SITING AND SIZING OF PUBLIC-PRIVATE CHARGING STATIONS WITH IMPACTS ON HOUSEHOLD AND PRIVATE ELECTRIC VEHICLE FLEETS

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ABSTRACT

To facilitate the provision of electric vehicle charging stations (EVCS) in urban areas, this study investigates the benefits of co-locating fleet-owned chargers with public charging stations, enabling receiving incentives during construction and cord-sharing during use. Shared EVCS can serve charging demand from both user types: private (household) EV owners and those managing fleet vehicles – like shared and fully automated EV (SAEV) fleets. Using POLARIS to simulate all person-travel across the 6-county Austin, Texas region, new EVCS were sited and sized with DC fast-charging (DCFC) plugs to lower operating and construction costs while providing public + private (PP) service across an 81-square-mile core geofence (where 200 SAEVs were active) over 24-hour days. When co-location is permitted, 115 DCFC cords were added to the 23 existing (publicly available) stations to enable SAEVs and household EVs (HHEVs) charging access, within the geofence. Each 250-mile-range SAEV was simulated to travel an average of 330 miles per day, serve over 92 trip requests, and recharge 2.7 times a day (for 2.4 hours per session). The new DCFC plugs were primarily added to public EVCS at shopping centers and schools, and in residential settings along freeways. The average plug served 4.8 EVs per day. Most co-located PP EVCS permitted immediate (no-wait) charging, except for 2 stations along freeways that averaged 8 minutes of wait time to begin charging. The co-location strategy lowered fleet owners' initial EVCS construction costs by 12% (thanks to cord-sharing to avoid cord duplication), while reducing

SAEV wait times to just 3.1 minutes (versus 10.7 minutes if SAEV managers had to build and operate their own EVCS).

Key words: Shared autonomous electric vehicles, charging infrastructure planning, EV charging modeling, public-private partnership (PPP); agent-based simulation

1. MOTIVATION

In recent decades, electric vehicles (EVs) have advanced and been used to help lower the growing greenhouse gas (GHG) emissions of transport (Ding and Jian, 2022; Yang et al., 2023). Emerging technologies, such as ride-hailing fleets composed of self-driving ("autonomous") and all-electric vehicles (or SAEVs), further boost the transportation electrification trend by offering safer, less expensive, and more efficient travel than most motorized household vehicles (Loeb and Kockelman, 2019). In 2023, there were over 3 million EVs on U.S. roads, supported by over 130,000 public chargers nationwide (White House, 2023). By 2030, 33 million EVs are estimated to be on U.S. roads, requiring 28 million EV charging ports, including 26.8 million Level 1 private ports (120V), 1 million public Level 2 (240V) ports, and 182,000 public DC Fast Charging (DCFC) (400 V to 1000 V DC) ports (Wood et al., 2023). However, accelerated EV adoption is hindered by challenges related to charging infrastructure availability. Key concerns include 'range anxiety', which refers to the user's fear of running out of battery without access to nearby charging options, along with long charging times, both of which can impede the widespread adoption and use of household EVs (HHEVs) and SAEVs (Teebay, 2023; Sun et al., 2020). Substantial investment and expansion in EV supply equipment (EVSE) is important to accommodate the rising demand and deliver fast-charging services, reasonably comparable to internal combustion engine counterparts (Zafar et al., 2021). However, planned investment schedules reveal an infrastructure gap, with Edison Electric projecting a shortfall of 140,000 DCFC ports in the U.S. by 2030 (Satterfield and Schefter, 2022). Since many ride-hailing operators are starting to transition or require their fleets to be EVs (Gao and Li, 2024), charging infrastructure shortages may become more pronounced soon. As a result of this shortage, searching for charging stations with usable cords may lower the efficiency of shared EV fleets, leading to a rise in empty vehicle-miles traveled (eVMT) (Anastasiadis et al., 2023). Addressing these issues underscores the pressing demand for targeted strategies to expand charging networks and support broader EV adoption.

Charging station operators (CSOs) mainly consist of upstream EV manufacturers like Tesla, independent operators such as ChargePoint, and private fleet operators like Cruise and Waymo (Ding and Jian, 2022). These entities continue installing charging stations to meet rising demand from HHEVs, while fleet operators often build EVCS at depots to serve their EV fleet. Public EVCS are primarily developed by the first two types of CSOs, which face difficulties, including financing, returns on investment, and managing EVCS serviceability (Shabbiruddin and Pradhan, 2021). While fleet-owned charging infrastructure is often regarded as private (Brown et al., 2023), fleet managers face added siting challenges (of cost and access) if they do not make their chargers available to the general public, as many cities incentivize EVCS investments for public use. Moreover, fleet EVs are typically operated in densely populated areas where limited and expensive land makes it difficult for fleet operators to deploy their facilities. Therefore, collaborative strategies and innovation solutions are needed to address EVCS siting issues while improving resource use.

Researchers have highlighted the importance of close collaboration among public and private CSOs to popularize charging facilities and ensure the provision of sufficient stations and ports to meet user demand (Pardo-Bosch et al., 2021; Huang et al., 2022; Su and Kockelman, 2024). Transforming fleet-owned stations into public-private (PP) EVCS by opening access to public use could potentially alleviate the supply-demand gap in public infrastructure, expand service coverage, reduce charging congestion, and enhance reliability by reducing downtime through better maintenance (Zhang et al., 2018; Song et al., 2021). Fleets can also benefit by saving costs, reducing charger idle times, and enjoying shared benefits. Moreover, both public and private CSOs contend with uncertainties in future demand, varying user preferences, and technological advancements. Despite these potential benefits, collaborative strategies that integrate shared land use, and cord-sharing have yet to be proposed, and their implications have not been adequately studied.

While previous studies have focused on examining public or private EVCS, little attention has been given to the PP approach that co-locates fleet-owned/private chargers alongside public EVCS. This strategy addresses the urgent needs of fleet operators to site new fleet-owned EVCS while also opening private charging access to the public. A significant gap remains in understanding the impacts of this strategy on fleet operations, EVCS performance, and whether it presents an opportunity or challenge for ride-hailing fleets' electrification. Given these research gaps, this study addresses the following research questions:

1. What are the comparative advantages and challenges of the PP approach with the co-location strategy, in contrast to fleet operators building and operating their own dedicated EVCS or using a non-co-location PP approach?
2. What are the impacts of PP EVCS on fleet operations, service use and performance, and user experience?
3. What challenges might CSOs face, and what strategies can they adopt to overcome them when deploying PP EVCS?

Through this aim, the following work simulates the growing demand for charging infrastructure from rising numbers of HHEVs and emerging SAEV fleets (like those run by Cruise and Waymo), using the Austin area as a case study. Using the agent-based model (ABM) called POLARIS, this work identifies potential locations and sizes for PP charging stations while illuminating their use and performance attributes. The first key contribution of this study is a proposed co-location strategy for PP EVCS that supports fleet operators in deploying charging infrastructures. The second contribution lies in developing a parameterized siting algorithm that enhances understanding of co-location benefits and informs infrastructure planning. Additionally, this study provides insights to guide the design of PP EVCS and offers collaborative strategy recommendations for diverse stakeholders, including fleet managers, policymakers, and public CSOs. By integrating advanced simulation tools and novel strategies, this study informs policy and guides sustainable urban transportation systems that align with evolving EV adoption and charging infrastructure development trends.

2. LITERATURE REVIEW

2.1 Integrate Charging Infrastructure

Charging infrastructure planning has gained significant attention, with extensive studies addressing siting and sizing problems. Two dominant streams have emerged in integrating public charging infrastructures: gas-station-based (Cai et al., 2014; Li et al., 2021) and parking-based (Chen et al., 2013; Luo and Qiu, 2020; Dvořáček et al., 2020), each with pros and cons. Gas stations are selected as candidate charging stations, as they align with refueling habits and already have the basic civil conditions and infrastructure for vehicle traffic, lowering costs (Ghodusinejad et al., 2022). However, it's impractical to expect drivers to wait at gas stations if charging takes hours. In contrast, parking-based charging stations cater to long-duration charging needs by integrating charging with other activities during a trip (like work or shopping), without requiring extra time. Nonetheless, high parking fees can hinder adoption, making it economically infeasible.

Recent studies have sought to merge charging with other infrastructure. For example, integrating chargers with streetlights reduces installation costs and leverages existing grid connections. In Los Angeles, 550 Level 2 ports have been added to city streetlights, in collaboration with public agencies (Teebay, 2023). Similar efforts in Kansas City (Bouallegue et al., 2024) and many European cities (where base voltage is double the US standard) (Balgaranov, 2022) highlight the potential of using existing infrastructure when deploying new chargers. Integrating new charging facilities with existing infrastructure is a promising approach, yet further research is needed to align these initiatives with charging behaviors effectively, particularly in the context of evolving electrification trends such as fleet charging.

