



Proceedings of 8th Transport Research Arena TRA 2020, April 27-30, 2020, Helsinki, Finland

The potential of route based ERS network optimization

Gyözö Gidofalvi^{ab*} and Can Yang^b

^a*Integrated Transport Research Lab (ITRL), KTH Royal Institute of Technology, Drottning Kistinas Väg 40, 114 28 Stockholm, Sweden*
^b*Div. of Geoinformatics / Dept. Urban Planning and Env., KTH Royal Institute of Technology, Teknikringen 10A, 114 28 Stockholm, Sweden*

Abstract

The large scale deployment of Electric Road Systems (ERS) is a necessary and viable choice for reaching the emission reduction targets in the road-bound heavy freight sector. The per-kilometer infrastructure development cost of ERS is large, thus selecting segments that yield a high utility is important. According to a newly introduced concept, the electrification utility of a segment in a network is highly dependent on the freight routes-, the powertrain technology-, the energy supply and demand- and the transport loads of the vehicles as well as the topographic aspects- and traffic state of the road network. This paper explains these concepts and aspects and provides first empirical evidence about the potential of route based ERS network optimization that takes these aspects into consideration. Results show that the potential cost savings are up to 75%, which for national expressway networks is estimated to be in the range of 120M€ to 8,520M€.

Keywords: electrification utility; infrastructure planning and development; big mobility data analytics; routes; combinatorial network optimization; business case

1. Introduction

1.1. Motivation

Sweden has rather ambitious climate related objectives and visions. In particular, as it was recently presented by the Director of Strategic Development of the Swedish Transport Administration (Trafikverket) at the 3rd Electric Road System Conference:

- Alongside 193 states and the European Union, Sweden has signed the Paris Agreement.
- Sweden will become one of the world's first fossil-free welfare countries.
- Goal for 2030: Reduction of emissions of CO₂ from domestic transport with 70% compared with 2010.
- Goal for 2045: Sweden shall have no net emission of CO₂.

In a recent debate article in the Swedish newspaper *Altinget*^{*}, representatives for five international transport consortiums together with the Swedish industry and the Swedish employer organization for transport companies (Transportföretagen) agree that to reach the 70% target (reduce carbon dioxide emissions by 70%) by 2030, a large-scale investment in electrification of the transport sector is required. Electric Road Systems (ERS) for heavy traffic are pointed out as a cost-effective way to reduce the climate impact of long-distance freight transport. According to the Swedish National Roadmap for Electric Roads (Pettersson et al., 2017), "truck traffic accounts for almost 89% of the domestic freight transported by domestic vehicles. The heavy road-borne freight traffic accounts for about 25% of the road transport system's energy use and carbon dioxide (CO₂) emissions". According to a recent analysis of the Swedish Transport Analysis (Trafikanalys)[†], due to projected increased transport demand, despite the current policies and incentives, without large-scale ERS investments, the greenhouse gas emission (including CO₂) of heavy transports on roads is expected to roughly remain at the current level of approximately 3.5 million tons annually. Thus, provided a zero emission (fossil free) energy supply mix, these emissions represent the emission reduction potential of ERS technology for the Swedish heavy freight sector.

To drive the realization of this potential, the Swedish Governmental Assignment on "Electric roads" resulted in Sweden's "National road map for electric road systems" (Pettersson et al., 2017), which forms the basis for electric roads to be part of the state owned road network that is supported by a road map and a deployment plan. Additionally, the German and Swedish governments issued a joint declaration with the title "Innovation and cooperation for a sustainable future – A German & Swedish partnership for innovation" (German-Swedish Joint Governmental Declaration, 2017). The declaration states that the Federal Government of Germany and the Swedish Government have agreed on four actions as a basis for cooperation. One of the actions is that a joint study on the electrification of roads will be conducted.

1.2. Aspects of ERS

There are many aspects to consider for ERS network infrastructure development. Sweden's "National road map for electric road systems" (Pettersson et al., 2017) identifies eleven areas one of which is the area that deals with the "placement and selection of road network". These identified areas and aspects are also reflected in the scientific literature that surrounds ERS. Some of the most important and relevant aspects include: technologies, trends, and interaction between vehicles, powertrain, battery and ERS infrastructure (Balieu et al., 2018; Kühnel and Hacker, 2018; Jöhrens et al., 2018b); current and future transport demand (Balieu et al., 2018; Bernecker et al., 2018; Jöhrens et al., 2018b); energy system and supply requirements (Jelica et al., 2018; Malmquist and Ramos, 2018; Taljegard et al., 2018; Taljegard et al., 2017); logistics operations (Jöhrens et al., 2018), environmental impacts and business models and policies (Hasselgren, 2018; Wang and Berlin, 2018).

1.3. ERS demos and pilots in Sweden

In Sweden, there are two demo facilities, each 2 km in operation, one at Arlanda with conductive transmission in the road surface and one at Gävle with conductive transmission via lines in the air. In addition to these, there are plans to build up a few new demo facilities in Sweden through the pre-commercial procurement of knowledge base for electrical roads that the Swedish Transport Administration carries out together with the Swedish Energy Agency and the Swedish Innovation Agency Vinnova, three of which are being evaluated. Of these three, one is

^{*} <https://www.altinget.se/artikel/satsa-storskaligt-paa-elektrifiering>

[†] <https://www.transportstyrelsen.se/globalassets/global/nyhetsarkiv/vag/pm-vagtrafikens-utslapp-190221.pdf>

conductive with a rail that is visible in the roadway, one is conductive with a rail that is laid on top of the roadway and one is inductive with coils in the roadway. All three are supposed to be about 2 km. Furthermore, there are currently more proposals for the placement of pilot projects in Sweden. The pilot projects should be 20-30 km long and contain the entire chain for the electricity system, including the payment system and the like.

