Transportation Research Part D 124 (2023) 103943

Contents lists available at ScienceDirect

Transportation Research Part D

journal homepage: www.elsevier.com/locate/trd

Deployment priority of public charging speeds for increasing battery electric vehicle usability☆

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ARTICLE INFO

Keywords:
Public charging infrastructure
Deployment priority
Charging behaviors
National Household Travel Survey (NHTS)
Extreme fast charging

ABSTRACT

To inform charger deployment decisions, this paper aims to understand the potential utilization and deployment priority for public charging infrastructure. A data-driven Cumulative Public Recharging (CPR) model is developed to explore the travel patterns by using 2017 National Household Travel Survey data. Given the daily trip sequence, trip distance, and dwell times, the study examines the daily expected driving range and BEV feasibility under different charging speeds, battery capacity, and charging behaviors. The results suggest that more advanced public chargers increase the daily expected driving range. Home charging is sufficient for most daily short-distance trips while public chargers are still needed for medium- and long-distance trips. Extreme fast charging (xFC) may not be necessary for people with home charging but could be more useful for people without home charging and for urgent charging. xFC becomes even less important to drivers with longer BEV ranges, a finding that contradicts conventional thinking.

1. Introduction

To become mainstream, Battery Electric Vehicles (BEVs) need to compete with gasoline vehicles with respect to not only ownership cost, but also convenience and usability. Sufficient driving range for middle and long-distance travel is essential to satisfy travel demands and increase BEV usability and acceptance. Most BEVs on the market today have all-electric range (AER) around 80–350 miles (mean AER is 236 miles) excluding all the Tesla models (EVAdoption, 2021). Clearly, the AER of most BEV products is far less than the typical driving range of gasoline vehicles. Insufficient driving ranges put BEVs into even greater disadvantage in view of widespread gasoline stations outshining the limited availability of public fast chargers. One important attribute of charging stations is the charging power, which determines charging time for a given amount of electricity to be charged or electric range to be extended. Table 1 shows the typical charging speeds in two metrics of existing charger technologies, assuming BEV energy consumption at 285 Wh/mile (Ahmed et al, 2017), illustrating the difference in user convenience among charging technologies that are currently deployed

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https://doi.org/10.1016/j.trd.2023.103943
Received 9 February 2023; Received in revised form 21 August 2023; Accepted 5 October 2023
Available online 26 October 2023
1361-9209/Published by Elsevier Ltd.

or will be deployed in the future. Typically, a Level 1 charging station can offer 4 miles/hour of charging. A Chevy Bolt needs more than a day to be fully charged given its range of 238 miles. A Level 2 charger will charge a 250-mile BEV in about 9.5 h (Siuru, 2020). A direct current Fast Chargers (DCFCs) allows it to be fully charged in about 1 h and 20 min. Tesla's Supercharger Version 3 can extend 75 miles of range in 5 min (Howard, 2020). To move closer to the refueling experience of gasoline vehicles, extreme fast charging (xFC), i.e., charging rates of 350–400 kW, is being researched and developed.

It is estimated that 85 % of BEV charging occurs at home (Karner et al., 2016), which however probably reflects the disproportionally higher percentage of garage-equipped single-family houses among the high-income early adopters of BEVs. Currently, residential charging is where most of the charging will occur because it is convenient and inexpensive. BEV owners can take advantage of lower residential electricity rates. However, for mid- and long-distance road trips, the need to charge at public charging stations has become important, at least perceivably, and even essential. Most public charging infrastructures that have been deployed today are Level 2 chargers, with some DCFCs and few Level 1 chargers. According to the statistics from Alternative Fuel Data Center of the US Department of Energy (DOE Alternative Fuel Data Center, 2020), it is estimated that 637 Level 1 stations, 23,215 Level 2 stations, and 3,832 DCFCs have been deployed and available for public use in the US by 2020, as shown in Fig. 1. Due to the slow charging speed, Level 1 chargers are not preferable in public charging stations. Though Level 2 and DCFC are more efficient, drivers' recharging experience with BEVs today is still not comparable to refuelling experience with gasoline vehicles because of the longer charging waiting time and limited charging opportunities. "Range Anxiety" is one of the major concerns for BEV owners and potential consumers and can be alleviated with more powerful and more available public chargers.

In summary on research motivation, for Battery Electric Vehicle (BEV) to be as usable as gasoline vehicles, a certain level of public charging availability is needed, even though home charging has been viewed as most cost-effective and convenient. Direct current fast charging (DCFC) already faces profitability difficulty and scepticism on its cost-effectiveness, while more expensive xFC is being developed. To inform deployment decisions of charging technologies, it is important to better understand the potential utilization and deployment priority of different types of charging infrastructures. The overall objectives of public charging infrastructure deployment include (i) accelerating EVs adoptions, (ii) increasing Electric Vehicle Miles Traveled (eVMT), and (iii) keeping grid stability and reliability. For these reasons, advanced public charging infrastructures, e.g., DCFC and xFC, have several significant advantages. Increasing availability and use of these technologies enable the AER to be extended beyond that provided by the overnight charging at residential charging infrastructure, resulting in an increasing eVMT and a potential increase of BEV adoption. However, there are still many challenges and limitations if these advanced technologies are widely deployed, such as high charging infrastructure costs (Smith and Johnathan, 2015), damaging BEV batteries (Sebastian et al, 2020), and affecting power system voltage stability (Dharmakeerthi et al., 2014). The pros and cons further encourage investigating how current public charging infrastructure performs in terms of supplementing residential charging and serving daily charging demands. It is also worthwhile to study what types of charging infrastructures should receive the priority to be deployed and fill the current gap.

Hence, this study aims to answer the questions and identify the deployment prioritization of public charging infrastructure. Specifically, A data-driven Cumulative Public Recharging (CPR) model is developed to explore the personal vehicle's travel patterns as revealed by 2017 National Household Travel Survey (NHTS) data. Given the daily trip sequence, trip distance, dwell times, and the assumptions of vehicle recharging behaviours, the method examines what will be the maximum charging potentials and daily expected driving range with different types of public chargers. We further explore the BEV feasibility given the daily expected driving range and the past driving experience.

Our proposed method makes several unique contributions.

1. Existing studies either relied on old historical data of travel behaviours, such as data before 2006, or used the data from early BEV adopters who are generally wealthier (may bring in sample biases). Our study is developed based on a national representative dataset (NHTS data) which is better for large-scale electrification analysis.
2. We consider the probabilistic "charging opportunities" in the BEV recharging model, which is hardly considered in the literature.
3. The trip dependencies are considered in the model, i.e., given the trip chain information from NHTS, the influence of battery depletion from the previous trip on recharging behaviours have been considered in the CPR model.
4. We consider xFC and generate important insights to hopefully prevent wasteful investments or priority of xFC.

In this paper, Section 2 discusses the literature review on planning and deployment of public charging infrastructure based on travel behaviours. Section 3 describes the data used in this study. Section 4 present CPR model to investigate revealed travel patterns. Section 5 shows the numerical results. Section 6 summarize the conclusion of this paper.

Table 1
Description of charging infrastructure compared with xFC.

