CODEN:LUTEDX/(TEIE-5485)/1-39/(2022)

Industrial Electrical Engineering and Automation

Electric road system

A case study on the bridge of Öresund

Jakob Svensson

Division of Industrial Electrical Engineering and Automation
Faculty of Engineering, Lund University

Electric road system:

A case study on the bridge of Öresund

Source: (Nordiskt samarbete 2021)

Author: Jakob Svensson

Supervisor: Mats Alaküla

Examiner: Olof Samuelsson

Division of Industrial Electrical Engineering and Automation

Faculty of Engineering, Lund University

Abstract

Combustion of fossil fuels is single-handedly the largest contributor of global warming. The transportation sector is responsible for about a third of the greenhouse gas emissions yearly in Sweden. In turn, road traffic makes up the largest share within the transportation. The Swedish government has set out an ambitious goal to reduce domestic carbon emissions caused by the transportation sector with 70% (compared to 2010) by the year 2030, and as a part of this transformation a commission was formed with the purpose of speeding up the electrification process of heavy-duty traffic as well as the transportation sector.

As awareness of the potential benefits of electric vehicles increases, the number of battery-electric vehicles in use are increasing consistently. In 2021, the share of chargeable vehicles in new car sales reached an all-time high in Sweden with 45% of all new car sales being chargeable. However, with the number of electric vehicles rising steadily, a question emerges of how the infrastructure surrounding the charging of the vehicles will work. The electrification of road transportation can be carried out via multiple different strategies: 1) through the use of electric vehicles that charge from static charging, 2) through using alternative fuels produced from clean electricity, and 3) through using dynamic charging through an electric road system.

This report aims to explore the possibility of implementing an electric road system on a limited distance, the bridge of Öresund. Traffic flow, charging capability and electrical grid load are all important factors to understand who can benefit from an electric road system, and what is possible in terms of power supply. The cost of an electric road system is finally compared to a system of static charging.

The result shows that it is the shorter routes that are driven on a daily basis that can benefit from an electric road system. 150 heavy-duty and 1 140 light-duty trucks are needed to drive on a regular basis in order for the costs of both systems to break even. The cost is heavily based on the battery size and the further away the trucks start from, the less beneficial an electric road system is.

Sammanfattning

Förbränning av fossila bränslen är den enskilt största bidragare till växthuseffekten. Transportsektorn står för en tredjedel av Sveriges årliga koldioxidutsläpp, varav vägtransporter är skyldig för den största delen. Sveriges regering har satt ett ambitiöst mål att minska inrikes koldioxidutsläpp med 70% år 2030 (jämfört med 2010), och som en del av denna målsättning har en elektrifieringskommision startas med mål att skynda på elektrifieringen av tung trafik och transportsektor i helhet.

Då medvetenheten om de potentiella fördelarna med elektriska fordon ökar, ökar även antalet elektriska fordon i användning. 2021 slog nådde andelen laddbara fordon bland nyförsäljningar i Sverige 45%, ett nytt högsta resultat. Då andelen laddbara fordon ökar uppenbarar sig ett problem angående hur de ska laddas. Elektrifieringen av transportsektorn kan genomföras på ett antal olika sätt: 1) genom användning av elektriska fordon som laddas statiskt, 2) genom producering av alternativbränslen från ren elektricitet, och 3) genom dynamisk laddning på elvägssystem.

Den här rapporten syftar till att undersöka potentialen för ett elvägssystem på en begränsad sträcka, Öresundsbron. Trafikflöde, laddningskapacitet och elnätslast är viktiga faktorer för att förstå vem som kan dra nytta av ett elvägssystem, samt vilken effekt som är möjlig att tillförse. Slutligen jämförs kostanden för ett elvägssystem med ett system av enbart statisk laddning.

Resultatet visar att det är de kortare rutterna som körs dagligen eller regelbundet som främst gynnas. 150 tunga och 1 140 lätta lastbilar behövs använda sig av elvägssystemet dagligen för att kostnaderna ska gå jämt ut gentemot statiskt ladda dessa fordon. Kostnaderna är starkt kopplade till batteristorleken i fordonen, och ju längre bort fordonen kär från, desto mindre gynnas de av elvägssystemet.

Table of Content

1. Background

The transportation sector faces significant challenges due to the effects of climate change becoming ever more apparent each year. Combustion of fossil fuels is single-handedly the largest contributor of global warming, and the transportation sector is responsible for about a third of the greenhouse gas emissions yearly in Sweden. In turn, road traffic makes up the largest share within the transportation sector (Naturvårdsverket n. d a). The Swedish government has set out an ambitious goal to reduce domestic carbon emissions caused by the transportation sector with 70% (compared to 2010) by the year 2030, and as a part of this transformation a commission was formed with the purpose of speeding up the electrification process of heavy-duty (HD) traffic as well as the transportation sector.

As awareness of the potential benefits of electric vehicles increases, the number of battery-electric vehicles in use are increasing consistently. In 2021, the share of chargeable vehicles in new car sales reached an all-time high in Sweden with 45% of all new car sales being chargeable. This is an increase from 32% in 2020. The reduction of carbon emissions from new cars reached 19% and in both 2019 and 2020 Sweden was among the top countries within the EU to effectively reduce carbon emissions from new cars (Mobility Sweden 2022). Simultaneously, the EU average also reached an all-time high with 11% of new car registrations in 2020 being electric. Sweden comes in third place, with only Norway and Iceland having a higher share of electric vehicles in new car registrations (European Environment Agency 2021).

However, with the number of electric vehicles rising steadily, a question emerges of how the infrastructure surrounding the charging of the vehicles will work. The electrification of road transportation can be carried out via multiple different strategies: 1) through the use of EVs that charge from static charging, 2) through using alternative fuels produced from clean electricity, and 3) through using dynamic charging through an electric road system (ERS). The Swedish government has come up with a plan of action with the purpose of exploring how the major roads can be electrified. The first step towards electrification is more public static charging spots available along the major roads. However, only a few of these static chargers are suited for HD traffic and busses. The second step of action is the continued development of both ERS and hydrogen as a fuel. ERS enables charging whilst driving either conductively or inductively. Currently four different systems are currently being tested, or have been tested, in Sweden and the first permanent electric road between Hallsberg and Örebro is set to be put in operation in 2025 (Infrastruktursdepartementet, Regeringskansliet 2021).

1.1 Static charging

Today's charging infrastructure consists of public and non-public static chargers. Sweden has over 2 550 public static chargers with over 13 800 connection points with varying sockets and charging power. Most of the charging, around 80 – 90% occur at non-public chargers, usually private parking spots for either homes or workplaces (Energimyndigheten 2021). This is a concept that works fine for commuting traffic and shorter business trips but if more traffic, mainly long-haul traffic, is to be electrified problems start to appear. If long-haul traffic is to be electrified it will either require very big batteries or a lot of stops to charge them. Research shows that 1 fast static charger is required per 100 EVs (Alaküla 2019a). In Sweden there are around 5 million cars meaning 50 000 public fast chargers would be needed. That would be an increase of 1 860% that will be placed in the cities, parking lots, malls and gas stations. If every gas station in Sweden were equipped with static chargers it would still mean that 50 fast-charging poles would be needed at every gas station, which is not realistic (Alaküla 2019b).

1.2 Electric Road Systems

ERS, as shortly mentioned earlier, enables charging whilst driving, also known as dynamic charging. It allows for less charging stops and smaller batteries in the vehicles. ERS is currently being tested in several projects with Sweden and Germany leading the way, but also in several other countries. The energy transfer from the road can be either via direct contact (conductive) or contactless (inductive). There are currently three main concepts being tested; overhead lines, rails and wireless, see figure 1 (Gustavsson, Hacker & Helms 2019).

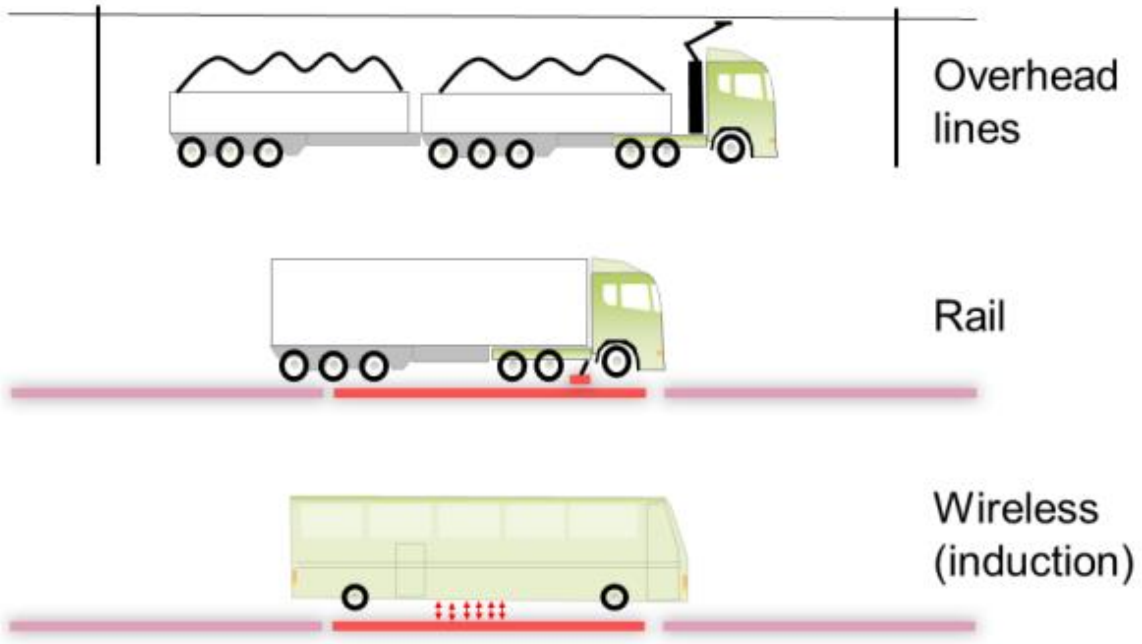

Figure 1. Overview of the different ERS technologies (Gustavsson, Hacker & Helms 2019)

1.2.1 Overhead lines

Charging conductively through overhead lines is a technique that is similar to that of trolley busses. It is possibly the most mature technique out of the three. The energy is transferred via a power receiver device on top of the vehicles, see figure 2. The power receiver has two degrees of freedom in order to remain in contact at all times. The advantages of this technique are that there is no impact on the road surface and that high power can be transferred. The main disadvantage is that only HD traffic can connect to the lines since they are too high up in the air for most vehicles (Gustavsson, Hacker & Helms 2019).

Figure 2. Truck driving with Siemens´ overhead lines technology (Energipress 2015)

1.2.2 Rails

The rail system uses conductive rails installed either on top of the road or in the road, depending on the technique. The power is transferred via a pick-up system underneath the vehicle that slides along the rail, keeping a constant connection. The pick-up system is connected to an electric power conditioner that transform the electricity to the wanted properties in terms of AC/DC and voltage level. The ERS is only activated in segments whilst driving on it. This way of connecting can be used by any vehicle and can provide a high power transfer. The disadvantage of this system is the impact it can have on the road and the need for maintenance from dirt, snow and ice, see figure 3 (Gustavsson, Hacker & Helms 2019).

Figure 3. On the left: Elways´ rail in the road (Kvaser 2017). On the right: Elonroad´s rail on the road (Smart City Sweden 2020)

1.2.3 Inductive charging

Inductive charging is a contactless connection between the road and the vehicle. It is based on Faradays Law:

$$e = -\frac{Nd\Phi}{dt}$$

$$\Phi = BAcos(\phi)$$

Where N is the number of turns of the coil, Φ is the electromagnetic flux and t the time. This induced force gives rise to an induced current when the magnetic field, B is varied. When the ERS is supplied by an electric current, a coil generates a magnetic field, received by a second coil placed in the vehicle. This creates a current, see figure 4. The less air between the coils, the better the efficiency of the power transfer is.

