The Optimal Location of the Electric Vehicle Infrastructure with Heterogeneous Batteries in the Highways

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Abstract: The dynamic wireless charging makes the possibility of charging electric vehicles without contact and while it is in motion from the transmitters buried (segments and inverters) under the road. This technology is applied for homogeneous buses by the Korean institute of advanced technology (KAIST), called online electric vehicles (OLEV) (Jang, 2012). Our contribution in this work is to study the problem of locating wireless charging infrastructure on a long route between origin O and destination S, with heterogeneous battery vehicles. On the first side, each type of vehicle requires its allocation of segments in the road because of the heterogeneity of batteries, which increases the number of recharge transmitters in the highway; for this purpose, we search to minimize the infrastructure cost by reducing the number of segments and inverters. On the other hand, the activity of a recharge segment may be helpful for one vehicle and useless for the other since each vehicle type has its characteristics (autonomy, puissance, battery capacity). For this reason, we aim to minimize the use of the recharge transmitters for each vehicle type. We propose to model the problem as a mathematical problem and to solve it by CPLEX optimizer for limited instances.

1 INTRODUCTION

Since the previous years, the characteristics of electric vehicle (EV) batteries have improved considerably. For the same weight and similar volume, the quantity of energy available increased, which increases their autonomy, and it is sufficient to travel on daily trips (for small to medium trips). However, it is not enough for long journeys like the highway. It is characterized by a long distance between the origin and the destination, and the high speed of vehicles on this kind of road drains their battery very quickly.

Wireless charging (WC) is an effective solution for long journeys; since it can charge the batteries dynamically while the vehicle is in motion from a set of inductive cables and inverters placed on the road to meet the vehicle's charging requirements at all times. This technology makes it possible to transfer several tens of kilowatts over short distances (a few tens of centimetres) with good efficiency and safety for the human body if a correctly sized magnetic shielding is present. The advantage would thus be to recharge vehicles on the highway.

The WC system (WCS) is composed of EV and power transmitters (see figure 1). An inverter converts the DC power into high-frequency AC or voltage. After converting the alternating magnetic fields generated by an underground electric power line to electric power, a pickup coil installed on the bottom of the vehicle receives this electric power. The received power goes through a rectifier and regulator before arriving at the battery (Chun, 2014).

The WCS is an ideal solution for the highway, but the high cost of this technology limits the use only when the charge is needed. Many works presented the problem of locating a minimum cost infrastructure of electric vehicle induction charge. However, researchers considered the vehicle's batteries to be homogeneous. In reality, each vehicle battery has its characteristic, so our contribution is to find an optimal location of the electric vehicle infrastructure with heterogeneous batteries in the highways. The heterogeneity of vehicle batteries adds more difficulty to search for places of lack of charge because each type has its characteristics (range power, consumption, charging rate). It requires a mathematical study to find a minimum cost

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infrastructure that ensures the movement of each type of vehicle without remaining out of load by the minimum use of the segments for each vehicle type; this is precisely our goal to this work.

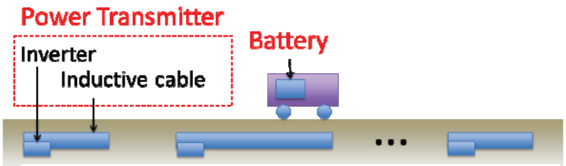

Figure 1: Wireless charging system

2 LITERATURE REVIEW

Wireless charging (WC) allows charging the vehicle's battery without contact, known as Wireless Power Transmitters (WPT), existing in two types. The first type is the stationary WPT, which presents a recharging mode from which the VE can be charged by induction when it is in stop mode. The use of this world is equivalent to the use of a charging cable, except that stationary WPT technology has the advantage of being practical and more secure for more details see (Young, 2016). The second type is dynamic WPT, which allows an EV to be charged by induction while it is in motion. The Korean Advanced Institute of Science and Technology KAIST has installed this technology on its campus to allow its buses to charge by induction while running called by one line electric vehicle (OLEV) (Jang, 2012).

