Service for optimization of charging stations selection for electric vehicles users during long distances drives: time-cost tradeoff

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Abstract. One of the weighty curb to electric vehicles (EV) acceptability is their constraints when performing long-distance trips. Even if improvements made on fast charging technology enable to recover up to 300 km range in 20 minutes, the low density of this kind of infrastructure and the variability in their availability can lead to significant waiting times for users. In this context, it is useful to provide users with information about the availability of charging stations to facilitate the use of EVs. In this article, we present a vehicle/infrastructure communication system. EVs ask charging stations for estimated waiting times at a specific time. Stations calculate these estimates based on notifications of intention to charge received from other vehicles. Thanks to this information, vehicles will be able to optimize their journey. This system has the advantages of being easily scalable because it is distributed, simple and only require the sharing of little personal information. However, the stations on the route may have different charging powers and prices. This raises the question of the criteria for optimizing these trips, depending on whether users favor the cost or the duration of the trip. In this article, we examine this tradeoff using multi-objective optimization and Pareto fronts, as well as the impact of such a communication system on recharge decisions.

1. Introduction

In the Intergovernmental Panel on Climate Change special report “Global warming of 1.5°C”, the first chapter [1] highlights the consequences of global warming of more than 1.5°C and links it to greenhouse gases. The second chapter [2] demonstrates the need to return to a zero-carbon footprint as soon as possible and estimates the remaining carbon credit for the temperature to exceed preindustrial temperature by no more than 1.5°C. This emission-reduction requirement is to be applied in all emitting sectors, in particular in the transport sector [3].

Within the sector, we must consider several strategies: the optimization of existing solutions as well as the use of alternative energy storage and propulsion systems. The promotion of battery electric vehicles, which do not emit any gas when driving (for a tank-to-wheel evaluation), appears promising. However, a broad approach is needed through life-cycle analysis and well-to-wheel studies. This type of study, presented in [4] and [5], clearly shows the potential reduction in greenhouse gas emissions,
while pointing to the battery production phase and the electricity production mix used, as having a substantial impact on the final balance.

The advantage of electric vehicles (EV) in terms of greenhouse gas emissions demands further study of its acceptability and economic viability. First, EVs are adapted to city trips, with high efficiency, lower noise, and air pollution than thermal vehicles [6]. Major global cities are promoting its use by delineating low-emission areas. The batteries of these vehicles also permit another use with vehicle-to-grid (V2G) technologies: electric vehicle fleets can offer a frequency or voltage regulation service by extracting or supplying electrical power to the grid in a pilot-controlled way [7]. However, the primary remaining obstacle to the deployment of this technology is the ability to store energy: batteries remain expensive, heavy, and bulky (even if the mass and volume energy densities are increasing), resulting in high purchasing costs and low inherent autonomy for use over long distances. Fast charging, with powers between 50 and 150 kW, provides a solution for a growing number of vehicles.

The deployment of charging infrastructure is hence the prerequisite for the spread of electric vehicles. A well-established charging network increases effective electric vehicle range, relieving range anxiety, and reducing inconvenience in the charging process. In [8], Funke et al. compare the utility of investing in fast-charging infrastructure or longer battery ranges, pointing out the cost efficiency of an infrastructure increase.

However, heavy traffic will likely saturate the charging stations. This situations can lead to long waiting times. Also, the operators of these stations may charge different prices, which will depend in particular on the maximum power delivered.

This leads us to our research question: how can electric vehicle users optimize their travel time and cost on long-distance journeys? In this article, we will present a communication system between vehicles that permits this optimization, and then we will study its performance.

2. Methodology

2.1. Communication schema

The quality of a communication system depends not only on its performance but also on its ability to be easily deployed. Let us present all the constraints that we must consider. First, such a system must rely on wireless connections between vehicles, charging stations, and a central server, called V2X communication. These connections can be based on mobile networks or WLAN, the first technology operating for long distances, and the second one for local communication (less than a few kilometers). The risk of dead zones and the latency of these communications demands that we set apart solutions requiring continuous or rapid exchanges.

A centralized server gathering the requests of all users allows for finding optimal solutions, however, its implementation, reliability, and required computing power can be a significant hurdle, especially if the system were to be deployed on a large scale. A distributed system, without a centralized server, eliminates this problem. Users can also be reluctant to share personal data, such as destination, average speed, or state of the vehicle.

Finally, constraints of robustness and cohabitation must also be considered.

Considering all constraints mentioned in the previous paragraph, figure 1 describes the innovative communication schema that we propose. Communications between EVs and charging stations use mobile networks. This process, from the vehicle point of view, follows five steps:

1. The EV calculates several possible combinations of stops, with different stations and amounts of energy to be stored to guarantee to reach its destination. This computation is done on the vehicle CPU resources.
2. The EV requests the expected waiting time at charging stations at a specific arrival time, for all combinations.
3. Charging stations (CS) respond to this request thanks to an updated arrivals list.
4. The EV can now choose the quickest charging plan, it then sends a notification to the selected stations, including a given arrival time with an estimated charging duration.

