CHALMERS
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The effect of electric roads on future energy demand for transportation

A case study of a Swedish highway

Master's thesis in Industrial Ecology

DARIJAN JELICA

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Division of Energy Technology
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Cover:
A conductive overhead line electric road system on highway E16 by Sandviken, Sweden.

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ABSTRACT

This thesis centers on the technology Electric road systems (ERS), which aims to solve the current range issue with electric vehicles by continually supplying vehicles in motion with energy. The aim of the thesis is to provide a thorough system description of ERS, and to investigate how a potential implementation of the technology will affect energy use and CO_2 emissions in the transport sector in Sweden. The effects of an implementation of ERS was done through a case study using an hourly traffic pattern model for route E4 between Stockholm-Jönköping.

The model showed that implementing an ERS on the investigated route with current traffic levels and assuming a 100% vehicle connection would electrify 4% of the annual traffic volume in Sweden, with an energy demand of 1.55 TWh/year and would decrease the CO_2 emission by approximately 1 Mton CO_2/year. Comparing the ERS with a diesel system, the total energy demand of the road will decrease by 1.66 TWh/year, which corresponds to 48% of the yearly energy demand for the route and 2% of the total yearly energy demand in the Swedish transport sector. The mitigated CO2 emissions correspond to a 5.3% national yearly decrease compared to the current transport system. Heavy vehicles required 66% of the aforementioned energy demand and were responsible for 50% of the resulting CO_2 emission mitigation, while only comprising 15% of the traffic load on the road compared to light vehicles.

The consequences of implementing ERS are also compared to environmental goals and visions set by the Swedish government concerning the future development of the transport system for the years 2030 and 2045.

Keywords:
Electric Road Systems, ERS, Energy Demand, Transportation CO_2 Emissions,
ERS System Description, Impact on Electric Grid, Hourly Traffic Patterns,
Power Transfer Technologies, Swedish Transportation Scenarios

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Darijan Jelica
Gothenburg, May 2017

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1. INTRODUCTION

One of the big challenges facing humanity this century is how to deal with the increasing concentration of greenhouse gases in the earth's atmosphere and the problems a higher concentration brings to the environment, our current way of life and our future development (IPCC, 2013). As the world collectively needs to move away from fossil power and the emissions from burning fossil fuels, one of the largest sectors affected by this change is the transport sector (IPCC, 2013). The transport sector is currently utilizing fossil fuels as its main energy source, and as of 2014 transportation accounts for approximately 14% of global greenhouse gas emissions (ITF, 2016), 23% of greenhouse gas emissions in the EU (Eurostat, 2016) and 33% of greenhouse gas emissions in Sweden (SEA, 2016a). The transportation sector has a great challenge to shift its primary energy source from fossil fuels to renewable alternatives. Other sectors in Europe, such as the electricity generation sector has already started this shift away from fossil sources to renewables.

Sweden currently has a number of extensive environmental targets aimed at achieving a net-zero GHG-emission status by the year 2045 (SOU 2016:21) across all sectors. A detailed scenario of the transportation sector for a possible pathway towards fossil free transportation can be found in a governmental investigation called "Fossilfrihet på väg" (SOU 2013:84). The investigation suggests intermediate goals for the coming years with a specific focus at the year 2030 and subsequently paves the way for the common 2045 goals. The governmental vision for the transport sector also mentions electrification as one of its main solutions, currently including electric vehicles (EVs), plug-in hybrid electric vehicles (PHEVs), fuel cells and electric road systems (ERS) technologies (SOU 2013:84).

In recent years EVs and PHEVs have seen rapid technological development and have started to penetrate the market (EVWSD, 2017), but still face technological problems compared to conventional road vehicles. One of the biggest problems with EVs and PHEVs is currently the range issue, translated into the term "range anxiety" among consumers, meaning the fear that the car won't reach its destination on the charging of the battery (Boulanger et al., 2011). According to Gomez-Ibanez et al. (2010), two of the six main barriers for the widespread adoption of EVs are directly connected to the range of the vehicle, namely consumer range anxiety, and availability of charging infrastructure. The range issue is even more prevalent when it comes to heavy vehicles since they require a lot more energy per kilometer (thus resulting in more greenhouse gases) compared to light vehicles, making heavy vehicle batteries extremely heavy if they are designed to travel longer distances.

Electric road systems are a charging technology that could solve this problem as ERS aims to electrify the road so that vehicles can get a continuous supply of energy for as long as the electrically powered segment of the road continues. The concept of ERS is much like modern tram- and train systems. The road will continually be connected to the electrical grid, meaning that as soon as an EV is connected to the road it will also be connected to the centralized electric grid of that particular region/country. ERS is considered as an option to shift the transport sector away from fossil fuels to renewable alternatives, considering that the Swedish electricity generation is almost fossil free and the electricity system in Europe and elsewhere is being transformed towards renewable electricity generation.

1.1 Aim and objective

The aim of this thesis is to establish a comprehensive system description of ERS based on current technology and how it may develop in the future. It is important to map the structure and technological potential of ERS since it is a novel technology. The aim of this report is also to study what electrification of roads means in terms of energy use and CO_2 emission by using a case study for implementing an ERS on route E4 between Stockholm-Jönköping. The effects of a potential switch to ERS will then be examined from the point of view of important policy targets in Sweden, such as a fossil independent vehicle fleet by 2030 (SOU 2013:84) and the net-zero greenhouse gas emission target for 2045 (SOU 2016:21). A specific focus of this thesis is also to evaluate how an ERS will affect the current electricity grid, both in terms of capacity and energy use over time. This evaluation will be based on specific traffic data (traffic intensity, vehicle type etc.) for route E4 that will subsequently be translated into energy load and compared to the electricity system in Sweden.

Specific main questions that will be answered in this report are:

- What are the core components of electric road systems?
- How will an ERS affect the energy use and nearby electric grid for route E4 between Stockholm-Jönköping and the transport sector in Sweden?
- How will an ERS affect the emission of CO_2 for route E4 between Stockholm-Jönköping and the transport sector in Sweden?

This thesis is part of a research project that centers around ERS and its impacts on society. The project is executed by the research institute RISE and is called “Research and innovation platform for electric roads”. In detail, the project is centered on establishing an innovation platform for ERS with the purpose of strengthening the research and development of the technology in Sweden.

This thesis will not assess other similar efforts to reduce for example energy use or CO_2 emissions in the transportation sector, i.e. competing/overlapping technologies. Furthermore the case study will only consider the Swedish transportation and energy system.

Chapter 2 (background) covers some background information concerning the Swedish environmental goals and scenarios, what transport electrification means specifically for cars and trucks and the Swedish electrical grid system. Chapter 3 (electric road systems) describes the theory behind the subsystems and stakeholders of electric road systems in detail. Chapter 4 (method) consists of information about the chosen case study, and the data, model groups and formulas used in the analysis of the chosen road. Chapter 5 (results) is an empirical chapter showing the results from the modelling of the case study, along with key impact parameters, such as energy consumption and CO_2 emissions. Chapter 6 (discussion) discusses the findings in chapter five, and how they relate to environmental goals and scenarios from chapter two. Chapter 7 concludes the findings in this report and summarizes the answers to the core questions.

2. BACKGROUND

2.1 Swedish transportation scenarios

The long-term goal for the Swedish transport sector is a net-zero greenhouse gas emission rate by the year 2045. To achieve this, a vision by the Swedish government regarding the future development of the transport sector has been detailed in the report “Fossilfrihet på väg” (SOU 2013:84). The report covers two different future scenarios that focuses on four main areas of technological advance: Societal transport development, energy efficiency, biofuels and electrification. Their individual contribution to the imagined future transportation paradigm can be seen in Figure 1.

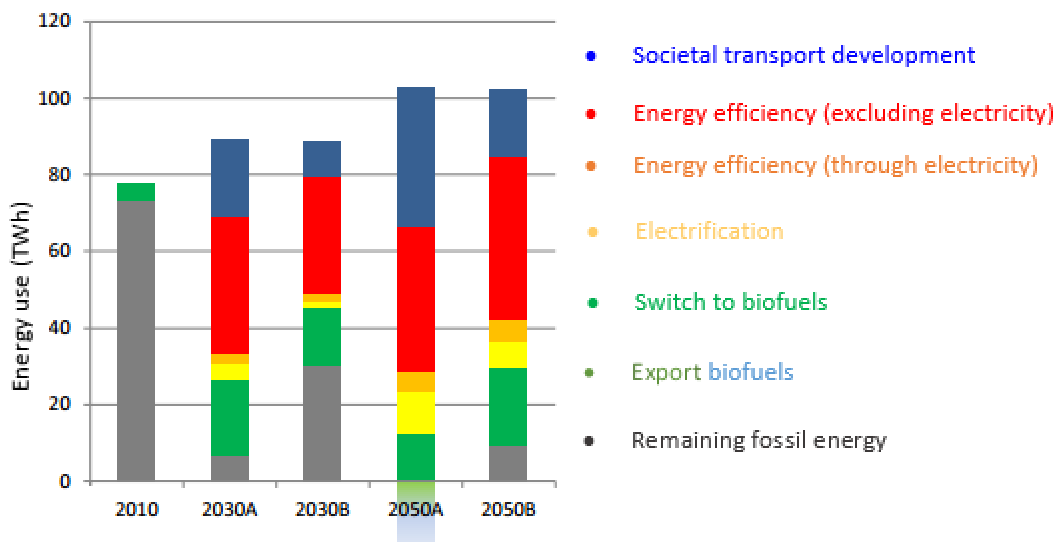

Figure 1. Swedish future transportation scenarios in terms of energy use (SOU 2013:84). The total height of the bars corresponds to the total energy use if the noted efficiency measures are not taken, meaning that the real end energy use value is where the electricity section (colored yellow) ends. The two scenarios (A and B) correspond to if the potential energy reduction in each sector reaches its maximum and minimum value respectively.

Important to note in Figure 1 is also that there is a discrepancy between the displays of biofuels (green) versus electrification (yellow) in terms of contribution toward decarbonization, since electric motors has an engine efficiency around 95%, while the same number for biofuels is 30%. This efficiency gap means that for the year 2045, electrification will have a transportation work contribution at least as high as biofuels in both scenarios.

As stated in (SOU 2013:84) there is an estimated potential decrease of greenhouse gas emissions from the transport sector (except aviation) of 90% toward the 2030 target (scenario 2030A). This estimate is described as a best-case scenario where every measure taken achieves its maximum potential. However, this is considered as an optimistic perspective, and a conclusion was reached that this level is unrealistic given the many uncertainty aspects of future development and the short timespan covered. Instead, the report centers around an average value between scenario 2030A and 2030B, resulting in an 80% reduction target for the year

2030 as compared to 2010 levels, with targets also set for 2020 at a 35% decrease and 2025 at a 60% decrease. So far, data from the Swedish environmental protection agency shows that the actual level of greenhouse gas emissions from the transport sector have decreased by approximately 11% between the years 2010-2015 (SEPA, 2016).

2.2 Electrifying transportation

In 2015 the Swedish transportation sector released roughly 18 Mton CO_2eqv (SEPA, 2016), which corresponds to 33% of the national yearly greenhouse gas emissions in Sweden, making the transport sector the largest source of greenhouse gas emissions among all sectors (SEPA, 2017). Within the transport sector, the overwhelming majority (94%) of the emissions originate from road traffic (as depicted in Figure 2) as this share accounted for 17 Mton CO_2eqv released in 2015 (SEPA, 2016), while the total greenhouse gas emission across all sectors in Sweden reached 56 Mton CO_2eqv in 2013 (SEPA, 2015).

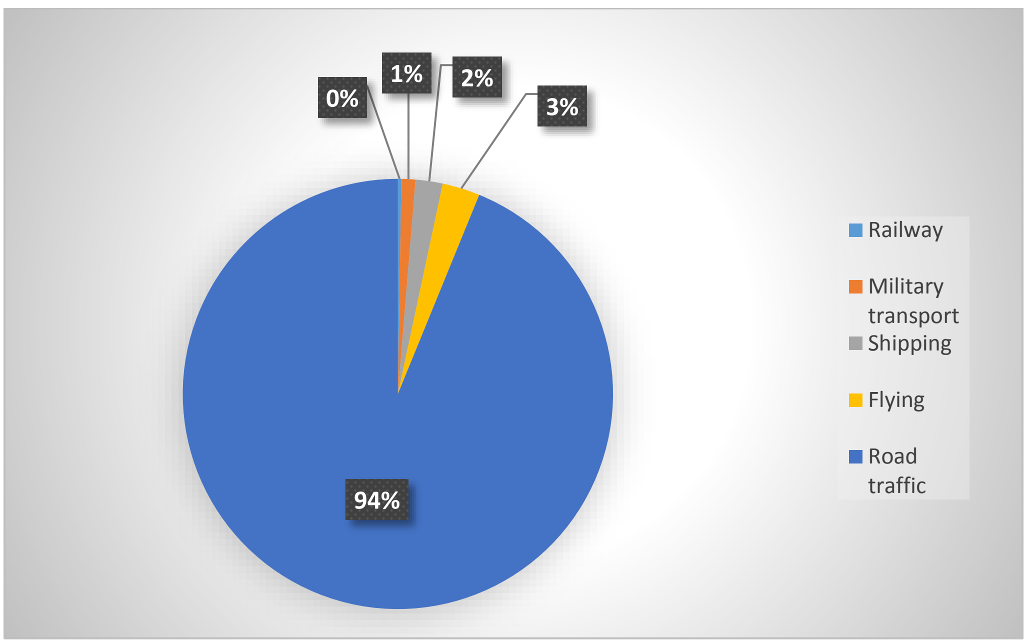

Figure 2. Share of transportation sector greenhouse gas emissions according to different modes of transportation in Sweden, 2015 (SEPA, 2016).

The high share of greenhouse gas emissions from road traffic means that it is an important part of the transport sector to include when finding carbon neutral alternative transport solutions. This thesis focuses on one such solution (electrification) with one particular technology (ERS).

For vehicle categories like cars, trucks and buses to utilize an electric motor as its drivetrain is not a new concept. The electric motor was in fact one of the main powertrains of early car models in the 19th and early 20th century. However, its role as a drivetrain technology diminished over time due to innovations of the internal combustion engine (ICE), according to (Loeb, 2004). Currently there are rising concerns over the emissions caused by ICEs, namely CO, CO_2, N_2O, NO_x, SO_x, unburned hydrocarbons and particulate matter (Bauman & Tillmann, 2009). These pollutants bring with them a myriad of environmental problems, such as global warming, acidification, air pollution (smog), eutrophication, photo-oxidant formation and toxicological impacts to both humans and ecosystems (Bauman & Tillman, 2009).

The emission from burning fossil fuels and their problems are directly connected to the fuel used to power the car, thus if the energy source is changed (for example to electricity) the impact of emission problems could be eliminated, depending on the source of the electricity. If the electricity mix of the generated energy has a large part of fossil fuel-based power plants (for example coal fired power plants), the emission rate for the transport will rise. Likewise, if the electricity mix is comprised to a large degree of renewables (solar, wind, hydropower etc.), the emission rate for transport will decline. Since actual implementation of ERS is still far off, there is merit to examine this problem in a long-term marginal perspective. This view constitutes that the environmental impact of energy use by an ERS will be dependent on the development of energy technologies and the surrounding electricity system. In a European context, new investments into electricity generation technologies and their CO_2-impact is governed by the EU Emissions Trading Scheme, which can limit the amount of CO_2 released by generating electricity for an ERS in the future.

There are of course other factors affecting the total emission rate for EVs, namely manufacture emissions, grid losses and indirect grid emissions, which include transport, storage, distribution, extraction and processing of fuels (Wilson, 2013). One big issue currently is the energy intensive manufacturing processes for EVs, especially the battery that accounts for around 40% of the total manufacture emission (Wilson, 2013). Another important factor is that EVs are currently not expected to reach the same mileage as conventional vehicles before the need for component change or retirement ensues (Wilson, 2013). However, both of these factors are expected to become less prominent as battery technology progresses. If the ERS is completely powered by a carbon neutral energy source, its implementation will potentially diminish the total transportation emission levels to that of vehicle manufacture emissions. Further decrease is thus currently dependent solely on how EVs are manufactured.

2.2.1 Electric cars

The environmental concerns over conventional vehicles, coupled with technological advances in relevant areas such as battery technology (Nykvist & Nilsson, 2014) have resulted in electricity-powered vehicles now undergoing a revival phase. This uptick in electric vehicle sales is still in its early phase, but nonetheless it has penetrated the vehicle market to some degree, and is seeing considerable growth, as seen in Figure 3. The electric vehicle world sales database puts the sales of EVs and PHEVs at a total of 773 600 units for the year 2016, an increase of 42% compared to the previous year (EVWSD, 2017), which means a growth rate 20-times that of traditional vehicles. Still, electric vehicles currently hold a global market share of only 0.86%. By December of 2016 EVs passed a landmark of 2 million total units sold worldwide. Furthermore, there are extremely important niche-markets existing today. The most prominent one being the current car-market in Norway, where in January 2017 EVs and PHEVs together accounted for 51.5% of all new vehicle sales, outperforming traditional vehicles for the first time in the modern era (OFV, 2017). As of the end of 2016, EVs also account for 5% of all vehicles on the road in Norway, another world first (Hybridcars, 2017). Sweden does not currently possess the same subsidy policies as Norway, and saw a yearly market share for EVs at 2.3% for 2015 with a 2.8% estimation for 2016 (EVWSD, 2015).