	Level 1 110 V, 1.4 kW	**Level 2** 220 V, 7.2 kW	**DC Fast Charger** 480 V, 50 kW	**Tesla Supercharger (SC)** 480 V, 140 kW	**xFC** 800 + V, 400 kW
Range per minutes of Charge (miles)	0.082	0.42	2.92	8.17	23.3
Time to Charge for 200 miles (min)	2,143	417	60	21	7.5

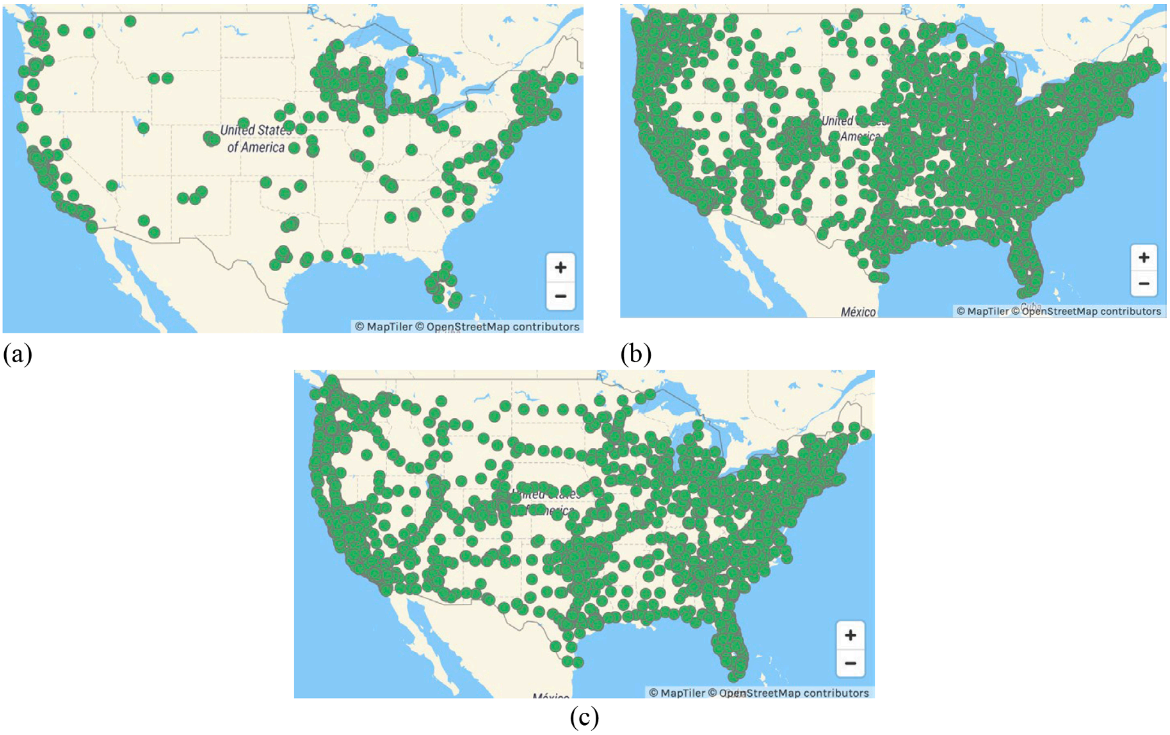


Fig. 1. Public charging infrastructures deployed in the US. (a) Level 1 charger: 637 stations and 1,486 charging outlets. (b) Level 2 charger: 23,215 stations and 67,218 charging outlets. (c) DCFC: 3,832 stations and 14,640 charging outlets.

2. Literature review

Literature is rich on charging infrastructure planning, but only a few discuss deployment prioritization of different types of charging infrastructure, especially with extreme fast charging for passenger BEV. Karner et al. (2016) proposed a charging infrastructure roadmap to prioritize charging infrastructure actions and promote EV adoption. This study leverages the experience from the authors and other EV industry experts along with the data collected by the US Department of Energy to identify the means of maximizing use of existing and future charging infrastructure. The roadmap also examined the obstacles and recommended means to overcome the obstacles. This study concluded that home charging was the most important location for all types of EVs and the workplace charging was the next priority. DCFC can extend intra-urban travel for BEVs during the early and transitional phases of charging infrastructure deployment. Overall, this study provided a guideline relating to charging infrastructure deployment from a macroscopic perspective. The details of how charging infrastructure, especially public charging, can potentially impact travel behaviors of BEV owners and increase eVMT in middle-range and long-range trips were not discussed and covered. Zhang et al. (2020) examined the feasibility of BEVs and charging infrastructures from an economic aspect. They used multi-day activity travel patterns to create a BEV usage profile. The profile contained battery status at different locations with varying charging opportunities. They suggested that a certain number of chargers deployed in shopping and leisure locations would be profitable and have higher charger utilization rate. Dong et al. (2014) examined the impacts of different levels of public charging infrastructure on reducing BEV range anxiety using an optimization model considering the recharging behaviors and deployment cost. They found that with a small budget, Level 1 chargers could provide the necessary network coverage at a lower cost. Level 3 chargers were less attractive due to the high costs. To evaluate the public charger availability on BEV travel needs, it is important to explore the relationships between recharging behaviours and daily travel activities. Dong and Lin (2012) examined the role of public charging infrastructure in increasing the eVMT using GPS-tracked household travel survey data. The drivers' recharging behaviours is modelled as a boundedly rational decision considering the constraints of travel activities and public charger availability. It was found that extensive public charging service would reduce gasoline consumption of plug-in hybrid electric vehicles by 30 % compared with residential charging only.

3. Data Preparation

This study uses 2017 NHTS data to extract daily individual travel behaviors and macroscopic travel patterns. The dataset contains travel activities of U.S. residents during a travel day by different transportation modes. The NHTS data contains a few errors, e.g., a trip length of 1600 miles per day. To filter out the errors, the trip records that fail to meet the following criteria are excluded from consideration:

1. Because this study mainly focuses on the travel behaviours of personal trips, only four trip modes are selected from the dataset, i.e., car, SUV, van, and pickup truck.
2. Dwell time are positive values.
3. The destination of each trip in a trip chain is *non-home* because this study evaluates public charging behaviours.
4. Daily maximum driving range should be less than 1600 miles.

The important trip characteristics used in this study are listed in Table 2. HOUSEID, PERSONID, and TDTRPNUM are the index to identify personal trip chains during the trip day. The variable VEHID links NHTS Trip file to Vehicles file which contains the vehicle characteristics, e.g., vehicle fuel types. DWELL and VMT_MILE are two important features to identify trip patterns, which will be explained in detail in the next subsection.

