Impacts of vehicle fleet electrification in Sweden – a simulation-based assessment of long-distance trips

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***Abstract*—Electrifying road transport is seen as one of the key components in decreasing the carbon footprint of the society as a whole. Recent developments in electric drivetrain and battery technology have helped to design vehicles with ranges that make them independent of public charging infrastructure during most sub-urban and commuting trips. Once long-haul trips are planned, however, these vehicles require a dense network of charging infrastructure. In this paper, the impact of a large-scale electrification of vehicles in long-distance trips is evaluated by combining an agent-based long distance transport model of Sweden with a detailed model of energy consumption and battery charging. Energy consumption and charging schemes are simulated for different types of vehicles and chargers. In a first application, all vehicle traffic is electrified. Results demonstrate that the daily estimate for energy consumption is in the region of 150 GWh. This equals roughly 40% of the current Swedish electricity consumption. Energy consumption is the highest along in the motorway network connecting the south of the country (Malmö, Göteborg and Stockholm). Along these motorways, also the highest demand for charging infrastructure arises. Nationwide, two peak times for vehicle charging seem to exist: One is around lunch time and another in the mid-afternoon. During the first peak, overall energy demand is presumably the highest.**

***Index Terms*—Electric Vehicles, Transport Simulation, MATSim, long distance travel, Sweden**

I. Introduction

The electrification of road transport is one of the biggest challenges towards an environmentally sustainable transport system over the next years. Several countries have already announced an upcoming ban on the sales of fossil-fueled passenger cars, triggering a replacement of older vehicles with alternative solutions such as Battery Electric Vehicles (BEVs) or hydrogen powered Fuel Cell Electric Vehicles (FCEVs). Countries that have introduced a ban include Norway (by 2025), France, and The United Kingdom (both by 2040) [7]. More recently, Sweden and Denmark have announced a ban on sales for the year 2030 [9]. The BEV market is taking up on this and an adequate selection of vehicles will be available. The main adaption that needs to be undertaken lies, however, in the charging infrastructure. To fulfill everyday mobility needs, the majority of people will be able to charge their vehicles at home, the workplace or other activity locations, such as shopping centers. Realistic vehicle ranges of over 300 km have the potential to reduce the need for vehicle charging to a few times per month and vehicle. Similarly, urban freight distribution could be electrified using BEVs and adding charging infrastructure at the depot locations.

A bigger concern are long-distance trips that are longer than a vehicle's range. These will require travelers to break the trip recharge the vehicle en-route. Thus, some sort of charging infrastructure along the way is needed. The selection of the technology, its location, design and sizing must be undertaken with good care, not only because of the economical and practical implications entailed for both users and society in general, but also for the requirements placed on the electric power grid not least for heavy vehicles charging.

Agent based transport simulations are a standard tool for transport infrastructure and policy planning. However, most simulation scenarios tend to focus on everyday mobility and are of limited spatial extent. In this paper, we develop a

This paper was co-financed by the Swedish Electromobility Centre.

nationwide multi-agent based simulation model for Sweden that depicts both passenger car travel as well as freight transport. This simulation scenario is then paired with an in-depth consumption and charging model for Electric Vehicles and a first use case for a mass-electrification of vehicles is presented. This holistic and cross-disciplinary approach combines research from both transport and electrical engineering and allows a very detailed, spatially explicit and dynamic analysis.

The remainder of this paper is structured as follows: First, an overview of the state of the art in simulating Electric Vehicles and their integration into the transport system is provided. This is followed by details about the model generation, the available data sources and the validation of the transport model. Then the vehicle consumption and charging models are introduced. Finally, this is all combined into a first case study followed by a discussion of results.

