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Could Petrol Stations Play a Key Role in Transportation Electrification? A GIS-Based Coverage Maximization of Fast EV Chargers in Urban Environment

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ABSTRACT To achieve net-zero in the transportation sector, there is a need to deploy public electric vehicle (EV) fast chargers to boost customer confidence. Currently, charge point operators and EV manufacturers focus on deploying chargers to cover highway networks and the progress in urban environments is inadequate. This is becoming an obstacle for potential EV buyers who do not have access to dedicated chargers or cannot afford expensive EVs with larger battery packs. Since mainstream combustion engine vehicle drivers are accustomed to using petrol stations, this paper examines the suitability of such sites as candidate locations to deploy fast chargers. Spatial analysis is carried out by comparing their coverage performance with existing locations of the fast chargers. More specifically, the location problem is modelled as a maximum coverage location problem (MCLP) and solved using a geographic information system (GIS) based platform. The spatial optimization problem is solved using a linear-programming relaxation based MCLP algorithm developed in Python. Five cities with growing populations, namely San Clara, CA, Salt Lake City, UT, Raleigh, NC, Denver, CO, and Los Angeles, CA, are chosen as case studies. The location analysis is carried out with two demand metrics (population and road traffic) using actual GIS data collected from public authorities. The results show that deploying fast chargers at existing fuel stations significantly increases the coverage needed for EVs. This study will provide useful insights into EV fast charging station planning in urban cities, as the related research is still in its infancy.

INDEX TERMS Electric vehicles, fast chargers, GIS systems, location analysis, petrol stations.

I. INTRODUCTION

A. BACKGROUND

Electric vehicles (EVs) form a nexus between transportation and power sectors that are under epochal transformation towards a net-zero future. It has been well-documented in the literature that EVs offer substantial societal benefits, such as climate change mitigation and improvement of urban air-quality [1]. Furthermore, EVs can be used to support the power systems operations through ancillary services [2] and enable higher penetrations of renewables by smoothing solar duck curves [3] and reducing wind curtailment [4].

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To support EV adoption, a number of countries including the UK, EU, and the USA have introduced time-bound, bold, and front-loaded plans to reach net-zero to decarbonize the transport sector [5]. By year 2030, more than ten of the world's leading economies such as Norway, UK, and Netherlands aim to ban the sales of petrol/diesel cars, while the number of countries aiming to reach 100% EV sales is expected to be doubled by year 2040 and will include the majority of the Group of Twenty (G20) countries that represent more than 80% of the global economy [6].

More recently, major car manufacturers such as Ford, Volvo, and General Motors have signed the Glasgow Declaration on Zero Emission Cars and Vans at the United Nations Climate Change Conference (COP26) to manufacture low

carbon vehicles by 2035 [7]. In parallel, the EV market has witnessed a rapid growth and global EV stock has exceeded 10 million in 2020 [1]. EV sales in the European Union have exceeded one million and accounted for 15% of the new car sales in the first half of 2021 [8].

Despite a growing political and environmental push, several challenges still need to be addressed to accelerate EV adoption. The first barrier is related to customer purchasing behavior and education. Similar to any other mass-market adoption of critical technologies, early adopters of EVs are typically technology enthusiastic (as described by Roger's diffusion of innovation model [9]) who are usually from a high-income family and have dedicated chargers [9]. For instance, the work presented in [10] shows that 80% of the early adopters in California have higher income than the median income in California. This study further shows that the majority of the EV owners have dedicated level 1 or 2 chargers. On the other hand, the characteristics of mass market adopters will dramatically change as the market evolves. Mass adopters may not be as informed as the early adopters and there will be a need for a higher number of EV charging stations, particularly for drivers with no access to garage charging.

At present, two-thirds of the EV charging occurs at customer premises because most of the early adopters have access to private charging space. On the other hand, public charging activity is expected to grow by tenfold in Europe and half of the EV demand will be supplied by public stations [11]. Urban fast chargers located at petrol stations will play a critical role in the evolving EV ecosystem as they own critical assets that can not only sell EVs but also provide charging service.

The second barrier is called as "range anxiety" that is defined as the psychological fear that a driver experiences due to the limited driving range of EVs [12]. Recent field study in the UK show that majority of the EV drivers recharge their vehicles after every trip, although the remaining stored energy could support further trips [13]. Therefore, the presence of public chargers is essential for promoting EVs. For instance, Ref. [14] shows that 290 "charging locations" could cover 98% of all driving in California and 88% of long-distance driving. In this study, freeway exists, and highway intersections were used as candidate locations to deploy chargers.

A recent study presented in [15] shows that one fifth of EV owners in California have switched back to combustion vehicles due to dissatisfaction (lack of coverage and long service durations) with the charging infrastructure. Moreover, a scaled and transformational change towards electric transportation is beyond a technical challenge, but also includes economic and behavioral challenges. Electric vehicles will be fuelled by electrical power grids, which are aging and require significant network reinforcements to support EV charging. A scenario-based cost-benefit analysis for the UK is reported in [16].

The presence and wide-coverage of fast charging stations is a key to enable higher penetrations of EVs and beat range-

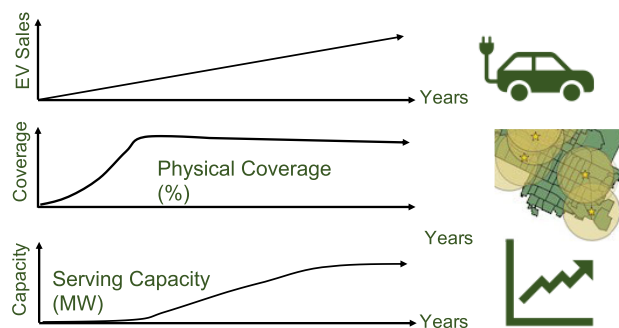


FIGURE 1. Overview of EV infrastructure capacity and coverage problems.

anxiety [17]. One of the primary reasons is that internal combustion engine vehicle drivers are accustomed to the convenience and coverage that ubiquitous petrol fuelling stations provide. The main differences between the petrol fuelling stations and EV charging network are related to delivery and storage of the supply. Petroleum and its derivatives can easily be stored and delivered to end users via well-established petroleum industry networks.

On the other hand, electric power networks are real-time supply demand systems with limited storage capacities and tight control on supply-side. Therefore, charging station deployment is a more complex problem and requires addressing two key components: coverage and capacity. Coverage can be described as the ability of an EV driver to access a charging station within a certain time and travel distance. On the other hand, capacity problem deals with increasing the number of EVs that a station can serve at the same time, hence related to capital investments. Charging station facility location problems are capital-intensive one-time decisions that have long-lasting ramifications and require careful planning. An illustrative schematic view of the capacity and the coverage problems is shown in Figure 1.

B. CONTRIBUTIONS

The contributions of this paper can be listed as follows:

- We present a systematic literature review on EV charging standards, EV fast charging systems and approaches to create charging networks in urban and highway networks.
- We propose a methodology to deploy fast charging stations using QGIS software and implemented spatial optimization problem in Python. We show how to use population and traffic data as demand metrics to maximize the charging station network coverage with minimum number of stations.
- We present collected GIS data sets (maps, highways, population, petrol, and EV charging station locations) of five major cities in the United States with growing populations to analyze the coverage of petrol and existing EV fast charging stations.

TABLE 1. An overview of DC fast charging standards [18].