5. The EV remove solutions that do not correspond to what are no more feasible. For example, if it already passes by a given station without stopping, it can remove solutions using this station.

6. The vehicle repeats the cycle composed of the steps 2 to 5, every period $T$.

The vehicle will first do this cycle when starting the trip, before entering the highway. It will then refresh according to a period $T$. We note $T_{adv,n}$ the time between the beginning of the trip and the moment when the vehicle enters the highway. Stations will compute expected waiting times using notifications sent by all the vehicles.

From the station point of view, the system is composed of a device that must receive requests of waiting time estimation and notification of recharge, to then compute scheduled waiting times.

2.2. Charging price

We assume that charging sessions may have different prices depending on the charging station. The driver will, therefore, have the choice between routes with different duration but also different prices. In order to compare them, we introduce the compromise variable $X$, varying between 0 to 1, as well as $Sol_{perf,i}$, the performance of the solution $i$ defined by equation (1). $Sol_{cost,i}$ (€) and $Sol_{duration,i}$ (min) respectively represent cost and duration of solution $i$.

![Figure 1. Communication flow chart from the vehicle point of view.](image-url)
\[
S_{\text{perf},i} = X S_{\text{cost},i} + (1 - X) S_{\text{duration},i}
\]

This variable \(X\) is linked to the drivers’ value of time by the following relation:

\[
X = \frac{1}{1 + \text{value of time}}
\]

There are several types of billing for recharging sessions: flat rate (€/session), price per recharging time (€/min), or price proportional to the charged energy (€/kWh). We use a price proportional to the energy, more representative of the cost borne by the recharging operator. The recharging price per kWh is assumed to be the same for all users at one charging station, even if the vehicle does not support the maximum power delivered by the terminal and charges at a lower power level. We then used Ionity network recharge prices [9] for the most powerful stations (0.8 €/kWh), and assumed that the cheapest ones were half of the most expensive (0.4 €/kWh).

2.3. Valuation method

To compare the behavior of the communication scenario, we simulate a traffic flow on a highway during one day. During these simulations, the following elements are fixed:

- Characteristics of the highway: position of the entrances and exits as well as the position, maximum power, number of charging points, and the price of the charging stations.
- A fleet of vehicles, with the characteristics of the EVs and their routes: origin and destination, departure time.

For a given situation, we vary \(X\), in order to reproduce several value of time of the users.

2.4. Scenarios comparison

We then compared the performance of this system with two other situations. In the following, we will thus compare three scenarios:

- Without communication scenario. This is the reference case, for which there is no coordination. It is the upper bound of the problem. Users make their choices according to the positions, powers, and prices of the charging stations, but without knowing in advance the waiting times.
- Optimal solution scenario. This is an offline search for the optimal solution. The algorithm considers all the journeys over a day. It then looks for the best distribution of vehicles between the different stations. This solution constitutes a lower bound to the problem. We use a differential evolution algorithm: this kind of algorithm uses a population of solutions and repeats a process of mutation, crossover and selection. However, this scenario is difficult to achieve in practice, as it requires high computing power and knowledge of all the characteristics of the journeys in advance. An adapted NSGAII algorithm is used for the computation of the pareto front in section 3.
- Communication scenario. It is the proposal for a communication structure between vehicles and stations, described in paragraph 2.1. It is an online and deployable algorithm. Trips are known by the drivers but not by the system (charging stations).

For scenarios with and without communication, we start by simulating the behavior of vehicles for \(X\) being zero and one. Each time we obtain an average cost and an average travel time. Then we search for intermediate solutions by dichotomy. After that, we will represent all the solutions found, as well as the Pareto front.
3. Application

3.1. Case study

The generated data represents the situation of a highway in a course of a day with 100 or 150 electric vehicles. The road has one way, 11 entrances and exits, and is 553 km long. It includes six charging stations, each with three charging points of 50, 100, or 125 kW maximum available power. Figure 2 displays their implantation. There are three types of vehicles in this simulation: urban, sedan, and luxury. Table 1 gives their respective characteristics.

We based our daily highway flow modeling on the data found in [10]. Figure 3 shows the average daily flow of vehicles entering the French A6 motorway in the Ile-de-France region in France in the year 2017. These are the data of highway entrances equipped with counting loops. It indicates an almost constant flow between 8 a.m. to 9 p.m. We also notice that the traffic during the night is more than three times lower than during the day. As we want to study crowded situations, we will focus on the daytime scenario. Therefore, we modeled the distribution of departure with the previous data, between 3 a.m. to 11 p.m. We choose entry and exits number randomly for vehicles, while imposing a minimum distance of 250 km.

