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## Determining electric vehicle charging point locations considering drivers' daily activities

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### Abstract

In this paper the daily temporal and spatial behavior of electric vehicles (EVs) is modelled using an activity-based (ActBM) micro-simulation model for Flanders region (Belgium). Assuming that all EVs are completely charged at the beginning of the day, this mobility model is used to determine the percentage of Flemish vehicles that cannot cover their programmed daily trips and need to be recharged during the day.

Assuming a variable electricity price, an optimization algorithm determines when and where EVs can be recharged at minimum cost for their owners. This optimization takes into account the individual mobility constraint for each vehicle, as they can only be charged when the car is stopped and the owner is performing an activity.

From this information, the aggregated electric demand for Flanders is obtained, identifying the most overloaded areas at the critical hours.

Finally it is also analyzed what activities EV owners are underway during their recharging period. From this analysis, different actions for public charging point deployment in different areas and for different activities are proposed.

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## 1. Introduction

By 2030, it is forecasted that the global energy demand will increase by 50% with a corresponding increase in CO<sub>2</sub> and greenhouse gas (GHG) emissions, because most of this energy demand will be met using fossil fuels<sup>1</sup>.

In order to reduce their external energy dependence and also for environmental reasons, governments around the world are promoting different actions to reduce their fossil fuels consumptions<sup>2-6</sup>.

EVs are more efficient than equivalent conventional internal combustion engines (ICE) vehicles<sup>7</sup> and generate lower GHG emissions, although this reduction varies from one country to the other depending on their particular electricity generation mix<sup>8</sup>. An additional benefit of EVs is the improvement of the air quality and noise in the cities. But EVs have also three important barriers: their total cost (mainly due to the battery cost), the time needed to be recharged and the most significant impediment: their limited range.

Public policies have been mainly focused at two different features of the EVs: firstly, the increment of the demand of these types of vehicles through the establishment of fiscal incentives<sup>9-12</sup>, free parking in the city center<sup>13</sup>, avoiding congestion charge<sup>14</sup>, etc. and, secondly, providing public charging infrastructure which is critical for the growth of the EV market and to avoid range anxiety<sup>15</sup>.

Charging points in home are inexpensive and public authorities can support their installation providing a line of credit to owners of EVs<sup>16</sup>. By contrast, quick charging station requires an important investment of several hundred euros<sup>17</sup>. Therefore, it is important to assist public entities to allocate public charging infrastructure efficiently.

There are different approaches in the literature to determine the charging point locations for electric vehicles: Dong et al.<sup>17</sup> develop an activity-based system for electric vehicle charging infrastructure deployment, but considering only three different type of activities: at home, at work and other situation. Charger points are installed in the most popular destinations and authors use a genetic algorithm to determine the more convenience type of charger to be installed under limited budget constraint, minimizing the total number of interrupted trips. The paper considers neither the variable electricity price nor the optimal time instant to recharge the EVs. Frade et al.<sup>18</sup> develop a model to locate a certain number of charging stations maximizing the demand covered for a given distance in Lisbon (Portugal). Ge et al.<sup>19</sup> present a method for locating and sizing the charging station based on the minimization of the users' loss on the way to the charging point, using genetic algorithms, but no consider variable electricity price. This reference does not use any information to estimate the real mobility behaviour. Wang et al.<sup>20</sup> present a multi-objective planning for charging stations taking into account the actual location of the gas stations, road map, the location of the distribution transformers in the electric grid and the location of public facilities such as hospitals. In this case, no description of the optimization function or algorithm is shown.

In order to minimize the impact of EVs charging on electric grid, these vehicles will be charged at low power during the night off-peak periods, filling up the load curve and reducing the load peaks. Therefore, in the first stage of EV deployment, most of the vehicles will be charged at home during the night and the public charging network will be used occasionally<sup>21</sup>.

In this paper, several aspects related to electric mobility are analyzed: firstly, the total percentage of ICE vehicles that can be replaced by EVs without modifying the daily mobility behavior is determined.

Assuming that only a small percentage of the EVs will be recharged during the day to complete their daily schedule, an optimization algorithm to charge these vehicles with minimum cost is developed. This charging process will increase the electric demand in different TAZs. An evaluation of the most overloaded TAZs and the type of activities that the owners are performing during this charge is presented, allowing proposing different public actions to promote EVs.

