

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

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## Abstract

I'll write this later - could maybe use some help

## Introduction

Developed economies require the continuous flow of persons and goods in astounding volumes. This dependency justifies investment in the development and maintenance of a transportation sector which is, in its own right, economically significant. It is intuitive that the function of all transportation systems is to enable the actualization of latent activity. It follows that transportation systems should be assessed on that basis and that well designed systems are those which efficiently enable latent flows. Encompassing this paradigm is the field of transportation accessibility. Transportation accessibility is, in short, the study of the related phenomena of how structural and individual factors create latent flows and how transportation systems accommodate them. More efficient built environments minimize the edge traversal costs which exist between demand and supply nodes. More efficient transportation allows for individuals and businesses to access more opportunities for the same cost. In the long term, co-optimization of land-use and transportation is vital to maximizing accessibility.

Transportation accessibility is, inherently, 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. 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 distribution and demand for amenities such as jobs and services at different locations. Transportation systems determine the edge traversal costs such as travel time, effort, and price which impede flows [2]. Temporal availability of opportunities and transportation modes restrict the utility of opportunities and transportation modes. Finally, individual characteristics such as age, income, and education predict attraction to opportunities and transportation modes [3] effecting their utility.

The US and similar western nations are unusually car-centric by global standards [4] for personal transportation. The access provided by a road transportation system for Battery Electric Vehicles (BEVs) is different than that for Internal Combustion Engine Vehicles (ICEVs) 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 vehicle ranges and the extensive availability of fueling stations in contrast to DC charging 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 concerns about 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.

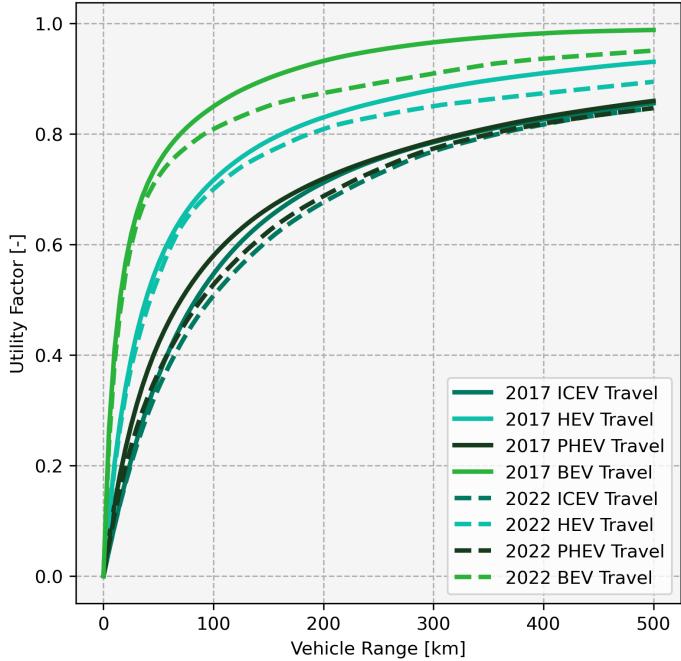


Figure 1: Individual vehicle routine travel utility factors as a function of range by powertrain type for National Highway Transportation Survey (NHTS) 2017 and 2022 editions.

Disparities between the fueling and DC charging networks result from differences in their 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, often at private chargers [8]. 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 risk attitudes.

This study introduces a novel methodology to assess

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 20<sup>th</sup> 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. The field of transportation accessibility uses this framework to study regional efficiency considering both voltage and resistance 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 voltage factors such as land use and temporal availability, resistance 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 the selection of opportunities. 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 edge traversal cost for O/D pairs within the isocost region. These methods have been used widely [14] due to their 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 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, altogether, obvious what the threshold of disambiguation is for a given individual. Thus, researchers have proposed to use Discrete Choice Modeling [20] to explain revealed choices wherein ease-of-access is one of several possible factors in determining the utility of a given opportunity for an individual [21–23].

There are, thus, a variety of methods which can be used to quantify the accessibility of a given region with varying computational and data requirements. The relationship between land-use, transportation, and demography is circular rather than linear. Which method one chooses for an analysis reflects the scope and purpose of that analysis. Definition of scope can be difficult and can lead to self-defeating policies [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 valid for all travel scales. 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

For region  $R$  with a set of  $N$  selected locations  $O = \{O_1, O_2, \dots, O_N\}$  and a corresponding set of importance weights  $W = \{W_0, W_1, \dots, W_N\}$ , the accessibility of the region is quantified by the metric  $A_R$  as

$$A_R = \frac{1}{N^2} \sum_{i=0}^N \sum_{j=0}^N \frac{C W_i W_j}{Z_{ij} W} \quad (1)$$

where  $Z_{ij}$  is the cost of the optimal path from  $O_i$  to  $O_j$ ,  $W = \sum_{i=0}^N W_i$ , and  $C$  is a constant. The location specific regional accessibility  $A_{R,i}$  can be computed for region  $R$  and origin  $i$  as

$$A_{R,i} = \frac{1}{N} \sum_{j=0}^N \frac{C W_i W_j}{Z_{ij} W} \quad (2)$$

for any origin  $O_i \in O$ .  $A_R$  is a weighted mean of flows resulting from the potential interactions between important locations in a region and the difficulty to traverse the arcs between them. Generally,  $W$  will be the set of population masses for each location  $M = \{M_0, M_1, \dots, M_N\}$ . A physical meaning for  $A_R$  may be attained if the units of  $W$  are [persons] and the units of  $Z$  are [hours]. In this case the units of  $A_R$  would be [persons-hours<sup>-1</sup>] reflecting the average long-trip flow in the region. It is expected that  $C$  will be dimensionless and fractional. In essence, a given location might be presumed to attract a small portion of the populations of other cities on any given day in proportion to its population, economy, or other factors. However, the attraction of remaining in one's current location will be quite strong, limiting potential travel. A strongly connected region will have higher average accessibility than a weakly integrated one. All else being equal, regions which are more populated/productive, more compact, and enjoy better transportation networks will experience higher average flow. Regional Accessibility refers to the all-pairs average as in (1) and Specific Regional Accessibility refers to the single-origin average as in (2).

