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Constructing a Corridor-Based Model for Estimating the Cost of Electric Vehicle Charging Infrastructure on Highways

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Summary

One of the major barriers holding back the large-scale development of Electric Vehicles (EVs) is underdeveloped charging infrastructure. This work presents a simplified infrastructure model for comparing the deployment costs of two EV charging solutions on a highway corridor: fast charging stations and dynamic charging lanes. The model first defines the required charging capacity based on projected future demand and then calculates the related infrastructure cost, revenues and net present value. A numerical example based on the French highway context is also presented.

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

1 Introduction

Electric mobility and Electric Vehicles (EVs) are set to gain importance in the coming years [1, 2]. This raises questions as to the required EV charging infrastructure and its deployment costs. How many charging stations or lanes are needed, where should they be deployed, how much will this cost and who will pay for the investment? This paper aims to provide tentative answers to two of these questions—the sizing of the infrastructure and its cost—in the context of EV charging infrastructure on a highway corridor. The objective of our work is to provide a high-level cost estimate in view of future investments.

The charging infrastructure for EVs has been studied in different contexts in recent years. An extensive review of the literature in this field can be found in [3]. A common aim is to find the optimal locations for charging stations while meeting given constraints. However, few works place their main focus on the quantity of required charging points [4]. The deployment of charging lanes has been studied along with that of charging stations, notably using network equilibrium models [5, 6]. Information on wireless inductive charging technology can be found in e.g. [7, 8]. Electric road infrastructure and its challenges in general are discussed in [9].

The cost aspect of charging infrastructure has also received attention in various papers. Works in this field include notably [3, 6, 10–12]. Empirical information on cost values assumed in infrastructure simulations can be found in [6, 10, 11]. One paper proposes break-even tariff information [12]. Charging infrastructure business models have been considered in [13]. Cost information on non-residential EV infrastructure in the US and its costs can be found in [14]. A French cost-benefit analysis of EVs has also been proposed [15]. Another analysis compares EV charging costs on highways to fuel costs of internal combustion engine vehicles [2].

A decision-making model for the capacity of EV batteries and the power of charging facilities is proposed in [10]. This model assumes a traffic corridor with evenly spaced charging stations. The aim is to minimize the total cost of battery manufacturing and of charging facility construction. Later works also take into account charging delays [16]. In another article, charging lanes and stations are compared using a traffic corridor based approach [6]. This paper notably analyses the charging facility choice equilibrium of EVs. Two deployment strategies are analysed: 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 sizing of charging infrastructure 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 charging stations or dynamic charging lanes (electric road). The model constructed and numerical example given here are a first attempt at modelling the situation; the aim is to improve the work over time and enrich it with new scenarios and input data.

2 Methodology

In this work, the need for charging infrastructure and the related costs are analysed through a simplified corridor based model. This model was initially developed for VEDECOM by Maxime Roux [17]. This work does not intend to provide forecasts or 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. Two scenarios were considered: EV charging using fast charging stations and electric road with dynamic charging lanes.

2.1 Basic Assumptions

The basic modelling hypotheses can be summarised as follows:

i. The model focuses on a highway corridor with either charging stations equipped with fast charging points (scenario 1) or dynamic charging lanes (scenario 2)—these scenarios are detailed with a numerical example in section 3.1.
ii. Charging stations are placed at regular distances along the highway corridor as are the highway sections equipped with charging lanes.
iii. Both charging stations and lanes shall supply 100% of the energy consumption of EVs along the highway corridor.
iv. The infrastructure requirements in terms of maximal charging power are based on peak hour traffic.
v. The travel speed is assumed constant; reductions in speed e.g. for stopping at charging stations are not taken into account. In the case of charging lanes, EVs are assumed to charge dynamically while driving.
vi. All EVs are assumed to have the same energy efficiency per km.
vii. Infrastructure costs taken into account 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.
viii. All EVs use the available charging infrastructure; in the case of dynamic charging, hypotheses on EV compatibility with the charging technology are taken into account.