1.4. State-of-the-art ERS network infrastructure optimization and planning

Current cost for ERS range between 0.5M€ and 0.8M€ per kilometer. Thus, selecting the “right” segments to electrify is important. Research efforts like the one generally carried out within the framework of the Swedish Research and Innovation Platform for Electric Roads (Vinnova-ERS, 2016) often adopt a very wide scope and try to take into account a lot of interacting aspect of ERS (e.g., energy supply requirements, environmental, technical, business, policy aspects of ERS) and evaluate the transport economic effect of ERS for a handful of plausible ERS infrastructure development scenarios (e.g., electrification certain percent of equally spaced unit segments of the Stockholm-Göteborg-Malmö triangle). More specifically, research within the Research and Innovation Platform for Electric Roads mainly analyses which stretches / road segments have the highest potential for electrification from an environmental perspective (i.e., CO₂ emissions reductions) and investigates which requirements such deployments put on the energy system in terms of energy demand. There is also ample of examples of research like the ERSET (TrV-ERSET, 2018) project that try to select segments for electrification optimally based on simple segment based statistics like the Annual Average Daily Traffic and information about the average speed on and incline of the segments and result in knowledge like: seen from an emission and cost perspective, it is optimal to provide ERS on larger roads and that ERS is most effective on uphill stretches.

Current, state-of-the-art methods that utilize freight routes try to optimize the ERS network infrastructure based on the amount of freight routes that include a road segment / link (Jöhrens et al., 2018b) based on select link analysis which, based on network assignment models / assumptions or real data, provides information of *where traffic comes from and goes to at selected links*, i.e., it provides the spatial distribution and origin–destination (OD) pair composition of aggregate link flows (Bernecker et al., 2018).

1.5. Shortcoming of segment based- and motivation for route based optimization

However, as it is suggested in a recent prior work of the authors (Gidofalvi and Yang, 2019), it is not sufficient to select segments simply based on the number of routes that include the segment or based on the OD-information. In particular, different Vehicle-Powertrain-Energy-Storage (VPES) technology configurations and ERS technologies have different energy consumption, energy storage and charging characteristics. The energy consumption and charging characteristics of these VPES configurations are also heavily affected by the load that they carry as well as the surface and 3D geometry of the roads that they are operated on. Finally, last but not least, as the vehicles have a finite energy storage and an objective to complete maximal part of their routes on electric energy, the electrification utility of segments / links in a network are not independent of one another, but largely depend on which part of the routes include the segments. This *Route Based Electrification Utility* (RBEU) concept is illustrated on Fig. 1, where while $R1$ and $R2$ are roughly equally frequent in routes and therefore could be falsely assumed to have similar electrification utilities, the green routes (representing frequency weighted remaining parts of the routes) reveal that the individual route based electrification utility of $R1$ is potentially significantly larger than that of $R2$. It is also important to emphasize that route based electrification utility is effected by 1) the geometry and surface of the road network as well as 2) the load that is transported and is both important to accurately determine energy flows (potentially in both directions) between the energy grid and the vehicles that move on the ERS. In particular, given the VPES configuration-, the transport load-, the energy storage level-, and the remaining route of a vehicle, on a partially electrified road network the vehicle can either not utilize an electrified segments or draw from- or deliver energy to the grid from its supply. The herein presented RBEU concept, methods and results take these route based aspects of electrification utility and its use in network optimization into considerations and therefore, to a large extent, are complementary to conducted or ongoing work on ERS infrastructure planning like ERSET (TrV-ERSET, 2018) and Research and Innovation Platform for Electric Roads (Vinnova-ERS, 1016) financed by the Swedish Transport Administration (Trafikverket) and the Swedish Innovation Agency (Vinnova). Consequently aim of the present paper is to overcome these shortcoming by presenting the RBEU concept and the outline of the *Route Based Network Optimization* (RENO) methodology that utilizes this concept to find an optimized ERS network given an infrastructure budget, i.e., find which parts of the road network to electrify to maximize the network’s electrification utility given a set of freight routes.

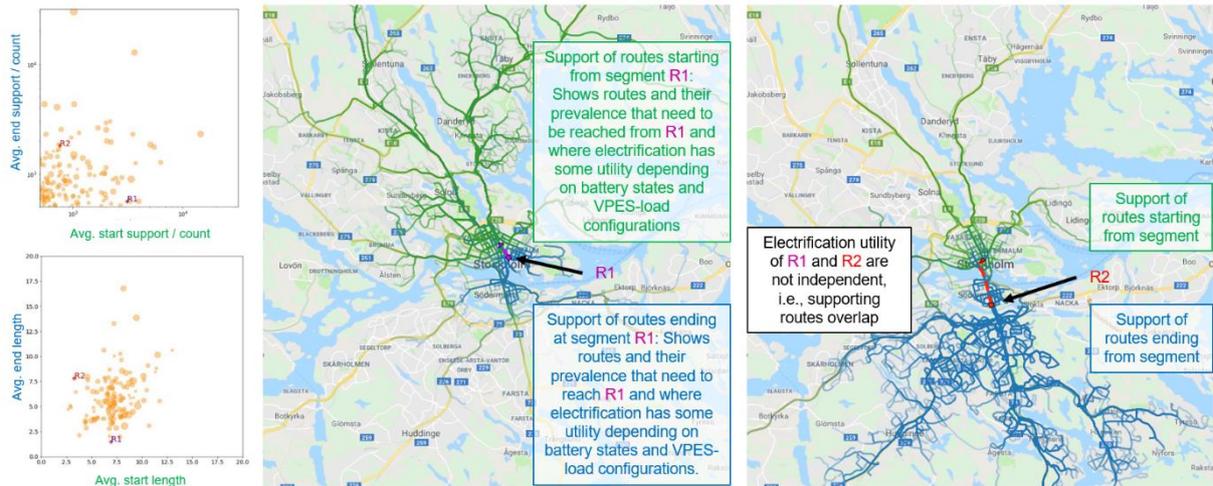


Fig. 1 Pre-study based on 600 thousand taxi routes during one month. Scatter plots show the variability of the number of routes (top) and the frequency weighted average length (bottom) of routes that start and end at the top 100, roughly equally frequent segments. Maps show largely differing spatial characteristics and prevalence of routes that start (green) and end (blue) at segments R1 (left map) and R2 (right map), which are roughly equally frequent in routes.