II. State of the Art

Transport simulation models are often divided into three different groups: 1) Macroscopic four-step models [17], 2) Mesoscopic models where a synthetic population is assigned, but traffic flow is simplified [2], [11], 3) Microscopic simulations with a very detailed simulation of traffic flow [3]. Of these, static models require the lowest computational effort and are thus very well-suited to model flows in long-distance travel. However, they are too coarse for a detailed, vehicle-type specific and dynamic analysis of electric energy consumption and charging requirement such as required in this study. On the other side, microscopic simulations provide a high level of vehicle-specific detail, including data about vehicle specific acceleration and deceleration phases that have a high impact on energy consumption. However, their computational requirements only allow the simulation of scenarios up to the city level. Mesoscopic models have proven to be a good compromise: they provide person- and vehicle-specific details, but leave out detailed lane and acceleration changes. Still, the level of detail is sufficient for a detailed analysis of vehicle-specific aerial [14] and noise [13] emissions and their computational requirements are low enough to allow for nationwide . One of the most well-known simulation tools in this scope is MATSim [11]. It combines a queue-based traffic model with a detailed demand and vehicle model. Route and mode choice is conducted via genetic algorithms over the course of several iterations. Some simulation scenarios of a similar, nationwide scale exist for Switzerland, South Africa and Germany[1] and are applied in research, industry and policy planning. As an open-source software written in JAVA, MATSim is highly pluggable and extensible and is therefore used as the simulation platform in this paper.

Modeling EVs and their charging use is often conducted by analyzing travel diary or other transport survey data. These analyses help to find vehicle use patterns and define charging profiles [5], [6]. In MATSim, some initial proposals for simulating electric vehicles exist and have been applied to taxi fleets [4], [15] and charging infrastructure integration [22]. However, for a full and large-scale integration of different EV and types and charging styles some additional integration work is required.

III. Simulation Model

MATSim has a certain set of input that is required for all simulation scenarios. These must include a synthetic population ("agents") with daily activity chains ("plans") and a network model. Depending on the use case, additional information, such as delivery chains for freight traffic and public transport schedules may be needed. Additionally, some extra functionalities need to be integrated for the simulation of EVs. These include information on elevation changes on the road, an assumption of the mix of the vehicle fleet and energy consumption and charging models representative of the different vehicle types and charging infrastructure considered.

A. Model Data Sources

1) Network: MATSim networks consist of nodes that are connected by links. These links have several attributes, including the number of lanes, free flow speed and capacity. The most commonly used approach to generate a network is by converting data from OpenStreetMaps (OSM) [1]. This is an often used functionality and most required network attributes can be directly converted from corresponding OSM data. The network spans a bounding box around Sweden and some surrounding countries. Relevant domestic ferry connections, such as to and from the island of Gotland, have been implemented as low-speed road links into the network. The network depicts all major roads in the country. In and around Stockholm, Gothenburg and Malmö, also smaller roads are included. An overview of the network is depicted in Fig. 1. To accurately calculate the energy consumption of EVs (essential to estimate the vehicle's range and charging needs) the slope of the road is an important parameter that is not usually reflected in OSM data. However, in Europe elevation data is available via the openly available Copernicus Land Monitoring Service[2]. In an approach first used for the simulation of bicycles, these data can be added to nodes in a MATSim network [24]. This approach is sufficient for shorter, inner-city network links. Along longer links in rural areas, gradient changes along the link are tracked in sections of a maximum of 500 m using additional measurement points.

2) Synthetic population: Currently, two nationwide transport models for Sweden exist, one for passengers and one for freight. Both of them are using static assignment and have been developed over a long time-span. The idea of converting static models into a synthetic population for MATSim has been proposed and successfully realized by others [18]. The nationwide passenger model, SAMPERS [19], is a multi-modal assignment model that contains passenger flows both for business and leisure travel using car, airplane, bus and

