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Thermal design of an electric road system

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Abstract

Electric road systems (ERS) have the potential to be the next step in charging infrastructure for electric vehicles. To be able to dynamically charge electric vehicles, would not only extend the electric vehicles range but also reduce their need for large battery packs. Despite the relatively high efficiency of the ERS, the generated losses result in a great amount of heat, making the thermal properties important to consider. The purpose of this paper is to investigate the surface temperature of an ERS based on Elonroad's design for different traffic intensities, power levels and length of the ERS.

Keywords: conductive charger, DC-DC, dynamic charging, modeling, thermal management.

1 Introduction

A drawback of todays electric vehicles is the limited distance before the batteries need to recharge. This is especially a problem for heavy vehicles as they consume a lot more energy than lighter vehicles. By being able to charge the batteries while driving, range would not be a problem anymore. An electric road system (ERS) is a piece of equipment placed in, on, by the side or above the roads in order to charge electric vehicles while driving. There are currently a number of different ERS solutions under development, both conductive and inductive solutions. The cost level for an ERS system is in the interval 1...3 MEuro/km for one lane in each driving direction of a highway [1]. This cost balances against a significantly reduced need for batteries in the vehicles.

Conductive ERS technologies use a sliding contact and can be located either a few meters above the road as overhead lines or a few cm below the road in slots. Siemens eHighway is an example of an ERS using overhead lines [2]. The major drawback of overhead lines is that only heavy vehicles are able to use the ERS as the overhead lines are too high up for a normal passenger car. Another possible location for the ERS is at ground level which does not have the drawback of only being able to provide power to heavy vehicles. A ground level placement has therefore a greater potential of utilization. A few examples of ground level ERS designs are Elonroad's design which is placed on top of the asphalt [3], Alstom's design which is leveled with the asphalt [2] and Elways' design which is located in slots [4]. This paper's focus is on Elonroad's design.

Inductive ERS technology relies on wireless power transfer between the ERS and the vehicle. Energy is transfered in the same way as it is transfered in a transformer, from a coil located in the ERS to another coil located in the vehicle. The air between the ERS and the vehicle is the air gap of the transformer [1]. There are available solutions for static charging on the market today.

2 The Elonroad ERS design

Figure 1: A prototype of the Elonroad ERS.

The ERS has to have a design which is both visually appealing and safe to drive on. Dimension wise, a road bound ERS has to be very low and fit well in between the wheels of a car, bus or truck. This paper focus in particular on the ERS design made by Elonroad. It is of particular interest since it is place on top of the road, not requiring any cutting in the road surface. This simplifies installation in both city environments as well as on a highway. Elonroad's design is approximately 31 cm wide and 5.5 cm high. Tests show it can be crossed comfortably with a passenger car even at high speeds. To cross the ERS with a two wheel vehicle the ERS may need an anti-slip surface, this needs further investigation.

3 How Elonroad's design works

Fig. 2 shows the general design of the ERS. What is not shown in Fig. 2 is that the ERS is put together by sections of 10 meters. These 10 m sections make it easy to both install and maintain the ERS. As shown, the ERS is divided into one meter segments where every other segment has the capability to provide high potential while the remaining segments are always connected to low potential. When a segment is not being used it is always connected to a low potential for safety reasons. The switching elements used to switch a contact segment between low and high potential when a vehicle requests power from the ERS are IGBTs. IGBTs are fast enough to ensure that only the sections underneath the vehicle become active by suppling power to the vehicle while still being at a safe potential around the vehicle. As an extra measure of safety the transformer station has the capability to disconnect the ERS if a fault is detected. While the whole ERS is disconnected a slow mechanical switch is switched to physically disconnect the faulty 10 m segment. Once the faulty segment is disconnected the transformer station resumes supplying the ERS with power. Possible distance between these transformer stations is one of the things this paper investigates.

By having at least three pickups located at a clever distance from each other, seamless commutation can be achieved while driving. Seamless commutation is a necessity in order to prevent arcing which causes wear and tear on the ERS as well as on the pickup.

