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Article

A Corridor-Based Approach to Estimating the Costs of Electric Vehicle Charging Infrastructure on Highways

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Abstract: One of the barriers holding back the large-scale development of electric vehicles is underdeveloped charging infrastructure. The optimal location of charging stations has received much attention, whereas the development of charging infrastructure over time and its economic implications remain a less explored topic, especially in the context of dynamic inductive charging. This work compares the infrastructure costs for two electric vehicle charging solutions deployed on highways: fast-charging stations and a dynamic charging lane based on wireless inductive charging technology. The deployment costs are estimated using a simplified infrastructure model for a highway corridor. The model first defines the required charging capacity based on projected future demand, sizes the charging infrastructure, and then determines the related costs, revenues, and net present value. A numerical example based on the French highway context is also presented. The results show that the payback period is much longer for dynamic charging lanes that for charging stations. In addition, the charging lane infrastructure cannot be installed gradually over time but requires a major investment from the start while bringing in little revenue early on.

Keywords: charging; deployment; electric vehicle (EV); electric vehicle supply equipment (EVSE); infrastructure

1. Introduction

The charging infrastructure for electric vehicles (EVs) has been studied in many different contexts in recent years. An extensive review of the literature available in this field can be found in [1]. A common aim is to find the optimal locations for charging stations in a road network under different constraints (see, e.g., [2–5]). The flow-refueling location model (FRLM), which maximises the number of covered long-distance trips with several refueling stops, is one of the possible ways to formulate this problem [6]. Some works place their main focus on the quantity of required charging stations [7]. The deployment of charging lanes has been studied along with that of charging stations, notably using network equilibrium models [8,9]. Electric road infrastructure and its challenges, in general, are discussed in [10]. The required number of fast-charging stations for the European highway system has also been studied [11], like that of the German autobahn network [12]. Information on wireless power transfer (WPT) technology and inductive charging can be found, e.g., in [13,14].

The cost aspect of charging infrastructure has also received attention in various papers. Works in this field include notably [1,9,15–17]. Information on empirical cost values assumed in infrastructure simulations can be found in [9,15,16]. One of the papers proposes break-even tariff information [17]. The profitability of fast-charging stations along highways was studied in [11]. Charging infrastructure business models have been considered in [18]. Cost information on non-residential electric vehicle (EV) infrastructure in the United States can be found in [19]. A French cost-benefit analysis of EVs has also been proposed [20].

A decision-making model for the capacity of EV batteries and the power of charging facilities was proposed in [15]. This model assumes a traffic corridor with evenly spaced charging stations. The aim is to minimise the total cost of battery manufacturing and of charging facility construction. Later works by the authors also take into account charging delays [21]. In another article, charging lanes and stations were compared using a traffic corridor based approach [22]. This paper notably analysed the charging facility choice equilibrium of EVs. Two deployment strategies analysed were public provision to build and operate charging lanes and stations while minimizing the social cost, and private provision maximizing profits.

Despite this body of work, the deployment of charging infrastructure over time and its economic implications remains a topic that has not been fully explored. This paper aims to address this research gap in a high-speed highway corridor context with either plug-in charging stations or dynamic charging lanes (forming an electric road) with the objective to estimate and to compare the infrastructure costs in view of future investments. The ultimate purpose is to provide guidance to potential investors and public powers and to contribute to the business case for EV charging infrastructure. The model constructed and numerical example given here are a first attempt at modeling the situation; we hope to improve the work over time to be able to apply it to a large-scale highway system.

2. Materials and Methods

In this work, the need for charging infrastructure and the related costs were analysed through a simplified corridor based model. This model was initially developed for Vedecom by Maxime Roux [23]. This work does not intend to provide forecasts or to assign probabilities to the scenarios studied; the aim is to sketch out a high-level estimate of the potential infrastructure costs related to electric mobility on highways for the given numerical example.

