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The optimization of DC fast charging deployment in California

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HIGHLIGHTS

- 290 Level 3 charging stations are required in CA for BEVs with a 60 mile range.
- 126 Level 3 charging stations are required in CA for BEVs with a 100 mile range.
- Congestion occurs at a number of these Level 3 stations requiring extra chargers.
- A reservation system can reduce congestion and extra chargers needed at each station.

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ABSTRACT

Battery electric vehicles (BEVs) are important for reducing fuel consumption and vehicle operating cost, and have the potential to reduce GHG and pollutant emissions. However, the range limits and long recharging times serve as obstacles to mass deployment. Well planned Level 3 DC fast charging stations are a potential solution to satisfy long distance travel demand instead of an expansive Level 2 non-home charging infrastructure. This paper identifies candidate charging routes and uses freeway exits and highway intersections as approximate candidate charging locations, and consequently solves a set covering problem to minimize the number of charging stations. Results show that 290 Level 3 charging locations are required for the State of California based on the 2000 California Travel Survey and BEVs with 60 mile range. With this optimized station network, electric light duty vehicle miles travelled (VMT) can reach 92% and BEVs can be used by 98% of drivers. If BEVs with 100 or 200 mile range are used, 126 or 31 Level 3 charging locations are required, respectively. This study also assesses the temporal utilization of charging stations. Congestion at several stations suggests extra chargers are required. A reservation system can benefit both the BEV drivers and station operators by reducing the wait times, decreasing the extra chargers needed, and more evenly utilizing all the stations. Related policies are also discussed to better deploy fast charging stations.

1. Introduction

Plug-in electric vehicles (PEVs) include plug-in hybrid electric vehicles (PHEVs) having internal combustion engines onboard to extend vehicle range, and battery electric vehicles (BEVs) which solely rely on the on-board electric storage. By partially or fully shifting vehicle energy usage from petroleum to electricity, PEVs can provide benefits for energy security, greenhouse gas (GHG) reduction, and urban air quality.

As with other alternative fueled vehicles, the infrastructure required for mass commercial adoption poses a significant obstacle for BEVs. However, with the existing infrastructure of gasoline stations and Level 1 (120 V) [1] home charging the market hurdle for PHEVs is relatively small. Previous studies suggest that for PHEVs, home charging alone can significantly reduce gasoline consumption and vehicle operating costs [2–4]. Additionally, several studies have shown the potential energy, emissions, and economic benefits of PHEVs with different scenarios of Level 1 and Level 2 [1] charging [4–8]. Unfortunately, the purchase price for PHEVs can be high, in part due to the requirement of two full powertrains [9]. Additionally tailpipe emissions still exist, and can possibly be worse than equivalent hybrid electric vehicle (HEV) emissions, depending on the vehicle design [10,11]. Alternatively, BEVs having just one powertrain offer the opportunity to lower purchase prices and guarantee zero tailpipe emissions [12]. However, a critical issue for widespread BEV adoption is charging infrastructure that can satisfy personal travel demand while mitigating the characteristics of limited range and long recharging time.

If non-home charging infrastructure is unavailable, BEVs can still meet some driving needs with the condition that drivers cannot travel long distances [13]. For example, only 9% of drivers

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in the study reported that they never travelled more than 100 miles on any given day. As a result, to use BEVs, most drivers must make changes to their driving habits. A different charging infrastructure study [4] showed that if Level 2 charging is accessible at all destinations, then BEV60s (BEVs with 60 mile range) could meet the need of 96% of drivers for any given day; this represents a BEV "feasibility" of 96%. However, it is not likely that this level of infrastructure could be funded or constructed in the near-term. Furthermore, the exact locations for Level 2 electric vehicle supply equipment (EVSE) are not likely to be optimized [4], ultimately increasing costs and redundancy. Consequently, compromised long distance travel demands or expansive non-home EVSE will not facilitate widespread BEV adoption, especially in the near term.

Alternatively, Level 3 DC fast charging [1] promises fewer charging stations while satisfying a significant portion of long-distance travel demand. Additionally, the development of a deployment roadmap is more straightforward compared to that for Level 2 EVSE. For example, the length of time required for sufficient charging at a Level 2 site implies that the charging needs to coincide with normal destinations. Therefore, designing an infrastructure system that meets many drivers' needs requires many EVSE at many destinations. Conversely, the relative speed of Level 3 charging can enable drivers to more easily alter their behavior and make deliberate stops for charging, more like traditional gasoline refueling. Level 3 charging can supplement the insufficient Level 2 EVSE and increase BEV feasibility, although fast charging might not be profitable in the near-term [14]. Several studies have focused on fast charging station design and simulation to meet the charging time requirements of DC fast chargers [15,16].

Some studies address DC fast charging station allocation indirectly. Nicholas et al. [17] used GPS recorded vehicle routes from 48 households during one month to simulate the scenario of BEV driving and evaluate fast charging requirements in the Sacramento, California area. Furthermore, the Nicholas et al. work [18] presented at the Electric Vehicle Symposium 26 used CHTS data to investigate Level 3 station allocation in California. However, it was not clear in those models when the charge demand was determined, thus the station locations appear to not be optimized. Liu assessed battery swapping and fast charging stations in the city of Beijing by considering gasoline station candidate sites and the distance from electrical substations [19]. The work focused more on land coverage than BEV travel patterns. Hiwatari et al. proposed an algorithm to move charging stations close to where many BEVs would run out of electricity [20–22]. A similar concept can be seen in [23,24], which also assumed fast charging will occur when the battery energy drops to a low level. However, these studies rely on the assumption that BEVs will use fast chargers only when running low on energy. Other studies used data on the electric system as the primary criterion in determining the location of fast chargers [25,26]. Other work [27,28] optimizes hydrogen station locations for fuel cell vehicles (FCVs) in a specific area with the criteria that all the demand points (home addresses) are able to reach a candidate hydrogen station location (gasoline station) within a certain time; this is essentially a set covering problem [29]. But this method cannot be applied to fast charging stations directly since home addresses cannot be used as demand points, and gasoline stations cannot be treated as the only candidate charging stations. The locations where BEVs require fast charging are likely to be far away from drivers' homes and not only at existing gasoline stations, but also locations like grocery stores, shopping malls, and large department stores.

The study herein optimizes Level 3 charging station deployment by considering actual vehicle routes and potential candidate charging locations, as well as evaluating the temporal utilization of charging stations.

2. Material and methods

The study's methodology is summarized as:

1. Obtain petroleum fueled light-duty vehicle long-distance travel pattern data and assume that BEV owners drive in the same manner.
2. Identify approximate candidate charging locations.
3. Identify potential routes for BEVs that require Level 3 charging.
4. Minimize the number of stations needed to cover the maximum potential charging routes (set covering problem).
5. Model the operation of each BEV under the optimized station network with different charging strategies to determine temporal charging characteristics.