[1]For an overview, see https://matsim.org/gallery/

[2]see https://land.copernicus.eu/

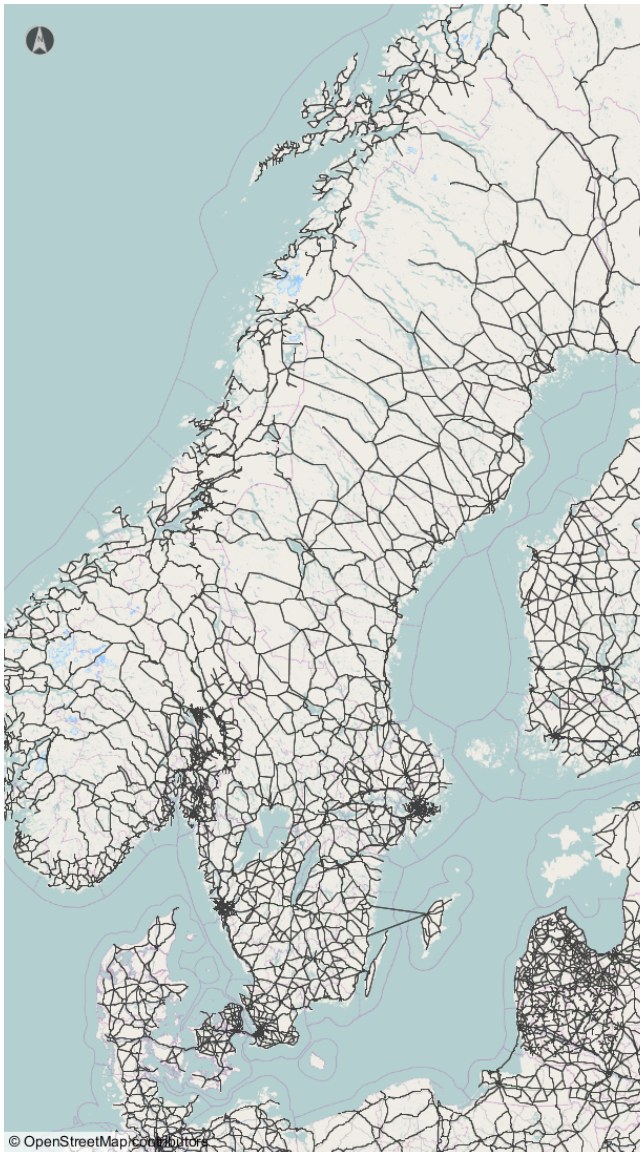

Fig. 1. MATSim Network of Sweden

train modes. A central output of the model are average daily flows of passengers between traffic cells by each mode. In the MATSim model, these flows were converted into simulation agents. For longer travel distances of over 300 km, where a return trip on the same day is rather unlikely, the model outcome was converted 1:1 and departure time choice was set to a reasonable, non-night time departure for the agent. An example for such a trip is depicted in Fig. 2, where an agent resides in Östergötlands county and travels in the morning for roughly two hours north on a business trip to Örebro. In the evening, the agent returns home. Its total daily driving distance is roughly 380 km. For shorter distances of 100 to 300 km, a return trip was scheduled for the agent at the same day with a certain probability that reduced with increasing distance. The modes of the SAMPERS model were reduced to reflect only passenger car and public transport (combining bus and

Fig. 2. Example of a simulated long distance trip

train modes). Airplane mode is not reflected in the MATSim model. The actual location coordinate of an agent's start and destination in the traffic cell is drawn from built up area in the cell using Corine Land Cover Data. Additionally, commuter traffic was depicted into the model by evaluating the Swedish Commuter Statistics. Commuters may not be important when it comes to charging behavior in long-haul traffic but form an important factor for congestion in and around urban areas. Their mode choice in metropolitan regions has been calibrated in accordance with a recent report [21]. Secondary activities, such as shopping or leisure, are not part of the synthetic populations' daily schedules.