	Chademo	CCS-1	CCS-2	Tesla
Rated Power	50 kW	312 kW	350 kW	350 kW
Maximum Power	400 kW	350 kW	350 kW	250 kW
Region	Global	US, South Korea	Europe	Global
Output DC Voltage	50-1000V	200-1000V	200-1000V	300-480 V
Output DC Current	400 A	500 A	500 A	800 A
Time/100 km	13.73 min	4.4 min	1.96 min	2.74 min
Range/5min	36.4 km	113.54 km	254.73 km	181.95 km
Example	Delta Ultra Fast Charger	Charge Point Express Plus	ABB Terra HP	Tesla V2 Supercharger

- Detailed case studies are designed, and results are analyzed to discuss the relationship between the percentage of station coverage, required number of facilities, demand metrics, and population/size of the city. The results indicate that existing petrol stations could significantly increase the coverage of urban charging networks when compared to existing approaches.

The present paper builds upon of our previous work [19] in which we investigated the coverage performance of petrol stations in a single city (Raleigh, NC). To provide stronger evidence to support our hypothesis on deploying fast chargers primarily at petrol stations in urban settings, this present paper investigates four more cities with distinct characteristics shaped by population and traffic dynamics. The overarching goal is to provide useful insights for network planners and show how parameters such as traffic and population density impact charging network coverage.

The rest of the article is organized as follows. Section II presents a detailed literature review of EV chargers, trends, and charging infrastructure planning approaches. Section III presents theoretical approaches to spatial optimization and facility location theory. Section IV presents the optimization problem, discusses solution methods, analyzes data sets for GIS maps and case studies. In Section V, the results of the case studies are presented in detail along with a detailed discussion. Finally, in the last section, conclusions, limitations of the study, and future directions are given.

II. LITERATURE ON EV CHARGING LANDSCAPE

A. EV CHARGER TYPES

Depending on the location of facilities, EV chargers can be divided into two groups. The first group is composed of (i) dedicated garage charger that are mostly level 1 (120 V, single phase) and use standard outlets with rated AC power up to 1.9 kW or (ii) level 2 chargers with a typical charging rate of 7.2 kW (240V, split phase) [18]. Chargers located at public places form the second group, which is composed of level 2 chargers (can go up to 19.2 kW depending on the maximum current) and fast DC chargers. It is noteworthy that AC chargers discussed so far follow Society of Automotive Engineers (SAE) J1722 standards and used in the United States, Japan, and South Korea. A detailed analysis of charging standards can be found in [18] and [20].

DC fast charging, on the other hand, uses off-board power electronics and uses higher maximum power (up to 400 kW) with a typical charging rate of 50 kW. Convenient and publicly accessible chargers will be increasingly important as EVs scale up. Therefore, DC fast charging stations are designed to compete against petrol stations and primarily used to extend EV usage in short durations [21]. An overview of DC fast charging stations and standards are presented in Table 1. It can be seen that the time to charge an EV that can drive 100 km can be as low as 1.96 minutes. However, it is important to note that not all EV models can accept such high charging currents. For instance, high end sports EVs and SUVs can typically be charged with ultra-fast charging speeds (100 kW and more), while many sedans only accept 50 kW charging rate due to limited battery size and battery management capabilities. Moreover, the physical size of fast charging stations cannot be ignored. The typical size of a Tesla charging station with only four chargers is composed of the following equipments [22]:

- Tesla Supercharge panels,
- Panels for distribution, main breaking and metering, and incoming cable,
- Medium to Low Voltage Transformer.

The total size of the supporting electrical equipments is about 26 square meters. To that end, candidate locations for deploying fast chargers require availability of land, such as petrol retail locations.

B. EV CHARGING INFRASTRUCTURE PLANNING

EV infrastructure planning is often referred to as “chicken-egg” problem: drivers are reluctant to switch to electric transportation if the charging infrastructure is not sufficient, but the private sector is hesitant to invest in charging infrastructure if the charging stations are underutilized and not profitable [24]. Therefore, initial phases of charging infrastructures are usually supported by public funds to boost customer confidence and unlock environmental benefits. Moreover, the EU has recently updated the Alternative Fuels Infrastructure law and asked the member states to deploy 1 million public chargers (both AC and DC) by 2024 and 3 million chargers by 2029. An overview of fast and slow charging deployment since 2014 in various parts of the world is presented in Figure 2.

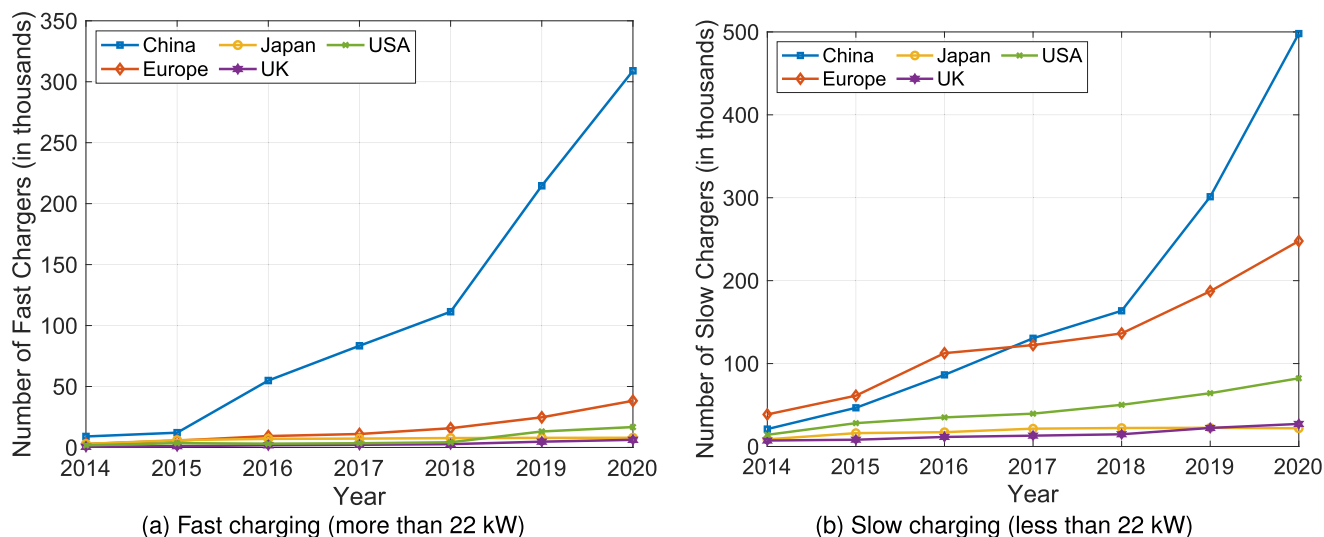


FIGURE 2. Annual fast and slow charging facilities in selected regions/countries (Data: International energy agency [23]).

In year 2020, there were almost 386,000 publicly available fast chargers worldwide, more than 80% of which were found in China. Similarly, there were 922,216 public slow charging (level 1 and 2) stations with more than 54% of them were in China [23]. In EV charging infrastructure planning, a natural question arises: Is there a golden ratio for the number of EVs to the number of public charging stations so that a steady increase in EV adoption is sustained? Answering this question is not easy and requires a region-specific framework that considers factors such as percentage of home charging, driving durations, battery types, weather conditions as critical inputs [25], [26]. For instance, in countries like China, Japan, and Singapore, the share of multi-dwelling buildings is higher than detached housing. Therefore, the share of fast charging points needed is significantly higher than other countries. The availability of garage charging reduces the capacity requirement for fast charging for short daily trips, particularly for the early market diffusion. On the other hand, investments for building home charging are also needed. In the US, nearly three-fourth of households are single-family houses with access to a garage, however, 52% of all households park no car within six meters of an electrical outlet [27].