2.1. Basic Assumptions

The basic modelling hypotheses can be summarised as follows:

1. The model focuses on a highway corridor with either charging stations equipped with fast charging points (scenario 1) or a dynamic charging lane (scenario 2)—these scenarios are detailed in Sections 2.3.1 and 2.3.2.
2. Charging stations are placed at regular distances along the highway corridor, as are highway sections equipped with the charging lane.
3. Both charging stations and the charging lane shall supply 100% of the energy consumption of EVs along the highway corridor.
4. The infrastructure requirements, in terms of maximal charging power, are based on peak hour traffic.
5. The EV fleet is assumed homogenous in terms of its energy consumption per kilometre.
6. Travel speed is assumed constant; reductions in speed, e.g., for stopping at charging stations, are not considered. In the case of the charging lane, EVs are assumed to charge dynamically while driving.
7. Infrastructure costs considered include initial installation, material, and maintenance costs, as well as the replacement of the infrastructure at the end of its useful life. The cost of transformers for connecting to the electric grid is also included.
8. All EVs use the available charging infrastructure; in the case of dynamic charging, the compatibility of EV with this charging technology is taken into account.

2.2. Sizing the Infrastructure

The charging infrastructure is designed to cover the energy needs of peak hour traffic. These energy needs are used to set the corresponding power level supplied during the peak hour.

In the charging point scenario, the energy needed per charge can be obtained by multiplying the energy consumption per kilometre e with the distance between charging stations d and the charging frequency f (the driver will pull over to charge every f stations). This energy requirement is then multiplied by the number of vehicles. The corresponding peak power in year t per charging station is, therefore, calculated as

$$P_t^{cs,peak} = e \times d \times f \times \frac{EV_t^{highway,peak}}{f}, \tag{1}$$

where $EV_t^{highway,peak}$ is the peak hourly number of EVs venturing on highways in year t. The peak power level allows us to determine the number of charging points by station. It should be noted that the hypothesis that drivers charge every f stations does not, in fact, impact the sizing of the charging station infrastructure and, therefore, its costs.

In the charging lane scenario, it is assumed that the highway sections are only partially equipped with dynamic charging technology. The equipment ratio α is calculated based on the vehicle speed v, the energy consumption per kilometre e and the induction efficiency η:

$$\alpha = \frac{e \times v}{p^{CL} \times \eta}, \tag{2}$$

where p^{CL} stands for the nominal charging power of the charging lane. We assume here that only one highway lane is equipped with inductive charging technology. This gives us the peak power demand as

$$p_t^{CL,peak} = \alpha \times p^{CL} \times \eta \times \frac{l}{v} \times EV_t^{highway,peak} \times \gamma_t, \tag{3}$$

where l is the length of an inductive section and γ_t is the percentage of EVs compatible with dynamic charging technology.

The number of transformers is calculated based on the peak power demand per charging station or inductive section. One additional transformer is added for safety. The lifetime of transformers has not been taken into account in this analysis.

2.3. Numerical Example

A numerical example based on the French highway context was implemented. Two scenarios were studied: EV charging using fast-charging stations and a dynamic charging lane integrated into the road surface. The charging infrastructure is thought to be developed gradually over a period of 25 years, from 2020 until 2045.

2.3.1. Charging Station Scenario

In the charging station scenario, the charging infrastructure is based on charging stations with an increasing number of fast charging points installed over the simulation period. The charging stations or areas are to be installed at regular distances along the highway; we assumed a charging station every 30 km. We estimated that all EV drivers will stop to charge every three stations to cater for EVs with small batteries. However, changing this assumption does not change the results of the analysis; the energy consumption per kilometre is the key sizing factor. The number of required charging points per station is calculated based on the power requirements of peak hour traffic. Transformers are placed next to each charging area; their number also depends on the peak power demand.

The following hypotheses have been taken in terms of the evolution of the charging infrastructure over time. Fast charging points of 150 kW are installed starting from 2020. In 2030, there is a transition from 150 kW charging points to 350 kW ones. Existing 150 kW charging points remain in service until the end of their life cycle; however, newly installed charging points all provide 350 kW. It is assumed that EV drivers will continue to use both types of charging points proportionally to the available power. We assumed that EVs will be able to exploit the full power supplied by the charging points. If the maximal battery charging power is lower than the power supplied by the charging point, it is assumed that several EVs will be able to charge their batteries simultaneously.

The infrastructure costs included the unit costs of charging points, installation costs, maintenance costs, and the cost of transformers. Maintenance costs are paid yearly, whereas all the other costs are one-off. When a charging point is replaced at the end of its life cycle, the unit cost is, however, paid again. We assume that there will be no additional installation costs for replacements as this cost is mostly due to wiring and civil engineering components.