The market penetration of BEVs in 2017 NHTS is around 0.2 %. To evaluate the impacts from public charging infrastructure on BEVs' daily travel, this study assumed that gasoline vehicles in the 2017 NHTS will be replaced by BEVs while their trip characteristics remain unchanged, i.e., dwell time and trip distance of gasoline vehicles are treated as BEVs. The assumption also existed in other studies that evaluated BEVs charging behaviours (Hu, Dong, and Lin, 2019). This assumption is reasonable in the way that one of the goals of BEVs is to create the similar driving behaviours as gasoline vehicles, as we discussed in the Introduction section. Fig. 2–Fig. 4 show comparisons on dwell time, trip distance and daily driving distance between gasoline vehicles and BEVs using 2017 NHTS data. In Fig. 2, the dwell time distributions of gasoline vehicles and BEVs are similar. Around 35.4 % gasoline vehicles and 39.3 % BEVs have dwell time less than 1 h per trip (each bar represents a 30 min time interval). The average dwell times are 117 min for gasoline vehicles and 116 min for BEVs separately. In Fig. 3, the trip distance of more than 60 % of total trips are less than 5 miles for both gasoline vehicles and BEVs. The average trip distances are 8.6 mile for gasoline vehicles and 7.3 mile for BEVs. Fig. 4 shows daily travel distance per person. Around 64 % of trips of gasoline vehicles and 50 % for BEVs have daily travel distance less than 10 mile. The average travel distances are 13.23 miles and 17.77 miles for gasoline vehicles and BEVs. These statistics suggest that most daily trips are short-range trips and are less than 20 miles. Still, for a certain portion of long-range trips and trips with urgent charging demand, the advanced chargers such as DCFC and xFC will improve the charging flexibility.

4. Methodology

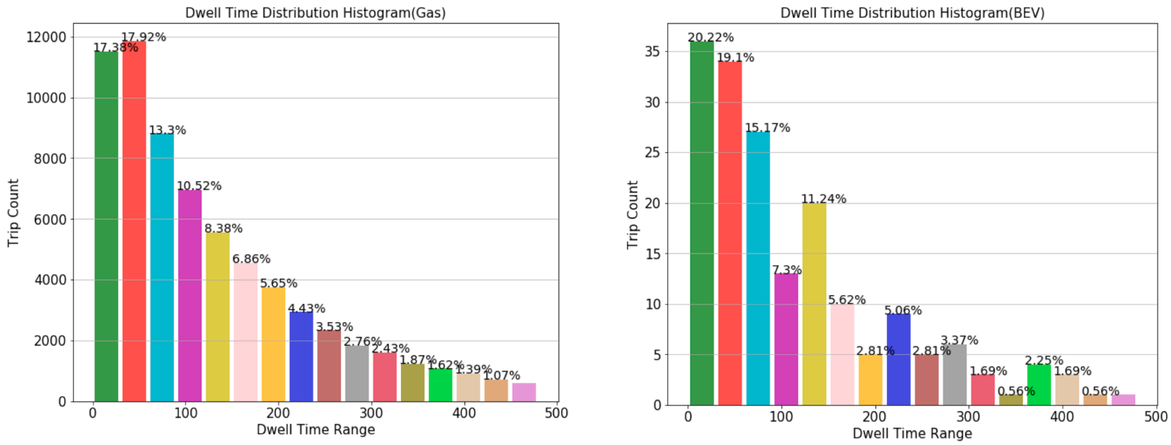
This section presents the data-driven Cumulative Public Recharging (CPR) model to examine the relationships between public charging infrastructures and travel behaviours using 2017 NHTS data. Fig. 5 illustrates the overall framework of this study. Specifically, the key question will be answered, i.e., what will be the maximum charging potentials and daily expected driving range with different types of public chargers and how different variables will influence the daily expected driving range and BEV feasibility. There are two categories of variables that influence the charging potentials. One category relates to the features of public charging infrastructures, such as different levels of charger powers and various charging opportunities. Other important variables associate with BEV owners, such as BEV battery capacity and the availability of home charging. The variations of these variables define different charging availability and constraints for BEV owners. They are the inputs to the CPR model. The objective of the CPR model is to estimate the daily expected driving range and BEV feasibility for daily trips for all travellers according to their trip patterns learnt from NHTS data.

This study evaluates four different scenarios:

- **Scenario 1**: BEVs are charged whenever they stop longer than 15 min and there is no constraint of battery capacity and trip chain influence, i.e., the expected range only relates to the daily accumulated dwell time. Not realistic, but it is intended to reflect the theoretical maximum utilization.
- **Scenario 2**: BEVs are charged whenever they stop longer than 15 min while the charging electricity is constrained by the battery capacity.
- **Scenario 3**: BEVs are charged whenever they stop longer than 15 min but charged electricity energy is constrained by the remaining battery capacity as well as the travel distance of previous trips. This is the scenario we describe in the CPR model by the Methodology section.

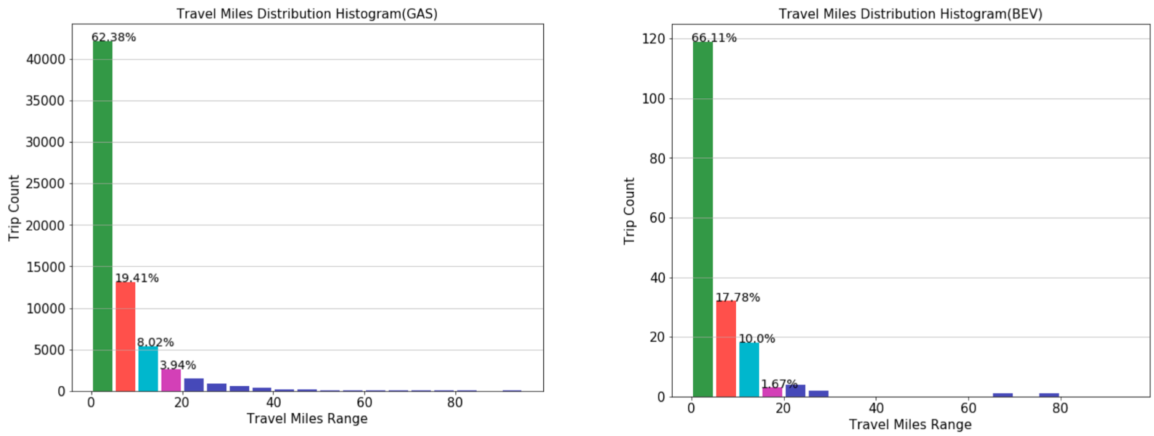
Table 2
Important features in 2017 NHTS used in this study.

Name	Label
HOUSEID	Household identifier
PERSONID	Person identifier
VEHID	Household Vehicle Identifier used on trip
TDTRPNUM	Incrementing travel day trip number
STRTTIME	Trip start time
ENDTIME	Trip end time
WHYTRP1S	Trip purpose summary
DWELLTIME	Time spent at the destination
VMT_MILE	Trip distance in miles for personally driven vehicle trips



(a) (b)

Fig. 2. Dwell time for gasoline vehicles and BEVs to non-home destinations (each bar = 30 min): (a). All gasoline vehicles. (b) All BEVs.



