

A Quantitative Framework for Assessing Long-Trip Transportation Accessibility for Road Vehicles

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Abstract

Battery Electric Vehicles (BEVs) are an important part of transportation de-carbonization goals globally and especially in car dependent countries such as the US. While BEVs provide a nearly equivalent experience to Internal Combustion Engine Vehicles (ICEVs) for routine and short-trip travel, their limited ranges and long recharge times make them less well-suited to long-trip travel. Long-trip travel has repeatedly been shown to be an important consideration in individual and household vehicle purchasing decisions. In order to better enable long-trip travel, public money has been invested into the public DC charging network. In order to enable the assessment of network performance in providing long-trip access, this paper proposed a novel and quantitative framework. This framework accounts for network, vehicle and individual characteristics allowing for holistic and extensible assessments. The framework is demonstrated using the State of California as a case study. Results show the importance of improved ranges and charge rates as well as the differences in outcome based on individual risk attitude and charger network availability.

Introduction

Developed economies require the continuous flow of persons and goods in astounding volumes. Transportation systems serve to enable these flows by minimizing friction. An effective transportation system is one which allows the economy to function with minimal losses. Encompassing this paradigm is the field of transportation accessibility. Transportation accessibility is the study of two related phenomena. (1) how structural and individual factors create latent flows or demand. (2) how efficiently transportation systems accommodate said flows. Economic growth, diversification, and specialization increase transportation demand. More efficient built environments and transportation systems reduce the cost of meeting demand. The interaction between economic development and transportation system development is reinforcing up to a saturation point. With the development and proliferation of new transportation technologies, the ultimate impacts on accessibility are important to measure.

Transportation accessibility measurement is a network problem. Any method which seeks to quantify accessibility must define the nodes and edges which comprise the region

in question. In the modern world, all nodes are, to a greater or lesser extent, connected. It is often the case that several modes and paths can be nearly equal in cost. Scoping an accessibility analysis can be highly determinative of outcome. Researchers and planners have primarily utilized the concept of transportation accessibility as it applies to routine household behavior and local travel [1]. From the personal transportation perspective, access is defined as the ease with which individuals can reach the opportunities they desire subject to land-use, transportation infrastructure, temporal availability, and individual preference. Land-use dynamics determine the spatial distribution of amenities such as jobs and services as well as that of potential customers. Transportation systems determine the edge traversal costs including travel time, effort, and price which impede flows [2]. Temporal availability of opportunities and transportation modes restrict the utility of opportunities and transportation modes. Characteristics such as age, income, and education predict attraction of opportunities and transportation modes of individuals [3]. Any transportation accessibility analysis must, thus, be stochastic.

Regions will vary both in infrastructure and resident preferences. The US and similar western nations are

unusually car-centric by global standards [4]. Car dependence will not vanish in a short period. The differences between different types of car are important to consider. The access provided by a road transportation system for BEV drivers is different than that for ICEV drivers due to vehicular and supply network characteristics. Modern BEVs possess sufficient practical ranges to accomplish much daily of daily travel as shown in Figure 1 with data from [5, 6]. However, for long itineraries ICEVs offer greater accessibility compared to BEVs due to greater maximum ranges and the ubiquitous availability of fueling stations. Fueling stations are widely distributed across urban, suburban, and rural areas, ensuring that drivers have convenient access to refueling points wherever they travel. In contrast, the charging network is less developed and distributed. This infrastructure gap poses challenges for BEV drivers, especially in remote or less densely populated areas, leading to range anxiety and limitations on travel options. Inadequate long-trip accessibility for BEV may result in cancellations or mode switches, often favoring ICEV or air travel. By the same token, the lower operating costs of BEVs may cause short trips to be increasingly shifted towards them.

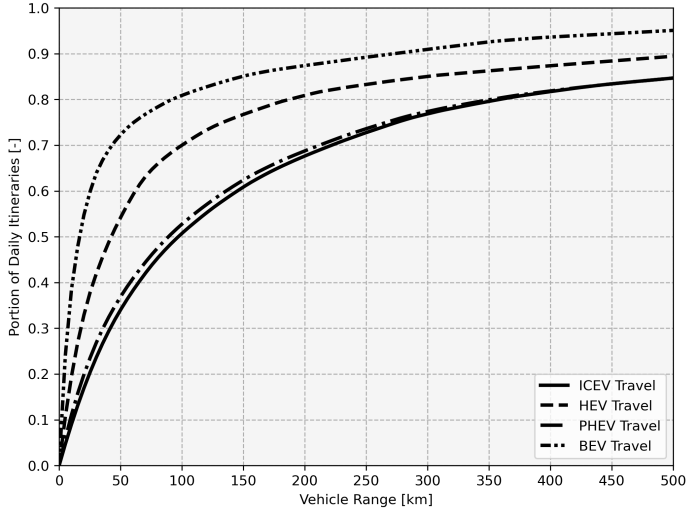


Figure 1: Individual vehicle routine travel utility factors as a function of range by powertrain type for National Highway Transportation Survey (NHTS) 2022 edition

Disparities between the fueling and DC charging networks result from differences in their underlying economic models. Gas pumping equipment requires lower up-front costs than DC Electric Vehicle Supply Equipment (EVSE), is cheaper to operate [7], and has

been deployed for far longer. Gas is often sold at low margin with stations making most profit on convenience items. Nearly all light-duty ICEV drivers source all of their fuel from public fueling stations regardless of travel behavior. BEV drivers are expected to, and currently do, source much of their electricity from AC supply equipment during long dwells [8]. These long dwells often take place at private chargers. Thus DC charging stations are subject to higher capital expenditure, lower revenue potential, and less accumulated investment. To overcome these disadvantages, public investments in DC charging infrastructure must be made judiciously. Evaluation methods for potential charging stations should consider their network-wide impact on accessibility considering vehicle types, equipment reliability, and driver behavior.

This study introduces a novel framework for the assessment of transportation accessibility for long vehicular trips. The methodology measures accessibility by computing optimal-feasible travel routes for Origin-Destination (O/D) pairs using a stochastic routing algorithm subject to vehicle range limitations, supply infrastructure, and driver risk attitudes. This methodology is powertrain agnostic and can be used to directly compare accessibility for vehicles with different ranges and which rely on different supply networks. Additionally, a case study is presented for the state of California showing a comparison between ICEVs and BEVs access for important O/D pairs within the state. The methodology introduced, as well as the open-source code provided in the supplemental information is a valuable tool for planners and policymakers in originating and evaluating EVSE deployment policies.

Transportation Accessibility

Transportation accessibility has been studied as a tool for urban and regional planners since the middle of the 20th century. Accessibility derives from the theory of population migration proposed by Ravenstein in 1885 [9]. The movement of populations over a given time-scale can be analogized to Ohm's Law. In this analogy push and pull factors determine the "voltage" separation, traversal difficulty is the "resistance" and the resulting "current" is the flow. Human migration is subject to endogenous and nonlinear effects as flows lead to changes in their origin and destination locations as well as on the arc between. The field of transportation accessibility uses this framework to study regional efficiency considering both demand and impedance

simultaneously. The accepted definition of transportation accessibility is the ease with which individuals can access relevant opportunities subject to the transportation system in the relevant area. Thus, accessibility is a framework which encompasses demand factors such as land use and temporal availability, impedance factors such as transportation system design, and universal factors such as personal preference [2]. Literature provides four essential frameworks for computing access as surveyed in [1–3, 10, 11] and discussed below.

Much of the difference between methodologies is in scoping. Individuals are assumed to need or desire location-specific opportunities such as employment and physical retail. However, there may be several near-equivalents for any given opportunity type. The simplest methods for selecting opportunities are based on nearest proximity [12, 13]. Proximity methods consider that a person has a level of access to a given need as determined by that person's proximity to the closest relevant opportunity. These methods do not account for heterogeneity within an opportunity category nor for the benefits of redundancy within an opportunity category. The inverse are isocost methods wherein a person is said to have access as determined by the number of opportunities available within a given isocost polygon. This method has the drawback of not considering the differences in arc traversal cost for O/D pairs within the isocost region. These methods have been used widely [14] due to their transparency and computational lightness and form the basis for modern big-data methods such as the US DOE's Mobility Energy Productivity metric [15].

Proximity and isocost methods are easy to compute because they treat redundancy arbitrarily. In practice, equivalent and near-equivalent opportunities compete with one-another if sufficiently proximate or if the paths required to reach them overlap [16]. Gravity/entropy methods [17, 18] address this shortcoming. These methods are so called as they concern the cumulative effect of opportunities for a given origin. Effects can accumulate on the basis of demand over proximity (gravity) or information content (entropy). Such methods were first formalized into a quantitative framework in 1959 [19] as a generalization of previous methodology for quantifying the efficiency of urban land use. Gravity/entropy methods define accessibility as the intensity of the possibility for interaction. Implicit in the formulation of gravity/entropy methods is that every opportunity has some effect on every individual, even if negligible, and the effect of any one opportunity is determined by its network position.

Proximity and gravity/entropy methods rely on the

assumption that traversal cost is the primary factor determining individuals decision to select one opportunity from among a set of similar entities. While this is certainly true if the difference in traversal cost is large enough it is not obvious what the threshold of disambiguation will be for a given individual or population. Researchers have proposed to use Discrete Choice Modeling [20] to explain revealed choices wherein ease-of-access is merely one of several contributing factors in determining the utility of a given opportunity for a given individual [21–23].

Which method one chooses for an analysis should reflect the scope and purpose of that analysis. Definition of scope can be difficult and arbitrary and can lead to self-defeating policies in the worst cases [24]. This study is concerned with the effects of electrification on long-trip accessibility for road vehicle users. This scope simplifies opportunity selection. It is necessary that a transportation system provide for access between large population centers within a region of interest and to those in adjacent regions. This study is focused on non-routine regional travel rather than routine local travel as this is where supply infrastructure becomes important. It should be noted that the method is, nevertheless, valid for all travel scales. Said methodology is developed in the following section.

Methods

The focus of this study is long-trip accessibility for road vehicles. The metric proposed reflects the ease with which a given individual, driving a given vehicle, can access the important locations in a region from one-another. It is assumed that travelers, when considering non-routine long trips have a specific destination in mind and would not consider nearly equivalent and/or equidistant locations as fungible. Rather, having determined to travel to a given location the traveler will then select a mode. Accessibility is a function of demand and impedance. Demand can be estimated by considering the relative attractiveness of given cities as a function of population, economy, or some other metric. Impedance can be quantified by calculating the mode and person specific lowest-cost-paths for all pairs of selected locations within the region and taking the average. Example costs which might be used are travel time and travel price.

A transportation accessibility metric should have land-use, transportation, temporal, and individual components [23]. The metric proposed contains all required components.

The land-use within a region has two principle effects. First, for a multi-city region, peripheral cities should experience worse regional access than central cities. Second, geographically large and/or sparse regions should experience worse overall accessibility than compact regions. The transportation infrastructure determines the efficacy of various modes. Where only vehicular travel is concerned, the mode choice is reduced to vehicle choice. Vehicle specific infrastructure is not necessarily the same for all vehicles of a given fuel type but is necessarily different between fuel types creating effectively separate modes. The temporal component arises from the schedules of public transportation services and road traffic patterns. Finally the individual component is the traveler risk attitude and route cost weights.