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

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

where  $W = \{W_0, W_1, \dots, W_N\}$  is the set of importance weights assigned to each origin and destination. Specific

Regional Impedance is defined as

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

for a single origin. The Regional Impedance is the weighted average cost of traversing an arc between important locations in a region. Impedance is strictly a measure of travel costs imposed by the transportation system and is usage rate independent. For the purposes of computing impedance it is beneficial to utilize relative weights ( $W_i = NM_i / \sum_{j=0}^N M_j \forall M_i \in M$ ). For a region  $R$  with population masses  $M$  and arc traversal costs  $Z$ , if each value in  $M$  was doubled and nothing else changed  $A_R$  would increase and  $Z_R$  would remain the same. Any increase to arc costs  $Z$  would decrease  $A_R$  and increase  $Z_R$ .

## 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 avoided where possible. 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, and do actually, 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  $D \subseteq V$  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,  $S_0$  is the initial values of the states,  $U$  is a control (route) between  $i$  and  $j$ ,  $\bar{U}_{i,j}$  is the set of possible routes between  $i$  and  $j$ ,  $\Phi$  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 a the state vector at any node and time-step can be computed from a histogram of the values. States can be

changed at nodes and edges. Routes are considered feasible if state expectations remain within set bounds. Comparison between routes is performed using cost expectation. Routing depends on vehicular, infrastructural, and individual models.

### 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 1.

Table 1: Vehicle Parameters for Routing

Parameter	Description	Unit
ESS Capacity	Accessible energy storage capacity	[kWh]
Energy Consumption	Energy required to move the vehicle	[kJ/km]
Supply Rate	ESS maximum energy addition rate	[kW]
Supply Limits	SOC bounds for supply	[-]

### Supply Infrastructure Network Model

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 rather than the industry definition which covers stations operated by a single Charge Point Operator (CPO). 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". Network redundancy also varies by location with "thinner" and "thicker" coverage areas.

Vehicle optimal routing serves to find the lowest-cost-path between two points on a road atlas. A road atlas is a

graph with a large number of nodes and a low edge-to-node ratio. When considering a multi-leg itinerary, such as when solving the Traveling Salesman Problem or Vehicle Routing Problem, the atlas need not be stored in entirety. 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. 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  $\hat{E} = \{P_{ij} \forall (i, j) \in \hat{E}\}$  is the set of shortest-paths between all nodes in  $\hat{V}$ . An example of a reduced subgraph is shown in Figure 2.

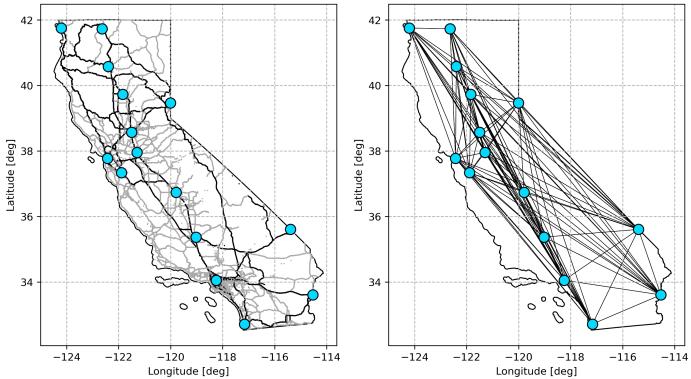


Figure 2: Example original graph (left) containing locations and an atlas and reduced subgraph (right) containing locations and arcs.

For a given vehicle type, the Supply Network Graph (SNG) is the reduced subgraph containing the trip origin, trip destination, and all supply stations reasonably likely to be utilized. In-station redundancy for a SNG is a nodal parameter. In-station redundancy  $\xi_{is}$  for any node  $v \in V$  on SNG  $G = \{V, E\}$  is the number of ports at node  $v$ . Between-station redundancy  $\xi_{bs}$  for an SNG is a clique parameter. Between-station redundancy for any clique  $C \subseteq V$  on SNG  $G = \{V, E\}$  is the sum of the ports at nodes  $v \in C$ . A more meaningful result for  $\xi_{bs}$  may be returned by limiting the cost of edges considered. For example,  $\xi'_{bs}$  may be computed for  $G' = \{V, E'\}$  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.

## Supply Station Network Model

Supply station characteristics significantly impact the expected cost of utilizing a given station. Supply stations are defined by number of ports, reliability of ports, maximum supply rate of ports, durations of supply events, and arrivals ratio. 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 2.

Table 2: Supply Station Parameters for Routing

Parameter	Description	Unit
Arrivals Ratio	Arrival rate at station per port and unit of time	[cars/port/hour]
Supply Rate	Maximum rate of energy supply	[kW]
Supply Energy	Expected energy supplied to vehicles	[kWh]
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) [25], and information on chargers is taken from [26]. Arrivals ratio reflects the scale of vehicle arrivals at the station compared to the ability of the station to process vehicles. Arrivals ratio is defined as

$$\rho = \frac{\lambda}{\mu s} \quad (10)$$

where  $\lambda$  is the number of vehicle arrivals in a given time period,  $\mu$  is the expected number of vehicles that can be served by a port in the same time period, and  $s$  is the number of ports. As an example, if a station of 5 ports supplies a mean of 36 kWh per vehicle at a mean rate of 80 kW with 3 minutes between events and receives 10 vehicles

per hour then  $\rho = 1$  for the station. Unfortunately, with the exception of the number of ports and the maximum supply rate, little of this information is available before arrival. As a result, arrivals ratio, supply energy, and reliability must be estimated. To reflect this uncertainty, in this study distributions are used for arrivals ratio and supply energy. The delays which result from DC charging station congestion are modeled as M/M/s queues and are demonstrated in 3.