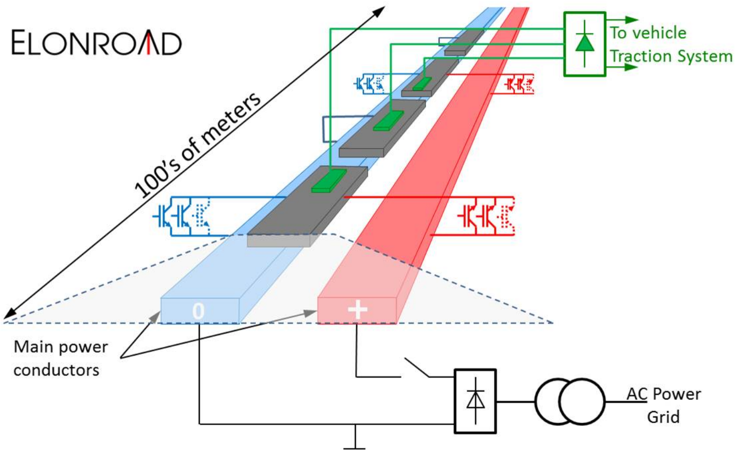


Figure 2: Shows a simplified internal view of the Elonroad ERS. The blue and red bars are the main conductors which are connected to the contact segments (in gray) by IGBTs. The pick-up is represented by the green bars.

A minimum of two main power conductors, one with high- and one with low- voltage, are required to supply power to an ERS. The larger the conductor area is, the lower the power losses in the conductors are. As every other segment is connected to low potential at all times the voltage drop in the low voltage conductor should be kept as small as possible. The reason for this is that a voltage drop causes the low voltage segments to get a voltage potential relative to ground potential. A large potential difference between the low voltage segments and the ground is a safety issue as the segments are exposed. By increasing the low voltage conductor area and as a result reducing the high voltage conductor area, safety is gained at the cost of power losses. This conductor area trade-off is important to consider. The power losses in the conductors are also material dependent, as different materials have different conductivity. Copper is a great conductor but is also costly and increases the risk of theft. Aluminum is the chosen material to use in the conductors as an alternative to copper because of its good conductivity and low cost compared to copper.

IGBTs have large power losses while conducting and must therefore be closely thermally connected to a large thermal mass with good thermal conductivity. In Elonroad's design the IGBTs use the large conductors as heat sinks to benefit from the large aluminum mass. It is important to choose a thermal paste or other adhesive with high thermal conductivity to keep the thermal resistance between the IGBTs and the large thermal mass as small as possible.

Insulation is needed around the conductors to prevent short circuits. This insulation layer results in higher conductor temperatures due to the thermal properties of the insulation material. As long as the thermal expansion is considered and the maximum operating temperature of the insulation material is not exceeded, the conductor temperature is not important. What is important is to make sure the IGBTs do not overheat due to the conductors being too warm.

For surface materials, emissivity and solar absorptivity are important parameters affecting the ERS temperature. As the ERS has a large portion of its surface area facing the sun, the sun is a large contributing factor to the total heat affecting the ERS.

The bottom layer as well as how the ERS is connected to the ground may depend on weather conditions at the location of the ERS. For warm weather conditions, good thermal contact is preferred as the ground cools the ERS during peek traffic hours. At colder locations where heating is required there may be a trade-off between the ability to easily heat the ERS and the ability to have good cooling.

4 Thermal considerations

Efficiency is one key factor in the thermal problem of the road. The lower the losses are the less heat has to be removed from the ERS, resulting in a cooler ERS. As this design relies on conductive charging, a sliding contact is used to transfer energy from the ERS to the vehicle. Two surfaces sliding against each other cause friction, which both heats the ERS as well as reduces the overall efficiency of the system. Heat sources affecting the temperature of Elonroad ERS include electric losses in the IGBTs, conductors and pickup as well as friction between the pickup and the ERS. Another source of heat is the sun which contributes to the total incoming heat without being an energy loss for the system. Losses regarding the pickup are being neglected in this paper since the pickup has not yet been designed. A warm surface can be cooled through conduction, convection and radiation and the Elonroad ERS is cooled by all of the three cooling mechanisms

It is important to investigate the weather conditions at the location where the ERS is going to be located. If the located is in a warm climate where it never snows or freezes only cooling has to be dealt with. If it is located in a cold climate, heating may have to be considered to keep the ERS ice free. In this paper, the focus is on cooling as it is both a safety concern as well as a lifetime concern of the electronics.