Metric Definition

Regional travel is often modeled using gravity models. Gravity models theorize that the attraction between two entities is in proportion to the general attractiveness of each and the intervening distance. The units of the resulting attraction have no physical meaning. A region where the sum or average attraction is higher will be a more integrated region. Being concerned with regional performance, this study proposes the Regional Gravity metric G_R . For region R of N nodes $O = \{O_1, O_2, \dots, O_N\}$ and a corresponding set of importance weights $W = \{W_0, W_1, \dots, W_N\}$, G_R is computed as

$$G_R = \frac{1}{N^2} \sum_{i=0}^N \sum_{j=0}^N \frac{CW_i W_j}{Z_{ij}^2} \quad (1)$$

where Z_{ij} is the cost of the optimal path from O_i to O_j and C is a constant tunable parameter. The Specific Regional Gravity $G_{R,i}$ at any node in region R can be computed as

$$G_{R,i} = \frac{1}{N} \sum_{j=0}^N \frac{CW_i W_j}{Z_{ij}^2} \quad (2)$$

for origin $O_i \in O$. Generally, W will be the set of population masses for each location $M = \{M_0, M_1, \dots, M_N\}$. All else being equal, regions which are more populated/productive, more compact, and enjoy better transportation networks will experience higher G_R . This quantity will vary within the region. This study is primarily concerned with the transportation system which contributes directly to arc traversal cost rather than arc demand. Thus a second metric, Regional Impedance is defined as

$$Z_R = \frac{1}{N^2} \sum_{i=0}^N \sum_{j=0}^N Z_{ij} \quad (3)$$

for region R . Specific Regional Impedance $Z_{R,i}$ is defined as

$$Z_{R,i} = \frac{1}{N} \sum_{j=0}^N Z_{ij} \quad (4)$$

for a single origin. The Regional Impedance is the average cost of traversing an arc between nodes in a region. Any increase to Z_R would result in a decrease to G_R .

Metric Computation

Powered vehicles are range-limited due to the finite capacity of their energy Storage Systems (ESSs). In order to traverse an O/D arc whose energy requirement is greater than a vehicle's ESS capacity, the vehicle must stop at a supply station. In practical terms, the limit is defined by the vehicle's ESS capacity, starting State of Charge (SOC), desired finishing SOC, and the driver's low SOC tolerance. Because supply events add time to a trip, they will usually be minimized where possible [25]. For sufficiently long trips, where at least one supply event is necessary, computing the shortest-time path requires considering the time added during supply events and the time required to deviate to supply stations. For ICEVs, supply events are brief and supply stations are ubiquitous in most areas of the developed world. Thus, conventional routing services often neglect supply considerations. For BEVs, supply events are relatively lengthy and DC supply stations are comparatively rare. Ignoring supply events when computing a shortest-time path for a BEV carries non-negligible risk of a lengthy stop or an out-of-charge event. For this reason, dedicated BEV routing services such as A Better Route Planner compute routes considering supply events.

All drivers deal with uncertainty and latency issues when computing an optimal route. Certain categories of disruption such as traffic, accidents, supply equipment functionality, and supply equipment local demand cannot be precisely known at the start of the trip. This uncertainty will cause different drivers to evaluate the same arc differently and may result in the selection of different routes. Compounding uncertainty is latency. Although a driver may have access to on the current state of roads and stations to be encountered in the future this may provide little information about conditions upon arrival. Without the ability to reserve a slot

at a supply station, drivers cannot be certain of equipment availability until they physically arrive at the station. As such, drivers have to optimize an expectation of route costs when selecting routes. Such optimization may take the form of electing to take a longer ring highway to avoid city traffic, stopping for fuel more often in a sparsely populated area, sitting through a traffic jam rather than diverting, or any number of other strategies. This mental process is modeled via stochastic optimization.

Stochastic Optimal Routing

The purpose of stochastic optimal routing is to find lowest-expected-cost paths from origin $i \in V$ to a set of destinations $D \in V$ on graph $G = \{V, E\}$. The output is tree P containing the optimal-feasible paths from the origin to the selected destinations. The objective of routing on arc (i, j) $i, j \in V$ is

$$\min_{U \in \bar{U}_{i,j}} \mathbb{E}[J(S_0, U)] \quad (5)$$

where

$$J(U) = \sum_{k=0}^M \Phi_k(S_0, U) \quad (6)$$

s.t.

$$b_l^k \leq \mathbb{E} \left[\int_0^t \Phi_k(S_0, U) dt \right] \leq b_u^k \quad (7)$$

$$\mathbb{E} \left[\int_0^T \Phi_k(S_0, U) dt \right] \geq b_f^k \quad (8)$$

$$t \in [0, T] \quad k = 1, 2, \dots, M \quad (9)$$

where T is the final value of time for a route, S is the state vector of M states, S_0 is the initial values of the states, U is a path between i and j , $\bar{U}_{i,j}$ is the set of possible paths between i , and j , Φ is the set of cost functions, b_l^k and b_u^k are the upper and lower bounds for state k respectively, and b_f^k is the final state minimum value for state k . \mathbb{E} denotes an expectation. State vector S is initialized and stored as vectors containing N discrete variables. A distribution D for the state vector at any node and time-step can be computed from a histogram of the values. Routes are considered feasible if state expectations remain within set bounds. Comparison between routes is performed using cost expectation. the goal of the optimization is to find the optimal path U_{ij}^* such that

$J(U_{ij}^*)$ is equal to the global minimum cost J_{ij}^* for each arc (i, j) $i, j \in V$.

For vehicle routing, common states are time, distance, price, number of stops, and remaining range. Limits are, often, placed on states and these may not be violated at any time. Limits may also be placed on the final value of a state. Time, distance, price, and number of stops are examples of metrics of minimization which may be used individually or in combination. Upper limits may be set on metrics of optimization in order to terminate the optimization when it is no longer possible to find a feasible route. Remaining range will, necessarily, be subject to upper and lower limits and may be subject to a final value limit (an example of this would be preserving enough range for a return trip).

The values of states are static at nodes and are changed in the process of traversing edges. Intuitively, if a vehicle has 50 km of remaining range at node i and traverses edge (i, j) of distance 20 km ($\Phi_d(i, j) = 20$) then it will arrive at node j with 30 km of remaining range. If node j contains a supply station then range can be added before progressing further. Adding range will cost time and money and should, therefore, be done sparingly. In order to progress from node j to node k , the vehicle needs only sufficient range to avoid violating the associated lower bound, in this case 10 km. If $\Phi_d(j, k) \leq 20$ then no resupply is needed. If $\Phi_d(j, k) > 20$ then a resupply event is needed and should add only enough range to make (j, k) feasible. Thus the cost of traversing (j, k) depends on whether or not and how much resupply is needed.

The extent to which range can be added via resupply is limited by the capacity of the vehicle's ESS and remaining range constraints. Certain edges will be infeasible regardless of supply as a result. In addition, supply will not be available at all nodes and the cost of supply is neither guaranteed to be homogeneous throughout a network nor to be linear with respect to range added.

The structure of the optimization process is as follows. First, a graph is created to represent the supply network and its interactions among itself and with origins and destinations of interest. All arcs which are feasible should be included as edges in this graph, including those directly between origins and destinations. This graph is described in the Supply Network Graph (SNG) subsection. Second, edge costs in terms of problem states are assigned using models which will be described in the Driver Model, Vehicle model, and Supply Station Model subsections. Third, stochastic optimization is performed using an optimal routing algorithm such as the Dijkstra or Bellman-Ford

algorithm.

Supply Network Graph

Supply networks effect routing both in structure and in the characteristics of individual stations. In this paper, the supply network refers to all stations which the vehicle can utilize. Supply networks ultimately consist of individual supply ports (chargers or fuel pumps) and serve geographically and temporally distributed demand. A network consisting of more than one port can develop redundancy either by concentrating ports in a single confined space "in-station" or via a more evenly distributed approach "between-station". In-station redundancy is simply the number of ports in a given station. Between-station redundancy is the number of ports in the set of stations which are sufficiently close as to be reinforcing. The distance that defines whether or not two stations are reinforcing varies between individuals and by a variety of factors. Network redundancy also varies by location with "thinner" and "thicker" coverage areas.

The physical connection between supply stations is provide by the road network. Without consideration of range, each station, origin, and destination is reachable from all others. The SNG is formed from these nodes. Edges are created for all origins and destinations based on shortest paths computed on the road map. Only the locations of and relationships between relevant nodes are necessary. The graph formed from the relevant nodes and their relationships is a reduced subgraph with a low number of nodes and relatively high edges-per-node and cycles-per-node ratios when compared to the road map.

A reduced subgraph is defined as follows. For a graph $G = \{V, E\}$ where V is the set of nodes and E is the set of edges, a reduced subgraph $\hat{G} = \{\hat{V}, \hat{E}\}$ can be computed where $\hat{V} \subseteq V$ and $\hat{E} = \{P_{ij} \mid (i, j) \in \hat{E}\}$ is the set of shortest-paths between all nodes in \hat{V} . An example of a reduced subgraph is shown in Figure 2.

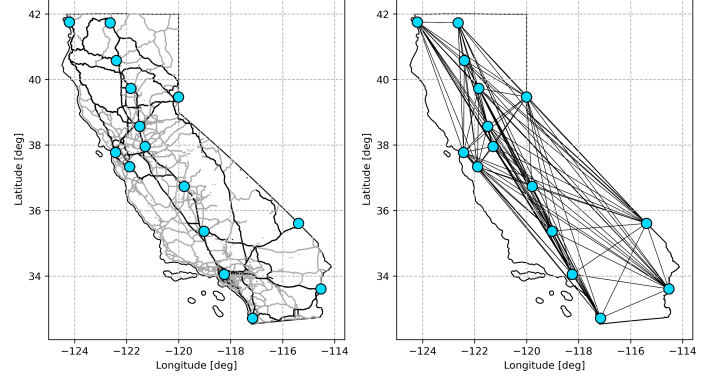


Figure 2: Example original graph (left) containing locations and an atlas and reduced subgraph (right) containing locations and arcs.

Most of the nodes on the SNG will be supply stations each with different equipment types and numbers of ports. In-station redundancy for a SNG is a nodal parameter. In-station redundancy ξ_{is} for any node $v \in V$ on SNG $G = \{V, E\}$ is the number of ports at node v . Between-station redundancy ξ_{bs} for an SNG can be computed for cliques of nodes after solving the maximal clique problem. Between-station redundancy for any clique $C \subseteq V$ on SNG $G = \{V, E\}$ is the sum of the ports at nodes $v \in C$. Meaningful cliques may be attained by removing edges above a set cost before solving for maximal cliques. For example, cliques may be found on $G' = \{V, E'\}$ where $E' \subseteq E$ contains all edges of less than 10 minutes drive time.

The SNG is the graph on which long vehicle trips should be optimized if supply events are expensive and/or constraining. The relevant SNG for ICEVs and BEV are neither equivalent nor isomorphic. Different vehicles within a given powertrain type may also have different SNGs but this is far more common for Electric Vehicles (EVs) than ICEVs. The SNG informs routing by providing a set of possible paths between origins and destinations. The structure of a network may make for a greater or lesser number of available paths depending on the number and location of stations.