2.3.2. Charging Lane Scenario

In the inductive charging scenario, the charging infrastructure consists of a charging lane equipped with wireless charging technology providing 70 kW of power. Charging is assumed to take place dynamically while vehicles drive over the inductive sections without stopping. The induction-based charging lane infrastructure is installed in 2025; we assumed that the charging needs will be satisfied by 50 kW plug-in charging points before this date (2020–2024).

The number of EVs compatible with induction is assumed to increase exponentially from 2025 to attain 100% in 2035 (Figure 1). As inductive charging becomes available to all car owners, no new charging points get installed after 2035, although existing ones remain in service until the end of their life cycles. It is assumed that EV drivers will continue to exploit these two charging systems in parallel.

The inductive lane is installed by 30 km long sections. Transformers are placed next to each section, as in the case of charging stations. However, the inductive lane does not cover the entirety of a given section but only the distance necessary to charge the energy consumption over the section length. The power supplied by the inductive lane is 70 kW with an efficiency of 90%: This efficiency corresponds to the power drawn from the grid taken up by the vehicle. It is assumed that EVs will exploit this power both for propulsion and for charging their batteries. The inductive lane allows for the charging of an important number of vehicles simultaneously; this number is only limited by the physical dimensions of the lane.

The costs taken into account in this scenario include installation and material costs (grouped together), maintenance costs, and transformer costs. To decrease installation costs, it is assumed that the inductive lane is installed during regular road surface maintenance. The installation costs include both the cost of the inductive technology and the additional installation costs with respect to regular road surface maintenance.

2.3.3. Simulation Parameters

The calculations were performed for a 200 km long highway corridor with one-way traffic. It should be noted that the situation would be identical with a 100 km corridor with two-way traffic. The charging needs were based on an EV with an energy consumption of 0.27 kWh/km. This value is based approximately on the energy consumption of a Renault ZOE in highway conditions [24].

The traffic corridor under study corresponds to a highway with an annual average daily traffic (AADT) of 120,000 vehicles (or 60,000 in one direction) over 2×3 lanes. This level of traffic corresponds approximately to the French A6 highway [25,26]. The corresponding peak hour traffic, or 9600 vehicles, was obtained by assuming a traffic engineering K factor of 16%: design hourly volume (DHV) = K $\times$ AADT. The traffic was thought to remain stable over the simulation period.

The number of EVs in the global fleet increases linearly, as does the percentage of EVs venturing onto highways and requiring charging services (Figure 1). The percentage of EVs in the personal vehicle fleet is thought to reach 30% in 2045, with 100% of the vehicles used in highway conditions from 2040. The share of induction compatible EVs increases in an exponential manner starting from 2025. In our example, only one highway lane over three is equipped with inductive sections; however, this is enough to power all the EVs in the simulation (30% of traffic by 2045) as all EV traffic can be directed to the charging lane.