The ERS can do two types of charging, dynamic and static charging. Dynamic charging, charging while driving, is what the ERS is intended for and power losses are spread out over the entire ERS. Static charging occurs when a vehicle stops on the ERS but is still charging. This results in continuous power losses in the IGBTs in one or a few segments of the ERS, raising the temperature of those segments. If a vehicle is left to charge statically over a long period of time, the temperatures may reach critical levels for the electronics as well as for the surface temperatures. As long as the vehicle is charging the surface temperature underneath the vehicle is of little concern. Problems arise when the vehicle moves away after having charged statically over a long period of time, as the high surface temperature is exposed. To improve static and dynamic charging, the IGBTs should be well connected to a large thermal mass with good thermal conductivity such as copper. This mass absorbs the heat from the IGBTs and evens out variations in temperature. The larger the thermal mass, the longer it takes before the temperature of the IGBTs to reach critical temperature.

5 Losses and sources of heat

Power losses and heating of an ERS are directly connected to traffic flow and weather conditions. More vehicles mean more current flowing through the conductors and the IGBTs on average. At the same time, an increased amount of vehicles results in less solar heat absorbed by the ERS [5]. To describe the traffic flow as accurately as possible, hourly traffic data is gathered from the Swedish Transport Administration [6] and presented in Fig. 3.

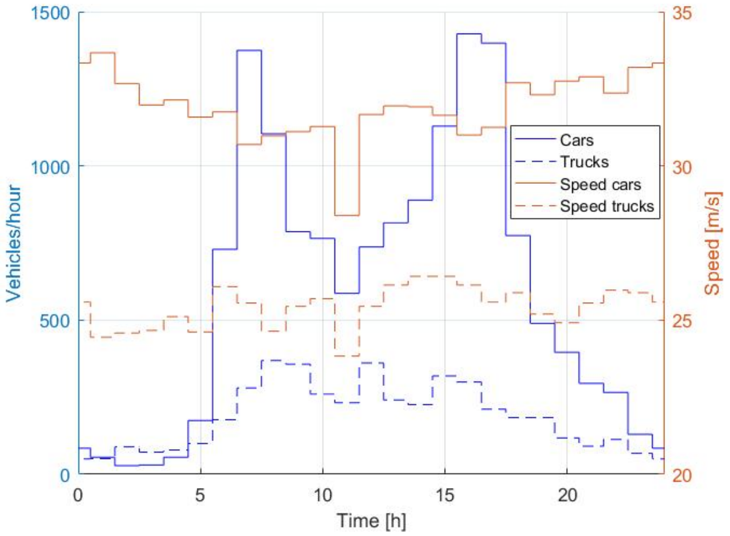


Figure 3: An example of what traffic data can look like and is from the Swedish Transport Administration on the road E6 south of Helsingborg [6]. The data includes the number of cars and trucks and their average speed. This is the data used as input for the simulations.

Since the data gives the hourly average amount of vehicles, an error is introduced as the current/loss relationship is not linear. Due to the thermal mass of the ERS, this error is reduced but not removed. A truck is assumed to draw 300 A while a car draws 80 A. This equals 180kW for trucks and 48kW for cars, these figures for power are referred to in this paper as the reference power. These numbers are most likely going to be reduced as more ERS is built. With only a short section built, the vehicles have to charge their batteries in a shorter time resulting in higher charging power. Only a brief description of the different losses and sources of heat is presented in this section. For a more in depth explanation of sources of heat affecting an ERS a previous paper is recommended [5].

Resistive losses in the *conductors* can be calculated when knowing the average current from the traffic data, area of the conductors, and resistivity of the material.

