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Using multi-agent transport simulations to assess the impact of EV charging infrastructure deployment

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***Abstract*—Over the last two decades, electrification has gained importance as a means to decarbonise the transport sector. As the number of Electric Vehicles (EVs) increases, it is important to consider broader system aspects as well, especially when deciding the type, coverage, size and location of the charging infrastructure required. In this article, a Multi-Agent model depicting long distance transport in Sweden is proposed, allowing to simulate different scenarios and enabling a more detailed analysis of the interaction between these vehicles and the charging infrastructure.**

Keywords: Electric Vehicles, charging infrastructure, transport modelling, cost analysis.

I. INTRODUCTION

OVER the last two decades, both public and private organisations have devoted significant resources to evaluate the potential of vehicle electrification as a way to decarbonise the transport sector. At the beginning of this Electric Vehicle (EV) revival in the later years of the 20^{th} century, most of these research efforts were directed towards the development of the technology on-board the vehicles. The battery technology available at the time offered limited energy density and therefore Hybrid Electric Vehicles (HEVs) were the preferred alternative. As technology evolved, it became possible to equip vehicles with batteries with enough capacity to enable full-electric drive for reasonable distances, leading to Plug-in Hybrid Electric Vehicles (PHEVs) and ultimately Battery Electric Vehicles (BEVs).

However, in order to take full advantage of the latter types of vehicles they need to be charged from an external supply. For this reason, substantial research efforts have also been devoted to the development of charging technology, initially focusing on the physical components required to charge the vehicles in a time effective and energy efficient way. However, as the number of EVs increases, it is important to consider also broader system aspects. Decisions concerning the deployment of charging infrastructure such as the choice of charging mode (static or dynamic), the power rating of the charging point, the density of the charging network and the pricing policies applied will have a significant impact on the rest of the transport system (e.g. traffic flows in different roads, total traffic volumes and the corresponding energy consumed, choice of transport mode, number, location and duration of charging events, etc.) as well as on other supporting systems such as the power grid to name the most obvious one.

In order to assess the impact caused by these choices, a model able to represent the decision processes related to charging for the vehicles in the fleet, like choosing when and where to charge (depending on the availability of the infrastructure and its characteristics) is needed. In this study, a MATSim model of Sweden depicting most of the long-distance travelling nationwide is presented, and a first simulation case is run and discussed to illustrate the capabilities of such model. As explained in the following section, this model represents each vehicle (agent) in a reduced-scale fleet, providing very detailed information of all relevant aspects of each trip, and therefore insights on how to develop future electromobility systems in the most effective way.

II. TRANSPORT MODEL FOR LONG-DISTANCE TRANSPORT IN SWEDEN

Transport models traditionally used in traffic planning, or to support the development of new road infrastructure, are based on a macroscopic approach in which aggregate data are used to predict traffic flows in the different parts of the transport system. Although very computationally effective, macroscopic models are too coarse and do not take into account the behaviour of individual vehicles, their interactions and their decision-making processes when it comes to e.g. where, when and for how long to charge the batteries. For this reason, they are less suitable to analyse the impact of different charging infrastructure deployment scenarios.

In order to have a better understanding on how the charging infrastructure will be used and what influence it will have on long-distance traffic flows, activity-based models may be used. In particular agent-based models, in which every agent

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is simulated independently. An agent in this context may represent any individual in a synthetic population such as a private traveller commuting to work, a truck part of a larger fleet, or a scheduled bus service between two distant cities [1], [3]. Each agent has a number of missions or activities to fulfil at specific geographical locations and times, and depending on how effectively it moves between missions it will receive a score (utility value). Accomplishing a mission earns utility points while the time spent in traffic between missions loses points. Although the objective of this study is to analyse the impact of different types of charging infrastructure for EVs (both light and heavy vehicles) the model is in principle multi-modal, thus agents can choose between different modes of transportation if that leads to better results. In order to limit the size of the model and keep it solvable, detailed information such as driving lanes and acceleration / deceleration profiles are left out. Moreover, only a fraction of the population is simulated (commonly 10% based on previous simulation experiences). The model is solved iteratively and, for each iteration, slight variations in the travel plan of the agents are introduced.
For the model to give accurate results, several components are needed:

