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Regional-Scale Allocation of Fast Charging Stations: Travel Times and Distribution System Reinforcements

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Abstract: Electric vehicle (EV) fleet is constantly increasing over the years and higher adoption is expected in the coming decades. A key aspect to support and boost the EV uptake is the adequate availability (number, locations and sizes) of fast charging stations (FCSs) to enable inter and intra-city travels. Since these studies require modelling large regions with uncertainties, a methodology able to provide the least-cost solution is needed. This paper proposes a scalable methodology that integrates high-resolution traffic flow and multi-phase electrical simulations to find the number, locations, and sizes of FCSs at the least societal cost considering the uncertainties in driving patterns. It determines potential FCSs locations based on traffic flow and progressively explores these FCSs quantifying capital (equipment and land) and indirect (loss of productivity and reinforcements) costs to identify the least-cost solution. Results from a Brazilian case study comprising a metropolitan region with 6 cities and 26 primary substations show that, with high adoption of EVs, the investments in equipment represent the most significant components of societal cost. Moreover, for metropolitan regions, the societal least-cost solution is found with more but smaller FCSs. Finally, it is found that neglecting the loss of productivity can significantly affect the results.

Nomenclature

Indices

n	case index (same as number of FCSs installed)
m	Monte Carlo simulation index
i	transformer connecting the FCS to the system index
w	vehicle index
c	cable replaced index
x	transformer replaced index
ζ	visited point index
t	time index
r	road index

Parameters

N	maximum number of FCSs installed
M	maximum number of Monte Carlo simulations
UCP	unitary cost of charging points
mt	maintenance cost of charging points
UTR	unitary transformer cost
UCC	unitary cable cost
tax	annual land taxes
DF	discount factor
DR	discount rate
EL	expected lifetime of FCSs
UTT	unitary travel time cost
Y	number of days in a year
W	set of vehicles (population)
Z	number of visited points
MR	EV maximum range
$SO C_{crit}$	critical state of charge of EVs
EF	EV efficiency (km per kWh)
P	charging point power

L_r	length of road r
\bar{v}_r	maximum allowed speed in road r

Variables

LOC	lowest overall cost
OC_n	average overall cost of case n
CC_n^m	capital cost of Monte Carlo simulation m in case n
IC_n^m	indirect cost of Monte Carlo simulation m in case n
CPC	total charging point cost
TC	total transformer cost to connect the FCS to the system
LC	total land cost
NP	total number of charging points installed
FTR	set of transformers to connect the FCSs to the system
$area$	land size
TTC	total travel time cost (loss of productivity)
T_{EV}^w	travel time of vehicle w with EVs being present
T_{NoEV}^w	travel time of vehicle w without EVs being present
RC	total reinforcement cost
$RCable$	set of cables replaced
$RTrans$	set of transformers replaced
γ_w	travel plan of vehicle w
β_ζ	time property of visited point ζ
$SoC_w(t)$	state of charge of EV w at time t
$dist_w(t)$	distance driven since last charging of EV w at time t
dur_w	charging duration of EV w

t_{FCS}	time that the EV arrives in the FCS
R_w	route of vehicle w (including road sections)
$v_r(t)$	speed in road r at time t
$\sigma_r(t)$	flow of vehicles in road r at time t

1. Introduction

Technological developments, price reduction, and government incentives are expected to continue supporting the growth of electric vehicles (EVs) over the coming decades [1]. However, to ensure the future widespread adoption of EVs it is crucial to have a timely and cost-effective deployment of the corresponding charging infrastructure. Fast charging stations (FCS) will play a key role in this endeavour [2]. This type of station can present multiple charging points, each one above 20 kW, electrically grouped in a single site [3], [4]. While FCSs will provide short charging times to EV users, their power requirements also raise concerns about the impacts on the electric distribution system (e.g., voltage and/or congestion issues).

From a societal perspective, however, the adequate allocation of FCSs (number, locations and sizes) not only depends on the indirect costs associated with the reinforcements needed to mitigate the impacts on the electric distribution system, but it should also at least consider the effects on traffic flows [5]. A poorly deployed charging infrastructure could result in larger travel times within the region (possible traffic jams) and, therefore, loss of productivity for the population. Consequently, the deployment of FCSs must be assessed in such a way that the solution corresponds to the minimum overall cost for society, considering capital costs (cost of charging points, land ownership acquisition, annual taxes) and indirect costs due to the impacts on the electric and transport systems.

In the literature, most of the studies investigating the allocation of FCSs focus either on the impacts on the electric distribution systems or on the traffic flows. In [6] and [7], multi-objective functions to minimize technical losses and voltage violations are applied. Others, such as [8]-[10], go further and also include demand response programs, reinforcements, capital expenditure of FCSs and maintenance. However, neither the stochastic behaviour of EVs nor the traffic flow aspects are incorporated.

Traffic flow studies involving the allocation of FCSs, on the other hand, mainly focus on ensuring that the transportation system (i.e., roads) are adequate to cope with the flows of EVs [11], [12]. In [13], a hierarchical approach is developed to determine locations and sizes of FCSs. Cost, specifically the capital expenditure of FCSs, is included in [14] and [15] as a constraint. While these studies can be useful to quantify the loss of productivity from different FCS allocation options, they do not consider the number of charging points within each FCS neither the diversity in the driving patterns of EV users. Moreover, the impacts on the electric distribution systems are neglected.

More recently, studies have investigated impacts in the interdependent system (electric and transportation systems coupled) when assessing FCSs [5]. In [16] and [17], time-series traffic flows are considered using multi-objective methodologies to minimize voltage deviations and technical energy losses, and maximize the traffic flow. Although these works highlight the importance of considering the time-varying nature of traffic flows, the use

of a low time resolution (hourly) can lead to overestimations given that fast charging is likely to be used for periods of less than half-hour. Furthermore, electric systems are significantly simplified as they are modelled as single-phase balanced systems with only medium or high-voltage lines. This unavoidably leads to inaccurate estimations of voltage problems due to the inherent topological and load unbalance found in distribution systems. This becomes even more critical when considering low-voltage systems to which residential customers (and their EVs) will be connected to.