IGBTs are usually a large source of heat in most applications. For this ERS the IGBTs are only a major source of heat during static charging as otherwise the IGBT losses are spread out over several segments of the ERS. In applications involving fast switching it is usually the fast switching that results in major power losses. In this ERS, switching losses are negligible compared to conducting losses due to the low switching frequency. Every vehicle passing a segment results in one switching cycle for the IGBTs in that segment, with one vehicle per second this would result in a frequency of one Hertz.

Heat from *solar irradiance and thermal radiation* is material dependent. A perfect black body absorbs all of the solar irradiance and thermal radiation, while polished metal reflects a large amount of this incoming radiation. The optimal surface material is a material that emits a lot of thermal radiation but also reflects a large amount of the solar irradiance.

Friction caused by the pickup sliding on the ERS generates heat but is not discussed in this paper.

6 Model

The thermal model is a Comsol Multiphysics 3D model which includes the major heat sources of the ERS: solar irradiance, resistive losses in the conductors and conductive losses in the IGBTs. This paper focuses on cooling of the ERS and how this is modeled. The ERS is cooled by conduction, convection and radiation. Convective cooling includes both cooling from natural convection as well as forced convection. In the model it is assumed that there is no wind except for the wind caused by vehicles traveling on the road. Equations regarding convective cooling and heating by solar irradiance are based on the assumption that the ERS is a flat horizontal surface. By using this assumption, previously verified equations for convective cooling can be used. Future work should include empirical tests to either verify the equations used in this paper or suggest improved equations for this design.

6.1 Convection

Natural convection is the main part of convective cooling at low traffic intensities as the wind speed is low. The first step in estimating the convective heat transfer coefficient is to calculate Grashof's number, Gr, by using equation (1) [7], where g is the gravitational constant, β the coefficient of expansion, T_s the surface temperature of the ERS, T_a the ambient temperature, v the kinematic viscosity and L_{ch} is the characteristic length.

$$Gr = \frac{g * \beta * (T_s - T_a) * L_{ch}^3}{v^2} \tag{1}$$

Equation (2) applies when the value of $Gr*Pr$ is larger than $2*10^4$ but lower than 10^6. With a value even larger but lower than 10^{11} (3) applies instead [7]. Pr is the Prandtl number of air at the film temperature.

$$Nu = 0.54 * (Gr * Pr)^{1/4} \tag{2}$$

$$Nu = 0.15 * (Gr * Pr)^{1/3} \tag{3}$$

The more vehicles traveling on the road the higher the wind speed will be, resulting in more cooling by forced convection. The flow is assumed to be turbulent all across the ERS. For forced convection that is turbulent over the entire plate (4) can be used to calculate Nu [7].

$$Nu = 0.037 * Re^{4/5} * Pr^{1/3} \tag{4}$$

By knowing the Nusselt number the heat transfer coefficient for natural convection and forced convection can be calculated through (5) where k is the thermal conductivity [7].

$$h = \frac{Nu * k}{L_{ch}} \tag{5}$$

6.2 Conduction

Conductive heat transfer occurs between two solids when the two are in physical contact. This occurs both inside the ERS as well as between the bottom layer and the asphalt. The conductive properties of the bottom layer of the ERS as well at its dimensions set the limits of the conductive heat transfer. This heat transfer is calculated by Comsol Multiphysics as the asphalt temperature is set as a boundary condition on the bottom of the ERS.

6.3 Radiation

Radiative heat transfer is present for every object warmer than 0 degK. As the ERS is placed outside it radiates towards the sky according to (6) where P is the radiated power, ϵ is the emissivity of the material, σ is the StefanBoltzmann constant, A is the surface area and T is the radiating temperature.

$$P = \epsilon * \sigma * A * T^4 \tag{6}$$

What makes it complicated is the large air mass between the ERS and outer space which radiates back onto the ERS. Equation (7) is an estimation of downwelling sky radiation which includes the effect of clouds where K is a factor which depends upon the height of the clouds, C is the cloud coverage, T is the ambient temperature in Kelvin and RH is the relative humidity in percent [8].

$$P = (1 - K * C^2) * 8.78 * 10^{-13} * T^{5.852} * RH^{0.07195} \tag{7}$$

In (7) the influence of traffic is not considered. A vehicle acts as a barrier which prevents the ERS from receiving thermal radiation from the atmosphere. Instead the undercarriage of the vehicle radiates towards the ERS.