2.2 Co-location and Joint Use of Public and Private Chargers

Co-location and joint use of public and private EVCS are underexplored yet crucial for optimizing charging infrastructure. EV fleets are often assumed to prefer dedicated charging stations exclusively owned and operated by the fleet (Moniot et al., 2022; Liu et al., 2023). However, shared charging strategies can unlock substantial benefits. Alp et al. (2022) affirmed the positive impact of shared charging infrastructure investments, using an e-truck fleet as an example. EV fleet operators face high charging demand, and co-locating fleet-owned chargers with public infrastructure can meet this demand while reducing costs.

Private charging port sharing has also emerged as a promising avenue to increase charging accessibility and reduce dependence on public EVCS. Yang et al. (2024) highlighted the efficiency of private home charger sharing in Beijing, achieving a 33.37% decrease in average electricity demand on public chargers during a working day. Similarly, innovative models, such as opening electric bus depot chargers for household EVs, demonstrate how private chargers can be opened to maximize resource use and expand new revenue streams (Jia, An, and Ma, 2024).

Public-private collaboration is particularly relevant with the rise of SAEVs, which rely heavily on efficient charging operations. Kullman et al. (2021) demonstrated that with efficient dynamic routing policies, strategies considering PP charging infrastructure soundly outperform the industry-standard private-only strategies. Despite these win-win benefits, few studies have explored this public-private collaboration comprehensively. This work fills this gap and stands out by focusing on the joint use of public and fleet-owned/private chargers, exploring cord-sharing during use to deliver novel insights into cooperative charging infrastructure strategies.

2.3 Advancing EVCS Planning with Performance and Demand Factors

EVCS planning increasingly incorporates performance metrics such as vehicle queuing and waiting time to enhance service quality and user satisfaction. Philipsen et al. (2016) revealed users' strong aversion to delays at chargers through a survey of EV owners in Germany, underscoring the importance of shortening waiting times in the planning model. Xiao et al. (2020) developed an optimization model that explicitly accounted for charging queue behavior with finite queue length to determine EVCS locations and capacities. Similarly, He et al. (2021) integrated charging infrastructure planning and vehicle repositioning with a queueing network model. Song et al. (2024) explored limitations in the existing business model, highlighting the importance of user-centric planning. This work advances the literature by incorporating queuing behavior and waiting time considerations in charging infrastructure planning, ensuring all EVs experience shorter charging delays while maintaining EVCS cost-efficiency and accessibility.

Existing research often focuses on private EVs, but with the rise of ride-hailing fleet electrification, it's important to develop models that consider fleet-specific behaviors, such as SAEVs' unique charging demands and routing constraints. Studies like Huang and Kockelman (2020) and Zhou et al. (2022) applied optimization-based strategies to site and size EVCS for private EVs, balancing cost-efficiency with accessibility. Building on insights from these works, our research simulates household/private EVs and SAEV fleet charging behavior and charging demand while siting and sizing the EVCS. The objective is to lower the necessary investments and shorten charging delays and detours while ensuring all EVs' charging demands are met to enable SAEV fleets to serve passenger travel requests timely. The following sections explain the framework of siting and sizing EVCS, and simulation details with the Austin applications, before describing simulation results and providing conclusions and policy suggestions.

3. METHODOLOGY

Agent-based simulations are a key method to explore both SAV and SAEV services owing to the greater degree of freedom in tracking traveler and vehicle states across the entire travel day (see, e.g., Huang et al., 2024; Dean et al., 2023; Gurumurthy and Kockelman, 2022; Gurumurthy et al., 2020), capturing the on-demand nature of ride-hailing service that traditional 4-step models cannot. The POLARIS framework (Auld et al., 2016) which is an activity-based agent-based forecasting tool is chosen to help with siting and sizing PP EVCS in this study. POLARIS, developed in C++, is capable of running large-scale transportation simulations on high-performance computers. It incorporates an activity-based model (adapted from Auld and Mohammadian, 2009) within its agent-based framework to simulate travel planning behavior, and then dynamically loads demand on realistic transport networks while tracking all agents and vehicles, typically for a 24-hour simulation period.

On the demand side, the simulation creates a synthetic population from data provided by region's metropolitan planning organization and the United States Census Bureau. Given the population's demographic attributes (like household size and income), each traveler agent plans activities and schedules the necessary destinations, modes, and departure times (Auld and Mohammadian, 2009). As for supply, the simulation employs time-dependent intermodal algorithms to determine the shortest time-dependent paths and then route vehicles on the road network (Verbas et al., 2018). POLARIS outputs include detailed link-level trajectories for all vehicle trips within the region (Verbas et al., 2023). These simulations closely monitor individual travelers and vehicles to derive key operational metrics, like VMT, trip counts, and idle time per SAEV per day, to predict cost, emissions, and other impacts, while using heuristics to site and size EVCS (Gurumurthy et al., 2021).

3.1 Charging Decisions for SAEVs and Personal EVs

A key benefit of agent-based frameworks is the ability to track EV battery SoC and remaining range, both of which travelers use in making decisions. SAEVs are charged only after their accepted rides are served, while maintaining the SoC above a minimum line (set at 20% in this study) before allowing the operator to add a new request to the vehicle's to-serve list. To ensure smooth service, the required energy to satisfy any new ride request is also estimated (using Euclidean distances between planned stops). If the SAEV's SoC falls below the minimum SoC threshold or is insufficient for serving an additional ride request, the vehicle will be identified as requiring charging and no longer accepting additional trip requests (Gurumurthy et al., 2021). The logic used to select the best EVCS for charging each SAEV is discussed in the following section.

Similar service and charging logic are used with HHEVs. Charging decisions vary by trip type, and depend on home-charger access, initial SoC, trip and tour distances, and available EVCS along routes to destinations. For EVs with SoC that satisfy the critical threshold, a pre-trip check will be conducted to predict whether the EV can complete the next activity without charging. If the SoC after completing the next trip is predicted to lie below the 20% threshold, the EV will need to recharge before use on the next trip. Verbas et al. (2023) offer detailed explanations of POLARIS' charging logic for HHEV trip chains.

3.2 Siting and Sizing EV Charging Stations

Past work with POLARIS has treated charging demand by HHEVs and SAEVs demands separately, with no shared charging infrastructure between them (Dean et al., 2022). Initial model only heuristically sites EVCS for the SAEV fleet, with the assumption that the SAEV accesses fleet-owned EVCS by default while HHEVs access public EVCS. POLARIS captures home chargers' availability and existing public charging infrastructure for EV owners, including the counts of each of 3 plug types: 3.3 kW (Level 1 charging), 7 kW (Level 2), and 50 kW (DCFC or Level 3). The station and plug information used in POLARIS can represent either the existing public charging infrastructure or hypothetical infrastructure with different power ratings. Figure 1 shows the location and counts of existing public chargers used as the basis for this study, obtained from the Alternative Fuel Data Center by the U.S. Department of Energy (DOE) (DOE, 2024a).