Driver Model

Different drivers will have different perceptions of cost for the same fundamentals based on their priorities and risk attitudes. In a basic sense, drivers will prioritize factors such as time, money, distance, and complexity differently. These priorities are modeled by computing overall cost as a linear combination of individual costs using constant

weights. Where any important factor is not known precisely drivers will consider a range of outcomes and decide based on an expectation. Driver risk attitude concerns what range of outcomes will be used to compute expected cost. Risk attitude is modeled using a superquantile risk function defined as

$$S(D, p_0, p_1) = \frac{1}{p_1 - p_0} \int_{p_0}^{p_1} Q(D, \alpha) d\alpha \quad (10)$$

where D is a distribution, p_0 and p_1 are the boundaries of the range of probabilities considered in the expectation, and Q is the quantile function of D . The superquantile is, thus, the mean value of a distributed quantity within a range of probability. $S(D, 0, 1)$ reduces to the mean of D . Drivers with an aggressive risk attitude will consider a low range of probabilities. Drivers with a neutral attitude will consider a central range of probabilities. Drivers with a cautious attitude will consider a high range of probabilities. Driver parameters are listed in Table 1.

Table 1: Supply Station Parameters for Routing

| Parameter | Description | Unit |
|----------------------------|--|------|
| Priorities W | Set of multipliers for route costs to be used in computation of weighted sum | [-] |
| Risk Attitude (p_0, p_1) | Range of probabilities for superquantile function | [-] |

The driver model serves to bias the routing by selecting a subset of information to use in optimization. As such it reflects individual perception. The results of the routing can be interpreted through the same bias, a different bias, or no bias. In this study, evaluation will be conducted on the basis of un-biased interpretation of costs.

Vehicle Model

Vehicles effect routing due to their range limits and supply methods. The vehicle model used herein is highly simplified due to the inexact nature of the problem. Vehicles are modeled as storing energy and consuming energy at a constant rate per unit distance driven. More

exact information on road conditions, traffic conditions, and atmospheric conditions among others can be used to compute edge-specific efficiencies. Vehicular parameters are listed in Table 2.

Table 2: Vehicle Parameters for Routing

| Parameter | Description | Unit |
|--------------------------|--|---------|
| ESS Capacity | Accessible energy storage capacity | [kWh] |
| Energy Consumption | Energy required to move the vehicle | [kJ/km] |
| Maximum Supply Rate | ESS maximum energy addition rate | [kW] |
| Linear Charging Fraction | Percentage of the battery capacity which can be charged in the linear (constant current) range | [kW] |
| SOC Bounds | Range in which SOC must be maintained | [-] |

DC charging is modeled using a CC-CV relationship wherein the first part of charging is linear and the second part follows exponential decay [26]. The inflection point which separates the linear and exponential decay sections is the Linear Charging Fraction η . The time required for a given charge event is

$$\Delta T = \Delta T_l + \Delta T_e \quad (11)$$

$$\Delta T_l = \begin{cases} \frac{(SOC_f - SOC_i)C}{v} & SOC_i \leq SOC_f \leq \eta \\ \frac{(\eta - SOC_i)C}{v} & SOC_i \leq \eta \leq SOC_f \\ 0 & \eta \leq SOC_i \leq SOC_f \end{cases} \quad (12)$$

$$\Delta T_e = \begin{cases} 0 & SOC_i \leq SOC_f \leq \eta \\ -\frac{1}{\alpha} \ln \left(1 - \frac{SOC_f - \eta}{1 - \eta} \right) & SOC_i \leq \eta \leq SOC_f \\ -\frac{1}{\alpha} \ln \left(1 - \frac{SOC_f - SOC_i}{1 - \eta} \right) & \eta \leq SOC_i \leq SOC_f \end{cases} \quad (13)$$

$$\alpha = \frac{v}{\eta C} \quad (14)$$

Where C is the vehicle ESS capacity, v is the actual

power of the charge event, ΔT_l and ΔT_e are the time spent in the linear and exponential decay portions of the charge event, and SOC_i and SOC_f are the initial and final values of SOC for the charge event. Charge events are modeled to occur at the minimum of the maximum powers for the vehicle and charger. A typical value for η will be in the range of 0.7 to 0.8. DC charging for a given quantity of energy past η will take substantially longer than the same quantity below η . The difference in effective charging rate may serve to favor more DC charge events in a given arc which terminate at a lower SOC.

Supply Station Model

Supply station design parameters are number of ports, reliability of ports, and the maximum supply rate of ports. The probability of port availability at a station is determined by the rate at which vehicles arrive at the station and how long they spend at the station. In combination, these factors determine the likelihood of a port being usable and available as well as the likely duration of queue if no port is usable and available. Supply station parameters are listed in Table 3.

Table 3: Supply Station Parameters

| Parameter | Description | Unit |
|-------------|--|------|
| Supply Rate | Maximum rate of energy supply | [kW] |
| Ports | Number of chargers/pumps at a station which can be used simultaneously | [-] |
| Reliability | Percentage of the time that a given pump will be usable | [-] |

Information on ports is taken from Alternative Fuels Data Center (AFDC) [27], information on equipment reliability is taken from [28], and information on port supply rates is taken from Google Maps.

Queue waiting time is computed using the M/M/c queuing formula with parametric uncertainty. The expected waiting time in an M/M/c queue is computed as

$$W_q = \pi_0 \frac{\rho(c\rho)^c}{\lambda(1-\rho)^2 c!} \quad (15)$$

$$\pi_0 = \left[\left(\sum_{k=0}^{c-1} \frac{(c\rho)^k}{k!} \right) + \frac{(c\rho)^c}{c!(1-\rho)} \right] \quad (16)$$

$$\rho = \frac{\lambda}{c\mu} \quad (17)$$

where λ is the arrival frequency, μ is the service completion frequency, c is the number of homogeneous servers, ρ is the ratio of arrival frequency to composite maximum service completion frequency, and π_0 is the probability of an empty system. M/M/c queues assume an exponential distribution for both arrival and service completion frequency centered on a known mean. Reflecting the lack of information on charger accessibility accessible to drivers, these parameters must be sampled from distributions. Arrival frequency is much more uncertain than service completion frequency for drivers unfamiliar with a station. As such the drivers are modeled as assuming that charge event times will reflect the time required to fulfill a charge event sampled from a normal distribution and then picking values of ρ based on their risk attitudes. In this study, charging event times in minutes are sampled from the normal distribution $N(30, 10)$. The effects of ρ and in-station redundancy are shown in Figure 3.

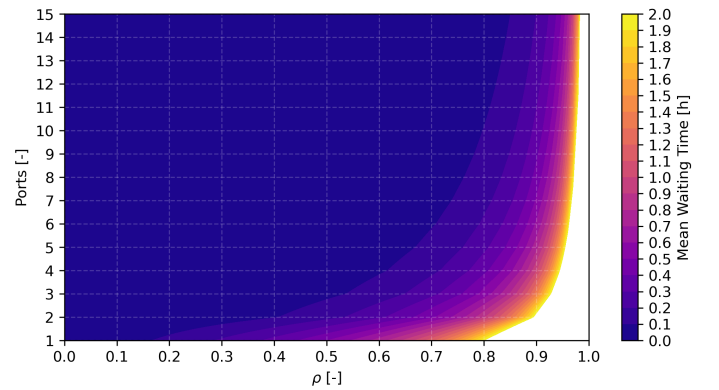


Figure 3: Effects of in-station redundancy and ρ on expected waiting time. Projected times of greater than 2 hours omitted in order to preserve scale.

Without prior information, a reasonable assumption is that a station will be sized, roughly, to meet demand. The ρ parameter reflects the ratio of demand to maximum capacity and scales with redundancy all else being equal. However,

unless completely saturated, a station with more port will be able to handle the same relative demand with a shorter queue due to heterogeneity in individual supply event times. With low demand, durable queues are unlikely to form at any station. As ρ approaches 1, the expected duration of a queue grows toward infinity in a phenomenon known as queue instability. The rate of queue growth as a function of demand growth is determined by redundancy. In practice, a queue of sufficient length will be intolerable to any driver in almost any circumstance limiting queue growth. If this limit is 2 hours then, as seen in figure 3, a cautious driver may view 1 and 2 port stations as ineligible.

Summary

The Regional Impedance metric Z_R quantifies the weighted average time of arcs between important locations in a region. Z_R can be computed for any mode or set of modes. For the context of road vehicles, those vehicles which must resupply energy from different networks are, in effect, different modes. Z_R is computed for a driver vehicle by building the relevant SNG and performing optimal routing based on the drivers preferences and perceptions and the physical characteristics of the vehicle and SNG. In this study the cost in question is total travel time. The total travel time is the combination of driving time, supply event time, and time spent queuing at supply stations. Each aspect of total travel time must be estimated by the driver with imperfect information when planning a route. Pure driving time is relatively knowable and a decent estimation may be obtained from many routing services. Supply event time is also relatively knowable, especially for experience drivers. Queue waiting time is far less knowable as accurate and timely information on charger utilization and equipment functionality is difficult to come by. Even where it is available beforehand, it may change by the time the driver arrives. These uncertainty and latency issues can substantially increase total travel times. In this study, queue waiting times are estimated by the driver based on the number of ports listed at a station while the actual queue waiting times are computed based on the number of functional ports. When equipment reliability is low drivers may end up spending more time than anticipated, especially if redundancy is also low. In the following case studies Z_R is used as a metric of evaluation to study the impacts of model parameters on transportation accessibility.

California Case Study

The randomly generated example is informative but does not reflect any actual SNG. In order to see effects on a more representative basis a case study is performed on the state of California using information on the states DC EV SNG with modes of common BEVs which enjoy different levels of access.

Background

The state of California is geographically large and diverse in demography and land use. Per 2022 US census bureau annual estimates [SOURCE], California's population numbers over 39 million persons with around 32.5 million living in 482 Incorporated Places including cities and towns. These Places range from Los Angeles with a population of 3.8 million located near the coast to Amador City with a population of 201 located in the Sierra foothills. Connecting these disparate locations are a collection of major road transit corridors. Running roughly north-south are S-1/101, I-5/S-99, and U-395. Running roughly east-west are I-8, I-10, I-15, I-40, and I-80. Much of the traffic on the east-west corridors represents interactions with adjoining states. Incorporated Places in California are shown in Figure 4.