7 Model calibration

The Elonroad ERS is still in development, making most measurements difficult. Therefore it is not possible to fully validate the model as there is not enough measured data.

In order to get an estimate of the surface temperature of the ERS under no traffic conditions, the ERS-prototype is placed on a roof with no shading of the ERS. Since the roof in question has a shorter thermal time constant compared to a road the measured temperature should be higher on the roof compared to on a road during same conditions. The test setup is shown in Fig. 4.

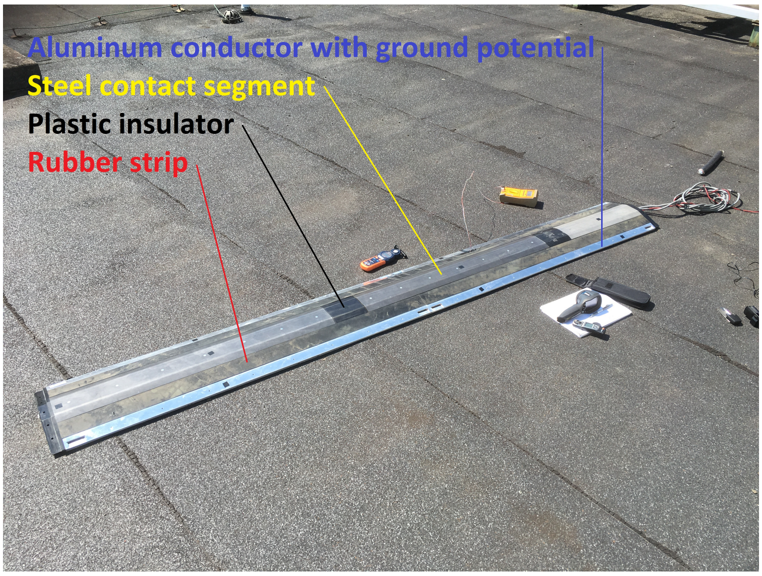


Figure 4: Shows the test setup where the a piece of the ERS is placed on a roof. The temperature is measured with an IR-camera at different points on the ERS.

Table 1: Shows ambient temperature measured by SMHI in Malmö [9], measured roof temperature and wind speed at the test location in Lund.

Time [hh:mm]	Ambient [°C]	Wind speed [m/s]	Roof [°C]
10:00	26.3	-	-
11:00	27.0	0.5-1.5	60
11:30	-	0.5-1.5	61
12:00	27.5	0.5-1.5	66
13:00	27.7	0.5-1.5	68
14:00	27.3	0.5-1.5	70
15:00	26.3	0.5-1.5	66

Table 1 shows data collected during the test and ambient temperature which is recorded at Malmö during the same time by SMHI [9]. Ambient temperature, wind speed and roof temperature are used as inputs to the simulation in order to try and replicate the test conditions as accurately as possible for the simulation. Temperature is measured with an IR-camera which can induce a small measurement error, this error is estimated to be approximately ±1 °C.