1.6. Scope and limitations

As the it is correctly stated in Sweden’s “National road map for electric road systems” (Pettersson et al., 2017) and is reflected in the scientific literature, the placement and selection of road network for ERS is only one of several aspects of ERS. Furthermore, it is clear that several of these aspects interact. For example, the “power supply-”, the “landscape, natural and cultural-”, the “business model-”, the “ownership-” and the “technology and deployment” aspects interact to a large extent with the “placement and selection of road network” aspect. However, as the herein presented route based aspects of electrification utility and its use in network optimization are so radically different to existing approaches and yield significantly different and superior results to existing approaches, the isolated treatment and evaluation of the concepts and methods is needed to delimit their effects. Conversely, final decisions regarding the placement and selection of road network for ERS should only be made after the examination the interactions between all aspects of ERS.

The transport loads the are carried by vehicles, the segment traversal speeds, and the 3D geometry (incline and curvature) aspect of segments are important factors in the placement and selection of road network for ERS. As the transport loads are carried by vehicles on their routes and as segments are part of routes, the role these factors are highly route dependent. This dependence is discussed in Section 2.4, but due to the lack of relevant data the effects of these factors is not evaluated in this paper.

Finally, the empirical evaluations of the proposed method are performed on the GPS traces that record the movement of taxis in an urban environment. Clearly, the taxis are significantly different in size and energy consumption from the target vehicles, i.e., heavy freight trucks. The taxis move on an urban road network that has

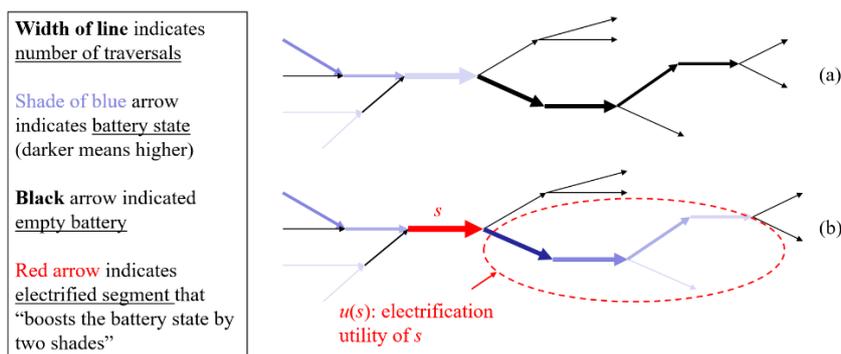


Fig. 2 Illustration of the RENO concept.

different characteristics to expressway networks. Lastly, the movement of the taxis based on the unique characteristics of the transport work they carry out might have movement patterns that are different from that of heavy freight trucks in logistics. The empirical evaluations in Section 3 have been designed to lessen the effects of these differences, but clearly further studies on real or realistically simulated heavy freight trucks are needed to draw final conclusions. The present paper merely provides a first rough evaluation of the RENO methodology.

1.7. Disposition

The remainder of this paper is organized as follows. Section 2 presents the methodology including the RBEU concept, an outline of the RENO methodology, the related computational challenges and some refinement options for the RENO methodology. Section 3 reports on the empirical evaluations based on real word vehicle routes and present a business case based on the extrapolation of the results. Finally, Section 4 concludes and outlines future work.

2. Methodology

2.1. Route based electrification utility concept

The RBEU concept and a preliminary RENO methodology has been developed within the framework of the Research and Innovation Platform for Electric Roads project that ITRL participates in and has recently been presented to academia, industry and government representatives at the 3rd Electric Road Systems Conference (Gidofalvi and Yang, 2019). The RBEU concept is depicted in Fig. 2. The schematic transport flow diagram, where the width of the arrows represents the magnitude of the flows, illustrates the RBEU concept. As it is shown in Fig. 2a, as the VPES configurations transport their loads on their routes, their battery level, which is illustrated by the shade of blue (lighter means lower battery level) of the directional movement arrows and is modelled through an *energy use function*, decreases. Without the electrification of segments, after some time, the vehicles deplete their energy storage and either have to turn to an alternative energy source and means of propulsion (e.g., fossil fuel and internal combustion engine, i.e., Hybrid Battery Electric Vehicle (HBEV) case) and complete the remaining parts of their routes (black arrows) in non-electric operation or have to stop to charge their batteries (Pure BEV (PBEV) case). As shown in Fig. 2b, through the electrification of segment s , the vehicles traversing s can not only complete s in electric operation mode, but can also charge their batteries while moving, which is modelled through a *charging function*, and can complete additional parts of their routes in electric operations. The additional part of routes for segment s are illustrated through the transport flows on the segments that are within the dashed red oval of Fig. 2b and are referred to as the *route based electrification utility* of segment s and is denoted by $u(s)$. Through a careful thought experiment, one can realize that due to the maximum energy capacity constraint of the vehicle batteries $u(s)$ depends on the battery level of the vehicles that are arriving and leaving s as well as the remaining parts of their routes. One can also consequently realize that in a *partial ERS network* where vehicles have the opportunity to charge on electrified segments, the *route based electrification utility of two segments s_1 and s_2 is not independent of one another*, but is a function of which parts of the routes include s_1 and s_2 and other segments in the partial ERS network as well as the energy use- and charging functions of various VPES configurations that carry various transport loads.