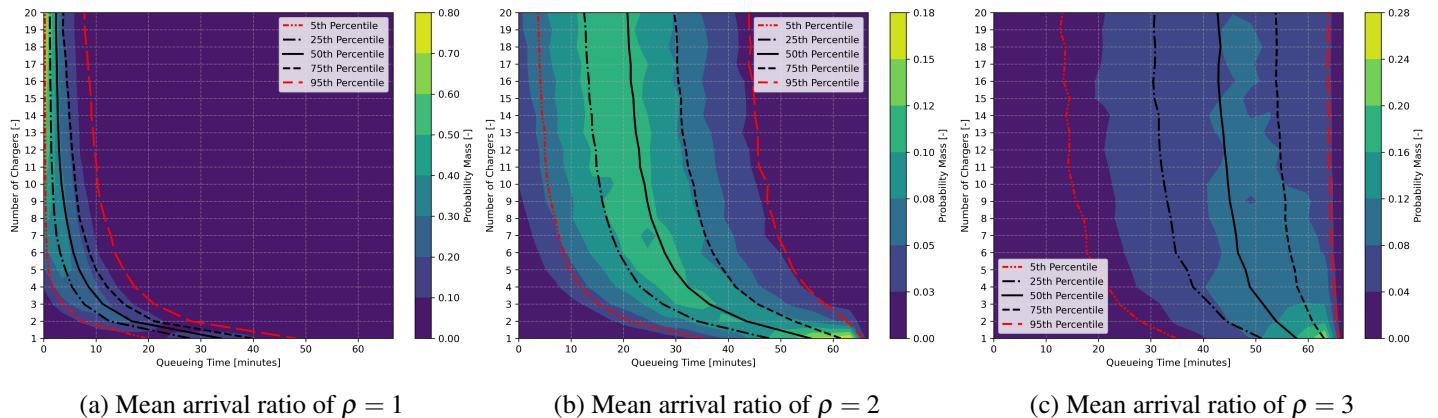


Figure 3: Effects of supply station saturation on expected queue times by in-station redundancy. Contours of PDFs of expected queue times are computed for stations with between 1 and 20 chargers with different arrival ratios. Arrival ratio is defined in equation (10). Higher arrival ratios saturate stations but stations with greater redundancy can better handle high demand per charger.

As can be seen in Figure 3, arrivals ratio and in-station redundancy each have a major impact on expected delay time. When  $\rho \leq 1$  a decently sized station should be able to accommodate demand with minimal delay. As arrivals increase congestion becomes unavoidable and even large stations can become saturated. Unreliability of equipment can, effectively, reduce in-station redundancy making queues more likely. Without better information, a driver will have to make an educated guess as to how busy a station is likely to be and how many of its listed chargers will be functional. Getting either factor wrong could have serious consequences if the driver does not have the option to easily reach a different station. Even if another station is reachable the driver is unlikely to have better information for that station.

## Drivers

Given the same underlying circumstances, different drivers will evaluate route costs differently. In a basic sense, drivers

will weight several factors such as time, money, distance, and complexity differently. 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

$$S(D, p_0, p_1) = \frac{1}{p_1 - p_0} \int_{p_0}^{p_1} Q(D, \alpha) d\alpha \quad (11)$$

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 3.

Table 3: Supply Station Parameters for Routing

Parameter	Description	Unit
Route Cost Weights $W$	Set of multipliers for route costs to be used in computation of weighted sum	[-]
Probability Range $(p_0, p_1)$	Range of probabilities for superquantile function	[-]

Where a quantity is to be maximized the Probability Range parameters can be adjusted as  $p'_0 = 1 - p_1$  and  $p'_1 = 1 - p_0$ . This is particularly applicable when evaluating states such as SOC where a cautious driver will underestimate the quantity and an aggressive driver will overestimate the quantity. 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.

## Randomly Generated Example

The methods and metrics defined above are demonstrated using a vehicle on a randomly generated SNG. In this example, a SNG containing 15 locations and 85 stations distributed across a 1000 km square is generated with randomized node locations. Each location has a population of one million persons. Each station contains between 1 and 5 ports. Edges exist between all nodes and are assigned Pythagorean distances. All edges are assumed to be traversed at 105 kmh. The supply stations deliver an average of 45 kWh per vehicle at an average rate of 80 kW. The arrivals ratio is sampled from  $N(1, 0.25)$ . The vehicle used has a relatively low range of 262 km. Two drivers are modeled. A cautious driver is modeled using  $(p_0 = 0.9, p_1 = 1.0)$  and an aggressive driver is modeled using  $(p_0 = 0, p_1 = 0.1)$ . Additionally port reliability at the stations is modeled as 75% in a low reliability scenario and 95% in a high reliability scenario.

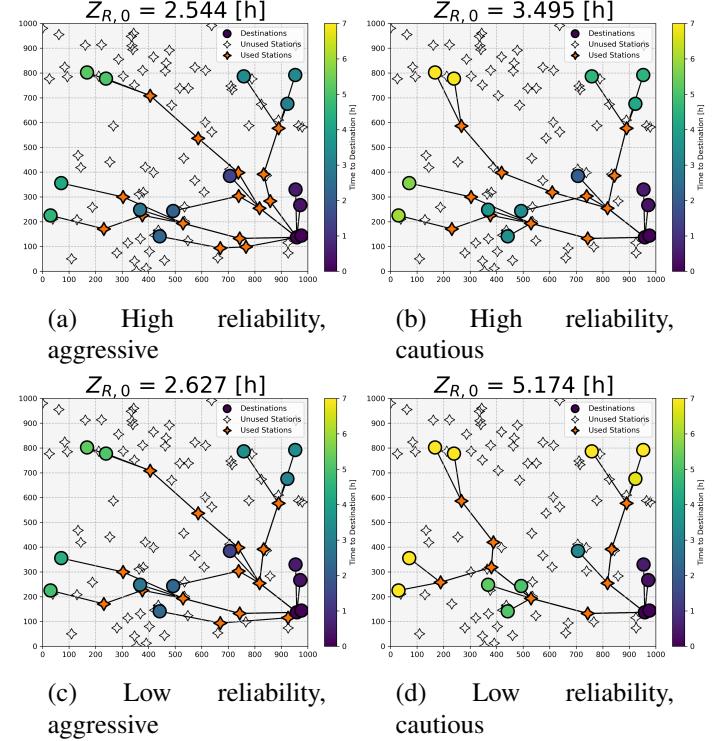


Figure 4: Perceived Specific Regional Impedance by risk attitude and port reliability.