2.1. California household travel survey

The vehicle travel pattern data used in this paper are derived from the 2000 California Household Travel Survey (CHTS) [30]. Several processing steps were required in order to prepare the data for input to the model. Trips occurring without a personally owned vehicle and/or without geographic destination information were deleted. Person-chain data were converted to vehicle-chain data. Vehicle routes and vehicle miles travelled (VMT) were determined using the ArcGIS [31] software platform by calculating the shortest path between the known geographic positions. Daily trip data with unlinked destinations or significant over-speed were deleted, and tours were organized into home based daily tours (first trip from home, last trip to home). After these data processing steps, the resulting travel survey data included 15,703 vehicles covering 64,084 single trips with an average of 7.8 miles per trip and 31.8 miles travelled per vehicle per day.

2.2. Model

Fig. 1 illustrates the model used in this work with a flow chart. The processed CHTS vehicle travel pattern data are input into a sub-model that determines the optimal charging strategy for Level 1 and Level 2 charging infrastructure allocation, which was described in a previous study [2,4]. This sub-model obtains the optimal pattern to charge a BEV during the 24-h time period, and further evaluates the charging infrastructure requirements in different location categories (e.g., home or work). This allocation sub-model can also determine "feasible" and "non-feasible" daily tours based on different Level 1 and Level 2 charging infrastructure scenarios. Feasible tours are accomplished with the given BEV characteristics and specified Level 1 and Level 2 charging infrastructure; non-feasible tours would result in stranded drivers with depleted batteries. The non-feasible tours are then used to investigate the fast charging station allocation. According to the vehicle and charging parameters, tours are divided into those requiring one fast charge, and those requiring multiple fast charges. Tours requiring just one fast charge are input into ArcGIS to identify the candidate charging routes on which the fast charging can take place. The next step uses the candidate locations along the candidate charging routes to form a set covering problem to solve for the minimal required locations. Once the optimized fast charging station network for tours requiring one fast charge is determined, tours requiring multiple charging events are examined to assess whether they are fulfilled. Since tours requiring multiple charges results in drivers having a choice between multiple fast charging locations available along the charging route, temporal utilization and capacity issues can be evaluated for different station selection strategies. Finally, it should be noted that several Level 1 and Level 2 charging infrastructure scenarios can be combined to evaluate

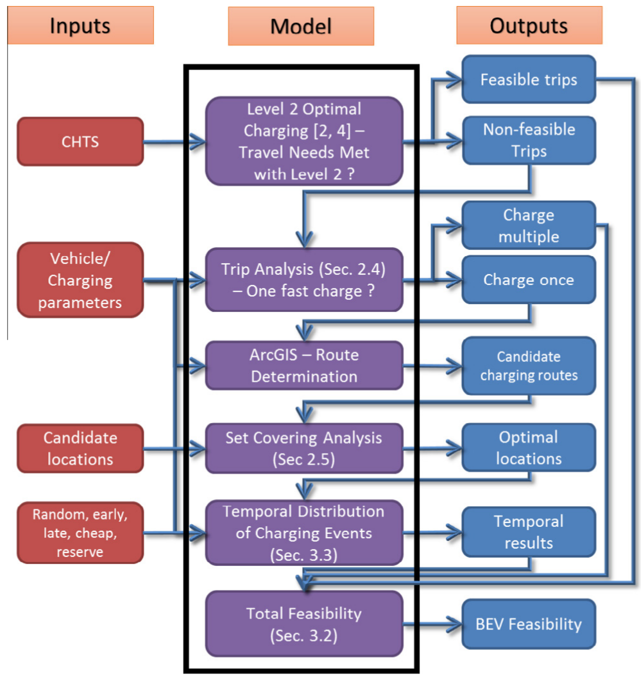


Fig. 1. BEV Level 3 fast charging station allocation optimization model.

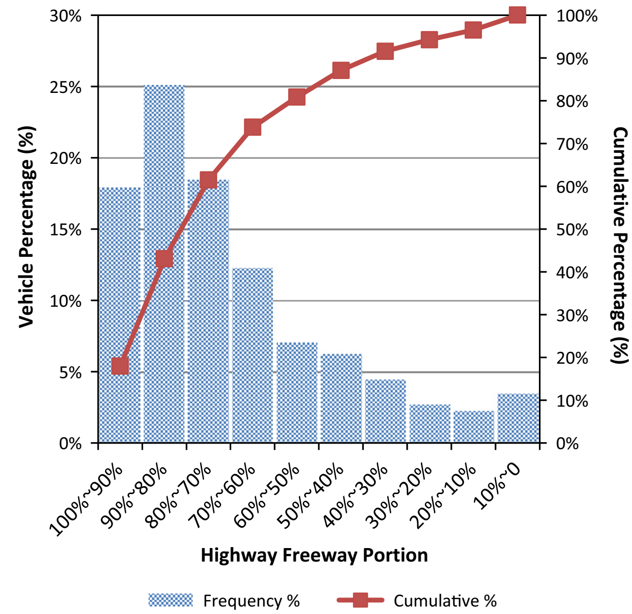


Fig. 2. Highway/freeway portion of driving for vehicle routes greater than 60 miles.

the public Level 3 charging station requirements, e.g., home charging plus public Level 3 charging or home and work charging plus public Level 3 charging. However, as a conservative estimate, this paper will only address a scenario with home charging after the last trip and no Level 1 or Level 2 non-home charging. This will result in the largest requirement of Level 3 chargers.

2.3. Long distance driving and candidate charging locations

This work assumes that each BEV is fully recharged at the beginning of the day and that the Level 3 charging stations are the only charging opportunities during the day before finally returning home. Consequently, based on conservative commercial BEV performance, any daily VMT beyond 60 miles will require at least one charging event. There are 2204 vehicles surveyed in the CHTS with daily VMT longer than 60 miles, accounting for 14% of the total surveyed vehicles.

A high correlation between long distance driving and highway use seems intuitive. To verify this assumption, ArcGIS was used to calculate the freeway/highway portion of each individual long distance tour. The histogram in Fig. 2 shows that more than 80% of long distance vehicles have at least 50% of their routes on a freeway/highway and that on average 73% of the long distance driving occurs on a freeway/highway. This result implies that it is reasonable to locate fast charging sites near freeways/highways.

The determination of exact candidate locations for charging stations is difficult since multiple real factors need to be considered, such as land use, electric circuit availability, and eligible and interested businesses. Thus, in this study, it is preferred to use approximate candidate locations assuming the actual station could be installed nearby with the consideration of the factors above and without much loss in the robustness of the fast charging network. Freeway exits and highway intersections are selected as approximate candidate locations for several reasons: proximity to freeways and highways and easy ingress and egress. Table 1 lists the number of approximate freeway exit and highway intersection candidate charging locations in California based on a network database from StreetMap North America, ESRI Data & Maps [32]. If specific, actual charger locations are available, they could be used as an alternative or supplement to the approximate candidate locations.

As shown in Fig. 3, most freeway exits exist in pairs. Thus, the freeway exit pairs were aggregated such that all readily accessible roadway near the freeway would be included as one candidate location, as shown in Fig. 3. This process reduces the approximate candidate locations to 2929, and potentially increases the service area.