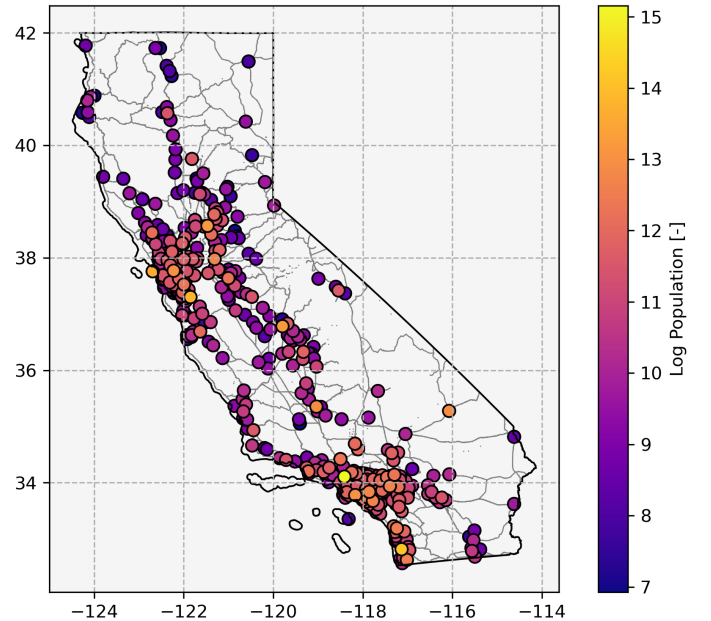


Figure 4: Natural logarithm of population for Incorporated Places in California

Many of the most heavily populated Places are adjacent

with each other or nearly so. The bulk of traffic between these will be local and routine. For the benefit of clarity and brevity these can be merged into super-Places. This is accomplished by the computation of maximally modular communities. First the distances for all pairs are computed. Second an inverse proximity is computed as

$$\Gamma_{ij} = \exp\left(\frac{\Phi_d(i,j)}{\varepsilon}\right) \quad (18)$$

where ε is a characteristic distance set at 10 km in this case. Solving for maximally modular communities, centroids of the 34 resulting communities are shown in Figure 5.

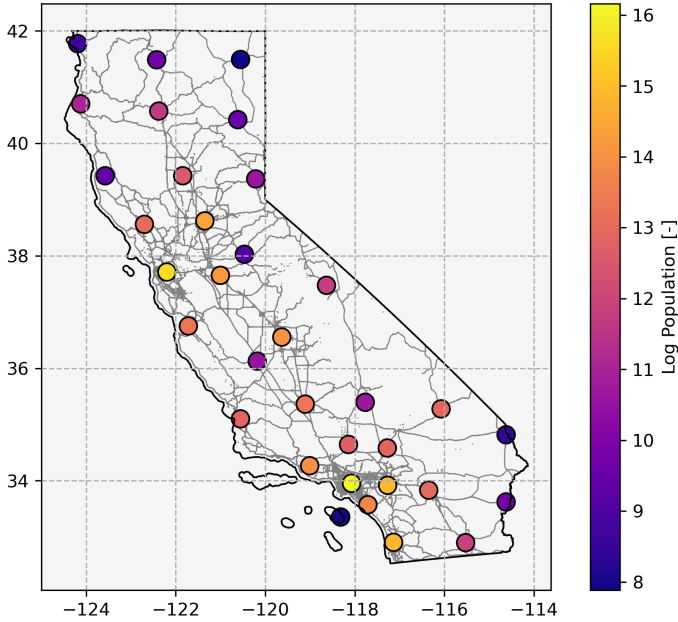


Figure 5: Natural logarithm of population for Incorporated Place Communities in California

Finally, for the purposes of analysis, points representing departure locations for Phoenix AZ, Las Vegas NV, Reno NV, and Portland/Eugene OR are added to the fringes of the map to represent the associated travel demand.

For long trips, BEVs will rely on DC charging stations. The locations of all DC charging stations in California are available from AFDC [27]. AFDC is a reasonable but imperfect source for Dc chargers [29]. In may 2024 AFDC listed 2,149 active stations with at least 1 DC charger. This number is somewhat misleading as certain networks report each charger as an individual station even if within line-of-sight of one-another. After merging all stations of the same network which are within 100 meters direct distance of each other the number of stations becomes 1,689. California’s DC charging stations include proprietary (vehicle Original Equipment Manufacturer (OEM) owned and operated) stations such as Tesla Superchargers and the Rivian Adventure network as well as non-proprietary stations such as those operated by ChargePoint, Electrify America, eVgo, and others. The selected locations and DC charging stations are mapped in Figure 6.

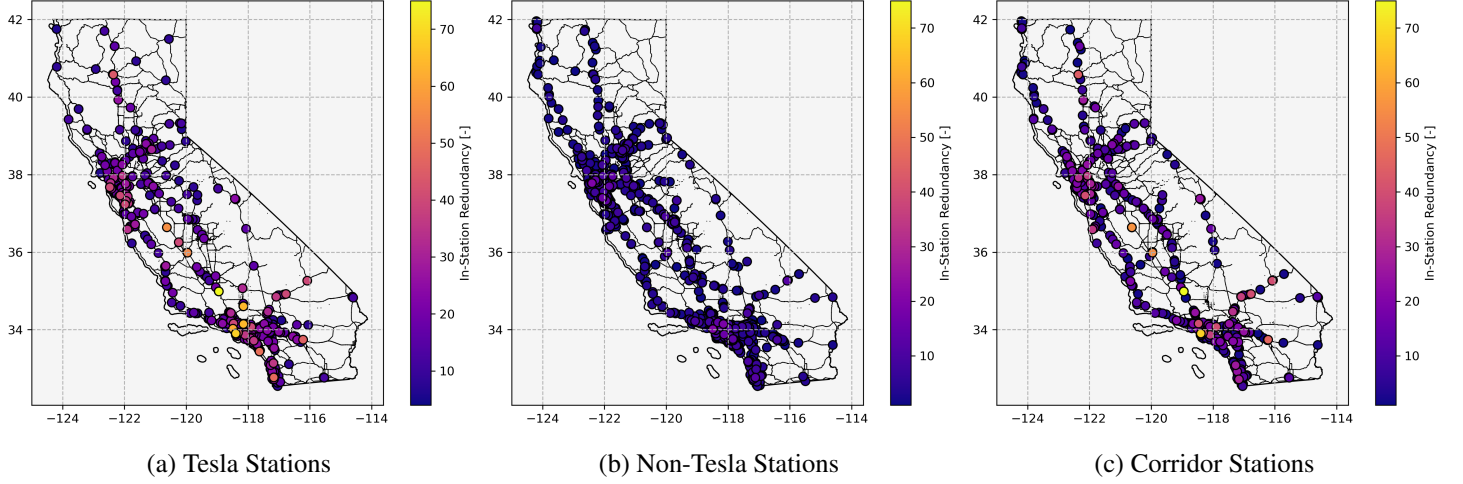


Figure 6: California DC charging stations from AFDC (May 2024)

There are 419 Tesla and 16 Rivian DC charging stations in the state as compared to 1,254 non-proprietary DC charging stations. In practice, many of these stations will be of little use for long distance travel being located far away from primary and secondary roads. Considering only those stations within 1 km of a highway as "corridor" chargers, there are a total of 500 corridor DC charging stations. Of the corridor stations, 156 are Tesla stations, 7 are Rivian stations, and 344 are non-Proprietary stations.

The non-Tesla networks overwhelmingly use CCS or combination CCS/ChaDeMo chargers which reflect the ports on the overwhelming number of non-Tesla BEVs. By contrast, Tesla chargers and vehicles use the NACS standard. The Tesla and non-Tesla systems are historically separate but increasingly interoperable with the aid of adapters. Tesla drivers use Tesla DC chargers almost exclusively [30]. The Rivian Adventure network is technically interoperable with other J1772 vehicles but is set aside for the exclusive use of Rivian vehicles. The purpose of the Rivian Adventure network serves to allow for Rivian vehicles to charge in remote locations and is not intended to be relied upon exclusively.

The difference between the Tesla DC charging network and the non-Tesla networks extends from function to form. Built out as an investment to entice sales of Tesla vehicles and, until recently, exclusive to them, the Tesla network is technically superior with high maximum charging rates and more greater port usability rates [28, 31]. The Tesla network is mainly composed of high redundancy stations. Non-proprietary networks have, so far, been utilization and subsidy driven [7] and are widely distributed with

low redundancy stations. A stark contrast is seen when examining the ratios of chargers to stations. In California there are 403 Tesla DC charging stations with a total of 7,101 DC chargers for an average of 16.9 chargers per station. Among non-proprietary networks there are a total of 1,254 stations with 4,129 chargers for an average of 3.3 per station. Redundancies for Tesla and non-proprietary networks are shown in Figure 7.

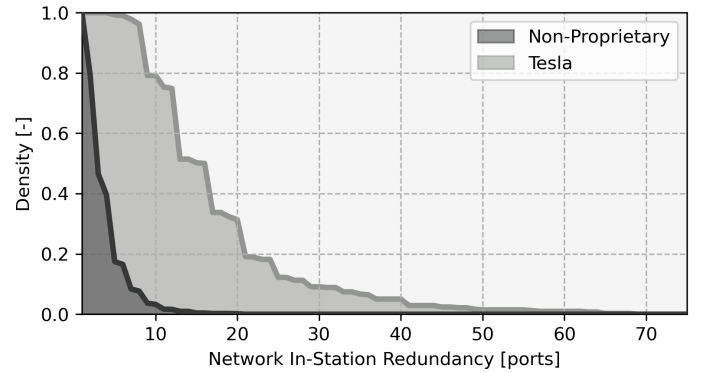


Figure 7: Survival functions for in-station redundancy for Tesla and other DC charger networks in California

The Tesla DC charging network develops redundancy primarily in-station where the non-proprietary networks develop redundancy primarily between stations. Non-Tesla chargers are also more likely to be sighted in urban areas suggesting a desire to capture local as well as corridor travel demand. Tesla stations are more often sighted along travel corridors suggesting a focus on enabling long distance travel. In more remote parts of California the proprietary

networks nearly match the non-proprietary networks in station numbers. In-station redundancies for DC charging networks in California can be found in Figures in the DC Charger Network Details section of the Appendix. Summary statistics for DC charging networks in California can be found in the DC Charger Network Details section of the appendix.

California ICEVs utilize a third and completely separate network of supply stations. There are estimated to be over 8,000 gasoline stations in California [32] and these are widely and proportionally distributed. Because no public database for the locations of gasoline stations in the state exists, and due to their ubiquity it is assumed in this study that ICEV driver optimal paths will not be effected by fueling station availability. For this reason, ICEVs are, herein, assumed to take the "direct" path between cities where BEVs need to find optimal paths on their SNGs.

Experiment

In order to understand the effects of vehicular, infrastructural, and behavioral parameters on road-trip accessibility an experiment was carried out on randomly generated combinations. As a baseline, three ICEVs were also modeled. These ICEVs represent different levels of efficiency present in the ICEV fleet. The ICEV models use ESS capacity numbers are pulled from manufacturer websites and energy consumption rates from [33]. Although substantially less efficient than equivalent BEVs the comparatively high specific energy of liquid petroleum allows for ICEVs to have high full-tank ranges. ICEV supply infrastructure is modeled to dispense fuel at the normal US rate of 7 gallons per minute which is an equivalent energy supply rate of 14.15 MW. When refueling, the Prius, Golf, and Pacifica, add highway range at rates of 631, 462, and 282 km per minute respectively. The ICEV models are shown in Table 4.

Table 4: ICEV models

| Vehicle Model | Parameter | Value |
|------------------------|--------------------|---------------|
| 2024 Toyota Prius | ESS Capacity | 381 [kWh] |
| | Energy Consumption | 1,346 [kJ/km] |
| | Full-Tank Range | 1,018 [km] |
| 2024 Volkswagen Golf | ESS Capacity | 445 [kWh] |
| | Energy Consumption | 1,839 [kJ/km] |
| | Full-Tank Range | 871 [km] |
| 2024 Chrysler Pacifica | ESS Capacity | 640 [kWh] |
| | Energy Consumption | 3,015 [kJ/km] |
| | Full-Tank Range | 764 [km] |

Regional Impedance for ICEVs was computed under the assumption of petroleum supply infrastructure ubiquity. As such, ICEVs were given the "direct" path between locations with stop times added where additional range was needed. For each necessary stop, time was added for refueling to full as well as 10 minutes to divert from the road and handle the transaction prior to refueling. Additionally, drivers of the ICEVs were assumed to keep a 10% buffer of remaining range. The ICEVs each had similar road-trip accessibility scores of roughly 5.5 hours. The longest arc considered in Crescent City (Location 0) to Phoenix - State Line (Location 13) which is roughly 1,530 km just exceeding double the usable range of the Pacifica.