The scenarios presented in Figure 4 consider Specific Regional Impedance as perceived by the driver. The aggressive driver is only concerned with the best 10% of outcomes while the cautious driver is only concerned with the worst 10% of outcomes. The differences in perceived costs-to-travel are quite stark between the aggressive and cautious driver in both cases but this difference is larger when reliability is low. Drivers may operate off of perception but a regional transportation authority may be more concerned with mean outcomes. The neutral expectations ( $p_0 = 0, p_1 = 1$ ) of the routes taken by the drivers are shown in Figure 5.

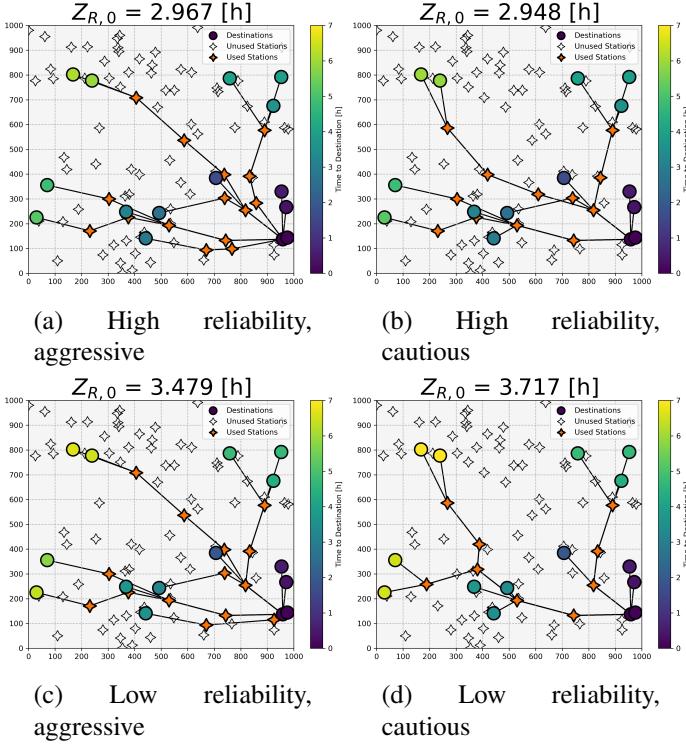


Figure 5: Neutral expectations of Specific Regional Impedance by risk attitude and port reliability.

The neutral expectations tell a different story. For the different levels of reliability, neutral expectations of impedance are similar for the routes selected by the aggressive and cautious drivers. The differences between biased and neutral perception are easy to understand. Both drivers selected routes based on a subset of the information and these routes are non-optimal when all information is considered. Drivers may adjust their priors over time but policy can only control the fundamentals. Thus, it is recommended to consider bias in route planning but neutral expectation in evaluation.

The composition of the routes taken by the drivers in the randomly generated example demonstrate an interesting dynamic as seen in Table 4. As in-station redundancy is highly important in determining expected queuing times cautious drivers opt, increasingly for stations with higher in-station redundancy at the cost of taking less direct routes.

Table 4: Average route distances and chargers per station utilized for example scenarios

Reliability	Risk-Attitude	Chargers per Station Utilized
High	Aggressive	3.774
High	Cautious	4.258
Low	Aggressive	4.032
Low	Cautious	4.471

## 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 contains major population centers distributed across the state. Major road transportation corridors form connections between the state's population centers and with population centers in adjacent states. This case study concerns the long-trip accessibility of California's road transportation network. For the purposes of analysis, 15 important cities in California and adjacent states were selected. Non-California locations are represented by the most-likely departure locations at the California state line. Because the state-line locations are midpoints the required arrival SOC at these points is set at 50% where it is set at 20% for all others. These locations are enumerated in Table 5.

Table 5: Locations Considered for Long Trip Accessibility

Index	Location	Approximate Metropolitan Population
0	Crescent City	6,000
1	Yreka	8,000
2	Redding	180,000
3	Chico	212,000
4	Reno (State Line)	491,000
5	Sacramento	2,397,000
6	Stockton	779,000
7	San Francisco	4,620,000
8	San Jose	2,001,000
9	Fresno	1,009,000
10	Las Vegas (State Line)	2,953,000
11	Bakersfield	909,000
12	Los Angeles	12,488,000
13	Phoenix (State Line)	4,948,000
14	San Diego	3,276,000

For long trips, BEVs will rely on DC charging stations. The locations of all DC charging stations in California are available from AFDC [25]. 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.