2.4. Candidate charging opportunities

Charging opportunities must be identified during the daily tour for each individual vehicle. Fig. 4 shows a histogram of the daily VMT for long distance tours, in which the frequency generally decreases with the daily travel distance. The vertical line in Fig. 4 delineates those trips greater or less than 110 miles (72% of long distance daily tours accumulate less than 110 miles and 28% accumulate greater than 110 miles.

Based on commercially available BEVs and fast charging station characteristics [33,34], it is assumed that BEVs have a 60 mile range when fully recharged and that fast charging is performed anytime, as long as the vehicle has at least 5 miles of battery energy remaining. Thus, any daily tours with VMT below 60 miles do not require fast charging. Tours greater than 60 miles need recharging, and the VMT between two consecutive charging events must be within 55 miles. For 60–110 mile tours, a minimum one time charge is needed, and multiple charges are required for the higher VMT tours. Table 2 classifies tours by VMT and indicates the number of vehicles in the CHTS falling within each category.

2.4.1. One time charging

Fig. 5 illustrates the candidate charging locations and candidate charging routes for vehicles requiring one charge. The total daily

Table 1
The approximate candidate charging locations used in the model.

Freeway exits	Intersections (between major highway and major highway)	Intersections (between major highway and secondary roads)	Total (aggregated locations)
6244	137	337	2929

Fig. 3. Aggregated polygon encompassing two freeway ramps and associated cross street.

VMT is represented by X, and there are several approximate candidate charging locations on the route symbolized by the orange and purple dots. From the origin O, the BEV has to be recharged once before reaching the position marked by Y, which is the range between charges (55 miles in this case). Similarly, from the position marked by X–Y to the final destination X(O), a charging event has to take place. Thus, the charging event must occur in the overlapped region, from X–Y to Y, which is the candidate charging route with potential charger locations indicated by purple circles. Previous studies all assume that drivers will take the last charging opportunity when battery energy is the lowest [20–22,24].

2.4.2. Tours requiring more than one charge

Fig. 6 illustrates the case in which 2 charging events are required. Using the same method as above, two regions are determined to be the sets of candidate charging routes. However, it becomes a combinatorial problem since the selection of a charging station in one region can determine which stations are eligible in another region. For example, if the first point (blue) is chosen in the first charging region, then the second point (green) cannot be chosen because the distance between the two will violate the criteria that the distance has to be within Y (55) miles. It is also considered that charging more than once might not be practical from the perspective of changing drivers' behavior because it will require more detouring to the stations and more charging time at charging stations during a single day. Consequently, charging more than once is not considered in the station optimization. Vehicles that require more than one charge are instead checked against the optimized stations determined by one time charging in order to determine BEV feasibility for these tours requiring more than one charge.

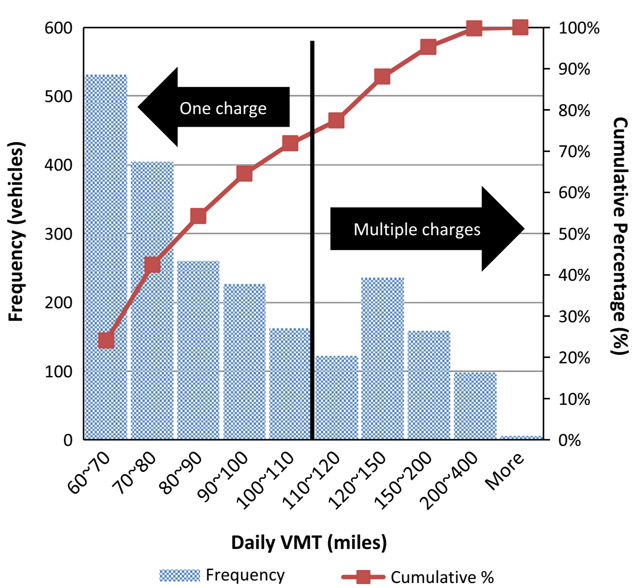


Fig. 4. VMT histogram for vehicle tours greater than 60 miles.

Table 2
Tour characteristics and associated charging assumptions.

	No charge	Charge once	More than once
Maximum range between charge	60	55	55
Daily tour VMT	<60	60–110	>110
Number of instances in CHTS	13,499	1584	620

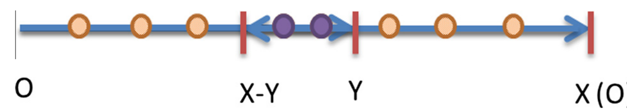


Fig. 5. Diagram of the candidate charging route for BEVs requiring at least one fast charging.

2.5. Set covering problem

With the basis of the candidate charging routes and the approximate candidate locations, a set covering problem is formed [29]. The objective is to choose the minimum set of the approximate candidate charging locations to cover all those candidate charging routes which have intersections with any of the approximate candidate charging locations. Binary integer programming functions in Matlab [35] and CPLEX [36] are used to solve this problem.

1. Decision variables:

The binary variable indicating whether the candidate location i should be chosen x_i

Where $x_i \in \{0, 1\}$

2. Cost function:

The summation of all the decision variables, i.e., the number of all the chosen locations

$$min \sum_i x_i$$

3. Constraints:

Any of the candidate charging routes j needs to have at least one candidate location chosen

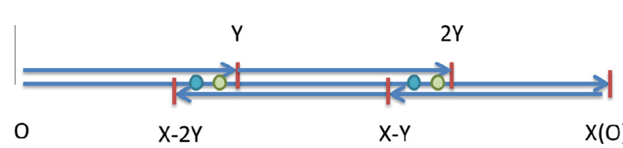


Fig. 6. Diagram of candidate charging routes for BEV required at least two times fast charging.

$$\sum_i A_{ji} \times x_i \geqslant 1.$$

where A is the matrix defining which candidate locations have intersections with which candidate charging route. If route j intersects with location i, A_{ji} has the value of one, otherwise it is zero. The route is excluded in the optimization if there is no candidate location on it. This avoided the optimization to be infeasible.

3. Results

3.1. Station number and allocation

Fig. 7a is an overview of the optimized charging station allocation in California for BEV with range of 60 miles. By using aggregated exits as the approximate candidate charging locations, just 290 sites are required. Also, most locations are distributed in the most populated areas (i.e., greater Los Angeles, San Diego, San Francisco Bay area, and Sacramento). From the detailed map for the Los Angeles region in Fig. 7a, it is clear that most locations appear to be close to freeway intersections. This is an intuitive result that those locations have more candidate charging routes intersected than other locations. In order to verify the result, different sets of candidate charging locations were also used to perform the optimization, including a set containing all the gasoline stations and shopping centers in California. Similar results are obtained with around 300 locations required and most stations sited in the populated areas.