A comparative analysis of early EV charging infrastructure planning for different countries is presented in [26]. Similarly, the US Department of Energy has developed an EV Infrastructure Projection Tool to estimate how much EV charging stations of all types are needed for a given region in the US and the number of EVs [28]. This tool uses a wide range of input data such as GPS traces, local temperatures, and top-selling vehicle attributes. In Europe, a number of different approaches have been followed in planning and deployment of public chargers. In Amsterdam, the City Council has installed fast chargers for taxis, which are also publicly accessible. In Paris, the City requires petrol retailers to install a fast charger to renew their contracts [27].

III. FACILITY LOCATION OPTIMIZATION

A. EXISTING METHODOLOGIES

Facility location, location theory, and siting are technical terms that are used interchangeably to represent spatial optimization methods that are used to decide on the locations of a certain number of facilities to serve demand in a given network [29]. In such problems, at least one “server” or “facility” is located among several existing demand points to serve them. The overarching goal is to optimize one or multiple quantifiable objectives related to customer demand, capital cost, and environmental benefits [30]. In related literature, EV charging location problem is divided into two groups. The first group of studies focuses on locating fast charging on a highway network [31], [32], while the second group of studies aims to locate both level 2 and fast chargers in an urban environment [33]. For the former case, continuous network models are used to locate fast chargers at anywhere in the highway network [29], [31]. In this case, the location optimization problem is usually modelled and solved by flow-capturing refueling problem (FCRP) and its variants [29]. In FCRP, the locations of the facilities are determined based on the origin destination traffic volumes and the all-electric range of EVs. It is noteworthy that in FCRP approach, all EVs are assumed that have the same driving range [31].

Locating charging facilities in urban environments differs from the highway case as the candidate locations (e.g. parking lots, petrol stations, etc.) are known in advance and discrete network models are applied [30]. Overall, there are two approaches for the urban setting, namely set covering problem from classical facility location theory and multi-criteria decision-making (MCDM) methods. Solving the set-covering problem is a widely preferred approach as it enables researchers to determine optimal locations without a need for acquiring sensitive and confidential information

about candidate locations such as population details and related finances. In a set-covering problem, the overall aim is to minimize the number of chargers (or other “servers”) such that customers (EV drivers) can reach a station within certain driving distance or duration.

In the literature, there are three subcategories of set covering problems, namely maximum coverage, p -center and p -median problems. In maximum coverage problem, which is used in this paper, the overall aim is to maximize the demand coverage for a given number of charging stations. In p -center problem, the aim is to minimize the maximum driving distance with for a given P stations. Similarly, p -median problem aims to minimize median driving range with P station [30], [34].

MCDM methods, on the other hand, use geospatial analysis for multi-criteria decision-making [35]. In this case, each candidate location is examined based on a number of factors such as the cost of the real estate, the availability of parking spaces, the distance to a green area, or even the slope of the location. A score is given to each category, and the locations are chosen based on the ranking of the total score for each site.

Note that existing studies on locating fast chargers in urban environment is part of wider research domain that falls under urban service facility location [36]. Existing methods are differentiated by assumptions, decision variables, input parameters, and constraints. What differentiates the present paper from existing ones primarily lies in the assumptions and input parameters. First, our primary assumption is taking existing petrol (referred as gas station in North America) stations as candidate sites for charging station location. Petrol stations have been accepted as the competitors of EV charging stations and, therefore, have not been considered as players in EV charging ecosystem. Moreover, petrol retail businesses need to be transformed in many countries to meet legislative requirements that ban the sales of new petrol and diesel cars.

Second, the proposed model is applied to five different cities with different traffic and population characteristics to provide sound evidence for our findings. Existing methods typically focus on a single city, and the results may vary in other case studies. Third, the methodology could be applied to other businesses such as car retailers and service centers who are expected to transform their businesses. Overall, this paper also aims to provide decision-makers with a comprehensive analysis to provide insights on the role of new players (e.g. petrol stations) in EV charging ecosystem.

B. PETROLEUM RETAIL BUSINESS

Petrol industry has a central role in modern economy by fuelling the transport sector that is essential for the mobility of the people and the goods. Fuel retail business are the distribution nodes and interfaces where drivers fill up their tanks. The first retail stations were opened in the early nineteenth century to support the growing passenger car needs [37]. Over the last century, the number of petrol stations has grown significantly; the number of retails has reached more than a

TABLE 2. List of selected abbreviations.

Abbreviation	Description
FCRP	Flow-capturing refueling problem
GIS	Geographic information system
LP	Linear programming
NP-hard	Non-deterministic polynomial-time
MCDM	Multi-criteria decision-making
MCLP	Maximum coverage location problem

hundred and ten thousand in the US, nine thousand in the UK and fifteen thousand in Germany [38].

Over the last two decades, the number of petrol stations has been declining due to fuel efficiency improvements in cars and evolving business models. The long-term demand forecasts envisage a decline in fuel retail business due to the commitment of companies and industries to support net-zero goals and increased use of shared and electric mobility [39]. On the other hand, a strong value pool is emerging in EV charging, and the public fast charging is expected to reach \$20 billion globally by 2030 from \$0.1 billion in 2020 [39]. In fact, several fuel retailers have started to deploy fast chargers at their facilities. For instance, Shell has announced to deploy half a million chargers globally by 2025.

Petrol retail business has a competitive advantage and can unlock additional value from their strategic real estate locations from EV charging. The retail business is a century-old industry and “optimized” to serve the refuelling needs of the drivers, and they come to the forefront as “good” locations to site chargers [19]. For instance, according to a GIS-based study presented in [40], 98% of the postal codes in the UK can reach a petrol station within ten minutes of driving, while the remaining 2% is located in rural parts of the country (e.g. Scottish Highlands). In this study, the travel times are estimated from the centroid of each postcode to the nearest fuel stations. In our calculation, we perform a similar approach and calculate the distances from the centroid of each zone. It is noteworthy that a partial coverage could also be allowed, however, this approach would require more granular GIS data that shows spatial distribution of demand inside a census zone.

IV. MAXIMAL COVERAGE LOCATION PROBLEM

In this section, maximal covering location problem (MCLP) is used to evaluate the and compare the coverage of existing EV charging stations with petrol stations [45]. The overall goal is to find and locate the minimal number of stations to ensure that demand request can reach a charging station within S km. Demand points are determined from population and traffic zones, two separate metrics, that are provided by local governing bodies such as city councils and county officials. It is noteworthy that in case studies various diameter ranges (3 km, 5 km, etc.) are used. Hence, if the centroid of a zone is less than S km away from a charging site, then that specific zone is assumed to be “covered.” Note that

TABLE 3. Detailed information on the cities selected for case studies.

City	State	Population	Census Ranking (out of 326)	Total Area (sq km)	No. of Census Zones	% of Single-family Units	% of Multi-family units	GIS Ref.
Los Angeles	CA	3,898,747	2	1300	1012	45.8	54.2	[41]
Denver	CO	715,522	19	400	481	55.0	45.0	[42]
Raleigh	NC	467,665	382	41	248	55.1	44.9	[43]
Salt Lake City	UT	197,756	122	286	94	52.7	47.3	[44]
Santa Clara	CA	127,647	217	47	80	54.6	45.4	[41]

the primary reason for choosing MCLP over other previously methods is that such facilities will act as “emergency service” facilities for refueling and needed within a certain distance.