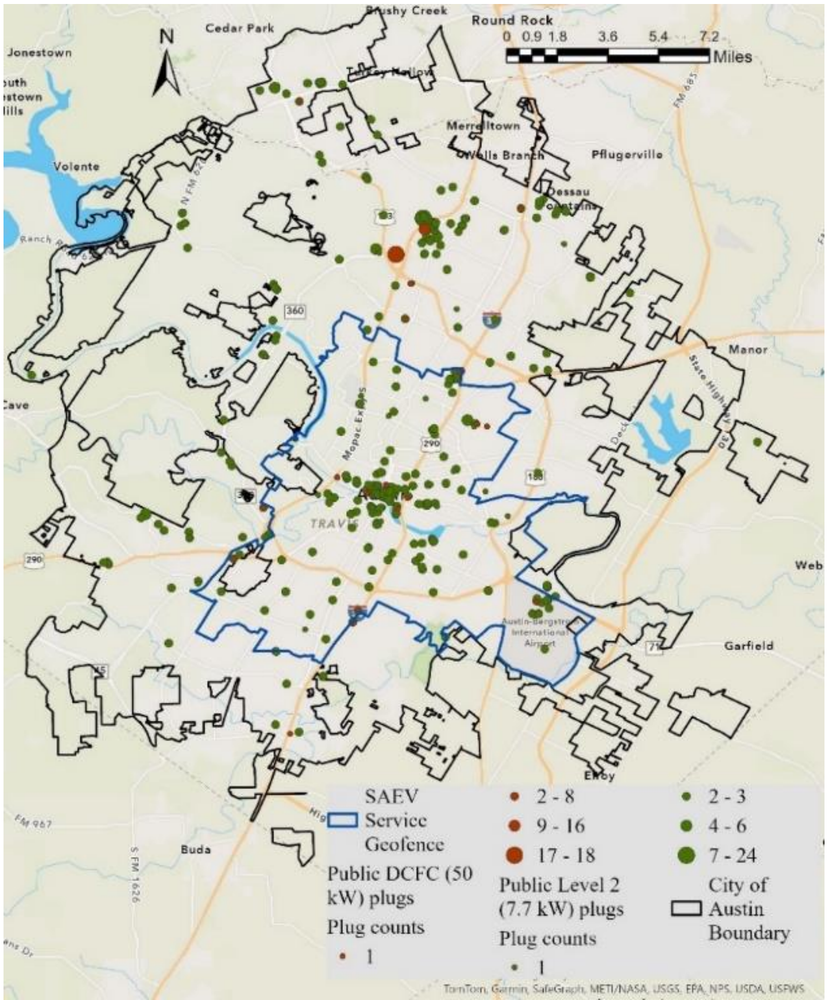

Figure 1. SAEV service geofence and public EVCS distribution (Source: U.S. DOE, 2024a)

POLARIS-generated EVCS are privately fleet-owned by default, representing a baseline private scenario. However, this study also considers the simultaneous charging demand of HHEVs and SAEVs to enable PP EVCS scenarios. Under such model, although the POLARIS-generated EVCS are nominally fleet-owned, they provide open access to the public, qualifying them as fleet-owned PP EVCS. Simulating the location of PP chargers is tied to the settings of the model's control variables. The model can either co-locate PP chargers alongside existing public EVCS or identify potential sites that directly accommodate the PP chargers to fulfill the emerging demand.

Previous research has used heuristics to place EVCS to prevent stranding vehicles (Loeb and Kockelman, 2019; Gurumurthy et al., 2021). The heuristic strategy outlined by Gurumurthy et al. (2021) was updated to site and size new EVCS based on charging requests and queuing constraints. This study assumes households bear the costs of lost time and energy consumption for their EVs, while fleet operators are responsible for land acquisition, charging infrastructure construction, and energy consumption for SAEV operations.

Three general costs are calculated to evaluate efficient operations and determine whether the charging infrastructure identified is the least costly option for an EV to recharge, with equations monetizing factors such as charging delays, durations, detours, and investment cost. Figure 2 describes the model framework for the heuristically-sited EVCS. The framework consists of two major parts: SoC checking (highlighted in blue), and EVCS site selection and capacity determination (highlighted in green). Entities flowing through the SoC checking parts are all EVs, including both HHEVs and SAEVs. As EVs move along the network, their SoCs and available ranges are updated continuously. Before serving the next ride request or trip in the tour, a pre-check ensures their remaining SoC is sufficient for safe travel. In the EVCS generation part, the entities are charging infrastructure identified or created to fulfill charging demand driven by SoC check. This process addresses scenario-specific EV charging demands: private EVCS generation focuses solely on SAEV fleet needs, while the PP EVCS considers both HHEV and SAEV demands. When scenario-specific EVs require charging, the model searches for accessible EVCS within the maximum distance considered for charging.

Situation 1 – No accessible EVCS nearby

If no accessible EVCS is found, the heuristic will site a new charging station with a pre-defined number of DCFC plugs based on the location where the EV charging demand emerges, incorporating factors such as land use planning. The general cost for assigning the EV to charge at this newly sited EVCS is evaluated as Cost 1:

$$Cost\ 1 = VOT \times T_{charging} + C_{energy} + C_{land} + C_{EVCS} \tag{1}$$

Where time-related variables are weighted by the value of time (VOT), $T_{charging}$ is charging duration, C_{energy} is energy consumption, C_{land} is land acquisition, and C_{EVCS} represents EVCS development costs.

Situation 2 – Accessible EVCS nearby with an acceptable queue

If accessible EVCS exists within the search buffer, plug availability and queuing feasibility will be further examined. The general cost (Cost 2) for selecting the least costly EVCS in terms of charging detour time T_{detour}, waiting time T_{wait}, and detour cost C_{eVMT} is determined as:

$$Cost\ 2 = VOT \times \left(T_{charging} + T_{detour} + T_{wait}\right) + C_{energy} + C_{eVMT} + INF \times F_{queue} \tag{2}$$

Where L_{detour} indicates the Euclidean distance between EV and nearby EVCS. The detour cost (C_{eVMT}) to the EVCS is calculated as:

$$C_{eVMT} = C_{operating/mile} \times L_{detour} \tag{3}$$

Where $C_{operating/mile}$ represents the operating cost per mile, and F_{queue} is a dummy variable indicating whether the queuing length exceeds a predefined threshold. This variable is multiplied by infinity, INF, to indicate queuing feasibility at nearby EVCS.

Situation 3 – Accessible EVCS nearby with lengthy queue

If the queue length at an EVCS is over the threshold, making Cost 2 becomes infinite ($F_{queue} = 1$), the heuristic will further assess adding plugs to existing stations instead of siting a new EVCS. The general cost for this option is calculated as Cost 3:

$$Cost\ 3 = VOT * \left(T_{charging} + T_{detour} + T_{wait}\right) + C_{energy} + C_{eVMT} + INF \times F_{plug} \tag{4}$$

Here, F_{plug} is a dummy variable a new EVCS will be sited to fulfill this charging demand. The EV will become available to serve the next rides and trips once its SoC is recharged to 80%. Charging demand and general costs for assigning an EV to charge are simulated and evaluated endogenously. However, factors such as the SAEV fleet size, EVCS accommodation capacity, and charger costs are exogenous inputs. These model components and value assumptions are detailed in the next section, where the City of Austin is used as a case study to validate the framework.