3) Freight traffic: The demand for freight traffic was converted from the static SAMGODS model output [20]. This is a multi-modal freight model, with the output being the *annual* number of freight vehicles per origin-destination-relation. Opposed to passenger traffic, also international relations for goods to and from Sweden are part of the model. The modeled modes include different types of trucks, trains, ships and airplanes. The annual values were transformed into typical weekday values (assuming 250 working days) and all kinds of truck modes were added into the model MATSim model. The maximum speed for trucks was set to 90 km/h, in line with speed limits in Sweden.

4) Public transport: Information about Public transport schedules can be retrieved via a Sweden wide GTFS, available from Trafiklab[3]. There is a standard approach to import GTFS schedule into a MATSim public transport supply that can be used for transit routing [25]. Agents assigned public transport mode are thus able to experience realistic travel times.

[3]see https://www.trafiklab.se/api/gtfs-sverige-2

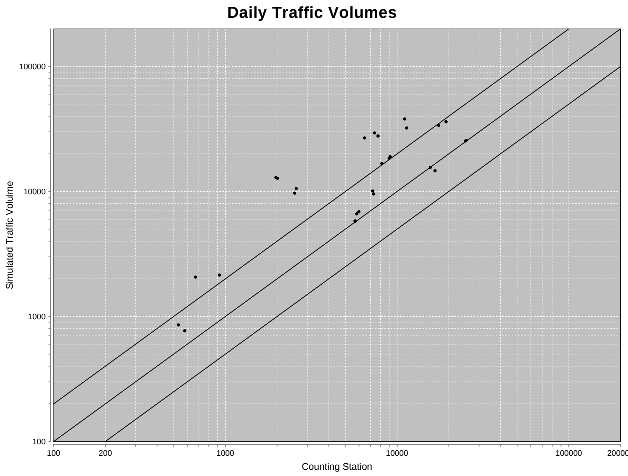

Fig. 3. Comparison of simulated and real-world traffic counts: Each dot represents one counting station with a real-world (x-axis) and simulated value (y-axis).

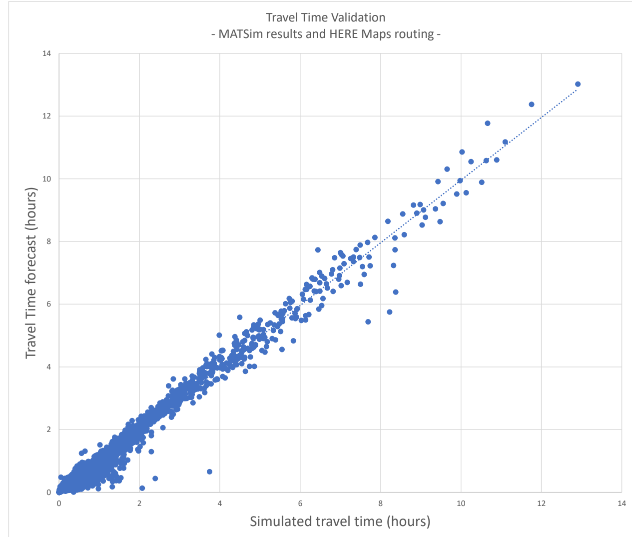

Fig. 4. Comparison of MATSim travel times and those acquired from HERE routing

B. Base case generation and validation

Using the above described data, a a base case simulation run, depicting the current status quo, can be run. For computational reasons, a 10 % sample of the described population was simulated, which is a standard practice for MATSim simulation runs. Road network capacities are adjusted accordingly. This results in a total of roughly 500 000 agents being simulated. This does leave out a certain share of the population that does not perform any trips relevant for the long-distance scope of the model. The simulation was run for 200 iterations. In between iterations, agents depicting freight and long-distance passenger transport may improve their plans by adjusting departure times and routes. For commuter traffic, mode choice was also enabled in order to calibrate the modal share in accordance with the input data.