2.2. Problem complexity and computational challenges

The dependence between the RBEU of segments in a partial ERS network calls for combinatorial optimizations. In particular, in a road network with n segments, in order to find the optimal partial ERS network with k segments, one has to calculate the joint RBEU of n -choose- k number of partial ERS network configurations given the routes and the energy use- and charging functions of various VPES configuration and the transport loads that they carry. The number of combinations for realistic national road network sizes is daunting. For example, Sweden has roughly 2000 km of bi-directional motorways / expressways. Considering 500 meter segments as the unit of electrification, the number of partial ERS network combinations for electrifying 1% of the segments is approximately 10^{169} , i.e., a number with 169 digits. For higher ERS network electrification rates and/or larger networks like Germany and China with 13,000 km and 142,000 km of expressways[‡] respectively, the number of combinations just explode. Indeed, one can show that the problem of finding the optimal partial ERS network is computationally intractable and belongs to the hardest class of problems in computer science, the so-called NP-complete problems, for which no known polynomial time algorithms exist. Thus, the best one can hope for is to optimize using various optimization methods, e.g., greedy search, various guided search methods, gradient descend optimizations, simulated annealing and genetic algorithms, just to name a few. To further complicate matters, to evaluate the joint route based electrification utility of a partial ERS network candidate, one has to “simulate” energy use and charging of the various VPES configuration that carry the various transport loads on their routes. Route information is often collected and stored in fleet management system of vehicle manufacturers or 3rd party providers. The size of these fleet management data sets can be in the terabyte range depending on the number of vehicles, positioning sampling frequency and sampling period. While current big data processing tools allow simple processing of datasets of this size, complex processing that is required to perform the “simulations” are not readily supported by the currently available tools, especially not at speeds that are needed to perform the partial ERS network optimizations.

2.3. Route based ERS network optimization

In a recent paper, based on prior research into moving object trajectory (i.e., route) data management and mining, Gidofalvi and Yang (2019) formulate the RBEU concept and outlined a generic framework to perform RENO for ERS. The present research developed an efficient prototype of the generic RENO framework using simple distance based linear energy use- and charging functions. The prototype implementation employs special data structures to compress the routes of vehicles to allow for fast estimation and simulation of RBEUs of segments. To enable the processing of large problem sizes the prototype implementation uses a greedy optimization method based on the RBEU concept. Due to patenting consideration at this time no further details can be given about the RENO prototype implementation, but Section 3 presents the results of the RENO methods for various electrification scenarios.

2.4. Refinement

As described above, the current RENO prototype implementation uses simple distance based linear energy use- and charging functions. This means that the energy used on segments and the charging on electrified segments does not depend on the loads that are transported along the routes, the amount time vehicles spend on the segments or the 3D geometric aspects (i.e., incline and possibly curvature) of the segments. The following describes and compares two refinement options for taking into account transport loads of routes, segment traversal speeds, and 3D geometry (incline and potentially curvature) aspect of segments.

2.4.1. Option 1: Utilization of fleet management data

Freight transport fleet management system of vehicle manufactures or third parties often includes position measurements together with fuel consumption measurements. It can be reasonably assumed that the fuel consumption of a vehicle on segments is proportional to the transport load it carries and the 3D geometric aspects of the segments. A simple way to account for these aspects is to weight the vehicle’s segment traversal by the fuel that the vehicle uses on the given segment. Effectively, these vehicle-segment traversal weights can simply be included as a segment based multiplicative factor in the current distance based linear energy use function used in the RENO methodology.

[‡] https://en.wikipedia.org/wiki/List_of_countries_by_road_network_size

2.4.2. Option 2: Utilization of simulations

An alternative approach to account for these aspects is through simulations as follows. In particular, national freight models like SAMGODS in Sweden can deliver aggregated annual transport flows or simulated routes of vehicles with loads which jointly make up the aggregated annual transport flows. These data sources can be thought of as rough substitutes for parts of the information typical fleet management data contains. To account for 3D geometric aspects (i.e., incline and curvature) of the segments, the road segments in a national road database, e.g., the Swedish National Road Database (NVDB), can be pre-processed and through GIS techniques “lifted up” using a national Digital Elevation Model (DEM) that is usually available for research from national land survey agencies, e.g., the Swedish National Land Survey (Lantmäteriet). Segment traversal speeds can either be based on maximum or estimated average segment speeds that are either present in the national road databases or is available from the national transport authorities.

2.4.3. Pros and cons of options

Working with simulated data is no match in quality to working with real route data and fuel consumption measurements. On the other hand, as the partial ERS network will be deployed gradually in stages, the freight companies will increasingly change their vehicle fleets to electric trucks. This will create new market conditions and transport alternatives which will generate different transport flows. For example, it is not at all unlikely that parts of the flows currently on rail will shift to road. Having a model that can account for these changes and deliver simulated result for future scenarios / conditions and having a refined RENO model that utilizes this simulated data will allow for simulation-optimization loops to account the for feedbacks in the system and provide potentially more accurate decision support for stage-wise ERS network infrastructure developments. A framework for this is presented by Gidofalvi and Yang (2019).

3. Empirical Assesemnt / Evaluations

3.1. Experiment setup

The proposed RBEU concept and RENO methodology is empirically evaluated using GPS traces of real word routes of taxis that move in an urban environment. As it is explained in Section 1.6, the characteristics of these vehicles, their movement and the environment different significantly from that of heavy freight trucks on expressways. To allow for a realistic assessment of the potential RENO methodology for a scenario where heavy freight trucks move on partially electrified expressways, the VPES configurations (in particular the onboard battery capacity) are adjusted to accounted for the differences in the settings. To understand the adjustments, first the taxi data set and the urban network is described.