A. PROBLEM FORMULATION

The MCLP problem contains of linear and integer variables and formulated as below:

$$\text{Maximize } \sum_{i \in I} a_i y_i \quad (1)$$

$$\text{s.t. } \sum_{j \in N_i} x_j \geq y_i \quad \forall i \in I \quad (2)$$

$$\sum_{j \in J} x_j = P \quad (3)$$

$$x_j = (0, 1); \quad \forall j \in J \quad (4)$$

$$y_i = (0, 1); \quad \forall i \in I, \quad (5)$$

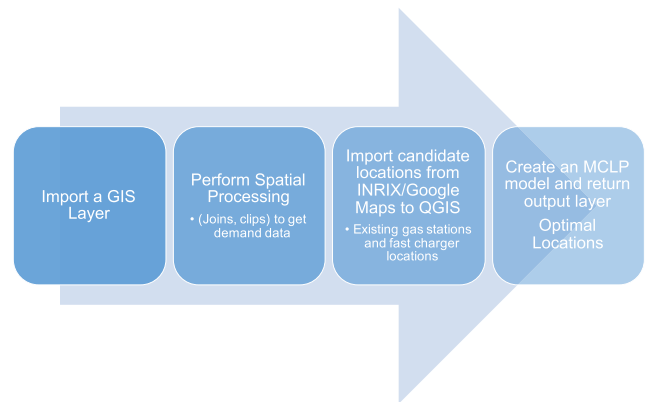
where I is the set of demand nodes (either population or traffic); J is the set of candidate facility sites (existing EV chargers or petrol stations). Moreover, let d_{ij} denote the shortest distance from node i to node j . Then the set N_i which shows the set of eligible locations to cover demand point i is written as $N_i = \{j \in J | d_{ij} \leq S\}$. Variable a_i is the population that is contained in the demand node i ; and P denotes the number of charging stations to be sited. Moreover, binary variables x_j and y_i are as follows

$$x_j = \begin{cases} 1, & \text{if potential station site } j \text{ is selected} \\ 0, & \text{otherwise} \end{cases}$$

and

$$y_i = \begin{cases} 1, & \text{if demand node } i \text{ is suitably covered by one} \\ & \text{or more stations} \\ 0, & \text{otherwise} \end{cases}$$

The objective function (given in equation (1)) aims to maximize the coverage of demand within the driving distance. The y_i decision variable reflects whether a demand node i is covered by a sited facility, hence the goal is to maximize the weighted sum of those demand nodes served by chargers. The constraint given in (2) shows that y_i equals to 1 when one or more stations are established at locations in the set N_i (i.e., one or more stations are located within S km of demand point i). The second constraint given in (3) ensures that exactly P stations are allocated. The remaining two constraints, (4) and (5) show x_j and y_i are binary variables.

**FIGURE 3.** Methodology for GIS analysis.

B. SOLUTION METHOD

The MCLP problem is an NP-hard optimization problem and can be either solved by heuristic methods as discussed in [46] or linear programming (LP) relaxation. In literature, some heuristic methods including greedy-add heuristic, greedy-add-with-substitution heuristic, and genetic algorithms are used to solve MCLP problems [46]. However, such methods do not guarantee optimal solution and could be slow compared to the guaranteed solutions. On the other hand, LP relaxation is another widely used approach, as LP programs are polynomial time algorithms with low computational complexity. In this case, the following steps are followed:

- Relax the integrality constraints (x_j and y_i as given in (4) and (5), respectively) and allow variables to take on non-integral values;
- Solve the resulting LP and obtain fractional optimal solution;
- “Round” the fractional solution to obtain an integral feasible solution [47].

Note that most LP solvers use Revised Simplex Method in which it is guaranteed to converge to solution to any problem in polynomial-time algorithm. Note also that every feasible solution to the original integer program lies in the feasible region of the transformed LP and the cost function (in this case negative of (1)) is less than or equal to the optimal solution of ILP. To that end, LP relaxation is used and implemented in Python’s PuLP with GLPK package [48].

C. CASE STUDIES

To examine the suitability of petrol station and compare their coverage with the existing fast charging stations, five cities,

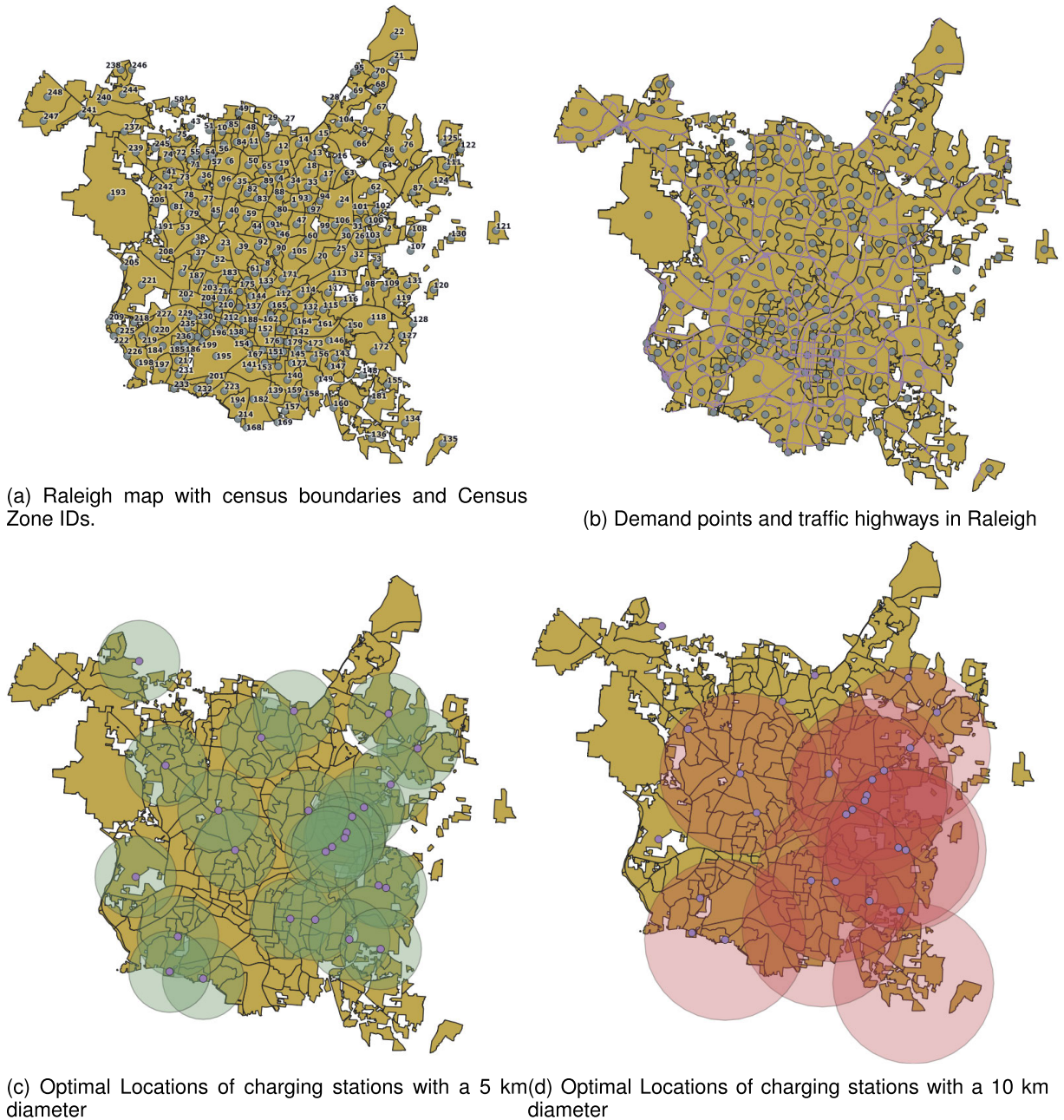


FIGURE 4. A detailed overview of GIS analysis for Raleigh, NC.

namely San Clara, CA, Salt Lake City, UT, Raleigh, NC, Denver, CO, and Los Angeles, CA with growing population levels and land areas are chosen. The primary reason for this selection is related to accessibility of high-resolution population and traffic data. Moreover, to make a fair comparison and have minimal socio-economic differences, all cities are chosen from the same country, United States. Detailed descriptions of the selected cities and related attributes are presented in Table 3.