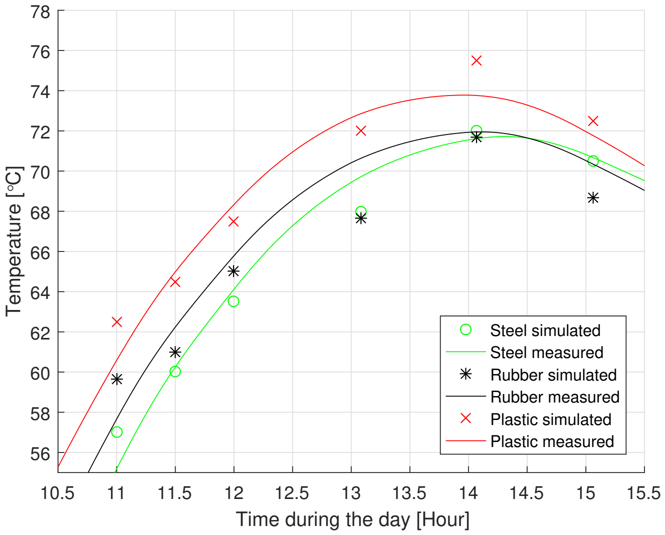


Figure 5: Measured temperature vs simulated temperature.

The conditions during the measurements are very hard to replicate, and for this reason the conditions in the simulation are not the same as during the measurements. For example, it is hard to replicate the solar irradiance as there can occasionally be small clouds affecting the irradiance. The simulation assumes a perfectly clear sky and a constant wind speed, both of which are not normal conditions during measurements. Fig. 5 shows the measured and simulated plastic-, rubber- and steel- temperature. The simulation results line up well with the measured data considering the uncertainty of the conditions during the measurements.

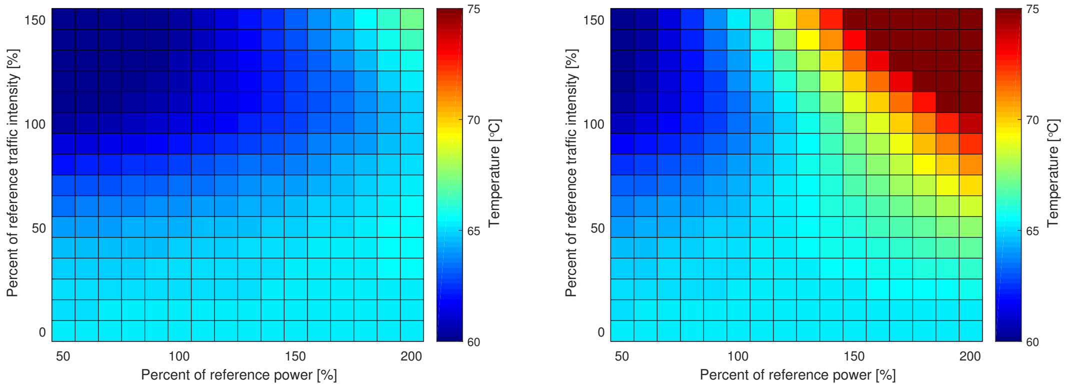
8 Simulation results

The base scenario investigated is a summer day in Lund in southern Sweden with no wind, clear skies, a constant ambient temperature of 28 °C and a constant asphalt temperature of 50 °C. The charging power is set to a constant value of 48 kW for cars and 180 kW for trucks, at a voltage of 600 V. It is assumed that 70 % of the cars and 100 % of the trucks drive in the right hand lane which is equipped with the Elonroad ERS system modeled. These charging powers and this traffic intensity is referred to in this paper as the reference power and reference traffic intensity. The simulation model is a 3D model and calculate the temperature at any location on the ERS track on the road. Since steel has a higher thermal conductivity than plastic and rubber it is the surface temperature of the contact segment (from which the power is drawn) that are made of steel that is of interest. A material with high thermal conductivity causes burns faster when touched compared to a material with low thermal conductivity. This assumes that the other non-metallic surfaces are not a lot warmer than the steel, which is not the case for the ERS. By performing parameter sweeps, an understanding of how different conditions affect the temperatures, in particular the contact segment temperature, is acquired.