(a) (b)

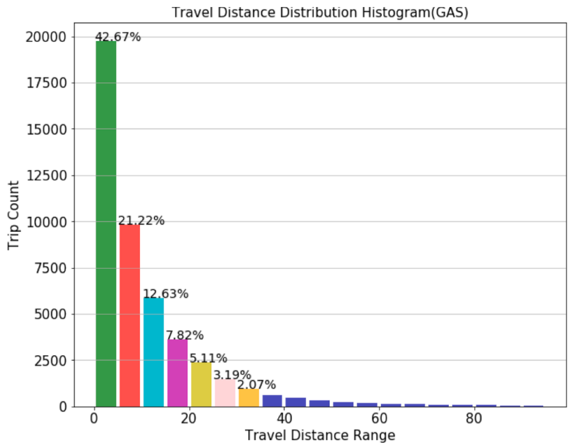
Fig. 3. Trip distance for gasoline vehicle and BEV to non-home destinations (Each bar = 5mile): (a). All gasoline vehicles. (b) All BEVs.

- **Scenario 4**: Vehicles are charged once at public charging stations per day, at the stop with the longest dwell time during the day. The charged electricity energy is constrained by the remaining battery capacity as well as the cumulative distance of the previous trips since leaving home.

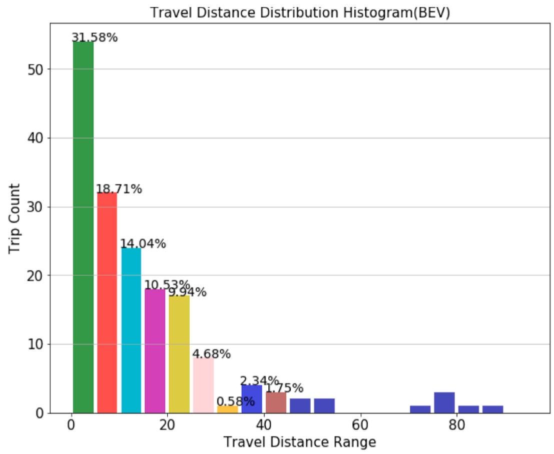
There are a few assumptions in the CPR model. *First*, as we mentioned in the Data Preparation section, all travel behaviours, e.g., trip sequence, dwell time, and trip distance, from the non-BEV drivers in NHTS data are assumed the same for the BEV drivers. For public charging, the battery is only charged during outside-home dwell time. This is to model the maximum public charging potential and understand the maximum impact of public charging on extending the AER of the BEV. *Second*, all BEVs are fully charged when they start a trip from home during the trip day. *Third*, BEVs at non-home stops can be charged because we only consider public charging behaviours in this study. As shown in Fig. 6, a typical daily trip chain for one person includes three trips and three stops. We consider workplace charging as one scenario in public charging. Workplace could be one stop in a trip chain where travellers can charge if necessary.

Table 3 summarized the notations and descriptions used in the section.

The CPR model is developed to estimate the maximum charging power electricity, the resulting daily expected driving range, and BEV feasibility. There are four constraints determining how much electricity can be charged: BEV battery capacity, travel distance of previous trips before the charging opportunity (i.e., depleted battery capacity), the charging power and the dwell time. A BEV can only be charged between two consecutive trips and its charged energy is constrained by the remaining battery capacity, the charging speed and the dwell time, as formulated by Eq. (1) on the extended amount of driving range after trip k:



(a)



(b)

Fig. 4. Daily travel distance for gasoline vehicles and BEVs to non-home destinations (Each bar = 5mile): (a). All gasoline vehicles. (b) All BEVs.

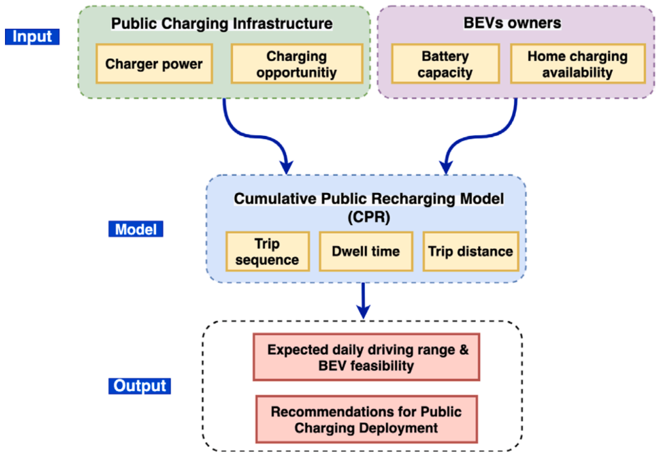


Fig. 5. Overall framework.

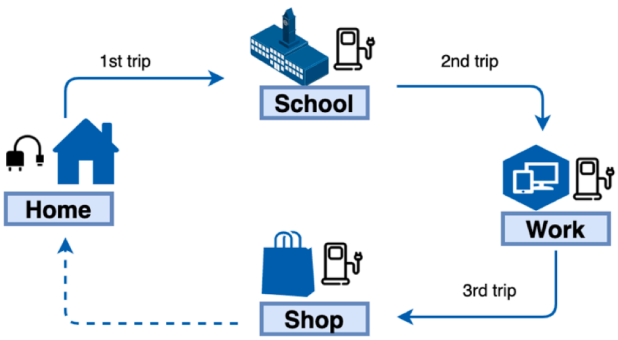


Fig. 6. A sampled trip chain during a day.

Table 3
Notation description.

Notation	Description
$dt_{n,k}$	Dwell time of vehicle n after trip k, (hour)
$d_{n,k}$	Trip distance of vehicle n during trip k, (miles)
CP	Charger power (kW)
E	Electricity consumption rate, (kWh/mile)
P	Public charging opportunity (%)
$I_{n,k}$	Indicator variable. $I_{n,k} = 1$ if vehicle n is recharged after trip k, 0 otherwise
$r_{n,k}$	Electricity range increase of vehicle n due to the recharge after k (miles)
AER	All electric range (miles)
$rr_{n,k}$	The remaining electricity range of vehicle n when finishing trip k (miles)
$f_{n,k}$	Indicator variable. $f_{n,k} = 1$ if trip k of vehicle n is feasible, 0 otherwise
b	Buffer distance (miles)

$$r_{n,k} = \min\left(\frac{CP \times dt_{n,k}}{E}, AER - rr_{n,k}\right) \quad (1)$$

where the charging power *CP*, all electric range *AER*, and electricity consumption rate *E* are predetermined parameters. The dwell time of vehicle *n* after trip *k*, $dt_{n,k}$, is obtained from NHTS data. The remaining electricity range $rr_{n,k}$ relates to the trip distance and charging opportunities along the way.

$$rr_{n,k} = \max(0, rr_{n,k-1} + I_{n,k} \times r_{n,k-1} - d_{n,k}) \quad (2)$$

where $I_{n,k}$ is a binary variable indicating if vehicle *n* is recharged after trip *k*. It is drawn from a Bernoulli distribution in Eq. (3) with charging opportunity *P*. The Bernoulli distribution is a discrete probability distribution that is often used to model binary variables, where there are only two possible outcomes: success or failure. There are many factors that affect charging opportunity, such as locations of charging stations, the cost of charging services, and the time and charging sessions. To model charging opportunity, data on agent-based trip information, location, capacity, and utilization of charging stations should be collected. However, this study aims to assess various charging scenarios and hypotheses across different charger deployment strategies, which lacks empirical data from real-world observations. Hence, we simplified the modelling process and used the single parameter P to represent the availability of an opportunity to charge an EV at a particular location or time.