From this table, it can be seen that the City of Los Angeles is the second most populous city in the US and also experi-

ences high traffic congestion. Moreover, State of California has bold transport electrification plans and the importance of urban charging networks will be quite critical in the near future. In the US, there are eleven cities with population higher than one million and Los Angeles represents such cities except of New York City which has significantly higher population density than the rest of the country.

Denver, on the other hand, is chosen to represent 26 cities with population 0.5-1 million. Similar to California, the State of Colorado has introduced bold plans to push EVs into mainstream [49]. Other case studies, namely Raleigh, Salt

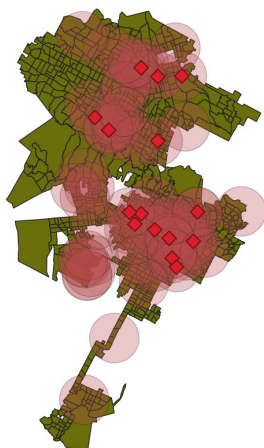


FIGURE 5. Los Angeles, CA GIS map.

Lake City, and Santa Clara are chosen similarly to mimic different population intervals.

D. GIS ANALYSIS

The GIS analysis using official census data (both population and traffic) are carried using QGIS software [50]. It is noteworthy that the demand points, denoted by set I in equation (2), relate to population data or traffic data.

Each bounded demand polygon hosts an attribute of the population of a specific census block. The demand points are computed as centroids of each bounded demand polygons, and a spatial join is used to append attributes to the centroids. For the second case where traffic is used as the demand metric, highways' sections typically pass through multiple census blocks. In this case, the traffic layer is averaged for a demand polygon and added as an attribute to the centroid that contains the highway road.

Another important part of the analysis is obtaining actual coordinates of petrol and EV fast charging stations. To acquire location information, Google Maps was used for petrol stations and the US Department of Energy Alternative Fuels Data Center was used to acquire fast charging station locations [51]. Next, candidate locations and demand data sets are imported and the modified spatial layers are fed into the MCLP algorithm. To calculate the distance between facilities and demand points, a Python API for QGIS was developed to create a matrix of distances using Euclidean distance metric.

As a final step, the MCLP algorithm calculates the locations of the charging stations to maximize the demand coverage for both demand metrics. An overview of the methodology is depicted in Figure 3, while a sample and detailed GIS analysis for Raleigh, NC are presented in Figures 4a, 4b, 4c, and 4d. For instance, Figure 4a shows census zones and point IDs for each zone. The highest population attribute for point ID 22 is 8745, hence, one of the first stations is deployed near zone 22. Figure 4b shows the highway network and as explained above, when multiple road

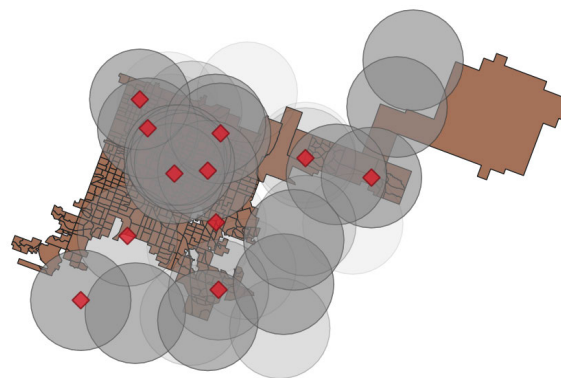


FIGURE 6. Denver, CO GIS map.



FIGURE 7. Salt Lake City, UT GIS map.

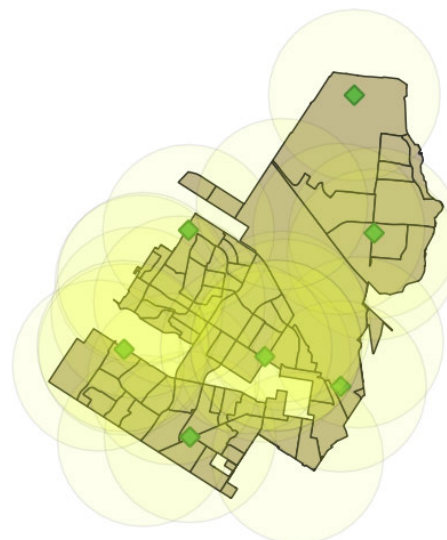


FIGURE 8. Santa Clara, CA GIS map.

segments passes through a zone, the total traffic is considered. Figure 4c presents an optimal allocation of charging stations with a coverage of 5 km diameter, while Figure 4d shows the coverage for 10 km for the same setting.

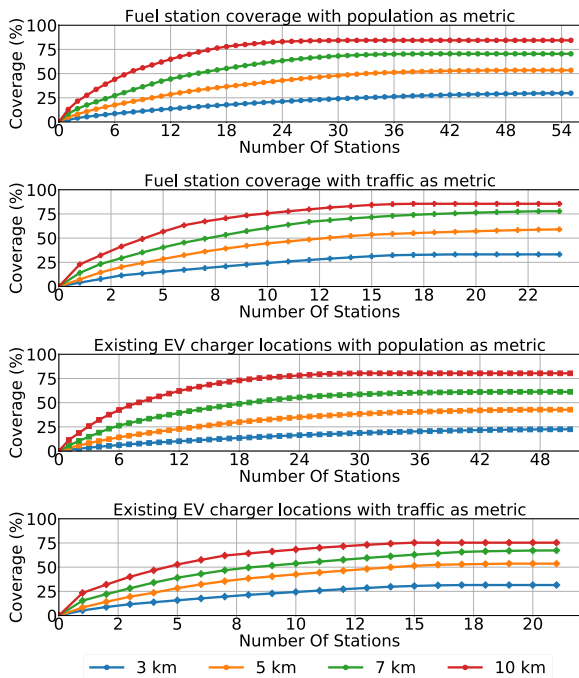


FIGURE 9. EV coverage results for Los Angeles, CA.

V. RESULTS

In addition to the coverage analysis presented for Raleigh, NC, the GIS analysis is further carried out for the remaining four cities with maps presented in Figures 5, 6, 7, and 8. For each city, four different coverage diameters, i.e., 3 km, 5 km, 7 km, and 10 km, are used to capture different local dynamics such as traffic and physical distance. For example, in large metropolitan cities, it could be acceptable for drivers to drive extra miles to reach a station (4-5 km), while a reasonable driving distance to a charger in small cities could be shorter (2-3 km). Ref. [52] presents an analysis of the time spent off-route to visit a petrol station in different cities in the US. The results show that there is a large discrepancy among cities; on average, it takes 5 minutes to reach a petrol station in Austin, TX, while it is 21 minutes in Los Angeles, CA.