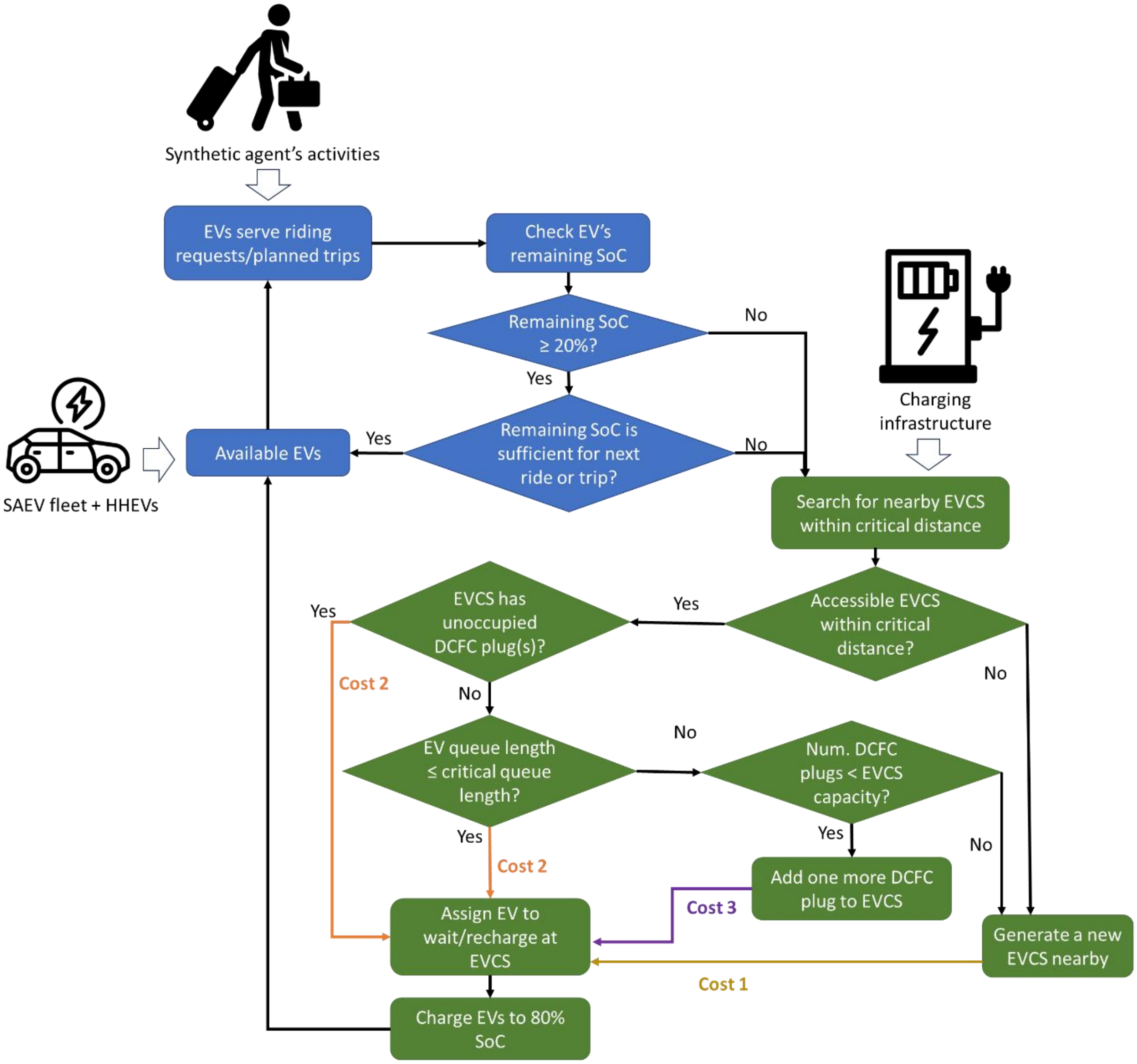

Figure 2. Siting and sizing EVCS flowchart

4. AUSTIN CASE STUDY

The City of Austin, with nearly 1 million persons, is at the heart of a 6-county metropolitan region in central Texas (Figure 1). This 5,300 square-mile metropolitan region is typically modeled with 2160 traffic analysis zones and 16,100 links. With one public charger (including Tesla Network) per 1,310 residents, Austin ranks No.11 among U.S. cities for residents served per charger (iSeeCars, 2022), placing it far ahead of other Texas metros. As an EV-friendly city, Austin city ranks 5th among US cities in total number of EVCS (Carlier, 2023).

4.1 Simulation Geofence

The SAEV fleet, in this study, is assumed to operate within an 81 sq mile geofence focused on the central business district (CBD) (Figure 1). The geofenced region covers about 422 traffic analysis zones, 4,166 links, and 2,512 nodes. Within this area, 511,569 residents have access to 275 public EVCS, including 482 Level 2 plugs and 32 sites with a total of 39 DCFC plugs for public use. The geofence aligns with the expectation that initial SAEV operations would likely be confined to Austin's most densely populated and destination-active zones, including the CBD, University of Texas, St Edward's University, and various hospitals, shopping centers, schools, and parks.

4.2 Scenarios Design

Scenario settings are outlined in Table 1, detailing the accessibility of HHEVS and SAEVs against public and private chargers. HHEVs are assumed to have default access to public charging plugs, including both Level 2 and DCFC chargers. In contrast, the SAEV fleet relies on fleet-owned DCFC chargers to minimize downtime and enhance competitiveness in ride-hailing. In PP EVCS scenarios, where fleet-owned DCFC chargers are co-located with public chargers, HHEVs can sue both Level 2 and all DCFC chargers, while SAEV remains exclusively reliant on either public or fleet-owned DCFC chargers.

In the first scenario, named *Private* EVCS, HHEVs are not able to access fleet-owned plugs while the SAEV fleet is not able to get charged at public EVCS. The second scenario, called *Flexible* PP EVCS, offers HHEVs additional access to the generated fleet-owned EVCS. Based on where the charging needs arise, the heuristic defined earlier would flexibly site the PP EVCS and determine the number of plugs, considering charging demand from both SAEV fleet and HHEVs. However, the SAEV fleet is still limited to charging at fleet-owned EVCS. Scenario 3, named *Co-located* PP EVCS, grants maximum access to chargers for all EVs. It includes all the settings of the second scenario and additionally grants SAEV fleets access to public chargers. In this scenario, the POLARIS model prioritizes locating the fleet-owned chargers alongside the current public chargers to enhance cord-sharing practicality. Under this site-sharing condition, the SAEV fleet needs to head to public EVCS to get charged by PP EVCS. Though allowed to use public chargers, SAEV fleet is modeled to primarily use the fleet-owned chargers. These scenarios allow for a comprehensive understanding of the financial and operational impacts of the co-located charging infrastructure.

Table 1. Plug access scenario settings

EVCS Scenarios	**EV Types**	**Control Variables**	
		Public Plug Access	**Fleet-owned Plug Access**
Private	HHEVs	True	False
	SAEV Fleet	False	True
Flexible PP	HHEVs	True	True
	SAEV Fleet	False	True
Co-located PP	HHEVs	True	True

	SAEV Fleet	True	True

Table 2 shows key parameters assumed in the POLARIS model. Passengers who choose ride-hailing service over alternative modes (like bus, walk, bike, etc.) exclusively use SAEVs, which account for 10.7% of the mode share. 200 SAEVs are expected to be modeled within the geofence area with a 250-mile range. Fares start at a $1 base pick-up fee, with additional charges of $2.25 per mile and 33 cents per minute. Ride-sharing is enabled, allowing SAEVs to pick up and drop off passengers at different points along a shared route. Fares are discounted to 50 cents per mile and 25 cents per minute to encourage ride-sharing. A SAEV is matched to a request within a 10-minute wait threshold; if unmatched, travelers will switch modes to get to their next activity. When an EV requires charging, if the distance to the nearby charging stations exceeds 5 miles, a new fleet-owned EVCS will be generated strategically with 3 default DCFC plugs to meet the charging demand. Each EVCS can only accommodate a maximum of 20 plugs.

Table 2. Simulation Key Parameter Assumptions

Category	**Parameter**	**Description**		**Assumed Values**
SAEV fleet	SAEV Fleet Size	Number of SAEVs.		200 vehicles
	Max Wait Time	Maximum wait time for new ride requests.		10 minutes
	SAEV Range	Vehicle range.		250 miles
	Cut Off Battery Levels	Cut off SoC during charging for battery health.		80% SoC
	Minimum EV SoC	Min SoC threshold to send EV to recharge.		20% SoC
	Operational Cost	Expected SAEV operational cost		$0.6/mile
	Ownership Cost	Daily ownership cost per SAEV		$40/day
EVCS Generation	Charger Power Output	The speed at which a charger can replenish the vehicle's battery.		50 kW
	Max EVCS Distance	Max distance to EVCS to generate a station.		5 miles
	EVCS Max DCFC Plugs	Max number of DCFC plugs at generated EVCS.		20 plugs
	EVCS Min DCFC Plugs	Min number of DCFC plugs at generated EVCS.		3 plugs
	EVCS Life Span	Expected service life of EVCS before requiring major repairs, upgrades, or replacement.		10 years
	Hardware Cost	Hardware cost per networked 50 kW plug.		$28,401
	Installation Cost	Installation cost per 50 kW plug, varying by total plug count per site.	3-5 plugs per site	$26,964
			6-50 plugs per site	$17,692
	Maintenance Cost	Annual maintenance cost per DCFC plug.		$800
	Site Service and Management Cost	Annual staff and resources cost per site to support charging and other operational activities.		$55,140

Various metrics are also examined to evaluate the benefits of deploying PP EVCS versus not having them, as shown in Table 3.

Table 3. SAEV fleet and fleet-owned EVCS performance metrics

Category	Metrics	Description
SAEV Fleet Performance	Service demand from passengers	Forecasted SAEV service requests from passengers based on assumed mode share.
	Avg. wait time per passenger	Mean waiting duration (minutes) for passengers to be picked up by SAEV.
	Avg. daily VMT per SAEV	Mean vehicle miles traveled (VMT) by each SAEV in a day.
	%eVMT	Ratio of the distance traveled by unoccupied SAEV fleet to its overall VMT.
	Avg. daily service trips per SAEV	Mean number of service trips per SAEV per day.
	Avg. daily idle time per SAEV	Mean duration (hours) that each SAEV is not in use per day.
	Avg. vehicle occupancy (AVO)	Mean number of passengers in a SAEV per VMT.
	Avg. daily recharging frequency per SAEV	Mean number of times each SAEV get recharged in a day.
	Avg. time spent at EVCS per SAEV	Mean time (minutes) spent at EVCS per SAEV.
Fleet-owned EVCS Performance	# EVCS	Total number of generated EVCS.
	# DCFC ports (50 kW)	Total number of 50 kW charging ports to be generated.
	Avg. charging ports per EVCS	Mean number of 50 kW charging ports housed by each generated EVCS.
	# SAEV charging trips	Num of SAEV charging trips occurred during the simulation.
	Avg. daily charging services per port	Mean number of charging services happened at each port per day.
	Avg. charging wait time per SAEV	Mean waiting duration (in minutes) for SAEVs to get charged by fleet-owned charger.
	Avg. charging wait time per HHEV	Mean waiting duration (in minutes) for HHEVs to get charged by fleet-owned charger.