2.2 Sizing the Infrastructure

The charging infrastructure is designed to cover the energy needs of peak hour traffic. These energy requirements define the power level to be supplied during the peak hour.

2.2.1 Charging Stations

In the charging station scenario, the peak energy demand and the corresponding one-hour peak power level allow us to determine the number of charging points per station. The peak power demand $P_t^{CS,peak}$ for a charging station is calculated as

$$P_t^{CS,peak} = e \times d \times f \times EV_t^{highway,peak} \quad (1)$$

where e is the energy consumption per km, d is the distance between charging stations, f the charging frequency (charge every f stations) and $EV_t^{highway,peak}$ the peak hourly number of EVs venturing on highways in year t. The energy demand for charging one vehicle can be expressed as

$$E^{CS} = e \times d \times f \quad (2)$$

The number of new charging points in year t at a given charging station is calculated as

$$CP_t^{new} = CP_t - CP_{t-1} + CP_t^{retired} \quad (3)$$

where CP_{t-1} corresponds to the number of charging points in year $t-1$, $CP_t^{retired}$ is the number of charging points retired from service in year t and CP_t is the number of charging points required to cover the peak demand. $CP_t^{retired} = CP_{t-\lambda^{CP}}^{new}$ where λ^{CP} is the lifetime of charging points. CP_t can be calculated as

$$CP_t = \left\lceil \frac{P_t^{CS,peak}}{p^{CP}} \right\rceil \quad (4)$$

p^{CP} is here the power provided by one charging point.

2.2.2 Charging Lane

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

$$\alpha = \frac{e \times v}{p^{CL} \times \eta} \quad (5)$$

p^{CL} is the nominal charging power of the charging lane.

We assume that only one highway lane is equipped with dynamic charging technology. The total energy demand corresponds to the energy consumption per km multiplied by the length of a section l and by the peak hourly number of EVs, $EV_t^{highway,peak}$. The peak power demand per section is therefore

$$P_t^{CL,peak} = e \times l \times EV_t^{highway,peak} \times \gamma_t \quad (6)$$

γ_t is here the percentage of EVs compatible with dynamic charging technology. Eq. (6) can also be expressed as follows given that the power provided by the charging section equals the EVs' energy requirements:

$$P_t^{CL,peak} = \alpha \times p^{CL} \times \eta \times \frac{l}{v} \times EV_t^{highway,peak} \times \gamma_t \quad (7)$$

The energy demand for one section per charge is

$$E^{CL} = e \times l = \alpha \times p^{CL} \times \eta \times \frac{l}{v} \quad (8)$$

The total length of equipped sections can be expressed as

$$CL = \alpha \times L \quad (9)$$

where L is the length of our highway corridor and α the equipment ratio from Eq. (5). The length of sections renewed in a given year is $CL_t^{new} = CL$ when t is a multiple of the electric road lifetime λ^{CL} and otherwise zero.

2.2.3 Transformers

The number of transformers is calculated based on the power demand per charging station or electric road section:

$$T_t^x = \frac{1}{2} \times \left\lceil \frac{2 \times P_t^{x,peak}}{p^{trans}} \right\rceil \quad (8)$$

$P_t^{x,peak}$ is here the peak power demand of either the charging lane or charging stations and p^{trans} the power provided by one transformer. It has been assumed that one transformer supplies energy for both directions of highway traffic; for this reason, we in fact calculate the number of "transformer halves" for our one-directional corridor. The lifetime of transformers has not been taken account in the analysis.

2.3 Cost Assessment

The Net Present Value (NPV) of the charging infrastructure over n years is calculated using the following formula where CF_t is the cashflow in year t and r the annual discount rate:

$$NPV = \sum_{t=0}^{n} \frac{CF_t}{(1+r)^t} \quad (9)$$

The cashflow corresponds to revenues minus costs:

$$CF_t = R_t - C_t \quad (10)$$

The yearly revenues depend on the number of charges δ_t:

$$R_t = \delta_t \times f_t^x \quad (11)$$

where f_t^x is the charging fee in year t. The fee can be different for dynamic charging and charging stations.