- Input data in order to create the synthetic population, with the characteristics corresponding to each individual (e.g. vehicle type, size, weight, battery capacity on board, etc.) and the missions that should be fulfilled
- The transport network in which the agents move, with an adequate level of discretisation, specifying the traffic capacity of the different links, their free flow speed, slope and the charging infrastructure available (specifying the number of charging points, type, power capabilities, geographical location, etc.)
- A model of the Electric Vehicles, more specifically the energy consumption per kilometre as a function of the vehicle's speed and the slope of the road, and the battery charging process as a function of the battery capacity and state of charge
- Calibration data (e.g. traffic counts) to validate the modelling approach and results

A brief description of each of the previous components is given below. A more detailed explanation of the development of the MATSim model for long-distance transport in Sweden is provided in [2].

A. *Population input data*

The synthetic population is based on the following data: the composition of the Swedish vehicle fleet (from the Swedish Transport Agency), goods transport flows from the Samgods model calibration case [5], long distance commuting trips (>100 km) from the Sampers model [6] and Statistics Sweden [9] and traffic counts at different points of the national road network also from the Swedish Transport Agency.

B. *Network for the whole Sweden*

The transport network used is derived from OpenStreetMap [10], with enough resolution to be able to capture congestion patterns in and around the largest cities. The average slope of each link is derived from the elevation of the extreme points - and some intermediate points in the case of long links - obtained from the Copernicus Land Monitoring Service [11]. The resulting network, and a detail view of the area around Stockholm can be seen in Fig. 1.

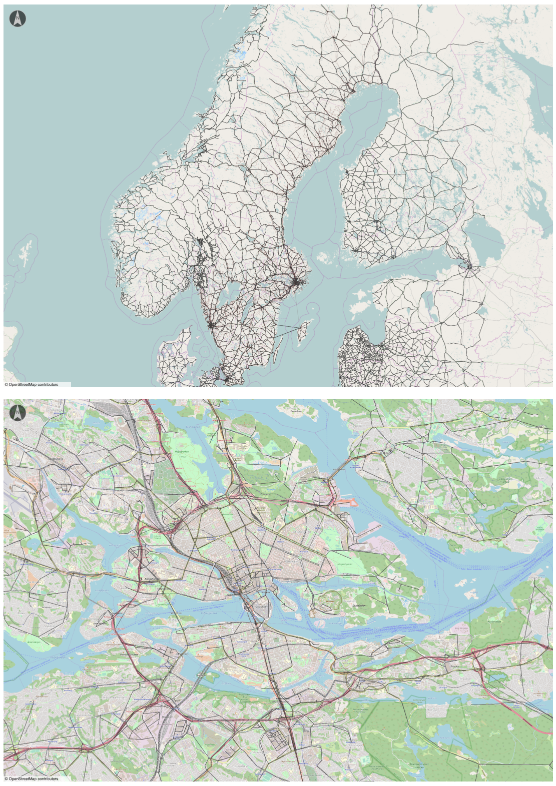

Figure 1: Model network for the whole Sweden (top) and the Stockholm area (bottom).

C. *Vehicle model*

Four types of vehicles are considered according to their size and performance, as shown in Table I.