Ko, Y. D. and Jang Y. J (Ko, 2014) introduced the concept of battery power that was instantly required. They introduced a mathematical model that seeks to minimize the cost of installing the power transmitters and the cost of the battery according to its capacity. They solved the model using the optimization algorithm for particle swarms. Jeong et al. (Jeong 2014) have added the impact of battery charging and discharge frequency on its life cycle.

Among the best-known works, we cite that of Young Jae Jang (Jang, 2012), who proposed a mathematical model to determine a compromise between the battery capacity of an EV and the location of the charge transmitters inductive on a fixed route a single path. They assumed that the bus travel speed is preset, and the batteries are identical. Liu and Song (Liu, 2017) studied the dynamic behaviour of this model using a nonlinear model solved by genetic algorithms. Young Jae Jang (Ko, 2014) compared the initial investment costs of three types of charging systems. The first type is stationary wireless charging (SWC), in which charging happens when the vehicle is parked or idle. The second type is quasi-dynamic wireless charging (QWC), which allows the charging when the car is moving slowly or in stop-and-go mode, and dynamic wireless charging (DWC), in which vehicle can charge even when it is in motion.

Nisrine Mouhrim et al. (Nisrine, 2018) do the generation of the multiple paths. They considered a multipath network between the origin and the destination station. They sought a compromise between the cost of installing the power transmitters and the cost of the batteries, which are assumed identical. Hassan Elbaz and Elhilali Alaoui Ahmed (Hassane, 2020) search for a compromise between the infrastructure cost and the battery capacity in a multipath network, round-trip.

Xiaotong Sun et al. (Xiaotong Sun et al., 2020) investigated the optimal deployment of static and dynamic charging infrastructure considering the interdependency between transportation and power networks.

3 PROBLEMS AND MODELING

3.1 Problem Description and Objective

We consider a highway of origin O and destination S, and a set of vehicles with heterogeneous batteries, and we seek to satisfy by the least cost its needs of the load during their journeys from O to the destination S by the allocation of the power transmitters on the road like a dynamic station (Fig. 2).

Figure 2: Highway with dynamic stations

We assume that the highway is divided into two zones, the 1st road zone without stations, and the 2nd that we will put the dynamic stations (Figure 2).

The 2ed zone is subdivided into several congruent segments, and we will consider each segment as a potential transmitter. If the charging is needed, the segment will be equipped with an inductive emitting cable plus an inverter or will fit only with an emitting cable, and if the loading is not needed, the segment will be inactive (see Fig. 4). We note that a single inverter can power a limited series of successive active segments.

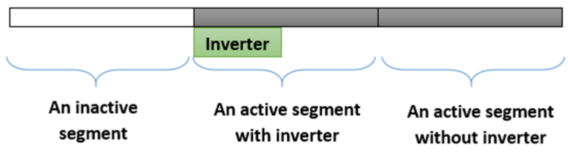

Figure 3: Types of segments

We search firstly to determine the minimum of active segments and inverters in the 2[ed] zone to meet the energy needs of vehicles.
On the other hand, each type of battery requires its allocation of the segments because of the heterogeneity of batteries; An active segment can be useless for one vehicle type and profitable for the other; for that, we search to minimize the number of segments used by each vehicle type.

3.2 Mathematical Model

We seek to model the problem as a mathematical problem with constraints. We present as follows a set of notations, data, constraints, and objective function. In this work, we assume that the fleet of vehicles has the same speed and acceleration on the highway, and the wireless charging system is capable of supplying each type of vehicle.

3.2.1 Notations and Data

As we mentioned earlier, we discretized the highway into segments of the same length; the first segment will be denoted by O, the last segment by f, and the other segments by g with $g \in \{O, \dots, f\}$.
Vehicles are considered to have a heterogeneous battery, let φ be the set of batteries and α the index of a type of vehicles with $\alpha \in \{0, \dots, |\varphi|\}$.

The infrastructure cost is composed of the cost of the recharge segments and the price of the inverters. Let C_{sgt} and C_{inv} respectively the unit cost of an active segment without an inverter and the unit cost per inverter.