In [18], the effects that a given set of FCSs have on traffic flows are catered for considering the maximization of FCS profitability. Others, such as [19], consider the electric reinforcements necessary to cope the power demanded by FCSs with the traffic flow included in the model. However, due to the complexity of the formulation, these two might suffer from scalability issues, requiring significant simplifications of models and/or topological data to be used for both traffic and power flow analyses across large regions. In [20], the authors proposed the minimization of the costs involved in the allocation of slow charging stations considering data with high-resolution time. The methodology, shown to be scalable using a large deterministic case study, can also be applied to FCSs and low-voltage systems. However, this study does not consider the effects that the location, number, and size of FCSs might have on traffic. Therefore, while existing traffic flows are used to identify potential FCS locations, once identified, those FCS options need to be assessed in terms of the traffic flows they will create, making it possible to quantify the impact on loss of productivity.

In this context, this paper proposes a scalable methodology to determine the most cost-effective number, locations, and sizes of FCSs considering the overall societal cost of EV infrastructure, accounting for the effects on traffic flows and on the electric distribution system considering also the uncertainties in driving patterns. It allows for the integration of high-resolution (e.g., 15 min) detailed traffic models (intra and inter-city) and electrical models (three-phase, medium and low voltages) of large metropolitan regions.

In summary, the contributions of this paper are: (i) a scalable methodology able to determine the most cost-effective number, locations and sizes of FCSs across large metropolitan regions considering the overall societal cost of such an infrastructure as well as uncertainties in driving patterns; (ii) quantitative results based on a Brazilian case study comprising a metropolitan region with 6 cities and 26 primary substations; (iii) a detailed discussion of results that demonstrates how significant each component of societal cost is, the consequence of neglecting some of them; and, (iv) the finding that the least-cost solution in metropolitan regions is achieved with more but smaller FCSs.

This paper is organized as follows. Section 2 describes the methodology with the definition of costs, models for traffic flow and electric analyses, and the detailed stochastic solution process. Section 3 provides the main characteristics of the case study, followed by results of traffic flow, electric and overall analyses; also includes a discussion about the breakdown of costs and a comparison with respect to other works in the literature. Section 4 concludes the paper summarizing the main results and future works.

2. Methodology

The first step in the proposed methodology is to identify potential locations within the region of interest based on a traffic flow analysis, i.e., a ranking is created considering the most utilized roads. Then, for a given EV penetration (percentage of EVs with respect to all vehicles) and a fixed number of FCSs (increased progressively and starting from one), it analyses the effects on the traffic flow as well as on the electric system. In each case, the total cost, i.e., capital cost (FCSs) plus indirect cost (loss of productivity, which quantifies the travel time, and reinforcements in the electric systems), is calculated considering the lifetime of the FCSs. This process is repeated for each of the multiple simulations (Monte Carlo simulations [21]) created using vehicle travel patterns derived from probabilistic functions related to the geographical points (start/end), and duration of the visits. Finally, a comparison is carried out to identify the FCS option with lowest cost. Details are provided in the following subsections.

2.1. Definition of Overall, Capital and Indirect Costs

The proposed approach will progressively investigate a pre-defined number of FCS cases, starting from a case with only 1 FCS up to N FCSs, i.e., a total of N cases. Within each case, a total of M Monte Carlo simulations will be assessed to cater for the uncertainties due to traffic flows (which in turn will produce different impacts on travel times and distribution system reinforcements). The objective is to find among the FCS cases the one with the lowest overall cost (LOC), as shown in (1). The overall cost in each case is calculated by extracting the mean overall cost considering all the corresponding Monte Carlo simulations. This is shown in (2).

$$LOC = \min\{OC_n\}_{n=1}^N \quad (1)$$

$$OC_n = \frac{\sum_{m=1}^M (CC_n^m + IC_n^m)}{M} \quad (2)$$

For each Monte Carlo simulation m within case n , the capital and indirect costs are calculated as follows (indices m and n removed for simplicity).

2.1.1 Capital Cost: In (3), the capital cost of a single Monte Carlo simulation is divided into three components: charging points, transformers and land. Eq. (4) accounts for the number of charging points installed and maintenance cost (in percentage of the unitary charging point cost). Eq. (5) accounts for the cost of each transformer used to connect the FCS to the electric system. Eq. (6) accounts for the area size and taxes. Eq. (7) accounts for the expected FCS lifetime and the discount rate.

$$CC = CPC + TC + LC \quad (3)$$

$$CPC = NP \cdot UCP (1 + mt \cdot DF) \quad (4)$$

$$TC = \sum_{i \in FTR} UTR_i \quad (5)$$

$$LC = area (1 + tax \cdot DF) \quad (6)$$

$$DF = \frac{(1 + DR)^{-EL} - 1}{(1 + DR)^{-1} - 1} \quad (7)$$

2.1.2 Indirect Cost: The indirect cost of a single Monte Carlo simulation, described in (8), is the sum of the loss of productivity (travel time) and reinforcements (electric system). Loss of productivity, (9), accounts for the difference in travel times of each vehicle with and without EVs being present, all transformed into present value cost. Reinforcement cost, (10), accounts for the cables and transformers replaced.

$$IC = TTC + RC \quad (8)$$

$$TTC = UTT \cdot Y \cdot DF \cdot \sum_{w \in W} (T_{EV}^w - T_{NoEV}^w) \quad (9)$$

$$RC = \sum_{c \in RCable} UCC_c + \sum_{x \in RTTrans} UTR_x \quad (10)$$

2.2. Traffic Flow Analysis

The first step of any traffic flow analysis is to define the scale of the study. To cater for the precise geographic positions of FCSs and drivers' behaviour, a detailed approach must be chosen. Thus, the microscopic scale is selected in this case as it can model vehicles individually [22]. The next step is to define the traffic demand model, responsible for generating the plans of the population W . Next, route assignment is used to calculate the shortest route for each vehicle. Finally, a traffic flow simulation (analogous to a time-series power flow) is applied to determine the travel times.

2.2.1 Conventional Vehicles: To each vehicle is allocated a plan of actions comprised of geographical start/end points (e.g., a house), points to be visited (e.g., work), and the corresponding duration of the visits throughout the period of interest (e.g., a day). This plan is described by (11). Each point in the plan has a time property, with the first point modelled as end time, while the remain points are durations.

$$\gamma_w = \{\beta_\zeta\}_{\zeta=1}^Z, \forall w \in W \quad (11)$$

In practice, due to the unavailability of individual travel patterns, census data can be used to realistically define the plans for each of the vehicles. For a given city in which activity areas (residential, commercial, etc.) can be defined, it is possible to produce individual plans by sampling vehicles from/to certain areas (using population density from census data) and combining it with the likelihood of departure times and duration of activities (using regional/national work hours). This allows the creation of probability functions that can then be used to produce vehicle travel patterns for a given simulation.