Table I: Main characteristics of the different vehicle types

Pass. cars	Mass	Power	Aux.	Battery
Small	1200 kg	50 kW	1 kW	40 kWh
Medium	1500 kg	85 kW	1.5 kW	60 kWh
Large	1800 kg	130 kW	2 kW	100 kWh
Heavy duty veh.	Mass	Power	Aux.	Battery
Trucks	21 Ton	200 kW	3.5 kW	1000 kWh

For each vehicle type, energy consumption maps are created as a function of the vehicle average speed and the road slope. To create this maps, a vehicle representative of each category is simulated in MATLAB - Simulink for a number of pre-defined drive cycles. For passenger cars, these drive cycles are created by scaling the speed of the part of the WLTP (Worldwide

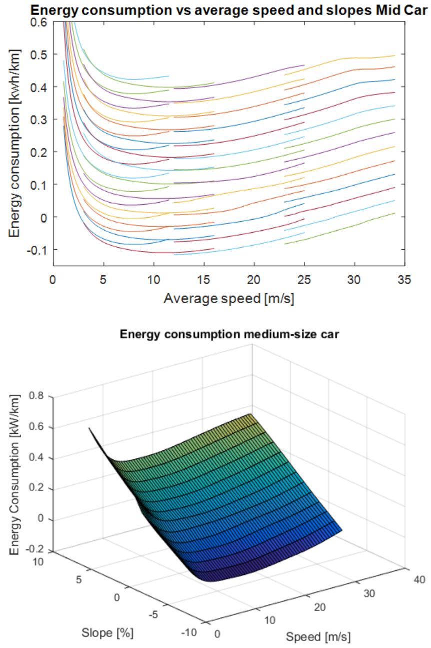

Figure 2: Energy consumption simulation results for a mid-size car for 0 - 12% slopes (top) and the resulting energy consumption map (bottom).

harmonised Light-vehicle Test Procedure) [8] drive cycle with the closest average speed. For average speeds between 1 and 43 km/h the first part of the WLTP cycle is used (low speed, with an original average speed of 26 km/h), between 10 and 58 km/h the medium speed part (original average speed of 45 km/h), between 45 and 90 km/h the high speed part (original average speed of 61 km/h) and between 83 and 123 km/h the extra-high one (original average speed of 94 km/h). In order to smooth the transition between different speed ranges, a spline function is fitted to the energy consumption results. As an example, Fig. 2 shows the energy consumption results for a medium-size passenger car at 0 to 12% slope as well as the final energy consumption map for the same type of vehicle. For heavy vehicles, a much simpler drive cycle consisting on an acceleration phase (limited to $0.5\,m/s^2$) followed by constant speed driving is used, since it resembles better the type of driving expected for these vehicles. The final result is however the same type of energy consumption maps as a function of road slope and average speed.

To preserve the life of the batteries in the vehicles, charging and discharging power must be limited. This limitation depends mostly on the capacity of the battery for a given battery chemistry. Additionally, the maximum power limitation imposed by the actual charging station must be considered. In order to have an accurate estimation of the charging times, a battery charging power profile has been implemented in the model (see Fig. 3). Depending on the State of Charge (SOC) of the battery when the vehicle arrives to the charging station, the charging power delivered will be limited as follows: 1.75 C between 0 and 50% State of Charge (SOC), 1.25 C between 50 and 75% SOC and 0.5 C between 75 and 100% SOC, where C (in kW) is the power needed to charge / discharge the battery in 1 hour - i.e. C is the battery capacity expressed in kW. This charging profile is based on publicly available data from Tesla Model 3LR users [7] since this is considered state-of-the-art battery technology, although at the time these charging events were logged, Tesla superchargers were limited to $120\,kW$.

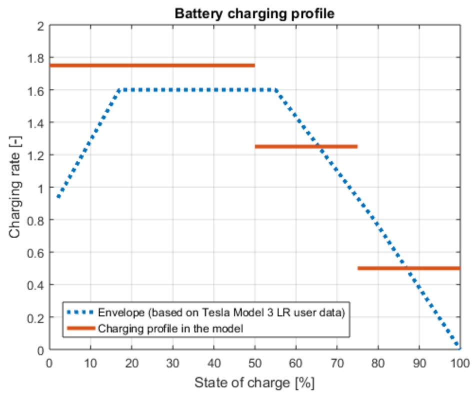

Figure 3: Charging profile implemented in the model as a function of the battery state of charge.