1) Traffic counts: A typical approach to validate MATSim simulation models is a comparison of traffic flow in the model and reality. Traffic counts are publicly available for all major roads in Sweden and for different reference days[4]. They have an hourly resolution and track both passenger cars and trucks. In this model, a total of 28 counting stations, situated along different road categories and spread across the country, are used to validate the model. As Fig. 3 depicts, the relative error among most counting stations seems acceptable. However, there is a tendency that the simulation has more traffic than what was counted in reality. A more detailed analysis of the counts data reveals that most mismatches occur along back-country roads, whereas the simulation results along motorways in proximity to larger urban areas match the counts sufficiently well.

2) Travel times: Travel times are another central aspect of the simulation output and should therefore also be validated, especially in a model, where most trips cover long distances. In this scenario, the output model is compared with routing data of HERE Maps. This is done by sampling 5000 random trips of the model. For these trips, a query is made via the HERE API[5] for each trip's given departure time on an average weekday. The deviation between the simulated and the expected travel times are around 11 % for all trips of 30 minutes and more. This seems reasonable and sufficient for the overall model, as Fig. 4 shows. There seems to be no clear tendency from the validation, so it cannot be said that either the routed or simulated travel times are in general too optimistic or pessimistic.

IV. Integration of Electric Vehicles

For the integration of EVs into the model the MATSim simulation cycle is extended at several points.

A. Vehicle Routing for Long Distance Trips

Breaks for vehicle charging at long-distance trips are pre-estimated at the beginning of each MATSim iteration. In a first step, the overall trip route is calculated. Taking the initial State of Charge (SoC) of the vehicle and the location of suitable charging infrastructure as a constraint, charging locations along the route are determined and the route is accordingly adjusted. Charging breaks are modeled as a MATSim activity, however the agent does not receive a positive score for performing. The duration of a charging activity is defined by the estimated required charging duration.

B. Energy Consumption

The queue model used in MATSim allows tracking of energy consumption by analyzing vehicles as they enter and leave links in the network. Based on this information, the average speed driven on the link can be retrieved, the energy consumption of the vehicle on the link can be calculated

[4]see http://vtf.trafikverket.se/SeTrafikinformation

[5]see https://developer.here.com

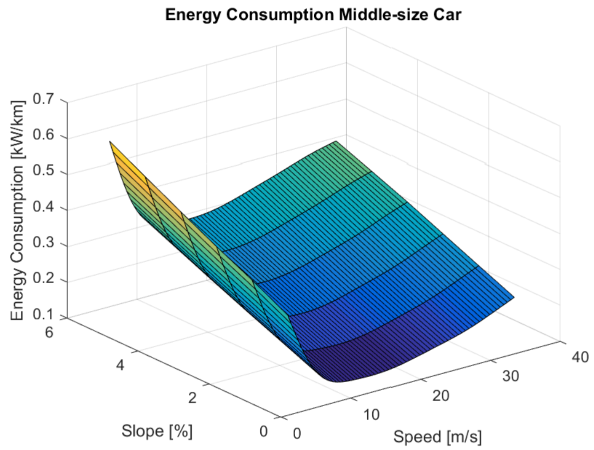

Fig. 5. Energy consumption profile for a Middle-size car

and the vehicle's SoC updated. The energy consumption model used in this paper is based on previous work by the authors [6], [16] and calculates energy consumption as a function of average speed and road slope based on the World harmonized Light vehicle Test Procedure (WLTP) drive cycle. Fig. 5 shows the consumption for a medium-sized compact class car. The relatively high consumption per distance at low speed reflects the more significant contribution of the auxiliary systems (modeled as a constant power load) compared to the energy invested in propulsion, as well as the more frequent deceleration and acceleration in stop-and-go situations which constitute the dominating form of traffic at low speeds.