2.2.2. Electric Vehicles and FCSs: To quantify the effects that the number and location of FCSs have on the electric system, the need for charging must be modelled. To do this, if the State-of-Charge (SoC) of an EV falls below a threshold, defined by SoC_{crit} and shown in (12), it will charge at the closest FCS as soon as possible (SoC_{crit} indicates the need for charging similar to the low gasoline level on conventional vehicles). The charging duration is defined by (13).

$$SoC_w(t) = \frac{MR - dist_w(t)}{MR} \leq SoC_{crit}, \forall 0 \leq t \leq 24 \quad (12)$$

$$dur_w = \frac{dist_w(t = t_{FCS})}{EF \cdot P} \quad (13)$$

The SoC_w is defined for any vehicle in every time instant within the 24 hours of the day. Charging duration is a function depending on the distance driven since last charging in the time the vehicle arrives in the FCS with the efficiency of the electric motor and charging point power.

From a simulation perspective, since the estimation of the SoC_w requires quantifying $dist_w$, a two-stage approach is needed to update the corresponding plan of the EV. First, these parameters are calculated without FCSs to estimate when and where the EV would reach the SoC_{crit} . Then, this, combined with the actual locations of the FCSs being assessed and the required charging time to achieve full charge, is used to update the corresponding plan of activities.

2.2.3 Route Assignment: Before the traffic flow simulation, the routes of each vehicle must be defined, i.e., the shortest path between the points in their plans (Dijkstra's algorithm [23]). After each traffic flow simulation, vehicles facing traffic jams have their routes recalculated.

2.2.4 Traffic Flow Simulation: This paper uses the simulation model with dynamic velocity [22] described by (14), (15). The travel time of each vehicle depends on the length of the section of road belonging to its route and the actual velocity. This velocity is time-variant depending on the actual flow of vehicles and the maximum allowed speed.

$$T^w = \sum_{r \in R_w} \left(L_r / v_r(t) \right), \forall w \in W \quad (14)$$

$$v_r(t) = \bar{v}_r \cdot \exp(-\sigma_r(t)), \forall 0 \leq t \leq 24 \quad (15)$$

All vehicles perform their routes concurrently. This process is repeated for a pre-defined number of iterations to reduce the travel times individually (user-equilibrium [22]).

2.3. Electric Analysis

The electric analysis determines the reinforcements required to cope with the demand added by the FCSs. First, it is carried out an impact assessment using a time-series three-phase power flow to capture the time component of EVs charging events as well as the unbalanced nature of customers in distribution systems. Although FCSs are likely to be connected to medium voltage (MV) systems (using a transformer), their impacts can be propagated to low voltage (LV) systems, thus, both MV and LV systems need to be modelled simultaneously for a more realistic assessment. The impacts investigated are the voltage magnitude at the connection point of LV customers and utilization level of assets (MV and LV lines and transformers). Then, if any violation is detected, i.e., voltages outside statutory limits and/or congested assets, the following steps are taken:

1. Replace congested assets by others with higher rated value (it also improves voltage profiles);
2. Carry out another impact assessment and inspect the reinforced system. If any voltage violation persists, go to step 3; otherwise, finish the process;
3. Replace the line (or section) featuring the highest voltage drop by other with lower impedance (higher rated current) and return to step 2.

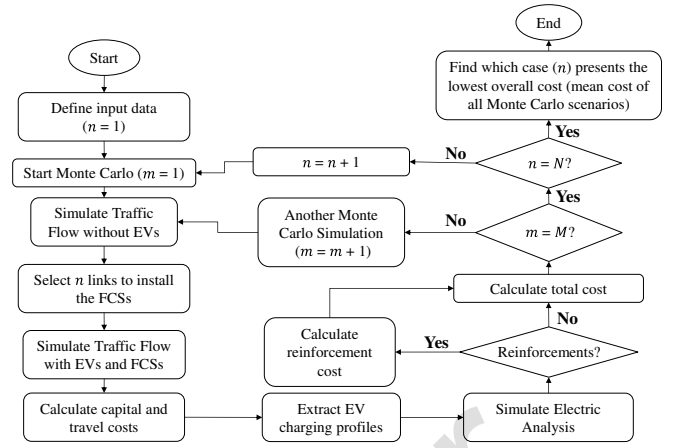


Fig. 1. Solution process for FCS allocation in distribution systems.

The above algorithm can be applied to radial systems [24].

2.4. Stochastic Solution Process

Fig. 1 shows the Monte Carlo-based stochastic solution process developed to cost-effectively allocate FCSs in a given region with defined transportation and electric systems. Before the process starts, the deterministic variables, such as the vehicle population, EV penetration and number of FCSs to be investigated, and the stochastic variables, such as the census data of plans, are defined.

Next, plans for every vehicle are defined and a traffic flow analysis is performed without EVs to assess travel times and determine potential places to install n FCSs. These locations are determined based on the sections of the roads with the highest daily flow of vehicles. Then, considering the specified EV penetration, regular vehicles are randomly replaced by EVs (same plan with a visit to the FCS, if necessary). The FCS is then installed on the busiest road. If more than one FCS will be installed, locations are progressively selected from the busiest to the less busy ones.

Another traffic flow analysis is carried out considering EVs and FCSs. This is used to determine the maximum number of simultaneous EVs charging at the same FCS which, in turns, allows determining the number of charging points required and the corresponding transformer size. The cost associated with these assets as well as with the corresponding land (vehicle area, area for manoeuvres, entry and exit) can then be calculated. Loss of productivity (indirect cost) is calculated based on travel time differences between the cases with and without EVs for the entire fleet. Reinforcement cost, also an indirect cost, is obtained from the electric analysis.

