck cannot run for more than 4.5 hours without charging.

There are charging stations along the road and the number of charging stations, their location and the individual number of chargers at each station varies from simulation to simulation. The price for charging depends on the station and the time but has been set at the same value in almost all simulations. However, in all simulations will have at least three charging stations along the way and these will be uniformly distributed along the highway. In this paper, all the chargers have a power $P = 700$ kW. It is assumed that this power can be used for all trucks regardless of SoC. This implies that a truck will charge its whole useful capacity in 43 minutes.

3.2. The Charging behaviour of the Trucks

In the simulation, each truck (i.e. each agent) will act according to the following rules:

1. The trucks will only charge when they need to complete their mission and only what is necessary to have the required SoC at their destination.
2. The trucks will not charge more times than necessary. Taken with the assumptions presented earlier, this implies that none of the trucks will charge more than twice. The assumptions also prevent a truck from reaching zero SoC before it reaches a charging station.
3. If a truck needs to charge twice, it will take a full charge the first time.
4. A truck arriving to charge at a charging station, will continue to the next charging station if there are too many queuing trucks and if it is able. A queue is deemed too long if the ratio of queuing trucks divided by the total number of chargers at the station is greater than the parameter $r_{queuing}$.
5. Trucks that can choose between stations while following the above rules will choose to charge at the lowest cost. Trucks that charge twice minimise the cost of the first charge. If the price at the two stations is the same the truck selects the nearest one.

3.3. Algorithm Description

Firstly, by studying the most extreme trip possible under the assumptions, it is established that no truck has to charge more than twice. The truck starts in Helsingborg with 50% SoC and should reach Stockholm with 40% SoC. According to the assumptions there must be at least stations at the 138 km, 276 km and 414 km locations. The truck starts at location 0 km and can drive the distance $50\% \cdot B_{cu} / \frac{dE}{dx} = 167$ km. This means it reaches the first station, where it charges to 100% SoC. The truck can now drive the distance $B_{cu} / \frac{dE}{dx} = 333$ km without charging, which means that it will reach the station at the 414 km location. At this station it can, if necessary, charge to 100% SoC again. So the truck needs $(S - 414 \text{ km}) \cdot \frac{dE}{dx} = 209$ kWh of energy to drive to Stockholm from the station. Arriving in Stockholm it should then have $40\% \cdot B_{cu} = 200$ kWh of energy stored in the battery, thus it must leave the station with energy of $209 + 200 = 409$ kWh stored in its battery. Hence, no truck has to charge more the twice.

Before the simulations, it is determined whether each truck can avoid charging or whether it will have to charge once or twice. This is determined as follows. Firstly, the energy the truck is allowed to use without charging is determined as the difference between the starting SoC and the required destination SoC, multiplied by the useful battery capacity. If this energy is greater than needed for the truck to move from its starting location to its destination, then the truck will not need to charge and is removed from the simulation. If the stored energy is not enough, then the truck must charge at least once. A calculation then determines how long the truck could drive with the available energy in the battery. This is compared with the distance to the stations along the road but before the destination. The station nearest the destination that can be reached without charging is then determined. It is then calculated whether the destination can be reached with the prescribed arrival SoC, if the truck leaves the station with 100% SoC. If so, then the truck must charge once; if not it must charge twice.

The simulations are run using a time-iterating, agent-based model. At the start of the simulation, the time equals -24 hours, with a typical day simulated twice to get proper initial conditions for the second day. The time then increases in increments of Δt until it reaches 24 hours. In the simulations conducted in this paper, the time step is set at one minute. The fact that the time step is not extremely small can result in some small errors, meaning that, in some cases, the battery might be overcharged by up to 2 %. However, this does not significantly affect the results and thus the time step is considered sufficiently small.

At the time -24 hours the roads and charging stations are empty. Before each time iteration, new trucks enter the highway according to the traffic flow described in the previous section. Each truck that has the maximum distance $v \cdot \Delta t$ to a charging station decides whether it should charge by following the charging rules for trucks presented earlier. The decision algorithm proceeds in the following way.

If the truck has one charging session left to do, an initial check is made to see that it can drive (starting with a full charge) from the current station to its destination and arrive with the prescribed SoC. If not, then no charging takes place at this station. If it is possible, then a check is made to see whether other stations can be reached before charging. If not, the truck *must* charge at the current station. If there are alternatives, then it becomes a matter of considering the queue. If there are more queuing trucks per charger than the parameter $r_{queuing}$, then the truck does not charge at this station. If the queue is shorter, the truck calculates its destination time at the other stations and compares the prices. If none of the other possible stations has a *lower* price, it charges at the current station. If any of the other possible stations has a lower price, then the truck does not charge at the current station. If a truck decides to not charge, it simply continues driving and must go through the same decision algorithm again when passing the next station. If the truck decides to charge, it takes only the necessary charge in order to reach its destination with the prescribed destination SoC.

If the truck has two charging sessions left to do, the closest station is determined which *must* be reached for the second charge so that the truck can reach its destination with the required SoC. If this station cannot be reached by fully charging at the current station, then no charge is taken at the current station. If this station can be reached, it is then determined whether other stations can be reached before a charge is needed. If not, then charging *must* happen at the current station. If there are possibilities to charge at several stations, one consider the queue. If there are more queuing trucks per charger than $r_{queuing}$ then the truck is not charged at the current station. If the queue is not too long, then prices are compared, as described earlier. Charging takes place at the current station if there are no other stations with cheaper fast charging. If there should be other stations, however, then charging does not take place at the current one. If the truck decides to charge, it charges fully.

The trucks that do not charge update their location and SoC according to:

$$X_i(t + \Delta t) = X_i(t) + v \cdot \Delta t \quad (1)$$

where X_i is the location of truck i and

$$SoC_i(t + \Delta t) = SoC_i(t) - v \cdot \Delta t \cdot \frac{dE}{dx} \quad (2)$$

where SoC_i is the SoC of truck i. Then there are queued trucks waiting for charging. These are neither moving nor charging but the trucks' total queuing time is updated by adding the queuing time Δt. Finally, there are trucks that are charging. These update their SoC according to:

$$SoC_i(t + \Delta t) = SoC_i(t) + P \cdot \Delta t. \quad (3)$$

For each charging station j, the total energy delivered from the charging station, $E^j_{charger}$, is updated according to:

$$E^j_{charger}(t + \Delta t) = E^j_{charger}(t) + N_j(t) \cdot P \cdot \Delta t \quad (4)$$

where $N_j(t)$ is the number of charging trucks at station j at the time t. Before commencing a new time step, the trucks that have reached their target SoC leave the charging station. If a truck that has finished charging only needs to charge once, it is now removed from the simulation. If it must charge twice, it will continue on the highway until it stops for its second charge and then be removed after the second charge. At the end of each time step, the number of queuing trucks is registered at each station.