We also used a uniform distribution for the state of charge (SoC) at departure in the 50%-100% range. SoC at arrival (when the car exits the highway) is required to be above 30%, and SoC when entering a charging station to be above 15%. EV are charged to a maximum of 80% or below.

| Entrance/exit | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|--------------|---|---|---|---|---|---|---|---|---|----|----|
| Charging station | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
| Power (kW) | 100 | 50 | 125 | 100 | 125 | 50 | 100 | 125 | 50 | 100 | 125 |
| Number of sockets | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| Price ($/kWh) | 0.6 | 0.4 | 0.8 | 0.6 | 0.8 | 0.4 | 0.6 | 0.8 | 0.4 | 0.6 | 0.8 |

Figure 2. Highway entrances and charging stations implantation.

Table 1. Studied vehicles characteristics.

| Car Type | Urban | Sedan | Luxury |
|----------|-------|-------|--------|
| Battery, kWh | 50 | 60 | 100 |
| Maximum charging power, kW | 50 | 100 | 125 |
| Consumption, kWh/km | 0.15 | 0.18 | 0.18 |
| Driving Speed, km/h | 110 | 130 | 130 |
| Generation probability | 0.3 | 0.6 | 0.1 |

Figure 3. Average daily incoming vehicle flow.
3.2. Pareto curves comparison

Figure 4 displays the time/cost compromise for the three scenarios with 100 and 150 vehicles. For the scenarios with and without communication, it displays all the obtained solution and the Pareto front, labeled as “Best”. In the following we will focus on points labeled (1), (2) and (3).

First, we can notice that the communication allows obtaining solutions close to those obtained by the differential evolution algorithm, overall range $X$. Moreover, there are not solutions too far away.

A the point for lower cost ($X=1$), the same solution is obtained with or without coordination. As waiting times are not taken into account, communication is not beneficial.

Second, without communication, a large part of the solutions is very distant from optimal solutions. As a result, communication can reduce the cost of travel by up to 10% for the same duration. This effect is even more visible in the situation with 150 EVs (figure 4(b)), which is more saturated, with a cost reduction up to 15% on equal time. We notice that the point in the pareto front for the lower time (label (1) in figure 4(a), $X=0$) leads to more expensive and slower solutions than if we slightly take into account the cost of recharging. Indeed, by optimizing time only, a large proportion of vehicles will want to recharge at the most powerful stations, which will saturate. Nevertheless, taking into account the cost of recharging, vehicles with only low maximum charging power will give priority to less powerful stations, which are also cheaper. In this way, there will be a better distribution between the stations. The solutions obtained minimizing the average time (label (2), $X=0.954$) are as good as or even better than with communication. However a priori the value of $X$ that allows this is not always the same. It may depend on the traffic and the highway. Moreover, this effect does not work if there are stations on the highway that are both more powerful and cheaper than others are.

Figure 4. Cost duration tradeoff for the three scenarios: a) 100 EV, b) 150 EV.

Figure 5 shows the use of charging stations as a function of vehicle type for three cases shown in figure 4. Stations numbers are defined in figure 2. The first case represents the situation obtained when vehicles do not communicate and only optimize their travel time. It can be seen that stations three and five, the most powerful, have a high demand. This situation is sub-optimal in terms of time and cost.

The second situation is the best case obtained without communication. Urban vehicles, considering prices, chose to go to cheaper stations that offer the same recharge time (as the EV side always limits the charging power). This makes it possible to rebalance the frequentation between the different stations. This situation is close to the optimum time.

The communication algorithm obtains the third situation by prioritizing cost reduction. In this case, the cheapest stations are used first. The others are used by those who have no choice (for example, if their battery level does not allow them to go to another station) or by those for whom this saves a lot of time. Indeed, moving from situation 3 to cost optimization only reduces the average cost by only 2.4% while increasing the time by 19.5%.
Figure 5. Utilization of the 6 charging stations:
(1) No communication, time optimization only (X=0);
(2) No communication, lowest average time (X=0.954);
(3) With communication, mainly cost optimization (X=0.998).

The use of such a communication system can be extrapolated in more complex situations, such as situations with traffic jams, several possible routes, variable consumption and speeds. Those functions more advanced can be added by refining the calculation of charging plans, without modifying the structure of the system.

4. Conclusion
In conclusion, the research question of this article was to find a way for electric vehicle users to optimize their travel time and cost on long-distance journeys. We were therefore able to study a feasible means of communication between vehicles that allows us to find good cost/travel time compromises for long journeys in electric vehicles. This study also allowed us to show that taking into account the cost of recharging could reduce travel time and cost in situations without communication. This better distribution is only possible if the price of recharging increases with power. Later on, it will be interesting to study the robustness of such a system, for example when not all the travelers use it, and to carry out a cost-benefit analysis.

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