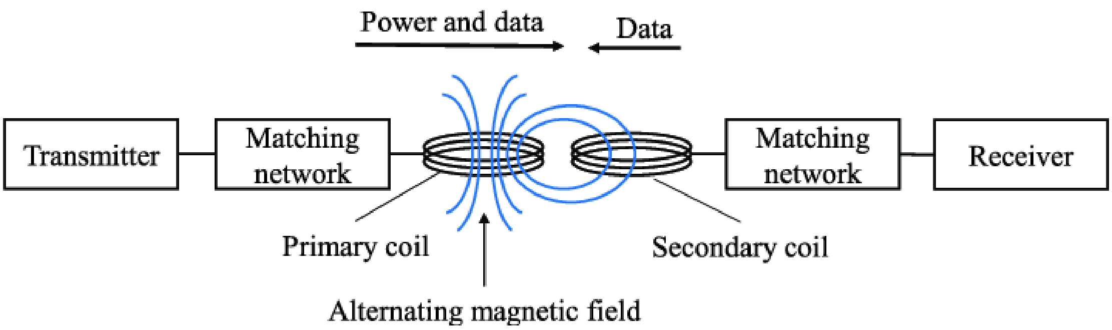

Figure 4. Concept of inductive coupling (Kim, Hirayama, Kim & Han 2017)

The advantage of inductive charging is that there is less mechanical wear since nothing is sliding on the ground or touching a surface but the technology is more advanced, see figure 5. The power that can be transferred is lower compared to conductive charging and the lateral tolerance whilst driving can be a problem (Schaap 2021).

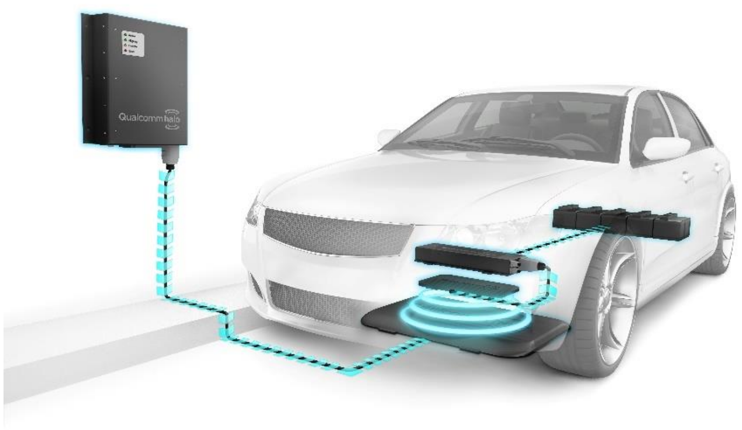

Figure 5. Wireless charging technology (Excell 2013)

1.2.4 ERS VS Static charging

Sweden has about 5 million cars and 50 000 heavy trucks. Assuming that all these vehicles were to be electrified the total cost of the societal cost can be compared, see figure 6. As mentioned before, one static charger is assumed to be needed for every 100 EVs. Furthermore, batteries are assumed to cost

1 000 SEK/kWh, static chargers 6 000 SEK/kW and ERS 10 MSEK/km. The societal cost for ERS is less than half of the static charging scenario, mainly because of the smaller batteries. In addition, the environmental impact of the ERS scenario is also less since the need for rare earth materials for the batteries is heavily reduced. Realistically, the charging infrastructure might be made up from a combination of both charging techniques (Aláküla 2019a).

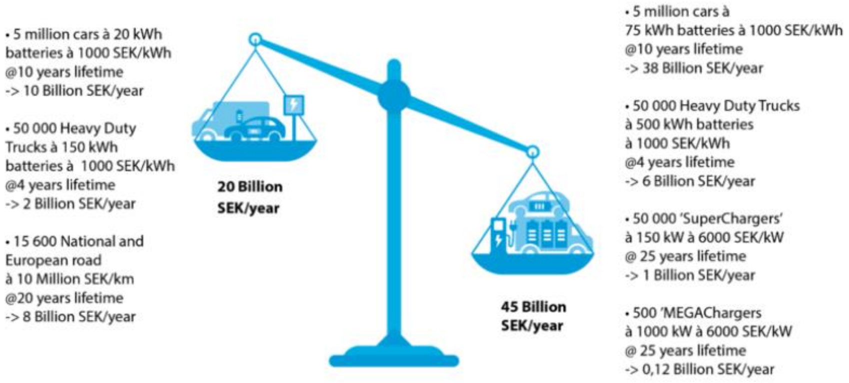

Figure 6. Societal cost of ERS VS Static charging (Aláküla 2019a)

When comparing the costs of the different ERS technologies against each other, road-bound conductive charging appears to be the cheapest. Inductive charging uses more advanced technology and has a lower power transfer ability than both-road bound and overhead conducive ERS. The reason for road-bound to be cheaper than overhead lines is the reason that all vehicles can connect to it, thus reducing the cost per vehicle for the infrastructure (Fyhr, Domingues, Andersson, Márquez-Fernández, Bängtsson & Aláküla 2017).

1.3 Goal and objective

The goal of this project is to understand under what conditions implementing ERS on the bridge of Öresund would be beneficial. The content is as follows:

- To collect data on what transports that use the bridge on a daily basis. What is important is what types of vehicles are used, how far they drive on each side of the bridge and how often the drive across it.
- To model these vehicles and simulating them driving across the bridge. This will give an idea of how much these vehicles can charge on a potential ERS and what electric grid load will be accompanied.
- To use these simulations to estimate an electric power load and compare this to the current electric grid supply and connection points on the bridge. Estimate additional costs for upgrading the current electrical system.
- To make a rough cost estimate comparing an ERS and a system of static chargers based on the traffic flow.

The bridge of Öresund has the potential for an ERS due to the high traffic flow and the fact that the road is privately owned. The high traffic flow can be contributed to two facts. The first is the daily commuting traffic between the south of Sweden and Denmark and the second is the heavy-duty traffic that connects Sweden to the north of Europe. Because of the higher traffic flows, more vehicles can connect to the ERS and share the cost, which is beneficial. The fact that the road is privately owned, decisions about major investments can be made quicker without having to change any laws about what can be done to state or municipality owned roads. This project has the potential of setting a precedent when it comes to electrifying transportation, which makes it interesting.

1.4 The bridge of Öresund

The bridge of Öresund is a connection between Sweden and Denmark but also functions as a connection between Sweden and northern Europe. It is owned by Øresundbro Konsortiet which in turn is co-owned between the Danish and Swedish states. Their mission is to promote a positive development of all traffic across Öresund (Øresundsbro Konsoriet n. d).

The bridge itself is split up into three parts; the bridge itself, the artificial island Peberholm and the tunnel. It was first consecrated in 2000 and is in total a 16 km long connection between Sweden and Denmark. The road has two lanes in each direction, and is also equipped with train tracks. In march of 2022 over 400 000 passages with cars were made and over 60 000 passages with trucks. The electric power is supplied from the Swedish grid, with the Danish grid functioning as a backup in case the is an outage on the Swedish side. The electrical systems for the road and the trains are separated with different connection points. The electrical power to the bridge mainly supplies lights and the gates for the parts above ground and also ventilation, heating or cooling and safety systems below the ground in the tunnel (Øresundsbro Konsoriet 2005).

2. Modelling

The purpose of this chapter is to give an understanding of the model that is used throughout this report. It includes an analysis of the traffic flow and its power and energy need and the accompanying effect on the electric grid supply.

2.1 Traffic flow

The traffic flow is analysed on two levels. The first level includes all traffic that drives across the bridge. This data is supplied by the consortium of the bridge of Öresund (SV. Öresundsbro konsortiet) who owns the bridge, and is in reference to the year 2019. Since the year 2020 the traffic has diminished as a result of the corona virus and the travel restrictions but the data from 2019 should provide an accurate depiction of what it will look like in the years to come as the restrictions are removed (Øresundsinstitutet 2021). The second level analysed is that of major haulage contractors who drive across the bridge on a multi-daily basis. With the help of a few selected contractors, accurate drive cycles and time tables have been provided. This is important since the data from 2019 doesn't show where the vehicles drive from or where they are going. This can give an estimate towards how much of the traffic can benefit from introducing an ERS on the bridge.

2.1.1 All traffic – 2019

The traffic data from 2019 is sorted into different vehicle classes, cars and trucks. They are also sorted into different payment methods as mentioned earlier. Since the ERS is supposed to be used by vehicles driving regularly across the bridge a couple of payment methods are more significant than others. For trucks it is mainly bridge pass business that is of interest, meaning the vehicles that use the bridge for business reasons that happen on a regular basis. For cars both bridge pass business and bridge pass commuter are of interest. This is mainly because the daily commuting traffic to and from work is one of the biggest contributors to the traffic. Excluded in both vehicle classes are one time only payers and other variations of the bridge passes since it is uncertain that they have the regular driving pattern that is necessary for this study.

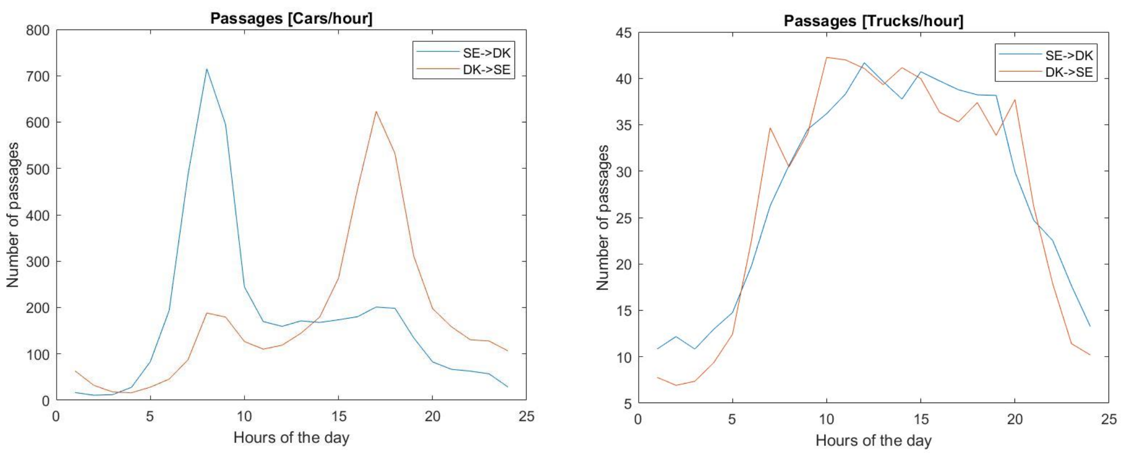

Figure 7. (a) Daily variation for car traffic. *(b) Daily variation for truck traffic*

Figure 7 (a), shows the variation during a day for cars. It shows a clear commuting pattern in which there are two spikes in traffic flow during the morning and in the afternoon. On average 4 240 trips are made daily in each direction. It also shows that the commuting is mainly from SE to DK and not the other way around. Figure 7 (b), shows daily variations for trucks. Unlike figure 7 (a), the same spikes in traffic doesn't appear but instead a steady traffic flow throughout the day with diminishing traffic during the night. On average almost 700 trips are made daily in each direction. In both cases it is unclear if each of these trips are made with individual vehicles or the same vehicles going back and forth possibly multiple times a day but it shows predictable patterns that correspond to a normal workday.

As an assumption and simplification, it is assumed throughout this report that the 700 and 4 200 trips in each direction are made by 700 trucks and 4 200 cars going back and forth one time each day. Adding more vehicles would only be an estimate. Assuming a lower number of vehicles also assumes less vehicles to share the cost of the road, which is something to keep in mind. Overestimating the traffic flow would only give a false depiction of the traffic flow whilst underestimating it only serves as a “worst-case” scenario.