5. RESULTS AND DISCUSSION

The generated EVCS and their charging plug counts under three simulation scenarios are illustrated in Figure 3. Private EVCS are concentrated in downtown Austin and west of the UT Austin campus. These locations are primarily shopping and dining centers, schools, and city parks. Due to their land use characteristics, which are typically associated with recreational purposes and dense job opportunities, there is a relatively high demand for ride-hailing services. Deploying private EVCS in these areas can support timely SAEV recharging to serve passengers. While more than 80% of EV charging occurs at home, residential areas such as multi-unit dwellings still lack developed public EV charging infrastructure (Teebay, 2023). After incorporating HHEV charging needs into EVCS siting considerations, the flexible PP EVCS sites extend further into residential areas along freeways. These locations align with earlier studies that recommend siting EVCS along highways, where charging demand is typically high, thereby maximizing profit and use (Huang and Kockelman, 2020). The *co-located* scenario adds fleet-owned plugs to public EVCS based on both HHEV and SAEV fleet charging needs, opening charging access for all EVs. More plugs are added to public EVCS located downtown, hospitals, and shopping centers near freeways at the north side. Moreover, many plugs are added to the public EVCS close to various city parks and schools. These locations help split up long trips such that charging during a long parking period can help relieve some range anxiety and help prepare for subsequent trips.

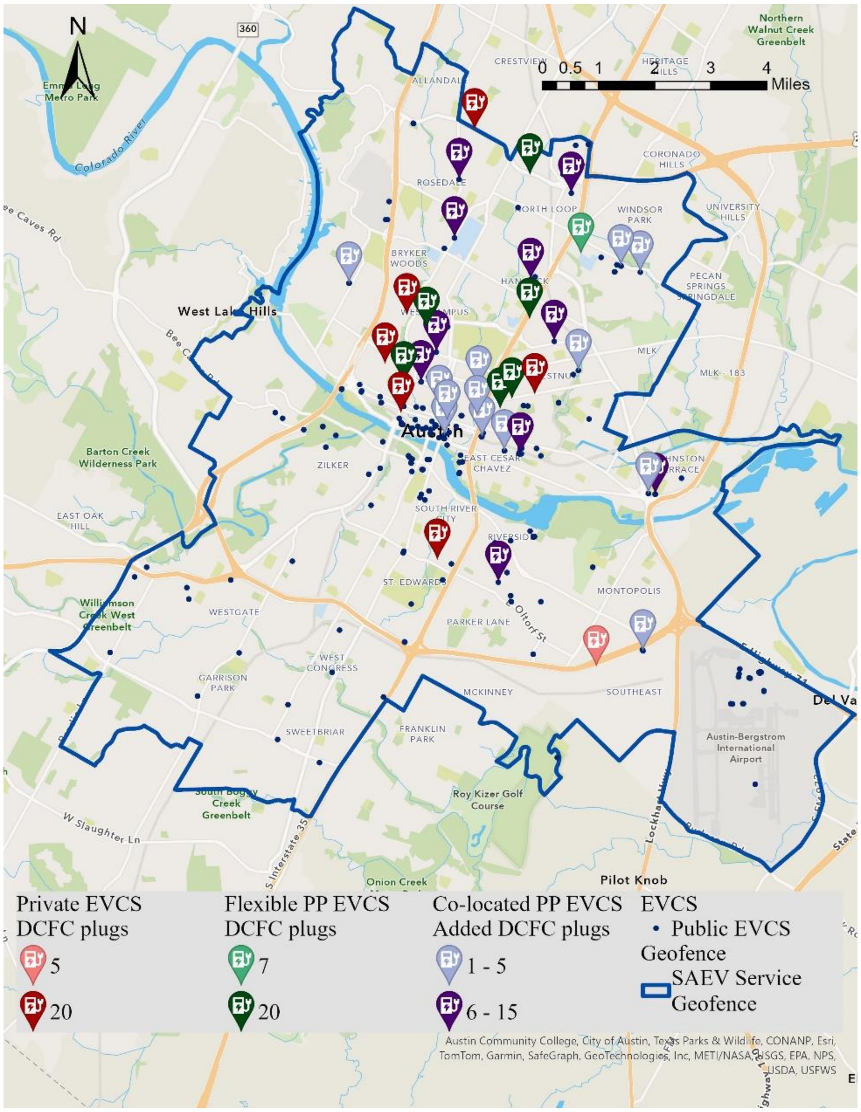

Figure 3. Generated DCFC plug distribution

5.1 SAEV Fleet Performance

The SAEV fleet performance across three testing scenarios is summarized in Table 4. The *co-located* scenario demonstrates the highest service demand, accommodating 18,456 passenger trips, compared to 17,507 in the *flexible* and 17,233 in the *private* scenario. On average, each SAEV travels approximately 330 miles per day, serves over 92 requests, and seeks to recharge nearly three times a day. Time spent at EVCS varies by scenario, with the *co-located* scenario showing the shortest average duration at 142.5 minutes. Despite these differences, fleet efficiency metrics such as %eVMT, and AVO remain consistent across all scenarios, with an AVO of 1.7 persons per revenue-mile. The average travel distance per SAEV trip is slightly lower in the *co-located* scenario (4.3 miles) compared to the *private* (4.6 miles) and *flexible* (4.5 miles) scenarios, with the median distance consistently shorter than the means, indicating a rightskewed distribution. Similarly, the average fare per trip remains stable across scenarios, ranging from $8.6 to $8.8, with medians ($7.6 to $7.8) consistently lower than the means, reflecting occasional higher-fare trips. The co-located scenario also generates the highest fleet revenue ($157,959) while maintaining comparable costs to the other scenarios, highlighting its potential for improved operational efficiency and revenue generation.

Table 4. SAEV Fleet Performance

Performance Metrics	**EVCS Scenario**		
	Private	***Flexible* PP**	***Co-located* PP**
Service demand from passengers	17,233 trips	17,507	18,456
Daily service trips per SAEV (Mean, Median, StDev)	(86.1, 90, 18.6) trips	(87.5, 91, 18.1)	(92.3, 97, 21)
Avg daily VMT per SAEV	325 miles	321	329.8
Daily recharges per SAEV (Mean, Median, StDev)	(2.7, 3.0, 0.76)	(2.7, 3.0, 0.7)	(2.7, 3.0, 0.8)
Time spent at EVCS per SAEV (Mean, Median, StDev)	(152.6, 143.7, 19.9) minutes	(158.6, 144.4, 27.9) minutes	(142.5, 140, 8.1) minutes
Avg. wait time per passenger	5.2 minutes	5.4	4.7
%eVMT	29%	29%	29%
AVO	1.7 persons	1.7	1.7
Travel distance per SAEV trip (Mean, Median, StDev)	(4.6, 4.0, 3.2) miles	(4.5, 3.9, 2.9)	(4.3, 3.7, 2.9)
Fare per SAEV trip ($) (Mean, Median, StDev)	($8.7, $7.7, $4.8)	($8.8, $7.8, $4.9)	($8.6, $7.6, $4.6)
Fleet total revenue ($)	$149,798	$153,201	$157,959
Fleet total cost ($)	$46,992	$46,508	$47,570

5.2 Fleet-owned EVCS Performance

The performance metrics of fleet-owned EVCS under each scenario are examined and summarized in Table 5.

Table 5. Fleet-owned EVCS Performance

Performance Metrics	**EVCS Scenario**		
	Private	***Flexible* PP**	***Co-located* PP**
# EVCS sites	7 stations	7	0 fleet-owned station (23 public EVCS used)
# DCFC plugs (50 kW)	125 plugs	127	115 feet-owned plugs (131 total with 16 public used)
Avg. charging plugs per EVCS	17.9 plugs/station	18.1	0.6 plugs/station [1]

# SAEV charging trips	529 trips	541	532
# HHEV	2988	2989	3001
# HHEV charging trips by DCFC plug	50 trips	45	46
Daily charging services per PP EVCS site (Mean, Median, StDev)	(75.6, 76, 29.8)	(78.6, 77, 31)	(12.74, 11, 8.5)
Charging wait time per SAEV (Mean, Median, StDev)	(10.7, 0.0, 18.9) minutes	(17.2, 0.0, 27.3) minutes	(3.1, 0.0, 7.7) minutes
Charging wait time per HHEV (Mean, Median, StDev)	(2.8, 0.0, 7.5) minutes	(1.7, 0.0, 5.9) minutes	(0.5, 0.0, 3.1) minutes
(Cost 0) Initial construction cost	\$5.81 M	\$5.85 M	\$6.04 M
(Cost 1) Cost 0 + savings from cord-sharing strategy	\$5.81 M	\$5.85 M	\$5.30 M
(Cost 2) Cost 1 + potential rebates	\$5.81 M	\$5.45 M	\$4.65 M
Amortized annual investment cost per EVCS	\$1.26 M	\$1.22 M	\$1.14 M

Note: [1]. For the *co-located* PP scenario, it indicates the average number of DCFC plugs per public EVCS within the SAEV service geofence after fleet-owned DCFC plugs joined.