In the case studies, two demand metrics, namely population and traffic (annual average daily traffic) are used. The rationale behind using the population metric is to represent the case where there is limited access to home charging, and the charging demand will be correlated to population and its spatial distribution. The traffic metric, on the other hand, is widely used in literature and aims to capture drivers who need extra charging during the day. From Figures 9, 11, 10, 12, and 13, it can be seen that the traffic metric leads to less chargers to reach the same coverage level when compared to coverage results with population metric. For instance, in Denver, CO to reach 90% coverage with 10 km diameter, 9 stations are needed with population metrics, while only 6 stations are sufficient to reach the same coverage with traffic metric. The reason for this difference is that more than half of the population lives in single housing units, and the population is typically dispersed across the city. On the other

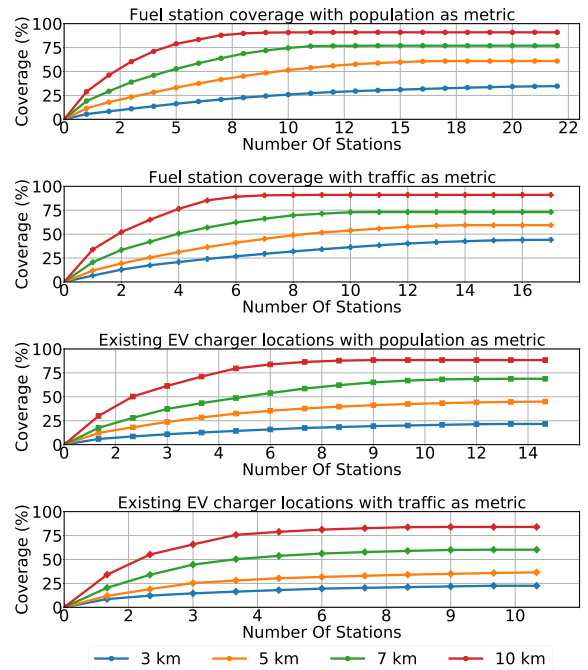


FIGURE 10. EV coverage results for Denver, CO.

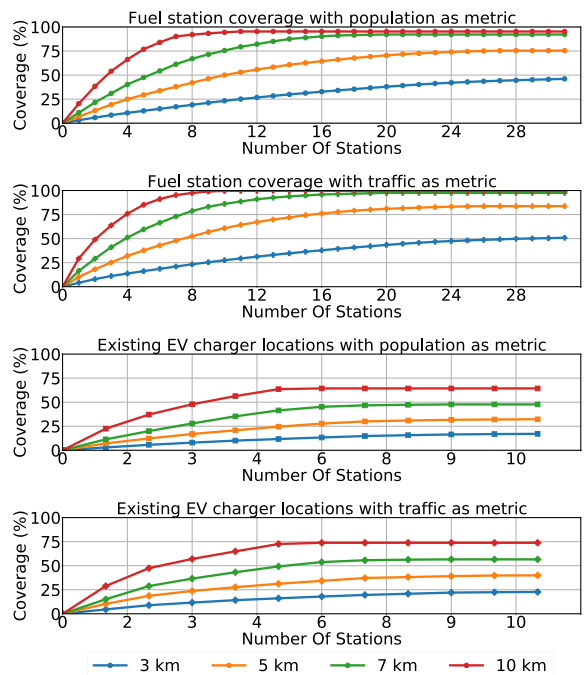


FIGURE 11. EV coverage results for Raleigh, NC.

hand, traffic demand is typically clustered across main roads and less number of stations leads to higher coverage.

An important comparison is made for the candidate locations, which are existing EV fast charging stations and petrol stations. For both demand metrics and four coverage distances, the coverage of both candidate locations are examined for all cities. It can be seen from the presented results that fuel stations provide significantly higher coverage when

TABLE 4. Comparison of results by percentage of covered demand.

City	Candidate Location PS or CS ²	Coverage Diameter	Population		Traffic	
			Max. Coverage - CS Corresp. Coverage - PS	Required Stations	Max. Coverage - CS Corresp. Coverage - PS	Required Stations
Los Angeles	PS	5 km	53.3%	47	56.5%	19
	CS		42.7%		53.6%	
	PS	10 km	84.3%	31	84.3%	15
	CS		80.8%		75.3%	
Denver	PS	5 km	59.0%	14	56.5%	11
	CS		55.84%		35.5%	
	PS	10 km	80.8%	13	91.1%	9
	CS		76.8%		83.9%	
Raleigh	PS	5 km	53.0%	11	64.3%	11
	CS		32.2%		39.9%	
	PS	10 km	84.0%	6	91.1%	6
	CS		64.3%		73.9%	
Salt Lake City	PS	5 km	66.4%	6	69.4%	6
	CS		42.3%		49.2%	
	PS	10 km	85.5%	3	87.6%	3
	CS		72.8%		81.2%	
Santa Clara	PS	5 km	78.5%	4	67.3%	1
	CS		58.7%		67.9%	
	PS	10 km	93.3%	2	88.4%	1
	CS		99.5%		99.7%	

¹ Abbreviations: PS: Petrol Station, CS: Charging Station, Corresp.: Corresponding, Max.: Maximum

² In all cases, CS leads to lower coverage, however, for fair comparison the same number of locations are considered for both cases.

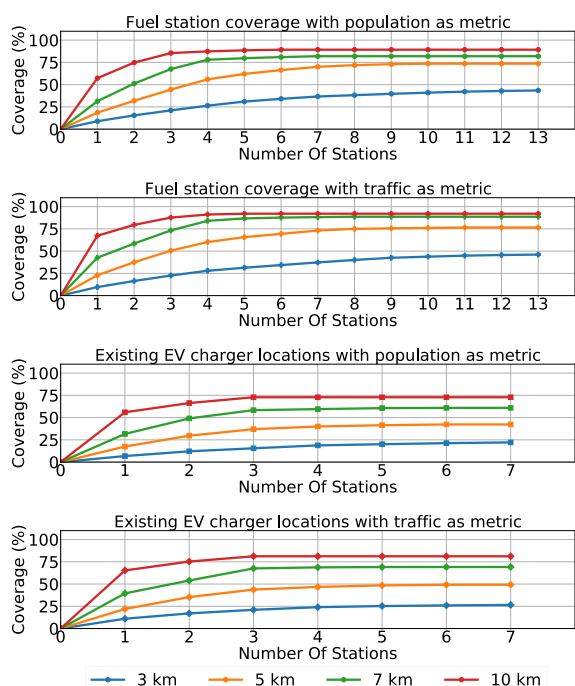


FIGURE 12. EV coverage results for Salt Lake City, UT.

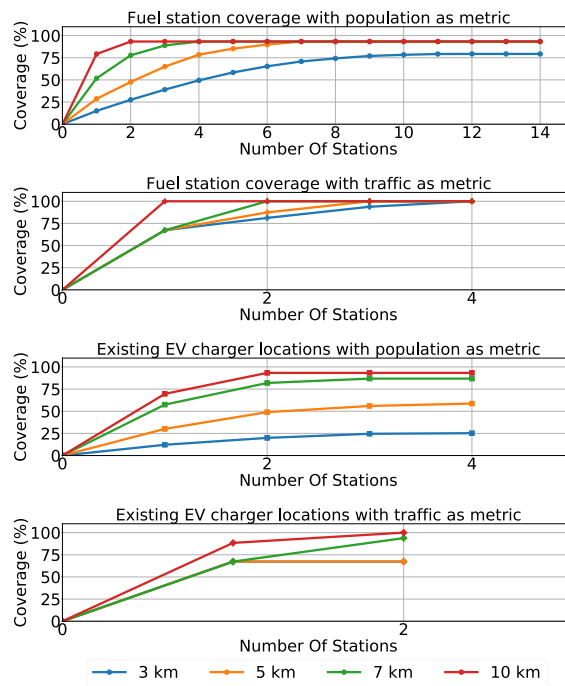


FIGURE 13. EV coverage results for Santa Clara, CA.

compared to existing fast chargers which are typically located in hotels, shopping malls etc.