The taxi GPS data records the movement of 1000 taxies in the greater area of Stockholm in Sweden during the period of a month. The locations of taxis (when occupied) are sampled every 1-2 minutes. To total number of GPS measurements in the data is approximately 6 million locations that make up approximately 630,000 taxi trip trajectories. The average length of a taxi trip is 11.7km. The movements take place in the road network of the grater area of Stockholm. The road network data was obtained from the National Road Network Database (NVDB), which for the 60km-by-60km study area contains approximately 57,000 directed road network segments. As the infrastructure budget N is expressed in number of road segments, to counterbalance the effect of selecting long segments, which would yield higher electrification utilities when all other aspects are considered the same, the road network segments are subdivided so that all segments are less than or equal to 500m, resulting in a network with approximately 74,000 directed road network segments. Out of these segments, approximately 27,000 segments are included in at least one taxi trip trajectory, i.e., not all segments are traversed by taxis.

In comparison, the daily routes of heavy freight trucks can be up to possibly two orders of magnitude longer than the taxi trips, i.e., can be reasonably assumed to be 1000km. Thus, assuming a realistic average electric energy consumption rate of 1 kWh/km and a 250 kWh (500 kWh) onboard battery capacity for a 40ton vehicle (Alaküla, 2019), heavy freight trucks can complete a quarter (half) of their average daily routes on a battery. Assuming the same and arguably high electricity consumption rate for taxis, an onboard battery capacity of 3 kWh (6 kWh) would represent the same battery constraints for the taxis on their trips (see Table 1 for details).

Consequently, the RENO methodology is evaluated on the taxi trips for five VPES-ERS configurations for taxis that are described in Table 1 and are related to comparable heavy freight truck (HFT) configurations.

Table 1. Taxi trip experiment scenario setups (varying battery capacities and electric charging rates and constant electric energy consumption rate of 1 kWh/km) with comparable heavy freight truck (HFT) route experiment scenario setups. Numbers in brackets in the setups denote the fraction of average length trips (12km for taxis and 1000km for HFTs) that can be completed on a fully charged battery and that is required to receive a full charge of battery under the scenario setup.

Scenario name	Taxi setup	Comparable HFT setup
Small Battery Slow Charging (SBSC)	3 kWh, 1.5 kWh/km [1/4, 1/2]	250 kWh, 1.5 kWh/km [1/4, 1/2]
Large Battery Slow Charging (LBSC)	6 kWh, 1.5 kWh/km [1/2, 1/1]	500 kWh, 1.5 kWh/km [1/2, 1/1]
Small Battery Fast Charging (SBFC)	3 kWh, 3.0 kWh/km [1/4, 1/8]	250 kWh, 3.0 kWh/km [1/4, 1/8]
Large Battery Fast Charging (LBFC)	6 kWh, 3.0 kWh/km [1/2, 1/4]	500 kWh, 3.0 kWh/km [1/2, 1/4]
Small Battery UltraFast Charging (SBUFC)	3 kWh, 6.0 kWh/km [1/4, 1/16]	250 kWh, 6.0 kWh/km [1/4, 1/16]

Experiments were performed for varying infrastructure budgets ($N = [10, 20, 30, 40, 50]$) for the RENO method and baseline methods that select segments based on segment based statistics, i.e., frequency of vehicles (denoted as FV) and segment length weighted frequency of vehicles (denotes as SLWFV). The performance of the methods were evaluated in terms of the transport work (vehicle-kms) that can be performed in electric operation on the optimized partial ERS network that is derived by the different methods. In the experiments all vehicles start with an empty battery.

To evaluate the degree of survivability of PBEV operations, a second set of the experiments evaluated the infrastructure budget N that is needed to reach a given percent of the total transport work of 7.459 Mvkm that can be performed in electric mode on the optimized partial ERS network that is returned by the different methods. In practice this meant that the methods were run for larger infrastructure budgets, i.e., $N = 2000$ for segment based methods and $N = 500$ for route based methods.

To understand the characteristics of the different optimization methods under the various scenarios, for both experiments the maps of the selected segments were derived.

3.2. Results

Fig. 3 shows the results of the first set of experiments for $N = [10, 20, 30, 40, 50]$. As the results show the segment length weighted frequency of vehicles (SLWFV) method for slow charging scenarios (xxSC) for small set of segments is roughly equals to the performance of the RENO method. However, for fast and ultrafast charging (xxFC and SBUFC) for all infrastructures budgets the RENO method outperforms the segment based methods. Moreover, as the infrastructure budget is increasing the performance gap between the segment based methods and RENO widens. For the ultrafast charging scenario outperforms the next best segment based optimization method by close to a factor of 2. Notably, the battery size does not seem to have a noticeable effect on the electrification utility performance of RENO (see SBSC vs. LBSC or SBFC vs. LBFC).