500 random scenarios were generated by uniform random sampling of the parameters listed in Table 5 and run on three SNGs as described in 6. All randomly sampled BEVs in this study are assumed to have an energy consumption rate of 608 kJ/km this being the EPA energy consumption rate of a Tesla Model 3 in highway operation [33]. Highway operation is assumed herein due to the focus on long trips. Thus BEV full-charge ranges will be between 237 and 711 km. When charging, sampled BEVs add highway range at a rate between 4.9 and 19.7 km per minute. Risk attitude is modeled as in (10) with the range centered around the mean parameter \bar{p} where $p_0 = \bar{p} - .1$ and $p_1 = \bar{p} + .1$.

Table 5: Parameters and ranges for experiment.

| Parameter | Range |
|---------------------------|-------------------|
| ESS Capacity | [40 kWh, 120 kWh] |
| ESS Max Charge Rate | [50 kW, 200 kW] |
| Driver Risk-Attitude Mean | [.1, .9] |
| EVSE Reliability | [.5, 1] |

Table 6: SNGs used in experiment.

| Label | Networks Included |
|-----------|------------------------|
| Combined | All stations |
| Tesla | Only Tesla stations |
| Non-Tesla | All non-Tesla stations |

Outputs were processed to compute neutral expectations of Regional Gravity and Regional Impedance as in (1) and (3) respectively. Boxplots of Regional Gravity and Regional Impedance by SNG are presented in Figures 8 and 9.

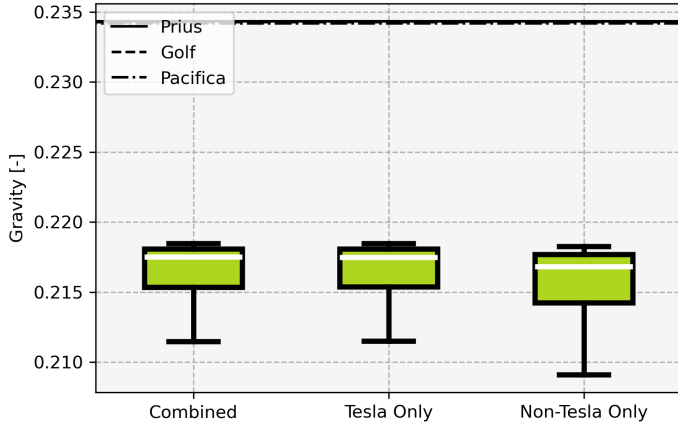


Figure 8: Boxplots of G_R outputs by SNG

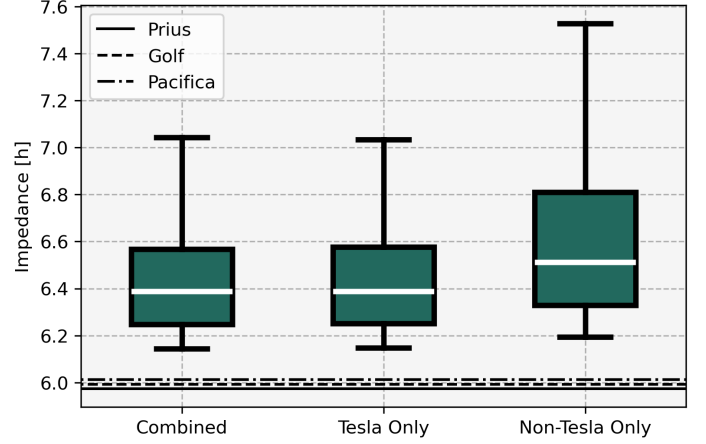


Figure 9: Boxplots of Z_R outputs by SNG

An immediate takeaway is the value of access to Tesla stations. The median performance of the Tesla SNG is only very slightly worse than that of the complete SNG while the performance of the non-Tesla SNG is notably worse than either. The outcome spread among the sampled cases is substantial ranging from marginally worse than the ICEVs to markedly worse. As gravity scales with the inverse of the square of impedance it follows that, purely from a road transportation perspective, the current BEV infrastructure would result in a noticeably less connected region. The bulk of the increase in impedance occurs at-station whether due to queuing or charging times. Although statistically significant, the time lost due to path deviations is minimal as seen in Figure 10.

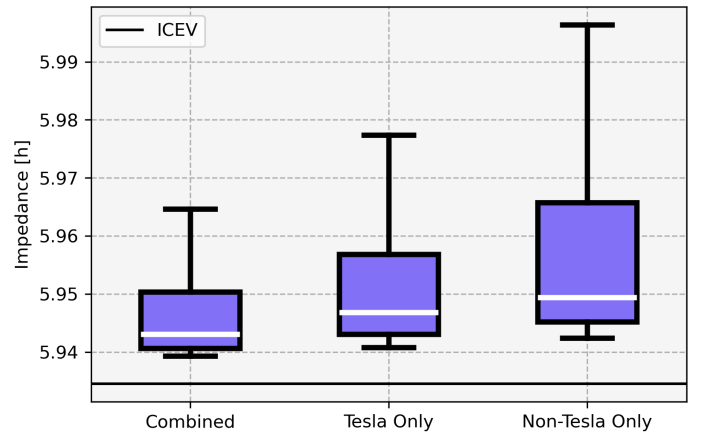


Figure 10: Boxplots of Z_R outputs by SNG neglecting supply time

Having identified the effects of SNG, the effects of

vehicular and behavioral parameters on experience for the given SNGs can be identified. Linear regression was performed on the Regional Impedance results of the random experiment and the experimental parameters for each SNG.

Significant parameters from the regression are shown in Figure 11. Regression details are tabulated in the Regression Details section of the Appendix.

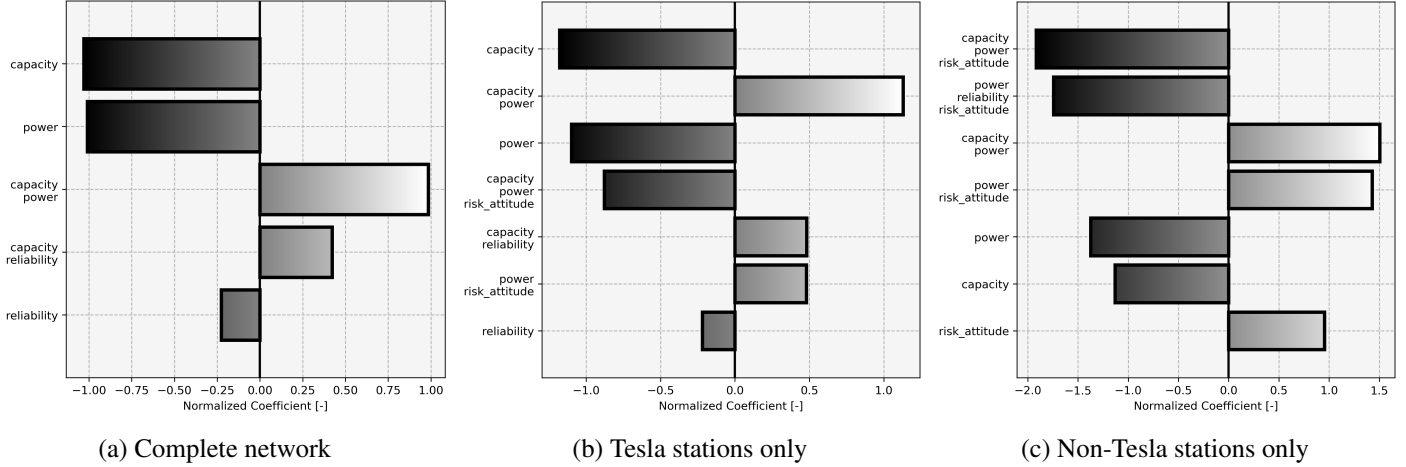
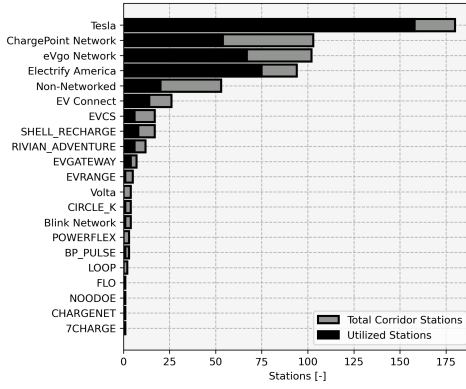


Figure 11: Coefficients for significant parameters from linear regression

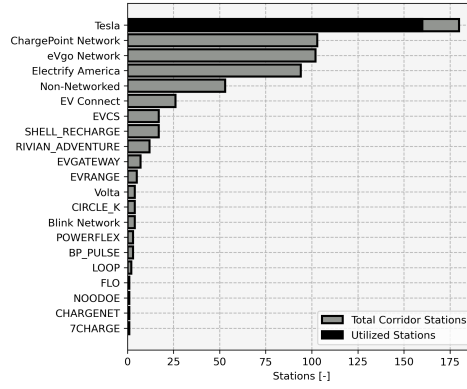
Regardless of SNG, ESS capacity and charging power were shown to be significant and important in reducing Z_R . The interaction between the two was shown to be subtractive indicating that vehicles with longer ranges benefit less from low recharge times and *vice versa*. Vehicles with high maximum charging speeds can only utilize this advantage at a subset of stations which boast maximum charging speeds equal to or in excess of their own. Vehicles with high ranges have more freedom to choose which stations to utilize on a given route. Past a point, however, these beneficial effects will be saturated. The role of equipment reliability is more complicated. In the model developed herein, poor equipment reliability may cause drivers to opt for paths which appear optimal but are worse in fact due to non-functional equipment. Reliability interacts heavily with risk attitude and in-station redundancy. Where the highly redundant Tesla stations are available the role of reliability in anticipated queuing time is low as, even in the worst case,

there is a good chance that the queue will be dissipated. Where these stations are not available, the perceptions of the drivers matter much more in determining expected queuing time. In general, the more and higher quality the stations within a SNG the less important risk attitude becomes as the fundamental drivers of queuing are lessened.

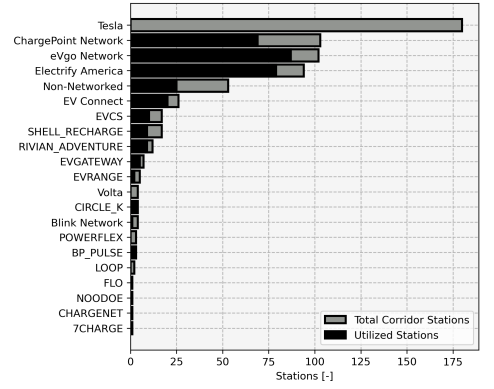
Some insight into the utility provided by each network can be gained by looking into utilization rates for networks and stations. Ratios of stations utilized at least once to total corridor stations are shown in Figure 12. Most of the utilized chargers belong to the top four networks. Where Tesla stations are available most were utilized at least once with those not utilized being remote locations. Where Tesla stations are not available, load is shifted towards the other top four networks. This observation indicates that as more vehicles are able to use Tesla stations, traffic will shift towards these stations or other stations which provide similar benefits.