III. Preliminary Results

Once the model is solved, several results can be extracted and visualised for an easier interpretation. This section shows some examples of the results that can be obtained from the model.

A. *Energy consumption per km of road*

This is one of the most immediate results coming from the model. The energy consumed per kilometre of road is a good indication of the traffic intensity and could be helpful when sizing and placing charging infrastructure, both static (the more traditional charging stations) and dynamic (charge-while-driving, also called Electric Road Systems). Figure 4 presents the results obtained for the whole network as well as around the city of Gothenburg.

It is interesting to see how the major roads forming a triangle between the three largest cities in Sweden (Malmö, Gothenburg and Stockholm) are those with the highest energy consumption per km. These are the roads not only with the highest traffic volumes, but also with a larger fraction of heavy vehicle traffic compared to the average. Zooming in over the city areas (e.g. Gothenburg in Fig. 4, bottom) the effects of congestion can be appreciated. Although in the simulation all vehicles are electric and thus very little energy is consumed for traction when moving slowly, the effect of the auxiliary loads, modelled as a constant power demand is visible. This phenomenon can also be seen in the upper plot of Fig. 4, where the energy consumed per km increases at low speeds.

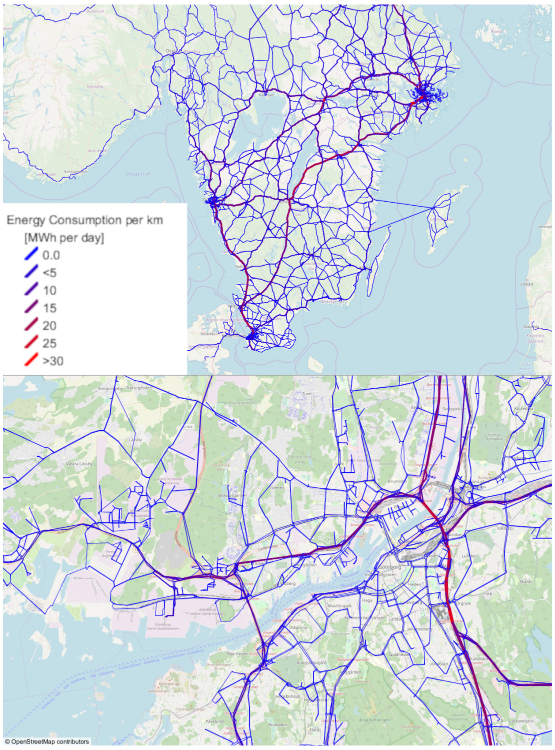

Figure 4: Energy consumption per km of road in the whole network (top) and around Gothenburg (bottom).

B. Charging infrastructure density

One interesting application of the model is to assess the need for charging stations and estimate the required density, location and power rating of these. Although a full optimisation of the charging infrastructure deployment at a country level is too large a problem to be addressed in this study, a first simulation is conducted in order to illustrate the capabilities of the MATSim model. In this example, fast DC-charging stations and overnight charging at home are the only charging modes available. All vehicles are assumed to be fully charged at the beginning of the day. A total of 2506 charging stations are considered, corresponding to the number of conventional fuel stations existing in the country. In each of these, there are 10 charging points for passenger cars and 2 for heavy vehicles, totalling 30072 charging plugs. However, these numbers are by no means optimised and further investigation with the model reveals that of those, only 4720 (3796 charging points for passenger cars and 924 for heavy vehicles) are actually required to meet the charging demands with minimum waiting times. Since the model only accounts for 10% of the population, the results should be multiplied by 10, resulting in 37960 charging points for approximately 5 million passenger cars in Sweden (1 charging point for every 130 cars). As an example, Figure 5 shows the utilisation of one of these charging stations during the simulation.