The societal (overall) cost is the sum of five components: cost due to loss of productivity, cost of charging points, cost of land, cost of transformers to connect FCSs and cost of reinforcements. For a given number of FCSs installed (n), each of these components are calculated and summed. This process is repeated for all corresponding Monte Carlo simulations (m). After the Monte Carlo convergence, the number of FCSs is incremented and the process restarts. Since each FCS case has multiple Monte Carlo simulations, the mean value of the total cost is used to represent the performance of each case. To clarify, the methodology does not analyse the cost of individual components separately as one component affects the others.

After assessing all the cases, the least overall total cost will indicate the most suitable number of FCSs to be deployed, including the location, number of charging points, transformer size and land area.

3. Case Study

This section presents the characteristics of the adopted case study and the results obtained from applying the proposed methodology to allocate FCSs.

3.1. General Considerations

Six central cities from the Campinas Metropolitan Region, in the state of Sao Paulo, Brazil, are studied in this paper. Combined, they account for 2 million inhabitants spread over 540 km². The geographical information of the transport system was extracted from OpenStreetMap [25]. It is comprised of 31,000 nodes (geographical points) and 80,000 sections of roads (straight lines connecting two nodes) with lengths ranging from a few meters up to 3.6 km (average of 100 m). Statistics from the most recent census [26], [27] are used to estimate activity areas (residential and commercial) as well as the number of residential vehicles. For the latter, approximately 1.3 vehicles per household and 1 million households are considered, i.e., a total of 1.3 million vehicles. Office/work hours are based on the Brazilian legislation [28]. This information is used to create the vehicles' plans.

The electric system of this region is comprised of 26 primary substations (69 kV/11.9 kV and 138 kV/11.9 kV) with 670,000 lines and 687,000 buses supplying approximately 1.1 million customers (of which 91 % are residential) and with an annual consumption of 8 TWh. The upstream 69 and 138 kV systems are modelled by a Thévenin equivalent using short-circuit levels at the substation; data provided by CPFL (the local utility). Medium voltage (11.9 kV) and low voltage (220 V phase to phase) systems are explicitly modelled, with the former three-phase three-wire (delta connected) and the latter three-phase four-wire (wye connected). Customer demand (single, two and three phase) is modelled using 15-min load profiles also provided by CPFL. The demand from customers as well as FCSs are modelled as constant power.

For the FCSs, each charging point costs 100,000 BRL plus 2% per year of maintenance (defined by manufactures [29]); the unitary costs of transformers and cables are provided by the local utility (see Appendix for values). In terms of land, the region's 2018 market values for every neighbourhood are considered [30]. This is shown in Fig. 2 where areas coloured in red cost 3,000 BRL per m² while areas in blue cost 150 BRL per m². For each charging point is defined a parking spot of 11.04 m² (average size of vehicles [31]). Also, FCSs are assumed to need extra 50% of area for manoeuvres, entry and exit of vehicles. Land taxes are 2% per year over the total land cost. To bring all costs to present value, discount rate of 5% per year and lifetime of 10 years are considered.

To assess how sensitive the overall cost of FCSs is to indirect costs, the loss of productivity is estimated considering three different travel time costs: 10, 25 and 40 BRL per hour per vehicle. This is based on a study that quantified how much people pay in travels [32].

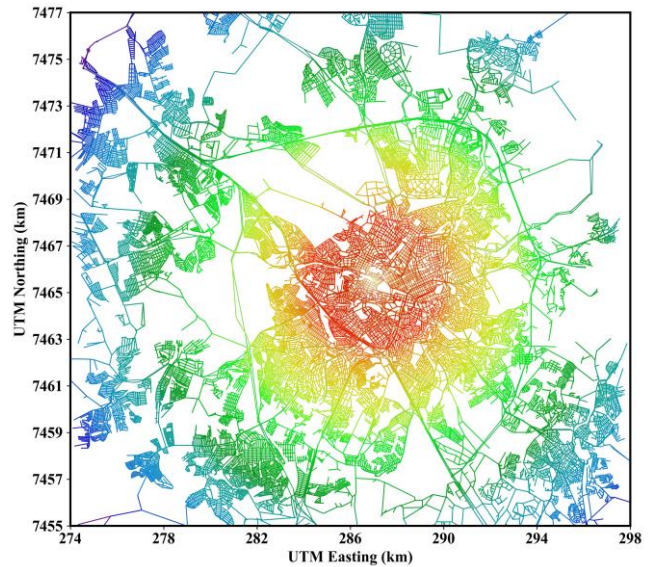


Fig. 2. Heat map of land costs per square meter (costly towards red).

Table I. Characteristics (Average) of EVs ([31]).

Variable	Value
Maximum range	125 km
Efficiency	5 km/kWh
Charging point power demand	50 kW
SoC_{crit}	40%

Finally, the EV penetration assumed in this study is 50%. This is considered large enough to create impacts on the electric and transportation systems and, hence, can be used to demonstrate the benefits of the proposed methodology. Other EV characteristics used in this paper are shown in Table I. Up to 20 FCSs are studied, separated by 1 km to avoid clusters of FCSs. 100 Monte Carlo simulations are considered for each FCS case (considered sufficient by similar studies [24]). FCSs are assumed to be immediately available to EVs that arrive for charging, i.e., EVs do not wait to charge.

3.2. Traffic Flow Analysis

The open-source tool Multi-Agent Transport Simulation (MATSim [33]) was used to perform the traffic flow studies applying the steps described in Section 2.2 with 10 iterations per analysis. To make it possible to use MATSim on a desktop PC with 8 GB of RAM, 3.5 GHz, and 4 cores, the vehicle population was reduced to an 8,000-vehicle sample (0.6%). To ensure traffic jams were adequately captured, the capacity of roads was reduced proportionally (to 0.6%).