In order to understand the impact of the range of the BEV on the infrastructure required, the same methodology has been applied to BEV100 and BEV200 with the same set of candidate charging locations. Results show that the number of the stations reduces dramatically with the increased range. In Fig. 7b, BEV100 needs 126 locations and it is 31 locations required by BEV200. Compared to the results for BEV60, the locations are more evenly spread out in the entire state rather than concentrated in the most populated areas. In particular, for the case of 200 miles, the majority of the locations are placed in the remote area. In summary, longer BEV range reduces the total number of charging location required while decreases its distribution in the populated areas. The following results are all based on BEV60 since it is the worst case scenario given the fact that the range for most of the existing BEVs is under 80 miles.

3.2. BEV feasibility

Given the optimized charging location network of 290 sites within California for BEV60, it is important to understand how many BEVs could fulfill daily travel needs. The corresponding BEV feasibility was defined in a previous study to be the ratio of the number of BEVs that could meet daily operating behavior to the total number of vehicles [4]. A high feasibility ratio is therefore required for mass BEV adoption.

By design, all of the vehicle tours used in the optimization are fulfilled by BEVs with one time fast charging, and all vehicles with daily tours less than 60 miles need no public charging. However, a portion of vehicles require more than one daily recharge (daily tour greater than 110 miles), which needs more investigation. Fig. 8 shows the charging station locations along with one specific vehicle route with a length over 110 miles. Visual inspection indicates that the optimization method performed on one-time charging tours produced sufficient charging sites to meet the needs of this multiple-charging vehicle. Quantitative analysis using ArcGIS

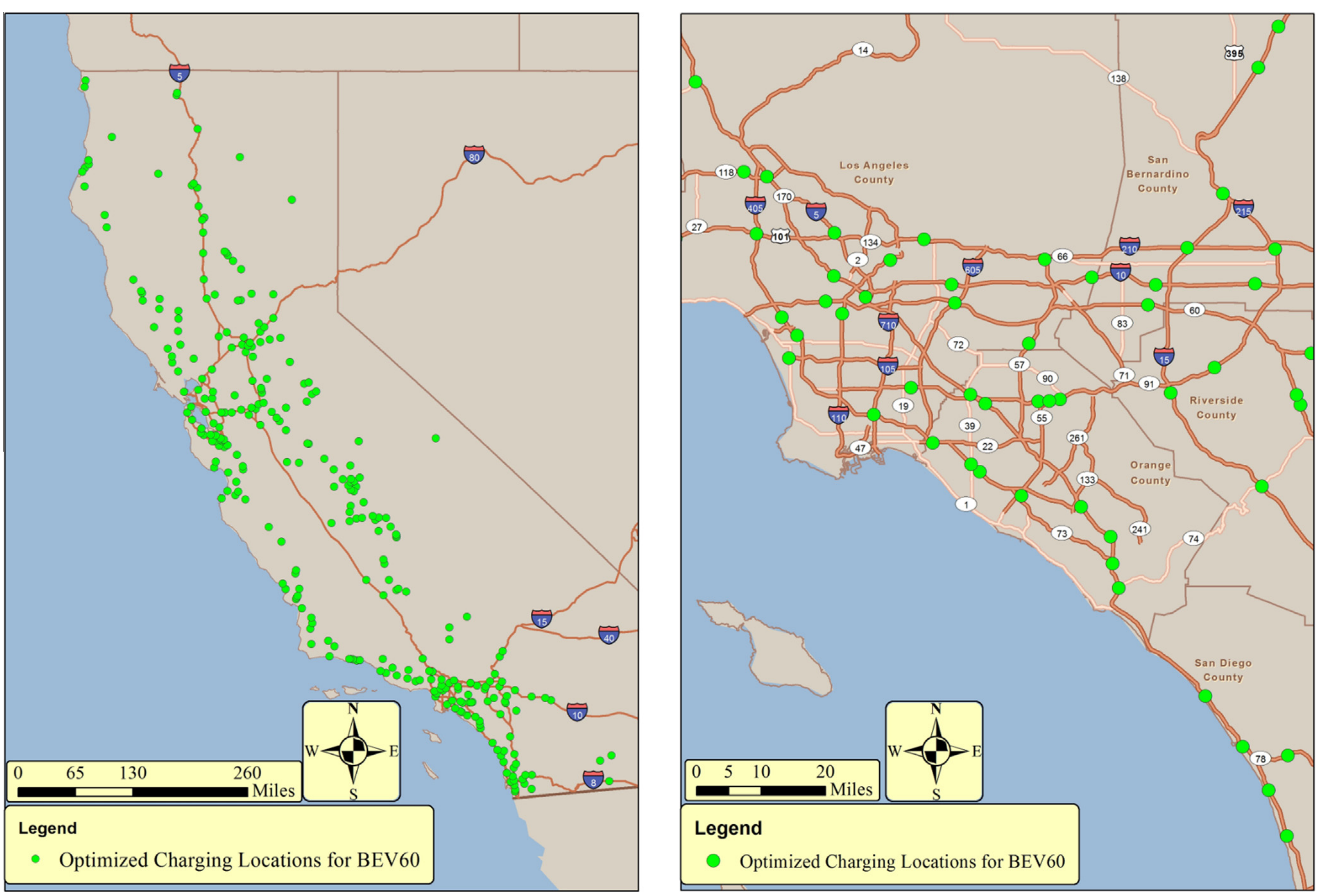


Fig. 7a. Optimized charging locations for California (left) and the Los Angeles region (right).

and Matlab confirms the visual analysis by breaking the route into segments shorter than Y (55) miles. The same analysis is performed for all the daily tours over 110 miles.

Table 3 and Fig. 9 show BEV and VMT feasibility. Eighty-six percent (13,499) of daily tours in the CHTS are shorter than 60 miles, so they are considered feasible routes. The optimized station network satisfies 93% of daily tours in the 60–110 mile range. The station network can also satisfy 75% of daily tours over 110 miles. Consequently, with just 290 charger locations, BEV feasibility is 88% and 98% for long distance driving and all driving, respectively. This is a stunning result compared to previous work on Level 2 charging infrastructure which showed BEV feasibility is 96% only when 3.3 kW Level 2 charging is available everywhere [4].

With regard to VMT feasibility, the impact of fast charging stations is different. For example, the VMT that are fulfilled by 60 mile BEVs with no public charging is only 55%, which indicates that long distance driving accounts for significant VMT and fuel consumption. The optimized Level 3 charging station network increases the feasible VMT to 92% by capturing 91% of the 60–110 mile tours and 71% of the tours longer than 110 miles.

An increase of BEV feasibility to almost 100% will seemingly make BEVs more acceptable to consumers in terms of the range limit, and the increase of VMT feasibility to 92% would dramatically increase BEV benefits related to petroleum use reduction and tailpipe pollutant emissions.