2.1.2 Ratio between heavy duty trucks and light duty trucks

The data from 2019 doesn’t distinguish between HD (from 10 tons and up) and LD (below 3.5 tons) trucks. For that reason, a ratio between these two vehicle classes has been introduced. It is based on the number of vehicles that have driven at least 10 km during the year 2020 and is registered in Sweden’s transportation register. The result of this is that there are 7.6 times more LD trucks than HD trucks (Trafikanalys 2021).

2.1.3 Haulage contractors’ traffic

Further traffic data has been supplied by a couple major haulage contractors that have agreed to be a part of this study. This is important since the data from 2019 doesn’t say much about which type of vehicle is driven or where the vehicle is going. The haulage contractors have provided this data.

What it has shown is that a lot of the HD traffic that goes across the bridge either arrives from south of Denmark, Germany or Poland and drives to either Stockholm or central Sweden. These are trips that can easily surpass 1 000 km of distance. If a fuel consumption of 1.5 kWh/km is assumed, a trip would equal 1 500 kWh. Assuming that they charge whilst driving across the bridge, the small amount of energy that can be charged compared to the total amount needed is basically nothing. Therefore, the more important trips are those that are closer to the border between Sweden and Denmark.

With the data from these companies, a drive cycle, that is similar to real trips, is used to represent these vehicles typical day. Depending on the size of the vehicles, they usually have different tasks and routes described below. It is based on the data and experience gained from the haulage contractors. It is assumed that all vehicles that connect to the ERS would drive these cycles, or similar in terms of distance. At each stop there is a potential static charging opportunity.

2.1.3.1 Heavy-Duty truck

The drive cycle for the HD trucks starts in Sweden around 15 km from the bridge. From there it drives across the bridge for 20 km into Denmark for a first 30 min stop. Afterwards it continues for 33 km further into Denmark for another 30 min stop before driving back towards Sweden. This trip is done once a day.

2.1.3.2 Light-Duty truck

The drive cycle for a LD truck starts at the same point as for HD trucks. It crosses the bridge into Denmark and drives for around 15 km and then stops for an hour. After the stop it drives back to the same spot as it started. This is done twice a day, representing a shorter, more frequent route.

2.1.3.3 Car

The car is meant to represent commuting traffic for work between Sweden and Denmark. Most commuting traffic is from Sweden to Denmark, which is the chosen direction for this drive cycle. The car drives from Malmö, around 15 km from the bridge to Copenhagen where it stops for 9 hours, meant to represent a work day. After the 9 hours it drives back to Malmö. This is done once a day.

2.2 Simulation of vehicles

The simulation of vehicles driving across the bridge serves as an important tool in understanding how much energy can be charged, and therefore which vehicles or trips would benefit from connecting to a potential ERS. This is done with the help of a model of the bridge and the ERS, being run in Simulink.

2.2.1 Model of the bridge

The model of the bridge contains information about the length and height variations, see figure 8 for an overview of the bridge. The model works a matrix containing the time and distance travelled, as well as the height and slope at each step of the way. Assuming a constant speed of 80 km/h the matrix will contain 718 rows based on the length of the bridge. The first column is the time, which in this case has an interval of 1 second. The second column is the speed reference which is set at 80 km/h or 22.2 m/s. The third column is the total distance driven which can be calculated by the velocity multiplied with the time and the fourth column contains the altitude, see bottom of figure 8. The fifth column is the slope which is calculated by the current height subtracted by the previous height and then divided by the distance between them.

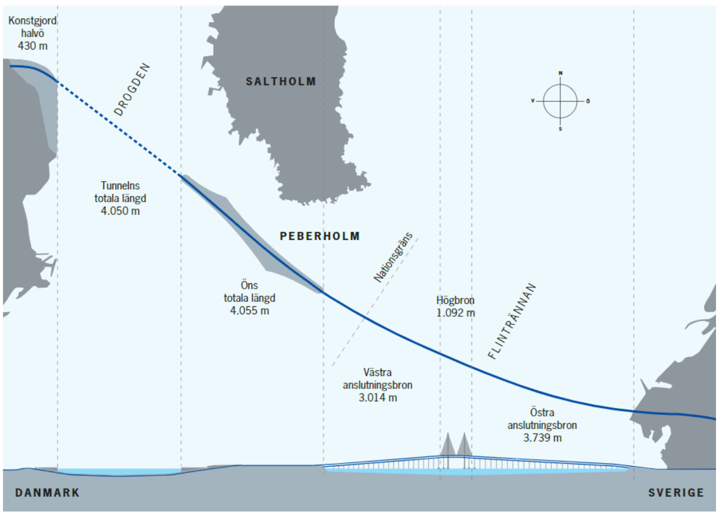

Figure 8. Overview of the bridge of Öresund (Øresundsbro Konsortiet 2005)

2.2.2 Model of the ERS

The ERS is represented as a power P_{ERS}, which is the maximum available power that a vehicle can use from the ERS. The power is primarily used to propel the vehicle forward, in other words compensate for the drive power, and secondly to charge the vehicle. Furthermore, the charging of a vehicle is set to a maximum of 2 C-rate, meaning if a vehicle has a battery size of 100 kWh it can charge at maximum $100 \text{ kWh} * 2 \text{ h}^{-1} = 200$ kW. The layout of an ERS is usually specified by the constants d_{ERS} and k_{ERS}, where d_{ERS} is the length of a repeating segment and k_{ERS} is the percentage of electrified road to non-electrified road of that segment. However, since the bridge of Öresund is short compared to a normal highway these can be ignored. ERS works best in uphill climbing or on a flat surface. The drive power going downhill is usually negative and the battery can be charged by regenerating that power. Regenerating the battery downhill is more efficient than having an ERS downhill and trying to feed back that power into the grid. This is why ERS is assumed to be covering every flat and uphill surface and not covering the downhill surface. This means that all flat surfaces will have ERS in both directions whilst all slopes only have one direction with ERS, the uphill one. If ERS is covering both lanes, the power is simply added to each other, assuming the same connection point to the grid.

The ERS is both connected and activated in segments. Driving across it only activates a shorter segment, usually below 100 m, whilst the connecting segment is assumed to be 1 km long. The road is then divided into separate segments of 1 km where the power for all vehicles driving across at the same time are added together.

2.2.3 The different vehicle classes

Three different vehicle classes will be used throughout this report and will be presented below, see table 1. These are what is used to simulate the vehicle driving on the bridge and charging from the ERS when possible.

Table 1. The different vehicle classes with ERS

	Heavy Duty Truck	Light Duty Truck	Car
Weight [Tons]	20	3.5	1
Speed [km/h]	80	80	80
Battery size with ERS [kWh]	150	40	30
Battery size without ERS [kWh]	400	80	70
Wheel radius [m]	0.506	0.506	0.3
Drag coefficient [-]	0.6	0.5	0.29
Roll resistance coefficient [-]	0.0032	0.0025	0.007
Front Area [m^2]	2.55*3.8	2.2*2.8	1.545*1.805
Max Speed [km/h]	90	120	167
Traction machine power [kW]	450	450	150
Number of gears	4	4	4
Auxiliary power [kW]	3	3	1.7

2.2.4 Simulation program

The different vehicle classes are run through a simulation program in MATLAB Simulink, see figure 9 for an overview. This is a program that has been developed and used at LTH for around a decade and has proven to give accurate results. It is used in the course EIEN41, Electric and Electric Hybrid Vehicle Technology.

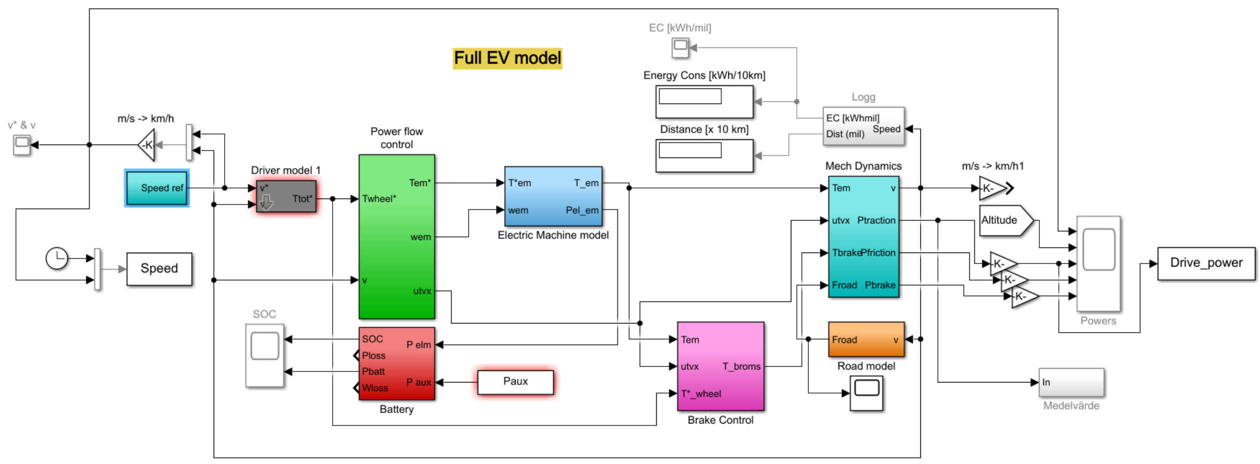

Figure 9. Overview of the simulation program

It is based on the drive cycle that is explained in chapter 2.2.1. On the left side in figure 9 is the speed reference which goes into the driver model. The speed reference is based on the wanted speed and the slope of the drive cycle. The driver model functions as a driver to the extent that it looks at the speed reference and the actual speed and either accelerates or decelerates based on that. It also calculates the change in torque which is the output Ttot*. The torque is fed into the power flow control. The power flow control uses the wheel speed and the torque to calculate the tractive power and chooses an optimal operating point. That in turn selects which gear the vehicle should be operated in and calculates the electric machine torque. The electric machine model then calculates the electrical power needed from the battery from the shaft power and the efficiency. The battery uses the electrical power and the auxiliary power to calculate the State of Charge (SoC). The last thing needed to calculate the drive power is the road model. It uses the vehicle weight and roll resistance coefficient to calculate the roll resistance and the drag coefficient, frontal area and the speed to calculate the air resistance.

2.3 Charge and electric grid load

The amount of energy that can be charged from the ERS is an important factor when analysing the potential of an ERS. With the help of the simulation of the vehicles explained above, the drive power can be estimated at every second of the cycle. The charging is a function of the drive power, vehicle weight and the power from the ERS, P_{ERS}. The charge can be calculated as the integral of the difference between the P_{ERS} and the drive power, in other words the remaining power available after supplying the power needed to propel the vehicle forward. Included here is a maximum charge of a 2 C-rate.

The integral only counts the segments that include ERS which leaves out the downhills as explained before. This is done for a number of varying vehicle weights and P_{ERS} to see how these two factors influence the charging. The electrical grid load can be calculated as the integral of the drive power and charging power, where ERS is present. The max load at any given time is P_{ERS}, meaning if the drive power exceeds that amount, the remaining power is supplied by the battery. The results of this are presented down below for each vehicle class.

2.3.1 Heavy-Duty Truck

The standard case for a HD truck is a vehicle weight of 20 tons and a P_{ERS} of 300 kW. In figure 10 is the simulation from a) Sweden to Denmark and b) Denmark to Sweden. The orange line is the drive power. It is higher in the beginning, as the vehicle has to accelerate to the wanted speed, and during uphill climbing, and lower at the flat surfaces and downhill. The blue line is either 0 or 300 kW based on if ERS is present. The yellow line is the charge, which is P_{ERS} subtracted by the drive power.