(a) Coefficients for significant parameters from linear regression



(b) Coefficients for significant parameters from linear regression



(c) Coefficients for significant parameters from linear regression

Figure 12: Corridor DC charging network utilization rates

As established in Figures 6 and 7, the Tesla stations have higher in-station redundancy. Location should also matter in charger selection for optimal routes. As such, a second regression analysis was performed on station utilization for the complete SNG. In this case, the output used was log of utilization (number of times a station appears on an optimal route). Regressors were in-station redundancy and station betweenness centrality using driving time as the cost. Betweenness centrality was computed by finding all-pairs optimal paths for each Place on the basis of driving time. This measure reflects the likelihood that optimal routes will pass by a given station independent of charging. Regression results are shown in Tables 7 and 8.

Table 7: Combined Network Linear Regression Analysis ANOVA

| R | R-Squared | Adjusted R-Squared | Std. Error |
|----------|----------------|--------------------|--------------|
| 0.614 | 0.377 | 0.371 | 0.005 |
| Category | Sum of Squares | DOF | Mean Squares |
| Model | 1135.565 | 3 | 378.522 |
| Error | 1873.617 | 414 | 4.526 |
| Total | 3009.182 | 417 | 7.216 |
| <i>F</i> | | <i>P(> F)</i> | |
| 83.639 | | 0.000 | |

Table 8: Combined Network Linear Regression Analysis Coefficients

| Parameter | Coefficient | P-Value |
|-----------------------|-------------|---------|
| Intercept | 1.919 | 0.000 |
| redundancy | 1.518 | 0.000 |
| centrality | 1.181 | 0.330 |
| redundancy:centrality | 0.987 | 0.098 |

The two factors can only partially explain the results due to the differences in vehicles and individuals. It is notable that redundancy and interaction terms are significant at $\alpha = 0.1$ while centrality, on its own, is not. A possible interpretation is that the redundancy has a more determinant effect and that drivers are sometimes willing to sacrifice route directness in favor of more redundant stations.

Discussion

Results of this study suggest that BEVs drivers experience increased Regional Impedance within California. The expected difference between a given ICEV and BEV is roughly 5%-10% of total travel time for long trips. A large part of this delta is the unavoidable difference in charging times vs. fueling times. Should BEV ranges or charging speeds substantially increase the delta will substantially decrease. The rest of the delta is due to the differences between the SNGs used by BEVs and ICEVs. the differences within the DC charging SNG are worth examining in light of continued and future public investment

in its build-out.

Because of the structure of the network, Tesla stations are well positioned to absorb traffic should they become fully open to the general light duty EV fleet. This may have the result of worsening the user experience at Tesla stations and improving it at other stations until a new equilibrium is reached. The results would also suggest that a second Tesla-style network could enjoy a competitive advantage over the existing non-Tesla networks. It is worth theorizing why such a network has not yet developed. When one single entity has control over all stations in a network and has a captive customer base that network can optimize its expansion. Tesla has, in the past, been able to concentrate chargers to maximize in-station redundancy and minimize between-station redundancy. Simultaneously, Tesla has been able to subsidize overbuilt remote stations with the revenues generated from highly utilized central stations and from car sales. When each network is developed by an independent actor game theoretical considerations come into play. The independent actors must build out their networks under the fear that a competitor could build a competing station near any of their stations at any time. The risk of building station only to lose business to a nearby competitor combined with the opportunity cost of not doing the same results in an inefficient combined network. As Tesla integrates into the wider DC charging network it may begin to behave more like the current non-Tesla companies rather than the other way around.

What makes the distributed network inefficient are the twin issues of uncertainty and latency. These issues can be mitigated by an integrated status reporting and reservation system. Some information is available to drivers. Crowd sourcing applications such as PlugShare have been available for years allowing drivers to get a better idea of the overall reliability and utilization of stations on the basis of user reviews. Google Maps has recently implemented active plug-level availability monitoring with some, but not all, networks. Finally the private applications of the various networks provide different degrees of information and reservation capability. Future work will investigate the impacts of these systems.

Often, the case for BEVs is made on an economic basis as BEV may have lower levelized costs of driving. This study focuses on travel times and routing did not optimize for cost. Partly, this is because at present there is no publicly available data on energy costs at a granular station-level for either gasoline or DC fast charging stations. Nevertheless, some sense of the relative economics of long-trip travel can

be attained by examining energy costs per km. Energy costs vary substantially by region in the US with California being the most expensive. Energy costs around the time of writing are shown in Table 9.

Table 9: Residential electricity and petroleum average prices USD

| Source | US | California |
|------------------------------------|-------------|-------------|
| Petroleum [gallon] | 3.609 | 5.138 |
| Residential Electricity [kWh] | 0.1668 | 0.3247 |
| Transportation Electricity [kWh] | 0.1520 | 0.1191 |
| DC Fast Charging (Estimated) [kWh] | 0.35 - 0.50 | 0.35 - 0.60 |

Petroleum prices are from AAA [34] and electricity prices are from EIA [35]. DC fast charging pricing schemes display much heterogeneity and may not be as easily accounted as metered electricity prices. An Ad-Hoc Text Mining study performed on over 90,000 recorded PlugShare events from 2019 and 2021 found the mode of DC fast charging prices to be in the range of 0.3 and 0.4 USD per kWh [36]. Prices did not significantly correlate with local energy prices. In the same time period California residential electricity increased from 0.1995 USD per kWh to 0.2282 USD per kWh and transportation electricity increased from 0.0891 to 0.1179 USD per kWh. By comparison with 2024 electricity prices, one would expect prices in the range of 0.35 and 0.60 USD per kWh for DC fast charging in California and 0.35 to 0.5 in the US, ranges backed by informal reporting [37, 38]. Thus, expected energy costs per highway km traveled can be computed and are shown in Table 10.

Table 10: Expected energy costs per highway km traveled in US cents.

| Vehicle | Source | US Price | CA Price |
|----------|-------------------------|-------------|--------------|
| Prius | Petroleum | 4.00 | 5.70 |
| Golf | Petroleum | 5.47 | 7.78 |
| Pacifica | Petroleum | 8.97 | 12.77 |
| BEV | Residential Electricity | 2.82 | 5.48 |
| BEV | DC Fast Charging | 5.91 - 8.44 | 5.91 - 10.13 |

In the US, DC fast charging a BEV presents no appreciable economic benefit over fueling an efficient ICEV. In much of the US, home-charging a BEV provides cost savings for daily travel and the initial part of a long trip. This is not the case in California where residential electricity is, on average, nearly twice as expensive as in the US as a whole.

If BEVs are a worse option than efficient ICEVs for long trips on a time basis and no better on an energy cost basis this will make them less appealing to customers who value the ability to make long road trips. That customers seem to so highly value these uncommon events is a continuing source of frustration for BEV advocates. Negative perceptions of BEV long trip utility on consumer stated preference were found to be quite important in the late 2010s [39–42]. In the intervening time period BEV ranges and maximum charge rates have markedly increased. Nevertheless, negative perceptions related to long trip utility persist for purchasers [43–46] and BEV range is a significant factor in determining usage share of BEVs in multi-vehicle household fleets [47]. In the same time period, a massive build-out of DC charging infrastructure has taken place yet is not evident that the increased presence of DC charging infrastructure changes perceptions [48]. It is, sometimes, argued that the time added to a trip due to DC charging is not relevant as breaks are needed regardless. This argument has been used to support the idea that time parity is relatively attainable [49]. While possibly true for a subset of drivers, in order to take advantage of natural breaks to charge a vehicle, the driver must time these breaks to coincide with good charging intervals. The loss of optionality is an inconvenience in this case even if total trip time parity is achieved.

Most travel is not long trip travel. As shown in Figure 1, a BEV with 300 km of range can accomplish 80% of

US daily itineraries on a single charge. Fundamentally, home and work charging lead to operational costs that are often cheaper and rarely more expensive than petroleum. Similarly, home and work charging can lead to convenience benefits for BEVs as compared to ICEVs [50] as ICEVs require trips and trip deviations to reach supply stations. In theory, the trade-off of lower cost routine travel for higher cost long-distance travel is one which works in favor of BEVs. This is the logic which underpins the "charging pyramid" model which places long dwell charging events at its base and corridor DC fast charging events at its peak. This model is also, to some degree, self-reinforcing. If BEV drivers prefer AC charging, DC charging infrastructure will have limited revenue potential leading to lower network capacity. Lower network capacity, in turn, leads to the perception that the network is inadequate and should be avoided.

The charging pyramid implies a different way of thinking about the role of car travel as a subset an individual's travel needs. Personal travel is inherently multi-modal and, for many O/D arcs and many individuals, the cost differential between different modes is within the threshold of disambiguation. The strengths and weaknesses of BEVs as compared to ICEVs may shift more short trips away from local transit and towards cars while shifting more long trips away from cars to air travel and inter-city transit. BEVs will only be one part of future mobility, unable to meet transportation needs or environmental goals on their own. Investments in BEV corridor infrastructure should be considered alongside investments into other low carbon inter-city transit modes.

Conclusions

Personal vehicles play a major role in the transportation systems of all major developed economies globally. The role of personal vehicles is particularly pronounced in the US. As the transition to BEVs continues, BEVs will be pressed into more unsuitable roles and less forgiving drivers. Where BEVs provide advantages for routing travel where long dwells enable slow charging events to suffice, they are disadvantageous for long-trip travel. As many customers disproportionately weight long trips in purchase decisions, public money has been poured into subsidy programs to build out a national DC charging network in the US. This paper provides a framework for the quantitative analysis of the performance of said network from the point of view

of transportation accessibility. The framework proposed accounts for the effects of vehicle and behavioral parameters as well as the precise structure of the network. The current DC charging network in California is analyzed and shown to enable BEV travel reasonably well. Outcomes are found to be also dependent on vehicle range and maximum charge rate and individual risk attitude. If vehicles can charge at existing Tesla stations then the time difference between BEV and ICEV is found to be mostly due to unavoidable differences in range-addition rates. Where Tesla chargers are not accessible, drivers can expect substantial additional time due to route deviations and queuing. The structure of the Tesla network with relatively few stations and relatively many ports per station is particularly conducive to long-trip travel. Current market dynamics have pushed the non-Tesla networks towards the opposite structure. Public investment may be more productively used to encourage more Tesla-like networks. However, even with a substantially improved DC charging network, BEV travel will not achieve total-time parity with ICEVs unless charging speeds are massively increased. thus investments in enabling inter-city vehicle travel should be considered alongside investments in other low-carbon inter-city travel modes.