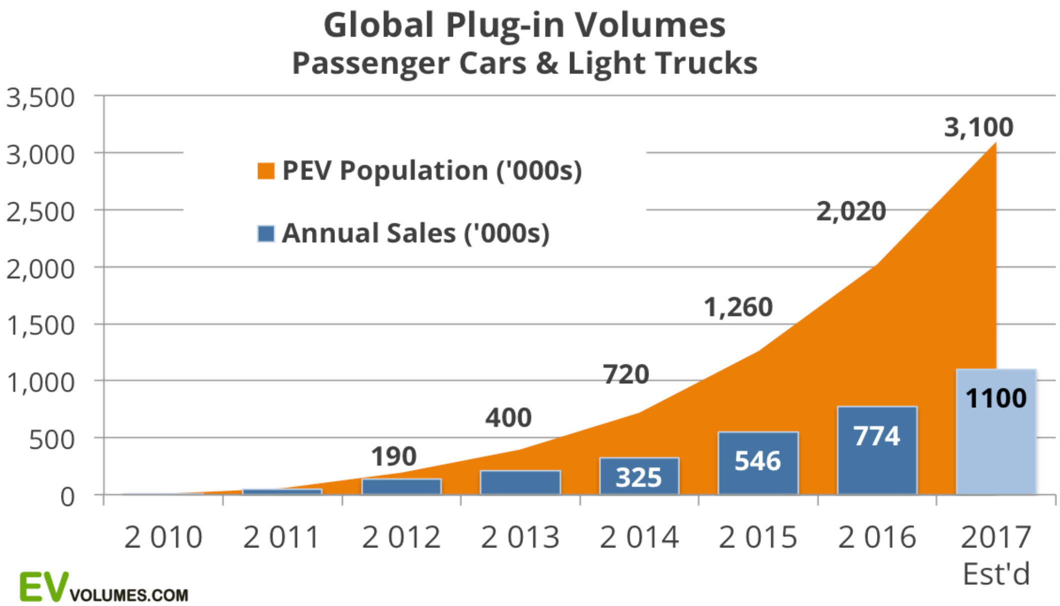

Figure 3. Global sales volumes for plug-in vehicles (EVWSD, 2017).

2.2.2 Electric trucks

Electric trucks, compared to electric cars, still have a long way to go to catch up to the same level of market penetration and technological compatibility with the existing road infrastructure as it stands today. This compatibility gap is mainly due to trucks requiring a considerably higher amount of energy to travel the same distance as light vehicles, which currently cannot be realistically solved by batteries of stationary charging. There are currently some projects where a functioning prototype has been implemented in a day-to-day working environment, such as the Mercedes-Benz Urban eTruck made by Daimler Trucks, the BMW YT202-EV (Figure 4) made by Terberg Trucks and the hybrid electric-diesel model G 360 4x2 made by Scania (Figure 5).

Figure 4. A BMW YT202-EV made by Terberg Trucks (The verge, 2015).

Figure 5. A hybrid G360 4x2 Scania lorry utilizing electrical energy from the conductive overhead line ERS solution at Sandviken, Sweden (Scania, 2016).

These electric trucks are still one of a kind prototypes (except for Scania who has two trucks of the same model) and they possess different characteristics when it comes to important performance parameters. The three trucks mentioned has the following properties: (i) The Mercedes-Benz eTruck has an effective range of 200 km on a single charge with a total weight of 26 tons, making it 1.7 tons heavier than its ICE-engineered counterpart (Daimler, 2017). (ii) The BMW model has a range of 100 km and a total weight of 40 tons, with an estimated recharge time of 3-4 hours (The verge, 2015). (iii) Scania's model has an internal battery charge range of 3 km, but can run on electricity for the length of the ERS and has a total truck weight on 9 tons (Scania, 2016). Important to note is that the Scania model is currently the only one with the possibility of transporting goods longer distances due to its compatibility with ERS, while the two other models are limited to be utilized for short-distance transportation within cities as they rely on battery technology. A prognosis by Daimler trucks also states that this kind of technology will be mature enough for a wide release within the transportation market in the early 2020s (Daimler, 2017).

2.3 The Swedish electrical grid

The Swedish national electric grid serves to supply customers in Sweden with electricity and permeates every aspect of the current technological society. The grid is comprised of different voltage levels depending on what purpose that particular part has in the system and what it is used for. There are four main voltage levels of the grid, the highest voltage level being 400 kV at the national voltage level and all the way down to 400 V at the local voltage level, as depicted in Figure 6. According to the Swedish Energy Agency, the rated capacity of the Swedish electricity system was 39.5 GW in 2014. The total yearly net production was 150 TWh, with 15 TWh being exported, putting the domestic use of electricity in Sweden at 135 TWh (SEA, 2016b).

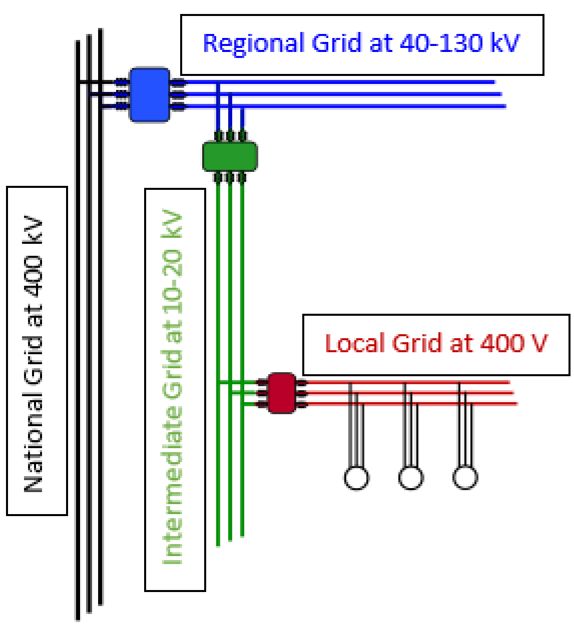

Figure 6. Showing the four different voltage levels of the Swedish electric grid.

3. ELECTRIC ROAD SYSTEMS

An electric road system aims to continually provide the vehicles travelling upon it with electricity. The technology is compatible with existing road infrastructure, and conventional vehicles propelled by other fuels will be able to travel upon the road without connecting to the ERS. The vehicles utilizing the ERS are likely equipped with small batteries or internal combustion engines for driving outside the ERS network, meaning that they can utilize conventional roads as well. The electric road system is divided into four subsystems:

- Energy supply
- Power transfer
- The road
- Road operation

These subsystems are described in detail in subsections 3.1-3.4.

3.1 Energy supply

To be able to continuously supply vehicles with energy, the ERS must have a continuous energy supply. This supply is suggested to be solved by directly connecting to the Swedish electricity grid. As mentioned in chapter 2.3 the grid consists of different voltage levels, and the ERS needs to be connected to a level above its own working voltage level. ERS are currently set to occupy the same voltage level as tramways presently do, namely 750 V DC (Olsson & Pettersson, 2017). This means that an ERS cannot be connected to the local grid, which holds a voltage level of 400 V. The ERS can be connected to the national grid (220/400 kV), the regional grid (40-130 kV) or the intermediate grid (10-20 kV), where each case requires its own tailored transformation equipment to transform the voltage down from the grid level to the ERS working voltage level.

The EVs are also fitted with a potential feedback energy mechanism, based on exploiting changes in potential and kinetic energy when the EV breaks. This mechanism can be used to either be stored in the battery of the EV for later use, or be returned to the grid via the ERS (Taljegard et al., 2016). The amount of regenerated energy depends mainly on vehicle configuration, drivetrain capacity and how the vehicle is driven.

3.1.1 The national grid

The Swedish national grid holds a voltage level of either 400 kV or 220 kV, and there is currently a 400 kV grid in the vicinity of route E4 between Stockholm-Jönköping as seen in Figure 7, meaning that there is a physical possibility for a national grid connection along this route. The national grid in Sweden is currently solely operated by Svenska kraftnät (SVK). SVK has a monopoly in this market, but must obey an obligation to connect any potential customer if the customer fulfills certain requirements (Ellag 1997:857). One of these requirements, which might concern implementation of ERS, is that SVK demands a capacity withdrawal of 300 MW to grant a connection to its 400 kV national grid (SVK, 2017). A connection to the national grid would most likely require further investments in grid infrastructure between the ERS and the national grid, although no concrete solution has yet been proposed. Furthermore the transformation equipment needed for a connection to the 400 kV grid is estimated to be more expensive than the equipment needed for a connection to the regional and intermediate voltage levels (SVK, 2017), although no exact figures are currently available.

Figure 7. Map over the national electricity grid in southern Sweden (SVK, 2016). Red lines correspond to a 400 kV voltage level, green to a 220 kV voltage level.

3.1.2 The regional grid

A connection to the regional grid would require a set of transformer substations to be connected to the regional grid every 30-40 km (Vattenfall, 2017). As described in chapter 2.3, the voltage level of the regional grid generally differs between 40-130 kV, however the aforementioned substations can be connected to entire voltage spectrum of the grid without problems. There are currently excellent possibilities for such connections along the entirety of the E4 route between Stockholm-Jönköping, detailed in Viktoria (2013).

One proposed solution for a connection to the regional grid relies on substations to transform the electricity down to a 10-30 kV voltage level and distribute it in a separate 10-30 kV electricity grid running parallel to the ERS (Vattenfall, 2017), although there might be other ways to continually transfer electricity to the ERS. This separate 10-30 kV grid does not exist today and thus requires to be constructed from scratch if this solution is chosen. Since the electricity is transformed down, the voltage level in this separate grid can be chosen by the operator before construction to suit their needs. Vattenfall has currently proposed a 30 kV voltage level as it would constitute only one actor owning and handling all energy transfer (at lower voltages there is specific inhibiting legislation regarding this issue). Furthermore this solution carries a synergy possibility with connection to nearby wind power farms at the current voltage level. This synergy is twofold in that if a 30 kV grid is built along the road and there are wind farms nearby, the cost of physically connecting the wind farm to the grid is lowered. The second part is due to current level of internal voltage of wind farms is usually around 20-30 kV (Chen, 2005), meaning if this voltage level can be maintained when connecting to an electric grid (at 30 kV in this example) there is little to no need for further transformation equipment (Energie, 2001).

3.1.3 The intermediate grid

The intermediate grid (10-20 kV) is the lowest grid level capable of delivering energy to the ERS with the current specifications. It has a significant advantage in that if an intermediate grid is already present along the road and can sustain the energy demand of an ERS it erases the need to construct a new wayside grid. Currently there is an intermediate grid along parts of the E4 (Natomraden, 2017), which might potentially be connected directly to the ERS, meaning that the aforementioned additional wayside grid might only be needed for certain sections of the route. However it would still require substations to transform the voltage level of the intermediate grid to the working voltage level of the ERS. Interesting to note is that if the intermediate grid voltage is at its maximum level (20 kV), it is also capable of synergizing with wind farms, depending on the structure of the wind farm (Chen, 2005). One issue with connecting an ERS to the intermediate grid is the current legislation in this area, which constitutes that control over this level of the electrical grid is given to a local actor, usually the local government, who also holds a monopoly over the system. Again, this actor is forced to connect a customer to its grid if it is demanded, however this practically constitutes that factors like prices, available energy capacity etc. will differ between regions. Route E4 as depicted in this case study currently cuts through 12 different intermediate level energy supply regions (Natomraden, 2017), each with its own managing organization, meaning that the ERS can have up to 12 different price points etc. along this route alone. This stakeholder situation naturally makes communication and setup of the system more difficult, but it also poses a challenge when dealing with issues of payment distribution, contracts etc.

3.2 Power transfer

Power transfer in an ERS is done through two sections, namely the road and wayside component groups. The road section is responsible for transferring power between the road and the vehicles traveling upon it. The wayside components are present to transfer power from the electrical grid to the road. An illustration of this division can be seen in Figure 8, which shows the concept of a conductive-based ERS.

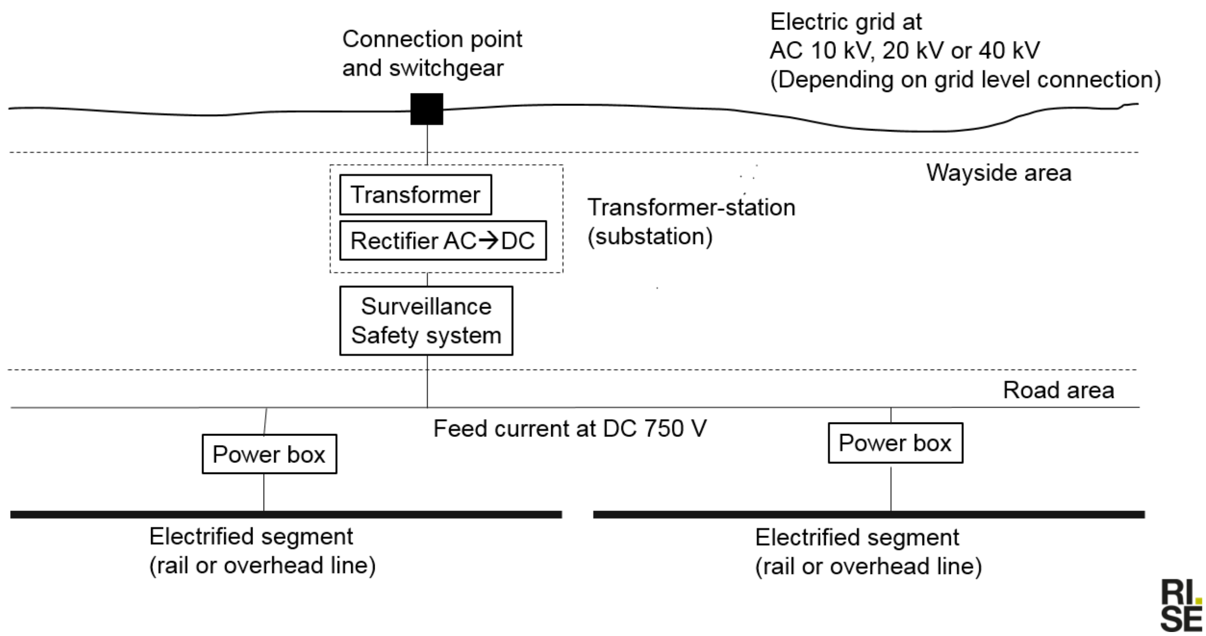

Figure 8. A general concept of basic ERS components in a conductive system with a 1/1 segment per power box configuration (RISE, 2017a).

3.2.1 Road to vehicle power transfer

Transferring electricity between the road and the vehicle can be done in mainly two different ways: conductively or inductively. Conductive power transfer is based on a physical connection between the road and vehicle, while the inductive is a wireless power transfer via fluxes in a magnetic field between the road and vehicle. The conductive approach currently offers two different solutions for the power transfer between the road and the vehicle. The power can be transferred either via overhead power lines that require the vehicles to connect to electric wires above the road and transfer power via a so called pantograph (depicted in Figure 10), or by an electrically charged rail built into the road that transfers power via a mechanical pickup arm (depicted in Figure 12).

All three different power transfer alternatives require power transfer to the road to be divided into road segments. The segments are powered by a power box that will activate the segment when a compatible vehicle connects to it, and will power this vehicle until it exits the segment, at which point the power supply to the segment will be turned off. The length of the segments are different between the solutions, and are presently set at roughly somewhere in between 20m/segment for inductive technologies (Viktoria, 2013), 1-100m/segment for conductive rail technologies (Viktoria, 2017), and about 1.5-2 km for conductive overhead lines (Siemens, 2017). Worth noting is that the conductive overhead lines solution only requires a power box every 1.5-2 km, and will unlike the other solutions, not electrify one segment at a time since they are suspended at high altitude. The length of the segments is determined by the nature of the transfer technology, installation cost, the traffic volume of the road, a safety risk assessment and the minimum speed for energization. The minimum speed for energization is currently set at 60 km/h for the conductive ERS and 50 km/h for the inductive ERS. Since ERS is a novel technology, details about the formation of the segments and what it means for the system have not yet been fully investigated. However there is a consensus among ERS technology developers that the length of the segments is a trade-off between the cost of the ERS (the shorter the segment is the more expensive the road becomes) and the safety risk (longer segments increases the chance of injury by electrocution) (Viktoria, 2017). The cost of the segment is directly tied to the so called power-box, which contains the equipment needed to distribute the electricity to the segment, while simultaneously collecting data that is sent back to the system operator (Viktoria, 2014). In the current design setup, one power-box will be connected to either one or two segments (Figure 9), depending on the exact power transfer solution.

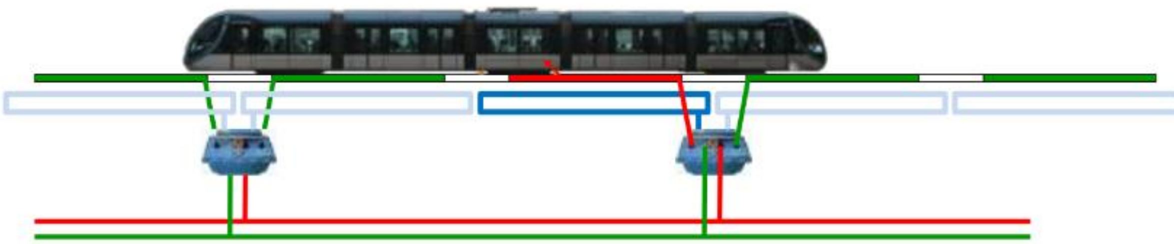

Figure 9. A 2/1 segment per power-box configuration based on the Alstom APS technology for trams (Viktoria, 2014).

3.2.2 Conductive overhead lines

A conductive overhead line ERS solution is currently under development by Siemens under the name eHighway (Siemens, 2012). This solution is the one that has reached the furthest in terms of development and feasibility, due to the fact that similar technology has been used for decades, for example in tramways and conductively charged buses (Viktoria, 2014).

This ERS technology is based on conductive lines mounted on roadside pillars directly connecting the vehicle to the electric grid through the pantograph (Figure 10). An important feature of the pantograph is that it is flexible in the way that the vehicle it is connected to may be free to move both laterally (overtaking another vehicle, changing lanes etc.) and vertically because of height variations or bumps in the road. The pantograph is also required to possess the function to connect and disconnect itself from the overhead lines whenever it is necessary, for example when the vehicle is crossing under a bridge.