Nevertheless, this is still a preliminary estimation since many variables remain to be investigated. For example, the location of the EV charging stations in this study remains

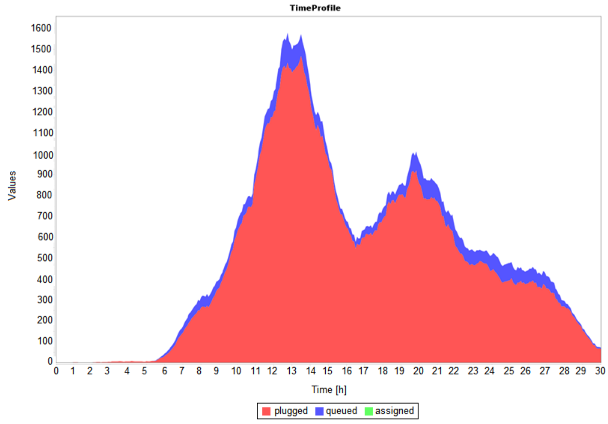

Figure 5: Charger utilisation over one day in the MATSim simulation.

the same as that of conventional fuel stations, the number of charging plugs of each type per station for the initial simulated case is fixed regardless of its geographical location (the final estimation of 47200 charging points is not uniformly distributed, since the less utilised charging spots have been eliminated) and a simplified representation of the fleet with just four vehicle types has been used.

C. Charging infrastructure dimensioning

The previous case with only static charging stations at the same location as conventional fuel pumps is simulated again, although this time there is no restriction on the number of vehicles that can charge simultaneously at each station. The two upper plots in Fig. 6 show the energy supplied by the charging stations during one day aggregated to 30 (top) and 50 km (medium).

The model is also able to output the power delivered by each station with a 1 second resolution. The bottom plot in Fig. 6 shows the charging power profile for the most utilised station aggregated to 5 minutes for clarity. This information is essential when dimensioning the corresponding charging station, as well as when assessing the impact on the power grid and the potential need for supporting measures such as grid reinforcing or local battery storage units.

Looking at the upper plots in Fig. 6, the areas with the most used charging stations in the country can be identified. A logical result when comparing these plots with the upper plot in Fig. 4 is that those stations located along the roads with the highest energy consumption deliver more energy. It should be noted that the areas located at the country borders, in the main roads to Copenhagen and Oslo present abnormally high energy values due to the way the model is initialised: there are vehicles starting their journey in Denmark and Norway with a full battery but there are no charging stations implemented outside Sweden, so when they arrive to the border their batteries are fully emptied and they use the first station available to recharge. This is particularly evident