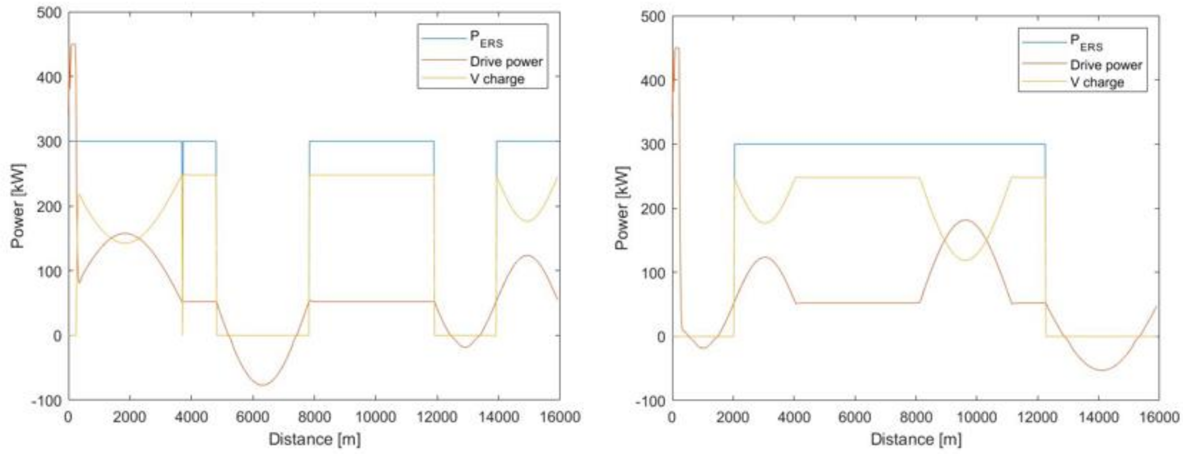

Figure 10 (a) Simulation of HD truck from SE to DK.   (b) Simulation of HD truck from DK to SE

The amount that can be charged from SE to DK is 28.6 kWh and the amount that can be charged from DK to SE is 27.4 kWh. By varying the variables vehicle weight between 10 and 20 tons with an interval of 1 ton, and P_{ERS} between 100 and 500 kW in intervals of 100 kW, the charge vary, as can be seen in figure 11. The result shows that the charge vary from around 5 – 55 kWh, mainly because of the varying available power, P_{ERS}. The vehicle weight, although less of an effect, changes the charge. The heavier the vehicle the higher the drive power is and less power can be charged.

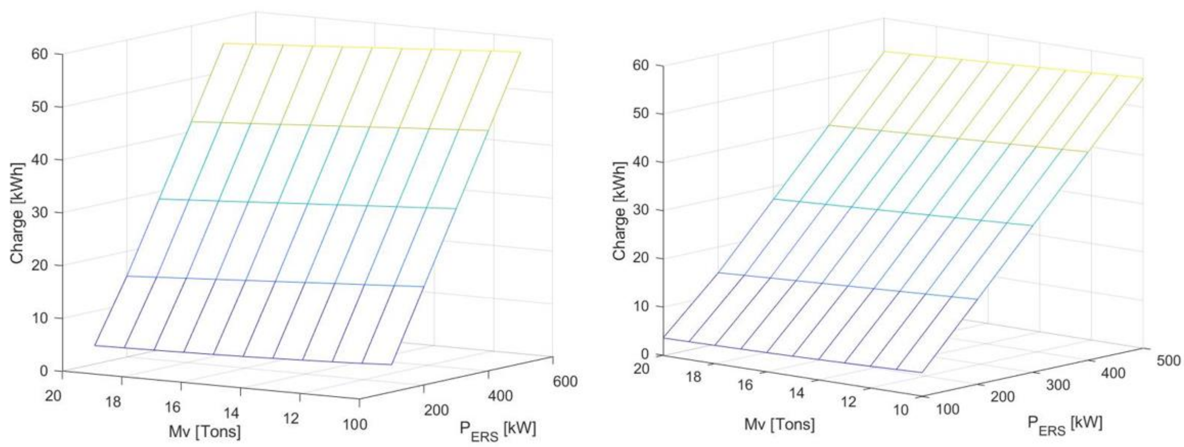

Figure 11. Simulation varying vehicle weight (Mv) and power (P_{ERS}) from SE to DK (left) and DK to SE (right)

2.3.2 Light-Duty Truck

The standard case for a LD truck is a vehicle weight of 3.5 tons and P_{ERS} of 300 kW. In figure 12 is the simulation from a) Sweden to Denmark and b) Denmark to Sweden.

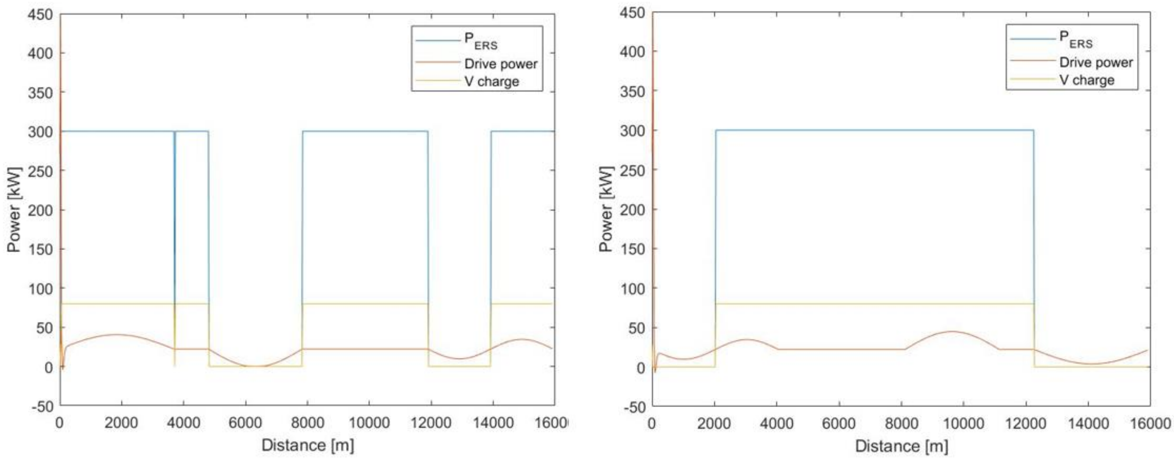

Figure 12 a) Simulation of LD truck from SE to DK.   b) Simulation of LD truck from DK to SE

The amount that can be charged for a LD truck from SE to DK is 10.8 kWh and from DK to SE is 10.2 kWh. Despite the smaller vehicle the charge is lower than for the HD truck. This is because of the smaller battery that limits the charging power. In figure 13 the vehicle weight varies between 2 and 3.5 tons with intervals of 0.5 tons and P_{ERS} between 100 and 500 kW in intervals of 100 kW. Unlike the HD truck, the charge doesn't increase after P_{ERS} exceeds 200 kW which again is because of the smaller battery size. The charge now only varies between 9.2 and 10.8 kWh.

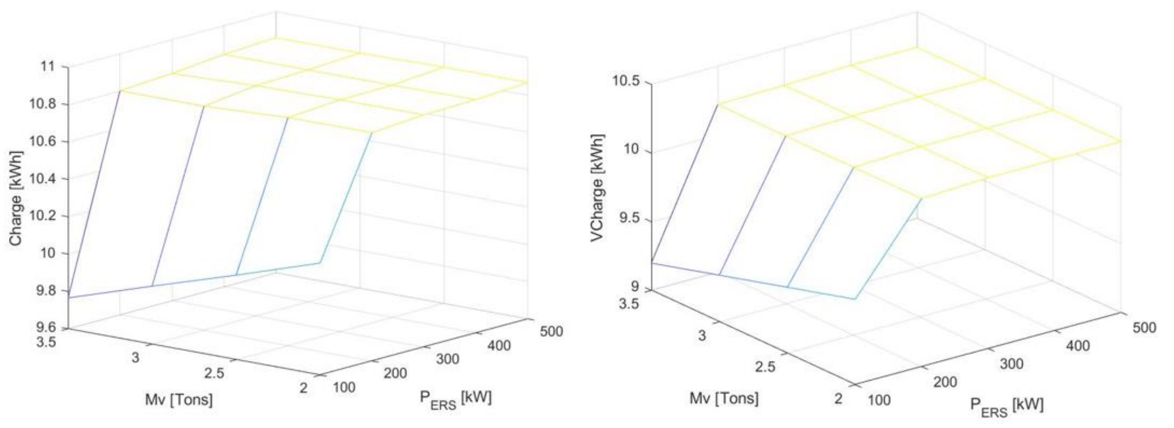

Figure 13. Simulation varying vehicle weight (Mv) and power (P_{ERS}) from SE to DK (left) and DK to SE (right)

2.3.3 Car

The standard case for a car is a vehicle weight of 1 ton and P_{ERS} of 300 kW. In figure 14 is the simulation from a) Sweden to Denmark and b) Denmark to Sweden.

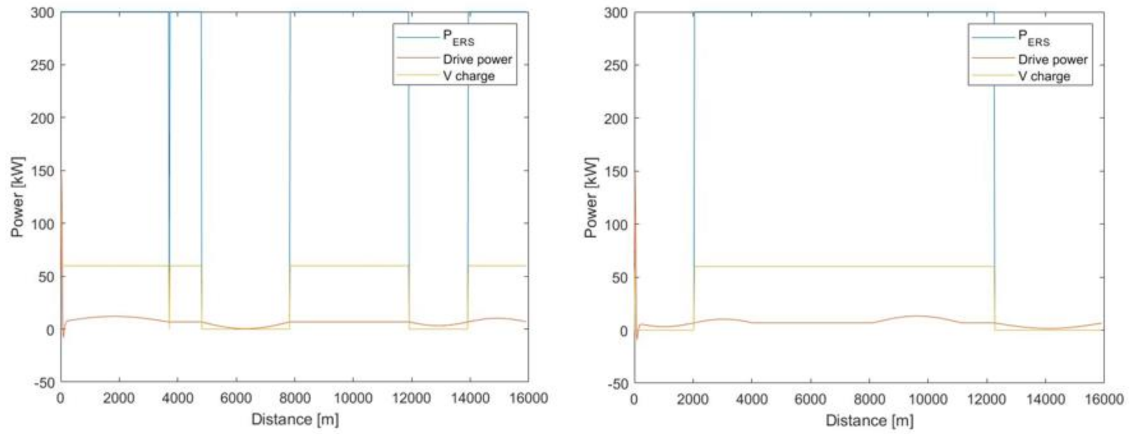

Figure 14 a) Simulation of car from SE to DK. *b) Simulation of car from DK to SE*

The amount that can be charged for a car from SE to DK is 8.15 kWh and from DK to SE is 7.68 kWh. In figure 15 the vehicle weight varies between 0.6 and 1 tons with intervals of 0.1 tons and P_{ERS} between 100 and 500 kW in interval of 100 kW. The charging amount varies from 7.6 kWh to 8.2 kWh. As explained for the LD truck, the smaller battery size again limits the charging.

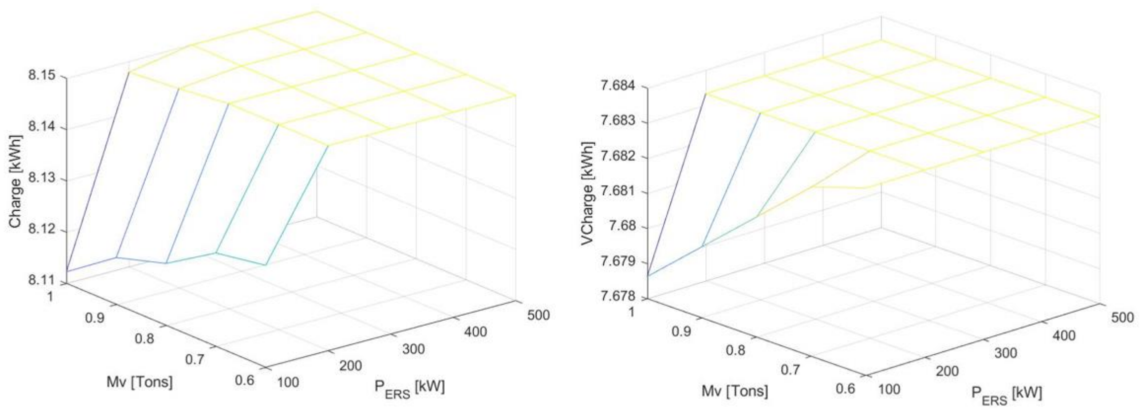

Figure 15. Simulation varying vehicle weight (Mv) and power (P_{ERS}) from SE to DK (left) and DK to SE (right).