$$Pr(I_{n,k} = 1) = P = 1 - Pr(I_{n,k} = 0), 0 \leq P \leq 1. \quad (3)$$

This study evaluates daily expected driving range and considers it as the maximum driving potential for BEVs. The daily expected driving range is defined as Eq. (4).

$$ER_n = AER + \sum_{k=1}^{K} r_{n,k} \quad (4)$$

BEV feasibility of daily trips is quantified by Eq. (5). It indicates that if remaining electricity range of vehicle *n* after trip *k* is greater than the sum of its next trip distance $d_{n,k+1}$ and a buffer distance *b* ($b > 0$), the trip $k+1$ is BEV feasible ($f = 1$). If remaining electricity range $rr_{n,k}$ is exactly equal to the next trip distance $d_{n,k+1}$ ($b = 0$), it suggests that vehicle *n* will run out of electricity after trip $k+1$,

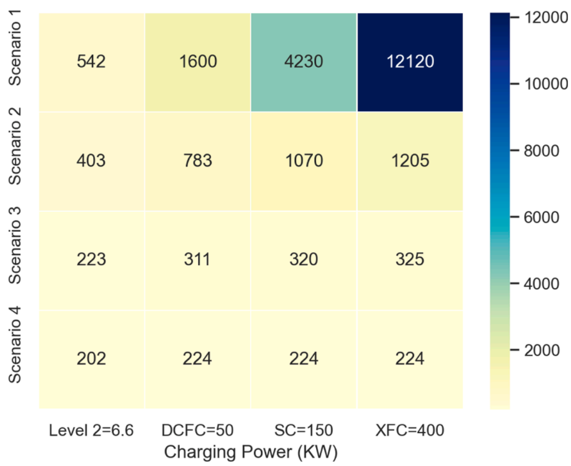


Fig. 7. Expected daily driving range by charging speed (95th percentiles of the expected range distribution as the expected driving range).

which is inconsistent with the driver's driving habits in a real-world situation. Hence, a positive buffer distance (e.g., 10 miles) is added to Eq. (5) to make it reasonable. It is noted that Eq. (5) defines if one trip is BEV feasible. For multiple daily trips of one person, the daily trip chain is BEV feasible only if all trips in a trip chain are feasible.

$$rr_{n,k} \geq d_{n,k+1} + b \tag{5}$$

To calculate the daily expected driving range per BEV and quantify BEV feasibility considering charging opportunities and battery capacity, we need to revisit the trip chain of each vehicle in NHTS data.

5. Results and discussions

With the CPR model described in the Methodology section, the maximum charged energy and daily expected travel range can be computed. In this section, several scenarios are created to evaluate the influence from various charger power, charging opportunity, BEV battery capacity, and availability of residential charger on BEV daily expected driving range. Recommendations on public charger deployment were also developed to guide deployment of public charging infrastructure.

5.1. BEV daily expected driving range and BEV feasibility under various charger powers

We evaluated four types of charger powers, i.e., Level 2 charger = 6.6 kW, DCFC = 50 kW, Supercharger = 140 kW, and xFC = 400 kW. The AER for all BEVs is set to be 150 miles in this section. Additionally, this section works under the assumption of a 100 % availability of charging stations whenever BEV drivers require charging. The authors' claim of achieving similar driving behaviors to gasoline vehicles originates from this assumption, suggesting that charging infrastructure is readily accessible and sufficient to meet the needs of BEV users. This assumption might be too optimistic. We further studied how different levels of charging opportunities affect daily driving range and the BEV feasibility in section 5.3. Fig. 7 shows the heatmap of daily expected driving range with different levels of charging power under four scenarios. Each sample driver/BEV is associated with a one-day trip chain and one resulting expected driving range. Given many samples, we selected the 95th percentiles of the expected range distribution as the expected driving range. Scenario 1 is a theoretical and ideal case that no charging constraint exists. Although it is not realistic, this scenario gives an overall benchmark on the expected driving range of the 150-mile-range BEV. Scenario 2 added the constraint of the battery capacity. Compared with scenario 1, the expected driving range decreases for all types of chargers. Scenario 3 is the case where we describe in the CPR model that considers the remaining battery capacity and trip chain constraints. It is the most realistic case. It

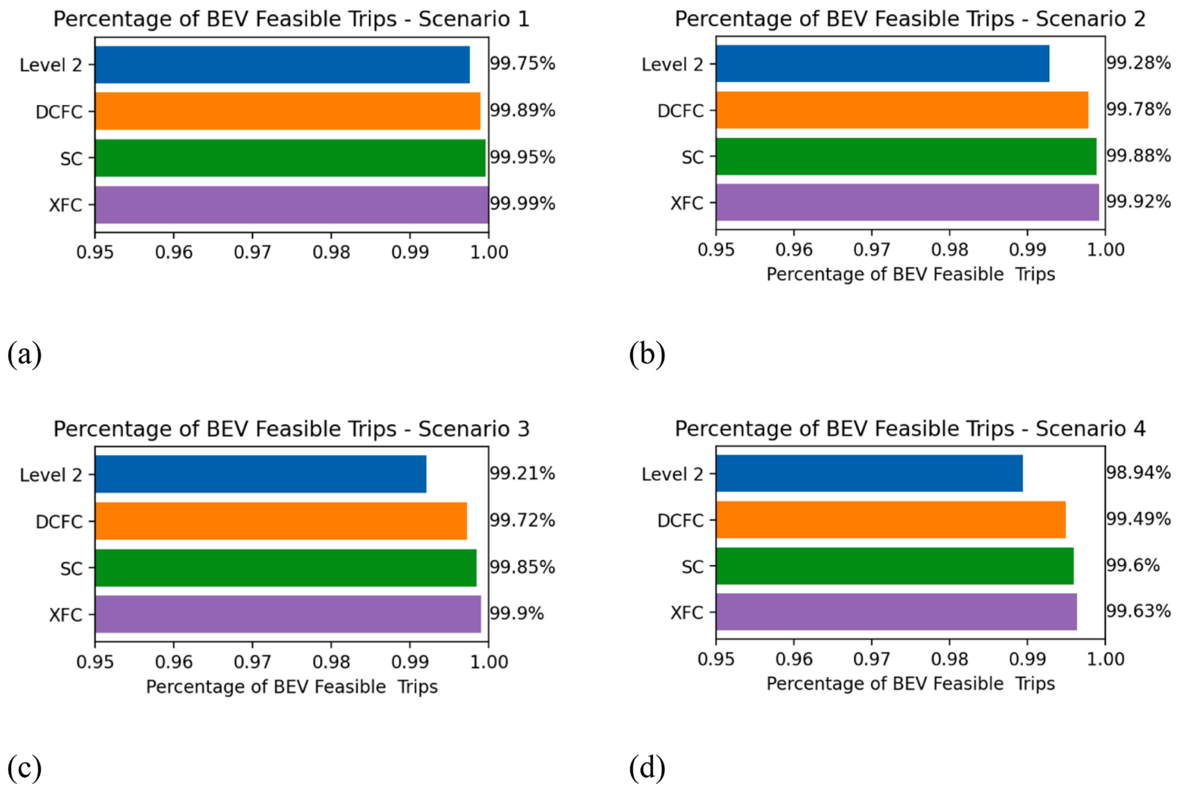


Fig. 8. BEV feasibility analysis of 4 scenarios: (a) Scenario 1 – Charging without constraint. (b) Scenario 2 – Charging considering battery capacity. (c) Scenario 3 – Charging considering battery capacity and trip chain characteristics. (d) Scenario 4: Charge at the stop with the longest dwell time.

suggests that the expected driving range given DCFC, SC, and xFC did not significantly different from each other. Scenario 4 is a special case of Scenario 3 that BEVs only charge once at the stop with the longest dwell time. Except the level 2 charger, all other three types of chargers did not increase the expected driving range in this case.