In Section II, a brief description of the activity-based model and the main assumptions related to the vehicle consumption, battery capacity and variable electricity price are shown. Section III describes the optimization algorithm run by each driver to determine the best time period to recharge the vehicle at minimum cost. Results are presented in Section IV and the main conclusions and discussions are described in the final section.

## 2. Activity-based model and assumptions

### 2.1. Activity-based model

An ActBM is microsimulation model that predicts the daily scheduled activities for each member of a synthetic population. In this work, FEATHERS model<sup>22</sup> is used to generate schedules for a given day-of-week for Flanders region (Belgium). This model is based on a synthetic population containing socio-economic information extracted from census data, a set of traffic analysis zones (TAZ), the land-use information of each TAZ, the impedance matrices of travel time and distance and finally a set of decision trees resulting from a data mining process on travel surveys<sup>23</sup>. The sequence of decision trees is used to sample consecutive agenda construction and travel related decisions taken by each individual.

The model determines, for each activity, the following information: activity type, start time, duration, location, duration for the trip to reach the activity location and the transportation mode used.

It is assumed that all EVs are charged during the off-peak periods and their batteries are completely full at the beginning of the simulation. Each individual of the model starts its agenda at three o'clock in the night with a fully charged battery and finishes at three o'clock the next morning.

### 2.2. Main assumptions

The EV considered in this analysis is a Nissan Leaf<sup>24</sup>. This car is a 5 door hatchback pure EV which uses an 80 kW synchronous motor, powered by a 24 kWh lithium ion battery. The battery capacity of this vehicle is representative of the current EV models<sup>25</sup> (BMW i3: 22 kWh, Citroen C Zero: 16 kWh, Ford Focus BEV: 23 kWh, Renault Zoe: 14.6 kWh, Tesla S: 60-80 kWh). Its range is 160 km under US LA4 city driving schedule, corresponding to 0.15 kWh/km<sup>24</sup>. In this work a more conservative value of 0.179 kWh/km has been used in the simulations.

There are two types of AC and one type of DC charging stations: Level 1 charger, using a standard 240 V voltage, 16 A, 3.3 kW, is found in an ordinary household outlet. The second type, Level 2 AC 7 kW-22 kW chargers are (one or three-phase) semifast chargers and are suitable for commercial buildings. Finally, Level 3 DC 50 kW fast chargers can charge a car battery about 80% in just 15-30 minutes<sup>26</sup>. Depending on the available public budget for charging infrastructure, different types of chargers may be installed. Dong et al.<sup>18</sup> have determined that with limited budget, it is preferred to install more low power chargers than fewer quick chargers in a particular region. Noting that only a small fraction of EVs will be recharged during the daily activities and observing that the average type of charging points currently installed in Flanders region<sup>27</sup> is Level 1, a 3.3 kW charger points will be selected.

The electricity price has been taken from the webpage of the Belgian Electricity Market regulator, BELPEX<sup>28</sup>, for an ordinary spring day. This price is variable and changes hourly.

## 3. Charging optimization algorithm

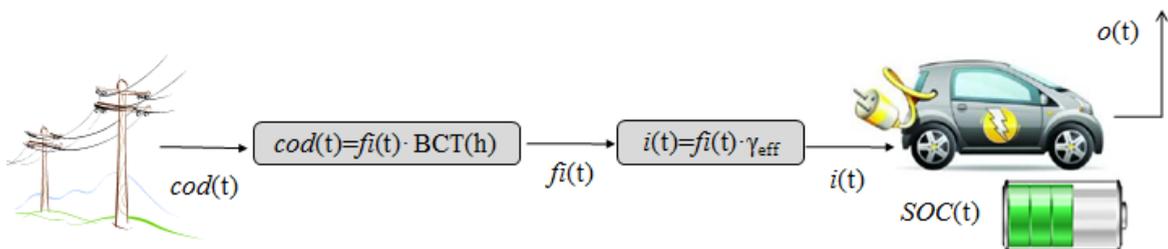


Fig 1. Charging scheme.

Considering the scheduled activities of each agent and taking into account the average consumption defined above, some vehicles are not able to accomplish all daily trips without intermediate recharging. For this set of vehicles it will be necessary to determinate when and where they must be optimally recharged to fulfil their agenda. Vehicle owners

will optimize their charging schedule according to the hourly electricity price and considering their mobility constraints given by the FEATHERS model.