For illustration purposes, Fig. 3 shows, for one Monte Carlo simulation, the transportation system indicating roads, as bold lines, that present more than 1% of the fleet of vehicles passing through per day (equivalent to 13,000 vehicles for the region, i.e., highly utilized). The top 20 busiest sections of roads are considered to be potential FCS locations (red dots in Fig. 3, labelled from A to T). Most of these FCS locations are outside the city centre, on the northern and western areas due to the population distribution. The traffic flow profiles of FCS locations A, I, and O are plotted on Fig. 4. Each profile is unique, consequence of vehicles flowing towards city centre in the morning and the

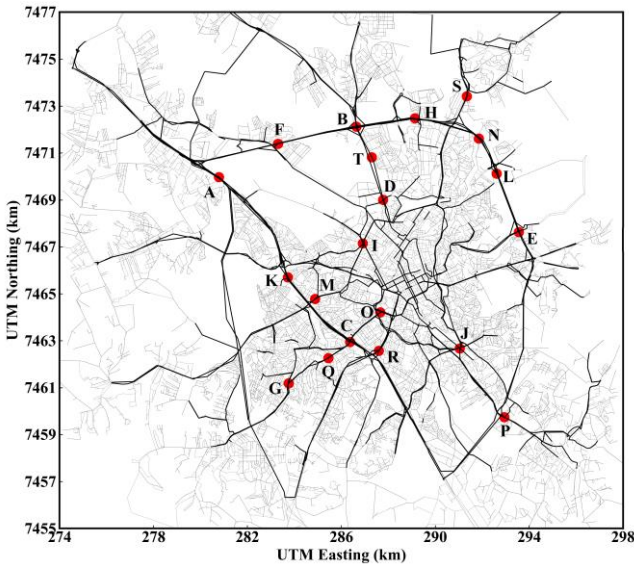


Fig. 3. Traffic flow results of one Monte Carlo simulation without EVs.

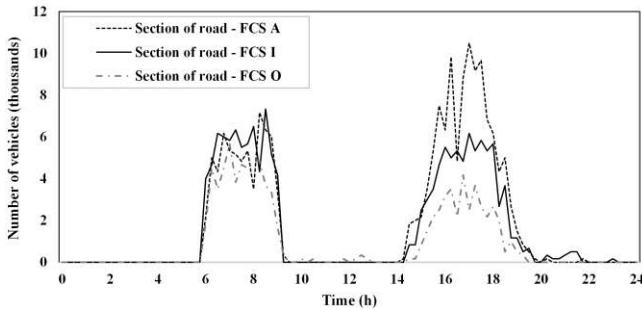


Fig. 4. Traffic flow profiles for three roads of intense vehicle movement.

other way around after work. High and thin peaks indicate possible traffic jams.

With the FCS locations identified, the traffic flow analysis is performed for each of the FCS cases: from one to 20 FCSs. The resulting travel times can now be translated into cost. Fig. 5 shows the corresponding cost (loss of productivity) over the lifetime of the FCSs (average of all Monte Carlo simulations for each FCS case). As one can notice, when only a few FCSs are available, the cost is much higher. The base case (without EVs) is the one used to initially select the locations to install FCSs, so that no information about EV's routes are considered. Thus, initially, FCS locations are selected using the most used routes of regular vehicles (based on traffic flows, mimicking common practices for petrol stations as these businesses select the 'busiest spots'). Then, in each Monte Carlo simulation, a different set of regular vehicles are replaced by EVs until the level of penetration under investigation is reached (mostly because it is uncertain which drivers will buy EVs). Consequently, although the selected FCS locations might be suitable for some EVs, it will not necessarily be aligned with the routes of all EVs. This, in turn, leads to larger travel times within the region. Moreover, the location of the fourth FCS is on an avenue, not a road as previous FCSs. Therefore, with high EV penetration, several EVs go to charge in this FCS causing traffic jams (seen by the higher cost of travel time – loss of productivity). This highlights the importance of evaluating the selected locations.

With more FCSs, the travel times reduce and,

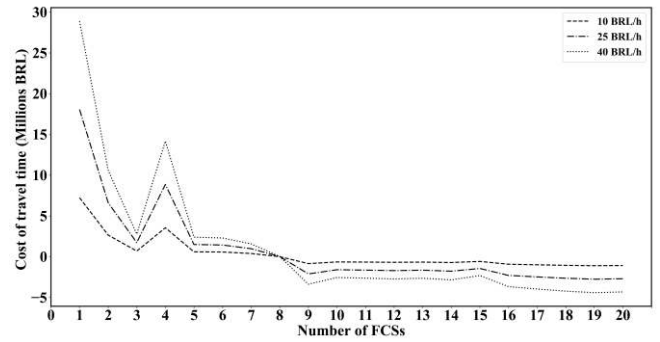


Fig. 5. Cost of travel time (loss of productivity) for each FCS case.

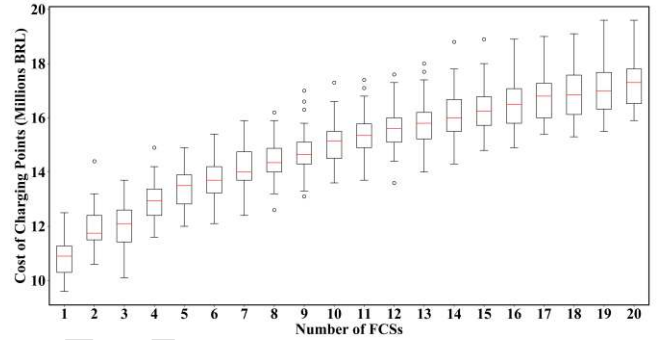


Fig. 6. Total cost of charging points for each FCS case.

therefore, the corresponding cost. Interestingly, with 9 or more FCSs, it was found that the loss of productivity could even be improved (negative cost). In other words, the entire population of vehicles is spending less time travelling when FCSs are adequately located as they re-arrange the traffic in a way that traffic jams are reduced. The metropolitan region under analysis has already some traffic congestion (as many urban regions in the world). In this context, if the FCSs are deployed in areas to reduce the detour of EVs, the impact on traffic flow and, consequently, the cost, will depend on the capacity of the selected location (as explained earlier) and the time those EVs are travelling to charge. If they are traveling during rush hours and need to charge (and, hence, stop), the roads will be clear for other vehicles to travel faster (velocity and number of vehicles are exponentially related). This is the situation in the adopted case study. On the other hand, if the EVs are travelling outside rush hours, travel cost will, at best, be the same as shown in the base case; same happens if traffic jams are unlikely in the region. Nonetheless, from the traffic flow perspective, the benefit from having many FCSs (more than 9 in this case study) can be considered marginal, particularly for low travel time costs.

Fig. 6 illustrates the total cost of charging points as a boxplot for each FCS case. The average of this cost increases with the number of FCSs, i.e., the more FCSs, the more charging points. This is because each FCS needs to meet its peak time requirements, i.e., the maximum number of EVs that simultaneously charge at any given time (estimated with the traffic analysis). Whilst an extra FCS will re-arrange the traffic, it will not necessarily reduce the peak time requirements of other FCSs as it might serve EVs at different times. This, in turn, can result in more charging infrastructure.