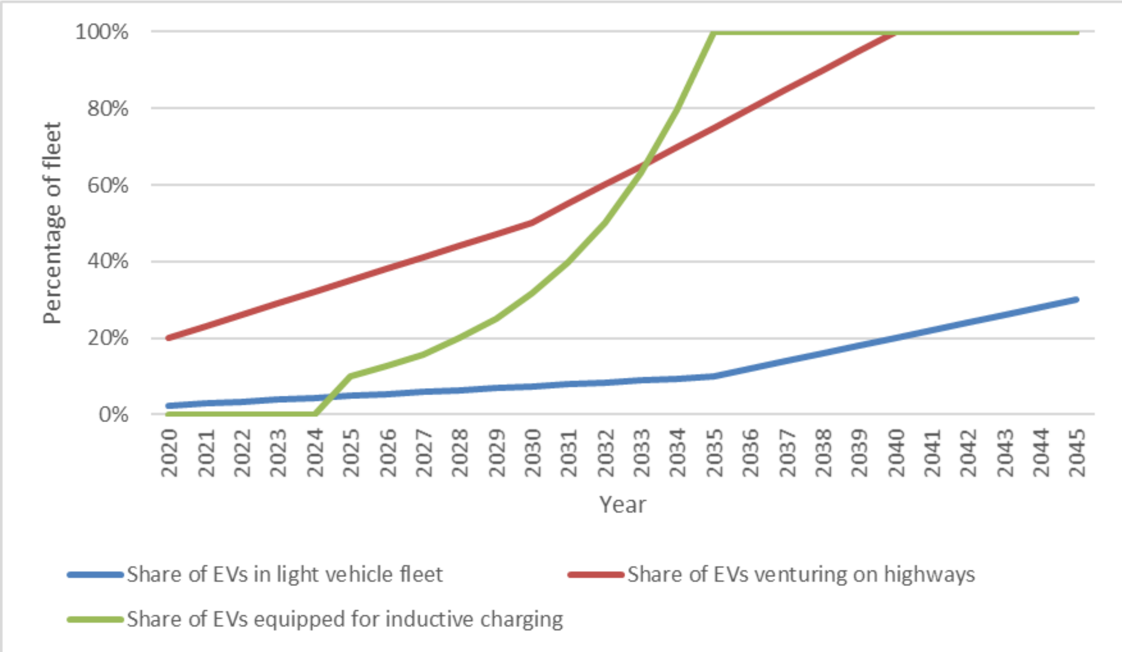

Figure 1. Hypotheses of electric vehicle (EV) penetration, the share of electric vehicles (EVs) venturing on highways, and the percentage of EVs equipped for inductive charging.

A summary of the simulation parameters can be found in Table 1. We have endeavoured to select the numerical values that represent reality as closely as possible. The power of the fast-charging stations (150 kW and 350 kW) is loosely based on projects currently underway in Europe (see, e.g., [27,28]). The estimated costs of fixed charging infrastructure have been inspired by various quotes and estimates (see notably [29]). The cost estimate for inductive charging was based on discussions with Vedecom engineers working on inductive charging. However, the cost per lane kilometre given here (including both installation and material costs) is undoubtedly low compared to other sources, such as [22]. A charging power of 70 kW seems reasonable with respect to the review presented in [1].

2.3.4. Economic Analysis

The total cost of charging infrastructure was calculated by adding up the different costs by scenario. The following cost evolutions have been assumed in the analysis: the cost of wireless power transfer technology is thought to decrease 4% per year while the other infrastructure costs decrease 1% annually. All the costs were actualised with a discount rate of 4.5% [30].

The revenue generated by the charging system was based on the number of charging events. The charging fee paid by users was set to cover the infrastructure costs incurred over the simulation period. In this analysis, the charging fee was thought to remain constant during the simulation period. In addition to infrastructure costs, the fee also included an operator margin that has been set to €2 for the 200 km corridor. In addition to the infrastructure costs and operator margin, the charging fee also included the price of electricity transferred to the user by the operator. It was supposed that the price of electricity increased by 1% per year.

As both the revenue generated by the charging infrastructure and its costs are known, it is possible to calculate the net present value (NPV) of the two investment options. In our model setup, the NPV was identical for the two scenarios.

Table 1. Values of simulation parameters.

Parameter Category	Parameter	Value
Highway corridor	AADT (one way) Peak traffic per hour (one way) Length	60,000 vehicles 9600 vehicles 200 km
Vehicle characteristics	Energy consumption Speed	0.27 kWh/km 130 km/h
Charging stations	Charging power Charging point unit costs Installation costs Maintenance costs Distance of two stations Charge frequency Life time	150 kW and 350 kW €80,000 and €150,000 €20,000 and €25,000 €2000/year and €4000/year 30 km Every 3 stations 6 and 8 years
Charging lanes	Charging power Efficiency Equipment ratio (see Equation (2)) Section length Installation and material cost Maintenance cost Life time	70 kW 90% ca. 56% of each section 30 km €0.5 M/lane km 10%/year of installation costs 15 years
Electric grid	Transformer power Transformer cost	15 MW €7.5 M
Other parameters	Discount rate Operator margin Decrease in infrastructure costs Decrease in costs of WPT technology Price of electricity Evolution of electricity price	4.5%/year €2 per 200 km −1%/year −4%/year €0.080/kWh +1%/year

3. Results

The results of the simulation are presented below (Table 2, Figures 2 and 3). The cost of the charging lane infrastructure was approximately €167 M versus €105 M for charging stations. The internal rate of return (IRR) stands at 8% and 13% for the charging lane and station scenarios, respectively. In addition to a higher IRR, the charging station scenario also offered quicker payback at 11 years compared to 22 years for the charging lane scenario. We can see that the "valley of death" of investment was deeper for the inductive charging scenario; at the end of our simulation period, the discounted infrastructure costs for charging lanes were over 60% higher than those of the charging stations. The NPV was identical for the two scenarios (€49 M).