2.4 Electric grid modelling

The feasibility of implementing an ERS heavily relies on the electricity supply. The ERS is connected in segments of 1 km, which means that the power to all the vehicles on that segment need to be provided at the same time. Both the traffic flow and the current electricity supply are important factors when analysing the implementation of ERS.

The simulations explained above provides a power profile for each type of vehicle in both directions of the way. This means that the power load is known for each second driving across the bridge, or each 22 meters assuming a speed of 80 km/h. By sorting theses power profiles into 1 km segments, the power accompanied to each ERS segment is attained. Finally, the number of passings per hour, attained from the data from 2019, is multiplied with the power profile depending on the directions and vehicle and also multiplied by 1/80. Assuming a speed of 80 km/h means that if the vehicles passing are spread equal during the hour, they will each spend 1/80 of an hour on a specific ERS segment.

2.4.1 Electric supply to the bridge

The electrical supply to the bridge of Öresund can be split up into two separate parts, the road traffic and train traffic. The electrical systems are separated and since the ERS is based on the road traffic, the electrical system of the trains is ignored in this report. The electricity to the bridge is modelled such that the power is provided from the Swedish side. The Danish side works as a backup in case of a blackout or similar faults were to happen on the Swedish side. The main electricity consumers on the bridge are the lights and the gate area, whilst in the tunnel more systems, such as air condition, fire systems and heating/cooling, are present which raises the consumption. Because of that, the transformers in the tunnel have a higher rating. However, several energy improvements such as switching and removing lights, have made them over dimensioned to what is currently being used. What is still very important is that the security systems still have the main priority when there is a fault. The ERS could be turned off during faults, or only supplying the vehicles who don't have enough charge to make it across the bridge when there is a fault.

Presented below in table 2 and figure 16 are the transformer stations positions, ratings and normal consumption.

Table 2. Transformer stations rating and normal consumption.

Station	Transformer rating [kVA]	Normal consumption [kW]
ST1	2 500	178
ST1*	2 500	49.7
ST2	1 000	78.7
ST3	1 000	51.8
ST4	2 000	46.2
ST4*	2 000	39,3
ST5	500	51.1
ST5*	500	53.1
ST6	315	36.8
ST7	315	30.8
ST8	500	29.7
ST9	500	34
ST10	400	22.3
ST11	315	27.6
ST12	500	142.6
ST12*	500	156.9

. Some transformer connections have two separate transformer stations connected to them denoted by

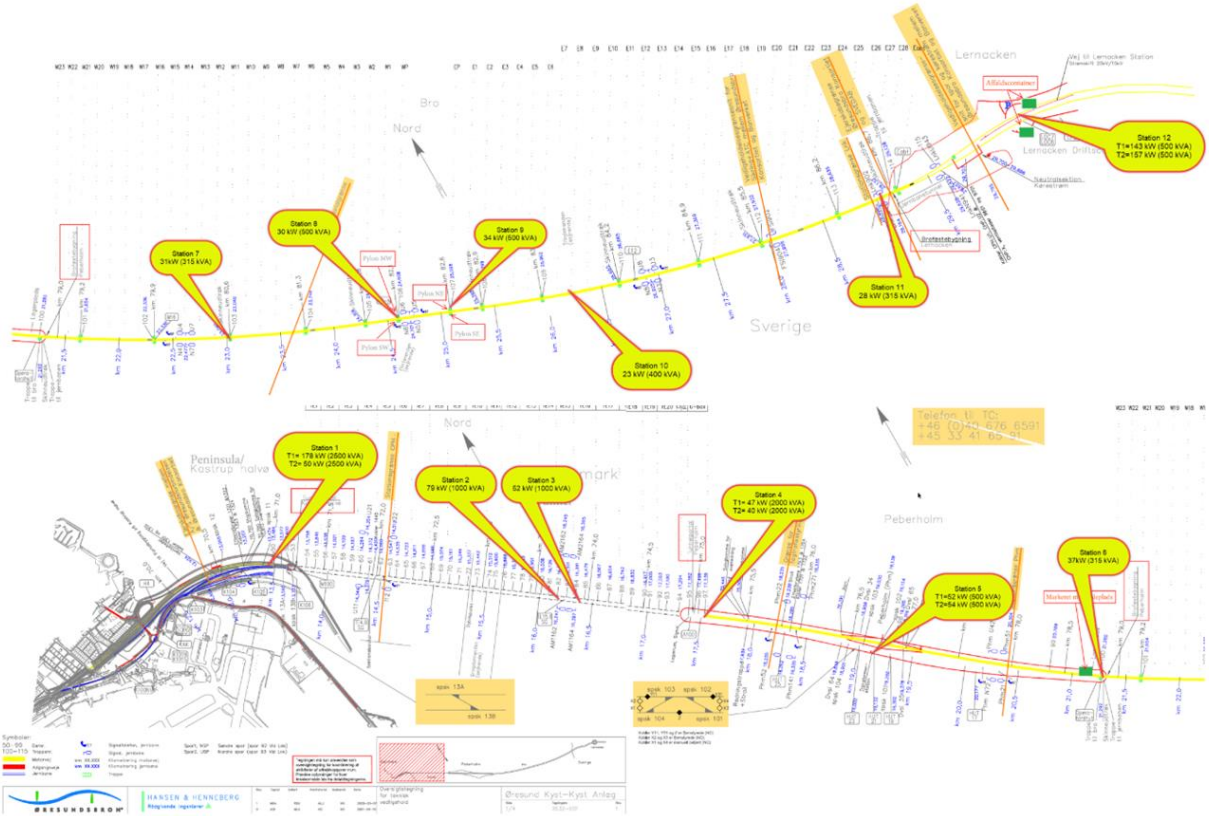

Figure 16. Layout of the transformer stations on the road.

2.4.2 Assumptions

As previously mentioned, the ERS is connected in segments of 1 km. Each segment is then connected to a transformer close by that have the most available power. When simulating the traffic flow, multiple vehicles will be on the road at the same time and at the same segment. The traffic data shows the number of trips during an hour. Assuming all the vehicles drive at 80 km/h, they will spend 1/80 of an hour on a specific segment of the road. Furthermore, if ERS is present on each side of the road, the power from the two sides is simply added together and assumed to be connected to the same transformer.

2.5 Cost modelling

The implementation of an ERS comes with a variety of different costs, and a lot of different assumptions. This part presents these costs and assumptions. The result of the cost modelling is presented as a financial analysis, where the cost of an infrastructure involving ERS is compared to a system reliant on static charging.

2.5.1 Batteries

The battery size is different in all the vehicle classes. However, it is also different depending on if ERS is active or not. If all major roads were to be covered in ERS, the battery size can be reduced by up to 80%, but it is also a question of the power density in batteries and being able to propel the vehicle forward in all conditions. Listed in table 3 are the different battery sizes for the different vehicle classes. Lastly, the battery is assumed to cost 1 000 SEK/kWh, with a life expectancy of 15 years (Alaküla 2019a).

Table 3. Battery size and cost for the different vehicle classes.

Vehicle class	Battery size [kWh]	Cost [SEK/(year*vehicle)]
HD Truck (No ERS)	400	26 667
HD Truck (ERS)	150	10 000
LD Truck (No ERS)	80	5 333
LD Truck (ERS)	40	2 667
Car (No ERS)	70	4 667
Car (ERS)	30	2 000

2.5.2 Static chargers

Static charging is used to charge up the vehicles when standing still at the terminals. It is mainly used in the cases not involving ERS, but can also complement ERS on the longer trips where extra charging is needed. It is assumed that a fast charger has a charging power of 150 kW, but the vehicles are still capped at a 2-C charge rate. It is also assumed that the cars have a smaller static charger at home, which has a charging power of 11 kW. The cost of a fast charger is assumed to be 6 000 SEK/kW, with a life expectancy of 15 years. Based on the time that vehicles spend on the road versus in the terminals, it is assumed that 20 linehaul vehicles share the cost of the static chargers. For the remaining traffic, one static charger is needed per 100 EVs, which means 100 passenger cars share the cost of a static charger. The static charger at home, with a power of 11 kW, is shared by a singular vehicle (Alaküla 2019a).

The static charging is placed in a way that the SoC never drops below 20%. If that is the case, either more static chargers are introduced, longer stops are made or a bigger battery is chosen. When analysing linehaul traffic, time is always important, hence longer charging stops are not the chosen method to charge up the vehicle. If possible, a static charger is added to another terminal otherwise a bigger battery is chosen.

2.5.3 ERS

The ERS has two major costs. The obvious one is the road itself. The road is assumed to cost 10 MSEK/km, with a life expectancy of 20 years. It includes one lane one each side of the road. Furthermore, 70% of the road is assumed to be covered with ERS, the rest being downhill. The sharing of the cost is based on the amount of charging in kWh´s. A HD truck, that charges more than a car, also pays a higher share and vice versa. The second cost is the pick-up system on each vehicle. An EV needs to be modified with a pick-up system to be able to connect to the ERS and charge from the road. This cost is assumed to be 30 000 SEK per vehicle with a life expectancy of 15 years (Alaküla 2019a).

2.5.4 Transformer stations

Depending on the electric load of the simulations, an additional cost of upgrading the current electric grid system might be needed. To simplify, only the cost of the actual transformer stations is included and not the cables, net stations or ground work etc. These costs are based on an industry used standard value list. It is used by the entire industry for all electrical equipment costs as a way of making sure no one is charging higher prices. These costs are presented in table 4. A transformer station is assumed to have a life expectancy of 40 years (ABB n. d).

Table 4. Costs of transformer stations

Transformer rating [kVA]	*Cost as of 2018 [SEK]*
2 500	*344 842**
1 250	*219 704*
1 000	*156 969*
800	*133 135*
500	*98 482*
315	*80 071*
200	*60 628*

**The 2 500 kVA transformer station wasn't included in the list. Source: (SecondSol n. d)*

2.5.5 Scaling factor

The cost modelling is based on assumptions regarding battery sizes, density of static chargers and the cost of the ERS infrastructure etc. Therefore, a scaling factor is introduced to vary the distances between each point and the bridge of Öresund. The reason for this is to see what effect the distances driven and between each point have on the need for battery sizes and density of static charging. The scaling factor is a factor that changes all the variable distances by the same factor. The distances that aren't affected is the length of the bridge since it is considered constant. By changing the distances that is driven, more vehicles could be connected to the ERS, but also the energy consumption and charging need changes. By then varying the distances, the density of static chargers or battery size has to change in order to not go below 20% SoC. Changing either battery size or static charging changes the results of the study and functions as a sensitivity analysis in this report.

3. Result and Analysis

The result will be presented in terms of three different traffic scenarios. The first one is a break-even scenario. It is based on the amount of traffic that is needed for the ERS to break even with the static charging scenario. The second and third scenario is based on simulating all traffic across the bridge. The difference between them is how the HD traffic is split up. The second scenario assumes that all passing trucks are HD trucks, whilst the third scenario assumes that the HD traffic is split in a 1:7.6 ratio between HD trucks and LD trucks as explained in chapter 2.1.2.

The results itself consists of an electric power load simulation, a financial analysis and a sensitivity analysis using the scaling factor. How the result is presented varies slightly between the break-even scenario and the others. To add the cost of the transformers to the financial analysis the electrical power load simulation is required. However, for this the traffic flow has to be known but for the break-even scenario the traffic flow is the result of the financial analysis. This is solved by first doing a financial analysis and simulating the traffic flow to then add the transformer stations and doing it again.

What is important to remember is that the peak load that is used is the average during the peak hour. This is because the traffic data only shows traffic flow per hour. What this means is that the transformer stations shouldn't be dimensioned to sustain the peak hour load. The peak load might be higher at any given time during that hour and lower at some. The traffic flow at any given second is unknown. It is therefore important to over dimension the transformers so that they can sustain the peak load at any given time.