4. Simulated cases and results

The model is executed for different cases which are presented below in the results. In all the simulated cases, except Case 9, the total number of chargers for the system is 105. In this section, the *maximum queuing time*, the *average queuing time*, the *charger utilisation factor* for an individual charging station and the *system charger utilisation factor* are presented as results from the simulations alongside the number of queuing trucks per charger, as a function of time for the different stations. The maximum queuing time and average queuing time refer to the queuing time per truck during a typical day and not per charge (some of the trucks charge twice). The maximum queuing time is the longest total time a truck had to wait for charging on a typical day. The average queuing time is the mean queuing time for the trucks that actually charge. The charger utilisation factor for an individual charging station is defined as the energy delivered by all the chargers at the station during the typical day, divided by the highest possible energy that *can* be delivered by the station during that day. The system charger utilisation factor is the total energy delivered by all the chargers in the system during a typical day divided by the maximum amount of energy that *can* be delivered by all the chargers in the system over one day.

Case 1 is a reference case which was defined by manually testing combinations of various different charging stations, their location and the number of chargers until it resulted in a high charger utilisation rate and lingering minor queuing problems. All nine presented cases are described below but first, an overall description of how the different cases differ from Case 1 is presented in Table 3.

Table 3. Differences between the cases and the reference case (Case 1).

Case	Difference from Case 1
Case 1	Reference case
Case 2	Higher price for charging at Station 3 at rush hour
Case 3	The trucks unconcerned with queues at charging stations
Case 4	Same total number of chargers as Case 1, but spread across 6 stations instead of 3
Case 5	Increase in traffic flow of 11%
Case 6	Increase in traffic flow of 32%
Case 7	Increase in one peak of the traffic flow
Case 8	Like Case 7 but trucks unconcerned with queues
Case 9	Like Case 7 but total number of chargers is increased

Case 1 is designed to represent a good system solution. Case two shows an attempt to improve the system solution by pricing. Cases 3 and 8 investigate whether the unwillingness to queue is an important system-level attribute. Case 4 examines whether it is more beneficial to have a few stations with many chargers or many stations with few chargers. Cases 5 and 6 evaluate the system's resistance to an overall increase in traffic flow. Case 7 explores whether an unexpected peak in the traffic flow can cause severe queues. Case 9 is designed to show a reasonable safety margin in selecting the number of chargers for the system.

Case 1:

In this case, $r_{queuing} = 0.15$ queuing trucks per charger meaning that the trucks avoid large queues if possible. The price for charging is the same for all stations, regardless of time. Table 4 shows how the chargers are distributed in this case.

Table 4. Location of the chargers for Case 1.

	Section	Location [km]	No. Chargers
Station 1	1	138	50
Station 2	2	276	25
Station 3	3	414	30

Results for Case 1:

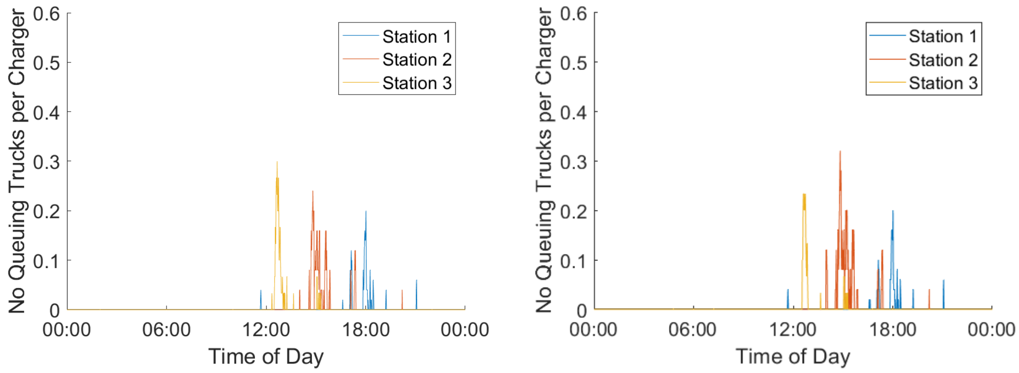
The maximum queuing time was nine minutes and average queuing time 0.22 minutes. The system charger utilisation factor was 59% and the individual charger utilisation factor for the stations was 60%, 59% and 58% for Stations 1, 2 and 3 respectively. Figure 4a shows the number of queuing trucks per charger at the different stations as a function of time for Case 1. The results indicate that a high charger utilisation will be possible without having major problems with queuing at the charging stations.

Case 2:

This case is identical to Case 1, with the exception that the price for charging is higher at Station 3 between 12:00 and 14:00, which is when there are a lot of trucks queuing at Station 3 in Case 1, see the yellow spike in Figure 4a.

Results for Case 2:

The maximum queuing time was 12 minutes and average queuing time 0.22 minutes. The system charger utilisation factor was 59% and the individual charger utilisation factor for the stations was 60%, 60% and 58% for Stations 1, 2 and 3 respectively. Figure 4b shows the number of queering trucks per charger at the different stations as a function of time for Case 2. The results seem to show that the queue moved from Station 3 to Station 2 but that the overall level of queuing did not improve. The maximum queuing time actually increased!



(a) **(b)**

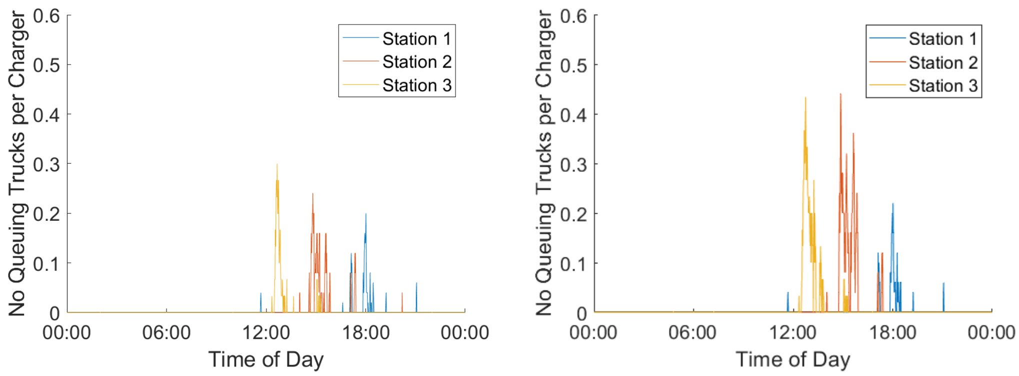
Figure 4. Number of queuing trucks per charger at the different stations as a function of time. (**a**) Results from Case 1. (**b**) Results from Case 2.

Case 3:

This case is identical to Case 1, except that $r_{queuing} = 100$ queuing trucks per charger. In this context, the implication is that the charging trucks do not take queuing time into account when selecting their charging stations.

Results for Case 3:

The maximum queuing time was 15 minutes and average queuing time 0.36 minutes. The system charger utilisation factor was 59% and the individual charger utilisation factors for the stations were 60% for Station 1, 59% for Station 2 and 58% for Station 3. Figure 5 shows the number of queuing trucks per charger at the different stations as a function of time, Figure 5a shows the results from Case 1 and Figure 5b the results from Case 3. These results show that the station queuing conditions clearly worsened when the agents did not avoid queues.



(a) **(b)**

Figure 5. Number of queuing trucks per charger at the different stations as a function of time. (**a**) Results from Case 1. (**b**) Results from Case 3.

Case 4:

This case is designed to test whether it is better to distribute the same number of chargers across more stations or fewer. The system now has six stations distributed according to

Table 5 and the number of chargers at each station was manually selected to minimise queuing problems. For this case $r_{queuing} = 0.15$ queuing trucks per charger and the price of charging is the same for all stations, regardless of time.