Fig. 8 shows BEV feasibility of four scenarios. Each sample driver is associated with a one-day trip chain and one evaluation of BEV feasibility. It shows that under all scenarios, the 150-AER BEV feasibilities are higher than 99 % given different charger levels except Level 2 in scenario 3 and 4. For scenario 3 and 4, which are more realistic cases, the improvement of BEV feasibility using DCFC from Level 2 charger is most obvious compared to other more advanced chargers. It suggests that DCFC can have comparable performance to Super chargers and xFC in terms of improved BEV feasibility.

5.2. Daily expected driving range and BEV feasibility under various AER

Battery capacity is an important feature affecting BEV recharging behaviors and their driving experience. The different values of AER from 75 miles to 400 miles are evaluated under scenario 4. Fig. 9 shows five AER values under each level of charger power. It was reported that under severe weather conditions, e.g., cold winter and hot summer days, the BEV driving range could decrease to 40 % of AER (Yuksel and Michalek, 2015). Thus, the 75-mile case can be viewed as the 150-AER BEV operating with severe weather. In Fig. 9, under each charging power, a longer AER indeed increases daily expected driving range. Under each level of AER, increasing charging power did not increase the expected driving range, especially for DCFC, Supercharger, and xFC. Given most trips in NHTS are short-range travel, the improvements of expected driving range due to the improvement of AER and charging power were not obvious.

Fig. 10 shows the percentage of BEV feasibility of vehicle with five choices of AER under four charging levels under scenario 4. It suggests that with Level 2 public chargers with AER = 75 mile, 97 % daily trips are BEV feasible. Increasing charger levels and AER, the percentage of BEV feasible trips slightly increases as well. The BEV feasibility does not have much difference when using Super Charger and xFC.

5.3. Daily expected driving range under various charging opportunities

As shown in Eq. (2–3), the Bernoulli variable $I_{n,k}$ denotes if BEV *n* can charge after trip *k* with charging probability *P*. Fig. 11 shows daily expected driving range with various charging opportunities. The AER for all BEVs is set to be 150 miles in this section. The daily expected range indeed increases as charging opportunity increases. Again, under each charging opportunity level, the improvement of charging power did not markedly increase the expected range.

Fig. 12 shows BEV feasibility under different public charging opportunities under scenario 4. As opportunity decreases, the percentage of BEV feasible trips decreases slightly. With only 10 % of public charging opportunities, the percentage of BEV feasible trips with Level 2 charger is as high as 98.31 %. There are two main reasons. First, we assumed that residential charging is available for all BEV drivers so that their initial SOC is 100 % at the start of the day. Second, most trips are short-range trips, as shown in Fig. 3, that they do not rely on public chargers to complete trip chains.

5.4. Daily expected driving range - impacts from residential charging

It is estimated that more than 80 % of BEV charging occurs at home (Karner et al., 2016). Residential charging is the major charging source for daily trips currently. Fig. 13 compares four cases. There are 30 %,50 %, 80 % and 100 % of BEVs that can be fully charged at home. Other BEVs that cannot charge at home will have an initial 50 % of AER as initial state of charge. This assumption might be

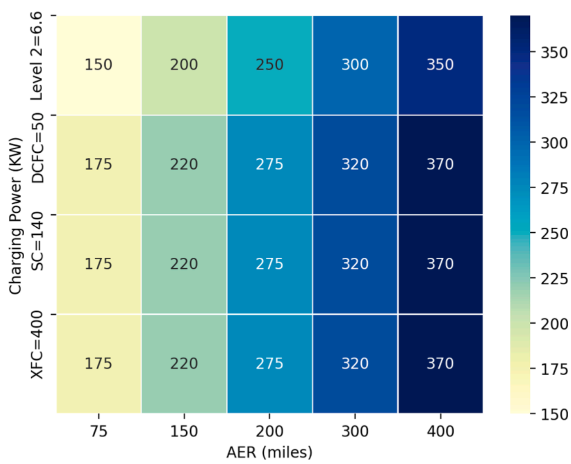


Fig. 9. Daily expected driving range with various charging power and AER (95th percentiles of the expected range distribution as the expected driving range).

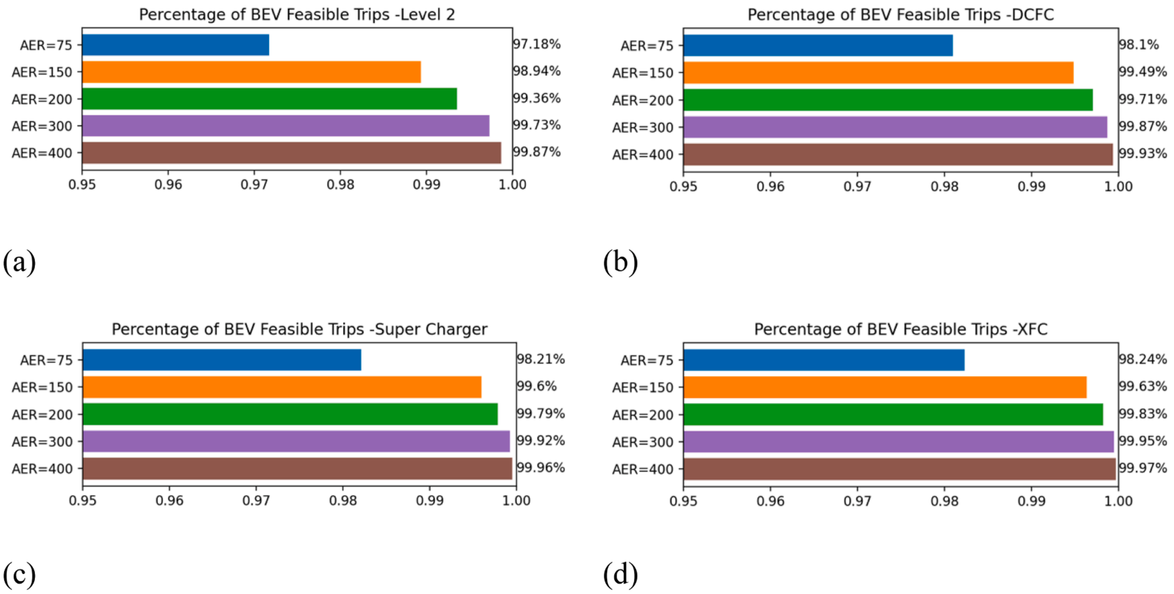


Fig. 10. BEV feasibility with various charging power and AER: (a) Level 2 charger = 6.6 kW. (b) DCFC = 50 kW. (c) Supercharger = 140 kW. (d) xFC = 400 kw.