C. Charging Logic

In long-distance travel charging is expected to happen as fast as possible, to minimize the delay and disruption to the initial travel schedule. Therefore, only fast charging or dynamic charging (i.e., charging while driving by means of Electric Roads Systems) are suitable technical solutions for this case. In this paper, all vehicles are assumed to be able to charge during night and therefore start their long-distance trip with a fully charged battery, and all charging happening during the trip is handled by fast charging infrastructure. When vehicles arrive at a charging station, charging either commences immediately, if there is a free spot available, or the vehicle is queued. The charging process itself is modeled mimicking real-world fast charging behavior, where charging at full speed occurs up to 50 % SoC and then decreases linearly [10].

V. A FIRST CASE STUDY

As initially stated, a full de-carbonisation of transport is a long-term goal in many European countries. As a first application of the described model, a full electrification of long-distance road transport is assumed. In this case study, all vehicles are assumed to be BEVs.

TABLE I
VEHICLE TYPES AND CHARGING POWER

Vehicle Type **Vehicle Type**	**Battery Capacity**	**Maximum charging power**	Fleet share Fleet share
City Car	40 kWh	70 kW	15%
Mid-size	60 kWh	105 kW	50%
SUV	100 kWh	175 kW	35%
21t Truck	1 MWh	1.75 MW	100%

A. Assumptions

Some assumptions need to be undertaken regarding both the vehicle fleet and the charging infrastructure.

1) Fleet: It is assumed that the mix of the vehicle fleet in terms of vehicle size remains roughly similar to today's situation for both passenger and freight transport. For passenger cars, three different vehicle types are used: A small city car, a medium sized car and a large SUV type. For trucks, only a single type (averaged at 21 ton [23]) is assumed. An overview of the vehicle types, battery sizes and charging types can be found in Table I.

As the majority of long-distance trips is pre-planned, we assume that vehicles in general start their trips with a fully charged battery, as already discussed.

2) Charging Infrastructure: To position chargers, the current locations of gas stations were picked as a reference point. Overall, there are roughly 2500 of them in the whole country. Their locations were retrieved from OSM data. In this initial model, a flat ten charging points per location for passenger cars and two for trucks are assumed. This is a rather unrealistically high number, so wait times at chargers should almost not occur. The maximum power per passenger car charging point was set to 300 kW, for trucks 1 MW is assumed. Both values are expected to be reached with future generations of fast chargers. Effects on the power grid and the potential limitations imposed by it are left out in this study.

3) Simulation Setup: In this first case study, the agents are only able to adapt the routes in accordance with their re-charging requirements. The rest of the simulation is kept in a similar state to the base case scenario. As such, only 50 iterations are required to reach an equilibrium state.

B. Results

The overall results of this first case study demonstrate the general sensitivity of the models towards a mass-introduction of EVs.

1) Energy Consumption: In Fig. 6 the daily energy consumption per road-kilometer in South Sweden is shown. The figure suggests quite clearly that most energy is used along the major motorways connecting Stockholm, Malmö and Gothenburg. In these areas, up to 5 MWh per day (in a 10 % model, so these values should be scaled up) are used by vehicles. North of Stockholm, consumption significantly decreases and the only road with significant consumption is the motorway E4 up to Sundsvall. Therefore, the area north is not depicted. Summed up and scaled to a full population