Table 5. Location of the chargers for Case 4.

	Section	Location [km]	No. chargers
Station 1	1	138	33
Station 2	1	200	23
Station 3	2	276	18
Station 4	2	320	8
Station 5	3	414	12
Station 6	3	470	11

Results for Case 4:

The maximum queuing time was 17 minutes and average queuing time 0.55 minutes. The system charger utilisation factor was 59% and the individual charger utilisation factor was 57% for Station 1, 62% for Station 2, 61% for Station 3, 64% for Station 4, 54% for Station 5 and 60% for Station 6. Figure 6 shows the number of queuing trucks per charger at the different stations as a function of time for Case 4. The results indicate that it is beneficial to have fewer stations with many chargers rather than many stations with few chargers.

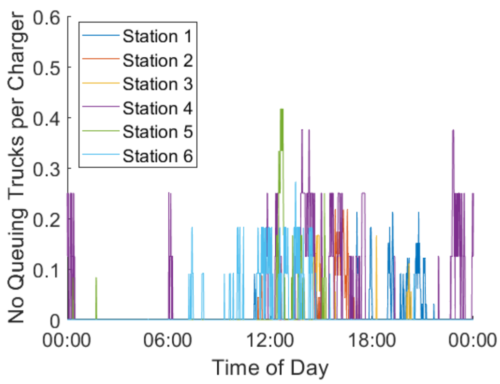


Figure 6. Number of queuing trucks per charger at the different stations as a function of time for Case 4. The blue, red, yellow, purple, green and light blue curves represent Stations 1 to 6 respectively.

Case 5:

This case is the same as Case 1 but 480 departing trucks have been added compared to the typical day. These extra trucks have been distributed so that 120 of them start from each city. The extra trucks in each city have three possible destinations, with 40 of them going to each alternative destination. The departure times for the extra trucks have been drawn from a uniform random distribution with minute precision. The extra 480 trucks correspond to an 11% increase in the number of daily trucks.

Results for Case 5:

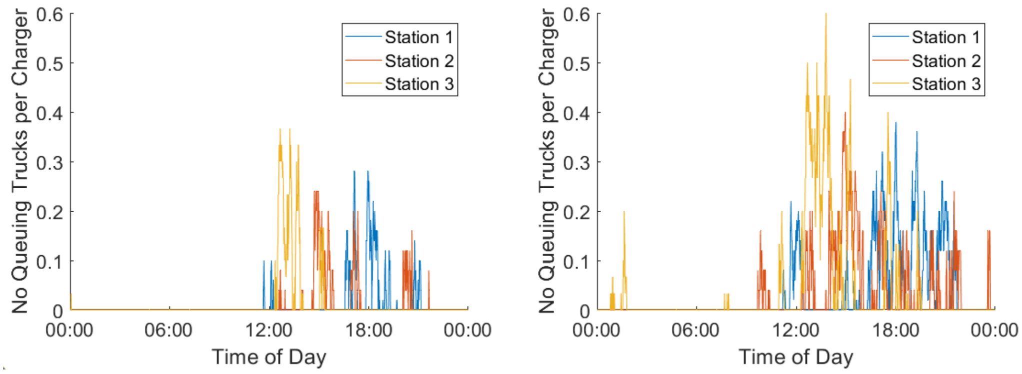
The maximum queuing time was 16 minutes and average queuing time 0.62 minutes. The system charger utilisation factor was 65% and the individual charger utilisation factor was 65% for Station 1, 65% for Station 2 and 66% for Station 3. Figure 7a shows the number of queuing trucks per charger at the different stations as a function of time for Case 5. The results show that this increase in the traffic flow is handled quite well by the charging stations.

Case 6:

This scenario is the same as in Case 1 but 1440 departing trucks have been added to the typical day. These extra trucks have been distributed so that 360 of them start from each city. The extra trucks in each city have three possible destinations, with 120 of them going to each alternative destination. The departure times for the extra trucks have been drawn from a uniform random distribution with minute precision. The extra 1440 trucks correspond to a 32% increase in the number of daily trucks.

Results for Case 6:

The maximum queuing time was 21 minutes and average queuing time 1.56 minutes. The system charger utilisation factor was 77% and the individual charger utilisation factor was 74% for Station 1, 77% for Station 2 and 81% for Station 3. Figure 7b shows the number of queuing trucks per charger at the different stations as a function of time for Case 6. The results show that this increase in the traffic flow causes some queuing problems at the charging stations.



(a) **(b)**

Figure 7. Number of queuing trucks per charger at the different stations as a function of time. (**a**) Results from Case 5. (**b**) Results from Case 6.

Case 7:

This case is the same as in Case 1 but there are 90 extra departing trucks compared to the typical day. All the extra trucks start from Stockholm, with 30 of them driving to Linköping, 30 to Jönköping and 30 all the way to Helsingborg. The departure times for the extra trucks have been drawn from a uniform random distribution in the interval [9.4, 10.4] hours, with minute precision where zero corresponding to midnight. This added truck flow is designed to roughly double the peak of Section 3's return flow, see the blue dashed line in the lower part of Figure 3.

Results for Case 7:

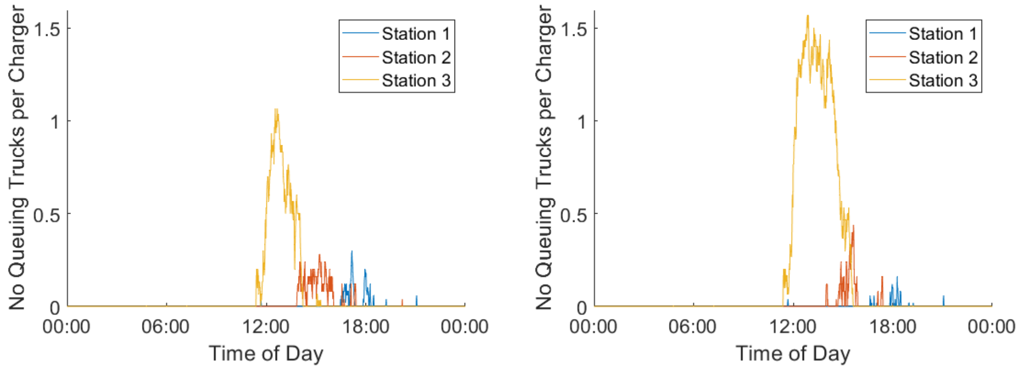
The maximum queuing time was 39 minutes and average queuing time 1.21 minutes. The system charger utilisation factor was 61% and the individual charger utilisation factor was 60% for Station 1, 61% for Station 2 and 62% for Station 3. Figure 8a shows the number of queuing trucks per charger at the different stations as a function of time for Case 7. The results show that this system is not resistant to strong, unexpected peaks in the traffic flow. This will be further discussed in the next section.

Case 8:

This case is the same as in Case 7 with the exception that $r_{queuing} = 100$ queuing trucks per charger. In this context, that implies that the charging trucks are not taking the queuing time into account when selecting charging stations.