The yearly number of charges for a charging station can be expressed as

$$\delta_t^{CS} = \frac{1}{f} \times EV_t^{highway} \times \beta \quad (12)$$

β is here a scaling factor allowing to extrapolate mean hourly traffic numbers ($EV_t^{highway}$) to a yearly total. For the charging lane with electrified sections, the yearly number of charges per section can be expressed as

$$\delta_t^{CL} = EV_t^{highway} \times \gamma_t \times \beta \quad (13)$$

Costs include unitary, installation, maintenance, electricity and transformer costs. For charging stations, the unit and installation costs depend on the number of new charging points whereas the maintenance costs depend on the total number of charging points. The yearly costs for the corridor with charging stations can be calculated as

$$C_t^{CS} = \frac{L}{d} \times \left[CP_t^{new} \times \left(c_t^{CP,unit} + c_t^{CP,installation}\right) + CP_t \times c_t^{CP,maintenance} + \delta_t^{CS} \times E^{CS} \times p_t^{electricity} + T_t^{CS} \times c_t^{trans}\right] \quad (14)$$

where $c_t^{CP,unit}$, $c_t^{CP,installation}$ and $c_t^{CP,maintenance}$ are the unit, installation and maintenance costs for one charging point, $p_t^{electricity}$ is the price of electricity per kWh, E^{CS} the energy demand per charge, δ_t^{CS} the number of charges per station in year t and c_t^{trans} the unit cost of a transformer.

For the charging lane, the yearly costs can be expressed as follows:

$$C_t^{CL} = \frac{L}{l} \times \left[CL_t^{new} \times \left(c_t^{CL,unit} + c_t^{CL,installation}\right) + CL \times c_t^{CL,maintenance} + \delta_t^{CL} \times E^{CL} \times p_t^{electricity} + T_t^{CL} \times c_t^{trans}\right] \quad (15)$$

The unit and installation costs only apply to newly installed electrified sections whereas the maintenance costs are charged for all sections.

3 Numerical Example

3.1 Scenarios

Our two scenarios, infrastructure based on charging stations and dynamic charging lanes, are illustrated here using a numerical example. The charging infrastructure is thought to be developed gradually over a period of 25 years, from 2020 till 2045. The charging lanes are assumed to be based on wireless inductive power transfer technology integrated into the road surface.

3.1.1 Charging Station Scenario

In the charging station scenario, the charging infrastructure is based on charging stations with an increasing number of fast charging points. It is assumed that the charging stations with their charging points are installed over time at existing rest areas alongside highways to decrease installation costs.

The charging stations or areas are to be placed at regular distances along the highway; we assume a charging station every 30 km. It is assumed that all EV drivers will stop to charge every three stations. 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 charging infrastructure over time:

1. Fast charging points of 150 kW are installed starting from 2020.
2. Ultra-fast charging points of 350 kW replace the 150 kW charging points from 2030.

In 2030, there is a transition from 150 kW charging points of 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 assume that EVs will be able to exploit the full power supplied by the charging points. If the maximal battery charging power is lower that the power supplied by the charging point, it is assumed that several EVs will be able to charge their batteries simultaneously.

The infrastructure costs include 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 points is replaced at the end of its useful life, the unit cost is, however, to be paid again. We assume that there will be no separate installation costs for replacements as the necessary wiring is already in place.

3.1.2 Charging Lane Scenario

In the electric road scenario, the charging infrastructure consists of a charging lane equipped with wireless inductive charging technology. Charging is assumed to take place in a dynamic manner while vehicles drive over the inductive sections without stopping.

We have taken the following hypotheses with respect to the power supplied by the charging infrastructure:

1. Charging points of 150 kW are installed starting from 2020.
2. An inductive lane of 70 kW starts to compete with the charging points from 2025.