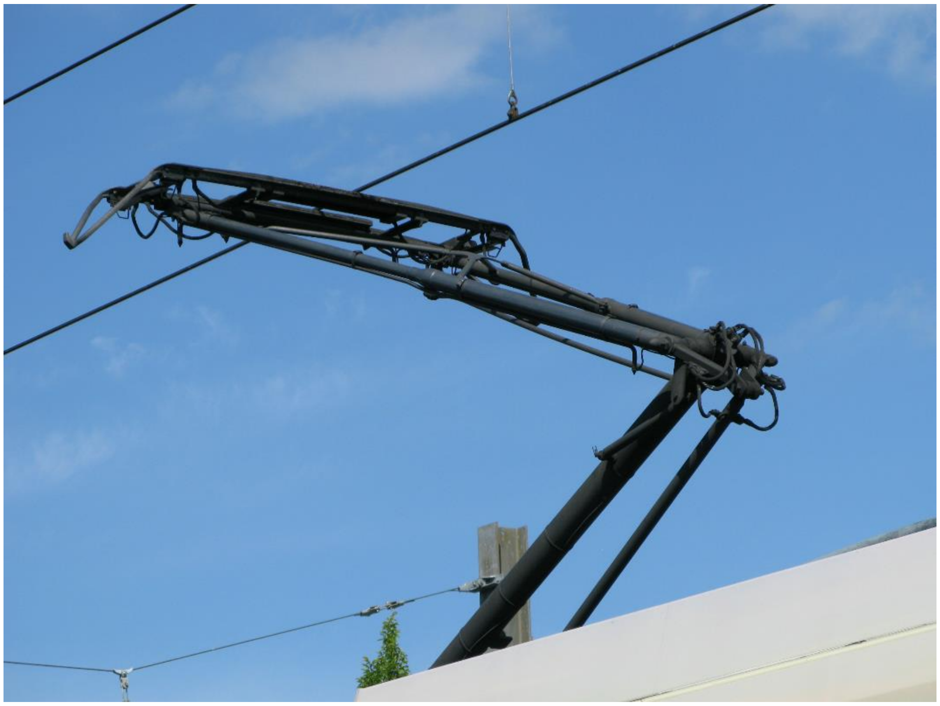

Figure 10. A typical pantograph connecting the vehicle to the electrical grid (Maxfaqs, 2010)

Since overhead line technology is a safe and proven technology that is already implemented in various transport sectors across the world it offers some substantial benefits compared to the conductive rail or inductive solutions. It can be completely incorporated into existing road infrastructure, as the only change that this solution requires (apart from the pillars and lines themselves) is a pantograph on the vehicle for connection to the overhead lines (Siemens, 2012). Furthermore it is a non-proprietary technology with the option of several different suppliers on a competitive market. Another important factor in ERS diffusion generally is the adoption of a standard. In this regard, there is an existing European standard for overhead line power transfer that can be infused into the adoption of ERS. On the contrary, there are also some drawbacks for this solution. The most prominent one being that only trucks and buses can use this type of ERS since the height distance between the lines and the pantograph requires a vehicle with a certain height. There is also an argument to be made that overhead lines are perceived as a somewhat old-fashioned and unattractive technology visually (Viktoria, 2014). The ERS overhead line solution has a system efficiency of approximately 80% (Siemens, 2012).

There is currently a pilot project in place for an ERS using overhead lines, located at Sandviken, Sweden (seen in Figure 5). This route is the world's first ERS solution applied on a public road as it occupies roughly 2 km of highway E16 between Kungsgården and Sandviken. The project is a partnership between the Swedish government, Scania, Siemens and a group of local companies and other actors (Sandvikens kommun, 2015).

3.2.3 Conductive rail

The second option relying on a conductive approach is a conductive rail built into or on top of the road, where the vehicles are connected to the ERS via a mechanical pickup arm designed to transfer electricity from the rail to the vehicle, as seen in Figure 11 (Elways, 2011). The rail in the road is then connected to the electrical grid via a number of transformer substations as described previously in Figure 8. There are currently two Swedish companies that are developing similar solutions for a conductive rail based ERS, Elonroad and Elways, where the main difference is the placing of the rail as Elonroad has it mounted on top of the road and Elways has it installed into the road. Elways currently has a conductive rail ERS test track that is 200 meters long in Arlanda, Sweden since 2012 (Elways, 2012).

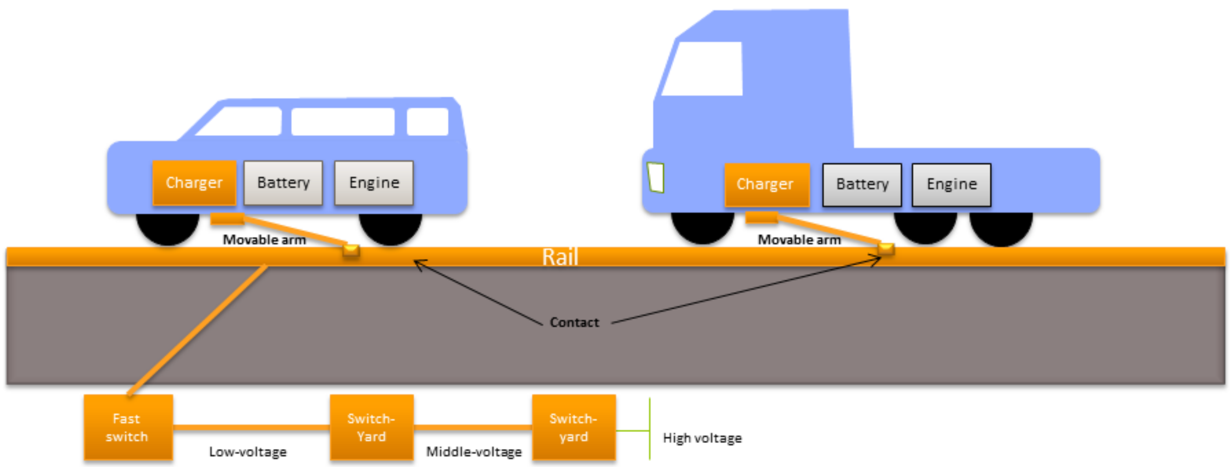

Figure 11. Schematic over a conductive rail ERS solution by Elways (2011).

The pickup that is mounted on the vehicle is a key factor of this technological system. Currently it will automatically connect to the track when the vehicle is travelling upon it, and will be able to move horizontally during driving. The pickup also has an automatic disconnect when the ERS ends or the vehicle initializes a takeover of another vehicle. This automatic flexibility means that the driver does not need to change his or her driving style when utilizing the ERS compared to travelling on a regular road. These features are key in making the solution flexible and consistent (Singh, 2016). As of 2014, two prototypes of pickup arms have been developed and tested by Volvo, both showing promising results. Figure 12 depicts one of these prototypes to be installed under the vehicle (left) and the other prototype designed to be installed at the rear of the vehicle (right). The Elways conductive rail system is based on a segment approach with a segment length of 50 meters, with vehicles being required to travel between 60-100 km/h for the segments to activate (Viktoria, 2014). The conductive rail ERS has a total system efficiency of 82% (Viktoria, 2014).

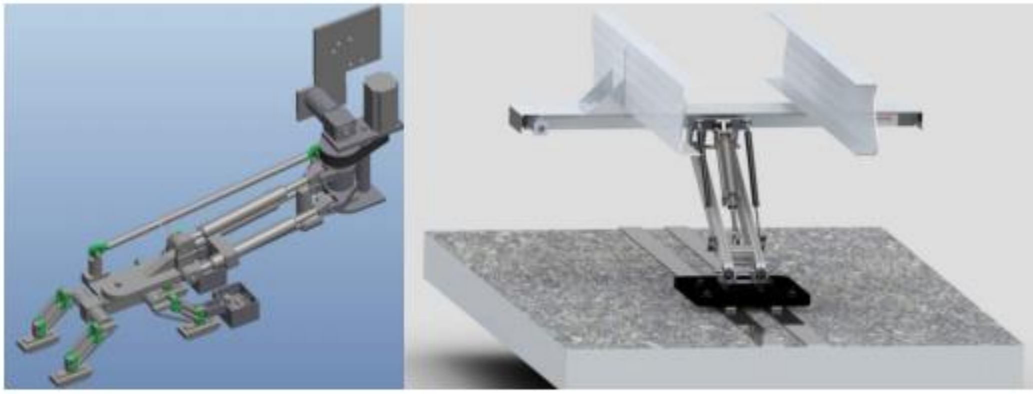

Figure 12. Two functioning prototypes for pickup arms made by Volvo. The first type (to the left) requires installation under the vehicle and the second type (to the right) is designed to be installed at the rear of the vehicle (Viktoria, 2014).

3.2.4 Inductive technology

The inductive approach is based upon wirelessly transferring power though an AC magnetic field between the ERS and the vehicle. The transfer is done as the same traditional mechanism present in AC power transformers, consisting of a laminated iron core. To make this transfer technology inductive, the core is split into two parts. Applying this technology to an ERS means that one part of the split core is present in the vehicle (as ferrite, a magnetic iron ceramic), while the road serves as an elongated version of the other core part (Viktoria, 2013). Figure 13 shows the concepts behind a traditional AC power transformer (left), a core separated inductive AC transformer (center) and the primove inductive ERS solution (right).

The Canadian company Bombardier has an inductive ERS solution called the Primove highway (Viktoria, 2013). It is based on a 20-meter segmentation and wayside substations that are connected to the electrical grid similar to that of conductive technologies, seen in Figure 14. The spacing between the substations is heavily dependent on the load coming from the ERS, with a current max value of 3 kilometers. Testing of this technology has proved that power transfer above 150 kW can be performed with vehicles travelling between 20-70 km/h (Singh, 2016), although a vehicle currently needs to travel at speeds of at least 50 km/h for the segments to be activated. The Primove highway has an estimated total efficiency of 79% (Viktoria, 2013).

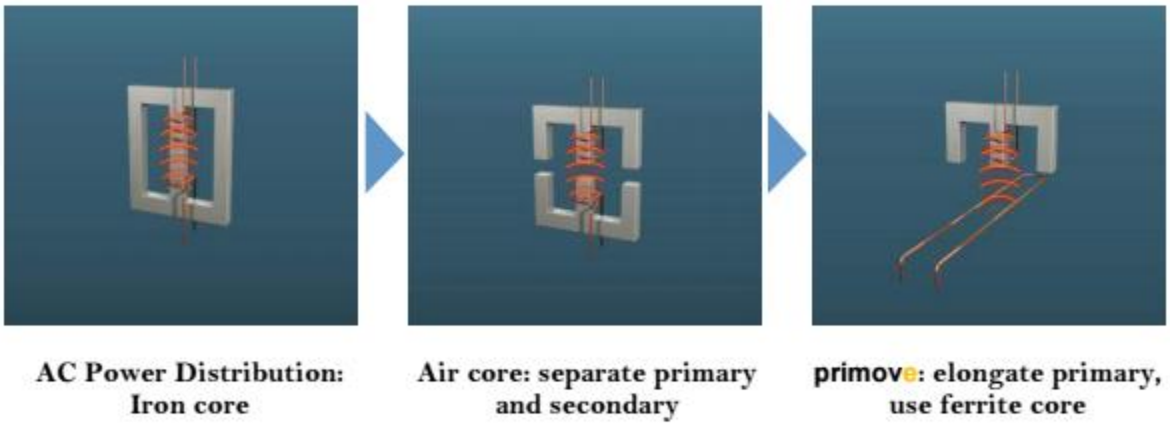

Figure 13. Core composition of a classic AC power transformer (left), an inductive AC transformer (middle) and an inductive ERS (right) (Viktoria, 2013).

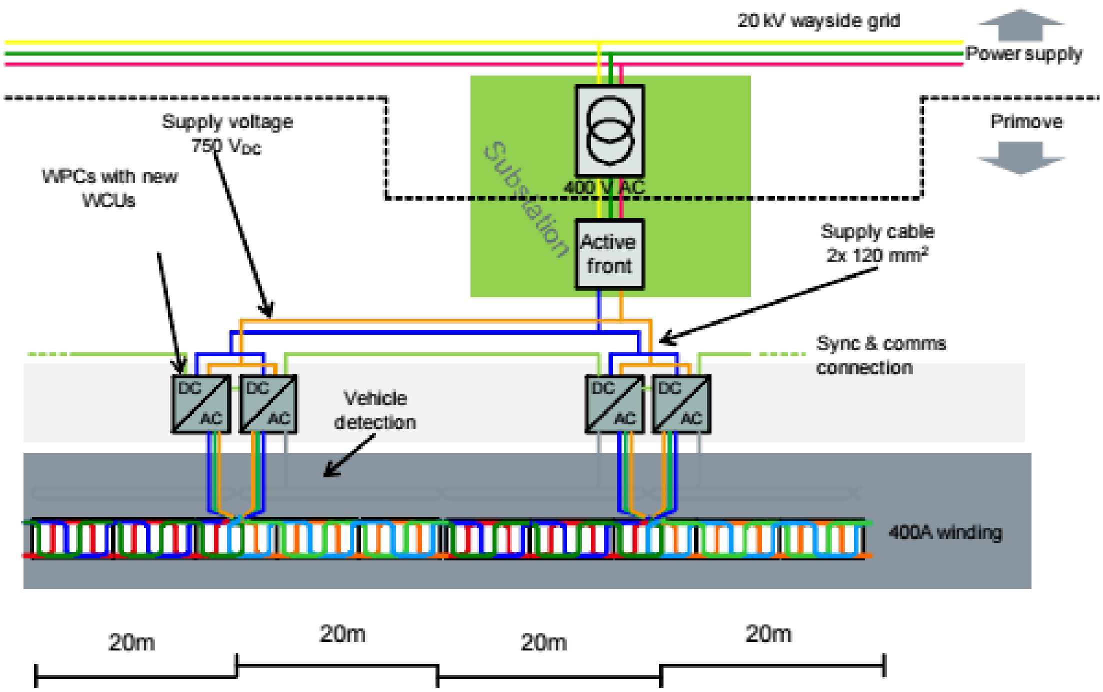

Figure 14. Primove highway inductive ERS architecture (Viktoria, 2013).

3.3 The road

Implementing an ERS can be done in two different ways; either build a completely new road and incorporate an ERS, or modify an existing road, with both options having different advantages and drawbacks. Constructing a completely new road with ERS is naturally more expensive than modifying an existing one if looking at the total cost of the construction. However, the specific cost of the ERS will be reduced since about a third of the total cost of implementation of an ERS is tied to installation (RISE, 2017a), which is absorbed by the construction of the road. However building a completely new road with an ERS is not seen as likely since there are no plans to build new highways in Sweden for the foreseeable future (RISE, 2017b). Therefore, all existing estimations on costs etc. for ERS implementation are based on modification with existing roads. If the opportunity arises that construction of a new highway in Sweden is proposed where it would affect a considerable portion of traffic volumes, the ability to incorporate an ERS into the road should be considered.

The choice of power transfer technology will affect the road differently. Overhead lines will cause little to no altercations to the road itself since it is mounted on pillars on the roadside, with the option available to skip one or two pillars in the row if complications arise (RISE, 2017b). The conductive rail approach is expected have a minimal impact on the road in terms of function and maintenance, as rational solutions for installation and maintenance have already been developed by the Swedish company NCC (RISE, 2017b). Bombardier has so far tested the inductive approach in concrete roads, but an adapted solution for asphalt roads has not yet been developed (RISE, 2017b). As Sweden currently legally requires asphalt roads, the impact of this option becomes hard to evaluate.

There is a risk with ERS of increased wear and tear of the road, as the electrification technology of the road will alter the way vehicles are driven and the amount of traffic on the road. For example if the power transfer technology is only installed in one lane of the road, this might lead to increased traffic, and thus wear and tear in this lane in particular. Installing an ERS might also lead to an increased number of vehicles choosing to travel upon that road in particular, especially if the price of electricity (fuel) is low. This could lead to more overall traffic, and thus increased wear to the road. More concrete information about this issue is expected to come from continued testing of ERS power transfer technology on current and future test sites.

3.4 Road operation

Operating and maintaining an ERS will look rather different compared to a conventional road. For the ERS there is an increased need of data collection and monitoring of the road and how it interacts with the vehicles travelling upon it since there is now a continuous interactive aspect between electric vehicles and the road. One important factor is for the ability of the vehicles to measure their energy consumption and relay this information back to a system operator of the ERS. This information link is crucial in establishing a payment and revenue system for the ERS, and is currently based on sensors in the vehicles measuring distance travelled (Viktoria, 2015). Research also shows that the monetary model for an ERS needs to be highly flexible and able to support multiple different business models, with concepts so far stemming from the telecom industry where this has been practice for some time (Viktoria, 2015). The need for flexibility stems from the increased amount of stakeholders in ERS compared to the current transport system and the complexities that come with that change.

Since there will most likely be an established data link between the driver and the system operator of the ERS, there are possibilities to utilize that link to share other relevant data between these two actors. Such information may include traffic management solutions, weather and road conditions, flexible pricing options etc. If this data link is established it also enables a more flexible energy supply situation for the vehicle and the surrounding energy supply actors. A situational example is that for a moment there is an abundance of energy in one sector of the grid where the road is located, while there is a deficit in another. Information about this between the vehicle and system operator thus enables the vehicle to run on its battery for the part of the road where energy currently is in high demand, and run on the ERS and charge its battery where the energy supply is adequate. Furthermore there is a possibility for energy stored in vehicle batteries to be harnessed in sectors where there is a high energy demand, meaning that EV drivers will have the option to be actors in managing the electrical grid for a steady and effective energy supply network, while simultaneously decreasing their own transportation costs.