Results for Case 8:

The maximum queuing time was 68 minutes and average queuing time 2.26 minutes. The system charger utilisation factor was 61% and the individual charger utilisation factor for the stations was 60% for Station 1, 60% for Station 2 and 62% for Station 3. Figure 7b shows the number of queuing trucks per charger at different stations as a function of time for Case 8. Again, the results show that the trucks' unwillingness to queue is an important attribute of the overall system.



(a) **(b)**

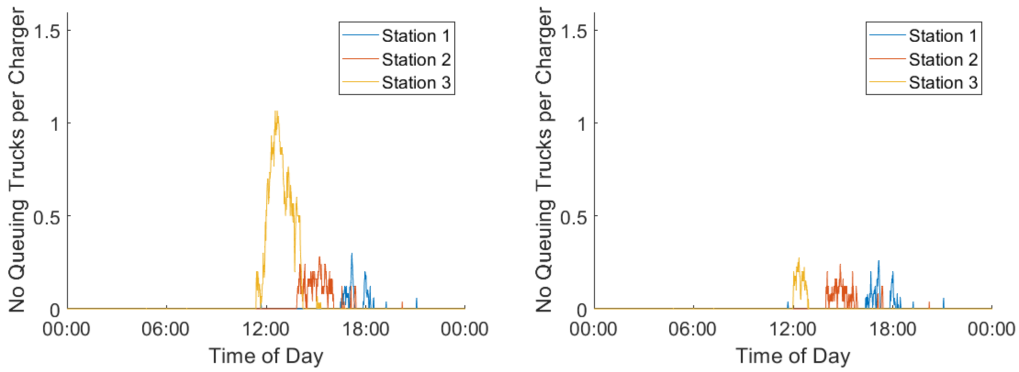
Figure 8. Number of queuing trucks per charger at the different stations as a function of time. (**a**) Results from Case 7. (**b**) Results from Case 8.

Case 9:

This scenario is the same as in Case 7 with the exception that 10 extra chargers have been added to Station 3, bringing the total number of chargers for the system to 115. This is the only case in which the total number of chargers is not 105.

Results for Case 9:

The maximum queuing time was 10 minutes and average queuing time 0.40 minutes. The system charger utilisation factor was 55 % and the individual charger utilisation factor for the stations was 60 % for Station 1, 60 % for Station 2 and 46 % for Station 3. Figure 9b shows the number of queuing trucks per charger at the different stations as a function of time for Case 9, while Figure 9a shows the results from Case 7. These results show that it is possible to achieve a system strongly resistant towards unexpected peaks in the traffic flow by increasing the number of chargers. This is trivial but the results will support the discussion of a realistic system of charger utilisation in the next section.



(a) **(b)**

Figure 9. Number of queuing trucks per charger at the different stations as a function of time. (**a**) Results from Case 7. (**b**) Results of Case 9. Note that the total number of chargers for the system is 115 for Case 9 and not 105, as in all other cases.

5. Discussion and conclusions

5.1. Promising results

The results from Case 1 indicate a promising future for the system of chargers and battery electric trucks along the highway between Helsingborg and Stockholm. Having a well-functioning system with low queuing times and system charger utilisation as high as 59% gives great opportunities for cheap public fast charging and profitable charging stations [5]. The reason for this high system charger utilisation factor is that the variation in traffic flow over the day is not that great. The trucks operate throughout the day and there is even a significant flow of trucks through the night. This makes it possible to select the number of chargers to almost meet the rush hour demand without having too much overcapacity in the calmer hours.

Moreover, according to the results of Cases 5 and 6, the system seems fairly robust in coping with increased traffic if it is uniformly distributed across the day. The simulation in Case 6 resulted in a maximum queuing time of 21 minutes. This is not so much given that the simulation involved almost 5,800 trucks and especially not if this extra-high level of traffic is rare. Still, this case did have some problems with queues at the stations. The system charger utilisation for the case was 77%, which constitutes a very high value. However, although this does seem promising, believing in a well-functioning system with low queuing times and a system charger utilisation factor as high as 59% is perhaps overly optimistic. This is discussed in the next subsection, which presents a more realistic system utilisation factor.

5.2. A more realistic system charger utilisation factor

The results of Case 1 indicate that the system charger utilisation factor could be as high as 59%. However, when considering the results of Case 7, with its strong increase in one of the traffic flow peaks, it becomes apparent that Station 3 does not have the capacity to provide charging for trucks during rush hour, see Figure 9a. For Case 7, the maximum queuing time was 39 minutes, which is too long. There were also queues of several hours at Station 3. By adding 10 more chargers at Station 3 (as in Case 9), the system works well again, see Figure 9b. For Case 9, the maximum queuing time is down to 10 minutes which should be acceptable. However, this comes at the cost of a reduction in charger utilisation. One might wonder whether it is necessary to scale the number of chargers for such extreme events as a doubling in traffic peak. However, this only represents a 2% increase in the total daily traffic flow. The system may not be deemed sufficiently robust if such long lines can be created at a single charging station even if the extra trucks start during rush hour. Thus there is a need for 10 extra chargers at Station 3, corresponding to an increase of 33%. Since it is not just Station 3 that can be affected by extra peak demand for charging, the 33% increase should be made for all charging stations, resulting in 140 chargers overall (1.33 x

105 chargers). By assuming that the average demand is represented by the demand for a typical day used in the simulations, we obtain a new system charger utilisation factor of $\frac{105 \cdot 0.59}{140} = 44\%$, where 105 is the old number of chargers, 140 is the new number of chargers and 0.59 is the old system charger utilisation factor. Taking a restrictive point of view, one might ask whether the same number of trucks is on the roads at weekends as on weekdays. The answer is probably not. If we assume that each truck is on the road only once per weekend, then the new system charger utilisation factor is $44\% \cdot \frac{6}{7} = 38\%$. Another factor which will lower the utilisation is if the charging power varies during a charging session. Typically, batteries accept high power during the initial charging phase and then less and less power as the battery's state of charge is increased. In other words, having an average power of 700 kW will typically require a 900 kW charger. That lowers the charger utilisation by a factor of 700/900. This effect need not be reflected by an equally low grid utilisation. Ultimately, it results in a new, more realistic utilisation factor of $38\% \cdot \frac{700 \text{ kW}}{900 \text{ kW}} = 30\%$; not as high as 59% but clearly still high and promising.

So what does a system charger utilisation factor of 30% mean for the price of public fast charging? Previous studies [5] presented a difference per kWh between the price of public fast charging and the price of electricity paid by the charge point operator. C_{diff} has to follow the following inequality in order to to achieve profitable charging stations:

$$C_{diff} > \frac{C_{ch}}{\Gamma_{ch}}. \tag{5}$$

where C_{ch} is a combined price for the cost of the chargers and grid connection per unit of time with a typical value of 117 €/kW/year = 0.0134 €/kWh and Γ_{ch} is the charger utilisation factor. Given a charger utilisation factor of 30%, we obtain:

$$C_{diff} > \frac{0.134}{0.30} = 0.05 \text{ €/kWh}. \tag{6}$$

This allows for both cheap public fast charging and profitable charging stations. Also, the system should have few problems with queuing and be robust in that it can handle increased traffic flow or an unusually high peak in it.