This induction-based infrastructure is installed from 2025; we assume that the charging needs will be satisfied by 150 kW charging points before this date. After the entire EV fleet becomes induction compatible in 2035, no new charging points get installed although existing ones remain in service till the end of their useful lives. It is assumed that EV drivers will continue to exploit these two charging systems in parallel. The number of EVs compatible with induction is assumed to increase in an exponential manner (Figure 1).

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 highway corridor is divided into 30 km long sections; the equipment ratio defines how much of these sections is covered by the inductive surface, see Eq. (5). Transformers are placed next to each section as in the case of charging stations. The inductive lane allows 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 (that have been grouped together), maintenance costs and transformer costs. In order to decrease installation costs, it is assumed that the inductive lane is installed during regular road surface maintenance. The installation cost per km therefore corresponds to the additional cost with respect to regular maintenance.

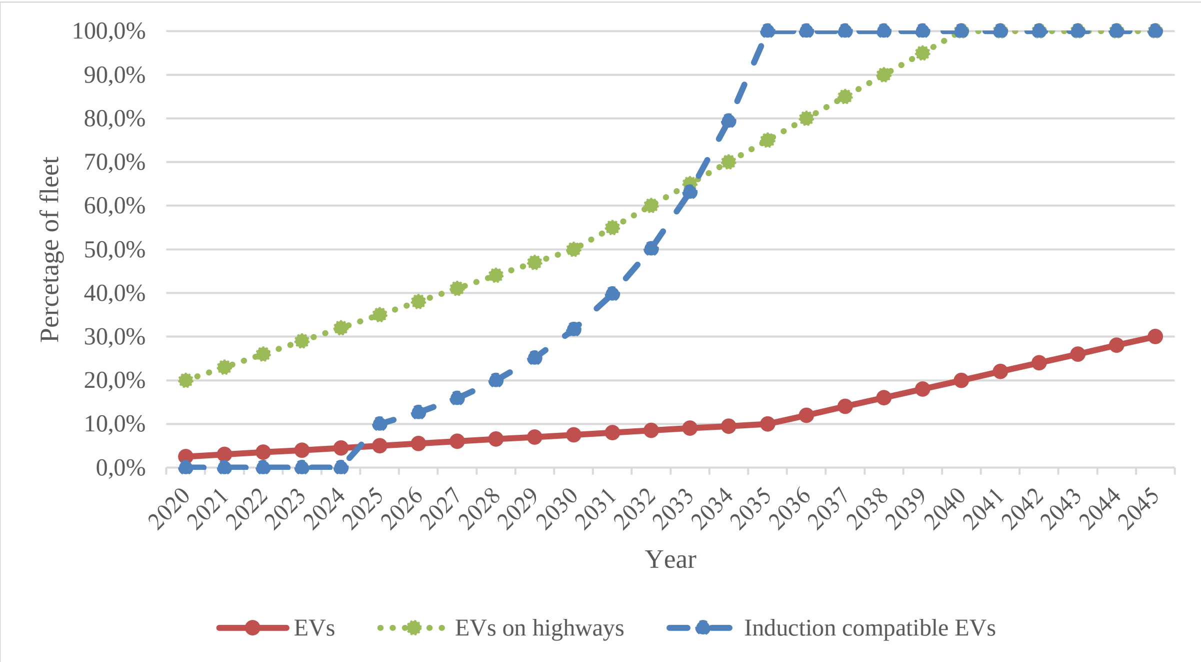

Figure 1: Evolution of EV fleet

3.2 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 for a 100 km corridor with two-way traffic. The energy requirements were based approximately on the consumption of a Renault ZOE in highway conditions [18].

The traffic corridor under study corresponds to a highway with an Annual Average Daily Traffic (AADT) of 120,000 vehicles (or 60,000 vehicles in one direction). This level of traffic corresponds approximately to the French A6 highway [19, 20]. The traffic is thought to be distributed evenly over a period of 16 hours with a peak that is 2.5 times higher than the hourly average. The yearly traffic is thought to remain stable over the simulation period.