3.3. Temporal distribution of charging events

Even with a sufficient Level 3 charging station network installed, BEV drivers have to choose between multiple stations along the candidate charging route. Table 4 shows the number of charging stations along the candidate charging routes derived from the 1469 feasible vehicles having 60–110 mile tours as shown in Table 3. Approximately 58% of the BEVs have only one available station. The remaining 42% can select from multiple stations on their tours. The selection of charging sites will impact electricity consumption, as well as charging station capacity. Thus, five charging station selection strategies were evaluated: *random*, *as early as possible*, *as late as possible*, *as cheaply as possible*, and with a *reservation system*. For the first four strategies, BEV drivers would only consider the geographic information of the charging stations and predict the arrival time at each station along their charging routes. The drivers could then decide where to recharge their vehicles according to the criteria of each strategy. These four strategies represent methods similar to those used by drivers to select gasoline stations; the approach is simple for the driver and does not require communication with charging stations or any other vehicle. The fifth strategy (reservation system) provides BEV drivers the opportunity to reserve, on a first-come-first-serve basis, a charger for a time period at a specific station prior to arrival such that schedule conflict is avoided. Each BEV needs to find out the charging stations on its charging route and the approximated time of arrival. At the same time, it receives, from the stations, what times have been blocked at each charging station. Then, the BEV locally calculates where the charging should happen such that the waiting time is minimized. Finally, it sends the reserved time window back to the station it will stop at. This is an idealized reservation system that serves to preliminarily show the benefit of a reservation system. Other studies more fully evaluate algorithms for use in more practical reservation systems [37–41]. With ever-increasing

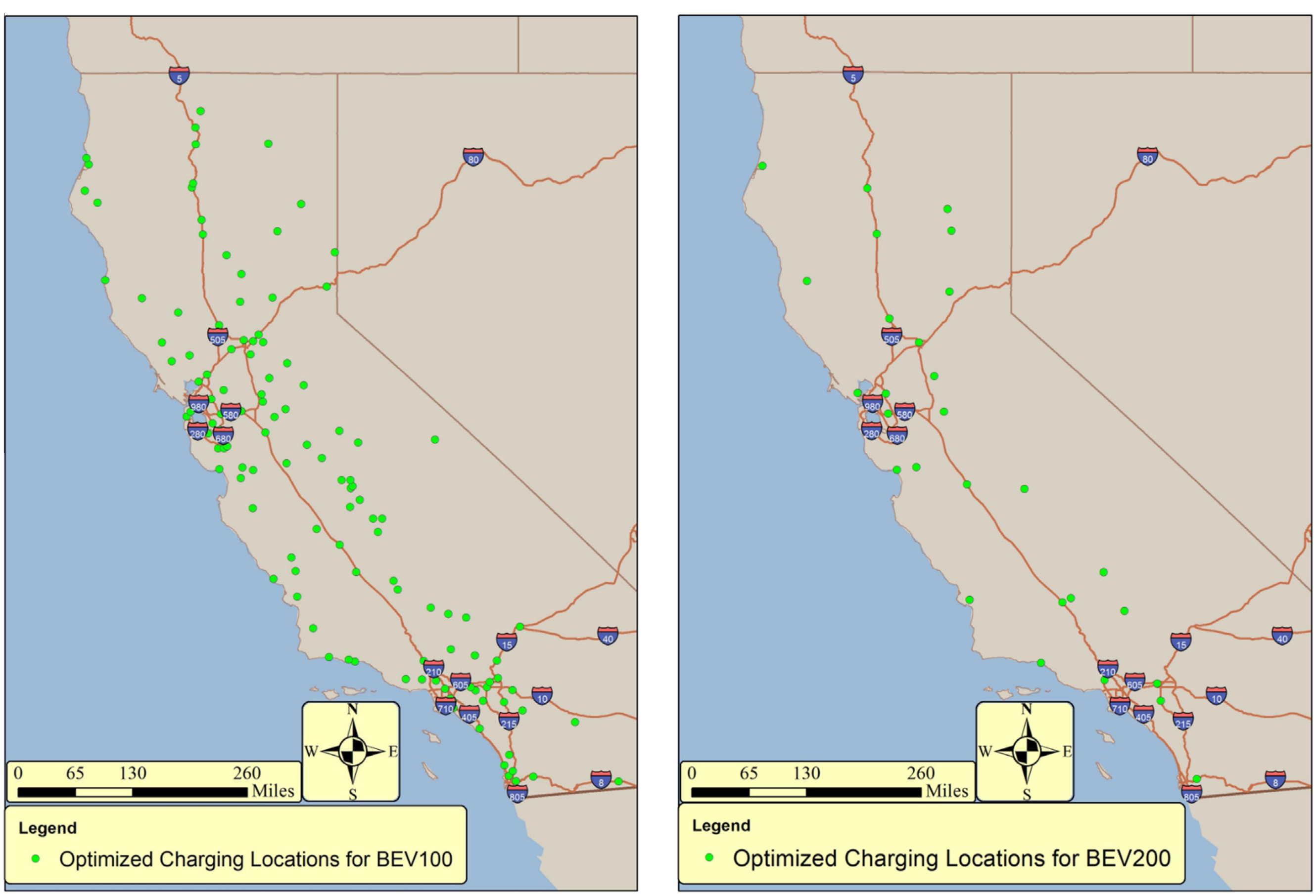


Fig. 7b. Optimized charging locations for BEV100 (left) and BEV200 (right) in California.

Fig. 8. An example tour for a vehicle requiring multiple fast charging events.

"smart" electronic capabilities available in phones, cars, and other devices, the mechanics of such a reservation system are easy to imagine.

Fig. 10 shows the distribution of charging events over 24 h for the *random* and *as late as possible* station selection strategies. The vehicle arrival time represents when vehicles enter a charging station. It is important to note that the model accounts for the delay of actual charging events due to limited station capacity. The estimated charging profile is determined by assuming that BEVs would be only *sufficiently* recharged (i.e., enough to return home). This assumption stems from the likelihood that Level 3 charging will be significantly more expensive than home charging and will, therefore, persuade drivers to use Level 3 as little as possible. Additional assumptions are listed in Table 5.

The charging profile of the *random* charging station selection strategy shows peaks in the morning and afternoon. The afternoon peak is longer and slightly larger than the morning peak. Interestingly, this trend is nearly identical to the daily VMT distribution during weekdays [42]. Also, the peak charging demand time overlaps with typical diurnal electricity demand peaks [5]. The consequences of this overlap with typical electric demand peaks would be increased peak electric load, higher time-of-use electricity costs, and increases in GHG and pollutant emission compared to other charging strategies [5].

The *as late as possible* station selection strategy requires no planning for the driver and has the potential to most extend the range of BEVs. However, from the grid perspective, the *as late as possible* strategy appears to be the worst case, as shown by the charging profile that exhibits a single large peak from 4 pm to 7 pm.

The *as early as possible* strategy results are shown in Fig. 11. This strategy demonstrates a large peak at 8 am. Although this strategy shifted the BEV charging profile peak, substantial charging events occur during the day for the three scenarios examined thus far. This implies that different Level 3 charging strategies cannot substantially shift BEV electrical loads from the day to the night.