This paper has assumed that there is one charger per charging truck. Furthermore, it has been assumed that this charger has access to its own grid capacity corresponding to its maximum power and that this power is constant during the charging session. This made it easy to define a charger utilisation factor and is a reasonable simplification which still allows analysis of one of the main system trade-offs. However, it also hides some interesting ways to allow high availability of chargers while still making effective use of the charger power electronics and grid capacity. Future studies should therefore also consider the possibility of offering charger power that can be distributed to different trucks depending on which truck needs the power, as well as perhaps offering more charging outlets for trucks than the total available charger power and grid capacity. This will avoid drivers having to queue for a charger before they can park their trucks and take their mandatory breaks.

5.3. Reducing queues with pricing

This study has attempted to reduce the amount of queuing at the stations through pricing. For example, consider the results of Case 1, in the left-hand part of Figure 4. There is a clear spike at noon for Station 3. Although this spike is slender, it does raise the question of whether better results might be obtained by temporarily increasing the price of charging during it. This would make some trucks select another station, even if some chargers were vacant when they arrived. The right-hand part of the figure illustrates this. Indeed, the queuing peak is a little lower for Case 2 but a couple of hours later the peak at Station 2 has increased. The maximum queuing time for the system is now 12 minutes instead of nine and the average queuing time has not improved. Thus, pricing has slightly improved the local queuing conditions but worsened them a little at system level. There will likely be a situation in which pricing can improve the overall solution but this example illustrates there is no guarantee that it can be improved by pricing, even if there is local improvement. In the simulations, the trucks that did not charge at one station had to go and charge elsewhere. Thus, if a lot of trucks reject a station during rush hour, they must charge at a subsequent station and will once again arrive simultaneously. It might seem that expensive charging during rush hour and lower pricing when demand falls would cause some haulage companies to reschedule their departure times, thus improving the queuing conditions on a system level. However, this has not been investigated.

5.4. Queuing reluctance improves the system solution

Case 3 is identical to Case 1 with the only exception that in Case 3, the trucks do not take the queuing conditions into account when selecting a charging station. The same goes for Case 8 which is identical to Case 7 but without queuing resistance. When comparing the results from the system in which trucks avoid charging at stations with long queues, with the results from the system in which long queues are not a concern, it is clear that the better solution is for the trucks to take some steps to avoid long queues. This is consistent with what was anticipated. In the simulated cases, both the maximum and average queuing times are increased by roughly 70% when the trucks' queuing avoidance is removed. A clear queuing difference is shown in Figures 5 and 8. The behaviour of avoiding long queues is undoubtedly realistic and the simulations show that this property is important in achieving good system solutions more easily. The system has some ability to regulate itself; this may make charger booking systems less important or even redundant.

5.5. Benefits of gathering chargers at fewer stations

To gain more choice as to where to charge along the road, simulations with more than three charging stations were run. Since the results were to be compared with Case 1 the number of chargers was kept the same. However, it was not possible to improve upon or even equal the results of Case 1 by using more charging stations. The simulation in Case 4 used six charging stations and resulted in the maximum queuing time and average queuing time being approximately doubled. To some extent, this might be explained by the fact that it is harder to find well-distributed chargers across six stations than across three, as there has been no "proper" optimisation. However, this cannot explain everything, as many different combinations of charger distributions were tested. Even the location and number of new stations was changed.

Thus, the simulations indicate that it is better to have fewer stations with many chargers than many stations with fewer chargers. This can be explained by the following two arguments. Firstly, consider a station with fewer chargers and another one with many. Both stations have the same number of queuing trucks per charger. If the trucks at the smaller station are unlucky, all of the (fewer) trucks charging at this station will have just started charging, leading to long queuing times. The probability of this scenario should be significantly less for the larger station with many chargers. This explains the longer maximum queuing time for the case with many stations and fewer chargers. Secondly, if we compare a situation in which all the chargers at one station are occupied, there will be no queue. Now imagine another case in which these chargers are distributed across several stations. Since the trucks are unlikely to always distribute in the exact same way, there will often be unused chargers at some stations and queues at others, despite the number of charging trucks being the same as the number of chargers. This is one reason why the average queuing time increases when there are many stations with few chargers.

5.6. Limitations of the Study

This paper has studied a complex system using a fairly simple model. As with any model, this one has weaknesses and the results and conclusions should be regarded as estimates and not absolute truth. For example, the method for finding the origins and destinations involves some assumptions which are not based on data. The data is a few years old and may not be representative of the traffic flow in the future. The data for the time variations of the flow is especially important to the results. The time variations are taken from a just few days and no long-term data was available at the measurement sites to allow a study of how representative these days were.

Although the rules for the agents sound reasonable, real drivers might not behave in this way. The simulations assumed that a truck moves on immediately when it has completed its charging, making the charger available again. But is it probable that a driver taking a break might move their truck just because the truck has finished charging? This behaviour influences the result. One way to address this problem is to have the drivers pay for the time spent at the charger and not just the energy. Then staying longer than necessary might not be so attractive (and if the truck lingers, the charge point operator will be paid for the extra time). However, this behaviour still leads to a blocked charger that might have been used by another truck. Another way to reduce this problem is to have more charger outlets than chargers at the station and design things so that the available chargers can be directed to the charger outlets which need them at that moment. In other words, a truck that lingers at a charger will not prevent that charger from being used as it occupies just one outlet.

The results of this system seem very promising, with the number of chargers selected to meet demand by a necessary margin. The goal was to satisfy users but having fewer chargers results in high utilisation and necessitates accepting some minor queues. But is this the case in the free market? If the system has all the chargers it needs, works well and is profitable, what is there to stop a new charge point operator from entering the market if there is money to be made? All the charge point operators might still profit but the system has too many chargers. So if utilisation becomes high enough, a free, competitive market may result in no queues, even during rush hour.

This subsection began with the fact that a complex system has been simulated by a fairly simple model. Naturally, it is possible to make the model more complicated but there is absolutely no guarantee that a more complicated model would yield more accurate results or a better understanding of the simulated system.

5.7. Conclusions

Despite having to rely on some assumptions (including ones about charging behaviour) to model how long-haul trucks drive, this investigation has produced some interesting conclusions on how well a system of public chargers for long-haul trucks might perform and on some factors influencing its effectiveness.

1. This type of agent-based model seems a good way of investigating a suitable design for a charging system and how to make it cost-effective while providing high availability of chargers with a low risk of queuing. The study also shows that many more things need to be included in the model and that better data is needed before the results can be used in a real system design.
2. Hourly data on the flow of heavy trucks with trailers on the E4 between Helsingborg and Stockholm suggests that long-haul trucks flow quite evenly throughout the day and with significant numbers at night. Combining the truck flow data with some assumptions about battery sizes and charging behaviour suggests that charging demand may also be quite even.
3. A future system of battery electric trucks and public fast chargers along the highway between Helsingborg and Stockholm seems likely to work well. The relatively uniform traffic flow of trucks results in high charger utilisation, which may lead to a system with low prices for public fast charging and profitable charging stations. Moreover, there seemed to be few queuing problems at the charging stations. The system will also be robust in the face of increased traffic flow or unusual peaks in traffic flow, as queuing times are not especially high even when the number of trucks increases.