References

- [1] Susan Handy. "Is accessibility an idea whose time has finally come?" In: *Transportation Research Part D: Transport and Environment* 83 (2020), p. 102319. ISSN: 1361-9209. DOI: <https://doi.org/10.1016/j.trd.2020.102319>. URL: <https://www.sciencedirect.com/science/article/pii/S1361920919315925>.
- [2] Karst T. Geurs and Bert van Wee. "Accessibility evaluation of land-use and transport strategies: review and research directions". In: *Journal of Transport Geography* 12.2 (2004), pp. 127–140. ISSN: 0966-6923. DOI: <https://doi.org/10.1016/j.jtrangeo.2003.10.005>. URL: <https://www.sciencedirect.com/science/article/pii/S0966692303000607>.
- [3] Eric J. Miller. "Accessibility: measurement and application in transportation planning". In: *Transport Reviews* 38.5 (2018), pp. 551–555. DOI: 10.1080/01441647.2018.1492778.
- [4] Rafael Prieto-Curiel and Juan P. Ospina. "The ABC of mobility". In: *Environment International* 185 (2024), p. 108541. ISSN: 0160-4120. DOI: <https://doi.org/10.1016/j.envint.2024.108541>. URL: <https://www.sciencedirect.com/science/article/pii/S0160412024001272>.
- [5] Federal Highway Administration (FHA). *2017 National Household Travel Survey*. <https://nhts.ornl.gov/>. 2017.
- [6] Federal Highway Administration (FHWA). *2022 National Household Travel Survey*. <https://nhts.ornl.gov/>. 2022.
- [7] Tisura Gamage, Gil Tal, and Alan T. Jenn. "The costs and challenges of installing corridor DC Fast Chargers in California". In: *Case Studies on Transport Policy* 11 (2023), p. 100969. ISSN: 2213-624X. DOI: <https://doi.org/10.1016/j.cstp.2023.100969>.
- [8] Scott Hardman et al. "A review of consumer preferences of and interactions with electric vehicle charging infrastructure". In: *Transportation Research Part D: Transport and Environment* 62 (2018), pp. 508–523. ISSN: 1361-9209. DOI: <https://doi.org/10.1016/j.trd.2018.04.002>.
- [9] E. G. Ravenstein. "The Laws of Migration". In: *Journal of the Statistical Society of London* 48.2 (1885), pp. 167–235.
- [10] S L Handy and D A Niemeier. "Measuring Accessibility: An Exploration of Issues and Alternatives". In: *Environment and Planning A: Economy and Space* 29.7 (1997), pp. 1175–1194. DOI: 10.1068/a291175.
- [11] Mei-Po Kwan. "Space-Time and Integral Measures of Individual Accessibility: A Comparative Analysis Using a Point-Based Framework". In: *Geographical Analysis* 30 (July 1998), pp. 191–216. DOI: 10.1111/j.1538-4632.1998.tb00396.x.
- [12] Martin Wachs and T. Gordon Kumagai. "Physical accessibility as a social indicator". In: *Socio-Economic Planning Sciences* 7.5 (1973), pp. 437–456. URL: <https://EconPapers.repec.org/RePEc:eee:soceps:v:7:y:1973:i:5:p:437-456>.
- [13] Roger Vickerman. "Accessibility, Attraction, and Potential: A Review of Some Concepts and Their Use in Determining Mobility". In: *Environment and Planning A* 6.6 (1974), pp. 675–691. URL: <https://EconPapers.repec.org/RePEc:sae:envira:v:6:y:1974:i:6:p:675-691>.

- [14] Said M. Easa. "Urban Trip Distribution in Practice. I: Conventional Analysis". In: *Journal of Transportation Engineering* 119.6 (1993), pp. 793–815. DOI: 10.1061/(ASCE)0733-947X(1993)119:6(793).
- [15] Yi Hou et al. "Novel and Practical Method to Quantify the Quality of Mobility: Mobility Energy Productivity Metric". In: *Transportation Research Record* 2673.10 (2019), pp. 141–152. DOI: 10.1177/0361198119848705.
- [16] Samuel A. Stouffer. "Intervening Opportunities: A Theory Relating Mobility and Distance". In: *American Sociological Review* 5.6 (1940), pp. 845–867. ISSN: 00031224. URL: <http://www.jstor.org/stable/2084520> (visited on 03/31/2024).
- [17] Anastasios Noulas et al. "Correction: A Tale of Many Cities: Universal Patterns in Human Urban Mobility". In: *PLOS ONE* 7.9 (Sept. 2012), null. DOI: 10.1371/annotation/ca85bf7a-7922-47d5-8bfb-bcdf25af8c72. URL: <https://doi.org/10.1371/annotation/ca85bf7a-7922-47d5-8bfb-bcdf25af8c72>.
- [18] Woo-Sung Jung, Fengzhong Wang, and H. Eugene Stanley. "Gravity model in the Korean highway". In: *Europhysics Letters* 81.4 (2008), p. 48005. DOI: 10.1209/0295-5075/81/48005. URL: <https://dx.doi.org/10.1209/0295-5075/81/48005>.
- [19] Walter G. Hansen. "How Accessibility Shapes Land Use". In: *Journal of the American Institute of Planners* 25.2 (1959), pp. 73–76. DOI: 10.1080/01944365908978307.
- [20] Moshe E Ben-Akiva and Steven R Lerman. *Discrete choice analysis: theory and application to travel demand*. Vol. 9. MIT press, 1985.
- [21] Robert Cervero, Timothy Rood, and Bruce Appleyard. "Job accessibility as a performance indicator: An analysis of trends and their social policy implications in the San Francisco Bay Area". In: (1995).
- [22] Q Shen. "Location Characteristics of Inner-City Neighborhoods and Employment Accessibility of Low-Wage Workers". In: *Environment and Planning B: Planning and Design* 25.3 (1998), pp. 345–365. DOI: 10.1068/b250345.
- [23] T Karst and Jan R Ritsema van Eck. "Evaluation of Accessibility Impacts of Land-Use Scenarios: The Implications of Job Competition, Land-Use, and Infrastructure Developments for the Netherlands". In: *Environment and Planning B: Planning and Design* 30.1 (2003), pp. 69–87. DOI: 10.1068/b12940.
- [24] Susan L. Handy. "Understanding the Link Between Urban Form and Nonwork Travel Behavior". In: *Journal of Planning Education and Research* 15.3 (1996), pp. 183–198. DOI: 10.1177/0739456X9601500303.
- [25] Yanbo Ge and Don MacKenzie. "Charging behavior modeling of battery electric vehicle drivers on long-distance trips". In: *Transportation Research Part D: Transport and Environment* 113 (2022), p. 103490. ISSN: 1361-9209. DOI: <https://doi.org/10.1016/j.trd.2022.103490>. URL: <https://www.sciencedirect.com/science/article/pii/S1361920922003169>.
- [26] Francesco Marra et al. "Demand profile study of battery electric vehicle under different charging options". In: July 2012, pp. 1–7. ISBN: 978-1-4673-2727-5. DOI: 10.1109/PESGM.2012.6345063.
- [27] Alternative Fuels Data Center (AFDC). *Alternative fuels data center home page*. 2023. URL: <https://afdc.energy.gov/>.
- [28] David Rempel et al. "Reliability of Open Public Electric Vehicle Direct Current Fast Chargers". In: *Human Factors* 0.0 (0), p. 00187208231215242. DOI: 10.1177/00187208231215242.
- [29] Bingzheng Xu, Adam Wilkinson Davis, and Gil Tal. "Estimating the Total Number of Workplace and Public Electric Vehicle Chargers in California". In: *Transportation Research Record* 2675.12 (2021), pp. 759–770. DOI: 10.1177/03611981211031214.
- [30] Anant Atul Visaria et al. "User preferences for EV charging, pricing schemes, and charging infrastructure". In: *Transportation Research Part A: Policy and Practice* 165 (2022), pp. 120–143. ISSN: 0965-8564. DOI: <https://doi.org/10.1016/j.tra.2022.08.013>.
- [31] Brian J. Kozumplik. *Electric Vehicle Recharge Time, Reliability, and Interoperability*. 2022.

- [32] California Energy Commission (CEC). *California Retail Fuel Outlet Annual Reporting (CEC-A15) Results*. 2022. URL: <https://www.energy.ca.gov/data-reports/energy-almanac/transportation-energy/california-retail-fuel-outlet-annual-reporting>.
- [33] Energy Efficiency & Renewable Energy (EERE). *www.fueleconomy.gov the official U.S. government source for fuel economy information*. 2024. URL: <https://www.fueleconomy.gov/>.
- [34] American Automobile Association (AAA). *Gas Prices*. 2024. URL: <https://gasprices.aaa.com/>.
- [35] U.S. Energy Information Administration (EIA). *Electricity Data Browser*. 2024. URL: <https://www.eia.gov/electricity/data/browser/>.
- [36] David Trinkan et al. "Combining Ad Hoc Text Mining and Descriptive Analytics to Investigate Public EV Charging Prices in the United States". In: *Energies* 14.17 (2021). ISSN: 1996-1073. DOI: <https://doi.org/10.3390/en14175240>. URL: <https://www.mdpi.com/1996-1073/14/17/5240>.
- [37] DriveClean. *Electric Car Charging Overview*. 2024. URL: <https://driveclean.ca.gov/electric-car-charging/>.
- [38] Greg Sowder. *California Electrification Statistics*. 2024. URL: <https://qmerit.com/blog/california-electrification-statistics/>.
- [39] Stephen M. Skippon et al. "How experience of use influences mass-market drivers willingness to consider a battery electric vehicle: A randomised controlled trial". In: *Transportation Research Part A: Policy and Practice* 92 (2016), pp. 26–42. ISSN: 0965-8564. DOI: <https://doi.org/10.1016/j.tra.2016.06.034>.
- [40] Scott Hardman, Eric Shiu, and Robert Steinberger-Wilckens. "Comparing high-end and low-end early adopters of battery electric vehicles". In: *Transportation Research Part A: Policy and Practice* 88 (2016), pp. 40–57. ISSN: 0965-8564. DOI: <https://doi.org/10.1016/j.tra.2016.03.010>.
- [41] Thomas Franke et al. "Does this range suit me? Range satisfaction of battery electric vehicle users". In: *Applied Ergonomics* 65 (2017), pp. 191–199. ISSN: 0003-6870. DOI: <https://doi.org/10.1016/j.apergo.2017.06.013>. URL: <https://www.sciencedirect.com/science/article/pii/S0003687017301461>.
- [42] Franziska Schmalfuß, Kristin Mühl, and Josef F. Krems. "Direct experience with battery electric vehicles (BEVs) matters when evaluating vehicle attributes, attitude and purchase intention". In: *Transportation Research Part F: Traffic Psychology and Behaviour* 46 (2017), pp. 47–69. ISSN: 1369-8478. DOI: <https://doi.org/10.1016/j.trf.2017.01.004>. URL: <https://www.sciencedirect.com/science/article/pii/S1369847817300591>.
- [43] Furqan Bhat and Ashish Verma. "A Bibliometric Analysis and Review of Adoption Behaviour of Electric Vehicles". In: *Transportation in Developing Economies* 9.5 (2022). DOI: <https://doi.org/10.1007/s40890-022-00175-2>.
- [44] Geerte L. Paradies et al. "Falling short in 2030: Simulating battery-electric vehicle adoption behaviour in the Netherlands". In: *Energy Research & Social Science* 97 (2023), p. 102968. ISSN: 2214-6296. DOI: <https://doi.org/10.1016/j.erss.2023.102968>.
- [45] Chiara Corradi, Edgardo Sica, and Piergiuseppe Morone. "What drives electric vehicle adoption? Insights from a systematic review on European transport actors and behaviours". In: *Energy Research & Social Science* 95 (2023), p. 102908. ISSN: 2214-6296. DOI: <https://doi.org/10.1016/j.erss.2022.102908>. URL: <https://www.sciencedirect.com/science/article/pii/S221462962200411X>.
- [46] Thara Philip, Jake Whitehead, and Carlo G. Prato. "Adoption of electric vehicles in a laggard, car-dependent nation: Investigating the potential influence of V2G and broader energy benefits on adoption". In: *Transportation Research Part A: Policy and Practice* 167 (2023), p. 103555. ISSN: 0965-8564. DOI: <https://doi.org/10.1016/j.tra.2022.11.015>. URL: <https://www.sciencedirect.com/science/article/pii/S0965856422002981>.
- [47] Debapriya Chakraborty, Scott Hardman, and Gil Tal. "Integrating plug-in electric vehicles (PEVs) into household fleets- factors influencing miles traveled by PEV owners in California". In: *Travel Behaviour and Society* 26 (2022), pp. 67–83. ISSN: 2214-367X. DOI: <https://doi.org/10.1016/j.tbs.2021.09.004>. URL: <https://www.sciencedirect.com/science/article/pii/S2214367X21000867>.