3.5 ERS stakeholders

ERS is considered a novel technology, with no sizeable prototype of the entire system existing today. However, some general stakeholders that will probably play an important role in such a system can be identified, depicted in Figure 15 (Viktoria, 2013 & 2014).

Figure 15. The major stakeholders within an ERS (Singh, 2016).

The electric utility companies will axle the role of primary fuel supplier for the ERS. They will need to develop and maintain an electric grid capable of handling the energy demand of the ERS, while simultaneously supplying and maintaining power substations that connect the ERS to the grid. Road power technology firms are the stakeholders supplying the technical solution behind the power transfer technology, for example Siemens with the eHighway conductive overhead lines solution. Users are private vehicle drivers as well as road carriers, and they could potentially reduce their transportation costs and their carbon footprint using an ERS. The automotive firms are the suppliers of the vehicles that will be travelling upon the ERS. They need to obtain and continuously develop technical competence regarding electrification of vehicles and their incorporation of the chosen power transfer technology. Petroleum firms are expected to remain important stakeholders, but will become secondary fuel suppliers if their business model remains unchanged as electricity to the ERS will be supplied by electric utility companies. There is a possibility for these firms to evolve into supplying complementary fuel solutions, such as biofuels for heavy vehicles. The role of construction firms will be to integrate the ERS technology into the road, and the subsequent wayside infrastructure into the electrical grid. There is a future possibility of collaboration between the public and private companies in this sector. It is expected that the government and agencies will play a major and vital role in the development and diffusion of ERS. They will likely be required to be financially involved in the initial phases of adapting the technology to national routes. Here lies a founded incentive in reducing the environmental impact of transportation, as well as increasing the energy efficiency. New monetary policies will likely be required since there will be a loss in revenue from oil taxes. There is also a possibility for new monetary opportunities in exporting matured ERS concepts and technology to other countries.

4. METHOD

The gathering of information in this thesis was limited to reading industry reports, scientific papers and discussing the topic with researchers and industry workers connected to the research around ERS, since ERS is a novel technology and research into its implications are still underway. A visit to the ERS pilot-project in Sandviken was also conducted at the start of the project to get a hands-on insight into how a future ERS would work. This information served as a base for the handling of data and the general shape of the calculations in accordance to the project research questions.

Two main pieces of software were utilized in this thesis. All calculations within and between the data sets, figures depicting traffic flows, model groups and calculations regarding energy parameters were done in Matlab. A geographical analysis regarding segment allocation for the model groups and how they correlate in terms of placement along the E4 was done in ArcMap.

4.1 ERS case study

This study aims to analyze energy use and CO_2-emissions down to an hourly data-resolution using a case study of an ERS on route E4 between Stockholm-Jönköping. The 323 kilometer long route is depicted in Figure 16. This part of route E4 represents one of the busiest roads in Sweden in terms of traffic volumes of both light and heavy vehicles, and should therefore give insight into how the electrification of one of Sweden’s main roads would impact the transport sector.

The choice of conducting an hourly resolute study was based upon requests within the research platform, as such studies have not yet been conducted within Sweden. Not only does this choice reflect a more accurate and detailed analysis, but it does also make it possible to easily compare the numbers to relevant energy industry parameters such as grid capacity, pricing, operational runtime, demand & supply variations etc. who are all based on an hourly resolute timeframe.

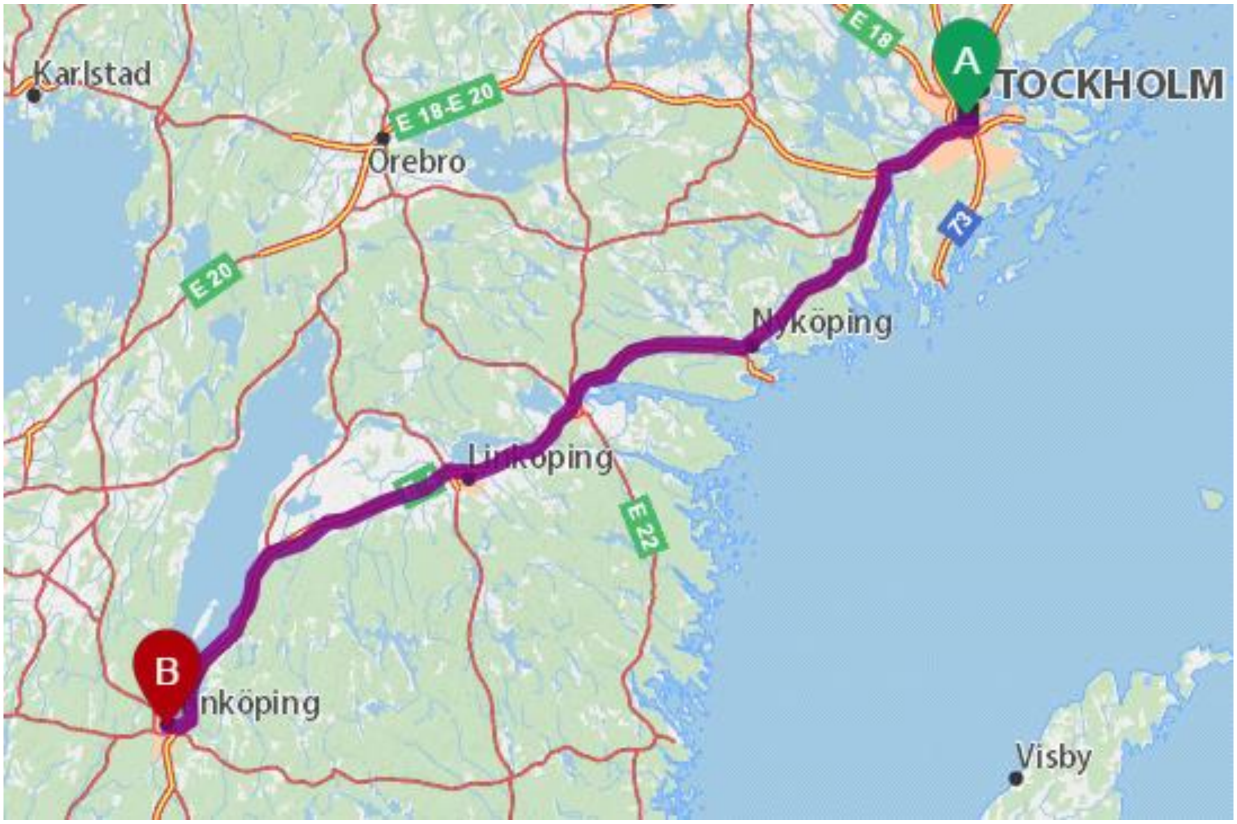

Figure 16. Map over central Sweden showing route E4 between Stockholm-Jönköping.

4.2 Data

The traffic data used in this study consists of two data sets called: hourly data set and average daily data set. The data sets are both obtained from the Swedish transport administration, with the hourly data set containing hourly traffic volume data for specific road points, and the average daily data set containing average daily traffic data values for the Swedish road network. A summation of the segment lengths in the average daily data set showed that the length of the road distance covered was 323 km, and this number was later used to calculate total vehicle kilometers, transportation work and energy use.

4.2.1 Hourly data set

The hourly data set contained 111 points in Sweden where the road traffic had been measured on an hourly basis in 2015 and contained information about:

- Daily date
- Hourly time
- Road/lane direction
- Type of vehicle
- Average daily traffic (ADT)
- Average speed

Vehicle types were categorized in six groups by the Swedish transportation agency:

1. Personal cars
2. Personal cars with trailers
3. Light trucks
4. Light trucks with trailers
5. Heavy trucks and buses
6. Heavy trucks and buses with trailers

These six vehicle categories were subsequently combined into two groups; light vehicles (vehicle types 1-4) and heavy vehicles (vehicle types 5-6). This combination was done to gain the ability to pair the hourly data set to the average daily data set, which measured the ADT of vehicles in light- and heavy vehicles. The definition of the light- and heavy vehicle groups in both data sets is based on the weight of the vehicle, with light vehicles weighing less than 3.5 metric tons and heavy vehicles weighing above 3.5 metric tons (STA, 2013). In field traffic measurements this categorization was done by measuring the distance between the vehicle axles in both data sets. The separation between light- and heavy trucks was defined according to the number of axles the truck had, where double and triple axle trucks fit into the light- and heavy truck groups respectively (STA, 2017).

Figure 14. Geographical locations of suitable hourly data points obtained from the Swedish transportation agency.

Among the 111 data points with hourly traffic measurements, only a handful were useful in this project. This was due to the nature of the road where the data was measured, as the majority of points measured small roads or a specific street in a city. The usable data points were all from major European routes through Sweden along with two points from national highways (Route 40 & 57). This geographical restriction essentially turned 111 initial data points into 12 potentially usable ones (depicted in Figure 17).

4.2.2 Average daily data set

The average daily data set covered both directions of route E4 between Stockholm-Jönköping and was comprised of 2594 segments covering the entire distance. Each segment in the data set covered all lanes in one direction of the road, and included three pieces of relevant information:

- Length of the segment
- Average number of vehicles per day (ADT)
- Average number of heavy vehicles per day (ADT)

The total amount of light vehicles from the average daily data set was calculated by simply subtracting the amount of heavy vehicles from the number of total vehicles per day. The separation between light and heavy vehicles in this data set was consistent with the hourly data set.

4.2.3 Data management

In both the hourly and average daily data sets there were gaps with missing values for certain hours and days. The hourly data set was already complemented by the Swedish traffic administration, whom based their complementation on a regression analysis that incorporated close by hourly values when dealing with a few missing hours, and on nearby weeks and their values when dealing with one or several missing days (STA, 2017).

The average daily data set had only the category of number of heavy vehicles containing missing values. For those segments where this was the case, the data was complemented manually by assuming that heavy vehicles held a proportional value of 13% of the total number of vehicles. This number was based on a random sample analysis that showed that in every studied segment, the proportion of heavy vehicles was between 11-14.5% of total traffic volumes, with most values being close to 13%.

4.3 Connection of data sets

Five road data points where the traffic was measured per hour were chosen to serve as basis for developing a traffic-pattern model that link the average daily traffic (ADT) with daily, weekly and yearly traffic patterns and traffic volumes. The hourly load profile generated from the traffic pattern model was then used in combination with the ADT for each segment of the route E4 between Stockholm and Jönköping to estimate the hourly energy demand. Their city proximity, route number and ADT for light and heavy vehicles, respectively, is shown in Table 1.

Table 1. The road data points from the hourly data set that were chosen to serve as model basis and their respective ADT.

	Data point	**ADT Light vehicles**	**ADT Heavy vehicles**
1.	Uppsala (E4)	34 500	2700
2.	Norrköping (E4)	24 550	4000
3.	Linderöd (E22)	8800	1000
4.	Järna (R57)	6100	280
5.	Vimmerby (R40)	2000	360

A geographical analysis regarding the data points was conducted in terms of where exactly on the route the data was measured, and subsequently what this resulted in concerning the hourly resolution of the traffic load. A good example of this can be seen when comparing the data points from Uppsala and Linderöd, where the data point near Uppsala is located on the highway between Stockholm-Uppsala which results in a type of commute-heavy resolution of the traffic compared to Linderöd. The effect of commuting travelling patterns on the load profile, here called commute-curve effect, is described in further detail in chapter 5.1.

The value of ADT for the data points, together with the geographical analysis resulted in each of the 5 data points being tied to one traffic pattern group of the hourly traffic distribution over a day, depicted in Table 2. Notice that Group A currently only holds a range value for the light vehicle group. This is due to the nature of the segment ADT values for heavy vehicles and their prominence according to the data. The data for the heavy vehicles simply did not contain enough different values to warrant a five group spread. Multiple variations on the range boundaries were tried in order to achieve a balanced spread of the route distance portions in regards to the original ADT values from the hourly data points with the result being four groups and a spread according to Table 2.

Table 2. Five model groups encapsulating the different ADT present on route E4 between Stockholm-Jönköping.

	Group name	Data point base	ADT Light vehicle group	ADT Heavy vehicle group
1.	Group E	Uppsala (E4)	20 000 – 75 000	4000 - 7500
2.	Group D	Norrköping (E4)	12 000 – 20 000	2000 - 4000
3.	Group C	Linderöd (E22)	8000 – 12 000	1000 - 2000
4.	Group B	Järna (R57)	4000 - 8000	0 - 1000
5.	Group A	Vimmerby (R40)	0 - 4000	-

By utilizing the traffic pattern groups based on the hourly data set, the ADT of every segment taken from the average daily data set could be multiplied with the corresponding group (based on its ADT value), thus combining the two data sets into one. This final data set now containing the entire route E4 between Stockholm-Jönköping, divided into 2594 segments each containing the segment length, ADT data for both light and heavy vehicles and their hourly load distribution.

The reasoning behind choosing specifically 5 data points to examine, and thus 5 groups, lies in the nature of the hourly data, meaning that of the 12 points available, several points had similar ADT and hourly distribution, thus more or less rendering them identical when analyzed mathematically. What this essentially means is that in the hourly data set, there were 5 different enough points in regard to ADT and hourly distribution curve to render 5 different groups for later use.

4.4 Data calculations & formulas

The hourly energy use and the total CO_2 mitigation potential when using an ERS can be calculated based on data from the hourly data set and the average daily data set. Considering the current and approaching state of renewable technology development in the electricity generation sector in Sweden and Europe, a 100% renewable energy supply was assumed for the ERS, resulting in zero CO_2 emissions from vehicles using the ERS. Important calculation factors, such as ERS energy consumption and CO_2 emissions from fossil fuel powered vehicles etc., were taken from similar studies, namely Taljegard et al. (2017a & 2016), depicted in Table 3 & 4. As indicated in Table 3, the two groups of light- and heavy vehicles were divided into four subgroups with corresponding energy consumption and CO_2 emission factors for increased analysis accuracy. Further information on the origin of numbers in Table 3 can be found in (Taljegard et al., 2017b) for energy consumption numbers and (Statistics Sweden, 2017) for vehicle distribution fractions and CO_2 emission factors.

Table 3. Calculation factors for vehicle category share of total traffic volume, energy consumption and GHG emissions (Taljegard et al., 2017a).

Vehicle category	**Share of light/heavy vehicles**	**ERS energy consumption [kWh/vehicle kilometers]**	**CO_2 emissions [g CO_2/vehicle kilometers]**
Cars	0.88	0.16	167
Light trucks	0.12	0.36	181
Buses	0.21	1.29	678
Heavy trucks	0.79	2.24	963

The efficiency factors in Table 4 involve every step from fuel supply to power-to-wheel effect for the vehicles for both the diesel system and ERS. Further information on the efficiency factors can be found in (Viktoria, 2013 & 2014), whereas specifics tied to diesel and ERS conversion can be found in (Ben-Chaim et al., 2013) and (Guzzella & Sciarretta, 2013) respectively.

Table 4. The efficiency ratios for different fuels for the transportation sector (Taljegard et al., 2016).

Type of fuel	**Efficiency**
Diesel	32.7%
Electricity (ERS)	77%

To calculate the energy demand for the road, the following equation was used:

$$E_{tot} = \sum_{i=1}^{2594} \frac{SL_i}{1000}\left((LV_i \times S_{car} \times EC_{car}) + (LV_i \times S_{LT} \times EC_{LT}) + (HV_i \times S_{bus} \times EC_{bus}) + (HV_i \times S_{HT} \times EC_{HT})\right) \quad (1)$$

Where SL is the segment represented by its length in meters, i is the index number for the current segment, LV is the total number of light vehicles, HV is the total number of heavy vehicles, S is the share of vehicles for a specific vehicle type, LT is referring to light trucks, HT is referring to heavy trucks and EC is the energy consumption coefficient for the corresponding vehicle type (numbers taken from Table 3).

To calculate mitigated CO_2 emissions for the road for a given year, the following equation was used:

$$CO_{2tot} = \sum_{i=1}^{2594} \frac{SL_i}{1000}\left((LV_i \times S_{car} \times CO_{2car}) + (LV_i \times S_{LT} \times CO_{2LT}) + (HV_i \times S_{bus} \times CO_{2bus}) + (HV_i \times S_{HT} \times CO_{2HT})\right) \quad (2)$$

Where CO_2 is the CO_2 emission per kilometer (taken from Table 3).

5. RESULTS

One main question of this study was to find values to key parameters linked to ERS implementation, specifically energy use and CO_2 emissions. These parameters are connected to the traffic flow of the studied road. The subsections in this chapter disclose the actual traffic flow of the hourly data points described in chapter 4.3 (subsection 5.1), the traffic flow of the route investigated (subsection 5.2), the resulting energy demand from implementing ERS (subsection 5.3) and the resulting impacts on the energy use and CO_2 emissions in the Swedish transport sector (subsection 5.4).

5.1 Traffic data

This study has investigated the traffic patterns of the route E4 between Stockholm-Jönköping by using five groups of traffic patterns for segments with different traffic volumes described in chapter 4.3. Figures 18-21 show the aggregated traffic volumes (i.e. number of vehicles) from all five groups and all 2594 segments for the traffic data point in Norrköping (E4). Corresponding traffic volume graphs for the rest of the traffic data points described in chapter 4.3 can be found in appendix A-D. Figure 18 shows the number of light and heavy vehicles per hour for an average day. One important factor that is present depending on the geographical location of the data point is the so called “commute-curve”, meaning elevated traffic levels for light vehicles around morning and afternoon commute hours (8-9AM and 4-6PM respectively). This particular traffic distribution is especially prevalent when examining the data point on route E4 between Uppsala-Stockholm (found in appendix A). Figure 19 shows instead the number of light and heavy vehicles per day for an average week, clearly showing a decrease in traffic volume for heavy vehicles during the weekend. This decrease is mainly due to lorry drivers having the weekend off from driving.