In Table 4, a more detailed analysis is presented using both demand metrics. A number of important observations are made as follows. First, in all cases, locations of petrol stations provide a significantly higher coverage than existing locations of fast chargers. Second, in smaller cities, the number of stations required for both demand metrics is similar. On the

other hand, this is high (31 stations versus 15 stations for 10 km diameter) in large cities such as Los Angeles. This can be explained by the level of traffic congestion. Los Angeles has one most congested in the world, and high-demand values are contained in small road segments when compared to dispersed population statistics. The third observation is related to small cities such as Santa Clara, CA. In the US, there are more than one hundred cities with a population of one hundred

thousand or less. In such cities, a high coverage for EVs could be provided just a few charger locations.

VI. CONCLUSION

A. LIMITATIONS OF THE STUDY

Limitations of this study can be listed as follows. Due to availability of GIS data, all case studies were selected from the United States where the housing profile is balanced among single and multi-unit dwellings. For cities with higher population density (e.g. London, Paris) a new demand metric, composed of the weighted sum of population and traffic, could be used. Similarly, the maximal coverage problem only considers the centroid of each census zone and does not allow partial coverage. If there is access to higher resolution data (spatial distribution of demand inside a census block), then the approach presented in this paper can be expanded to allow partial coverage of demand nodes, as outlined in Ref. [53].

B. DISCUSSIONS

Public charging infrastructure deployment is a critical step in sustaining a steady growth in EV sales and alleviating congestion at charge points. The methods and analysis presented in this paper are intended to assist policymakers and other stakeholders (e.g., charge point operators and petrol retailers) by highlighting an effective way of increasing EV fast charging network coverage in urban environments. The analysis showed that current approaches to locate fast chargers in areas such as hotels and shopping malls are far from optimal and petrol retail business could be a key in developing a network of fast charging stations in urban areas. Detailed spatial analysis for five cities in the United States was conducted. The results show that petrol retailers could transform their business to benefit from a growing value pool and inherently contribute to net-zero transformation. To the best of authors' knowledge, this is the first study that examines the suitability of petrol stations in EV charging ecosystem.

C. FUTURE DIRECTIONS

This present paper can be improved in two ways. First, by obtaining EV charging habits of drivers for a given city, corresponding demand metrics could be modified to eliminate those who regularly charge at home or work. This way, more stations would be allocated to regions with higher multi-dwelling buildings. The second direction is addressing the capacity problem. In this case, hypercube queuing models can be employed to enable multiple chargers to be deployed in a given location to minimize the waiting time of customers. By further allowing customers to be routed between neighboring stations, overall network performance could be improved as more vehicles could be charged with minimal system upgrades.

REFERENCES

- [1] *Global EV Outlook 2021*, International Energy Agency, Paris, France, Apr. 2021.
- [2] A. Ghazanfari and C. Perreault, "The path to a vehicle-to-grid future: Powering electric mobility forward," *IEEE Ind. Electron. Mag.*, early access, May 28, 2021, doi: 10.1109/MIE.2021.3072602.
- [3] R. Jovanovic, S. Bayhan, and I. S. Bayram, "A multiobjective analysis of the potential of scheduling electrical vehicle charging for flattening the duck curve," *J. Comput. Sci.*, vol. 48, Jan. 2021, Art. no. 101262.
- [4] J. Dixon, W. Bukhsh, C. Edmunds, and K. Bell, "Scheduling electric vehicle charging to minimise carbon emissions and wind curtailment," *Renew. Energy*, vol. 161, pp. 1072–1091, Dec. 2020.
- [5] A. Nurdawati and F. Urban, "Towards deep decarbonisation of energy-intensive industries: A review of current status, technologies and policies," *Energies*, vol. 14, no. 9, p. 2408, Apr. 2021.
- [6] *Global EV Outlook 2021*, Int. Energy Agency, Paris, France, 2021.
- [7] *Countries, Cities, Carmakers Commit to End Fossil-Fuel Vehicles by 2040*. Accessed: Dec. 20, 2021. [Online]. Available: <https://www.reuters.com/business/cop/six-major-carmakers-agree-phase-out-fossil-fuel-vehicles-by-2040-U.K.-says-2021-11-10/>
- [8] *Electric Vehicle Outlook: 2021 and Beyond. Analyzing EV Markets Around the World*, Bus. Wire, Dublin, Ireland, 2021.
- [9] J. H. Lee, S. J. Hardman, and G. Tal, "Who is buying electric vehicles in California? Characterising early adopter heterogeneity and forecasting market diffusion," *Energy Res. Social Sci.*, vol. 55, pp. 218–226, Sep. 2019.
- [10] J. H. Lee, D. Chakraborty, S. J. Hardman, and G. Tal, "Exploring electric vehicle charging patterns: Mixed usage of charging infrastructure," *Transp. Res. D, Transp. Environ.*, vol. 79, Feb. 2020, Art. no. 102249.
- [11] M. Hagenmaier, C. Wagener, J. Bert, and M. Ohngemach. (2021). *Winning the Battle in Charging Ecosystem*. Accessed: Dec. 2021. [Online]. Available: <https://www.bcg.com/publications/2021/the-evolution-of-charging-infrastructures-for-electric-vehicles>
- [12] L. Noel, G. Zarazua de Rubens, B. K. Sovacool, and J. Kester, "Fear and loathing of electric vehicles: The reactionary rhetoric of range anxiety," *Energy Res. Social Sci.*, vol. 48, pp. 96–107, Feb. 2019.
- [13] (2021). *Sciurus: Domestic V2G Demonstration*. Centre of Excellence for Low Carbon and Fuel Cell Technologies. [Online]. Available: <https://www.cenex.co.U.K./projects-case-studies/sciurus/>
- [14] L. Zhang, B. Shaffer, T. Brown, and G. Scott Samuelsen, "The optimization of DC fast charging deployment in California," *Appl. Energy*, vol. 157, pp. 111–122, Nov. 2015.
- [15] S. Hardman and G. Tal, "Understanding discontinuance among California's electric vehicle owners," *Nature Energy*, vol. 6, no. 5, pp. 538–545, 2021.
- [16] (2021). *Electric Vehicle Infrastructure Barriers. Research Report for Transport and Environment*. [Online]. Available: <https://www.cenex.co.U.K./app/uploads/2021/04/Electric-Vehicle-Infrastructure-Barriers-FINAL.pdf>
- [17] F. Guo, J. Yang, and J. Lu, "The battery charging station location problem: Impact of users' range anxiety and distance convenience," *Transp. Res. E, Logistics Transp. Rev.*, vol. 114, pp. 1–18, Jun. 2018.
- [18] S. Rivera, S. Kouro, S. Vazquez, S. M. Goetz, R. Lizana, and E. Romero-Cadaval, "Electric vehicle charging infrastructure: From grid to battery," *IEEE Ind. Electron. Mag.*, vol. 15, no. 2, pp. 37–51, Jun. 2021.
- [19] U. Zafar, I. S. Bayram, and S. Bayhan, "A GIS-based optimal facility location framework for fast electric vehicle charging stations," in *Proc. IEEE 30th Int. Symp. Ind. Electron. (ISIE)*, Jun. 2021, pp. 1–5.
- [20] H. S. Das, M. M. Rahman, S. Li, and C. W. Tan, "Electric vehicles standards, charging infrastructure, and impact on grid integration: A technological review," *Renew. Sustain. Energy Rev.*, vol. 120, Mar. 2020, Art. no. 109618.
- [21] *Key Strategies to Help Cities Overcome the Charging Challenge Quickly, Easily, and at Lower Cost*. Accessed: Dec. 20, 2021. [Online]. Available: <https://theicct.org/blog/staff/key-strategies-help-cities-overcome-charging-challenge-quickly-easily-and-lower-cost>
- [22] S. Srdic and S. Lukic, "Toward extreme fast charging: Challenges and opportunities in directly connecting to medium-voltage line," *IEEE Electric. Mag.*, vol. 7, no. 1, pp. 22–31, Mar. 2019.
- [23] *Global EV Data Explorer, International Energy Agency*. Accessed: Nov. 2021. [Online]. Available: <https://www.iea.org/articles/global-ev-data-explorer>
- [24] D. L. Greene, E. Kontou, B. Borlaug, A. Brooker, and M. Muratori, "Public charging infrastructure for plug-in electric vehicles: What is it worth?" *Transp. Res. D, Transp. Environ.*, vol. 78, Jan. 2020, Art. no. 102182.
- [25] D. Hall and N. Lutsey, "Electric vehicle charging guide for cities," Int. Council Clean Transp., Washington, DC, USA, Consulting Rep., 2020.
- [26] S. Á. Funke, F. Sprei, T. Gnann, and P. Plötz, "How much charging infrastructure do electric vehicles need? A review of the evidence and international comparison," *Transp. Res. D, Transp. Environ.*, vol. 77, pp. 224–242, Dec. 2019.