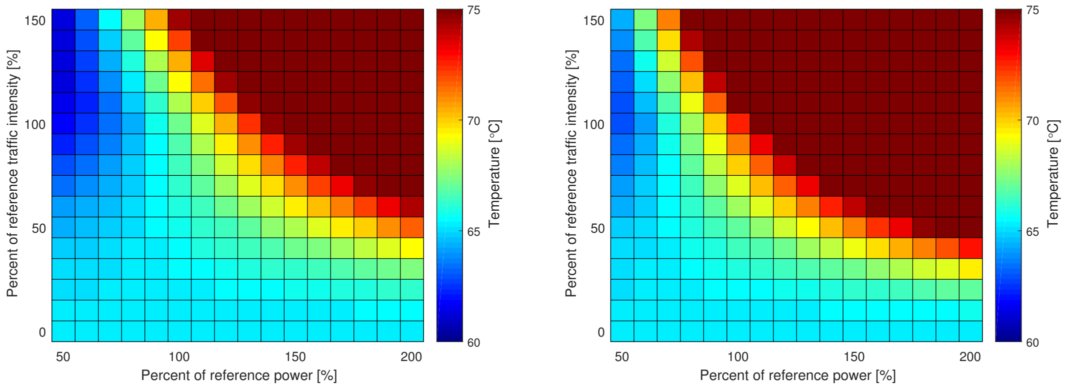
It is not necessary to cover a road with ERS technology to a 100 %. Since the batteries of each vehicle are capable of independent operation for many 10s of kilometers, there is a tradeoff between battery size and ERS coverage. A 100 % ERS coverage requires in principle no batteries. A 25 % coverage of e.g. 1 km out of 4 km requires the vehicles to charge at 400 % of the average traction power when on the ERS.

From a thermal point of view, a well utilized ERS system runs at highest possible power most of the time, summertime limited by highest allowed surface temperature. A higher ERS coverage means that lower power can be supplied to the vehicles and thus also a lower surface temperature. There is likely not one surface temperature that is the ”correct” temperature as different locations of the ERS have different requirements. For example safety is more important in cities compared to on highways. As shown in Fig. 5 the steel reaches 72 °C during the validation test, therefore a reasonable temperature limit is at least a few degrees warmer. In this paper 75 °C for the steel surface is considered the maximum temperature limit.

Traffic intensity, length of the individual ERS sections (usually 100s of meters) and charging power are three parameters that can be adjusted in a simulation model. In a real scenario the length of the ERS is fixed after the ERS is built and the traffic cannot be controlled in an easy manner. This reduces the number of controllable parameters down to one, charging power. An ERS section is supplied with electric power from one end and the total supply power is thus proportional to the ERS section length for the same traffic intensity since more vehicles are supplied from the same section. A longer ERS results in more current through the conductors which generates a higher amount of heat, in particular in the supply end. Therefore four different lengths of the ERS are investigated, 250 m, 500 m, 750 m and 1000 m.



(a) 250 m (b) 500 m



(c) 750 m (d) 1000 m

Figure 6: Shows the contact segment temperature near the feed in end of the ERS section at different combinations of charging power and traffic intensity for four ERS lengths. High power levels in combination with high traffic intensity results in a high surface temperature. At low power levels the surface cools down by adding more vehicles.

Note that the reference power on the horizontal axis is based on the nominal power per vehicle. This means that an increased traffic intensity with constant reference power also increase the power drawn from the ERS system since each vehicle still has the same power consumption.

For a length of the ERS of 250 m Fig. 6a shows that the power level can be a lot, over 200 %, higher than the reference power for traffic intensities up to at least 150 % of the reference traffic intensity. This basically means the ERS can handle almost any power demand from the vehicles during normal traffic conditions. This length does not utilize the full potential of the ERS as it can handle a lot higher power levels than what is normal condition.

Note that the surface temperature actually drops with increasing traffic flow at lower reference power levels (per vehicle), in spite of the increased power drawn from the ERS system. This is due to the fact that the shadowing effect and the air movement caused by the vehicles provide more cooling than the increased ERS losses caused by the power drawn by the vehicles.

An ERS length of 500 m is not very different from an ERS that is only 250 m long. The main difference is at high power levels and traffic intensities, where the steel surface temperature reaches 75 °C. This extreme power/traffic combination is going to be reached very seldom, if ever. A length of 500 m can handle the reference traffic intensity and reference power without a problem, see Fig. 6b.