- [48] Kelly Hoogland et al. “Understanding the Impact of Public Charging Infrastructure on the Consideration to Purchase an Electric Vehicle in California”. In: *Research Square Preprint* (2024). DOI: <https://doi.org/10.21203/rs.3.rs-2561573/v1>.
- [49] James Dixon et al. “On the ease of being green: An investigation of the inconvenience of electric vehicle charging”. In: *Applied Energy* 258 (2020), p. 114090. ISSN: 0306-2619. DOI: <https://doi.org/10.1016/j.apenergy.2019.114090>.
- [50] Aaron I. Rabinowitz et al. “Assessment of Factors in the Reduction of BEV Operational Inconvenience”. In: *IEEE Access* 11 (2023), pp. 30486–30497. DOI: [10.1109/ACCESS.2023.3255103](https://doi.org/10.1109/ACCESS.2023.3255103).

Appendix

DC Charger Network Details

Network characteristics for DC charging networks in California are shown in Figure 13 and in Table 11. Data pulled from AFDC in May 2024.

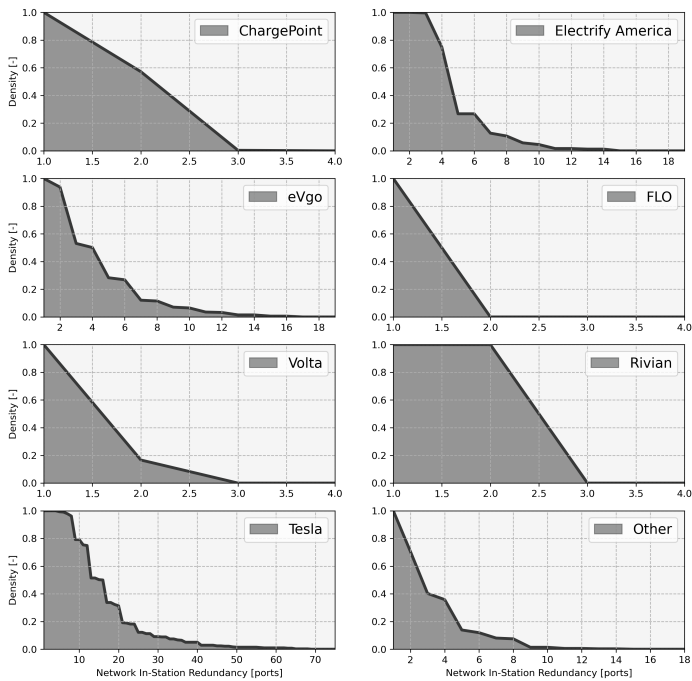


Figure 13: In-station redundancy for DC Charging networks in California

Table 11: Summary statistics for California DC charging networks from AFDC

| Network | Chargers | Stations | Chargers per Station |
|---------------------|----------|----------|----------------------|
| Non-Networked | 288 | 51 | 5.6 |
| Tesla | 2753 | 156 | 17.6 |
| Electrify America | 526 | 77 | 6.8 |
| EV Connect | 59 | 19 | 3.1 |
| ChargePoint Network | 186 | 79 | 2.4 |
| Volta | 2 | 2 | 1.0 |
| EVCS | 41 | 11 | 3.7 |
| SHELL_RECHARGE | 39 | 11 | 3.5 |
| EVGATEWAY | 21 | 5 | 4.2 |
| eVgo Network | 332 | 63 | 5.3 |
| BP_PULSE | 3 | 2 | 1.5 |
| POWERFLEX | 12 | 3 | 4.0 |
| FLO | 1 | 1 | 1.0 |
| EV RANGE | 11 | 3 | 3.7 |
| RIVIAN_ADVENTURE | 14 | 7 | 2.0 |
| CIRCLE_K | 16 | 3 | 5.3 |
| CHARGENET | 7 | 1 | 7.0 |
| Blink Network | 2 | 2 | 1.0 |
| NOODOE | 2 | 1 | 2.0 |
| LOOP | 6 | 2 | 3.0 |
| 7CHARGE | 4 | 1 | 4.0 |

Network characteristics for DC charging networks in California, counting only corridor chargers, are shown in Figure 13 and in Table 11. Data pulled from AFDC in May 2024.

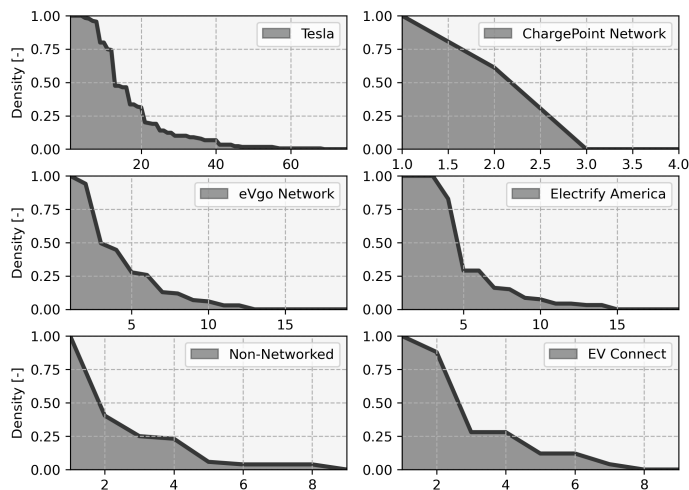


Figure 14: In-station redundancy for DC Charging networks in California

Table 12: Summary statistics for California DC charging networks from AFDC (corridor stations)

| Network | Chargers | Stations | Chargers per Station |
|---------------------|----------|----------|----------------------|
| Non-Networked | 274 | 50 | 5.5 |
| Tesla | 2745 | 155 | 17.7 |
| Electrify America | 518 | 76 | 6.8 |
| EV Connect | 58 | 18 | 3.2 |
| ChargePoint Network | 184 | 78 | 2.4 |
| Volta | 1 | 1 | 1.0 |
| EVCS | 35 | 10 | 3.5 |
| SHELL_RECHARGE | 37 | 10 | 3.7 |
| EVGATEWAY | 19 | 4 | 4.8 |
| eVgo Network | 329 | 62 | 5.3 |
| BP_PULSE | 1 | 1 | 1.0 |
| POWERFLEX | 10 | 2 | 5.0 |
| EV RANGE | 5 | 2 | 2.5 |
| RIVIAN_ADVENTURE | 12 | 6 | 2.0 |
| CIRCLE_K | 12 | 2 | 6.0 |
| Blink Network | 1 | 1 | 1.0 |
| LOOP | 2 | 1 | 2.0 |

Regression Details

Details of linear regression on random experiment results are displayed in the following tables. Tables 13 and 14 concern the combined network, Tables 15 and 16 concern the Tesla network, and Tables 17 and ?? concern the non-Tesla network.

Table 13: Combined Network Linear Regression Analysis ANOVA

| R | R-Squared | Adjusted R-Squared | Std. Error |
|----------|----------------|--------------------|--------------|
| 0.926 | 0.858 | 0.853 | 0.000 |
| Category | Sum of Squares | DOF | Mean Squares |
| Model | 28.706 | 15 | 1.914 |
| Error | 4.754 | 484 | 0.010 |
| Total | 33.460 | 499 | 0.067 |
| <i>F</i> | | <i>P(> F)</i> | |
| 194.848 | | 0.000 | |

Table 14: Combined Network Linear Regression Analysis Significant Coefficients ($\alpha = 0.5$)

| Parameter | Coefficient | P-Value |
|----------------------|-------------|---------|
| Intercept | 7.121 | 0.000 |
| power | -1.009 | 0.000 |
| capacity | -1.031 | 0.000 |
| reliability | -0.227 | 0.040 |
| capacity:power | 0.984 | 0.000 |
| capacity:reliability | 0.422 | 0.036 |

Table 15: Tesla Network Linear Regression Analysis ANOVA

| R | R-Squared | Adjusted R-Squared | Std. Error |
|----------|----------------|--------------------|--------------|
| 0.926 | 0.857 | 0.852 | 0.000 |
| Category | Sum of Squares | DOF | Mean Squares |
| Model | 27.188 | 15 | 1.813 |
| Error | 4.541 | 480 | 0.009 |
| Total | 31.728 | 495 | 0.064 |
| <i>F</i> | | <i>P(> F)</i> | |
| 191.609 | | 0.000 | |

Table 16: Tesla Network Linear Regression Analysis Significant Coefficients ($\alpha = 0.5$)

| Parameter | Coefficient | P-Value |
|------------------------------|-------------|---------|
| Intercept | 7.218 | 0.000 |
| power | -1.099 | 0.000 |
| capacity | -1.179 | 0.000 |
| reliability | -0.220 | 0.047 |
| capacity:power | 1.130 | 0.000 |
| power:risk_attitude | 0.479 | 0.035 |
| capacity:reliability | 0.481 | 0.016 |
| capacity:power:risk_attitude | -0.879 | 0.028 |

Table 17: Non-Tesla Network Linear Regression Analysis ANOVA

| R | R-Squared | Adjusted R-Squared | Std. Error |
|----------|----------------|--------------------|--------------|
| 0.866 | 0.750 | 0.742 | 0.000 |
| Category | Sum of Squares | DOF | Mean Squares |
| Model | 72.583 | 15 | 4.839 |
| Error | 24.215 | 484 | 0.050 |
| Total | 96.798 | 499 | 0.194 |
| <i>F</i> | | <i>P(> F)</i> | |
| 96.720 | | 0.000 | |

Table 18: Non-Tesla Network Linear Regression Analysis Coefficients

| Parameter | Coefficient | P-Value |
|---------------------------------|-------------|---------|
| Intercept | 7.095 | 0.000 |
| power | -1.373 | 0.000 |
| capacity | -1.130 | 0.000 |
| risk_attitude | 0.954 | 0.001 |
| capacity:power | 1.505 | 0.004 |
| power:risk_attitude | 1.429 | 0.006 |
| capacity:power:risk_attitude | -1.915 | 0.037 |
| power:reliability:risk_attitude | -1.744 | 0.047 |