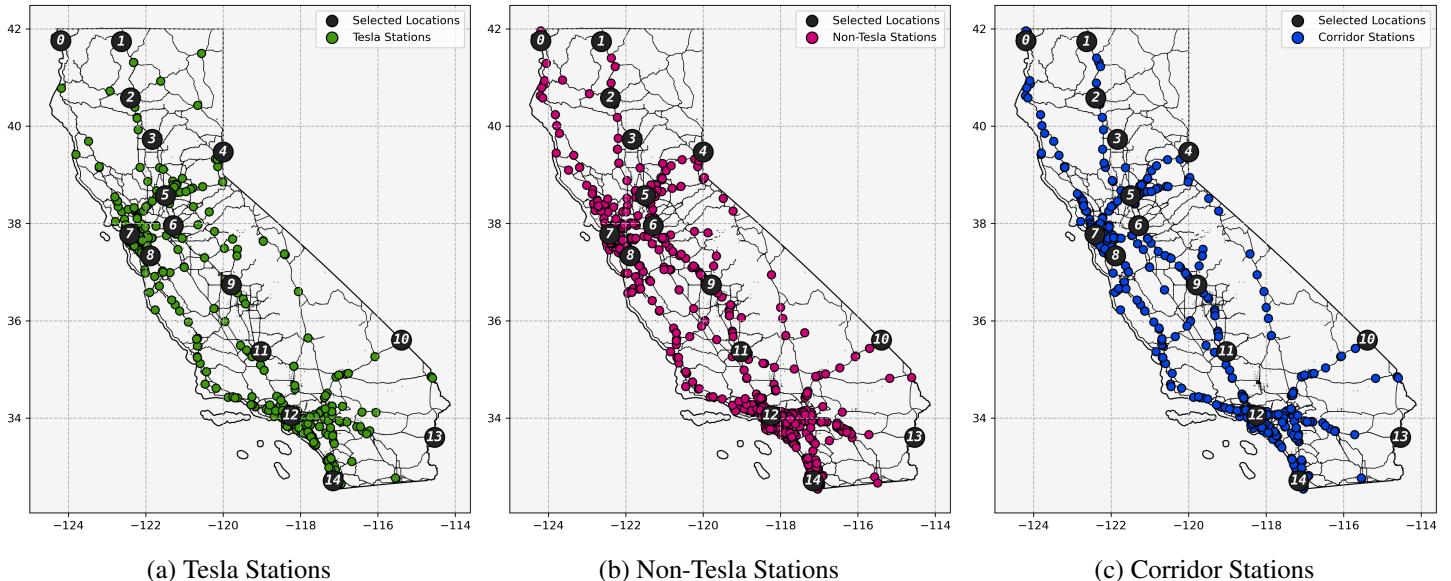


Figure 6: California DC charging stations from AFDC (May 2024)

The proprietary and non-proprietary networks in California are neither equivalent nor isomorphic. 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 combination CCS/ChaDeMo chargers as defined by SAE J1772 [27] which reflect the ports on the overwhelming number of non-Tesla BEVs. By contrast, Tesla chargers and vehicles use the NACS standard as defined by SAE J3400 [28]. The Tesla and non-Tesla systems are increasingly interoperable with the aid of adapters but should be considered separately in the present. Tesla drivers use Tesla DC chargers almost exclusively [29]. 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 higher maximum charging rates and more reliable chargers [26, 30]. 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.

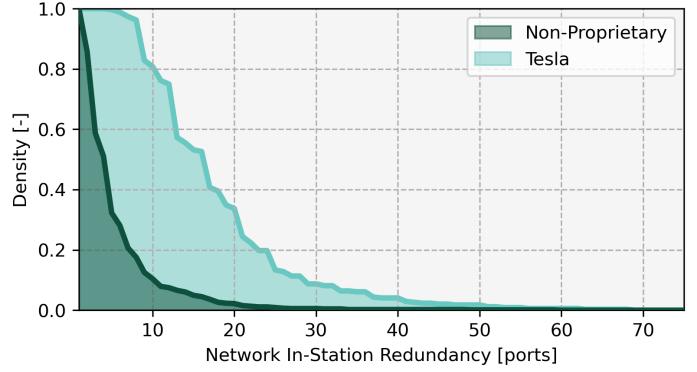


Figure 7: Survival functions for in-station redundancy for Tesla and other DC charger networks in California

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 14 and 15 in the Appendix. Summary statistics for DC charging networks in California can be found in Tables 11 and 12 in 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 [31] 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. ESS capacity

numbers are pulled from manufacturer websites and energy consumption rates are computed from EPA highway fuel economy ratings [32]. Although substantially less efficient than equivalent BEVs the comparatively high specific energy of liquid petroleum allows for ICEVs to have higher maximum 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 and corresponding Regional Impedance values are shown in Table 6.

Table 6: 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]
	California Regional Impedance	4.131 [hours]
2024 Volkswagen Golf	ESS Capacity	445 [kWh]
	Energy Consumption	1,839 [kJ/km]
	Full-Tank Range	871 [km]
	California Regional Impedance	4.151 [hours]
2024 Chrysler Pacifica	ESS Capacity	640 [kWh]
	Energy Consumption	3,015 [kJ/kM]
	Full-Tank Range	764 [km]
	California Regional Impedance	4.161 [hours]

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. The Prius, Golf, and Pacifica required averages of 0.43, 0.31, and 0.19 supply stops per route respectively.

500 random scenarios were generated by uniform random sampling of the parameters listed in Table 7 and run on three SNGs as described in 8. 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 [32]. Highway operation is assumed herein due to the focus on long trips. Thus BEV full-charge ranges will be between 237 and 711 km. Vehicles are assumed to fast charge only up to 80% SOC in order to remain in the constant current range. When charging, sampled BEVs add highway range at a rate between 4.9 and 19.7 km per minute. Risk attitude was modeled as in (11) with the range centered around the mean parameter  $\bar{p}$  where  $p_0 = \bar{p} - .1$  and  $p_1 = \bar{p} + .1$ .

Table 7: 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]
Station Arrival Ratio Mean	[1, 3]

Table 8: 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 a population weighted Regional Impedance as in (3). Impedance was selected as the metric of evaluation rather than accessibility

as travel demand for each arc was the same for all cases. Linear regression was performed on the results of the random experiment. Using as output, the neutral expectation of road-trip accessibility for each of the 500 randomly sampled vehicles on each of the SNGs. Significant parameters from the regression are shown in Figure 8.