3.1 Case 1: Break even

The first scenario is the break-even scenario. In this scenario it is assumed that only trucks are electrified and that the ratio of 1:7.6 between HD and LD trucks exists. Both these vehicles have their own drive cycle previously explained in chapter 2.1.3, their parameters in chapter 2.2.3 and the related costs in chapter 2.5. Since the traffic flow for this scenario is unknown to start with, the electrical load is unknown as well. Because of this the cost of the transformer stations are neglected at first.

3.1.1 Financial analysis

Without ERS it is assumed that all terminals are equipped with static chargers with a power of 150 kW. With ERS it is assumed that the HD trucks still have two out of three terminals equipped with static charging whilst the LD trucks have one out of 2 terminals equipped with static chargers.

The number of vehicles needed to break even is calculated as follows:

$$C_{ERS} + N_{HD}\left(C_{batt\_ERS\_HD} + C_{stat\_ERS\_HD} + C_{pick-up\_ERS\_HD}\right) + N_{LD}\left(C_{batt\_ERS\_LD} + C_{stat\_ERS\_LD} + C_{pick-up\_ERS\_LD}\right) = \\ = N_{HD}\left(C_{batt\_HD} + C_{stat\_HD}\right) + N_{LD}\left(C_{batt\_LD} + C_{stat\_LD}\right)$$

$$N_{LD} = 7.6 * N_{HD}$$

$$=> N_{HD} = \\ = \frac{C_{ERS}}{C_{batt\_HD} + C_{stat\_HD} + C_{batt\_LD} + C_{stat\_LD} - (C_{batt\_ERS\_HD} + C_{stat\_ERS\_HD} + C_{pick-up\_ERS\_HD} + 7.6(C_{batt\_ERS\_LD} + C_{stat\_ERS\_LD} + C_{pick-up\_ERS\_LD})}$$

Where C is the cost of the different parameters and N the number of vehicles. The result of the financial analysis is that 150 HD trucks and 1 140 LD trucks are needed for the ERS to break even with static charging.

3.1.2 Electric load simulation

The electric power load is based on the amount of traffic from the financial analysis, in other words the 150 HD trucks and 1 140 LD trucks. They are assumed to follow the pattern of all passing HD traffic but scaled down to the correct number of vehicles. The result can be seen in figure 17. What the result shows is the average power in kW during the hours of the day. Each line is a specific km segment of the road, which is how the ERS is connected. It can be seen that all segments follow the same pattern because it is the same traffic flow. The variations depend on the drive power during that segment. The segments with almost double the power are the flat surfaces which has ERS in both directions. During the slowest hours of the day the power is around 50 - 100 kW whilst during the busiest hours of the day, the power is around 250 - 450 kW. The reason that this is not higher is that it is unlikely that the vehicles will be at the same segment at the same time. 150 HD trucks passes the bridge 300 times in total. Each passing spends 1/80 of a hour, or 1/(80*24)=1/1920 of a day on one ERS segment. On average that is less that one truck at each segment, hence the low average power during an hour.

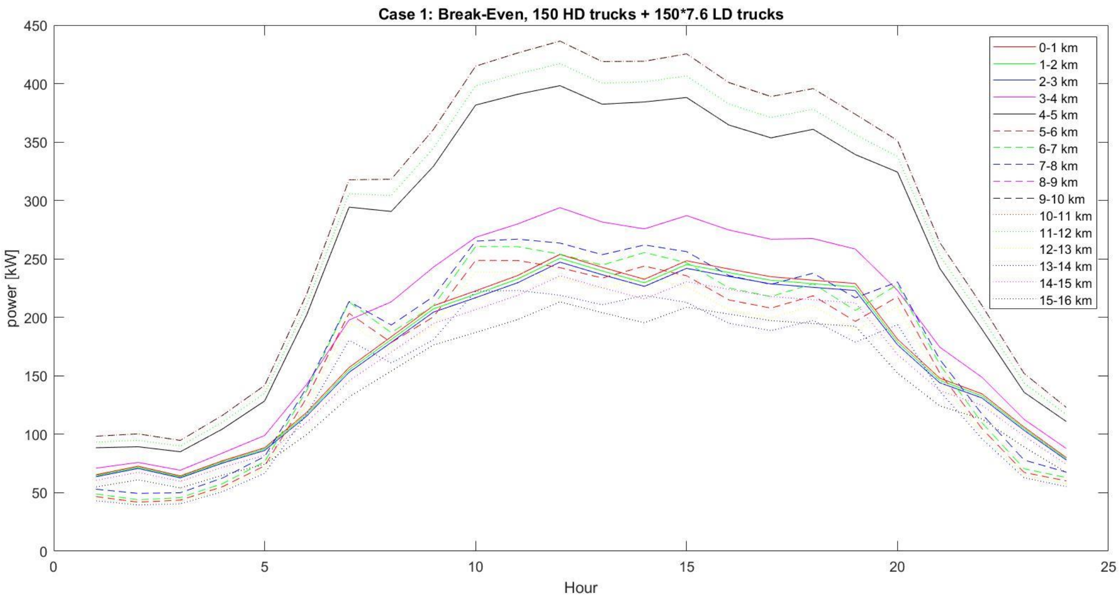

Figure 17. Electric grid load per km, case 1

The transformer stations need to be dimensioned to sustain even the highest load of the day, which is why the peak values are used for each road segment. The result can be seen in table 5 and table 6. In total, the peak value of all segments equals almost 4.9 MW.

Table 5: Peak load of each km-segment and its connection point:

Road segment [km from SE]	Peak load [kW]	Connection to ST
0 -1	253.9	ST12
1-2	250.6	ST11
2-3	247.2	ST10
3-4	293.9	ST10
4-5	398.2	ST9
5-6	248.8	ST8
6-7	260.6	ST7
7-8	266.9	ST7
8-9	436.4	ST6
9-10	436.4	ST5
10-11	436.4	ST5
11-12	417.1	ST4
12-13	239.1	ST4
13-14	223.1	ST3
14-15	235.6	ST2
15-16	213.3	ST1
Total	**4 857**	

Table 6: Connection points capacity and cost of upgrading the transformers

Transformer station	Available capacity [kW]	Available capacity – Load from ERS [kW]	Cost [SEK]
ST1	4 772.3	4 559	-
ST2	921.3	685.7	-
ST3	948.2	725.2	-
ST4	3 914.5	3 258	-
ST5	895.8	22.7	*98 482 (500 kVA)*
ST6	278.2	-158.2	*98 482 (500 kVA)*
ST7	284.2	-243.3	*98 482 (500 kVA)*
ST8	470.3	221.5	
ST9	466.0	67.8	*98 482 (500 kVA)*
ST10	377.7	-164.1	*98 482 (500 kVA)*
ST11	287.4	36.8	*98 482 (500 kVA)*
ST12	700.5	446.6	-
Total	**14 316.4**	**9 484.7**	**590 892**

As can be seen in table 6, a few transformers are under diminished and need to be switched which would equal a total cost of 590 892 SEK, which is 14 772 SEK/year. This is added to the financial analysis which changes the amount of traffic needed for it to break even from 150 HD trucks and 1 140 LD trucks to just over 150 HD trucks. The reason for this is that the cost of the transformer stations is only 0.3% of the cost of the ERS infrastructure and therefore don't have a big effect on the result.

3.1.3 Sensitivity analysis

The sensitivity analysis is a tool to check how the assumptions that are made in the financial analysis impact the result. The scale of all lengths will change with a factor, here called the scaling factor, see chapter 2.5.5. When the distances change, the SoC might go beneath 20% which is not desired. Hence a bigger battery or more charging is required which are additional costs. The scaling factor will change between 1, 2 and 3 and the result in terms of how many trucks are needed for the systems to break even is presented in table 7.

Table 7. Change in result based on the scaling factor

Scaling factor	Number of trucks [HD/LD]
1	150/1 140
2	196/1 492
3	313/2 383

It is mainly the HD trucks that are impacted by the change in distance. This is because of the higher energy consumption that requires bigger batteries or more charging. However, without ERS the battery size already is 400 kWh and it is not realistic to install even bigger ones. Instead, the time at the terminals is increased which doesn't add any costs. For the case with ERS however, more static charging is added and secondly a bigger battery is choses. This is the reason that the number of trucks needed for it to break even increases with increasing scaling factor.

3.2 Case 2a: All traffic

The second scenario is based on all traffic flow. It is assumed that all trucks and cars are electrified and that all passing trucks are HD trucks. Since the traffic now is known from the start the financial analysis will come after the electric load simulation and will include the potential cost of upgrading the electrical system. The traffic consists of 700 HD trucks and 4 200 passenger cars making one trip a day in each direction.

3.2.1 Electric load simulation

The result of the electric load simulation can be seen in figure 18 and table 8. The impact on the electrical system can be seen in table 9. The load has two peaks at around 8 and 18 hours. This is because of the commuting traffic to and back from work that the passenger cars are mainly responsible for. The peak load exceeds 1 000 kW´s for most road segments and because of the higher peaks, the electrical system needs improvements. It is assumed that the new transformers are added to the previous ones. The total cost of the improvements is 2 66 336 SEK, which is added to the financial analysis. Finally, the total load for all road segments would equal 22.7 MW.

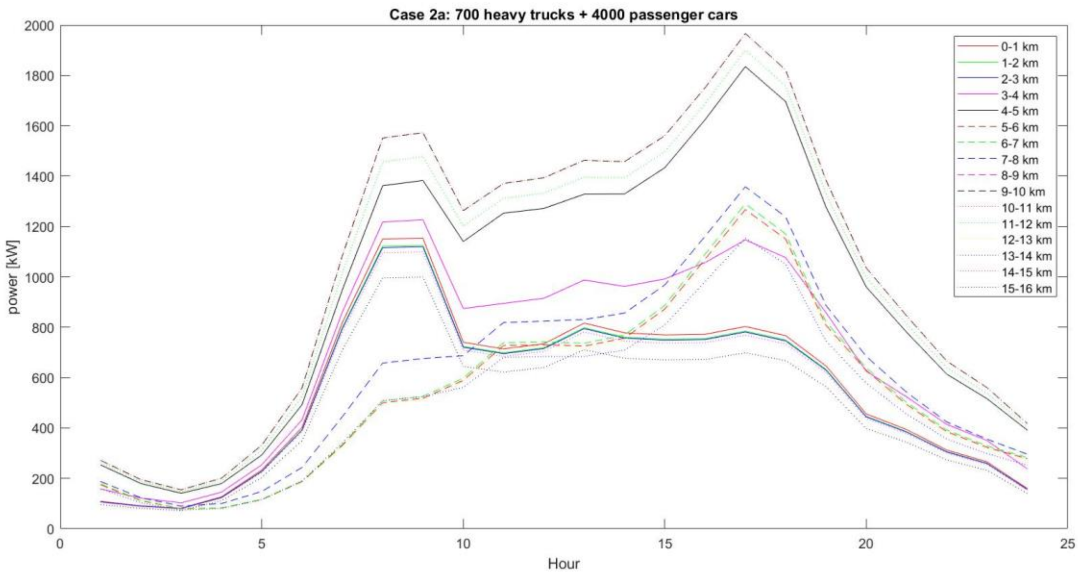

Figure 18. Electric grid load per km, case 2a

Table 8: Peak load of each km-segment and its connection point:

Road segment [km from SE]	Peak load [kW]	Connection to ST
0 -1	1 154	ST12
1-2	1 125	ST11
2-3	1 119	ST10
3-4	1 227	ST10
4-5	1 835	ST9
5-6	1 267	ST8
6-7	1 290	ST7
7-8	1 358	ST7
8-9	1 967	ST6
9-10	1 967	ST5
10-11	1 967	ST5
11-12	1 901	ST4
12-13	1 249	ST4
13-14	1 154	ST3
14-15	1 099	ST2
15-16	999	ST1
Total	**22 678**	

Table 9: Connection points capacity and cost of upgrading the transformers

Transformer station	Available capacity [kW]	Available capacity – Load from ERS [kW]	Cost [SEK]
ST1	4 772.3	3 773	-
ST2	921.3	-177.7	*98 482 [500 MVA]*
ST3	948.2	-205.8	*98 482 [500 MVA]*
ST4	3 914.5	764.5	-
ST5	895.8	-3 038	2**344 842 [2*2 500 MVA]*
ST6	278.2	-1 689	2**156 969 [2*1 000 MVA]*
ST7	284.2	-2 364	344 842 *[2 500 MVA]*
ST8	470.3	-796.7	*156 969 [1 000 MVA]*
ST9	466.0	-1 369	2**133 135 [2*800 MVA]*
ST10	377.7	-1 968	*344 842 [2 500 MVA]*
ST11	287.4	-837.6	*219 704 [1 250 MVA]*
ST12	700.5	-453.5	*133 135 [800 MVA]*
Total	**14 316.4**	**-8 361.8**	***2 666 336***

3.2.2 Financial analysis

Unlike case 1, the result will not be presented in number of vehicles since they are constant. Instead, it is presented as cost/year for the entire systems of vehicles and infrastructure, see table 10. The cost of the ERS-case with the assumptions made, is lower than without ERS. The main cost reduction is for the HD trucks, where the batteries is the main difference. The difference for the passenger cars is not as big but again it is the batteries that save the most money.