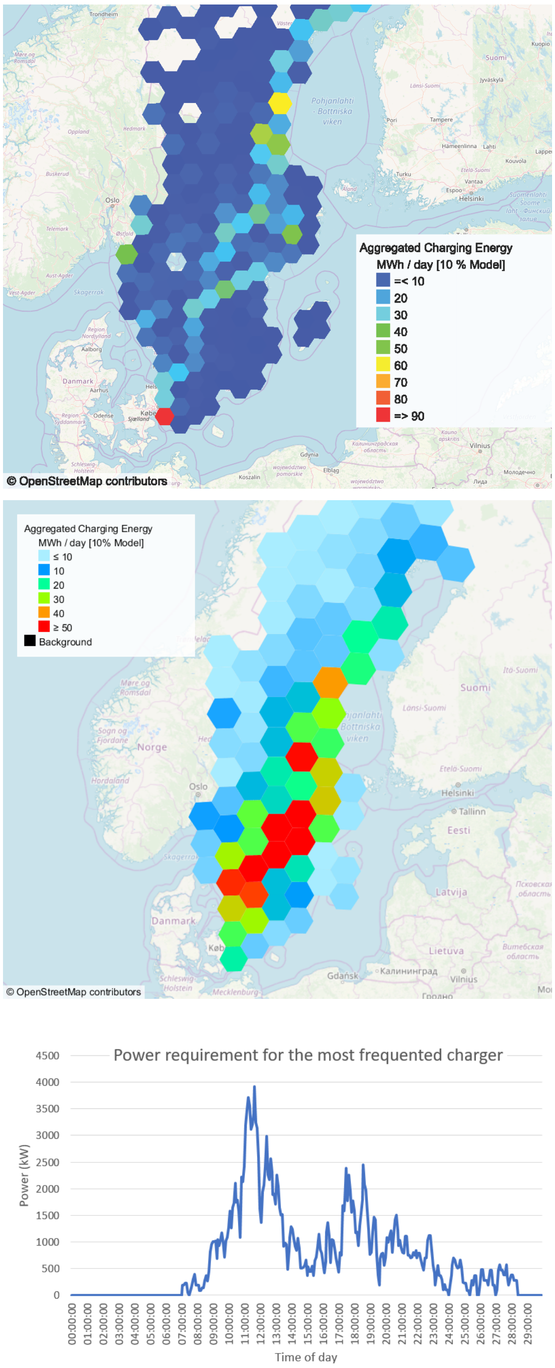

Figure 6: Energy consumption delivered by the charging stations aggregated in 30 km (top), 50 km (medium) and power demand for the most used station in Sweden (bottom).

in the upper plot (30 km aggregation level) and it is somewhat diffused with a larger aggregation area. There are also some areas in the east coast north of Stockholm - around Gävle and Hudiksvall - with a high energy output. While that particular section of the E4 road is not the most trafficked in the country, it is nonetheless heavily used and the density of charging stations (assumed to be the same as conventional fuel pumps) in that area is lower than in the southern part of the country. Focusing on the most used station (located around Hudiksvall, in the yellow area in Fig. 6, top), in order to cover its peak demand almost 40 MW are needed - 4 MW in the 10% model as shown in the bottom plot of Fig. 6. However, that peak power is only needed for a short time, with the average power delivered by that station over 24 hours being 8.6 MW instead. Hence, it will not be economically effective to dimension the charging station to the peak power level. Designing the station with a lower power rating will result in queues during peak-usage times if the excess demand is not covered by other nearby stations. In a more comprehensive study, the proposed MATSim model can be used to analyse how the degree of utilisation of the different charging stations, indicated for example by the ratio between the peak power and the average power delivered over one day, could be improved by different strategies such as varying the electricity prices, or using connected services (e.g. making the drivers aware of the availability of charging stations before hand, giving them the possibility to book a charging spot, etc.). These strategies are likely to result in the redistribution of vehicles among charging stations, thus improving their utilisation. It is worth pointing out that the simulated case represents an average day when it comes to traffic intensity. The expected power demand on a traffic intense day, such as a national holiday, is likely significantly higher than the one considered, and will impose more demanding design specifications. The analysis of such extreme cases is left for future work.

IV. Conclusions

This article presents a Multi-Agent Transport Simulation (MATSim) model of Sweden, depicting most of the long-distance trips nationwide, with the objective of analysing the impact of charging infrastructure deployment in the transport system as well as supporting systems such as the power grid. This type of models represents each vehicle in a reduced-scale fleet, providing very detailed information about all relevant aspects of each trip, including the decision processes related to the charging of the batteries, i.e. when, where and for how long to charge during a long distance trip depending on the availability of charging infrastructure and its characteristics. For this reason, a MATSim model is a very useful tool when deciding which type of charging infrastructure suits best the traffic demands at certain locations, as well as when sizing such infrastructure. A first example of such application is shown in this paper to illustrate the model's capabilities.In addition, MATSim simulations could serve as a basis for many other studies such as cost comparisons between different scenarios, assessment of the impact on the power grid, the effect of electricity pricing strategies, the impact of different connected services or even the feasibility of vehicle charging prioritisation schemes under limited resources or emergency situations.

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