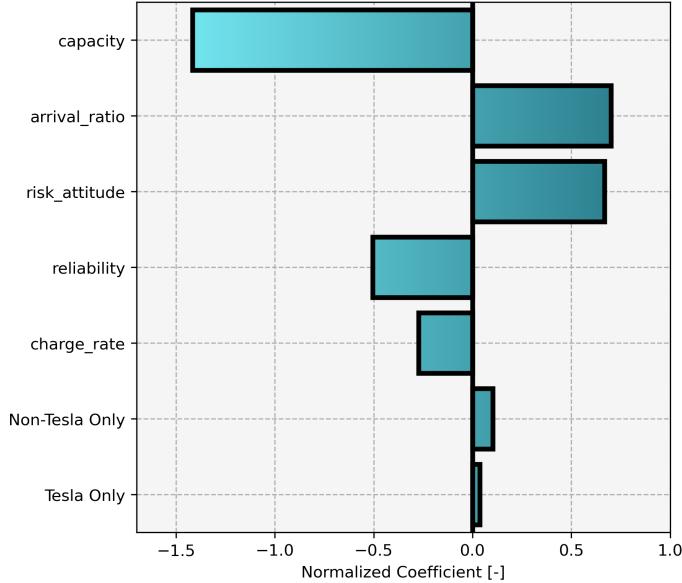


Figure 8: Coefficients for significant parameters from linear regression

Regression details are provided in Tables 13 and 14 in the Appendix. The regression analysis shows that vehicular, infrastructural, and behavioral parameters have significant impacts on road-trip accessibility. The vehicular parameters of capacity and charge rate have the predictable effect of reducing expected travel times. Capacity being the more important parameter is explicable as higher capacity vehicles offer the ability to stop less frequently. Saving an entire charging event can be very impactful in a region the size of California. Among the infrastructure parameters, higher reliability contributed to lower travel times where higher arrival ratios contributed to higher travel times. Both reliability and arrival ratio primarily effect queuing times as, even with 50% equipment reliability, most stations have sufficient redundancy to guarantee at least one operational charger. The range of arrivals ratios considered goes from normal to swamped and long queues can be expected for high arrival ratios even at high redundancy stations. Risk attitude was also significant in determining outcomes as those drivers with more cautious risk attitudes will tend

to maintain higher SOC and utilize more reliable and redundant routes. Finally, access to the entire network is better than restriction to just part of it but being restricted to only Tesla stations should be slightly less damaging than access to only non-Tesla stations. Boxplots of expected travel times are shown in Figure 9.

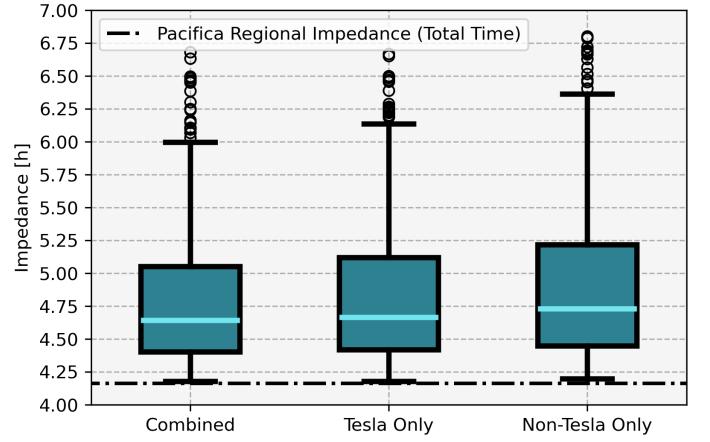


Figure 9: Boxplots of experiment outputs by SNG

While the differences between the BEVs on the basis of SNG access are observed to be slight, the differences between the means of each and the worst of the ICEVs is quite large. The difference is roughly 45 minutes much of which can be explained by the shorter ranges and longer supply times inherent to the BEVs. In the best of circumstances, BEVs can reach near parity with ICEVs. However, BEVs impedance will, nearly always, be substantially higher than ICEV impedance due to the necessity of charging events. Some will argue that this difference is unimportant as BEV drivers can charge their vehicles while stopping for meals or during other natural breaks. This logic has been used to show that BEVs may approach convenience parity with ICEVs in reasonable circumstances [33]. However, where such long breaks are optional for ICEV drivers, they are mandatory for BEV drivers and must be taken at specific points throughout the trip to coincide with charging. This loss of optionality must be accounted an inconvenience even for drivers who accustomed to long breaks.

Most of the difference in impedance is due to charging and queuing times while only a small part is due to route alterations. Isolating the driving times by subtracting supply and setup times, the differences between BEVs and ICEVs SNGs are substantially smaller than those in total trip time

as shown in Figure 10. It should, however, be noted that there is a long tail on the driving time distributions due to the occasional need to take a significantly altered route to confidently reach a remote destination.

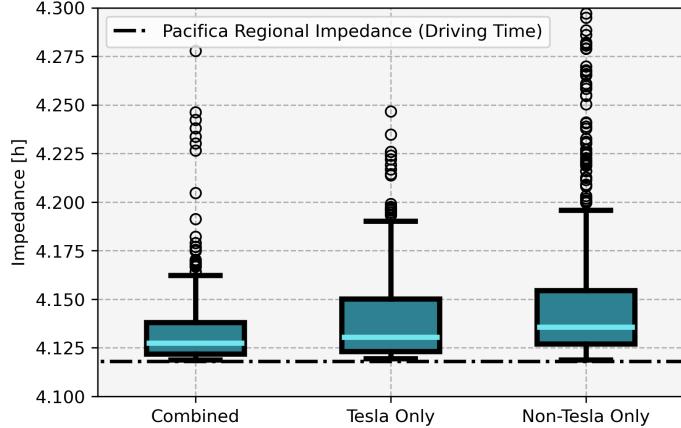


Figure 10: Boxplots of experiment outputs by SNG (driving time only)

Different parts of the state will have different experiences. Residents of large population centers which are proximate to other large population centers will expect to have lower travel needs than those in more remote areas. In general, the impedance disparities associated with different vehicular, infrastructural, and behavioral characteristics will also scale with impedance. As California is a large state with a diversity of land use and road infrastructure volume, there is a pronounced difference in Specific Regional Impedance as shown in Figure 11.