Table 10. Result of the financial analysis, case 2a

Without ERS	Cost without ERS [SEK/year]	Cost with ERS [SEK/year]	Number of vehicles
HD truck	22 446 667	14 996 524	700
Passenger car	32 200 00	30 321 476	4 200
Transformers	-	66 658.4	
Total	**54 646 667**	**45 384 658**	**4 900**

3.2.3 Sensitivity analysis

The result of the sensitivity analysis can be seen in table 11. The cost of the system without ERS is not increasing, but instead the time at each terminal is increased. Although not wanted, it is not realistic to install bigger batteries. For the case with ERS the battery is increased as the distances are further apart. When the scale factor is increased to 3, the battery size for the HD truck has increased to 325 kWh as to the start value of 150 kWh. Beyond that point it is more expensive with ERS since the distance becomes too far for the trucks to drive to the start of the bridge without having to charge beforehand.

Table 11.: Change in result based on the scaling factor

Scaling factor	Total cost without ERS [SEK/year]	Total cost with ERS [SEK/year]
1	54 646 667	45 384 658
2	54 646 667	48 882 658
3	54 646 667	53 551 325

3.3 Case 2b: All traffic with 1:7.6 ratio

The third and final scenario is similar to scenario 2a. However, instead of all trucks being HD trucks it is now a ratio of 1:7.6 between HD and LD trucks. This means that out of the 700 trucks, 81 are HD and 619 are LD trucks. The same methodology applies to this scenario as the previous one.

3.3.1 Electrical load simulation

The result for the electrical load simulation for case 2b can be seen in figure 19. The pattern is very similar to case 2a because it uses the same traffic flow, although scaled to the correct number of HD and LD trucks. However, the power is now slightly lower. This is the effect of replacing HD trucks with LD trucks that charge less. The difference per trip is higher but since the LD trucks drive across the bridge twice as many times, the difference is only minimal. This, as can be seen in table 12 and 13, doesn't affect the peak power or the cost of the transformer stations very much. The total load is around 21 MW, which is almost 8% lower than case 2a.

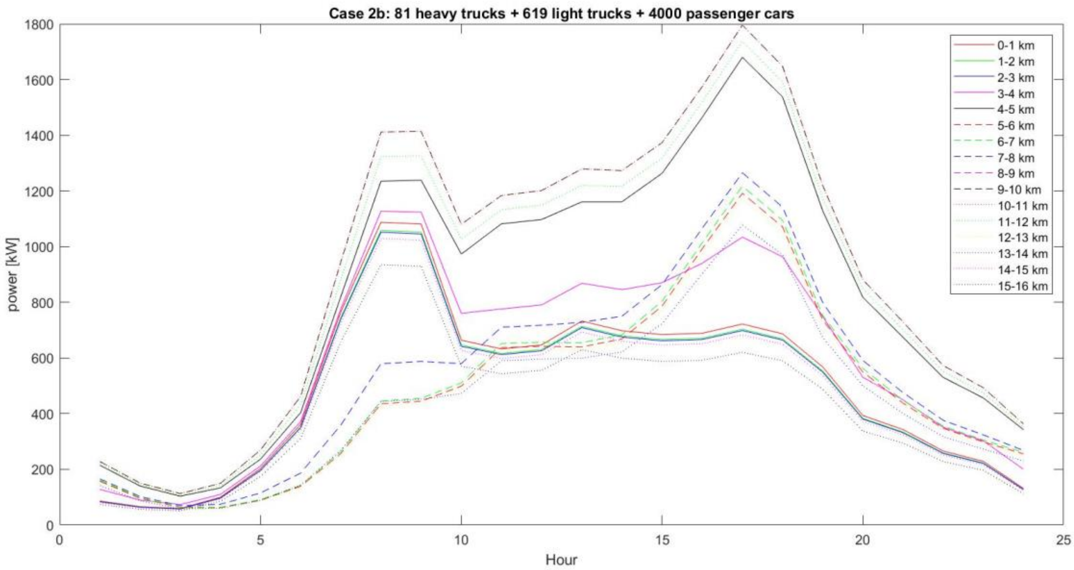

Figure 19. Electric grid load per km, case 2b

Table 12: Peak load of each km-segment and its connection point:

Road segment [km from SE]	Peak load [kW]	Connection to ST
0 -1	1 088	ST12
1-2	1 058	ST11
2-3	1 052	ST10
3-4	1 127	ST10
4-5	1 680	ST9
5-6	1 192	ST8
6-7	1 217	ST7
7-8	1 265	ST7
8-9	1 796	ST6
9-10	1 796	ST5
10-11	1 796	ST5
11-12	1 737	ST4
12-13	1 171	ST4
13-14	1 078	ST3
14-15	1 029	ST2
15-16	935.1	ST1
Total	**21 017**	

Table 13: Connection points capacity and cost of upgrading the transformers

Transformer station	Available capacity [kW]	Available capacity – Load from ERS [kW]	Cost [SEK]
ST1	4 772.3	3 837	-
ST2	921.3	-107.7	*98 482 [500 MVA]*
ST3	948.2	-129.8	*98 482 [500 MVA]*
ST4	3 914.5	1 006	-
ST5	895.8	-2 696	2**344 842 [2*2 500 MVA]*
ST6	278.2	-1 509	2**156 969 [2*1 000 MVA]*
ST7	284.2	-2 198	344 842 *[2 500 MVA]*
ST8	470.3	-721.7	*156 969 [1 000 MVA]*
ST9	466.0	-1 214	2**133 135 [2*800 MVA]*
ST10	377.7	-1 801	*344 842 [2 500 MVA]*
ST11	287.4	-770.6	*219 704 [1 250 MVA]*
ST12	700.5	-387.5	*133 135 [800 MVA]*
Total	**14 316.4**	**-6 702**	***2 666 336***

3.3.2 Financial analysis

The result of the financial analysis can be seen in table 14. Since the HD trucks are the main benefiter of an ERS, the cost now is more similar, although the ERS case is still the cheaper option. HD trucks also pay the highest share of the infrastructure cost, but since there are less of them that cost is shared more equally between the different vehicle classes.

Table 14. Result of the financial analysis, case 2b

Without ERS	Cost without ERS [SEK/year]	Cost with ERS [SEK/year]	Number of vehicles
HD truck	2 597 400	1 730 082	81
LD truck	5 529 733	5 303 321	619
Passenger car	32 200 00	31 371 064	4 200
Transformers	-	66 658.4	
Total	**40 327 133**	**38 471 125**	**4 900**

3.3.3 Sensitivity analysis

The result of the sensitivity analysis can be seen in table 15. The cost of the ERS scenario continues to rise because of increasing battery sizes, just like the other cases.

Table 15.: Change in result based on the scaling factor

Scaling factor	Total cost without ERS [SEK/year]	Total cost with ERS [SEK/year]
1	40 327 133	38 471 125
2	40 327 133	39 021 941
3	40 327 133	39 561 941

4. Discussion

This project explores the potential of an ERS on a limited distance, the bridge of Öresund, and under which circumstances it would be beneficial. The result is presented in three different cases based on different traffic flows and will be discussed individually below.

4.1 Case 1: Break even

Case 1 shows that the break-even point is at around 150 – 300 HD trucks and 1 140 – 2 400 LD trucks. The result is heavily reliant on the assumptions made regarding battery size and density of fast chargers. Comparing this result to the actual traffic flow of 700 trucks and 4 200 cars per day, it is hard to draw a certain conclusion about the feasibility. Since only shorter trips benefit from having ERS on the bridge it is unclear whether the traffic flow is high enough. The data from the haulage contractors shows that these trips exist and are driven daily. However, there are also a lot of longer trips from northern Europe, that are too long to make charging on the bridge useful. Depending on the size of the LD trucks, some will count as cars whilst some will count as trucks. Furthermore, the ratio of 1:7.6 HD to LD trucks is something that can be discussed as well. It is based on the registered vehicles in Sweden but if this applies to the traffic flow across Öresund is hard to know since the traffic data doesn’t differentiate between the vehicle classes.

The sensitivity analysis shows that changing the distances, that in turn changes battery size and charging need, also changes the result. The electrical load simulation is only done on the base case, meaning that increasing the battery sizes will increase the number of vehicles needed and hence, the electrical grid load. However, adding the cost of the transformer stations didn’t change the number of vehicles needed to break even substantially. The main reason for this is the longer lifetime of the transformers, which, per year, doesn’t affect the cost that much.

Whilst discussing the situation with the haulage contractors another issue appeared. If these shorter routes were to be electrified and equipped with a pick-up system, it would still be hard to reserve the electrified trucks specifically for the trips across the bridge of Öresund. This means that the trips use different trucks all the time because of tight scheduling and therefore cannot reserve the electric trucks for the electric roads.

4.2 Case 2a

Case 2a explores the consequence of electrifying all traffic across the bridge, assuming all trucks are HD trucks. In terms of the electrical load, it is substantially higher than the current electrical system is designed for. It would demand a lot of investments into new transformer stations and accompanying equipment that theoretically is possible, but realistically might cause problems.

The financial analysis shows that it is beneficial to implement an ERS. It is mainly the HD trucks that would benefit from it, since the battery can be reduced by hundreds of kWh´s. The smaller vehicles also have smaller batteries and therefore cannot reduce as much in terms of energy, not percentage. The cost of the road is shared based on the amount of energy charged. Whilst the LD trucks can charge up to around 11 kWh´s, a HD trucks can charge up to 40 kWh´s, therefore also paying a bigger share of the cost of the road than the rest.

Previous studies into ERS shows the benefit in terms of both cost and environmental impact, see figure 6. Although the environmental impact is not explored in this report, it shows the same financial benefits to some extent. What is interesting though is that this result is opposite to some previous research that shows that it is mainly passenger cars and smaller vehicles that benefit from ERS. The difference in this result is probably the fact that the bridge of Öresund has a limited length to implement ERS, unlike a highway system, and therefore a limited charging capability only benefiting a handful of vehicles. It becomes a whole other problem when investigating bigger regions infrastructure systems. Case 2a also assumes that all traffic is electrified and uses the ERS. Realistically, this is something that will not be accomplished soon and will take time. By then more roads would probably be electric and the shorter drive cycles used in this report can be longer, which would change the result.

4.3 Case 2b

Case 2b is similar to case 2a, but with the ratio of 1:7.6 between HD and LD trucks included. The ratio previously discussed in chapter 4.1 is based on registered vehicles. Because of the fact that less HD trucks are included, it changes the result from case 2a. The smaller vehicles both can´t reduce their battery size as much, but also pays a higher share of the infrastructure cost since there are less HD trucks. This is the main reason that it is more expensive than case 2a. However, it is still the less expensive option compared to static charging.