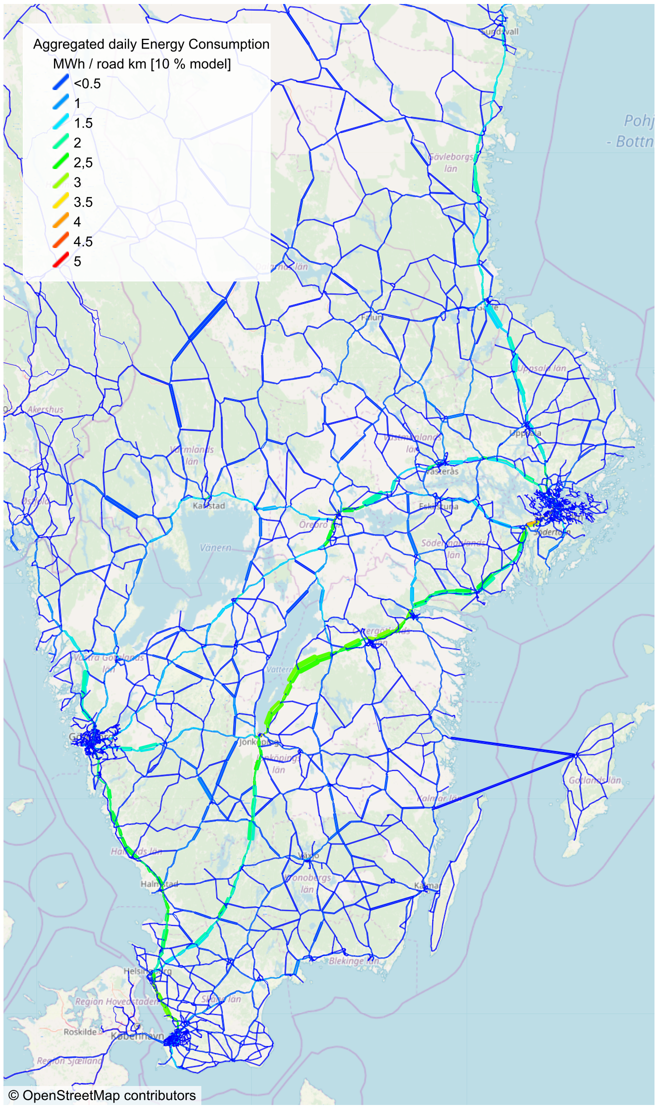

Fig. 6. Daily energy consumption per road kilometer in Southern Sweden (10 %).

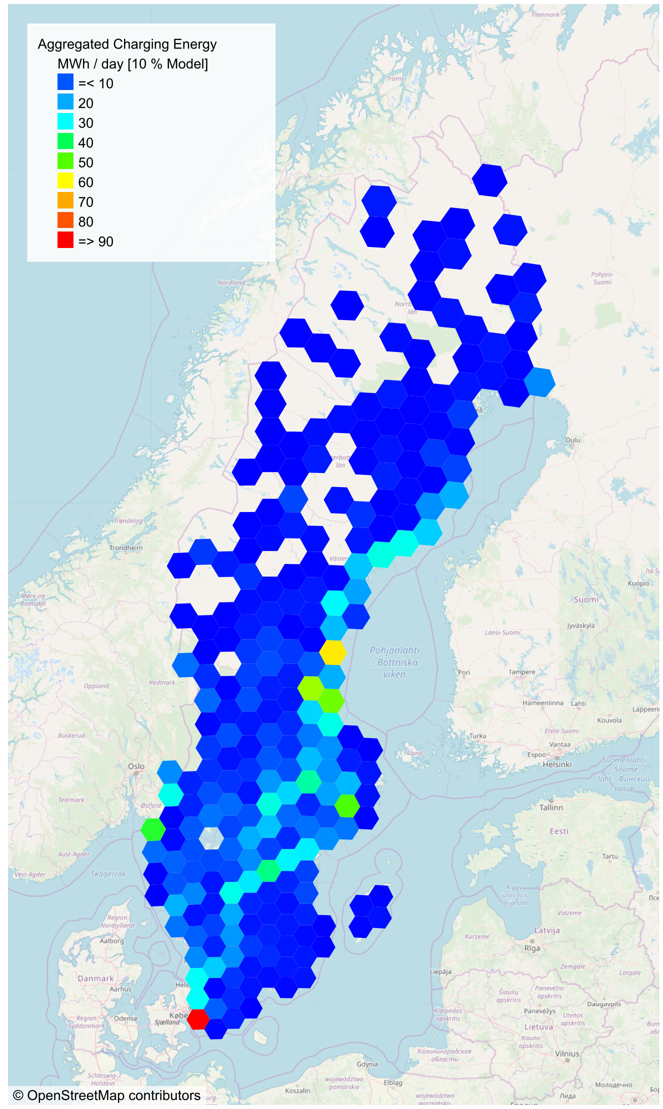

Fig. 7. Spatial allocation of consumed energy at charger locations.