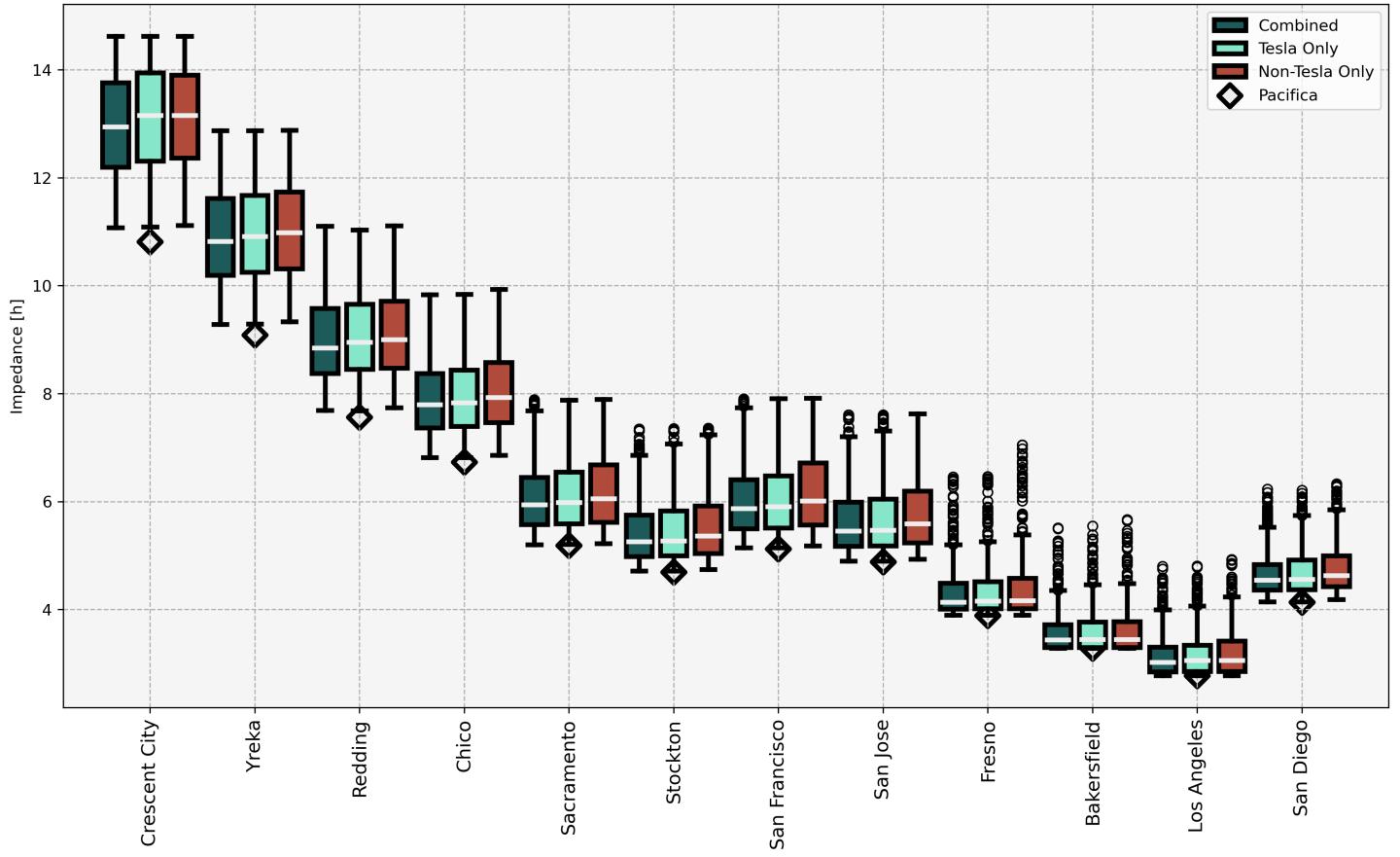


Figure 11: Boxplots of experiment outputs on combined SNG for each origin in California

## Discussion

The optimal routes generated in this study only selected corridor chargers. Some insight into the utility provided by each network can be gained by looking into utilization rates for networks and stations when using the combined SNG. Ratio of stations utilized at least once to total corridor stations in the combined SNG for each network is shown in Figure 12. Log of utilization (number of times utilized in random experiment) for corridor stations in the combined SNG is displayed in Figure 13.