Figure 1 shows the energy flows in the charging model, based on Alvaro et al.<sup>22</sup>. When the car is driving, the energy stored in its battery is discharged. Vehicles should charge according to an optimal schedule that has to consider the agent's activity agenda and a time-dependent electricity price.  $BCT(t)$  is vector whose components are equal to 1 when the vehicle is stopped and 0 when is driving. Table 1 describes the different variables and parameters (with their nominal values) considered in the system. No value has been specified for the variables of the optimization.

The optimization problem for each vehicle is defined in equations 1-6:

$$\min [cod(t) \cdot PEX_{supply}(t)] \quad (1)$$

Subject to the following restrictions:

$$SOC_{min} \leq SOC(t) \leq SOC_{max} \quad (2)$$

$$0 \leq i(t) \leq C \cdot CR \quad (3)$$

$$SOC(t) = SOC(t-1) + i(t) - o(t) \quad (4)$$

$$i(t) = fi(t) \cdot \gamma_{eff} \quad (5)$$

$$cod(t) = BCT(t) \cdot fi(t) \quad (6)$$

$$SOC(t), cod(t), fi(t), i(t) \geq 0$$

Table 1. Optimization model variables and parameters.

| Description                    | Symbol            | Value       | Unit  |
|--------------------------------|-------------------|-------------|-------|
| Energy hourly price            | $PEX_{supply}(t)$ | [ $PEX_i$ ] | €/kWh |
| Battery capacity               | C                 | 24          | kWh   |
| Energy extracted from the grid | $cod$             |             | kWh   |
| Charge input to the vehicle    | $fi$              |             | kWh   |
| Charge energy to the battery   | $i$               |             | kWh   |
| Discharged energy (driving)    | $o$               | [ $o_i$ ]   | kWh   |
| Minimum charge rate            | CR                | 0.1375      | -     |
| Charge efficiency rate         | $\gamma_{eff}$    | 0.95        | -     |
| Minimum allowed SOC            | $SOC_{min}$       | 5           | %     |
| Maximum allowed SOC            | $SOC_{max}$       | 100         | %     |
| Initial SOC                    | $SOC(0)$          | 100         | %     |
| Conn./Discon. Vector           | $BCT(t)$          | {0,1}       | -     |

The objective function (1) minimizes the charging cost. Constraint (2) sets the limits for the battery state of charge (SOC) in each time slot and constraint (3) represents the battery charging limit. Equation (4) describes the SOC time evolution due to charging and discharging processes. Efficiency is considered for battery charging through equation

(5). The vehicle's availability to be charged is given by equation (6). Finally, variables are defined as positive to guarantee that energy input is always positive.

GAMS® and Cplex Solver optimizer have been used for solving the individual problem for each agent. Due to the large number of existing equations, an interface was programmed in Matlab® in order to write the problem equations and read and analyze the results.

#### 4. Results

The vehicle mobility data extracted by the FEATHERS model is firstly used to check which percentage of drivers could use an EV without changing their current daily mobility behavior. That is, which vehicles, recharging at every moment they are plugged in, could fulfil the requested activities, supposing that chargers are always available at each moment and at every location at the rate power of the electric vehicle.

There are 1,141,735 vehicles driving around Flanders region daily. Assuming an average consumption of 0,179 kWh/km, this number is divided in three different sets: set *A* is composed by vehicles that can cover the daily schedule without intermediate charging. In this case, vehicles will be charged at home during the night. 81.18% of the vehicles belong to this set (926,983 vehicles).

Set *B* represents those vehicles that can finish their daily schedules, performing an intermediate recharging. This charging will be done, taking advantage of the time period that the car is stopped because its owner is performing a particular activity (at home, at work, etc.). Therefore, the owner does not change his/her mobility behavior. There are 123,580 EVs in this set (10.8%).

Finally, set *C* represents those vehicles which are not able to complete their daily schedule without modifying their mobility behavior because they will require stopping during a trip to be (fast) recharged. They represent 8% of the total number of vehicles (91,272 vehicles).

Figure 2 shows a histogram with the total amount of additional energy requested by the vehicles that perform intermediate recharges to fulfil their daily schedules. It is shown that most of the vehicles require a small battery capacity increment to finish their daily schedules without intermediate charging. For example, with an increase of 1 kWh of battery capacity (an increase of less than 4% of current capacity), 11% of these vehicles (from set *B*) would not need this intermediate recharge (13,593.8 vehicles) and they could be assigned to *A* set. Moreover, if this increase grows to 5 kWh (an increase of 20%), the number of vehicles that do not need intermediate recharges would increase to 50% of set *B*. (61,543 vehicles).