sample, this adds to a daily consumption of 152 GWh. The current overall average daily electrical energy consumption in Sweden is around 365 GWh, so the switch to EVs will increase the overall consumption of electrical energy by around 40 %. Assumptions on current energy use in road transport shows the same or perhaps a little smaller order of magnitude if converted to EVs [8].

2) Charger usage: In Fig. 8 the number of agents currently performing charging activities is plotted. For passenger cars, a peak can be expected around noon followed by a second, lower peak in the early evening hours. Charging of trucks occurs on a fairly constant level during the whole day. With a maximum of 2100 agents charging at the same time, no waiting times at the chargers occur. A look at the spatial distribution of the consumed charging energy is in line with the energy consumption: Most energy is consumed along charging stations close to the motorways. Additionally, the model shows a high consumption near border crossings (Malmö in the South and close to Oslo). This can, however, be considered an artifact, as charging infrastructure outside Sweden is not part of the model and it is hard to assign a realistic value to the SoC of the vehicles arriving to Sweden from abroad.

3) Travel Time Changes: In the base-case, agents can travel non-stop from their origins to their destinations. The need for vehicle recharging results in higher travel times that is spent at chargers. For trucks, this will increase overall travel times by roughly 11 %, whereas for cars the average travel time increase in the EV case is around 25 %. However, since the base case does not take any breaks into account, the effect may in fact be smaller, as breaks otherwise necessary for resting, eating and so on can be combined with the charging events.

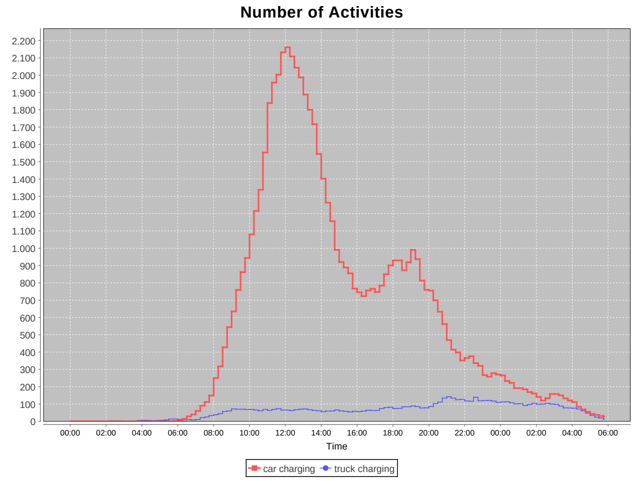

Fig. 8. Charging activities during the day.

VI. Conclusion

In this paper we were able to show that using an agent-based, microscopic transport model is a powerful tool to simulate large-scale and long-distance scenarios. The chosen approach allows a detailed and accurate analysis of passenger and freight transport along the major roads in Sweden.

The first application, a complete electrification of road transport in Sweden, provides some interesting first insights. Given the made assumptions, a good first impression of electric energy consumption in the Road Network can be achieved. The dynamic and spatial analysis of charger usage demonstrates where charging infrastructure is likely to be required. The overall daily energy consumption is perhaps rather a bit too high. This can be explained by the general tendency of having a bit too much traffic in the model as the counts reveal.

This study leaves room for extended further research: on one hand, user reactions to EV usage should be taken into account. These could include a pricing scheme for chargers and people's reaction to it. On the other hand, a better assumption of the required charging infrastructure could be made. The simulated energy consumption and the demand for charging infrastructure provide an excellent base for an optimization of charger allocation in the network.

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