Figures 20 & 21 show the daily traffic volumes for light and heavy vehicles over an average year, where traffic volumes for light vehicles increase during the summer, while they decrease for heavy vehicles for the same period. The reason behind this is that the vacation season affects the two vehicle groups in different ways, as many families use their car as transportation during vacation times. Industries on the other hand are closed during the summer, thus requiring less heavy transportation while the lorry drivers themselves are also on vacation from driving. Some holiday seasons are also seen quite clearly in the data, for example substantial decreases in traffic volume for both categories on Midsummer holiday, and an increase in light traffic around Easter while the heavy traffic decreases for the same time.

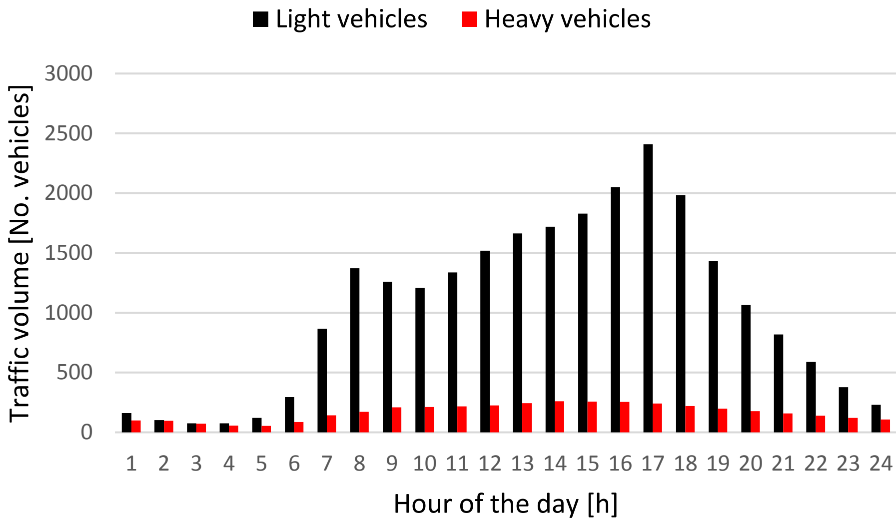

Figure 18. The hourly traffic flow over an average day for light vehicles (black) and heavy vehicles (red) over a day at route E4 south of the city of Norrköping.

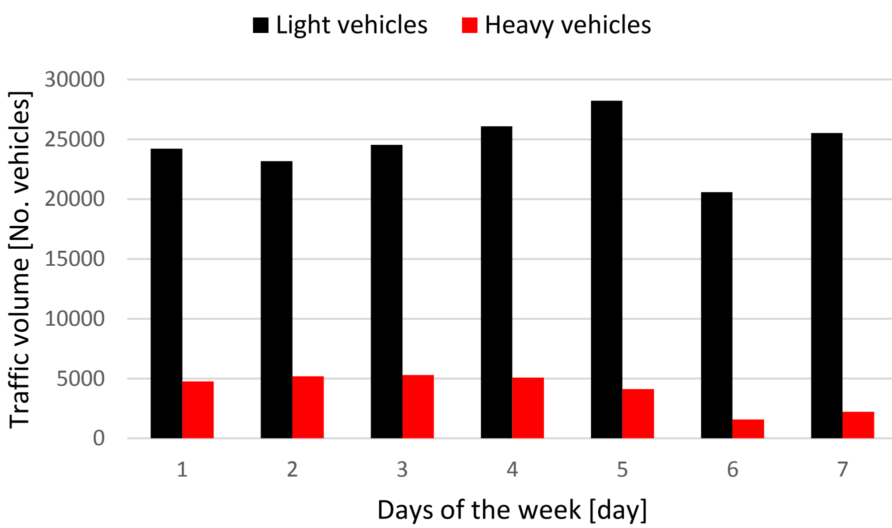

Figure 19. The daily traffic flow over a week for light vehicles and heavy vehicles at route E4 south of the city of Norrköping. Day 1 corresponds to Monday and so on.

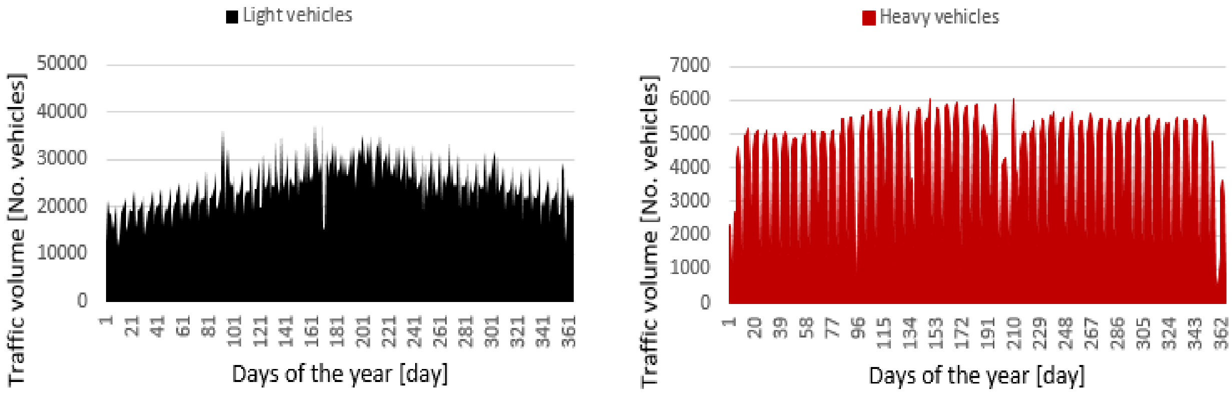

Figure 20. Daily traffic flow over a year for light vehicles (left) and heavy vehicles (right) at route E4 south of the city of Norrköping. The figure shows the difference in seasonal variations between the two vehicle groups. Note the traffic volume axis difference between the two graphs.

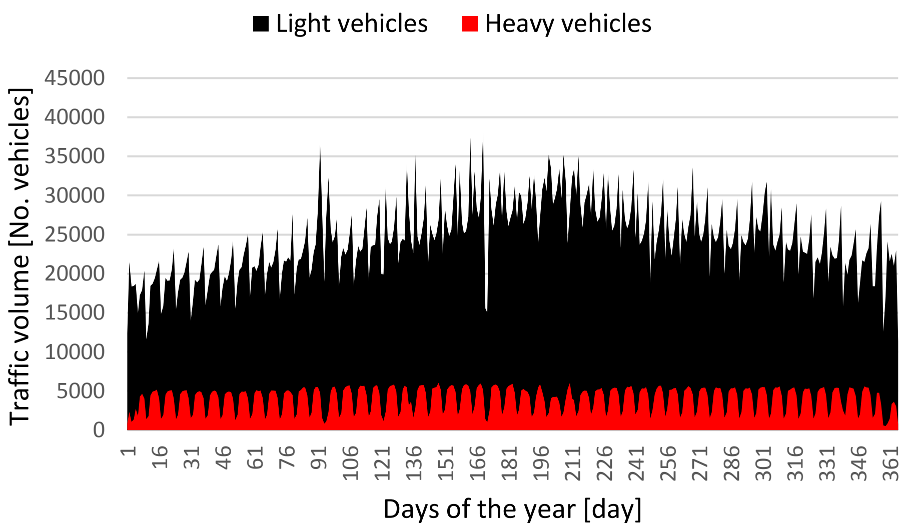

Figure 21. Daily traffic flow over a year for light vehicles and heavy vehicles at route E4 south of the city of Norrköping. The figure shows the magnitude difference in vehicle numbers between the two vehicle groups.

All of the factors affecting the level of traffic (commute and holiday traffic levels etc.), and their underlying nature are important since they are going to affect the varying demand of energy at different times. This demand will have a characteristic impact on the electric grid that will be caused by the implementation of an ERS. The total yearly amount of traffic on the studied route corresponds to approximately 4% of total annual traffic levels in Sweden, while the amount of heavy vehicle traffic corresponds to 6.7% of annual heavy traffic in Sweden.

5.2 Traffic pattern model groups

The groups described in chapter 4.3 subsequently served as a base for finding the traffic pattern for route E4 based on the segment ADT value. Two maps depicting what part of the E4 the different group segments occupied were created, one for light vehicles (Figure 22) and one for heavy vehicles (Figure 23). The total occupation of road distance for each group, and their corresponding color in the maps is shown in Table 5.

Table 5. Showing the share of the route distance the different model groups occupies.

	Distance share of the route in [km] and [%]				
Vehicle group	**Group A**	**Group B**	**Group C**	**Group D**	**Group E**
Light vehicles	15 km (2.3%)	185 km (28.7%)	313 km (48.5%)	65 km (10.1%)	66 km (10.3%)
Heavy vehicles	-	28 km (4.5%)	376 km (58.6%)	188 km (29.4%)	48 km (7.5%)

As Figure 22 shows, the heaviest light vehicle traffic (colored green in the map) can be found in the proximity to both Stockholm and Jönköping. This is showing the expected commute-situation close to big cities, especially prominent between Stockholm-Södertälje. Apart from this, the majority of the route occupies an ADT of either 8000-12 000 (colored blue) at close to 50% of the total route, or 4000-8000 (colored red) at roughly 30%. The exceptions between the two big cities are, as marked in the map, the two towns Norrköping and Nyköping, where there is an expected increase in traffic in their vicinity. In some places there are two colors that seem to overlap and occupy the same piece of the road. This situation occurs where there are more vehicles travelling in one direction of the road than the other, since the segments (and their coloring) only cover one direction of the road.

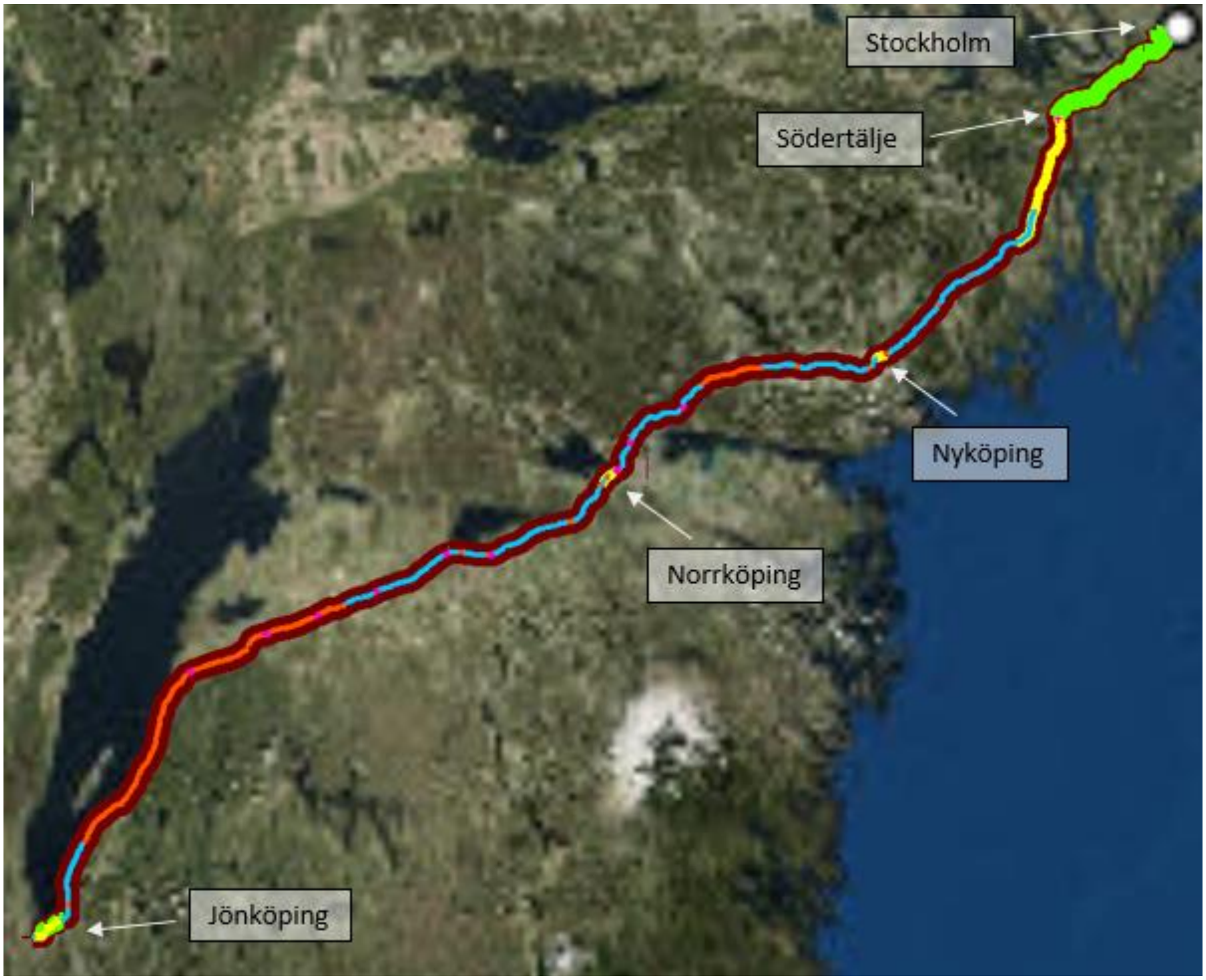

Figure 22. Route E4 between Stockholm-Jönköping with road segments color coded according to group belonging for light vehicles.

For the heavy traffic, Figure 23 shows that the majority of the road possesses an ADT between 1000-2000 (colored blue), in total occupying almost 60% of the route, while a somewhat higher ADT (colored yellow) occupies roughly 30%. Again, the highest ADT is found dominantly between Stockholm and Södertälje, with the area around Jönköping now not occupying a single instance of heavy traffic in the highest ADT model group. The towns of Norrköping and particularly Nyköping do not stand out as much in traffic variations when it comes to heavy vehicles, probably meaning that a majority of the heavy traffic on the route travels longer along the route than light vehicles. Interesting to note is that the route southwards from Norrköping has a higher ADT for a substantial piece of the road toward Jönköping, indicating a situation where considerable heavy transports are headed out of or into Norrköping.

Figure 23. Route E4 between Stockholm-Jönköping with road segments color coded according to group belonging for heavy vehicles.

5.3 Energy demand

Figure 24 shows the average daily energy demand for the highway route E4 between Stockholm-Jönköping, assuming all vehicles use the ERS. The maximum energy demand is 300 MWh/h occurring during 5-6 PM, as seen in Figure 24. The nightly (10PM-7AM) and daily (7AM-10PM) average energy demand varies in the range 20-100 MWh/h and 125-300 MWh/h, respectively. Noteworthy is that the energy demand for heavy vehicles is quite consistent between hours 9AM-5PM, making the driving pattern of light vehicles determine what hour is peak demand.

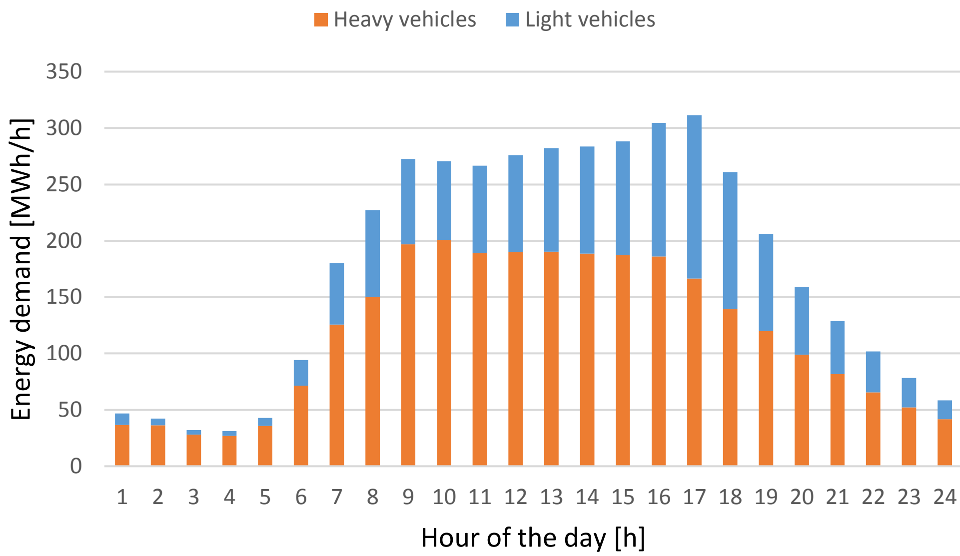

Figure 24. The hourly energy demand an average day for light and heavy vehicles for an ERS on route E4 between Stockholm-Jönköping.

Figure 25 depicts the daily ERS demand for an average week, clearly showing that heavy vehicles consume the majority of the energy demand on a daily basis. The daily average during weekdays is consistently around 5 GWh/day, while this number drops to between 2 and 3 GWh/day during weekends. As seen in Figure 25, this drop in energy demand is due to the driving pattern of heavy vehicles, as light vehicles maintain roughly the same energy demand throughout the week.

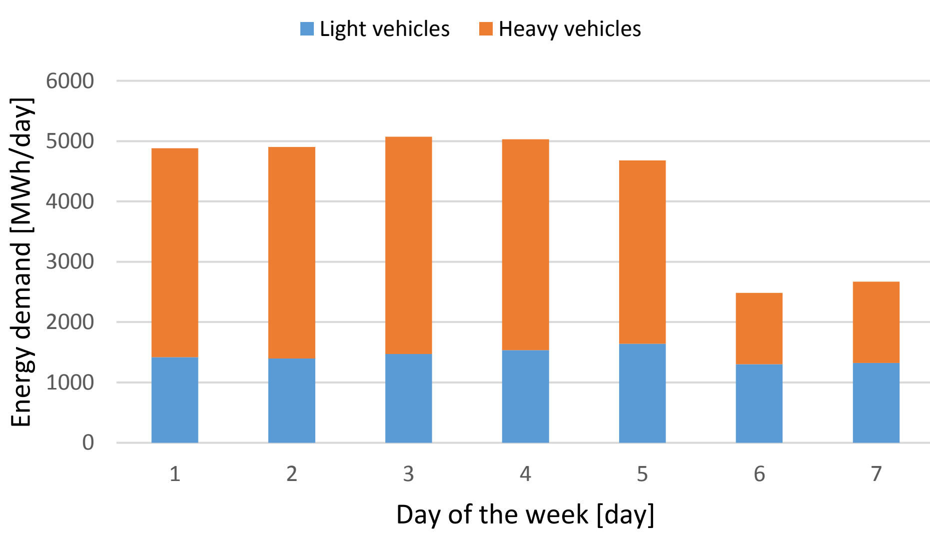

Figure 25. The energy demand for an average week for light and heavy vehicles using an ERS on route E4 between Stockholm-Jönköping. Day 1 corresponds to Monday and so on.