Fig. 6c shows an ERS length of 750 m and a temperature profile that is still below 75 °C at reference power level and reference traffic intensity. The safety margin at reference levels is smaller than for 500 m and 75 °C may be reached during a very warm day. This is unlikely to happen at the assumed location, Lund, Sweden, but can very well happen occasionally in a warmer country.

By increasing the length of the ERS to 1000 m the temperature is close to 75 °C at reference current level and traffic intensity, see Fig. 6d. This is the recommended length of the ERS for this particular case with a known traffic intensity and power level. If there is an uncertainty about these parameters a temperature safety margin may be preferred resulting in a need for a shorter ERS. If the traffic intensity rises over the reference level the current level has to be reduced. This makes the control within the ERS important to make sure that the temperature does not exceed 75 °C. Without a large safety margin this alternative is the cheapest as the transformer stations can be placed as far apart as possible and the ERS can still be fully utilized at the reference levels.

9 Conclusions

Further measurements have to be made in order to validate and calibrate the simulation model. Fig. 5 shows that the model is somewhat accurate for that particular case, but more data is needed before the model can be fully trusted.

The simulations show that when deciding on the length of the ERS it is important to consider the traffic intensity, power levels as well as deciding the allowed maximum surface temperature. ERS length and traffic intensity cannot easily be changed and must therefore be considered before building the ERS. In city traffic there might be a different surface temperature requirement than for a highway. In the scenario used in this paper a length of the ERS of 1000 m is suggested as it can handle the reference charging power at the reference traffic intensity. A 75 °C hot metal surface is potentially dangerous to touch as it will cause burns if touched for too long. This is likely not a problem at major roads as there are few people walking on those roads. During a hot summer day there are many other hot surfaces which means that people are more careful and expect the ERS to have a hot surface. During colder days the ERS can potentially present more of a danger as it can still be hot due to heating from losses within the ERS. A possible solution to this problem is to let the maximum allowed surface temperature depend on the ambient temperature. The allowed temperature could for example be allowed to exceed the ambient temperature by 5-10 °C with a minimum allowed maximum surface temperature of for example 55 °C.

The thermal model presented in this paper can also be used for estimation of the thermal cycles of the switching elements (IGBTs) of the ERS and thus for life time estimation. An analysis of the ERS lifetime related to thermal cycling will be presented in a subsequent paper by the same authors.

References

[1] P. Fyhr, G. Domingues-Olavarria, M. Andersson, F. J. Márquez- Fernández, H. Bängtsson, and M. Alaküla, *Electric Roads: Reducing the societal cost of transport electrification*, 2017 IEEE Transportation Electrification Conference and Expo (ITEC), June 2017.

[2] Viktoria Swedish ICT, *Slide-in electric road system: conductive project*, Publication number: 2013:02, Version: 1.04.16.1.

[3] *Elonroad*, http://elonroad.com/, accessed on 2017-03-08.

[4] G. Asplund and B. Rehman, *Conductive feeding of electric vehicles from the road while driving*, Electric Drives Production Conference (EDPC), 2014 4th International, Sept 2014, pp. 19.

[5] P. Abrahamsson, M Alaküla, *Sources of heat affecting an electric road system*, 11th IEEE International Symposium on Diagnostics for Electric Machines, Power Electronics and Drives, August 2017.

[6] *Swedish Transport Administration*, http://vtf.trafikverket.se/SeTrafikinformation.aspx, Measure point: 3210370, Direction: Forward, Date: 2015-09-17 11:00 2015-09-18 11:00, accessed on 2017-03-08.

[7] B. Sundén, *Introduction to Heat Transfer*, WIT Press, 2012.

[8] M. A. Goforth, G. W. Gilchrist and J. D. Sirianni. *Cloud Effects on Thermal Downwelling Sky Radiance*, Proc. SPIE 4710, Thermosense XXIV, 203 (March 15, 2002), doi:10.1117/12.459570.

[9] *SMHI*, http://opendata-download-metobs.smhi.se/explore/#, Measure point: Malmö A, Date: 2016-06-03, accessed on 2017-03-08.

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