Table 2. Economic analysis of the charging infrastructure.

Result	Scenario 1: Charging Stations	Scenario 2: Charging Lane
Cost	€105 M	€167 M
NPV	€49 M	€49 M
IRR	13%	8%
Payback	11 years	22 years
ROI	47%	28%

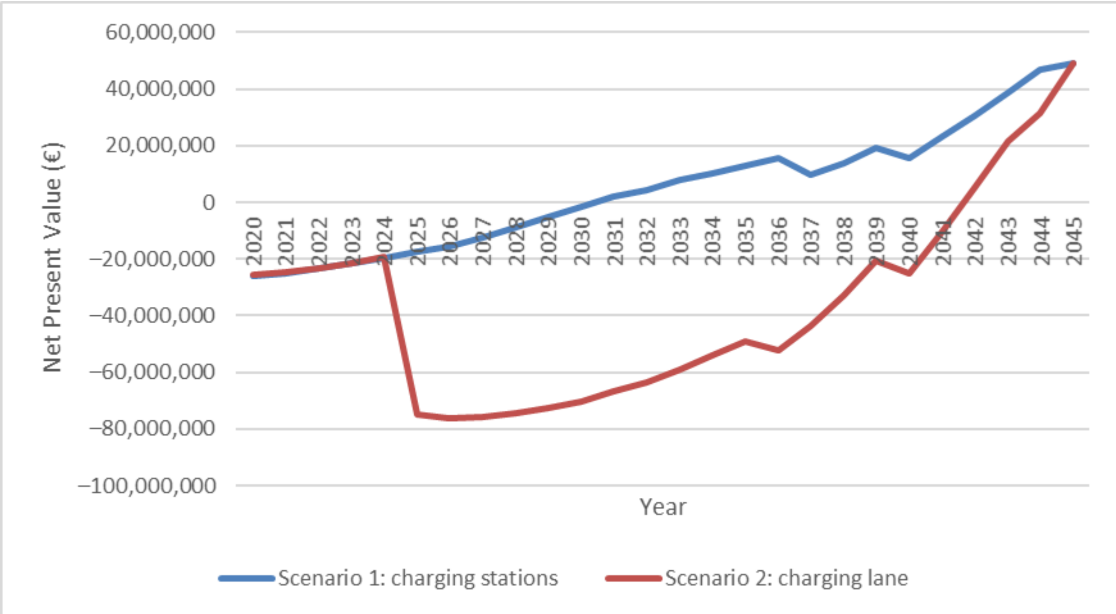

Figure 2. Evolution of the net present value of the charging infrastructure.