- [27] M. Nicholas and D. Hall, "Lessons learned on early electric vehicle fast-charging deployments," Int. Council Clean Transp., Washington, DC, USA, 2018.
- [28] *Electric Vehicle Infrastructure Projection Tool (EVI-Pro) Lite*. Accessed: Nov. 2021. [Online]. Available: <https://afdc.energy.gov/evi-pro-lite>
- [29] M. Kchaou-Boujelben, "Charging station location problem: A comprehensive review on models and solution approaches," *Transp. Res. C, Emerg. Technol.*, vol. 132, Nov. 2021, Art. no. 103376.
- [30] I. S. Bayram and S. Bayhan, "Location analysis of electric vehicle charging stations for maximum capacity and coverage," in *Proc. IEEE 14th Int. Conf. Compat., Power Electron. Power Eng. (CPE-POWERENG)*, vol. 1, Jul. 2020, pp. 409–414.
- [31] Y. He, K. M. Kockelman, and K. A. Perrine, "Optimal locations of U.S. fast charging stations for long-distance trip completion by battery electric vehicles," *J. Cleaner Prod.*, vol. 214, pp. 452–461, Mar. 2019.
- [32] P. Jochem, E. Szimba, and M. Reuter-Oppermann, "How many fast-charging stations do we need along European highways?" *Transp. Res. D, Transp. Environ.*, vol. 73, pp. 120–129, Aug. 2019.
- [33] D. A. Giménez-Gaydou, A. S. Ribeiro, J. Gutiérrez, and A. P. Antunes, "Optimal location of battery electric vehicle charging stations in urban areas: A new approach," *Int. J. Sustain. Transp.*, vol. 10, no. 5, pp. 393–405, 2016.
- [34] S. Y. He, Y.-H. Kuo, and D. Wu, "Incorporating institutional and spatial factors in the selection of the optimal locations of public electric vehicle charging facilities: A case study of Beijing, China," *Transp. Res. C, Emerg. Technol.*, vol. 67, pp. 131–148, Jun. 2016.
- [35] D. Guler and T. Yomralioglu, "Suitable location selection for the electric vehicle fast charging station with AHP and fuzzy AHP methods using GIS," *Ann. GIS*, vol. 26, no. 2, pp. 169–189, Apr. 2020.
- [36] R. Z. Farahani, S. Fallah, R. Ruiz, S. Hosseini, and N. Asgari, "OR models in urban service facility location: A critical review of applications and future developments," *Eur. J. Oper. Res.*, vol. 276, no. 1, pp. 1–27, 2019.
- [37] T. N. Beckman, "A brief history of the gasoline service station," *J. Historical Res. Marketing*, vol. 3, no. 2, pp. 156–172, May 2011.
- [38] *Number of Petrol Stations in Selected European Countries at the End of 2020*. Accessed: Nov. 2021. [Online]. Available: <https://www.statista.com/statistics/525523/number-of-petrol-fuel-filling-station-in-europe-by-country/>
- [39] *Fuel Retail in the Age of New Mobility*. Accessed: Dec. 20, 2021. [Online]. Available: <https://www.mckinsey.com/industries/oil-and-gas/our-insights/fuel-retail-in-the-age-of-new-mobility>
- [40] *Study of the U.K. Petroleum Retail Market*, Deloitte DLP, London, U.K., 2012.
- [41] *California State Geoportals*. Accessed: Dec. 20, 2021. [Online]. Available: <https://gis.data.ca.gov/>
- [42] *Denver Geographic Information Systems*. Accessed: Dec. 20, 2021. [Online]. Available: <https://www.denvergov.org/Government/Departments/Technology-Services/Services/GIS>
- [43] *Wake County Geographic Information Services*. Accessed: Dec. 20, 2021. [Online]. Available: <https://www.wakegov.com/departments-government/geographic-information-services-gis>
- [44] *Salt Lake City GIS*. Accessed: Dec. 20, 2021. [Online]. Available: <https://gis-slcgov.opendata.arcgis.com/>
- [45] R. Church and C. ReVelle, "The maximal covering location problem," in *Papers of the Regional Science Association*, vol. 32, no. 1. Berlin, Germany: Springer-Verlag, 1974, pp. 101–118.
- [46] M. S. Daskin, *Network and Discrete Location: Models, Algorithms, and Applications*. Hoboken, NJ, USA: Wiley, 2011.
- [47] G. Schäfer and B. G. Zweers, "Maximum coverage with cluster constraints: An LP-based approximation technique," 2020, *arXiv:2012.04420*.
- [48] *Optimization With PuLP*. Accessed: Dec. 20, 2021. [Online]. Available: <https://coin-or.github.io/pulp/>
- [49] C. E. Office. (2020). *Colorado EV Plan 2020*. Accessed: Jan. 2022. [Online]. Available: <https://energyoffice.colorado.gov/zero-emission-vehicles/colorado-ev-plan-2020>
- [50] *QGIS a Free and Open Source Geographic Information System*. Accessed: Dec. 20, 2021. [Online]. Available: <https://www.qgis.org/en/site/>
- [51] *U.S. Department of Energy, Electric Vehicle Charging Station Locations*. Accessed: Dec. 20, 2021. [Online]. Available: https://afdc.energy.gov/fuels/electricity_stations.html
- [52] *Geotab Fleet Refueling*. Accessed: Dec. 20, 2021. [Online]. Available: <https://www.geotab.com/blog/fleet-refueling/>
- [53] D. Tong, "Regional coverage maximization: A new model to account implicitly for complementary coverage," *Geograph. Anal.*, vol. 44, no. 1, pp. 1–14, 2012.



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