Using the number of charging points of each FCS and the region's 2018 market values (Fig. 2), the cost of land is

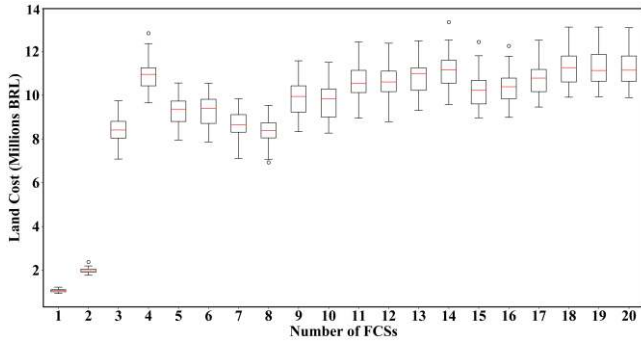


Fig. 7. Total land cost for each FCS case including annual taxes.

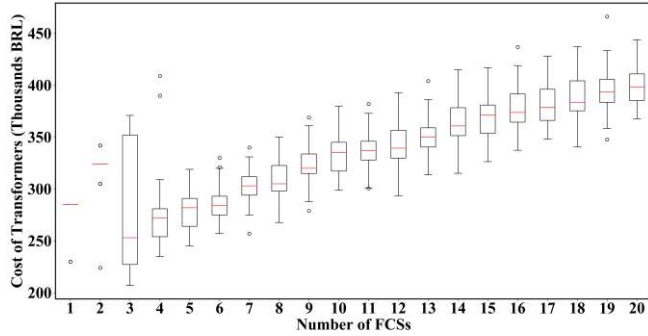


Fig. 8. Total cost of FCS transformers for each FCS case.

calculated. The results are shown in Fig. 7 as boxplots considering taxes over the lifetime of the FCSs. Although the total land area increases with each FCS case due to the larger number of charging points, the corresponding cost varies significantly because of the location and space requirements of individual FCSs. Among the cases with just a few FCSs, high fluctuations are more likely to occur because the locations of the busiest roads can have very different land costs. This can be observed with FCSs A and B compared to C and D (see Fig. 2 and Fig. 3). However, as more FCSs are installed, the overall cost fluctuates less as the remaining options tend to have similar land cost (e.g., FCSs K to Q).

Using the number of charging points of each FCS and the charging point rated power (50 kW), the transformer size is calculated. Fig. 8 illustrates the total transformer cost as a boxplot for each FCS case. With up to three FCSs, the cost varies significantly due to the unavailability of a transformer size that matches the FCSs demand, i.e., they are oversized. This occurs because the available transformers follow realistic rated powers (commercial values) which can have large differences between sizes. As more FCSs are installed, less charging points are in each location and, therefore, the available transformers sizes are a better match. As such, discarding the oversized FCS cases, having more transformers results, as expected, in higher cost.

3.3. Electric Analysis

The electric analysis consists of a time-series three-phase power flow performed using OpenDSS [34] and considering the Brazilian statutory limits, i.e., voltages of LV customers must be between 0.92 and 1.05 pu [35]. Following industry practice, it is assumed that line and transformer currents must be within the limits at least 95% of the day (around 23 hours) [36], [37].

Fig. 9 illustrates how the loading level of four MV

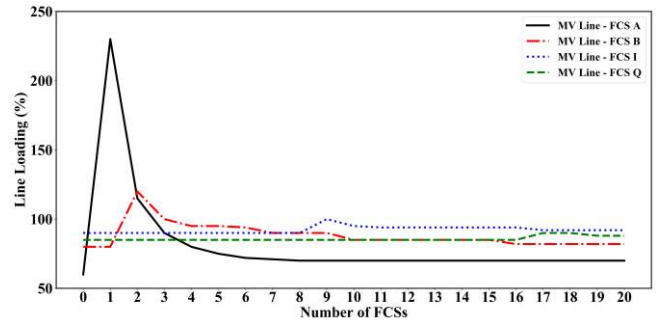


Fig. 9. Line loading comparative of four MV lines of systems where FCSs A, B, I, and Q are installed, respectively.

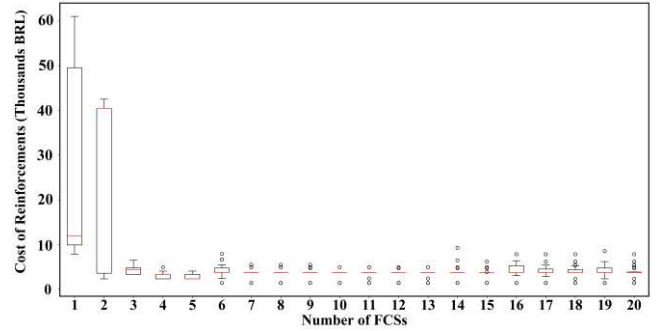


Fig. 10. Boxplot of total reinforcement cost for each FCS case.

lines (fed by four different primary substations) evolves as more FCSs are installed. The relative locations of these MV lines correspond to the sites of FCSs A, B, I, and Q shown in Fig. 3. For each FCS case, the average of the daily maximum loading level across all Monte Carlo simulations is considered. The spikes seen in each of the MV lines correspond to the time when the corresponding FCS (A, B, I or Q) is first used by the methodology. For instance, for the case with 1 FCS, location A is selected, resulting in a line loading of 230%. However, as more FCSs are installed, this asset congestion issue decreases. In other words, reinforcing this line is necessary only if 1 or 2 FCSs are installed in the region. In summary, as more FCSs are installed, congestion of assets is less likely.

The violations are detected and fixed (with reinforcements) by the electric analysis, which then calculates the corresponding cost. Fig. 10 illustrates this cost as a boxplot for each FCS case. As highlighted in the previous section, less FCSs create clusters of charging points, resulting in a very large peak demand, more lines overloaded and, therefore, higher costs. On the other hand, with more FCSs installed, smaller peak demands occur because the charging points are spread across different MV systems. This reduces the number of overloaded lines and, consequently, the reinforcement cost. In summary, the cost of reinforcements reduces as the number of FCSs increases.