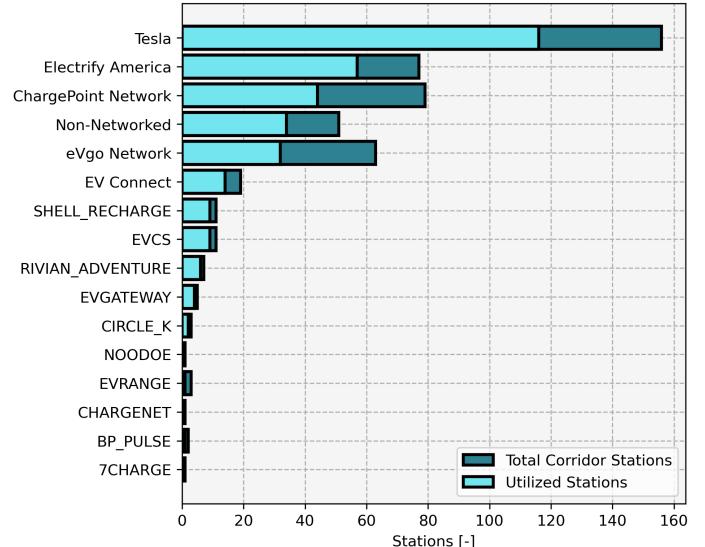


Figure 12: Corridor DC charging network utilization rates

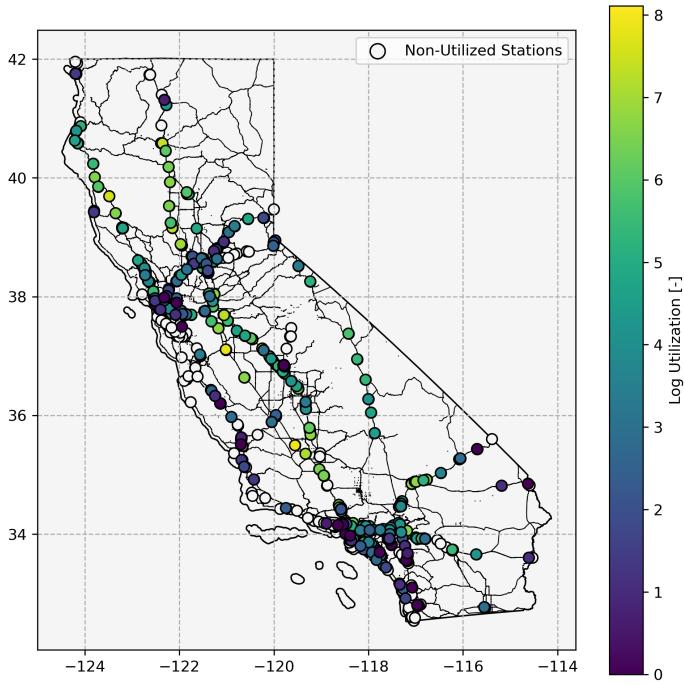


Figure 13: Corridor DC charging station log utilization

It follows intuition that those chargers most useful for drivers are those located between cities on busy transportation corridors and this is backed up in this study. It also follows intuition that those chargers most likely to see use are those with higher redundancy in-station and lower redundancy in-corridor. In this sense Tesla stations are well positioned to absorb traffic should they become fully open to the general light duty EV fleet. When one single entity has control over the locations of all stations in a network, that entity can concentrate chargers to maximize in-station redundancy and minimize between-station redundancy. That entity can, then strategically locate the highly concentrated stations. The result should be a network which experiences high utilization at each station and can benefit from economies of scale. When each network is developed by an independent actor these 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 a large station only to lose business to a nearby competitor combined with the opportunity cost of not using limited capital to do the same inevitably results in a more inefficient combined network. However, many of the issues inherent with the distributed structure could be mitigated if the uncertainty and latency issues inherent to such a network could be mitigated. These issues can, possibly, be mitigated by an integrated status

reporting and reservation system.

Often, the case for BEVs is made on an economic basis as BEV may have lower leveled 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	Percentage Increase
Petroleum [gallon]	3.609	5.138	42.37
Residential Electricity [kWh]	0.1668	0.3247	94.66
Transportation Electricity [kWh]	0.1520	0.1191	27.62
DC Fast Charging (Estimated) [kWh]	0.35 - 0.50	0.35 - 0.60	0 - 20

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].

As shown in Figure 1, a BEV with 300 km of range can accomplish 80% of US daily itineraries on a single charge. Fundamentally, the reality is that home or work charging leads to operational costs that often cheaper and rarely more expensive than petroleum. Similarly, home and work charging can lead to convenience benefits for BEVs as compared to ICEVs [49] 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 the top. This model is also, to some degree, self-reinforcing. Because BEV drivers prefer AC charging, DC charging infrastructure has 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 of 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

I'll write this later - could maybe use some help

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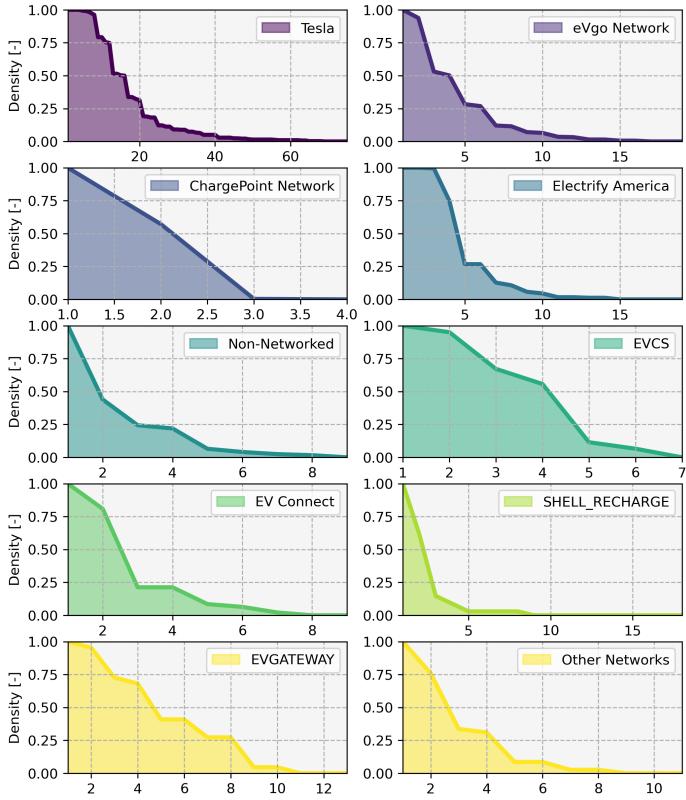


Figure 14: In-station redundancy for DC Charging networks in California

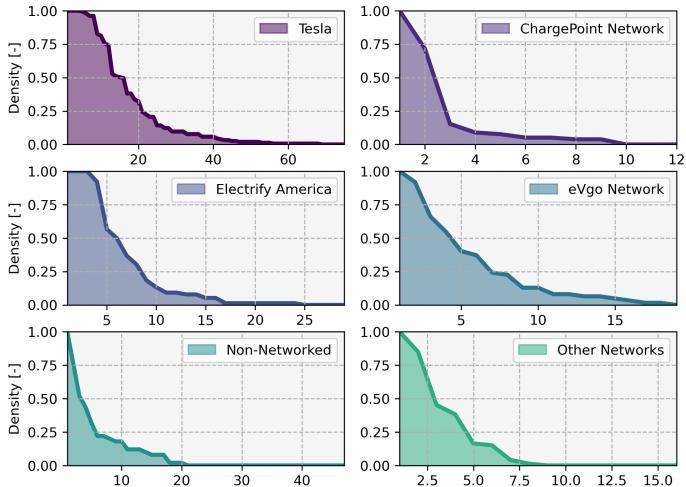


Figure 15: In-station redundancy for DC Charging networks in California

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
EVRANGE	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

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
EVRANGE	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

Table 13: Linear Regression Analysis ANOVA

R	R-Squared	Adjusted R-Squared	Std. Error
0.930	0.865	0.860	0.000
Category	Sum of Squares	DOF	Mean Squares
Model	405.979	47	8.638
Error	63.621	1452	0.044
Total	469.601	1499	0.313
F	<i>P(&gt; F)</i>		
	197.138		
	0.000		

Table 14: Linear Regression Analysis Coefficients and P-Values

Parameter	Coefficient	P-Value
Intercept	5.245	0.000
capacity	-1.417	0.000
Tesla Only	0.037	0.005
charge_rate	-0.273	0.000
reliability	-0.504	0.000
arrival_ratio	0.701	0.000
risk_attitude	0.669	0.000
Non-Tesla Only	0.102	0.000