In the *Private* EVCS scenario, 7 private EVCS are generated, each housing an average of 17.9 DCFC plugs. One station along State Highway (SH) 71 near Austin-Bergstrom Airport in the southeast is equipped with 5 DCFC plugs, while the remaining stations each house 20 plugs (Figure 3). A fleet of 200 SAEVs collectively undergoes 529 charging sessions in a single-day simulation, with each DCFC plug serving an average of 4.2 recharges per day. HHEVs are not served by fleet-owned EVCS in this scenario, as they are exclusively reserved for fleet use. Instead, HHEVs rely primarily on home charging, with 86% (2,001 sessions) of their total recharges occurring by Level 1 home chargers. Public Level 2 chargers account for 11.6% (270 sessions), while only 50 charging sessions use DCFC plugs.

The *flexible* scenario sees 7 PP EVCS generated as well, each outfitted with an average of 18.1 DCFC plugs to accommodate both SAEV and HHEV charging demand. Most stations reach their maximum capacity, except for one near the Medical Center along the I-35 freeway, which has 7 plugs. This scenario witnesses the highest total HHEV charging trips (2,240), with home charging dominating at 2,114 sessions (87.4%). Despite the increased DCFC plug availability, HHEVs complete 45 recharges using DCFC plugs, compared to 541 by SAEVs, indicating that HHEVs are less frequent users of the *flexible* PP EVCS network. On average, each flexible DCFC plug handles 4.3 EV recharges per day, though SAEVs experience the longest charging wait times at 17.2 minutes.

The *co-located* scenario takes a different approach, deploying no new EVCS but adding 115 fleet-owned DCFC ports to 23 public EVCS alongside their existing public chargers. This results in a total of 131 DCFC plugs, including 16 existing public DCFC plugs. Within the SAEV service geofence, each public EVCS houses an average of 0.6 DCFC plugs after PP DCFC chargers join. This strategy reduces charging congestion and enhances efficiency, enabling an average of 4.8 daily recharges per fleet-owned DCFC plug. HHEVs complete 46 recharges using DCFC plugs, with nearly immediate charging service (0.5 minutes), compared to 1.7 minutes in the *flexible* scenario. Home charging remains the primary option for HHEV, accounting for 91% of their total charging trips. SAEVs also benefit, experiencing the shortest average wait time (3.1 minutes) across all scenarios.

Detailed key metrics, such as charging wait time and use frequency by sites, are shown in Figure 4 and Figure 5 to illustrate spatial variations in EVCS performance. Charging delays tend to be longer at EVCS serving more charging requests. For example, private EVCS are busy recharging SAEVs around downtown Austin and schools at the southside, which are typically associated with high commute and recreational trip densities. In the *co-located* PP scenario, EVCS near schools and shopping centers support more recharges with shorter delays. However, longer charging wait times are observed at EVCS alongside highways, averaging over 18 minutes at flexible and private ones, and over 8 minutes in the *co-located* scenario. Despite this, *co-located* PP EVCS generally enable immediate recharge.