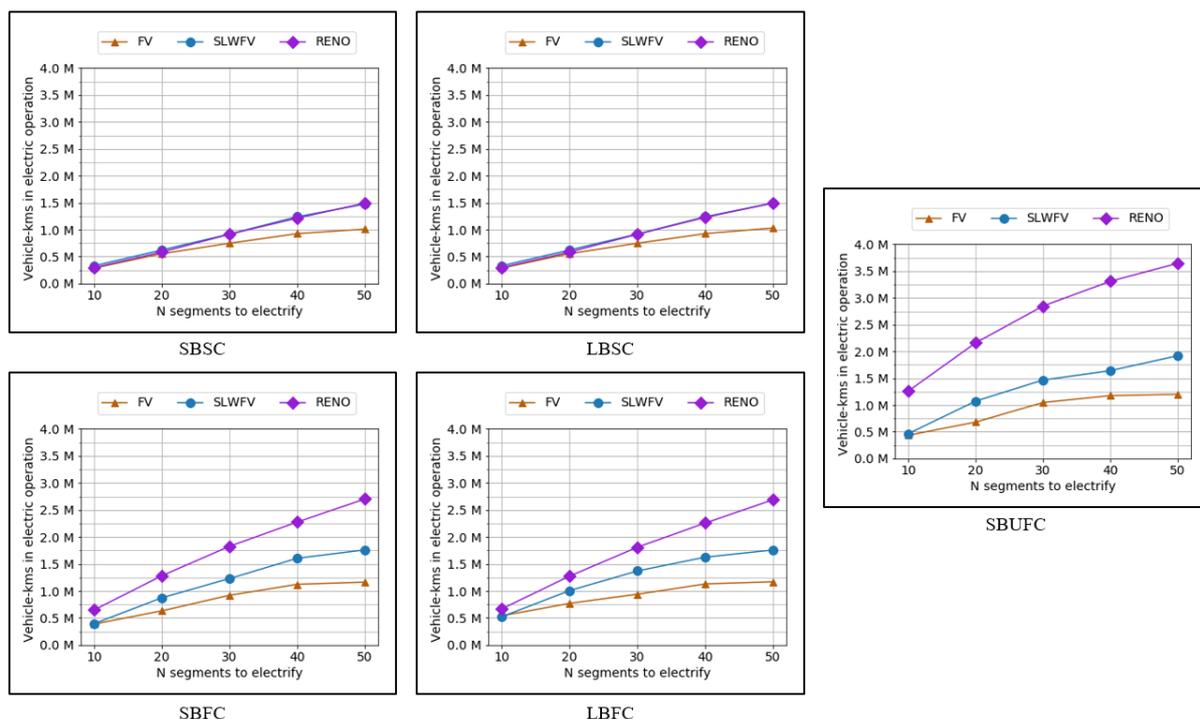


Fig. 3 ERS network optimization results of segment based (FV and SLWV) and the RENO method for various scenarios (SBSC, SBFC, LBSC, LBFC, SBUFC) and varying infrastructure budgets N .

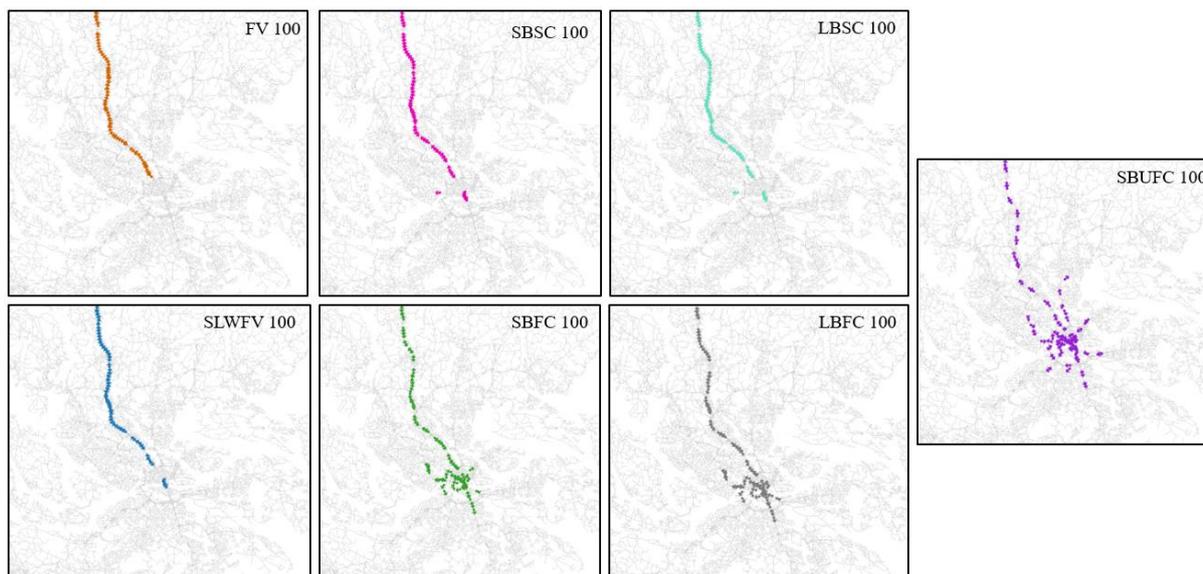


Fig. 4 Maps showing the top 100 segments selected by the segment based methods (FV and SLWV) and the RENO method (remaining five maps) for various scenarios (SBSC, SBFC, LBSC, LBFC, SBUFC).

Fig. 4 shows the first 100 segments that are selected by the different methods for various scenarios (SBSC, SBFC, LBSC, LBFC, SBUFC). Notably, there is only one map per segment based method, because these methods select the segments regardless of the battery state or route information of the vehicles. In the maps it is apparent that the segment based methods select the segments on E4, the major highway between the center of Stockholm and the international airport ARLANDA that is about 40km north of the center. This is because these segments are part of many taxi trips and hence have a high frequency of vehicles. Unlike the route based methods, segment based methods have no concept of routes or RBEU and hence do not consider the interaction between the RBEU of segments and select to a large degree all segments on E4. In comparison, RENO is aware of the concept of RBEU and the interaction between the RBEU of segments and thus only selects a segment if the majority of the