Interestingly, the *as cheaply as possible* strategy shown in Fig. 11 is nearly identical to the *as early as possible* strategy. The electricity pricing for this strategy was based on the PG&E summer weekday PEV charging rates and previous work [4,43,44]. The small differences when compared to the *as early as possible* strategy are the slightly reduced charging events in the late afternoon and the slightly increased charging events late at night.

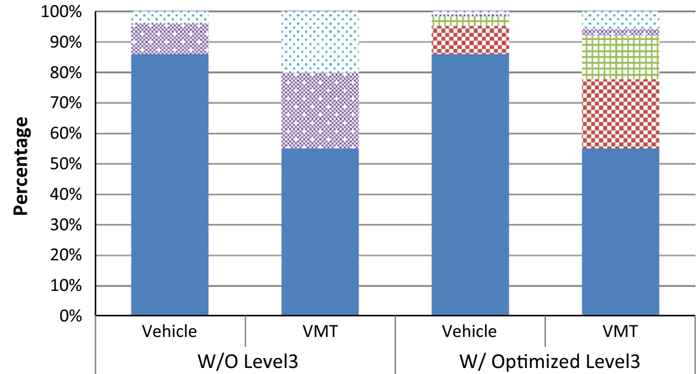
The *reservation system* strategy shown in Fig. 12 provides more evenly distributed charging events throughout the day. The *reservation* strategy has similar trends as the previous two strategies, however, the *reservation* strategy has a lower peak in the morning and more charging events in the afternoon.

From these results, it can be summarized that: (1) most of the Level 3 charging events and charging load will occur in the daytime no matter what station selection strategies are used; (2) both random charging and late charging would increase the grid demand in the afternoon; (3) early, cheap and reserve strategies have similar trends with a short peak from 8 am to 9 am and would be preferred given current electricity demand profiles.

It should also be noted from these results that the owners of these charging stations will have electricity demand profiles that have large peaks regardless of the station selection strategy and will impact their cost of electricity that they pay to the electric utility. This will primarily occur because the charging peaks will incur higher demand charges on the station owner than if the charging profile was nearly flat. Electric utility rate structures are typically classified into energy and demand charges. Energy charges are those paid for each kW h used. Demand charges are collected in different ways, but a typical way is to charge the customer based on their peak demand in a month. Therefore, the higher the peak demand the higher the cost of electricity. This situation will be exacerbated for those owners that already have electric loads in addition to the newly installed Level 3 chargers. Additionally, since these peaks typically occur during the day, if the owner's station or property is on a time-of-use rate structure then the owner could experience even higher demand charges. This results from time-of-use demand charges being higher during peak load periods of the day. This issue warrants further investigation by

Table 3
BEV and VMT feasibility for different charging requirement categories.

	Total	No L3 charging required	Need L3	Need L3 once	Need more than once
Total # of vehicles	15,703	13,499	2204	1584	620
BEV feasible	15,434	13,499	1935	1467	466
Percentage	98%	100%	88%	93%	75%
Total VMT	498,692	273,842	224,849	124,856	99,993
BEV feasible	458,653	273,842	184,810	113,480	71,330
Percentage	92%	100%	82%	91%	71%



	Vehicle	VMT	Vehicle	VMT
	W/O Level3		W/ Optimized Level3	
Infeasible (Charge More)	3.95%	20.05%	0.98%	5.75%
Infeasible (Charge Once)	10.09%	25.04%	0.75%	2.12%
Charge More	0.00%	0.00%	2.97%	14.30%
Charge Once	0.00%	0.00%	9.34%	22.91%
No Need	85.96%	54.91%	85.96%	54.91%

Fig. 9. BEV and VMT feasibility with and without the optimized fast charging station network.

Table 4
Number of vehicles versus available stations on the candidate charging route.

Available stations	Frequency (vehicle)	Cumulative (%)
1	848	57.81
2	397	84.87
3	176	96.86
4	42	99.73
5	3	99.93
6–10	1	100.00

policymakers to ensure that electric rate structures are not hindering fast charger deployment or cause fast charger stations to be abandoned after the cost of electricity becomes too high.

3.4. Wait time and station usage

Charging event distribution, potential wait time capacity issues, and charging cost (energy charges only) have also been assessed. These factors have been estimated based on the five charging station selection strategies. If there is any schedule conflict, it is assumed that the next driver's charging event begins immediately when the previous one finishes, otherwise it begins upon arrival at the station incurring a zero wait time. The waiting events and wait times are calculated and accumulated at each station. The electricity cost is the product of the charging load and the PG&E summer weekday PEV charging rates for the given time of day when charging occurs [44]. The results shown here are for the 1467 vehicle tours in Table 3 and analyze coverage versus capacity requirements for vehicle fueling infrastructure.

3.4.1. One charger per station

Table 6 shows the results for all the five scenarios with only one charger at each station. Comparisons are made from two perspectives: (1) the convenience and electricity cost for BEV drivers and (2) the benefit for station operators. It should be noted that the results for the *random* station selection strategy are different for each model run and the results here depict the average value for a total 10 runs.

Wait events exist for all of the strategies with *late* charging having the most, followed by *early*, *cheap*, and *random* charging. A *reservation system* decreases the number of wait events from 200 to less than 50. A *reservation system* would also make the average wait time at least 70% shorter than any other scenario. Although the average wait times per vehicle are all below 1.5 min which

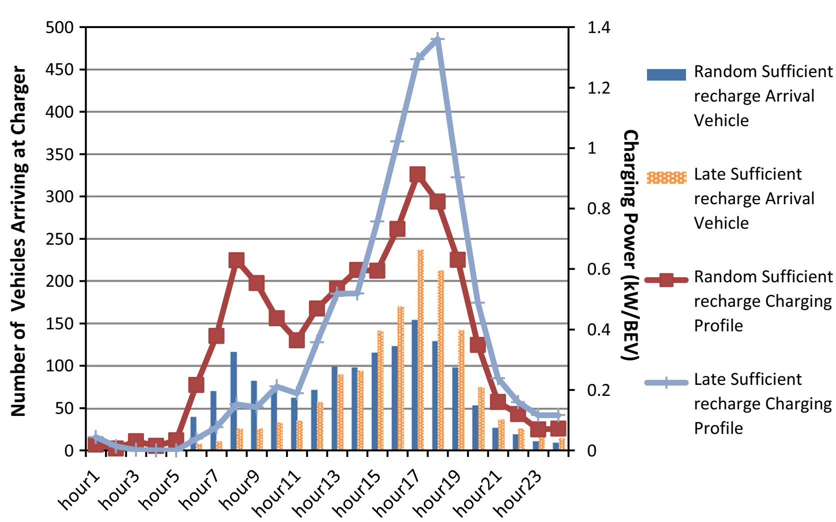


Fig. 10. BEV arrival time and charging load distribution for random and late charging.

Table 5
BEV operating and charging parameters.