4. It has been estimated that full electrification of the long-haul truck fleet would require 140 chargers along the highway between Helsingborg and Stockholm, each with the power of 900 kW.
5. The system charger utilisation factor has been estimated at 30 % which is very high, especially considering that it is achievable with such minor queuing problems.
6. The study indicates that a system with a constant number of chargers will better resist queues if there are few charging stations with many chargers rather than many charging stations with few chargers.
7. One simulation shows that varying the charging price may lead to more queuing across the whole system, even if it improves the local queuing at one particular station.
8. The truck drivers' unwillingness to queue is important and leads to less queuing on the system level.

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Abbreviations

The following abbreviations were used in this manuscript:

SoC State of charge

Nomenclature

B_{cu}	Useful battery capacity of the trucks [kWh]
C_{ch}	Combined price for the cost of the chargers and grid connection [€/kW/hour]
C_{diff}	Difference in price of electricity and public fast charging [€/kWh]
$\frac{\Delta E}{\Delta x}$	Energy consumption of the trucks [kWh/km]
Δt	Time step [min]
$E^j_{charger}(t)$	Total energy delivered by station j at time t [kWh]
F_{1f}	Outward flow in Section 1 [trucks/day]
F_{2f}	Outward flow in Section 2 [trucks/day]
F_{3f}	Outward flow in Section 3 [trucks/day]
F_{1b}	Return flow in Section 1 [trucks/day]
F_{2b}	Return flow in Section 2 [trucks/day]
F_{3b}	Return flow in Section 3 [trucks/day]
F_{1in}	Incoming flow to Jönköping [trucks/day]
F_{2in}	Incoming flow to Mjölby/Linköping/Norrköping [trucks/day]
F_{1out}	Outgoing flow from Jönköping [trucks/day]
F_{2out}	Outgoing flow from Mjölby/Linköping/Norrköping [trucks/day]
Γ_{ch}	Charger utilisation factor [-]
$N_j(t)$	Number of charging trucks at station j at time t [-]
P	Power of the chargers [kW]
$r_{ququing}$	Queuing parameter [trucks/charger]
S	Distance between Helsingborg and Stockholm [km]
$SoC_i(t)$	State of charge for truck i at time t [-]
v	Mean speed of the trucks [km/h]
x_i	Approximate number of trucks starting in city i [-]
$X_i(t)$	Location of each truck i at the time t [km]
y_{ij}	Approximate number of trucks traveling from city i to city j $[-]$

Appendix A Creating the traffic flow for the simulations

Appendix A.1 Traffic flow for a typical day

In order to be able to investigate the charging trucks, a traffic flow between Helsingborg and Stockholm was created. The aim was to create a traffic flow for long-haul trucks on a typical weekday. It was assumed that trucks only can join the road at points where the larger roads connect to the road being investigated, i.e. at Helsingborg, Jönköping, Mjölby, Linköping, Norrköping, Södertälje and Stockholm. Since some of these cities are geographically close to each other Mjölby, Linköping and Norrköping were regarded as one city located at Linköping, while Södertälje and Stockholm were seen as one city located at Stockholm (see the black dots in Figure A1). To create a plausible traffic flow, data from the Swedish Transport Administration [20] was used. The data used was the annual average daily traffic flow of trucks *with* trailers at three different intersections of the road; the small municipalities of Ljungby, Gränna and Tystberga. Trucks without trailers were excluded because it was assumed that this type of truck does not drive long distances and would therefore not need to charge along the E4. The three locations were selected because they are some distance from major cities, meaning that there would probably be only a few trucks that drive short distances. The available data does not cover every year, so 2018 and 2019 were selected. According to another Swedish government authority, Trafikanalys (Traffic Analysis) [21], the total number of truck transports was 45 million in 2018 and 43 million in 2019. Therefore when traffic flows from year 2018 have been used it is scaled by a factor 43/45. Figure A1 shows the data for the traffic flow along the studied road, plus the traffic flow of trucks with trailers from the larger roads connecting to the studied road. This data also came from the Swedish Transport Administration [20]. The variable name for the different flows are defined by the figure. The traffic flow along the studied road is marked with black arrows and the traffic flow connecting or leaving the road is marked with red ones. The studied highway was divided into three sections: Section 1 between Helsingborg and Jönköping, Section 2 between Jönköping and Linköping and Section 3 between Linköping and Stockholm (as illustrated in the figure). The location for the measurement points can also be seen in the figure; these points are marked with blue lines and correspond to the measurement stations at Ljungby, Gränna and Tystberga, with the flow shown as trucks per day. The outward direction from Helsingborg to Stockholm can now be marked with a black arrow in Figure A1, and the opposite way for the return.

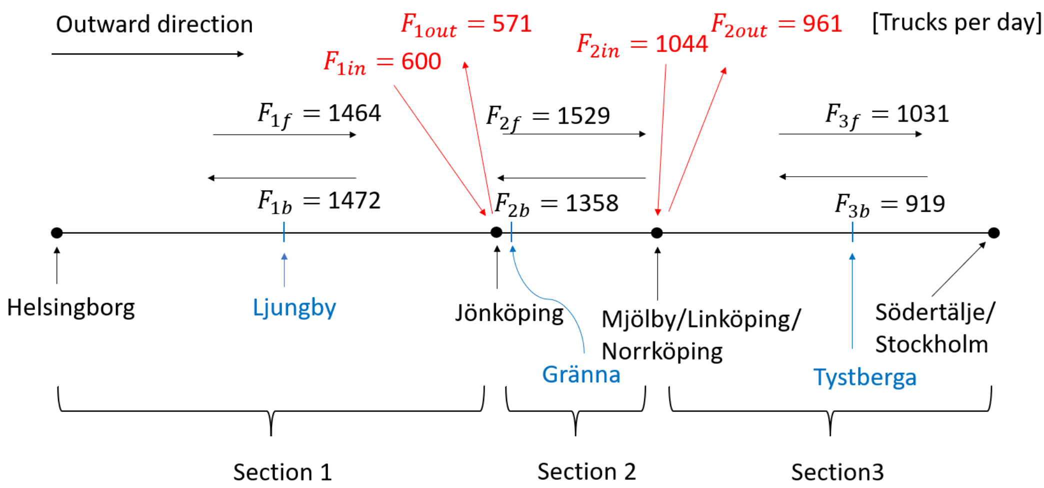


Figure A1. The traffic flow along the studied road is marked with black arrows and the traffic flow that connects or leaves the road is marked with red arrows. The flow is shown in trucks per day.

If we now place the origin of the one-dimensional highway described above at Helsingborg, the locations for the important cities and measurement stations can be found using Google Maps, see Table A1.

Table A1. Location of the cities and measurement stations.

City/Measurement Station	Location [km]
Helsingborg	0
Ljungby	134
Jönköping	228
Gränna	265
Linköping	355
Tystberga	470
Södertälje/Stockholm	553

The aim was to find reasonable values for how many trucks starts in each city (marked with black dots in Figure A1) and their destinations on a typical day so that the flows in Figure A1 (marked with black arrows) were properly fulfilled. Note that there are many different ways to do this, but to conduct the simulation it was sufficient to find just one realistic solution. Table A2 defines the number of trucks starting in each city as x_i where $i \in \{1,2,3,4\}$ and their corresponding destinations y_{ij} where $i \neq j$ and $i,j \in \{1,2,3,4\}$. Thus, x_i is the number of trucks starting in city i and y_{ij} is the number of trucks travelling from city i to city j with Helsingborg, Jönköping, Linköping and Stockholm corresponding to cities 1, 2, 3 and 4 respectively.