The starting point of each vehicle type is O, we not that t_0 the arrival time of the fleet at the starting point of segment O. As mentioned earlier, the fleet of vehicles has the same speed and acceleration on the highway, so it will have the same time to arrive at the starting point of each g^{th} segment, which we note by t_g. We consider the following notations:

- I_{bat}^{α}: The battery capacity of vehicle α
- $T^{\alpha}(t)$: The energy supply rate of vehicle α
- $D^{\alpha}(t)$: The energy consumption rate of vehicle α
- I_{low}^{α} *and* I_{up}^{α}: Are the lower and upper limits of the battery level, respectively. These values have the following relationship. $I_{low}^{\alpha} = I_{bat}^{\alpha} \times \delta$ and $I_{up}^{\alpha} = I_{bat}^{\alpha} \times \beta$ with $\delta, \beta \in [0,1]$
- N_{inv}: The maximum number of the active segment in each series that can use one inverter

3.2.2 Decision Variables

The highway is subdivided into several congruent segments, and we search the minimum number of active segments and inverters into the road, that we define two decision variables X_g *and* Z_g such as:

$$X_g = \begin{cases} 1 \text{ if the } g^{th} \text{ segment is active} \\ 0 \text{ otherwise} \end{cases}$$

$$Z_g = \begin{cases} 1 \text{ if the } g^{th} \text{ segment has an inverter} \\ 0 \text{ otherwise} \end{cases}$$

Each type of vehicle has its character because of the heterogeneity of the batteries, so the use of the segments is different from a kind of vehicle to another; we then define the decision variable y_g^{α} such as:

$$y_g^{\alpha} = \begin{cases} 1 \text{ if vehicle } \alpha \text{ uses the segment } g \\ 0 \text{ otherwise} \end{cases}$$

Let $I^{\alpha}(t)$ be the amount of energy in the battery α at time t.

3.2.3 Constraints

1. We assume that vehicles start at the beginning of segment O with the maximum load I_{up}^{α}

$$I^{\alpha}(t_0) = I_{up}^{\alpha} \quad \forall \alpha = 0, \dots, |\varphi|$$

2. The remaining charge at the beginning of each segment must always be greater than the battery's minimum capacity

$$I^{\alpha}(t_g) + \int_{t_g}^{t_{g+1}} (-D^{\alpha}(t) + T^{\alpha}(t) \times \boldsymbol{y_g^{\alpha}}) dt \geq I_{low}^{\alpha}$$

$$\forall g = 0, .., f-1 \quad ; \quad \forall \alpha = 0, \dots, |\varphi|$$

3. Updates the remaining charge at the beginning of each segment.

$I^{\alpha}(t_{g+1}) = \min \{ I^{\alpha}_{up} \,;\, I^{\alpha}(t_g) \int_{t_g}^{t_{g+1}} (-D^{\alpha}(t) + T^{\alpha}(t) \times \boldsymbol{y^{\alpha}_g}) dt \}, \forall g = 0, \dots, f-1 \;\; \forall \alpha = 0, \dots, |\varphi|$

4. A segment g may be used by vehicle α only if it is active.

$$y^{\alpha}_g \leq X_g \qquad \forall \alpha = 0, \dots, |\varphi|, \quad \forall g = 0, \dots, f$$

5. A segment g is active if it is used by at least one type of vehicle.

$$X_g \leq \sum_{\alpha} y^{\alpha}_g \quad , \qquad \forall g = 0, \dots, f$$

6. A segment g cannot have an inverter unless it is active.

$$Z_g \leq X_g \qquad \forall g = 0, \dots, f$$

7. The start of each series of active segments must contain one inverter, and one inverter can only supply at most N_{in} active segments.

$$Z_g = (1 - X_{g-1}) X_g \quad ; \forall g = 0, \dots, N_{in} \qquad (1)$$

$$Z_g = \left(1 - \left[\sum_{k=1}^{N_{in}-1} Z_{g-k} \times \prod_{a=1}^{k} X_{g-a} \right] \right) X_g \qquad (2)$$

$$\forall g = Nin + 1, \dots, f$$

- For (1) if the segment g is active and its predecessor is active in this case, the segment g does not have an inverter because it belongs to an active series of length less than or equal to N_{in}, otherwise, if a segment g is active and its predecessor is inactive in this case the segment g will have an inverter.
- For (2), a g-segment can only contain one inverter: If g is the start of an active series (i.e., g is an active segment and its predecessor is idle). Or if g is prefixed with a longer active string than N_{in} segments.