Electricity consumption rate (DC)	Charging efficiency	Charging rate	Station selection	Charging strategy
0.31 kW h/mi	0.85	2 miles/min	Random, late, early, cheap, reserve	Sufficient recharge

appears very low and acceptable, the average wait time per wait event is always greater than 8.5 min for non-reservation charging. Consequently, if the wait events occur, drivers would have to spend a relatively long time waiting. The maximum accumulated wait time is the maximum of the accumulated wait times of all 290 stations. In the worst case, the maximum accumulated wait time is nearly 7 h for the *late* charging strategy. For the other non-reservation charging strategies, the maximum wait time is around two and half hours, but the *reservation system* can decrease this value dramatically to less than 1 h. The same trend can be seen for the maximum wait events. As for the electricity cost, results range from \$1.35 to \$2.10 per charge. The *cheap* charging strategy provides the lowest electricity cost, but is only slightly better than *early* charging and *reserve* charging.

From the perspective of the station owner or operator, all charging strategies result in 5 charging events per station on average since the total station and vehicle numbers are fixed. However, the *reserve* charging strategy provides a much lower standard deviation for the charging events because charging events are more evenly distributed at all the stations. Consequently, charger operators may prefer a *reservation system* strategy.

3.4.2. More chargers to decrease wait time

In order to better understand the inconvenience caused by the station capacity limitations, additional chargers are assigned within the model to the stations with the longest accumulated wait times. Therefore, the relationship between extra chargers, wait events, and wait time is investigated. Figs. 13a and 13b show the results for *cheap* and *reserve* station selection strategies, respectively. Just three to four additional chargers for the *cheap* charging strategy could bring the maximum accumulated wait time and number of wait events to the same level as the original

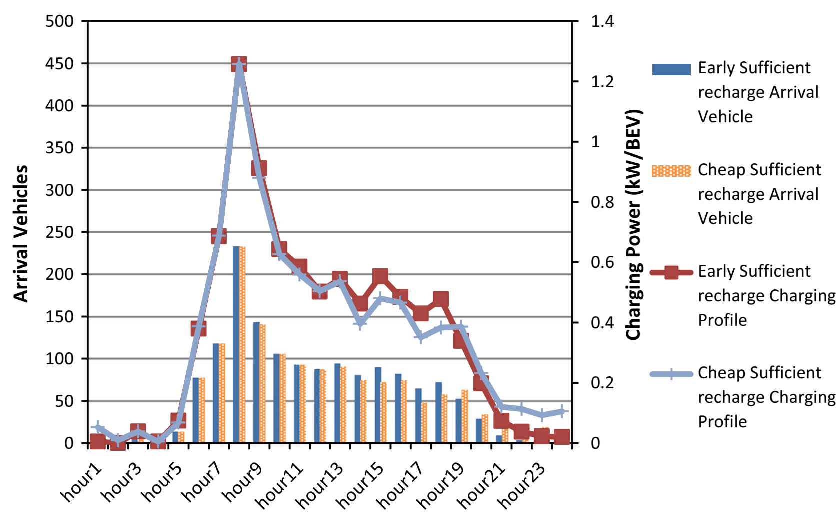


Fig. 11. BEV arrival time and charging load distribution for early and cheap charging.

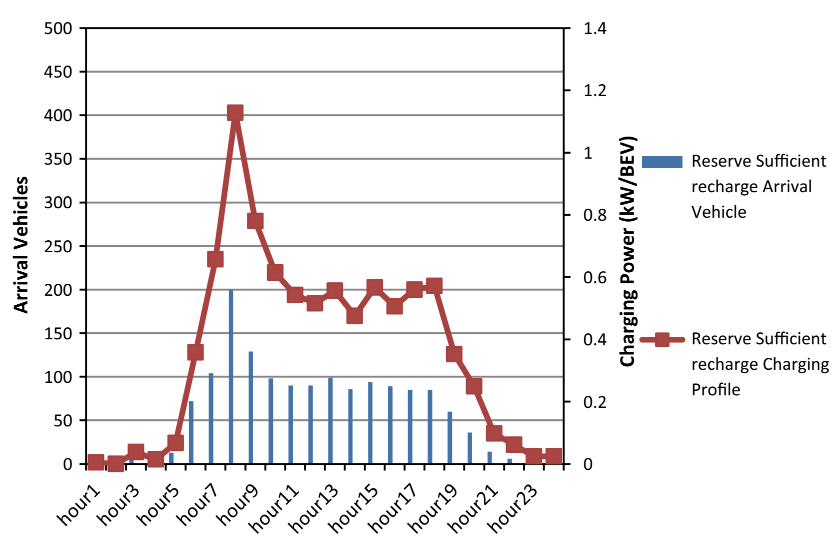


Fig. 12. BEV arrival time and charging load distribution for reserve charging.

Table 6
Wait time, wait event, electricity cost, and station operating status for different station selection strategies.

	Total wait time (minutes)	Total wait events	Average wait time for 1467 vehicles (minutes)	Average wait time for wait events (minutes)	Maximum wait events at any station	Maximum accumulated wait time at any station (minutes)	Electricity cost per charge (dollar)	Average charges/ station	Standard deviation of charging distribution
Random	1189	129.9	0.81	9.15	9.7	184.28	1.75	5.06	0.91
Late	2216	200	1.51	11.08	15	415.17	2.10	5.06	1.48
Early	1679	175	1.14	9.59	12	150.54	1.38	5.06	1.27
Cheap	1471	169	1.00	8.71	12	150.54	1.35	5.06	1.24
Reserve	313	46	0.21	6.81	3	47.49	1.45	5.06	0.47

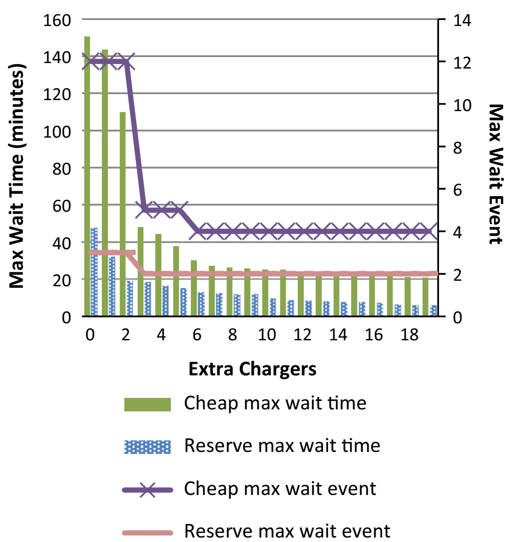


Fig. 13a. Extra chargers vs. maximum wait time and event.