Table A2. Variables for the number of trucks starting in different cities and their destinations.

Start city, no. trucks	**Destination Helsingborg, no. trucks**	**Destination Jönköping, no. trucks**	**Destination Linköping, no. trucks**	**Destination Stockholm, no. trucks**
Helsingborg, x_1	-	y_{12}	y_{13}	y_{14}
Jönköping, x_2	y_{21}	-	y_{23}	y_{24}
Linköping, x_3	y_{31}	y_{32}	-	y_{34}
Stockholm, x_4	y_{41}	y_{42}	y_{43}	-

By starting at Helsingborg and moving in the outward, direction it is apparent that we must start with 1464 trucks at Helsingborg to fulfil the outward flow in Section 1. Thus, $x_1 = 1464$. The 600 trucks entering Jönköping come from the road from Gothenburg. Since this is a detour, it might seem unlikely that trucks will dive from Gothenburg to Helsingborg via Jönköping, or vice versa. Therefore, it might seem that the trucks from Gothenburg would either drive through Jönköping or stop and turn back. The same may be assumed for trucks from Helsingborg. By assuming that equal shares, t, of trucks from Gothenburg and Helsingborg drive through Jönköping and that this total equals the outward flow in Section 2, we may formulate the equation:

$$F_{1in} \cdot t + F_{1f} \cdot t = F_{2f}. \tag{A1}$$

By solving the above equation, we find that $t \approx 0.74$ and may then conclude that the number of trucks starting in Helsingborg and stopping at Jönköping is:

$$y_{12} = (1 - t) \cdot F_{1f} = 379. \tag{A2}$$

Further on, assuming that the trucks moving in the outward direction in Section 2 either drive towards Stockholm or turn off the road at the end of Section 2, it is natural to believe that:

$$y_{13} = (x_1 - y_{12}) \cdot \frac{F_{2out}}{F_{2out} + F_{3f}} = 523. \tag{A3}$$

where $x_1 - y_{12}$ is the number of trucks from Helsingborg that do not stop in Jönköping and $\frac{F_{2out}}{F_{2out}+F_{3f}}$ is the share of trucks from the outward flow in Section 2 that turn off the road in Linköping. Thus, we know the number of trucks going from Helsingborg to Linköping. The rest of the trucks from Helsingborg go all the way to Stockholm and number:

$$y_{14} = x_1 - y_{12} - y_{13} = 562. \tag{A4}$$

We now start at Stockholm and move in the return direction. The number of trucks starting at Stockholm has to be 919 in order to fulfil the return flow in Section 3. Thus $x_4 = 919$. Using the same argument as earlier, the number of trucks going from Stockholm to Linköping is:

$$y_{43} = F_{3b} \cdot \frac{F_{2out}}{F_{2out} + F_{2b}} = 381. \tag{A5}$$

So the number of trucks going from Stockholm to Jönköping is:

$$y_{42} = (x_4 - y_{43}) \cdot \frac{F_{1out}}{F_{1out} + F_{1b}} = 150. \tag{A6}$$

Thus the number of trucks going from Stockholm to Helsingborg is:

$$y_{41} = x_4 - y_{43} - y_{42} = 388. \tag{A7}$$

Making the same assumption as earlier, the number of trucks starting at Jönköping and driving to Helsingborg may be written as:

$$y_{21} = x_2 \cdot \frac{F_{1b}}{F_{1b} + F_{2f}} = 0.49x_2. \tag{A8}$$

The number of trucks starting at Jönköping and driving to Linköping will then be:

$$y_{23} = x_2(1 - \frac{F_{1b}}{F_{1b} + F_{2f}}) \cdot \frac{F_{2out}}{F_{2out} + F_{3f}} = 0.25x_2 \tag{A9}$$

and the remaining trucks starting at Jönköping and driving to Stockholm becomes:

$$y_{24} = x_2 - 0.49x_2 - 0.25x_2 = 0.26x_2. \tag{A10}$$

For the trucks starting at Linköping, the number of trucks going towards Stockholm may be determined by:

$$y_{34} = x_3 \frac{F_{3f}}{F_{3f} + F_{2b}} = 0.43x_3. \tag{A11}$$

The number of trucks going to Jönköping can be determined by:

$$y_{32} = x_3 \cdot (1 - \frac{F_{3f}}{F_{3f} + F_{2b}}) \cdot \frac{F_{1out}}{F_{1out} + F_{1b}} = 0.16x_3 \tag{A12}$$

and the number of trucks to Helsingborg becomes:

$$y_{31} = x_3 - 0.43x_3 - 0.16x_3 = 0.41x_3. \tag{A13}$$

To fulfil the traffic flow according to Figure A1, the following equations may be formulated:

$$\begin{cases} y_{23} + y_{24} + y_{13} + y_{14} = F_{2f} \\ y_{24} + y_{34} + y_{14} = F_{3f} \\ y_{31} + y_{32} + y_{42} + y_{41} = F_{2b} \\ y_{21} + y_{31} + y_{41} = F_{1b} \end{cases} \tag{A14}$$

or equivalent:

$$\begin{cases} 0.25x_2 + 0.26x_2 + y_{13} + y_{14} = F_{2f} \\ 0.26x_2 + 0.43x_3 + y_{14} = F_{3f} \\ 0.41x_3 + 0.16x_3 + y_{42} + y_{41} = F_{2b} \\ 0.49x_2 + 0.41x_3 + y_{41} = F_{1b} \end{cases} \tag{A15}$$

which simplifies to:

$$\begin{cases} 0.51x_2 = 444 \\ 0.26x_2 + 0.43x_3 = 469 \\ 0.57x_3 = 820 \\ 0.49x_2 + 0.41x_3 = 1084. \end{cases} \tag{A16}$$

By using the least square method we find that:

$$x_2 = 864 \tag{A17}$$

and: 694

$$x_3 = 1244. \tag{A18}$$

Now, Table A2 becomes: 695

Table A3. Summary of traffic flow so far.

Start city, no. trucks	Destination Helsingborg, no. trucks	Destination Jönköping, no. trucks	Destination Linköping, no. trucks	Destination Stockholm, no. trucks
Helsingborg, 1464	-	379	523	562
Jönköping, 864	423	-	216	225
Linköping, 1244	510	199	-	535
Stockholm, 919	388	150	381	-

This set-up will result in a traffic flow as per Figure A2. 696

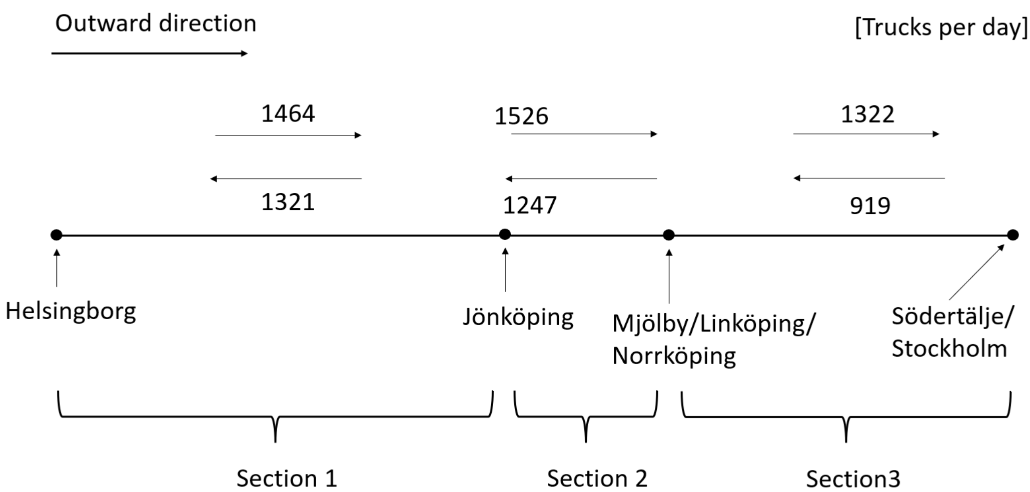


Figure A2. Traffic flow along the studied road with the set-up according to Table A3.