The following step is to solve the optimization problem for each vehicle requiring intermediate charging. Figure 3 shows the total aggregated energy consumption demanded by the EVs during their optimal intermediate charging for all TAZs, the time normalized dependent electricity price and the total normalized number of EVs that are moving per minute during the day under study.

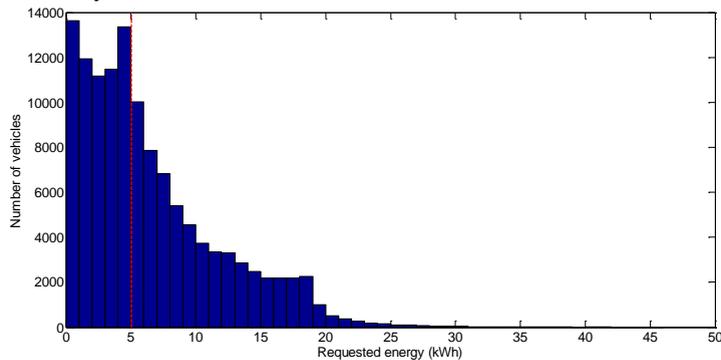


Fig 2. Additional energy required by vehicle.

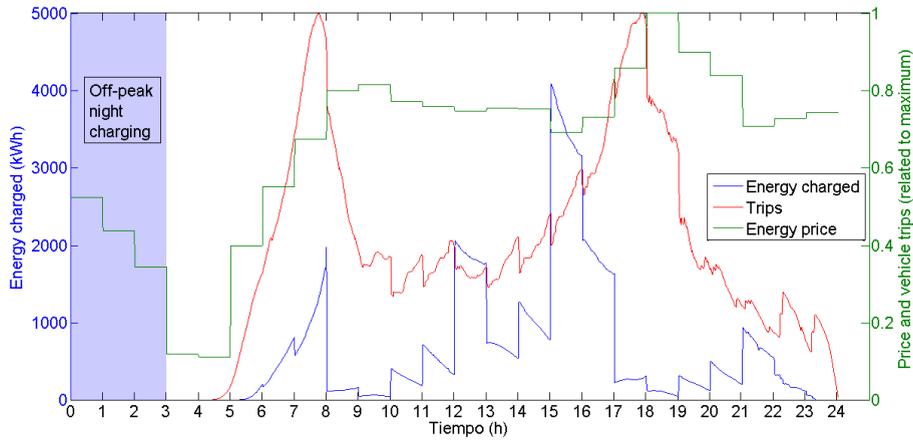


Fig 3. Energy consumption price and schedule dependence.

It can be noticed that at the beginning of the day most drivers have not started their activities, so they cannot profit from early low electricity prices, because the batteries are completely full. Vehicles start to be driven at 4:30-5:00 and the number of charges starts to increase as soon as vehicles arrive at their morning destinations. The number of charges grows until 8:00, when electricity price largely increases. Energy charged remains at low levels until 12:00, where the price reaches a local minimum. At 15:00 the electricity price is at the lowest point; therefore, most of the vehicles recharge at this time. At the next hour the price is also relatively low, but due to increase in the number of trips the energy charged remains at levels close to those at 12:00. Since price is high and the number of remaining trips is low, the energy charged in the following hours is at a reduced level. However, at 21:00, due to a new local minimum in electricity price, the energy charged increases again.

Another aspect analysed in this work is the number of charges performed by EVs and the total energy demanded in each TAZ necessary to cover the EVs charging consumption. In figure 4, the total energy demanded and the number of charges by zone due to the charging strategy explained in Section III are presented. It is shown that the energy demanded is not spread homogeneously along Flanders region and there are some zones with higher electric demand than others. That is, there are zones which are more adequate for installing public charging infrastructures because, at them, the density of parked vehicles, with need to charge at moments when electricity price is lower, is higher.