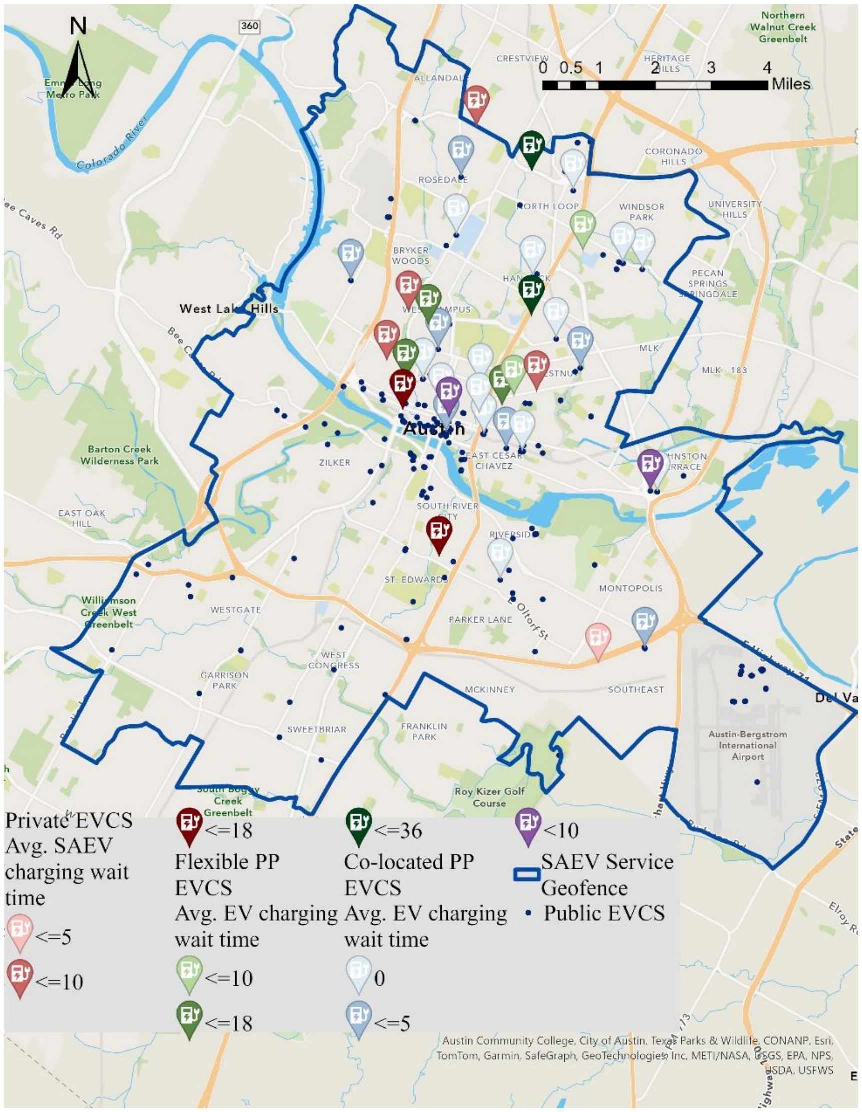

Figure 4. Charging wait time (in minutes) distribution

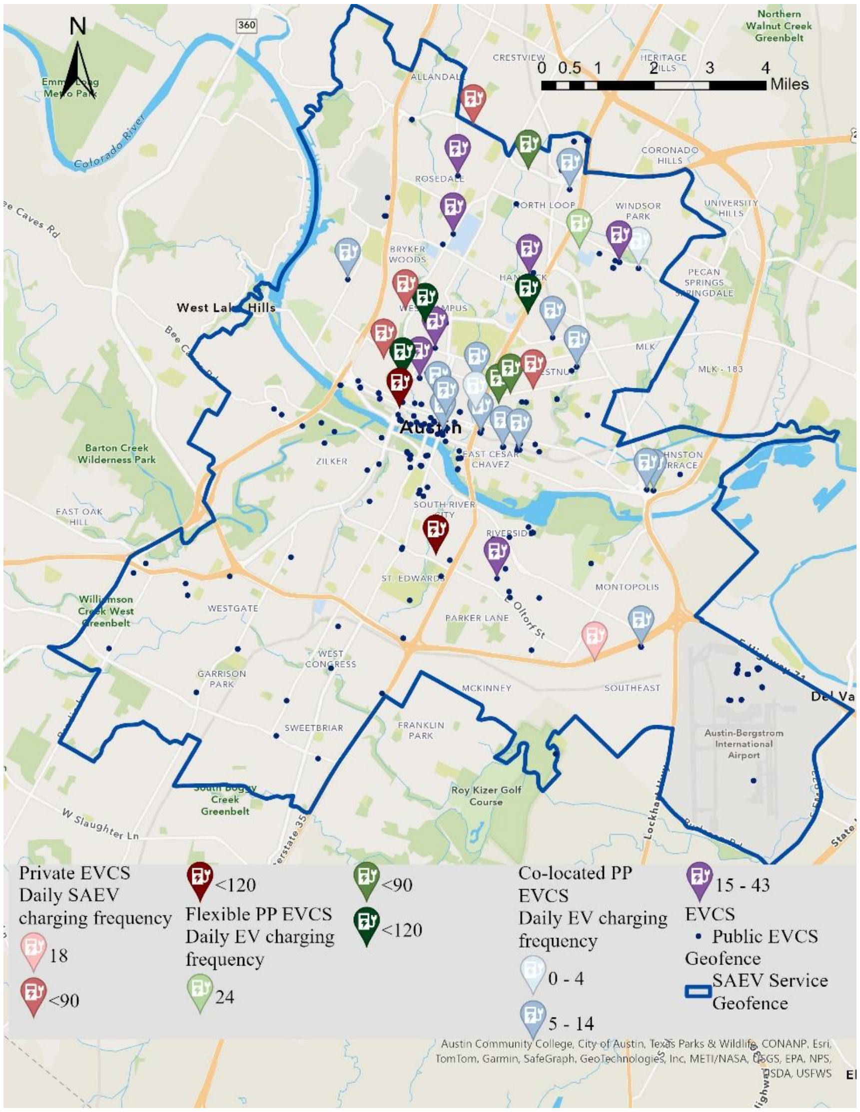

Figure 5. Charging frequency distribution

Charging frequency and energy consumption are important metrics to reflect charging demand. Figure 6 presents the energy consumption distribution by simulated EVCS sites. Both metrics follow similar patterns in the *private* and *co-located* scenarios, with higher energy consumed and more frequent recharges occurring at stations in residential areas, shopping centers, and parks, where long-duration parking aligns with other activities. Besides those places, *flexible* PP EVCS along highways, such as I-35, also serve a relatively high volume of recharges.

Overall, the SAEV fleet consumes more energy and recharges more frequently than HHEV at PP EVCS. In the *co-located* scenario, energy collectively consumed by SAEVs using the DCFC plug is 25 times that of HHEVs. This gap widens to 34 times in the *flexible* scenario. Given the need for quick refueling to serve subsequent ride-hailing requests, fleet operators may consider DCFC plugs as an appropriate solution. Unlike level 2 chargers, which require 8 to 9 hours for a full recharge, DCFC chargers can complete it in two hours. This fast-charging capability enables SAEV to minimize downtime and remain competitive in the ride-hailing market but also poses challenges to attracting HHEV due to higher charging fees.

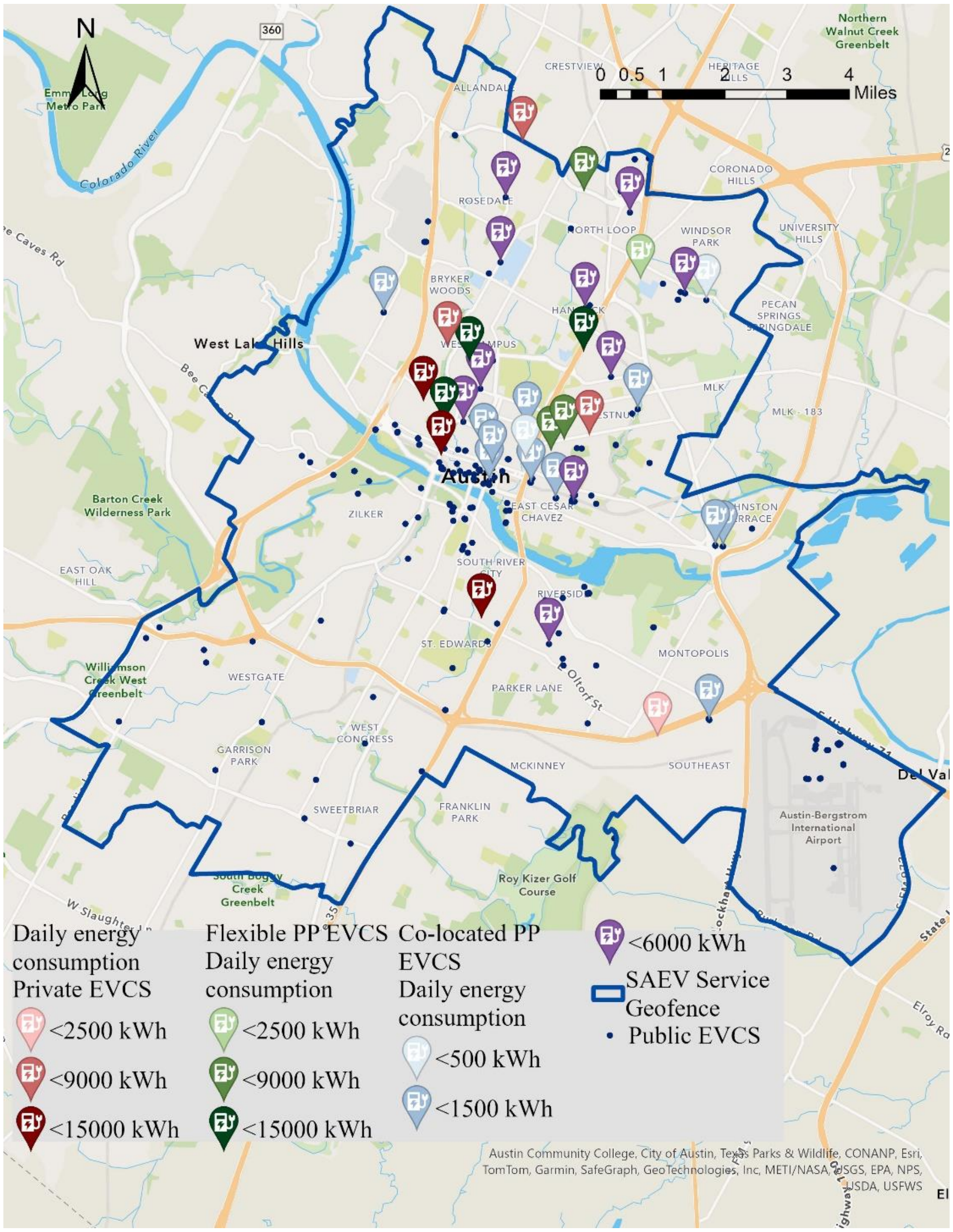

Figure 6. Energy consumption (kWh) distribution

5.3 EVCS Cost Analysis

Beyond siting and sizing PP EVCS to meet demand, assessing the investment required in each scenario is important, as DCFC infrastructure is typically capital-intensive. Equipment cost depends on various factors, including charging level, charger brand, and number of charging ports per pedestal. A 50-kW charger normally costs $20,000 to $35,800 (Nelder and Rogers, 2019), with an average cost of $28,401 (Nicholas, 2019). Installation costs vary by the number of chargers per site, location, materials, labor rates, permits, etc. According to the ICCT report (Nicholas, 2019), installation costs per DCFC charger range from $17,692 to $45,506, with economies of scale reducing costs at larger sites. For example, installing three 50-kW chargers costs around $26,964 per charger, whereas larger sites (6-50 chargers) see costs drop to $17,692 per unit (Table 2).

Beyond installation, efficient operations and maintenance are necessary for EVCS to survive over the long run. Operators usually procure data, network, and maintenance contracts to ensure EVCS functions properly (Nelder and Rogers, 2019). Routine maintenance includes regular check-ups, cleaning, and repairs, with annual extended warranty costs for DCFC chargers exceeding $800 per charger (DOE, 2024b). Since SAEVs are driverless, site service and management expenses are estimated at $55,140 annually per fleet-owned EVCS site to cover labor and operational support, such as manually plugging chargers into SAEVs and vehicle cleaning. Given a 10-year EVCS lifespan before major repairs or upgrades, Table 5 summarizes the initial construction costs and amortized annual investment.

The initial costs for fleet-owned EVCS under *private*, *flexible*, and *co-located* scenarios are $5.81 million, $5.85 million, and $6.04 million, respectively. PP EVCS is distinguished from private EVCS by allowing access to the public, thereby enabling cord-sharing and obtaining potential incentives. By sharing infrastructures, SAEVs can use existing public chargers, thereby avoiding redundant charger construction and lowering the total initial construction cost by 12% to $5.3 million in the *co-located* scenario, which is the least investment option.

Texas offers various incentives to accelerate transportation electrification and encourage clean energy use (https://afdc.energy.gov/fuels/laws/ELEC?state=tx). Utilities such as Austin Energy offer a $5,000 rebate per installed DCFC charger for approved commercial customers (Austin Energy, 2023). Similarly, Entergy's eTech program offers equipment incentives of up to $1,500 per DCFC charger (Entergy eTech, 2024). Benefiting from potential incentives upon opening public access, total construction cost drops to $5.45 million in the flexible scenario and achieves a 23% reduction to $4.65 in the *co-located* scenario million. Compared to the *private* scenario ($5.8 million), co-location lowers cost by 20%.