3.4. Overall Cost

Based on the indirect costs (loss of productivity and reinforcements), more FCSs reduce the impacts. On the other hand, less FCSs reduce the charging points cost (transformer varies according to the available sizes; land varies with the location). Consequently, to find the most cost-effective solution to this problem all costs must be simultaneously considered for each FCS case.

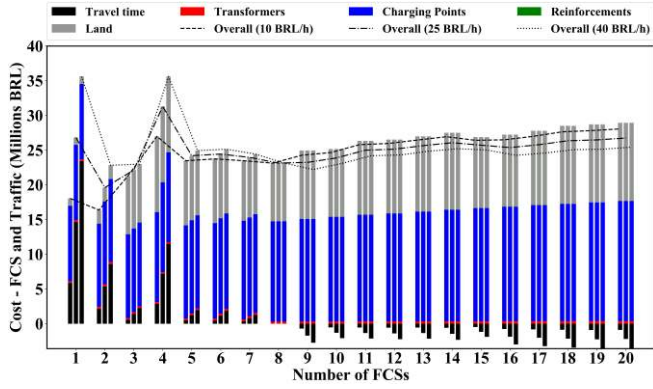


Fig. 11. Costs separated by component (bars) and overall cost (lines) for each FCS case considering 10, 25 and 40 BRL/h as travel time costs.

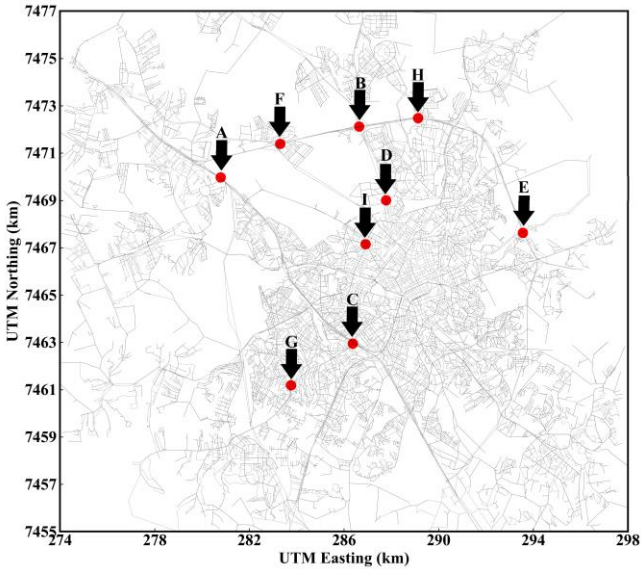


Fig. 12. Geographic distribution of the FCSs considering the highest travel time cost (40 BRL/h).

Fig. 11 illustrates the overall cost and their breakdown per FCS case considering 10, 25 and 40 BRL/hour as travel time costs (first, second and third parallel bars of each FCS case, respectively). With travel time costs of 10 and 25 BRL/hour, the most cost-effective solution corresponds to 2 FCSs. With 40 BRL/hour, it is better to have 9 FCSs. The corresponding 9 FCS locations are shown in Fig. 12 (geographically averaged from all Monte Carlo simulations). FCS locations A and B correspond to travel time costs of 10 and 25 BRL/hour. Crosschecking Fig. 12 and Fig. 2, it can be seen that most of the chosen FCSs are outside the city centre (only FCSs C, D and I are inside). This is because roads have higher flow (more vehicles passing per time), particularly in the more populated northern and western areas, and land is cheaper.

Every location in Fig. 12 has a specific number of charging points, transformer size, and land area. This breakdown is presented in Table II. The number of charging points is rounded to the closest integer after averaging all Monte Carlo simulations. For the solutions considering travel time costs of 10 and 25 BRL/hour, 119 charging points, two large transformers (2.5 and 5 MVA) and 1,970 m² of total area (two stations with 985 m² on average) are necessary. Considering 40 BRL/hour, 148 charging

Table II. Infrastructure Breakdown of the Cost-Effective Solutions.

Travel Time Cost (BRL/h)	FCS	Number of Charging Points	Transformer Power (kVA)	Area (m ²)
10 and 25	A	45	2,500	745
	B	74	5,000	1,225
40	A	11	750	182
	B	9	500	149
	C	30	1,500	497
	D	14	750	232
	E	20	1,000	331
	F	12	750	199
	G	19	1,000	315
	H	14	750	232
	I	19	1,000	315

Table III. Cost Breakdown of the Cost-Effective Solutions.

Travel Time Cost (BRL/h)	Capital		Indirect		
	Charging point (%)	Land (%)	Transf. (%)	Loss of prod. (%)	Reinf. (%)
10	72.69	12.05	1.96	13.13	0.17
25	60.75	10.07	1.64	27.40	0.14
40	66.44	44.41	1.44	-12.31	0.02

points, smaller transformers (most between 750 kVA and 1 MVA) and 2,452 m² of total area (9 stations with 272 m² on average) are required.

Table III shows the overall cost broken down into the different capital and indirect costs. The solution considering 10 BRL/hour is comprised of 86.70% capital cost and 13.30% of indirect cost. These values change to 72.46% and 27.54% with 25 BRL/hour. With the highest travel time cost, 40 BRL/hour, loss of productivity is negative, i.e., the entire population of vehicles is spending less time travelling when FCSs are adequately located. This is because they rearrange the traffic in a way that traffic jams are reduced. This, in turn, compensates part of other costs. Interestingly, for all travel time costs, transformer and reinforcements play minor roles, being responsible for up to 2.13% of the overall cost. This is a consequence of the values assumed to each component cost: a single charging point costs 100,000 BRL while the transformer to connect it to the electric system is up to 5,000 BRL – which is 5% of the charging point. Also, as the FCSs are connected to the MV systems through a dedicated transformer, reinforcements are less likely, and the unitary costs used for reinforcement are small compared to the charging point (see Appendix).

On the other hand, charging points correspond to at least 60%. Loss of productivity and land, however, had opposite trends. With a few FCSs, the more the prominent the loss of productivity is with respect to land and the overall cost. With more FCSs, this importance reduces, making land a more prominent cost. In fact, for the case with 10 and 25 BRL/hour, the FCSs A and B are placed outside the city centre, where land is cheaper; while the nine FCSs for case 40 BRL/hour are much closer to the centre, where land is more expensive (see Fig. 2).