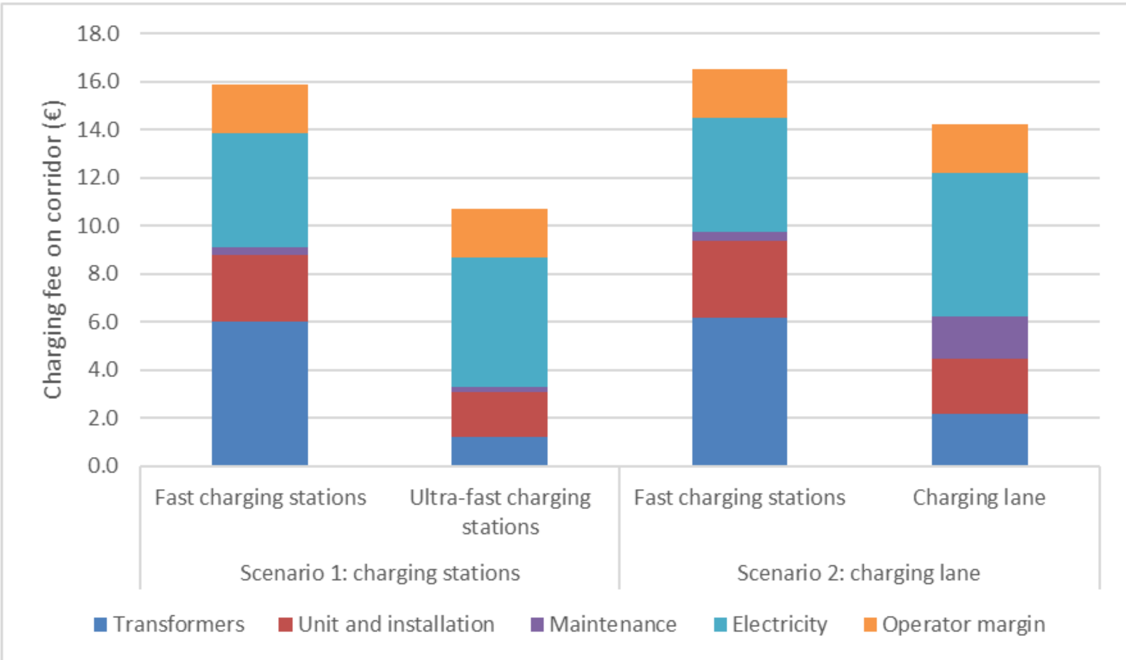

Figure 3. Breakdown of the charging fee for 200 km.

The charging fees along this 200 km long corridor varied between approximately €11 and €17, depending on the charging solution. If the value of time (VOT) for charging is considered, the user costs of charging points increased further. Let us take an EV with a battery of 60 kWh charging at the maximal power of 72 kW. Given that the value of time for an intercity journey of 200 km has been estimated as €10.67/h [31] (p. 44), the VOT for the total charge duration along the corridor (45 min for 54 kWh) would be about €8. Including this VOT would make the use of charging stations more expensive than the charging lane.

4. Discussion

The upcoming surge in electric mobility will require extensive investments in charging infrastructure. This underlines the need for evaluating infrastructure costs and imagining scenarios for infrastructure deployment. Of course, the underlying assumption in studying the deployment of EV charging infrastructure on highways is that EV owners will occasionally undertake long-range journeys with their vehicles, although most EV use is foreseen to take place in short-distance contexts.

This paper presents a simplified corridor-based model for EV charging infrastructure on highways. The main purpose of the model is to provide a high-level estimate of the potential infrastructure costs for a generic highway segment. Two alternative charging infrastructures were compared: fast-charging stations and a charging lane based on wireless inductive charging technology. According to the results of our numerical example from the French highway system, the payback period was much longer for charging lanes, which might be problematic for potential investors. Inductive charging infrastructure also requires a major investment at an early stage of development of electric mobility and remains more expensive than an infrastructure based on charging stations.

Given that this paper presents a relatively novel approach, it is somewhat difficult to validate the results by comparing them with other works. It has, however, been suggested elsewhere that in a private provision scenario, the operation of charging lanes is more profitable and hence, more attractive to private operators than charging stations [22].

It should be noted that the hypotheses of our model comprise important uncertainties. This is notably the case with respect to the size of the future EV fleet on highways and the maturity of wireless power transfer technology for a mass-market entry. There is also a high amount of uncertainty as to the lifetime and costs of charging lanes. For instance, the overall cost of the charging lane scenario would increase by nearly 50% should we double the cost per lane kilometre. Should we assume a lifetime of 7 years instead of 15, the infrastructure costs of the charging lane would increase by approximately 13%. The charging power provided by the inductive lane is also a key parameter as it impacts the equipment ratio of the road; however, a lower power charging lane might also be somewhat less expensive per kilometre. The installation costs for charging stations can also vary considerably depending on the civil engineering operations required.

The number of charging points is highly sensitive to peak hour traffic, whereas the charging lane is not. This means that the charging lane scenario performs poorly when peak traffic is low and is most profitable when the highway lane is used to its maximal capacity. In addition to the overall traffic volume, the numerical example presented in this paper is very advantageous for inductive charging as the charging line was almost fully occupied by induction compatible EVs at the end of the simulation period.

The value of time and other user preferences have not been taken into account in this work. In addition, phenomena such as the arrival patterns of EVs and queuing at charging stations have also been excluded from the scope. Although the charging stations have been sized to serve the energy needs of peak hour traffic, queues would no doubt occur in real-life situations where traffic volumes vary depending on the hour, day of the week, and season. When comparing the two scenarios, it should also be kept in mind that the charging station case requires drivers to make frequent stops to charge their vehicles, especially if they are driving an EV with a small battery. It has been concluded based on a choice equilibrium model that charging lanes become attractive to users beyond a given value of time [22].

In the future, we hope to develop a more complex highway infrastructure model to apply it to a case study of an existing highway system with its traffic flows varying over a period of one year.

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