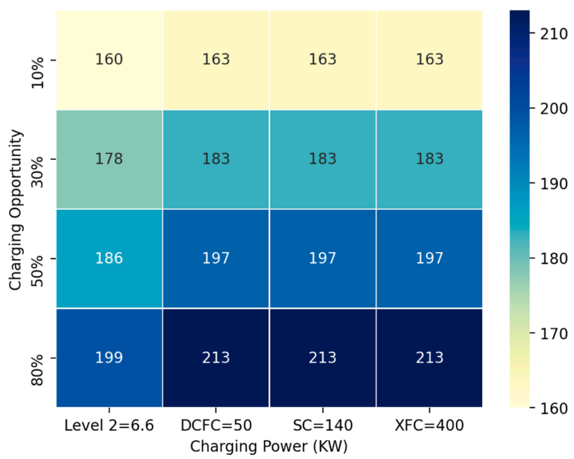


Fig. 11. Daily expected driving range considering charging opportunity (95th percentiles of the expected range distribution as the expected driving range).

naïve. Because 2017 NHTS data contain the daily trip chain without the information of trips on the previous day, there is no data to infer the initial SOC of individual BEV. The assumption will be updated to reflect the real-world situation as further data on BEV drivers becomes accessible. This will be pursued in the future study. As residential charging availability reaches to 50 %, the daily expected driving range does not change. Most of the trips extracted from the NHTS data set are short-distance trips. It suggests that residential charging is significant for short-distance travel. It cannot substitute for the important role of public chargers, especially for middle and long-distance trips.

Fig. 14 shows BEV feasibility under various levels of residential charging opportunities. As the opportunity increases, BEV feasibility increases slightly.

5.5. Recommendations for public charger deployment

Table 4 shows the recommendations for public charger deployment given the revealed travel pattern. Different combinations of the public charger types, public charging opportunity, and home charging availability are given as inputs. The table can be used to determine if the short-distance, mid-distance, and long-distance travel demands can be served by each combination. The evaluation criteria are determined based on the numerical analyses in this study. It is noted that the definitions of short-, mid-, and long-distance

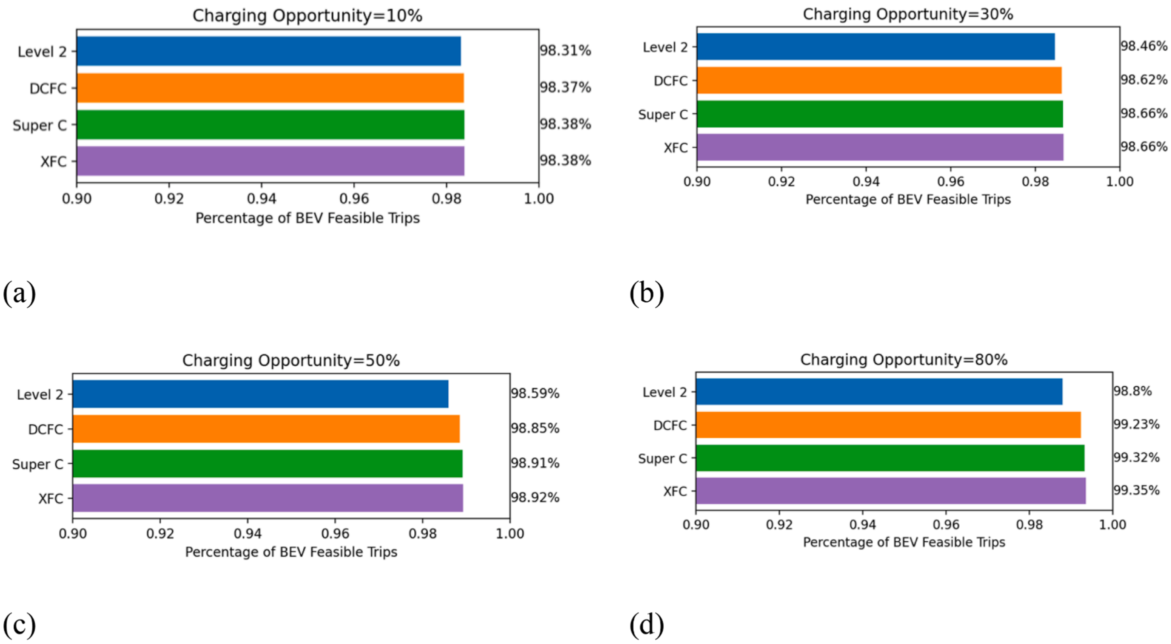


Fig. 12. BEV feasibility considering charging opportunity. (a). (b) Public charging opportunity = 30 %. (c) Public charging opportunity = 50 %. (d) Public charging opportunity = 80 %.

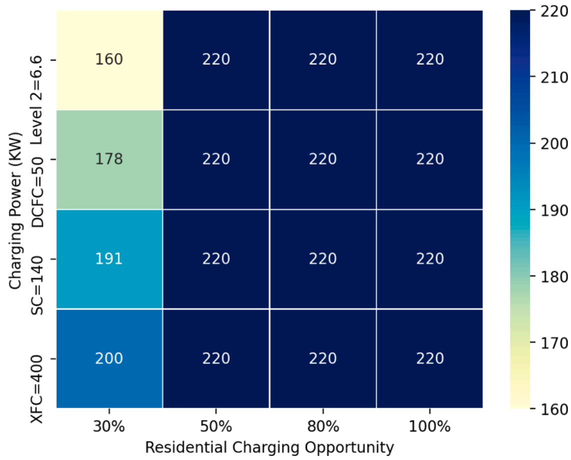


Fig. 13. Daily expected driving range considering residential charging (95th percentiles of the expected range distribution as the expected driving range).

trips are explained in Eqs. (6)–(8). The idea is that the BEV owners with different AER may have different feelings on travel distance. Hence, we categorize travel distance based on the AER. In addition, although we have conducted data cleaning before numerical analyses, there are still some samples that are not representative. Hence, the maximum travel distance corresponding to 95 % likelihood of occurrence were selected as reference.

$$\text{Short} - \text{distance trip} \in [0, AER] \tag{6}$$

$$\text{Mid} - \text{distance trip} \in [AER, 2AER] \tag{7}$$

$$\text{Long} - \text{distance trip} \in [2AER, \infty) \tag{8}$$

It is found that Level 2 chargers can serve short-, mid, and long-distance trips when public charging opportunity reaches to 80 % and home charging availability is 100 %. For DCFC, the requirements are relaxed to 50 % of public charging opportunity and 50 % of home charging availability in order to serve all types of trips. Both Supercharger and xFC require 30 % public charging opportunity and