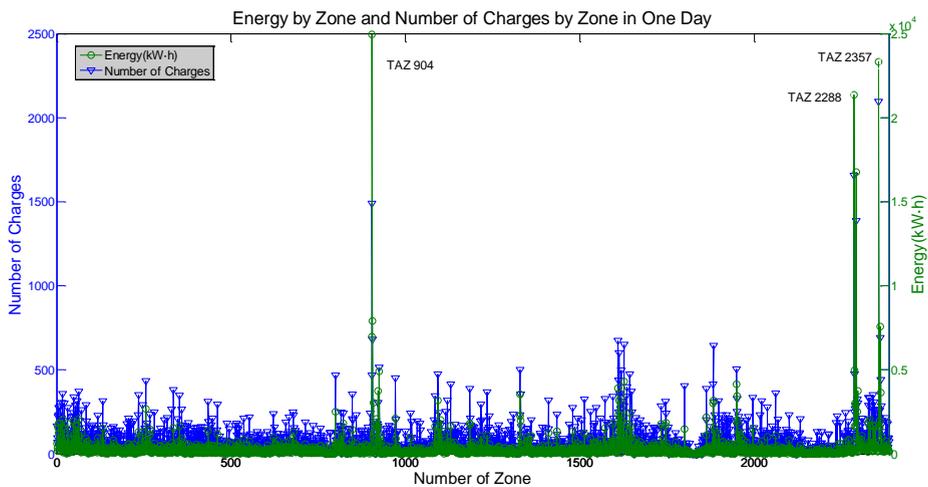


Fig 4. Number of charges by zone and Energy demanded by zone.

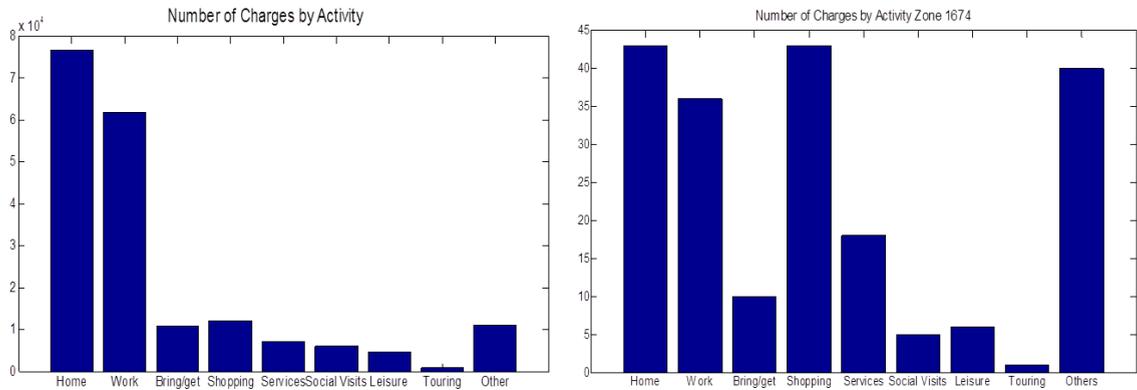


Fig 5a. Number of charges when the driver does a particular activity, on the whole Flanders region. Fig 5b. Number of charges when the driver makes a particular activity, in Zone 1674 and one day.

It has also been analyzed which activities are being made by the drivers while the vehicles are charged. Figure 5a shows a bar diagram with the number of total charges made while drivers are performing a particular activity, for the whole Flanders region. As it is shown, most of the charges are taking place when the vehicle users are at home or at working.

However, a more detailed analysis has been done studying the relationship between activity and charging for each TAZ, showing additional results. This analysis that depending on the studied zone, most charges could be done while the vehicle users are doing another activity not related with working or being at home. One example of that is depicted in Figure 5b, in which the number of charges taking place when EV owners are shopping and others are significant.

## 5. Conclusions and discussions

Considering the daily activities in Flanders region, 81% of drivers would only require night charging to handle their schedule using an EV. If intermediate slow charging infrastructure is available, this number increases up to 92%.

The additional average energy level demanding for each vehicle to complete their daily schedule is low (around 1-5 kWh), therefore it is possible to increase the total number of vehicles that can complete their daily trips without intermediate recharging promoting to EV car manufacturers to increase the nominal battery capacity in 5%-20%. According to Pike Research report<sup>29</sup>, Li-ion batteries prices will drop by more than one third by 2017, helping to increase the nominal battery capacity without increasing the total vehicle costs.

The lowest electricity price after most vehicles start to move is reached between 15 and 16 hours, and a significant increase of electric demand is observed in the simulations during this period.

Charging points cannot be homogeneously distributed across Flanders. There are some TAZs that are more overloaded than others and they will need more charging points.

Analyzing the activities done during the charging periods, it is shown that most of the charges are performed when the driver is at home. In this case, no additional infrastructure will be required because owners already have a charging point installed at home. The next most important activity is work. Therefore, it is important to promote the charging points at the workplace through public funding. It has been observed that in some particular TAZs the activities during the charging process are slightly different. That result requires that infrastructure policies consider the mobility particularities of each area.

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