The number of electric vehicles in the global fleet increases in a linear manner as does the percentage of EVs venturing onto highways (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 by 2040.

In the charging station scenario, given that the energy consumption is 0.27 kWh/km, the distance between charging stations 30 km and the charging frequency every three stations, the energy needed per charge is approximately 24 kWh. In the charging lane scenario, the equipment ratio is approximately 56%, see Eq. (5).

A summary of the simulation parameters can be found in Table 1. The power of fast charging stations (150 kW and 350 kW) is loosely based on projects currently underway in Europe, see e.g. [21, 22]. The estimated costs of fixed charging infrastructure have been inspired by various quotes and estimates, see notably [14]. The cost estimate for inductive charging is based on the expert opinion of VEDECOM engineers.

The total cost of charging infrastructure is calculated by adding up the different costs by scenario. The following cost evolutions have been assumed in the analysis: the cost of wireless induction technology is thought to decrease 4% per year while other infrastructure costs decrease 1% annually. It is supposed that the price of electricity increases 1% per year. All the costs are actualized with a discount rate is 4.5% [23].

The revenue generated by the charging system is based on the number of charging events. The price paid by users is set to cover the infrastructure costs incurred over the simulation period. In this example, the price per charge is thought to remain constant during the simulation period. In addition to infrastructure costs, the price also includes an operator margin that has been arbitrarily set to €2 for charging along the corridor.

Table 1: Values of simulation parameters

	Parameter	Value
Highway corridor	Mean traffic per hour (one way)	3,750 vehicles
	Peak traffic per hour (one way)	9,375 vehicles
	Length	200 km
Vehicle characteristics	Energy consumption	0.27 kWh/km
	Speed	130 km/h
Charging stations	Charging power	150 kW and 350 kW
	Charging point unit costs	€25,000 and €50,000
	Installation costs	€97,000 and €100,000
	Maintenance costs	€2,000/year and €4,000/year
	Distance of two stations	30 km
	Charge frequency	Every 3 stations
	Life time	6 and 8 years
Charging lanes	Charging power	70 kW
	Efficiency	90%
	Section length	30 km
	Unit and installation cost	€0.5 M / lane km
	Maintenance cost	10%/year of installation costs
	Life time	15 years
Electric grid	Transformer power	15 MW
	Transformer cost	€7,5 M
Economic parameters	Discount rate	4.5%/year
	Operator margin	€2
	Decrease in infrastructure costs	1%/year
	Decrease in induction technology costs	4%/year
	Price of electricity	€0.145/kWh
	Increase of electricity price	1%/year

4 Results

The results of the simulation are presented below (Table 2 and Figure 2). The cost of the charging lane infrastructure is approximately €165 M versus €94 M for charging stations. We can see that the “Valley of Death” of investment is deeper for the electric road scenario; the infrastructure cost of charging lanes is 1,7 times that of charging stations. The NPV of both infrastructures is €49 M.

Table 2: Economic analysis of investment options

	Scenario 1: fast charging stations	Scenario 2: electric road
Cost	€94 M	€165 M
NPV	€49 M	€49 M
IRR	13%	8%
Payback	11 years	22 years
ROI	52%	30%