Using the set-up according to Table A3 we come quite close to the actual flow from 697
the data presented in Figure 1. However, if the set-up in Table A3 is changed slightly (as 698
per Table A4) the exact same flow is obtained as in the data presented in Figure 1. This is 699
the final set-up of the traffic flow used in this paper to simulate a typical day. 700

Table A4. Final set-up of the traffic flow.

Start city, no. trucks	Destination Helsingborg, no. trucks	Destination Jönköping, no. trucks	Destination Linköping, no. trucks	Destination Stockholm, no. trucks
Helsingborg, 1464	-	381	520	563
Jönköping, 909	463	-	221	225
Linköping, 1063	621	199	-	243
Stockholm, 919	388	150	381	-

The method for determining the traffic flow may rightly be questioned. However, due to data privacy concerns, detailed data on individual truck movements has not been available to us. However, the results still serve their purpose, which is to roughly represent the flow of trucks on a typical day.

Appendix A.2 Time variations in traffic flow during a typical day

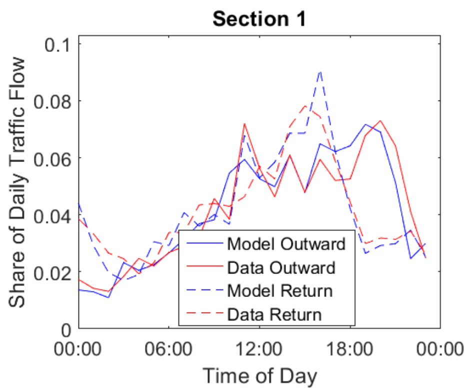
To create reasonable departure times for the trucks, data has been used [20] which covers the hourly traffic flow of trucks with trailers, over a 24-hour period at the three road sections. The times for starting to take measurements at the different sites are presented in Table A5. Unfortunately, the same day for the data was not available for all the measurement sites. However, this paper has assumed that this may still be deemed to reflect the same day. The red curves in Figure A3 show the data that was used, with solid curves representing the outward direction and dashed curves representing the return direction. The data is normalised to show the share of daily traffic flow as a function of time. Figure A3a shows the data for Section 1, Figure A3b shows the data for Section 2 and Figure A3c shows the data for Section 3.

Based on this data, the time variation is created by starting with the outward direction in Section 1, at Ljungby. Each truck's starting hour (0 to 23) from Helsingborg is randomly selected from a distribution so that, provided the trucks have a mean speed of $v = 75$ km/h from Helsingborg to Ljungby, the traffic flow will reflect the data. Where time equals zero corresponds to midnight. Once the Starting hour has been selected, an integer between -30 and 30 is selected at random and with equal probability. A corresponding number of minutes is then added to the starting time. The data flow in Section 1, at Ljungby, is then assumed to have been fulfilled. The trucks driving from Helsingborg and passing Jönköping are removed from the data in Section 2, at Gränna under the assumption that they travel from Ljungby to Gränna at the same mean speed v. Once the trucks have been removed from the distribution, a new distribution is obtained for the outward flow in Section 2, at Gränna. If the distribution is below zero for a given hour, it is set to zero for that hour. New departure times are now created for the truck from Jönköping in the outward direction, using the same method as for Section 1 but with the new distribution for Section 2. By setting the distribution in Section 3 as earlier (but with the trucks from both Helsingborg and Jönköping that reach Section 3 removed), the outward flow from Linköping is created. The same procedure was repeated for the return flow but with a starting point in Section 3. If the selected starting time for any truck happens to lie outside the interval of $[0, 24)$ hours (representing a typical day), the time is corrected by periodicity. Thus, say, -22 minutes is replaced by -22 minutes $+24$ hours $=$ 23 and 38 minutes.

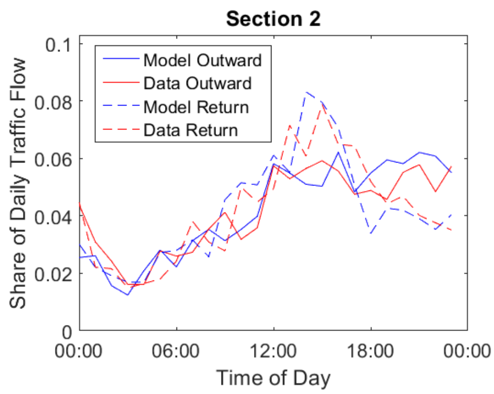
The start time for each truck is now selected with minute precision and can be used as input for the simulations. By rounding the starting time to hours and assuming that each truck will maintain a mean speed v, the traffic flow used in the model can be compared to the data. See the blue curves in Figure A3, in which the solid curves represent the outward direction and the dashed curves represent the return direction. Note that the actual flows in the simulations will deviate from the blue curves due to breaks for charging and any queuing at charging stations.

Table A5. Date for time variation of the data. The flow is given for each hour and is measured over one day.

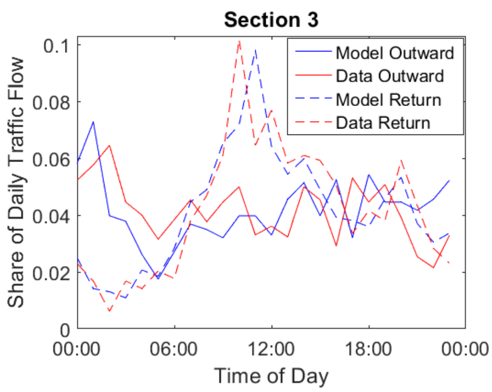
Measurement site and direction	Start
Ljungby, Outward	Thursday, 14th March 2019, 11.00
Ljungby, Return	Thursday, 14th March 2019, 12.00
Gränna, Outward	Wednesday, 20th March 2019, 13.00
Gränna, Return	Wednesday, 20th March 2019, 13.00
Tystberga, Outward	Wednesday, 11th July 2018, 23.00 p.m
Tystberga, Return	Thursday, 9th August 2018, 07.00



(a)



(b)



(c)

Figure A3. Share of daily traffic flow for each section in the outward and return directions. The blue curves correspond to the flow that would arise if the trucks were only driven at a constant speed $v = 75$ km/h without charging. (**a**) Flow in Section 1. (**b**) Flow in Section 2. (**c**) Flow in Section 3.

The number of trucks starting at each city and their destinations and departure times are now set.

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