Considering EVCS lifespan and annual site management expenses, amortized annual investments are estimated at $1.26 million for private EVCS, $1.22 for flexible PP EVCS, and $1.14 million for co-located PP EVCS, demonstrating the financial benefits of PP collaboration. Figure 7 shows the spatial variations in amortized annual costs per charger by scenario. Private sites with 20 chargers average $9,545 per charger annually, while a smaller site near the airport with 5 chargers sees the highest cost at $22,879. Similarly, the flexible scenario yields the lowest per-charger expense at $9,245 for 20-charger sites, while a seven-charger site along I-35 incurs $16,646. Co-located PP chargers' amortized annual costs range from $9,794 to $10,100, with most remaining below $10,000.

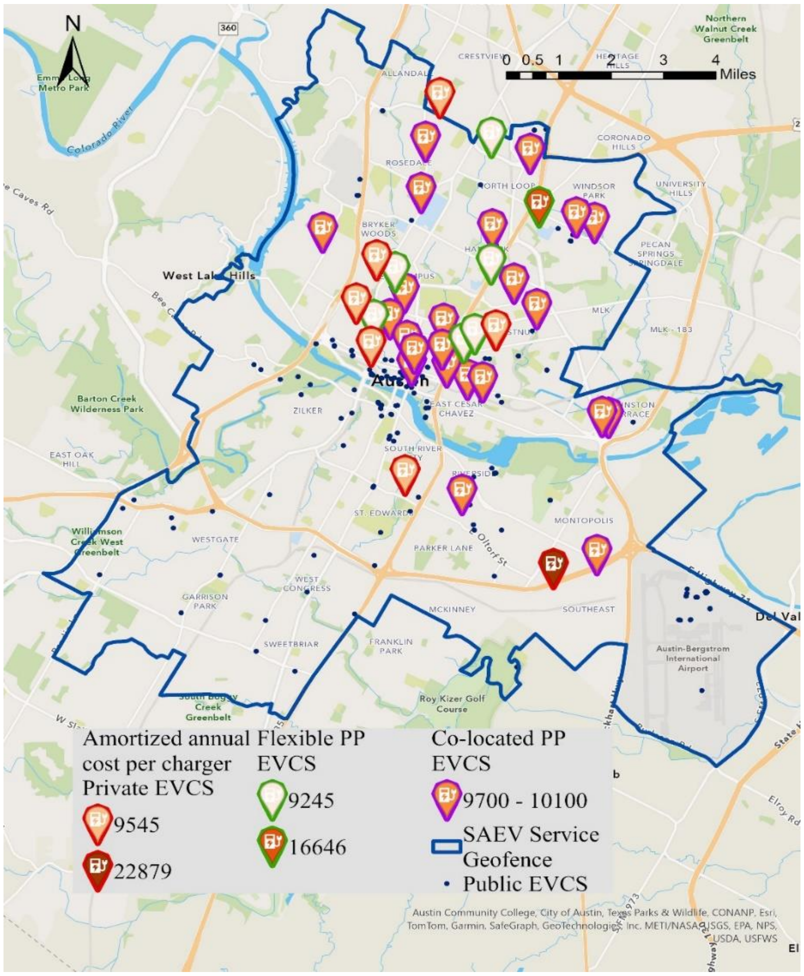

Figure 7. EVCS cost estimation

At the state level, the National Electric Vehicle Infrastructure (NEVI) program funds up to 80% funding to support DCFC infrastructure along major highway corridors, with Texas set to receive $407.7 million over the next five years (Texas DOT, 2022). Moreover, the TxVEMP DC Fast Charger grant program, provides up to $150,000 per unit, with a maximum reimbursement rate of 70% of the total eligible costs (TxVEMP, 2021). PP EVCS can capitalize on these financial incentives, reducing investment costs while expanding service coverage and social impact.

6. CONCLUSION

PP EVCS, formed by opening private charging infrastructure to the public, presents a promising solution to address growing charging demand and siting challenges. This study uses an agent-based model, POLARIS, to evaluate three scenarios: *private* EVCS, *flexible* PP EVCS, and *co-located* PP EVCS. Those EVCS offer distinct charging accessibility to address HHEVs' and SAEV fleets' charging needs. Results demonstrate that co-locating fleet-owned DCFC chargers with existing public EVCS effectively alleviates charging congestion, enabling more simultaneous recharges and minimizing charging delays. The *co-located* scenario facilitates the shortest average fleet charging delays of 3.1 minutes and allows HHEVs almost immediate charging. Most PP chargers are concentrated in high-trip-density areas, such as shopping and dining centers, schools, city parks, and along highways. Compared to the flexible PP EVCS, the co-located one is more attractive to HHEVs due to its proximity to existing public EVCS.

Cord-sharing strategy in the *co-located* scenario further enhances efficiency, allowing SAEVs to use existing public charging resources, thus avoiding charger duplication and achieving a 12% reduction in initial cost, with potential incentive rebates further lowering initial costs by 23% to $4.64 million, saving 20% compared to fleet operators need to build and operate their own EVCS in the *private* EVCS scenario ($5.8 million). However, longer wait times are observed at PP EVCS along highways, with 8 minutes at co-located PP chargers and 18 minutes at flexible ones. To mitigate congestion and encourage off-peak charging, demand-based dynamic pricing schemes that consider grid energy consumption patterns present a promising avenue for future research, enabling CSOs to better trade-offs among revenue strategies. Additionally, optimizing partial recharge policies could further enhance system performance. The adopted SAEV full recharge policy (charging from 20% to 80% SoC) ensures modeling consistency, but may not fully capture the cost-saving potential of partial recharges. Aligning charging durations with operational schedules could improve charger turnover rates, reduce downtime, and offer new perspectives for cost efficiencies and charging infrastructure optimization.

The SAEV fleets perform slightly better under the *co-located* scenario, with each SAEV seeking to recharge 2.7 times a day, highlighting the importance of timely recharging and chargers' fast-charging capabilities. However, higher charging fees associated with DCFC may deter private EV owners, who often prefer cost-effective options for non-home charging. Thus, fleet operators need to consider a mix of PP Level 2 and DCFC ports when deploying charging sites. Integrating Level 2 chargers enables fleet operators to coordinate charging infrastructure use (e.g., fleets' overnight charging by Level 2) at lower infrastructure costs, while accommodating diverse charging preferences. A tailored ratio of Level 2 to DCFC chargers could optimize system performance and user satisfaction.

Observed energy consumption patterns highlight the need to prioritize the high-power charging stations along freeways to support efficient travel, alleviate charging delays, and relieve range anxiety. Besides co-locating fleet-owned chargers with existing public EVCS, partnering with public agencies to upgrade Level 2 chargers to DCFC, and strengthening the electric grid offer additional solutions. While this study focuses on EV trips for charging, the next phase could incorporate various trip purposes such as cleaning and maintenance (Dean et al., 2023).

The study's framework considers charging queues, waiting times, and detour costs to site and size new EVCS. However, its reliance on the nearest station strategy may lead to unbalanced infrastructure use and longer waits near activity centers. Future research could investigate more realistic strategies that minimize total operational times across stations. Such strategies could improve the fleet-owned charging infrastructure efficiency and achieve additional cost savings for SAEV operations. In addition, the heuristic-based approach used in this study may not yield an optimal charging infrastructure configuration. Future research could benefit from optimization-based approaches, such as multi-server queuing models, to better capture the dynamics of charging service rates, vehicle arrival patterns, and waiting times at EVCS. These methods offer a more systematic framework for minimizing total system costs and improving infrastructure efficiency. Moreover, while siting the new EVCS is influenced by initial simulation conditions, consistent patterns emerge across multiple tests. High-demand areas like central business districts, residential neighborhoods, educational institutions, and shopping centers, consistently attract newly deployed EVCS. To further enhance stability and robustness, an iterative framework for refining siting and sizing could be explored as an extension of this research. For example, underutilized fleet-owned EVCS could be downsized or removed through iterative simulations, while congested EVCS could be identified and expanded. By incorporating performance feedback, this flexible framework ensures more realistic and effective EVCS solutions.

In conclusion, policymakers are encouraged to adopt comprehensive approaches to EVCS deployment, integrating technological innovation (such as wireless charging), policy incentives, and stakeholder collaboration. By prioritizing accessibility, efficiency, and cost-effectiveness, a sustainable and dynamic feedback charging network can accelerate the transition to electric mobility, fostering a greener and more resilient mobility system.

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