Figure 26 shows the daily energy demand for a complete year. As can be seen, the energy demand of light vehicles is quite consistent throughout the year, while the weekend traffic decrease for heavy vehicles are clearly marked. Some seasonal variation does also occur, most notably a decrease in energy demand during the summer due to lower volumes of heavy traffic. Holidays such as Easter and Christmas are similarly reflected in Figure 26 compared to Figure 20.

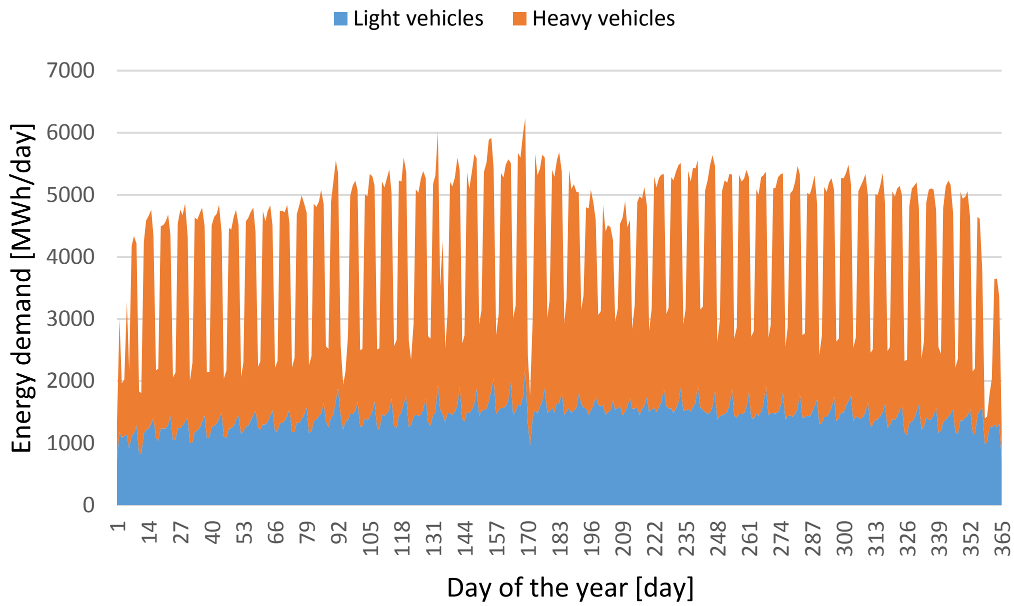

Figure 26. The year total energy demand for light and heavy vehicles using an ERS on route E4 between Stockholm-Jönköping.

5.4 Impact on energy consumption and CO_2-emissions

Chapter 5.1-5.3 showed that implementing an ERS on route E4 between Stockholm-Jönköping would electrify 4% of the annual traffic volumes in Sweden based on 2015 traffic volume numbers from (Statistics Sweden, 2017). The annual energy demand for the ERS was calculated to 1.55 TWh/year, using a 77% efficiency factor (Guzzella & Sciarretta, 2013), and by using the efficiency factors depicted in Table 4 the raw transportation work for the road was calculated to 1.19 TWh. As seen in Table 6, switching from a diesel system to an ERS will in this case also decrease total energy demand for the road by at least 1.66 TWh (48%), resulting in a national decrease in road transport energy by 1.9% (Åhman, 2009) from 89 TWh/year to 87.3 TWh/year. If the 2030 goal of 4 TWh of electrical transport (disclosed in chapter 2.1) is met solely by ERS it would electrify 10% of the Swedish annual traffic volumes and reduce 13% of the annual CO_2 emissions from the transport sector if national traffic volumes and greenhouse gas emissions are maintained at the current level. With the current efficiency of ERS, a 1 TWh energy unit will propel 2.6% of the annual traffic volume in Sweden using 2015 levels, while that number for diesel is only 1.25%.

Table 6. Efficiency & energy comparison between a diesel system and ERS. Efficiency factors taken from (Ben-Chaim et al., 2013) and (Guzzella & Sciarretta, 2013).

Type	Efficiency	Energy
Transportation work	-	1.19 TWh
Diesel system	32.7%	3.2 TWh
ERS	77%	1.55 TWh

The annual CO_2 reduction potential for an ERS on route E4 between Stockholm-Jönköping was calculated to 0.95 Mton CO_2eqv (compared to a diesel transport system). This reduction potential is based on the assumption of a non-fossil energy supply source for the ERS with zero CO_2 emissions. The reduction of 0.95 Mton CO_2 corresponds to 5.3% of the total yearly CO_2-eqv emissions (18 Mton CO_2-eqv/year) from the Swedish transport sector (SEPA, 2016). Heavy vehicles required 66% of the aforementioned energy demand, resulting in a 50% share of the emitted CO_2 while only comprising 15% of driven vehicle kilometers. This relationship is clearly envisioned when comparing the differences between corresponding traffic volume- and energy demand figures, i.e. Figure 18 to Figure 24 and so on. Implementing an ERS of this size also electrified 6.7% of annual heavy traffic volumes.

6. DISCUSSION

Using the described traffic pattern model in the case study of route E4 between Stockholm-Jönköping showed some considerable changes to the energy demand and CO_2 emissions of the road and the Swedish transport sector in general. Thus, implementing an ERS of this size will have considerable effect on for example the electric grid, the future development of the transport sector and how this development matches the scenarios set by the Swedish government. This chapter discusses the role of the ERS in this case, and in a potential future broader development perspective.

6.1 Impact on the electric grid

The impact on the electrical grid from ERS will depend on a number of characteristics. One important issue is on what voltage level of the grid the ERS is connected to, as there are possibilities to connect it to the national (220/400 kV), regional (40-130 kV) and intermediate grid (10-20 kV) along the entire route. Other crucial factors that have an impact on the grid include the ERS peak capacity demand, the energy demand over time, current and future connection possibilities/restrictions to the different grid voltage levels and the choice of power transfer technology. As mentioned in chapter 2.3, Sweden currently has a 150 TWh annual net energy production, of which approximately 15 TWh is exported to nearby countries every year, making the additional yearly energy demand of an ERS in this case (1.55 TWh) of little concern in terms of yearly national energy supply.

Since the national grid (owned by SVK) has a minimum capacity requirement of 300 MW, and the ERS in this case has only one hour/day that reaches that target (5-6PM) it might be so that the national grid would be able to handle both the capacity and energy load of the ERS without difficulty. Connection of the ERS to the regional grid is dependent on the current grid along the route owned by Vattenfall and its future development. Viktoria (2014) specifically describes the connection possibilities of an ERS to the regional grid between Stockholm-Jönköping, in which they argue that it is well suited for additional loading and future expansion, assumably both in terms of capacity and energy demand over time. Analysis over how well the intermediate grid would handle the aforementioned load proves difficult since this grid is owned and operated by 12 stakeholders for the road investigated, all with their own energy supply and grid structure. The availability of capacity and energy over time for this grid level was not investigated due to time constraints.

Interesting to note is that there is also a 220 kV voltage level of the national grid in Sweden (seen in Figure 7, section 3.1.1) also owned by SVK, where the minimum voltage required for connection is 100 MW (SVK, 2017). This requirement is fulfilled by this ERS case for large amounts of the day, and would possibly be another candidate for a grid connected energy supply. However, there is no such grid available along the route, as the 400 kV voltage level of the national grid powers most of southern Sweden. Although this alternative 220 kV grid is not available in this case, it would be of interest when studying energy supply options for other ERS cases.

There are some important advantages and drawbacks among the different grid levels. Since both the national and regional grid are set to voltage levels much higher than that needed to power an ERS, they both need a completely new electricity grid to be built along the route with substations connecting it to the national/regional grid approximately every 30-40 km. This additional infrastructure is estimated to cost roughly 7.2 MSEK/km when connected to the regional grid (Viktoria, 2014), including wayside components. The same infrastructure cost for a connection to the national grid is estimated to be higher than 7.2 MSEK/km, although no specific number is available at the moment (SVK, 2017). A connection to the intermediate grid does not require construction of a new grid along the route since the voltage level of this grid (10-20 kV) is already within the voltage range required by the wayside grid of an ERS (10-30 kV). Although, this level of the grid has a drawback in that the situation of whom owns and operates the grid is scattered among a dozen actors, which might make agreements and communication complicated (Viktoria, 2017). The voltage level that is best suited as an ERS energy supply is not yet determined and requires further research since no large scale ERS project has yet been constructed (Vattenfall, 2015), (Viktoria, 2017).

Figure 24 shows that the energy demand stemming from heavy vehicles is quite consistent during the day (9AM-5PM), while the energy demand stemming from light vehicles is clearly varying during the same time. Furthermore Figure 24 shows that there is a spike in energy demand from light vehicles for the hour 5PM-6PM, making this hour the peak hour of the average day. The total energy demand of the ERS naturally varies depending on time of day, day of the week and yearly seasons, however these variations are quite regular in their fluctuations, making the upcoming energy demand easy to predict.

This study also shows that there is an important difference in energy demand between weekdays and weekends, working weeks and holiday weeks, with some seasonal yearly variations. These variations are due to differences in driving patterns of heavy vehicles. There also seems to be similarities between the energy demands of an ERS and the demand for electricity from all other sectors in Sweden (Nordpool, 2017), especially for hourly and weekly total demand with a high demand during weekday daytime and decreases during the weekends. As expected, the findings in this study of a highway in Sweden are similar to results from a corresponding analysis for Norway (Taljegard et al., 2017a). This study does however show an increased share of heavy vehicle traffic flow, and thus a higher energy demand connected this vehicle group (66%) than the study in Norway (50%).

6.2 Why choose ERS?

ERS have a series of advantages compared to the current transportation system based on fossil fuels such as: (i) significant efficiency increase (2-3 times that of the current transportation system), (ii) the possibility for a fossil independent and emission free energy supply, (iii) lower operational cost since electricity is cheaper than petrol/diesel, (iiii) reduction of noise problems for communities and (iiiii) reduced maintenance costs for the electric engine compared to an ICE (Viktoria, 2014).

There are currently some barriers in the implementation of ERS that are important to consider. The most prominent one being the integration issue between the vehicles, the road and the power transfer technology, meaning that there is no current technology integrating these parts in an electrified system. Therefore the necessary technology for these parts in the system would all need to be invented and compatible with each other for the ERS to work. Furthermore an ERS would as it looks today require a closed-system design, where its subsystems (described in chapter 3.1-3.4) are closely connected to each other. Interestingly this is not how the current system is comprised since the original road system, fossil based fuel sources, ICE and vehicle technology etc. developed separately over the last century. Such a scattered system structure and century long time frame is not efficient enough for current technological standards (Viktoria, 2014).

It could also be argued that ERS is a technology that solves the range issue for EVs, but has competition in regard to the currently significant development in battery technology. According to (Nykvist & Nilsson, 2014), the cost for EV batteries has decreased significantly in the recent years, while the energy density has significantly increased in the same time, as seen in Figure 27. If this development continues, there is a possibility that batteries are sufficient in and of themselves to solve the range issue in the future, which may cast doubt as to if ERS is needed at all.

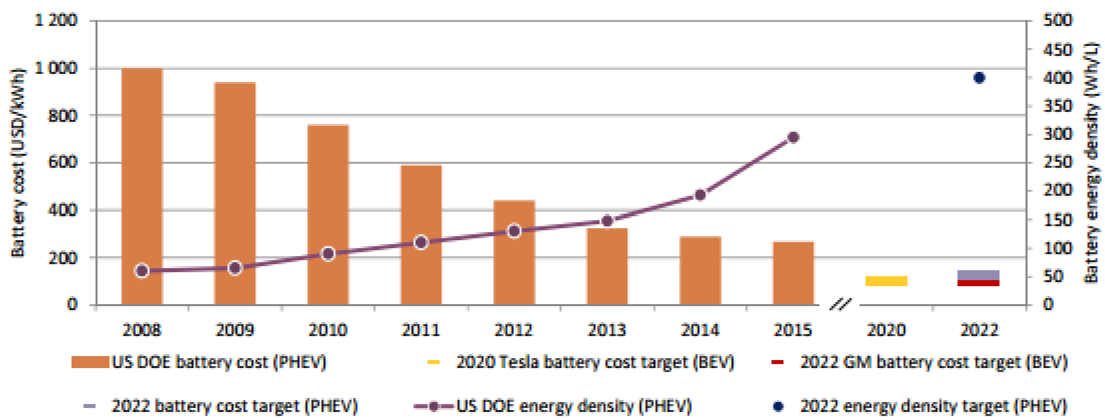

Figure 27. Past, current and projected development for EV batteries (IEA, 2016).

6.3 Implications of Power transfer technology choice

All three power transfer technologies have similar total system efficiencies, as the conductive technologies have a rated efficiency of 80-82% and the inductive solution has a rated efficiency of 79%. These efficiency numbers are expected to change in the future due to development of the technologies, and current uncertainty is especially prevalent with the inductive ERS as it still is an immature technology compared to the conductive solutions. The costs of implementation for the power transfer technologies are currently not fully investigated and differ greatly between sources, and have therefore not been an intrinsic part of the system description of ERS. However, current estimations put the cost of implementing either of the conductive solutions at around 10 MSEK/km and the inductive solution at a range of 25-56 MSEK/km. The cost range for the inductive solution is to large extent dependent on technology development and the design of the system. An example being if the entirety of a road will be electrified, or a “cluster-design” is chosen instead, where only parts of the road are being electrified. When the vehicle is connected to the ERS in a cluster it will provide electricity for the vehicle to move while simultaneously charging the battery, while the charge in the vehicle battery is expected to propel the vehicle between the clusters. Worth noting is that it is estimated that a segment length extension from 20 to 25 meters would decrease total construction costs of the inductive system by 13% (Viktoria, 2013).

If the development of batteries continues as the current trend suggests, there is a possibility that the range issue might be solved for light vehicles, based on a vehicle battery and sufficient charging infrastructure alone. However, this development is not predicted to solve the range issue of heavy vehicles, thus rendering the overhead conductive lines a viable solution in this hypothetical as they can only be utilized by this vehicle group. If battery development does not reach the aforementioned level however, and overhead lines become the chosen power transfer technology, light vehicle electrification development will be limited. If this path is chosen in the case study above, the ERS would only electrify 0.6% of annual traffic volumes and reduce annual CO_2 emissions by 2.65%, at a cost of 1 TWh. Comparing this to choosing one of the other technologies, using the same assumptions would put the same numbers at 4% traffic electrification, 5.3% CO_2 reduction at a cost of 1.55 TWh.

6.4 ERS in transport scenarios

An ERS on the route E4 between Stockholm-Jönköping would electrify 323 kilometer highway and use 1.55 TWh of electricity per year. In a scenario for the Swedish transport sector by 2030 (further described in chapter 2.1), approximately 4 TWh of electricity per year is used for transport. Thereby, implementing ERS on 2-3 equally sized highways in Sweden would already reach the goal of 4 TWh of electricity in transport. An ERS 2-3 times larger than investigated in this study would electrify 10% of the annual vehicle kilometers and decrease the CO_2 emissions with 13%, assuming the traffic level as of the investigated highway for 2015. Assuming a 100% vehicle compatible concentration on these ERS roads, and with the current pace of technological development, this vision seems manageable considering the given timeframe. There is an argument to be made that one of the challenges in accomplishing the aforementioned system is to develop, invest and achieve such a diffusion of electric vehicles that are compatible with the ERS for the scenario to be accurate. Another challenge is to build the necessary infrastructure surrounding ERS, as this will require enormous effort and economic funds that will have a payback period of several decades.

The 2030 transport scenario has currently set its vision to a 4 TWh electric portion of the transport energy demand contributed by EVs and PHEVs using stationary charging infrastructure (such as home charging and charging stations along roads). If an ERS is implemented, its energy demand would most likely exceed the 4 TWh already demanded by the stationary charging infrastructure.

The amount of electric energy in the 2045 transport system is not clearly defined in either (SOU 2013:84) or (SOU 2016:21) and an approximation put this number around 10 TWh for the 2045 scenario goal as of today. It is predicted that if the 2030 target is reached with the involvement of ERS, the 2045 target does not seem considerably challenging given the energy amount difference compared to the time horizon in both cases.

The goals set by the two scenarios can potentially be reached without involvement of ERS at all. The general goal of having 80% of the vehicle fleet independent by 2030 and a net zero greenhouse gas emission by 2045 can potentially instead be achieved by switching current fossil transport technologies to biofuels and hydrogen fuels. If the development within these two sectors can reach the goals, or how close they can get to them in the given timeframe will be determined by the forthcoming development of these technologies in particular, but also the evolution of the transport sector in general (surrounding infrastructure, vehicle integration etc.). The particular goal of having 4 TWh and 10 TWh respectively of electrical energy in the transport system can potentially also be fulfilled without the involvement of ERS. This is again determined by the development of EVs, batteries and surrounding infrastructure in particular, and it is estimated that if 100% of the current passenger vehicle fleet was electric it would utilize an energy consumption of around 10 TWh. Both of these hypothetical situations without ERS could possibly reach the environmental goals, although ERS are an effective way to electrify heavy vehicle transportation and thus reach, or even surpass the goals.