3.2.4 Objective Function

We seek to minimize the cost of the infrastructure by reducing the number of active segments and inverters on the road (3). On the other hand, we search to minimize the segments used by each vehicle type (4). Therefore, we have two objectives to optimize.

$$\boldsymbol{Min} \left[\boldsymbol{C_{sgt}} \times \sum_{g=0}^{f} \boldsymbol{X_g} + \boldsymbol{C_{inv}} \times \sum_{g=0}^{f} \boldsymbol{Z_g} \right] \qquad (3)$$

$$\boldsymbol{Min} \sum_{\alpha \epsilon \varphi} \sum_{g=0}^{f} \boldsymbol{y^{\alpha}_g} \qquad (4)$$

4 PROBLEMS AND SOLVING

Our objective in this work is to build at the lowest cost a wireless charging infrastructure that ensures the movement of the heterogeneous fleet of vehicles without remaining out of charge by the minimum use of the segments for each vehicle type. The problem is transformed into an equivalent linear programming problem and solved with a CPLEX optimizer for a limited instance.

4.1 Transport Network Data

The instances used in this example serve only to validate the model because the CEPLEX optimizer can only solve a limited instances problem. It solves our problem with four types of vehicles and 30 segments. Tables 1 and 2 contain the energy supply rate, the energy consumption rate of each vehicle type, and the other data.

Table 1: Vehicles data

	Battery Capacity I^{α}_{bat}	The energy supply rate	The energy consumption rate
Vehicle 1	8,8	4.2	1,8
Vehicle 2	32,2	3	1
Vehicle 3	18,4	5	4
Vehicle 4	25	5.5	0,9

Table 2: Other data

Notation	Description	Value
C_{inv}	The unit cost per inverter	3000
C_{sgt}	The unit cost of an active segment without an inverter	800
N_{inv}	The maximum number of the segment in each series can use one inverter	4
δ	The lower limit coefficients	0.2
β	The upper limit coefficients	0.8

4.2 Results

We solve the problem for each one of the objectives because CPLEX can only solve mono-objective problems. For the first objective, we search to minimize the infrastructure cost, and for the second objective, we search to minimize the set of segments used by each vehicle type. Table 3 contains the results for each objective.

Table 3: Results for each objective

	Minimizing the 1st objective	Minimizing the 2sd objective
The number of segments used by the vehicle 1	18	12
The number of segments used by the vehicle 2	7	6
The number of segments used by the vehicle 3	23	21
The number of segments used by the vehicle 4	8	2
The infrastructure cost (The cost of segments + the cost of inverters)	36400	41000
The uses number of segments by vehicles $\sum_{\alpha}\sum_{g}(y_g^{\alpha})$	56	41

When we search to minimize the infrastructure cost, each type of vehicle will necessarily use the activated segments to not remain in breach of the load even if they are useless for some vehicles, which increases the use of the segments.

When we minimized the number of segments used by the vehicles, the cost of the infrastructure increases because each type of vehicle uses the segments when the load is needed, which increases the number of active segments because the locations where the charge is required are different from one vehicle to another.

5 CONCLUSION

This work presented a mathematical model that aims to find an optimal location for the wireless charging infrastructure on the highway to ensure the movement of a heterogeneous fleet of vehicles without remaining out of charge by the minimum use of segments for each vehicle type. We solved the problem by CEPLEX optimizer for each objective function with limited instances. The next step is to find a compromise between the two objectives, so we will use a metaheuristic as a method of resolution.

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