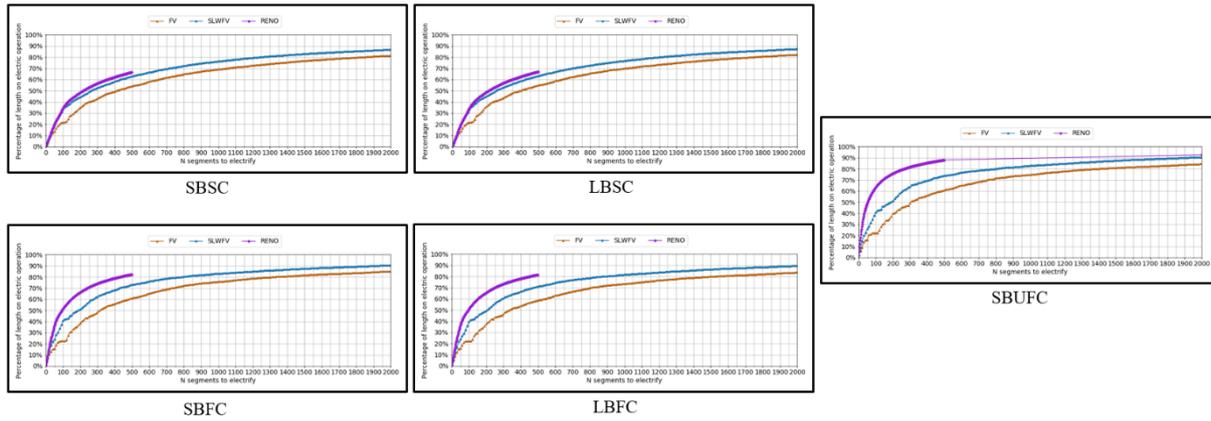


Fig. 5 Evaluation of degree of survivability of PBEV operations on the partial ERN networks returned by the different methods for different scenarios, i.e., the percent of transport work (vehicle-kms) that can be completed in electric operation given the partial ERS networks returned by the different methods for the different scenarios.

vehicles reaching the segment need charging based on their battery state and will have a good use for the charge they receive on this electrified segment during the remaining parts of their trips. Since for higher charging rates a larger fraction of the battery of the vehicles can be charged during the traversal of a maximum 500-meter-long segment, the RENO method, based on its awareness about RBEU interactions, if possible, avoids selecting consecutive segments on E4 and can strategically electrify segments from the saved infrastructure budget where it is needed the most. Notably, the battery size does not seem to have a noticeable effect on the spatial characteristics of the segments that are selected by RENO (see SBSC 100 vs. LBSC 100 or SBFC 100 vs. LBFC 100).

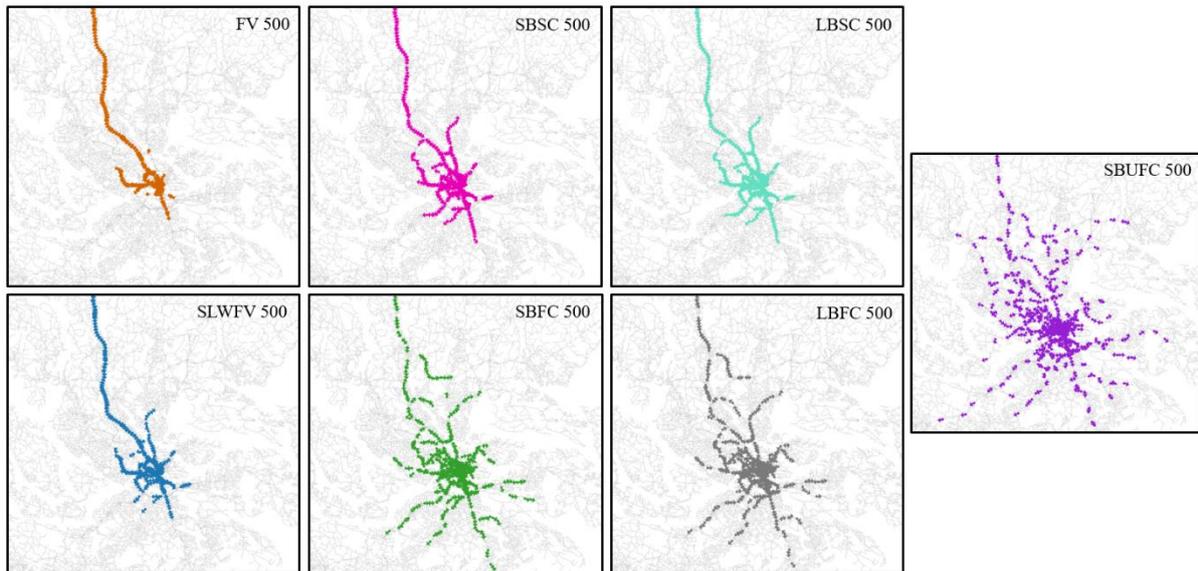


Fig. 6 Maps showing the top 500 segments selected by the segment based methods (FV and SLWV) and the RENO method (remaining five maps) for various scenarios (SBSC, SBFC, LBSC, LBFC, SBUFC).

Fig. 5 shows the results of the experiments that evaluate what is the minimum number of segments that the different methods need to select to guarantee a certain degree of survivability of PBEV operations for various scenarios. The superior performance of the RENO method is obvious for all scenarios, but it is more pronounced for fast and ultrafast charging scenarios regardless of the battery size. The reason for the increasing superiority of the RENO method for increasing charging rates is due to the fact that the selected segments can charge a larger fraction of the battery capacity on which the vehicles can complete longer and longer routes after charging. This effect also results in the fact that the RBEU interactions / interdependencies become relevant for larger sets of segments at increasing distances from each other, which the RENO method can account for and save even more of the infrastructure budget for the electrification of segments where it is needed. This effect is also clearly visible on Fig. 6 in the sprawling spatial distribution of the segments that are selected by RENO for the different scenarios.