6.5 Limitations of the study and continued future work

The present study is limited by the availability of relevant hourly data points. In this study it is assumed that data points located on other roads with similar ADT and geographical location can be used to match the traffic patterns in a segment of the investigated route (E4 between Stockholm and Jönköping). A greater number of data points with an hourly resolution (preferable on the actual route) would therefore increase the precision of the investigation if assessing Sweden as a whole.

The accuracy of the data complementation in the second data set (described in chapter 4.2.3) can be improved by for example by increasing the sample size and creating a mathematical formula to find the average relationship between light and heavy vehicles. This was not explored further due to time constraints.

The traffic pattern groups used in this thesis were developed to be as accurate as possible with the available data, however there are some deviations. The hourly data point that served as a base for Group E was located between Uppsala-Stockholm and represented the maximum group values for both light and heavy vehicles, while it actually only occupied the highest ADT value for light vehicles. The choice to use this point as the group base in Group E for heavy vehicles as well was due to the nature of the variations in traffic levels between the road data points. The segments belonging to Group E were located inside the city of Jönköping and between Stockholm-Södertälje and these sections were deemed as commute-heavy geographic locations. Because of this it was deemed likely that this road data point would describe the actual traffic patterns in the segments belonging to Group E with the most accuracy out of the data points available.

A sensitivity analysis was done in ArcMap concerning the ADT boundaries of the different groups and how they affected the division of segments (and thus hourly energy demand) for the route. For example the boundaries of Group D (2000-4000 ADT) were split into two groups, confining 2000-3000 and 3000-4000 ADT respectively, but with little to no resulting difference. Similarly, Group C (1000-2000 ADT) was split into two groups confining 1000-1500 and 1500-2000 ADT, again with no noticeable difference.

Examining the segment allocation of the route for both light (Figure 22) and heavy (Figure 23) vehicles shows that the segments belonging to the group determining the lowest ADT group (Group A and B respectively) to be very scattered along the entire route, even in between segments in the highest ADT group (Group E). The reason behind this was difficult to uncover in the data received by the Swedish transport administration. A possible solution is that these scattered segments cover entrance/exit sections of the road.

The efficiency and energy demand difference between a diesel system and ERS showed in chapter 5.4 is probably even greater than previously described. This is in part due to the assumption that diesel is used as a fuel to the entirety of the current transport fleet, while in reality around 60% of the passenger vehicle fleet is comprised by vehicles using petrol as fuel (Trafikanalys, 2016), which only reach an efficiency of 25% (Ben-Chaim et al., 2013). Furthermore the efficiency set for the ERS might rise as the technology develops over coming years would it be implemented.

Recommended future studies are to examine the effect ERS would have on the different electrical grid levels, and to determine what role ERS can play when evaluating national transportation scenarios set by the Swedish government in further detail.

7. CONCLUSION

This study concludes that implementing an ERS on the 323 kilometer long part of route E4 between Stockholm-Jönköping would electrify 4% of total traffic volumes in Sweden and reduce annual CO_2 emissions by 5.3%, while simultaneously lowering the energy consumption by 1.66 TWh, from a 3.2 TWh diesel system to 1.55 TWh for an ERS.

While heavy vehicles only account for 15% of driven vehicle kilometers, they constitute 66% of the energy demand and 50% of CO_2 emissions. Despite the considerable energy demand, heavy vehicles have a consistent energy consumption throughout the day, making the driving pattern of light vehicles determine what hour becomes peak energy demand, in this case 5-6PM. Examining weekly and yearly energy consumption, this pattern switches, meaning light vehicles have a consistent energy demand and driving pattern of heavy vehicles resulting in a reduced energy consumption during weekends and during the summer. Hourly energy demand peaks at 300 MWh/h, while an average weekday peaks at 5 GWh/day and the yearly peak for a day sets at 6 GWh/day.

The impact on the electric grid will wary depending on what level of the grid the ERS is connected to, but there are currently three levels (national, regional & intermediate grid) that all fit the required voltage level. The total energy demand from the ERS in the case study of 1.55 TWh can probably be supplied domestically since Sweden currently exports 15 TWh/year. How the capacity demand will affect the electricity grid needs further research to answer properly, but it will probably depend on what level of the grid the ERS is connected to and how that grid is developed in the coming future.

The study shows that ERS is a suitable candidate to accomplish the environmental goals set by the Swedish government, as it is a green and effective mode of transport. It could potentially be enough to implement ERS on 2-3 highways of the same size as the case studied to accomplish the electrification goal, suggested in the scenario for the Swedish governmental vision of a fossil free transport sector by 2030, assuming a sufficient diffusion of compatible vehicles and adoption of chosen power transfer technology.

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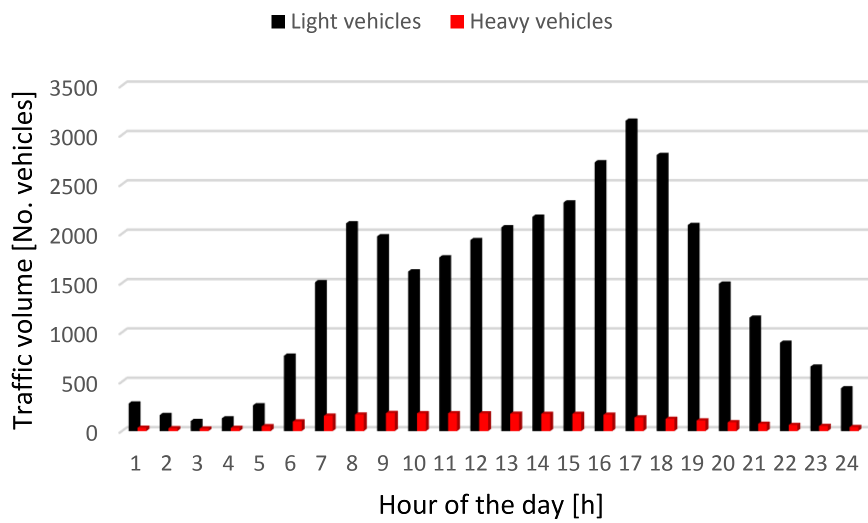
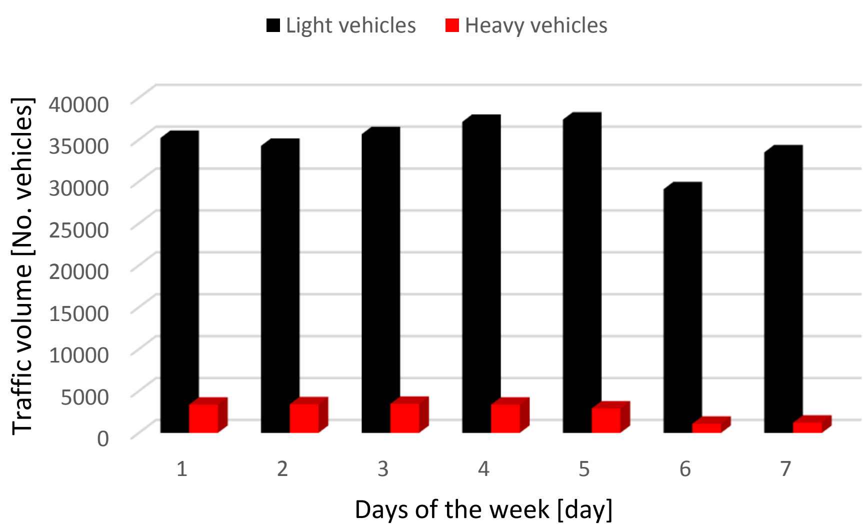
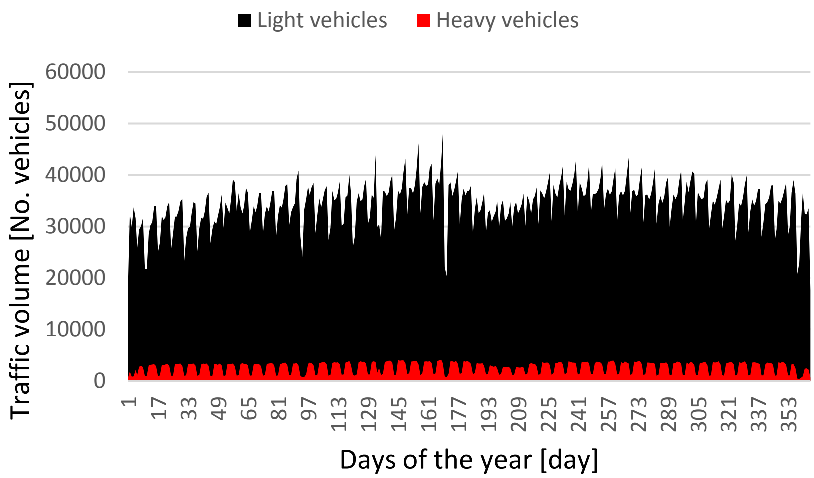
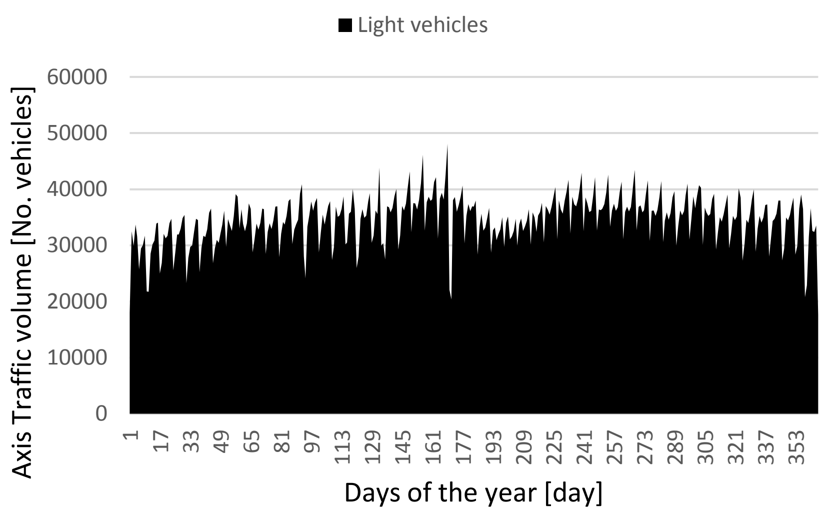
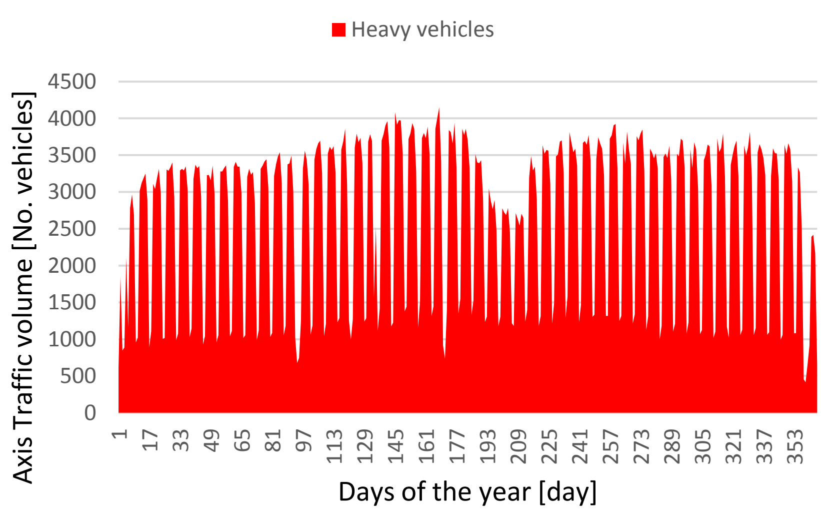
Appendix A – Traffic pattern graphs for data road point Uppsala (E4)



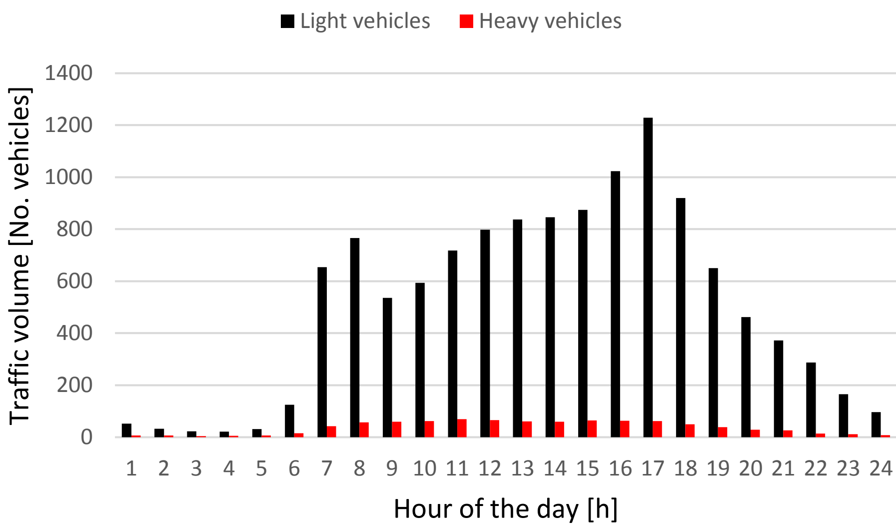


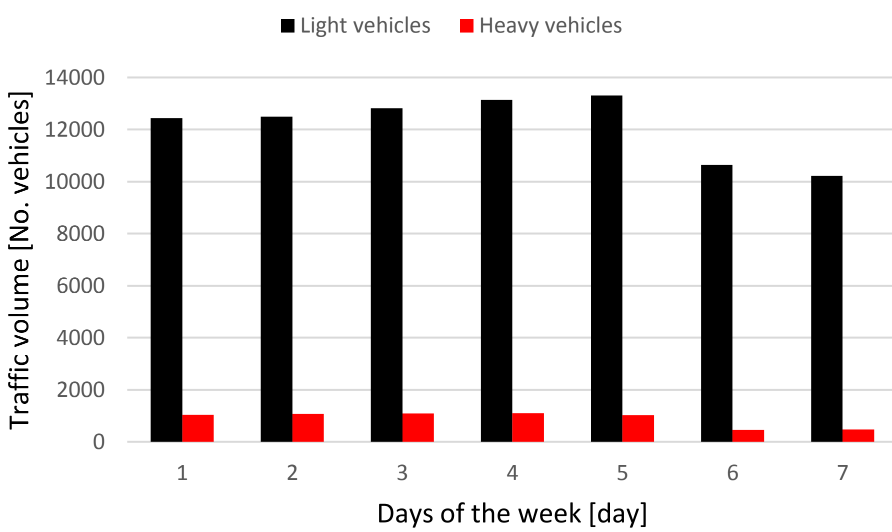

Light vehicles
Heavy vehicles
Traffic volume [No. vehicles]
60000
50000
40000
30000
20000
10000
0
1
17
33
49
65
81
97
113
129
145
161
177
193
209
225
241
257
273
289
305
321
337
353
Days of the year [day]

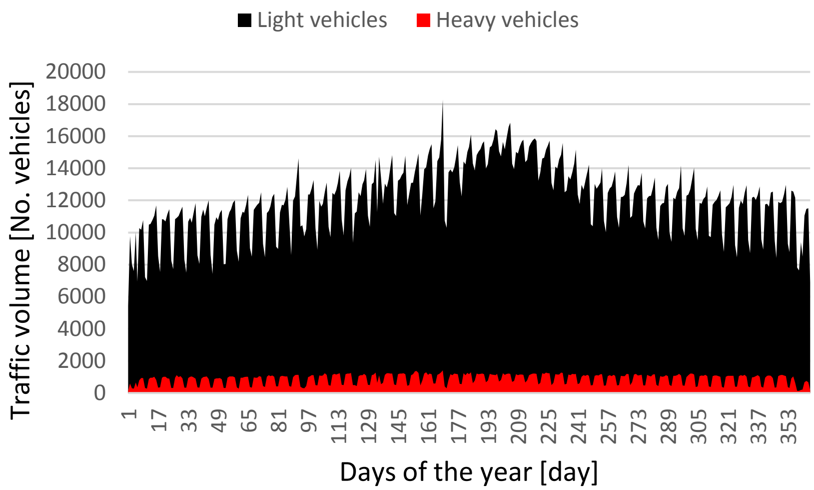

Light vehicles
Axis Traffic volume [No. vehicles]
60000
50000
40000
30000
20000
10000
0
1
17
33
49
65
81
97
113
129
145
161
177
193
209
225
241
257
273
289
305
321
337
353
Days of the year [day]


Heavy vehicles
Axis Traffic volume [No. vehicles]
4500
4000
3500
3000
2500
2000
1500
1000
500
0
1
17
33
49
65
81
97
113
129
145
161
177
193
209
225
241
257
273
289
305
321
337
353
Days of the year [day]

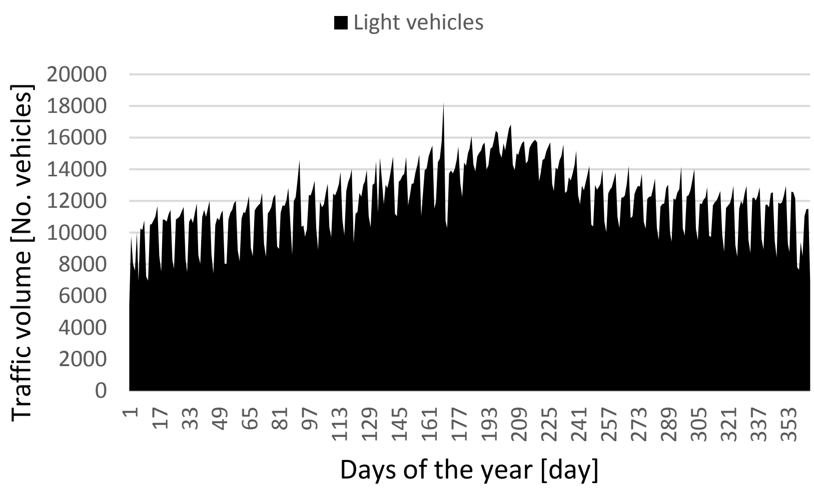
Appendix B - Traffic pattern graphs for data road point Linderöd (E22)