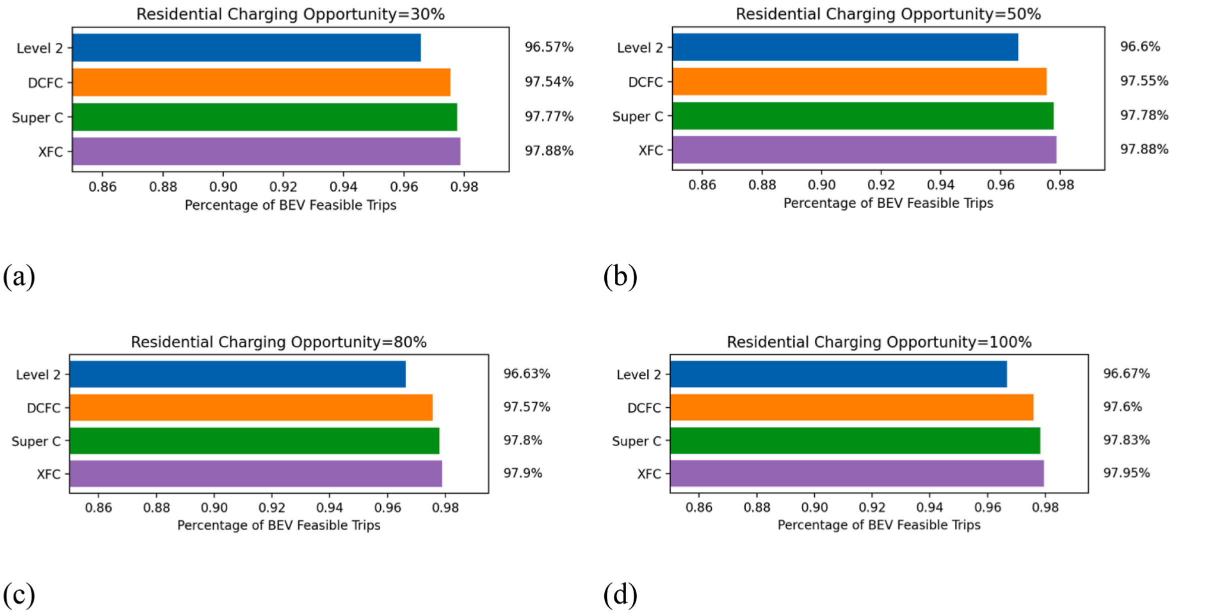


Fig. 14. BEV feasibility considering residential charging: (a) Residential charging opportunity = 30 %. (b) Residential charging opportunity = 50 %. (c) Residential charging opportunity = 80 %. (d) Residential charging opportunity = 100 %.

50 % home charging availability to meet all types of travel demands. Given travel demands estimated from the CPR model based on the trip patterns and travel behaviors extracted from 2017 NHTS data, the performance of Supercharger and xFC have no big difference. It indicates that although xFC is the most advanced technology today, from a travel demand perspective, it is not the highest priority to be deployed. Instead, high market penetration of Level 2 chargers and medium market penetration of DCFC should be considered first to serve all short-, mid-, and long-distance trips. Since BEV feasibilities under different AER values are all higher than 97 % (shown in Fig. 10), the variable AER is not shown in TABLE IV.

6. Conclusion

This study developed a Cumulative Public Recharging (CPR) model based on NHTS data to evaluate the impacts from various factors on the BEV maximum charging potentials and expected daily travel range. The factors include public charger powers, public charging opportunities, BEV battery capacity, and home charging availability. There were several interesting findings from the analysis:

- More advanced public chargers and high charging opportunities indeed increased the daily expected driving range. However, little incremental impact was observed from Supercharger to xFC with respect to expected daily driving range.
- Residential charging was sufficient for most daily short-distance trips while public chargers were still needed for middle and long-distance trips.
- xFC was less important with longer BEV ranges. This is probably because most daily trips in 2017 NHTS data are short-range and mid-range trips. In other words, it was most useful for short range BEVs, assumed to be capable of handling the xFC high power of charging.
- Longer AER could increase daily expected travel range while the improvements were not obvious, considering most trips and trip chains are short-range travel in 2017 NHTS.
- Increasing charging opportunities have less impact on short-distance trips compared to long-distance trips, since most BEV owners can charge their vehicle at home.

Given these insights, we developed recommendations for deployment of public charging infrastructures with priority. It is concluded that high market penetration of Level 2 chargers and medium market penetration of DCFC should be considered primarily for deployment to serve all short-, mid-, and long-distance trips.

There are a few limitations in this study. The assumption that all non-BEV trips are treated as BEV trips for this analysis, which may not be realistic. As BEV ownership and public charger coverage increase, BEV travel behaviours in the future might change compared to current BEV trips and gasoline vehicle trips. These changes are not captured in this paper and will be studied in the future work. In addition, this study developed the deployment prioritization based on benefits of public charging infrastructure while omitting the cost analyses for now. This will be the future work and will be present in the following papers. The analyses in this study were developed based on NHTS daily trip patterns. Most of the trips are short-distance trips, so the BEV feasibility evaluated under different scenarios

Table 4
Recommendations for public charger deployment.

Public Charger	Public Charging Opportunity	Home Charging Availability	Daily Expected Driving Range		
			Short-distance	Mid-distance	Long-distance
Level 2	10%	50%	✔		
	30%	50%	✔		
	50%	50%	✔		
	80%	50%	✔		
	100%	50%	✔		
	10%	80%	✔		
	30%	80%	✔		
	50%	80%	✔		
	80%	80%	✔		
	100%	80%	✔	✔	
	10%	100%	✔	✔	
	30%	100%	✔	✔	
	50%	100%	✔	✔	
	>= 80%	100%	✔	✔	✔
DCFC	10%	50%	✔		
	30%	50%	✔	✔	
	>= 50%	50%	✔	✔	✔
	10%	80%	✔	✔	
	30%	80%	✔	✔	
	>= 50%	80%	✔	✔	✔
	10%	100%	✔		
	30%	100%	✔	✔	
	50%	100%	✔	✔	✔
	>= 80%	100%	✔	✔	✔
Super Charger	10%	50%	✔		
	>= 30%	50%	✔	✔	✔
	10%	80%	✔		
	>= 30%	80%	✔	✔	✔
	10%	100%	✔	✔	
	30%	100%	✔	✔	
	>= 50%	100%	✔	✔	✔
XFC	10%	50%	✔		
	>= 30%	50%	✔	✔	✔
	10%	80%	✔		
	>= 30%	80%	✔	✔	✔
	10%	100%	✔	✔	
	30%	100%	✔	✔	
	>= 50%	100%	✔	✔	✔

are probably a little bit optimistic. What is missed here is the nearly every driver will make some long-distance trips over a year. Although the study results suggested that xFC was less important with longer BEV ranges, it opens the door to charge-on-the-way and wait-while-charging. These benefits will be evaluated by a different model in our subsequent papers.

CRediT authorship contribution statement

Wan Li: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing. **Zhenhong Lin:** Conceptualization, Project administration. **Shiqi(Shawn) Ou:** Investigation, Project administration, Funding acquisition. **Boyu Wang:** Data curation, Writing – original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research was supported by the US Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy, Vehicle Technologies Office. The authors thank the support from sponsors and remain solely responsible for the content and opinions expressed. The views and opinions of the author expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights.

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