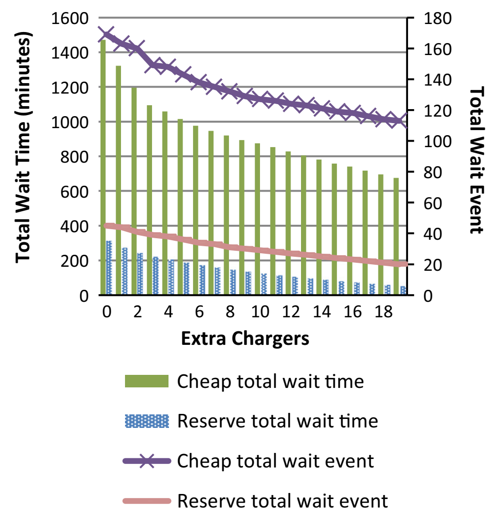


Fig. 13b. Extra chargers vs. total wait time and event.

reserve charging strategy. More chargers do little to further improve the results. As for the total wait time and total wait events, the *reserve* charging continuously shows a substantial improvement compared to *cheap* charging, regardless of additional charger installations. Consequently, the additional chargers for cheap charging might effectively mitigate the extreme conditions at specific stations, but the system-wide benefit is limited. Similar results were observed with the other non-reservation station selection strategies

4. Discussion

The methodology and the optimal solution discussed in this work require that two main conditions be satisfied such that the analysis is accurate. The first condition involves candidate locations and the assumption that all land owners are willing to install chargers (i.e., the real candidate locations are not difficult to find). The second condition is that the optimization be implemented at one time for a relatively large area. Existing policies and regulations obstruct using land for charging stations, which impacts satisfying the first condition. Some cities view the marking of stalls for EV charging as a loss of stalls. Policy could be designed to encourage the conversion of parking stalls to EV charging stalls. Additionally, most cities' zoning codes do not address EV charging stations further complicating installations. Commercial and residential zoning codes should include language stating whether a charging station is allowed as well as some details on guidance for approval to make station planning more efficient. With regard to the second condition, multiple entities in the same area are always involved in station allocation. For instance, in southern California, utilities, automakers, governments and some fast charging oriented companies are all planning station installations, but might not communicate with each other. This gives rise to decisions based on inadequate information leading to redundant plans and/or waste. An agency such as the California Energy Commission could provide a platform where stakeholders can exchange information, and a third party, such as universities or other agencies, can provide un-biased information and optimized solutions. Better information effectively supports a better station network roll out.

The parameters for BEV range used in this study are conservative and provide a "worst case" scenario. Longer BEV range will result in a decreased need for charging stations, but the optimized station allocations in this study will satisfy any longer range BEVs with at least the same BEV feasibility. The reason is that the candidate charging route generated by a shorter range BEV is also a portion of the longer range BEV candidate charging route. Future research should be focused on combinations of different BEV ranges and the corresponding requirements of the fast charging stations. It will be valuable to investigate more cost effective ways to deploy BEVs (e.g., shorter BEV range with more charging stations or longer BEV range with fewer charging stations).

The arrival times at the fast charging stations are estimated values because linear referencing is used assuming BEVs are driven at constant speeds for any specific trip. The wait times and waiting events are also estimated values because the actual charging time is generally non-linear and depends on the state of the vehicle battery. The time to setup the charging equipment should be much shorter compared to the real charging time, thus it is not considered in the model to accumulate extra charging time.

Compared to non-home Level 2 EVSE, the number of fast charging stations is significantly lower. Approximately 25 Level 2 EVSE (plus home charging at all residences) are required per 100 BEVs to achieve a 96% BEV feasibility, as described in a previous study [4].

However, the quantity of Level 3 chargers required to achieve 98% BEV feasibility is just 2 chargers per 100 vehicles (plus home charging at all residences). Furthermore, it is less difficult to optimize the exact Level 3 station allocations compared to the statistical EVSE distributions at different location categories for Level 2 charging.

For a BEV with 60 mile range, the 98% BEV feasibility and the 92% VMT feasibility shown in the results imply the upper bound. It is also possible that drivers will switch back to conventional vehicles for long distance tours rather than use fast charging BEVs since it would require behavioral changes and upwards of 30 min charging times. This is an especially important concern for those drivers needing more than one fast charge in a day. Technology to further increase the charging rate, and BEVs with longer range will mitigate this concern.

The methodology proposed in this study can be applied to other areas using travel pattern data other than CHTS as well as different BEV parameters. The model presented solves for approximate charging station allocation. The analysis can also be performed with existing or proposed Level 3 charging locations included in the network. In this case, the tours served by the existing or proposed charging locations will be ignored in the optimization. This would be highly advantageous for government agencies deploying many of the fast charging stations.

Although the CHTS includes data covering the whole state of California, actual BEV deployment will likely concentrate in certain areas. Consequently, the rollout plan for station allocation must consider real BEV deployment. Due to the limited data available, the amount of chargers required at each station to serve a specific number of BEVs in the future (e.g., 1 million BEVs) cannot be fully addressed. However, by scaling the current results, an upper bound can be established that not more than 1 Level 3 charger will be required per 50 vehicles.

5. Conclusions

A model that optimizes Level 3 charging station allocation and the temporal utilization of charging stations has been developed and applied. The CHTS serves provides travel pattern data in California, and vehicle parameters are based on commercial BEVs. The candidate charging route was defined for vehicles that require one fast charge per daily tour, and aggregated freeway exits and highway intersections were used as approximate candidate charging locations. This formulated a classic set covering problem. In addition, several charging station selection strategies were investigated to understand the utilization of the charging stations. From the methodology, data, results, and discussion above, the following conclusions are drawn:

1. By using around 3000 aggregated freeway exits and highway intersections as the approximate candidate charging locations, 290 locations are determined to be the minimum number required to meet CHTS driver needs. This network is shown to provide good coverage with 98% BEV feasibility and 92% VMT feasibility. The near 100% BEV feasibility can facilitate BEV consumer acceptance by mitigating range anxiety, and the high VMT feasibility can lead to significant reductions in petroleum consumption and tailpipe emissions. Compared to non-home Level 2 EVSE, the Level 3 station allocation is more precisely prescribed and provides a higher BEV feasibility. A maximum of two Level 3 chargers will be required per 100 BEVs to enable 98% of drivers to rely on BEVs and to replace 92% of current petroleum miles travelled with electric miles travelled.
2. The temporal distribution of charging events and charging load profiles are evaluated with five charging station selection strategies. Most of the events and load will occur in the daytime regardless of strategy. Both *random* and *late* charging will increase the grid demand in the afternoon. The *early*, *cheap* and *reserve* strategies have similar trends of evenly distributed charging during the day with a short peak from 8 am to 9 am. These strategies are preferrable since they do not contribute to the peak loads on the electric grid.
3. A *reservation* system can dramatically reduce the wait time and number of wait events as well as utilize all the stations more evenly. With only one charger per station the congestion and wait time at some locations would be unacceptable for the 1467 drivers considered in this study. A *reservation* system or the installation of extra chargers would reduce congestion. More travel pattern data are required to fully understand the required chargers at a specific station for a specific future BEV penetration.
4. Policies should be designed to encourage the conversion of parking stalls to EV charging stalls. Policymakers should encourage rate structures that support fast charging by altering or removing the demand charge for those customers with fast chargers installed. A state level government agency should provide a platform where stakeholders can exchange information so that a cost effective station network can be built. Fast charger operators should collaborate on implementing a *reservation* system.

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