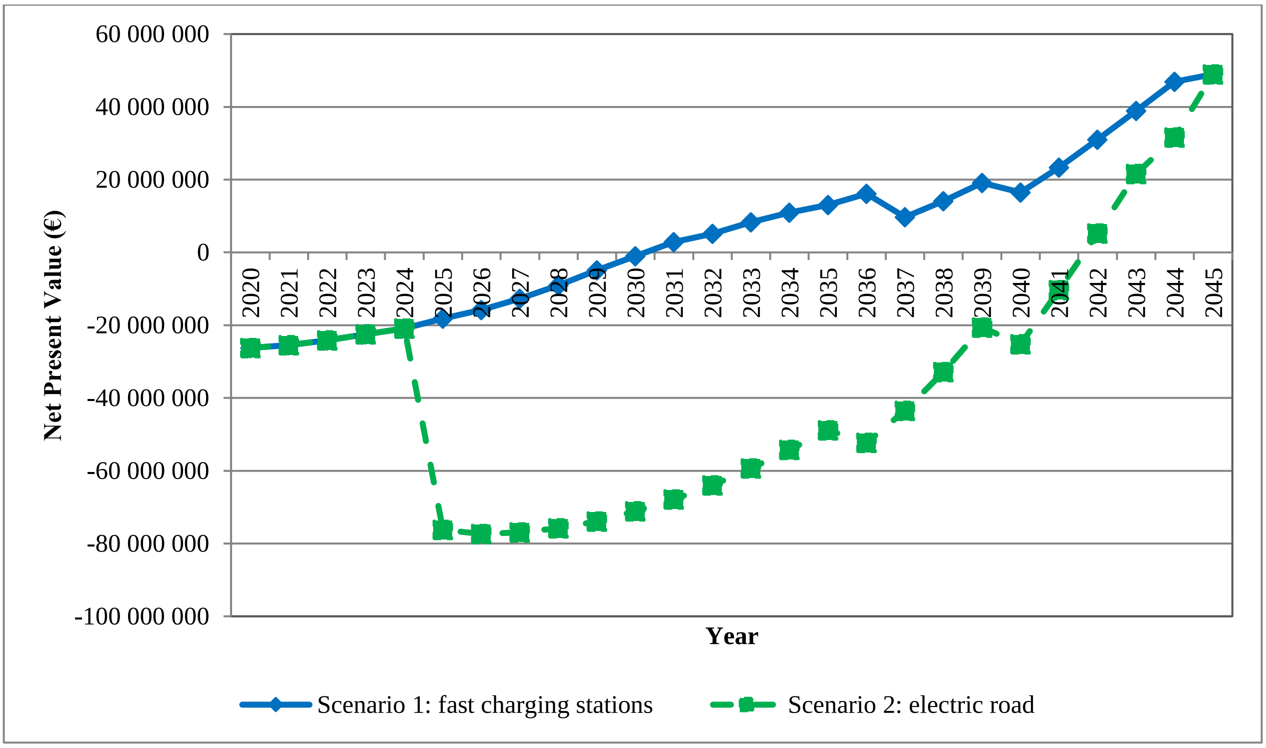

Figure 2: Cumulative net present value over time

The charging fees along this 200 km long corridor vary between approximately €14 and €20, depending on the charging solution (Figure 3). By comparison, the cost of fuel for an ICE vehicle is about €24 for 200 km [2].