One of the benefits of having the breakdown of cost is that it is possible to explore the effects that the absence of certain capital or indirect costs have in the FCS allocation. For instance, if the cost related to the charging points or the

FCS transformer is not considered, the most cost-effective solutions do not change. The same result is obtained if the reinforcement costs are removed. Not considering the land cost, however, can have a dramatic effect. It results in 3 and 9 FCSs as solutions for travel time costs of 10 and 25 BRL/h, respectively; but the solution for 40 BRL/h remains the same. Neglecting the loss of productivity (i.e., the effects on traffic flows) has also an impact. It results in only 1 FCS as the most cost-effective solution for all travel time costs.

It is important to highlight that similar works in the literature (such as [18] and [19]) also found that: (i) the recommended FCS infrastructure is mostly located along roads with high traffic flows; and, (ii) loss of productivity and capital costs are the most important component costs. While there is alignment in the qualitative nature of those findings, the deterministic and simplified models adopted in [18] and [19] can lead to inaccurate results. For instance, errors in the recommended locations of the FCSs can create unnecessary reinforcement costs. Furthermore, those works do not provide a deeper understanding of the costs involved and their interactions, which is valuable when searching for cost-effective solutions.

Although the proposed methodology provides a more holistic result for the allocation of FCSs, the EV penetration was held constant throughout the period of analysis in the case study. This, however, may not be valid throughout the horizon of interest. Nonetheless, the proposed methodology can be adapted to cater for growth patterns of the EV penetration, transport system and electric load, relating costs to the corresponding year of investment.

4. Conclusions

This paper presented, as a key contribution, a scalable methodology that allows determining the most cost-effective number, locations and sizes of fast charging stations (FCSs) across large metropolitan regions considering the overall societal cost of EV infrastructure. Characteristics of the methodology that ensure realistic results are:

- Accounts for the effects in the traffic flow quantifying the impacts on loss of productivity of the population (cost of travel times) from installing a given number of FCSs; which determines the corresponding number of charging points, land area, and FCS transformer size;
- Accounts for the effects on the electric system quantifying the required reinforcements (if needed);
- Allows for the integration of high-resolution (e.g., 15 min) detailed traffic flow models with uncertainties in driving patterns (intra and inter-city) and electrical models (three-phase, medium and low voltages).

The proposed methodology was applied to the transport and electric distribution systems of the Campinas Metropolitan Region in the state of Sao Paulo, Brazil. The results demonstrate that:

- Considering the overall cost of EV charging infrastructure, in particular, taking into account the loss of productivity due to increased travel times, can have a significant effect on the geographical location and sizes (number of charging points) of FCSs;

- Capital costs are larger as more FCSs are installed because each FCS must meet the maximum number of EVs that simultaneously charge at any given time. Whilst an extra FCS will re-arrange the traffic, it will not necessarily reduce the peak time requirements of other FCSs as this might happen at different times. This leads to a larger number of charging points, land areas, transformers sizes and, consequently, more costs;
- Indirect costs (loss of productivity and electric system reinforcements) reduce in metropolitan regions as more FCSs are installed because more FCSs re-arranged the traffic flow in a way that traffic jams are reduced, hence, shorter travel times for the entire population of vehicles. From an electric perspective, with more FCSs, smaller peak demands occur because the charging points are spread across different medium voltage systems. This reduces the number of overloaded lines and, consequently, the reinforcement cost.

In summary, considering only the capital cost in the allocation of FCSs leads to fewer locations and charging points, which can have a significant impact on traffic flows. Conversely, considering only the loss of productivity leads to more FCSs as this reduces traffic jams; but increases the investment. Consequently, the proposed methodology can help planners of future cities considering the overall costs and stochastic behaviour of drivers to determine the most adequate EV charging infrastructure.

Finally, this methodology can be expanded in two directions: (i) to cater for reinforcements in the transportation system as loss of productivity plays a major role; and, (ii) to cater for future operational aspects of the electricity system, potentially including energy markets, and interactions with distributed energy resources such as photovoltaic and storage systems.

5. Acknowledgments

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7. Appendix

The unitary cost of transformers used to connect FCSs to the MV system or reinforce the electric system is shown in Table IV. The unitary cost of cables for 15 kV (medium voltage) and 1 kV (low voltage) systems are shown in Table V and Table VI, respectively.

Table IV. Unitary cost of transformers per rated power.

Rated Power (kVA)	Cost (BRL)
15	0
30	4,222
45	4,525
60	5,000
75	5,531
112.5	6,522
120	6,900
150	7,288
225	9,000
300	10,700
500	20,000
750	29,000
1,000	38,000
1,225	47,000
1,500	56,000
10,975	1,000,000
26,600	1,800,000

Table V. Unitary cost of MV cables (class 15 kV) according to their rated current.

Size	Type of Conductor	Rated Current (A)	Cost (BRL/km)
6 AWG	Aluminium	103	9,568
4 AWG	Aluminium	115	9,869
2 AWG	Aluminium	152	10,669
2 AWG	Aluminium Steel Reinf.	175	11,736
1/0 AWG	Aluminium	200	11,849
2/0 AWG	Aluminium	235	12,779
4/0 AWG	Aluminium	375	15,179
120 mm ²	Cooper	425	15,253
336.4 MCM	Aluminium	495	22,239
336.4 MCM	Aluminium Steel Reinf.	500	24,463
447 MCM	Aluminium	540	25,039
447 MCM	Aluminium Steel Reinf.	615	27,543
240 mm ²	Cooper	670	30,506
300 mm ²	Aluminium	797	31,777
500 mm ²	Cooper	1,045	71,689
800 mm ²	Cooper	1,400	99,144

Table VI. Unitary cost of LV cables (class 1 kV) according to their rated current.

Size (mm ²)	Type of Conductor	Rated Current (A)	Cost (BRL/km)
10	Aluminium	44	4,790
16	Aluminium	59	5,040
25	Aluminium	80	5,565
16	Cooper	87	6,048
35	Aluminium	100	6,190
50	Aluminium	122	6,860
35	Cooper	136	7,428
70	Aluminium	157	8,022
90	Aluminium	190	9,190
70	Cooper	210	9,627
120	Aluminium	229	10,147
120	Cooper	296	12,177
240	Cooper	520	24,353