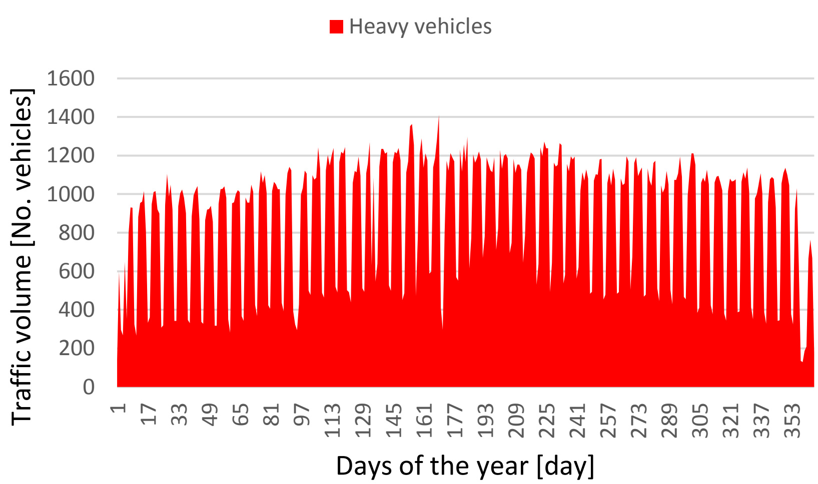




Light vehicles
Heavy vehicles
Traffic volume [No. vehicles]
20000
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
1
17
33
49
65
81
97
113
129
145
161
177
193
209
225
241
257
273
289
305
321
337
353
Days of the year [day]

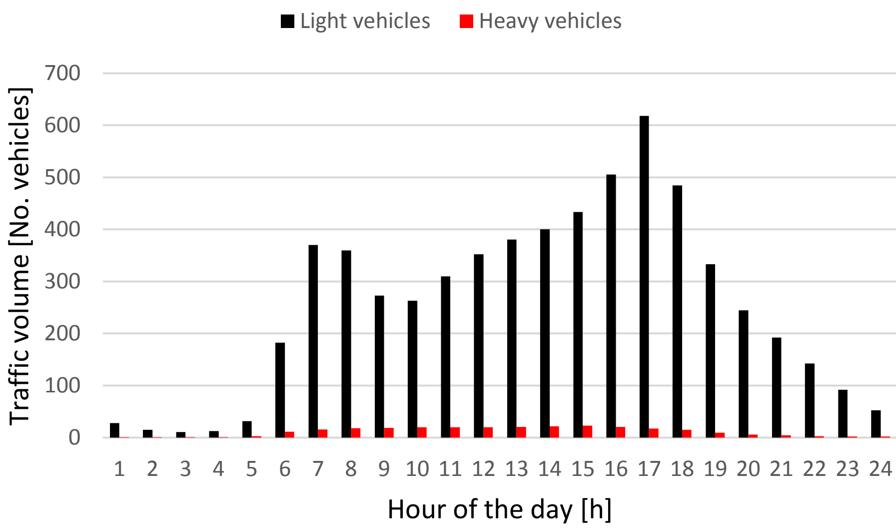


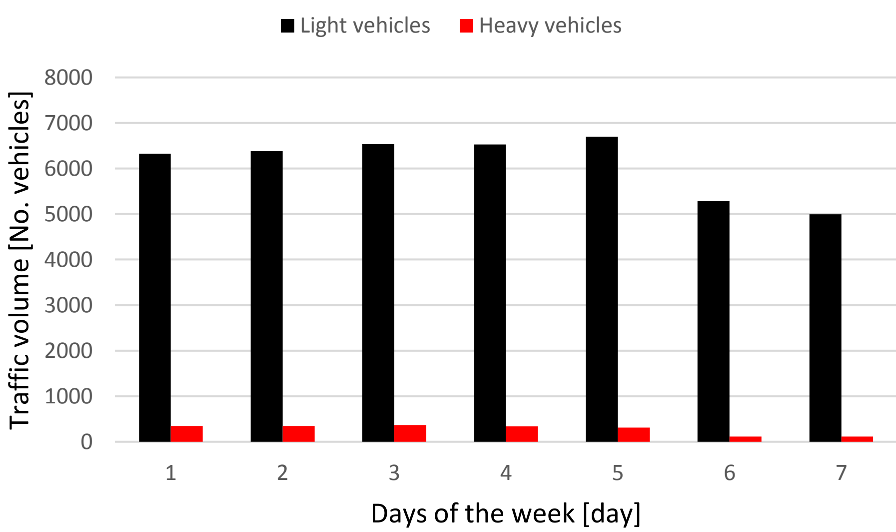
Light vehicles
Traffic volume [No. vehicles]
20000
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
1
17
33
49
65
81
97
113
129
145
161
177
193
209
225
241
257
273
289
305
321
337
353
Days of the year [day]

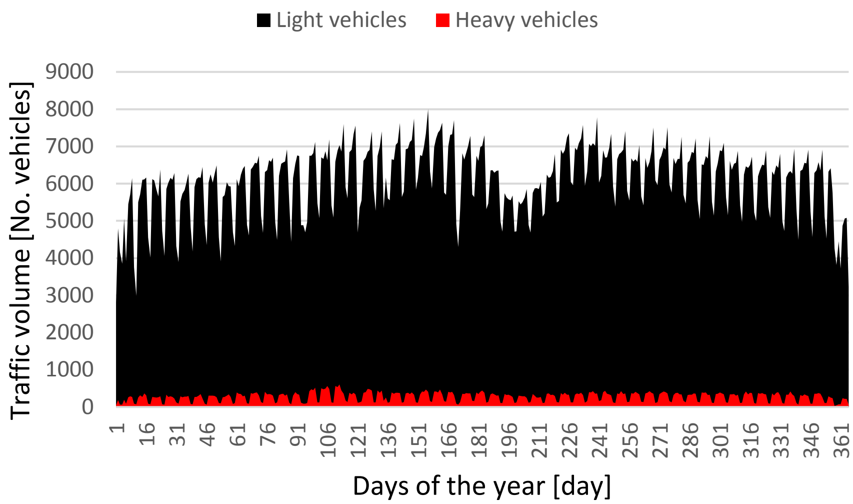


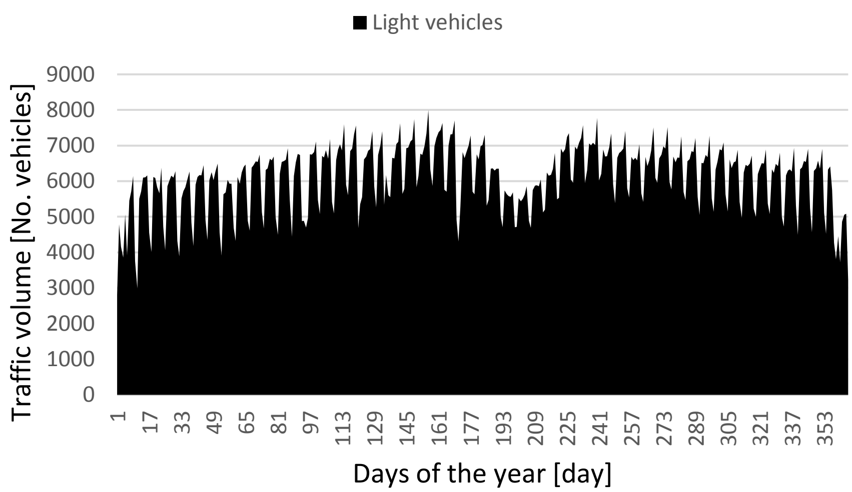
Heavy vehicles
Traffic volume [No. vehicles]
1600
1400
1200
1000
800
600
400
200
0
1
17
33
49
65
81
97
113
129
145
161
177
193
209
225
241
257
273
289
305
321
337
353
Days of the year [day]

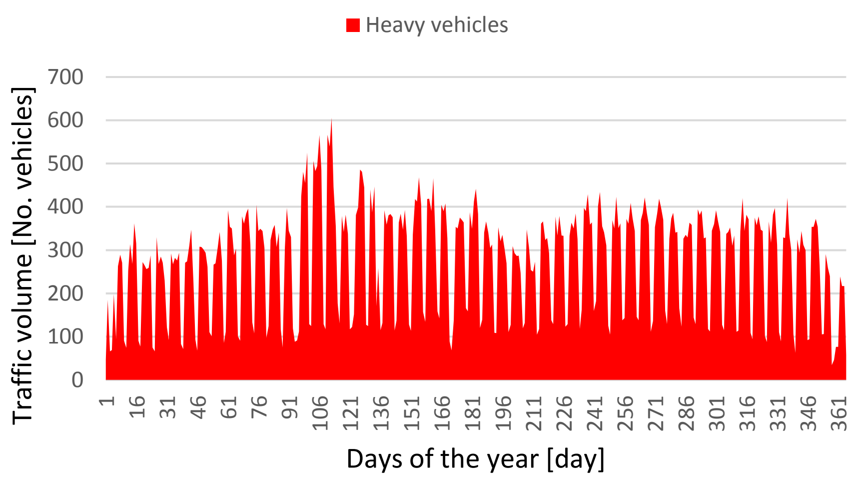
Appendix C – Traffic pattern graphs for data road point Järna (R57)



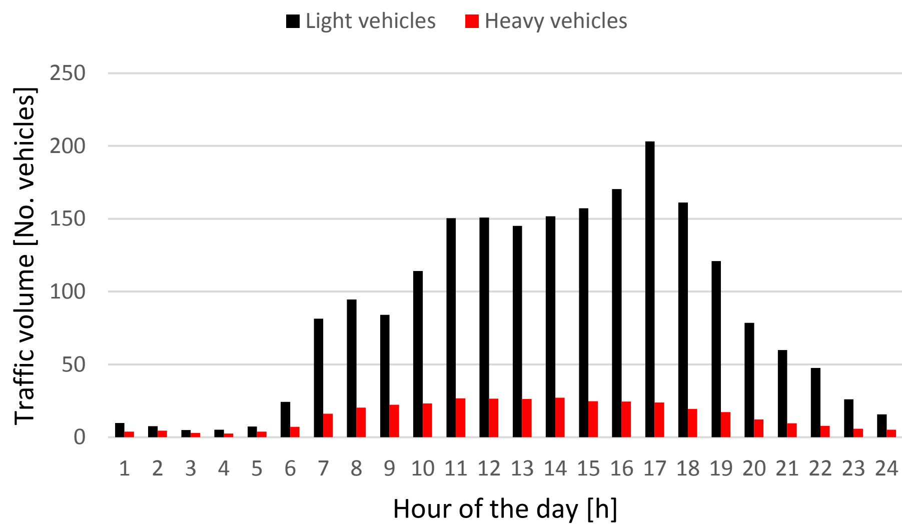


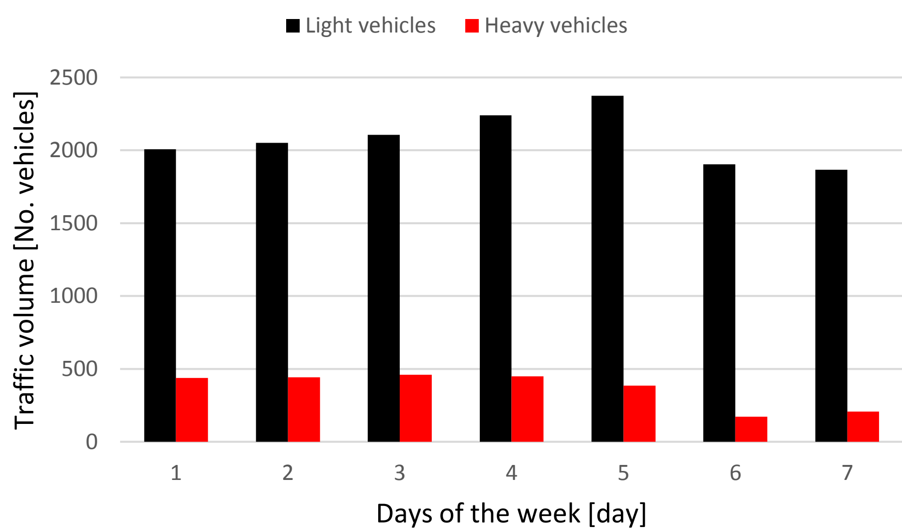

Light vehicles
Heavy vehicles
Traffic volume [No. vehicles]
Days of the year [day]

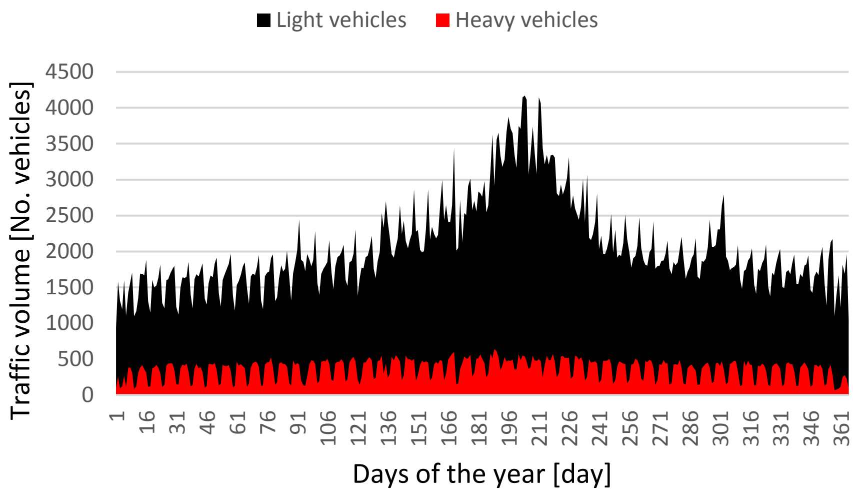

Light vehicles
Traffic volume [No. vehicles]
Days of the year [day]

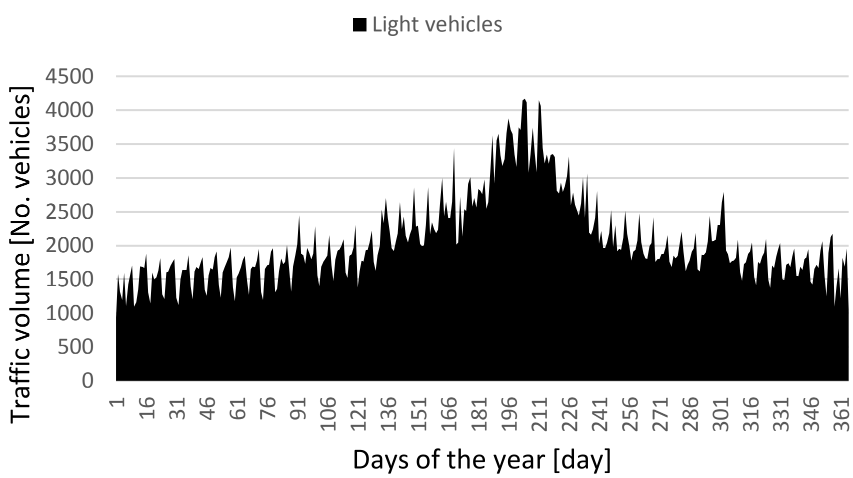

Heavy vehicles
Traffic volume [No. vehicles]
Days of the year [day]

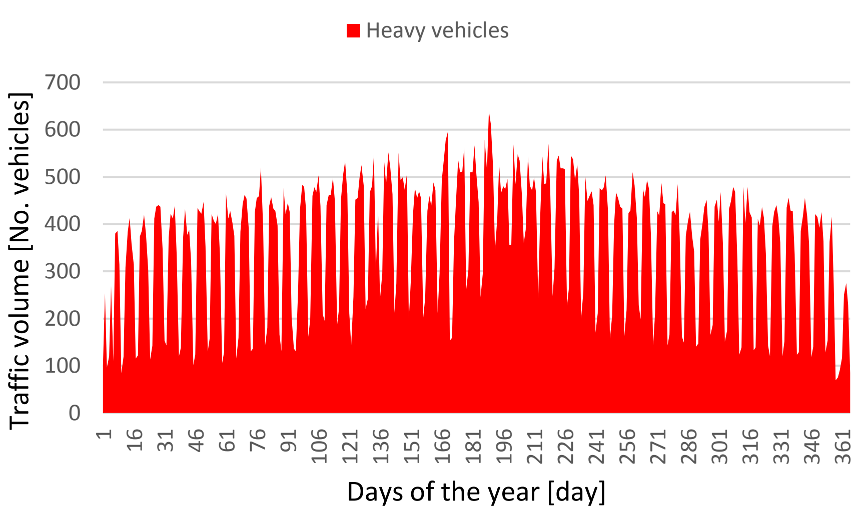
Appendix D – Traffic pattern graphs for data road point Vimmerby (R40)






Light vehicles
Heavy vehicles
Traffic volume [No. vehicles]
0
500
1000
1500
2000
2500
3000
3500
4000
4500
1
16
31
46
61
76
91
106
121
136
151
166
181
196
211
226
241
256
271
286
301
316
331
346
361
Days of the year [day]


Light vehicles
Traffic volume [No. vehicles]
0
500
1000
1500
2000
2500
3000
3500
4000
4500
1
16
31
46
61
76
91
106
121
136
151
166
181
196
211
226
241
256
271
286
301
316
331
346
361
Days of the year [day]


Heavy vehicles
Traffic volume [No. vehicles]
0
100
200
300
400
500
600
700
1
16
31
46
61
76
91
106
121
136
151
166
181
196
211
226
241
256
271
286
301
316
331
346
361
Days of the year [day]