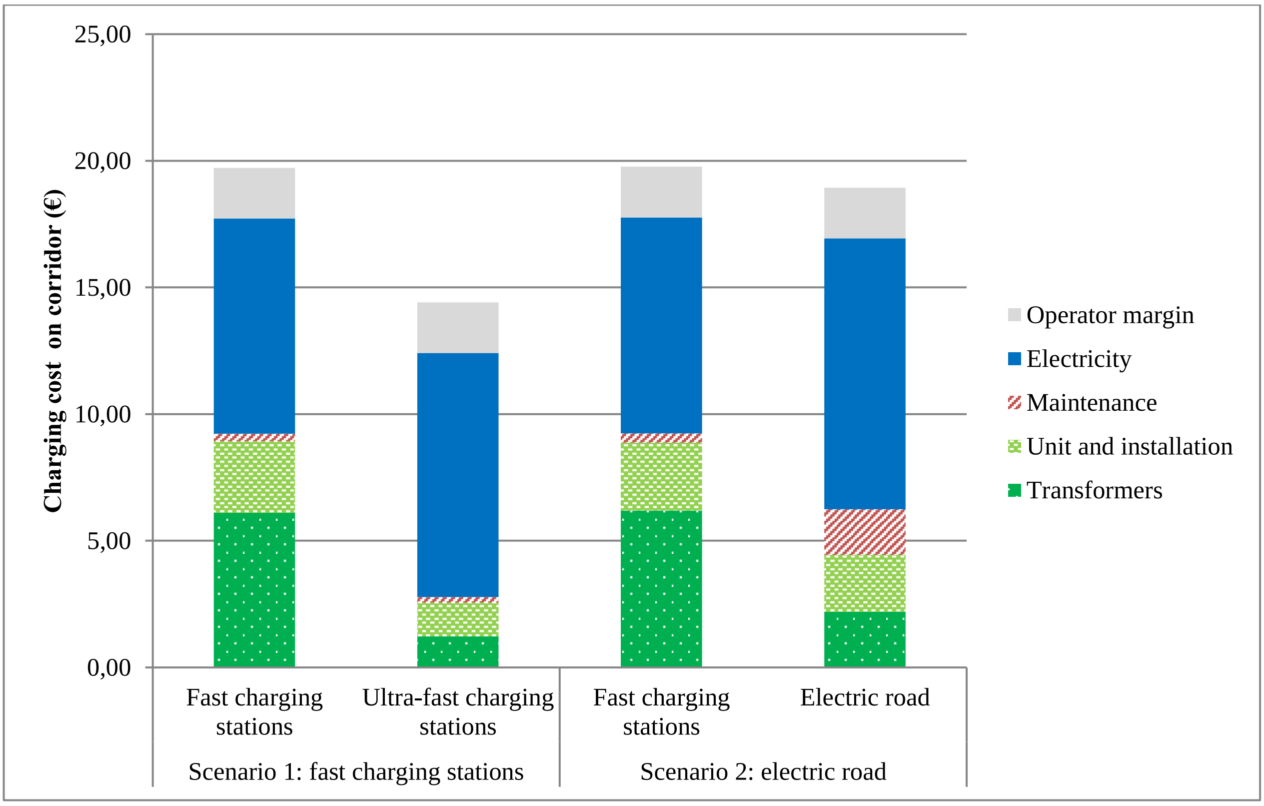

Figure 3: Breakdown of average user costs

5 Discussion and Conclusion

The coming 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. The underlying assumption in studying EV charging infrastructure on highways is that EV owners will expect long range capabilities from their vehicles, although most EV use might take place in short-range urban environments.

This paper presents the first version of 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. Two alternative charging infrastructures were compared: fast charging stations and charging lanes based on wireless inductive charging technology. According to our numerical example, both are feasible candidates for investment. Inductive charging infrastructure requires, however, a bigger initial investment and remains approximately 70% more expensive than infrastructure based on charging stations.

Given that this paper presents a first attempt at sketching the infrastructure costs, the verification and validation of the model structure is to be undertaken in detail. Further work will also involve refining the scenario hypotheses and input data, and analysing the model sensitivities.

Currently there is a high degree of uncertainty as to the cost of charging lanes both in terms of their installation and maintenance. The installation costs for charging stations can also vary considerably depending on the civil engineering operations required. Important uncertainties also exist with respect to the future number of EVs in the personal vehicle fleet, the number of EVs on highways and their induction compatibility, and the maturation of different charging technologies.

It should be noted that the number of charging points is highly sensitive to peak hour traffic whereas charging lanes are not. This means that the charging lane scenario performs poorly when peak traffic is low and is most profitable when the highway is used to its maximal capacity. The transformer costs are less sensitive when comparing the two scenarios of our model as they impact both scenarios in a similar manner. The same is true for the assumed energy consumption per km.

The value of time and other user preferences have not been taken into account in this work. This should be kept in mind when comparing the two scenarios as the charging station scenario requires drives to make regular stops to charge their vehicle. It has been concluded based on a choice equilibrium model that charging lanes are attractive to users above a given value of time [6]. It has also 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 [6].

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