3.3. Business case

Fig. 5 shows that it is possible to guarantee high degrees of PBEV operations with only selecting a few segments. Even the segment based methods are able to guarantee 80-90% PBEV operations by selecting approximately 7.5% of the segments, i.e., 2000 segments out of the 27,000 that are traversed by the taxis. Depending on the scenarios and the desired degree of PBEV operations, the RENO method, especially for fast and ultrafast charging scenarios, is able to select segment so that only about 2-4% of the total segments are needed to achieve the same degree of PBEV operations. For example, RENO requires 500 segments as opposed to 2000 segments to reach 90% PBEV operation for the SBUFC scenario. Assuming an ERS implementation cost of 0.5 M€/km, this savings of 1500 maximum 500-meter-long segments represents an infrastructure cost savings of 375 M€ for the given road network in the experiments. Given the length of expressways in Sweden, Germany and China are 2,000 km, 13,000 km and 142,000 km, respectively[§], the corresponding infrastructure cost savings for the SBUFC scenario are 120 M€, 780 M€, and 8,520 M€, respectively.

4. Conclusions and Future Work

This paper presented the RBEU concept and the RENO method that, under an infrastructure budget constraint, utilizes this concept and tries to find a partial ERS network that maximizes the electrification utility given the freight routes on it. Empirical evaluations on a real world data set illustrated the superiority of the RENO method over segment based optimization methods for a wide range of electrification scenarios and analyzed the characteristics of the solutions found by the RENO methodology. The potential infrastructure cost savings resulting from RENO are up to 75%, which for national expressway networks is estimated to be in the range of 120M€ (Sweden) to 8,520M€ (China).

Future work will include the exploration of the refinement options presented in Section 2.4 as well as the application of the RBEU concept and the RENO methodology to other transport related infrastructure optimizations, e.g., location of charging stations or the location of 5G network components to guarantee wireless communication connectivity and quality of service in vehicular applications. Finally, future work will also consider vehicle grid interactions and operational optimization problems, e.g., which vehicles should charge on an electrified segment so that the energy demand is balanced in the electric network.

Acknowledgements

This work was in part funded by the Research and Innovation Platform for Electric Roads that is financed by the Swedish Transport Administration (Trafikverket) and the Swedish Innovation Agency (Vinnova) and the internal strategic project RENO that is financed by the Integrated Transport Research Lab (ITRL) at KTH.

References

- Alaküla, M., 2019. A Hybrid ERS Cost Perspective. 3rd Electric Road Systems Conference.
- Balieu, R., Chen, F., Kringos, N., 2018. Infrastructural aspect of electrified road systems: Long-term performance prediction by Finite Elements integrated into a Life Cycle Assessment. 2nd Electric Road Systems Conference.
- Bernecker, T., Boysen, J., Schubert, M., Nebauer, G., 2018. Development of a core network for the use of overhead line heavy duty vehicles on the German motorway network. 2nd Electric Road Systems Conference.
- German-Swedish Joint Governmental Declaration: Innovation and cooperation for sustainable future: A German & Swedish partnership for innovation. The Swedish Government, 31 January 2017. Online: <https://www.regeringen.se/490ab0/contentassets/a8f2545e3b6147ed8050ba060d8123c3/innovation-and-cooperation-for-a-sustainable-future.pdf> [Last visited: 2019-05-30]
- Gidofalvi, G., Yang, C., 2019. Delivery Route Based ERS Network Optimization. 3rd Electric Road Systems Conference.
- Hasselgren, B., 2018. Industrial dynamics and path dependency – the case of implementing ERS-systems in Sweden. 2nd Electric Road Systems Conference.
- Jelica, D., Taljegard, M., Thorson, L., Johnsson, F., 2018. What is the hourly electricity demand when implementing ERS? 2nd Electric Road Systems Conference.
- Jöhrens, J., Rücker, J., Helms, H., 2018. Logistical Constraints on Commercial Applications for ERS. 2nd Electric Road Systems Conference.
- Jöhrens, J., Rücker, J., Helms, H., Waßmuth, V., 2018. Identification of economically viable ERS routes in Germany. 2nd Electric Road Systems Conference.
- Kühnel, S., Hacker, F., 2018. Benefits and system design of ERS in the context of falling battery costs. 2nd Electric Road Systems Conference.

[§] https://en.wikipedia.org/wiki/List_of_countries_by_road_network_size

- Malmquist, A., Ramos, J.A.A., 2018. Energy system model for electric roads. 2nd Electric Road Systems Conference.
- Pettersson, J., Lindgren, M., Berndtsson, A., Viklund, V., Andersson, M., Öhrnberg, Å., Söderberg, U., Eriksson, D., Grudemo, S., Hasselgren, B., Andersson, L., Bülund, A., Grönvold Andersson, A.-K., 2017. National roadmap for electric road systems. Swedish Transport Administration. Online:
https://www.trafikverket.se/contentassets/4c00abedf6794077a1e2a443cde60349/national_roadmap_for_electric_road_systems_20171129_eng.pdf [Last visited: 2019-05-30]
- TrV-ERSET, 2018. Electric Road Systems Engineering Toolbox (ERSET). Trafikverket project reference number Online:
<https://www.itrl.kth.se/research/completed-projects-a/erset/electric-road-systems-engineering-toolbox-erset-1.632619> [Last visited 2019-05-30]
- Taljegard, M., Göransson, L., Odenberger, M., Johnsson, F., 2018. Impact of electric road systems on the Swedish-German electricity mix. 2nd Electric Road Systems Conference.
- Taljegard, M., Göransson, L., Odenberger, M., and Johnsson, F., 2017. Spacial and dynamic energy demand of the E39 highway – Implications on electrification options. *Applied Energy* 195:681-692.
- Vinnova-ERS, 2016. Research and Innovation platform for electric roads. Vinnova project reference number: 2016-02930 Online:
<https://www.vinnova.se/en/p/research-and-innovation-plattform-for-electric-roads/> [Last visited 2019-05-30]
- Wang, Q., Berlin, D., 2018. Stakeholder Assessment Tool from the ERS Engineering Toolbox: The Case of eRoadArlanda. 2nd Electric Road Systems Conference.