Even though there now are less HD trucks included, the electrical load is just slightly lower than case 2a. The reason for this is that the LD trucks are assumed to be driving a shorter trip that is made twice every day, unlike the HD truck that only does one trip but further.

4.4 Electrical system

Although touched upon shortly, the electrical system is dimensioned for mainly lights, ventilation and heating/cooling. It is under dimensioned and would need an upgrade to implement an ERS. The transformers have little to none available capacity, except for some in the tunnel. Without looking into the actual mapping of the electrical system, which lies outside of this project, it is hard to know how much can be added in terms of spacing, weight and contracts with electricity suppliers. It is however safe to say that some improvements would be needed. The tunnel also has a lot of different rules and regulations accompanied in terms of safety precautions. It is unclear how an ERS would fit into these and if it is possible at all to accomplish. Without the connection in the tunnel nearly one fourth of the road disappears, and the transformer stations with the most available capacity as well. As mentioned previously, the result of the electric load simulation is only the average of an hour. If all vehicles would drive at the same time the power would be even higher. If only one or two vehicles passes during an hour, the average is less than one vehicle but the electrical system still needs to be able to sustain the load of both vehicles passing at the same time. Although the traffic flow probably is equally spread out during the hour, it should be over dimensioned in order to sustain the load at any peaks in traffic. There are also some seasonal variations in the traffic flow. During the summers there is vacation which affects both the HD traffic and the commuting traffic. It makes the traffic flow difficult to simulate and calculate correctly at any given moment, hence the average during an hour is used.

4.5 Sensitivity analysis

The sensitivity analysis shows that the further away from the bridge that you are, the less useful it is. This is to be expected since the charge on the bridge is limited. For it to be meaningful, the charge that you get should amount to a substantial part of the route. Otherwise more stops to charge along the way is needed. The result of this can be seen in all cases, in case 1 in terms that more traffic flow is needed for it to break even and in case 2a and 2b that it gets more expensive. The static charging example doesn't experience the same effect. It is assumed that the battery size of 400 kWh´s for a HD truck is a realistic number of what is available today and raising it is therefore unrealistic. Also, all terminals or stops are already equipped with static chargers and the only solution to charge more energy is to make longer stops, which doesn't affect the financial analysis. Time however, is not meaningless when it comes to haulage contractors and their businesses but not included in this report.

4.6 The model

The model is thoroughly explained in chapter 2. It uses a created version of the bridge to simulate the different vehicle classes driving across the bridge. This gives a realistic result of the actual drive power, and the available charging power. It also uses a 2 C-rate as a maximum charging power, which is a realistic limitation for all vehicles.

By using a combination of the actual traffic data and data and information from the haulage contractors, assumptions about the behaviour of vehicles and the traffic flow were made. Some simplifications, such as that 700 passages in each direction can be seen as 700 vehicles going back and forth, were made in order to draw an easier conclusion about the traffic flow. Although simplifications, from the experience gained from the haulage contractors, it is still a realistic picture. There are probably more than 700 vehicles that are responsible from the HD traffic but without more specific data it is unnecessary to try and guess an estimate towards how many they are. The assumption made was a low number of vehicles and therefore sort of a worst-case scenario. Adding more vehicles would only help to benefit the financial analysis.

The vehicle classes are based on actual vehicles that are available to buy. The same goes for the chosen battery sizes, with the exception of the ones connected to the ERS where the assumption is made that it is possible to reduce the battery sizes with up to 80%, although less than 80% is used.

The costs and the accompanied life expectancies are also assumptions. Since the technology of ERS´s is still in development it is difficult to get an accurate number on what it will cost. The life expectancy of 15 – 25 years on most items is however quite low and probably will be a bit higher. This can also be seen as sort of a worst-case scenario.

4.7 The future

At some point there are going to be electric roads available as a commercial charging solution. If this would be the first of its kind, as there are no commercial ERS´s available at the time, could be valuable in terms of setting a president and from a financial point of view. However, it could also be costly if the wrong technology is chosen, in regards to what will be chosen on the other roads. This report is just a first case study for this project and more research would have to be made before any type of decision.

5. Conclusions

The goal of this project is to try and analyse under what circumstances implementing an ERS on the bridge of Öresund would be beneficial. Electrification of the transportation sector is inevitable, and Sweden has already started projects regarding ERS whilst trying to build up an infrastructure for static charging. By comparing these different charging solutions, a nuanced result that considers both options can be achieved.

The simulations show that HD trucks can charge up to 40-50 kWh, LD trucks up to 10-12 kWh and cars up to 6-8 kWh depending on vehicle weight and power from the road, P_{ERS}. Because of the finite distance that can be electrified, the energy that can be received is also limited. This makes it difficult to electrify all traffic since some trips require too much energy, and therefore charging on the bridge would mean next to nothing. The traffic that is interesting, and should be targeted, is the daily commuting traffic and the shorter routes from southern Sweden to the east of Denmark. The three cases investigated derives from these shorter routes and assumes that each vehicle drives them on a daily basis.

Case 1 shows that at least 150 HD trucks and 1 140 LD trucks are needed for an ERS to break even with only static charging. What case 2a and 2b shows is that electrifying all traffic might be difficult in terms of the electrical load, although financially beneficial under certain circumstances. The sensitivity analysis shows that the result of all these cases is heavily reliant on the battery size. That in turn is reliant on the total distance travelled, which is studied using the scaling factor. Using the scaling factor as a sensitivity analysis shows that the further the routes, the less beneficial the ERS is. This is because of the charge that is limited and by making the routes longer, more battery or static charging has to be added to the ERS case, thus reducing the benefits of the technology.

To be able to be sure that this would be a successful project more studies about the traffic would be required. It is hard to make a certain conclusion without more accurate data about routes, number of vehicles and the frequency. What can be said though is that it can be possible to make it profitable. At some point there are going to be electric roads commercially available and connecting the bridge of Öresund to the rest of Sweden's infrastructure could be valuable financially, for the environment and by setting a president for the ERS technology.

5.1 Future research

As mentioned above, more research is needed to be able to make a certain conclusion about the feasibility. Mainly into the traffic flow and the electrical system. The traffic flow needs more data to be able to verify the exact traffic flow and where it is coming from, and where it is going. Partnering up with more haulage contractors would benefit the bigger picture. The electrical system is only covered in terms of available capacity on the bridge. Outside of that is cabling and other electrical equipment and also the connection points to the high voltage grid on either side of Sweden and Denmark. Also looking at the spacing and feasibility of adding the additional transformer stations needed for the high electrical load that electrifying all traffic would amount to. Finally, the different ERS technologies, mentioned in chapter 1.2, can be studied in order to make a decision regarding which technology is best suited for the bridge of Öresund.

References

ABB (no date). *Livslängdskostnader på transformatorer.* *https://search.abb.com/library/Download.aspx?DocumentID=9AKK106103A1738&LanguageCode=sv&DocumentPartId=&Action=Launch* [10-05-2022]

Alaküla, M. (2019a). *What is the cost of electric roads? https://www.evolutionroad.se/en/electric-roads/what-is-the-cost-of-electric-roads/* [31-03-2022]

Alaküla, M. (2019b). *Why electric roads when there are charging stations? https://www.evolutionroad.se/en/electric-roads/why-electric-roads-when-there-are-charging-stations/* [18-05-2022]

Energimyndigheten (2021). *Laddinfrastruktur. http://www.energimyndigheten.se/laddinfrastruktur* [18-05-2022]

Energipress (2015). Siemens bygger första eHighway i Sverige. *Energipress, 2015-06-05. https://www.energipress.se/el-energinat/siemens-bygger-forsta-ehighway-i-sverige*

European Environment Agency (EEA) (2021). *New registrations of electric vehicles in Europe.* Copenhagen: European Environment Agency. https://www.eea.europa.eu/ims/new-registrations-of-electric-vehicles

Excell, J. (2013). *Your questions answered: inductive charging for road vehicles.* The engineer. https://www.theengineer.co.uk/content/in-depth/your-questions-answered-inductive-charging-for-road-vehicles

Fyhr, P., Domingues, G., Andersson, M., Márquez-Fernández, F., Bängtsson, H. & Alaküla, M. (2017). *Electric roads: Reducing the societal cost of automotive electrification.* 2017 IEEE Transportation Electrification Conference and Expo (ITEC).

Gustavsson, G. H. M., Hacker, F. & Helms, H. (2019) *Overview of ERS concepts and complementary technologies.* CollERS, Swedish-German research collaboration on Electric Road Systems.

Infrastruktursdepartementet (2021). *Eldrivna transporter på väg* (I2021.03). Stockholm: Regeringskansliet. https://www.regeringen.se/4b0da2/contentassets/d0a474ce90c8429bbb33e9690d9de1a4/211222_handlingsplan_el_webb.pdf

Kim, H-J., Hirayama, H., Kim, S. & Han, K. J. (2017). *Review of Near-Field Wireless Power and Communication for Biomedical Applications.* IEEE Access (Volume: 5). Page(s): 21264 - 21285 DOI: 10.1109/ACCESS.2017.2757267

Kvaser (2017). Elways Electric Road Project: Charging On The Go. *Kvaser, 27-01-2017. https://www.kvaser.com/elways-electric-road-project/*

Mobility Sweden (2022). *Rekordstark utveckling för laddbara bilar under 2021 trots ett ryckigt fordonsår. https://www.hb.se/globalassets/global/hb---externt/biblioteket/akademiskt-sprak/harvard_snabbguide_2021.pdf [18-05-2022]*

Naturvårdsverket (no date a). *Klimatet och transporterna. https://www.naturvardsverket.se/amnesomraden/klimatomstallningen/omraden/klimatet-och-transporterna/ [18-05-2022]*

Naturvårdsverket (no date b). *Sveriges klimatmål och klimatpolitiska ramverk. https://www.naturvardsverket.se/amnesomraden/klimatomstallningen/sveriges-klimatarbete/sveriges-klimatmal-och-klimatpolitiska-ramverk/ [30-05-2022]*

Nordiskt samarbete (2021). Öresundsbron har fortfarande en outnyttjad potential. Nordiskt samarbete 05-07-2021. https://www.norden.org/sv/news/oresundsbron-har-fortfarande-en-outnyttjad-potential

Regeringen (no date). *Elektrifieringskommissionen. https://www.regeringen.se/regeringens-politik/transportsektorn-elektrifieras/el-1/ [30-05-2022]*

Schaap, S. (2021). *Review of Electric Road Systems.* BEeng. Stockholm: KTH. https://kth.diva-portal.org/smash/get/diva2:1567949/FULLTEXT01.pdf

SecondSol (no date). *ABB – 2 500 kVA Transformator.* https://www.secondsol.com/en/anzeige/25972/accessories/connection-technology/transformers/abb/2500-kva-transformator [25-05-2022]

Smart City Sweden (2020). *Evolution Road testing the next generation of electric roads. https://smartcitysweden.com/evolution-road-is-testing-the-next-generation-of-electric-roads/ [01-06-2022]*

Trafikanalys (2021). *Körsträckor med svenskregistrerade fordon. https://www.trafa.se/vagtrafik/korstrackor/ [11-05-2022]*

Øresundsbro Konsortiet (no date). *Om Øresundsbro Konsortiet. https://www.oresundsbron.com/sv/info/foretaget* [23-05-2022]

Øresundsbro Konsortiet (2005). *Vägen över Öresund.* Malmö: Øresundsbro Konsortiet. https://data.oresundsbron.com/cms/download/V%C3%A4gen%20%C3%B6ver%20%C3%96resund.pdf

Øresundsinstitutet (2021). *FAKTA: Trafiken över Öresundsbron.* Øresundsinstitutet, 05-02-2021. https://www.oresundsinstituttet.org/fakta-trafiken-over-oresundsbron/