A Deep Dive into Corridor DC Fast Chargers in California

By

TISURA DASITH GAMAGE
DISSERTATION

Submitted in partial satisfaction of the requirements for the degree of

DOCTOR OF PHILOSOPHY

in

Transportation Technology and Policy

in the

OFFICE OF GRADUATE STUDIES

of the

UNIVERSITY OF CALIFORNIA

DAVIS

Approved:

Alan T. Jenn (Chair)

Gil Tal

Daniel Sperling

Committee in Charge

2024

Dedication

I dedicate this dissertation to my committee members and the University of California, Davis institution, for their unwavering support and for upholding the spirit of research community during an exceptionally challenging time globally. I am especially grateful to my advisors, Dr. Alan Jenn and Dr. Gil Tal, who was understanding and compassionate during my personal and professional challenges and guided me to the completion of my Ph.D.—a feat I could not have achieved without their mentorship. I would also like to thank the California Department of Transportation for funding my study and for generously providing access to data and information, which were invaluable to my research.

I extend my heartfelt gratitude to my parents and my wife for standing by my side throughout this journey.

My thanks also go to Kellen Schefter, Becky Knox and Rick Tempchin at the Edison Electric Institute (EEI) for introducing me to the world of transportation electrification and thank you to Rick for giving me a chance at EEI, despite being an immigrant. Lastly, I am grateful to the people of Sri Lanka for the gift of free education up to my undergraduate studies, without asking anything in return.

Abstract

Transportation is the largest contributor to greenhouse gas (GHG) emissions in the United States (US) among major economic sectors. That is due to the widespread reliance on petroleum-based vehicles that result in direct emissions. However, the U.S. transportation sector is undergoing a transition to zero-emissions vehicles with electric vehicles having the most promise of wide adoption. That is partly a result of financial and other incentives introduced by policymakers to nurture the growth of plug-in electric vehicles (PEV). There are also other trends such as the declining costs, PEV technology maturity, decarbonization of the electricity grid and increased charging opportunities that fuel this trend. By 2035 and beyond we can expect our passenger mobility and logistics services dependent on electric vehicles. In 2018 California established a target of five million zero emission vehicles (ZEVs) by 2030 and 250,000 public EV charging stations to be installed. In 2020 California established a goal for all in-State sale of passenger vehicles to be ZEVs by 2035. Studies have suggested that PEVs are being adopted not only by high income families, but they continue to be adopted by other income groups across various socio-demographic groups. Overall PEVs are seeing a growth in adoption fueling the need for other support services such as charging infrastructure.

Just as internal combustion vehicles (ICE) depend on refueling infrastructure, these new energy vehicles are going to be dependent charging solutions. Studies have indicated that the most important location for PEV charging is at home, followed by work, and then public locations. Studies have found that charging behavior can differ among PEV owners based on their travel patterns, preferences and access to infrastructure and that cost differences in charging options play an important role in the demand for different charging options/ locations. While studies suggest that PEV charging may not impact electricity grids in the short term, charging needs to be managed as PEV adoption increases long term. Studies have also identified that a high adoption scenario of 6 million electric vehicles in California will require upgrades to nearly 20% of all circuits in PG&E service territory, and less than one fourth of them have planned upgrades. More recent studies find the need to upgrade 50% of the feeders in California's distribution grid by 2035, and 67% the feeders by 2045 costing between $6 to $20 billion.

A network of publicly available, reliable, convenient, and rapid recharging stations is necessary to facilitate long-distance BEV trips. Such a national network is beginning to take shape with infrastructure funding made available by the Infrastructure Investment and Jobs Act of 2021 (IIJA) and other State and local initiatives. While most Battery Electric Vehicles (BEVs) can meet the energy needs of typical vehicle use in the US with a night-time home charger, long-distance BEV trips require a higher amount of energy. While plug-in hybrid electric vehicles (PHEVs) can continue to operate without being solely dependent on charging, BEVs are reliant on recharging infrastructure after the battery is depleted. Public direct current (DC) Fast chargers can also support routine charging for BEV drivers who cannot charge at home and support irregular charging for drivers who miss charging and/or have unplanned trips.

In 2020, the UC Davis-ITS Electric Vehicle Research Center was tasked by the California Department of Transportation (Caltrans) to study the construction and operations of such a network of publicly available corridor DCFCs. The project consisted of 54 different DC Fast Charger installation projects in 36 different locations. These sites were selected under the Caltrans ZEV 30-30 project along priority highways, such as Interstate 5, State Route 99, and U.S. Highway 101. The objective of the "30-30" project was to "fill the gaps within California's DC Fast Corridor Network along key routes of the State Highway System where sufficient commercial zero-emissions vehicle (ZEV) fueling opportunities do not currently exist". Uniquely, these sites are at remote or underserved locations that other commercial networks likely did not consider to be economically viable in their business model but were found to be necessary to support long distance travel using BEVs. This was a great opportunity for us to study a futuristic network of corridor DCFC here in California. Even in 2020, this project had the makings of an infrastructure project that had the potential to be replicated nationally. The passage of the Infrastructure Investment and Jobs Act (IIJA) in 2021 has made the learning outcomes of this project even more relevant and timely. Therefore, the **first chapter** of my study focuses on the complex nature of the cost drivers of corridor DCFCs along major transportation corridors.

While the construction of these charging stations was successful, recent issues have arisen regarding the reliability of this infrastructure. A new study found that public open-access charging stations in the Greater Bay area are far less reliable than what station operating companies have reported. Out of a random survey of public, open access DC fast charging stations, only 72.5% were found to be functional. A survey conducted by the California Air Resources Board (CARB) found out that many drivers cite 'charging station operability issues' as a top barrier to using charging stations and many drivers contacted customers services because charging station unit was not working. One common measure used to understand charging station reliability is called "uptime". This time-based metric is calculated as a percentage of time a charger is functional based on a 24-hour, 7-day week. Many authors and studies have questioned the validity of this time-based measurement This is because (1) there is no standard definition of "uptime", (2) because many studies have findings that are at odds with 95-98% uptime reported by charging station operators, and (3) it is unclear who is responsible for maintaining and measuring the uptime of stations. The new California Assembly Bill 2061 passed in 2022 also aims to understand this issue by encouraging the development of additional reliability metrics. Whichever metric is used to measure this issue, unless resolved, low charger reliability has the potential to derail the State's goals to achieving a cleaner passenger transportation system.

Chapter 2 will focus on developing better metrics to understand charger reliability in the context of DCFCs and aim to first (1) measure the real-world operational reliability of corridor charging stations and secondly (2) understand the factors that determine better operational reliability of public fast charging stations. The Caltrans ZEV 30-30 project is a unique source of charging behavior data from charging stations. When chapter 2 aims to understand reliability of individual charging stations, Chapter 3 aims to explore the level of reliability that is desirable in the context of drivers who are taking trips.

The National Electric Vehicle Infrastructure (NEVI) Formula Program created as part of the IIJA aims to have public fast recharging stations at least every 50 miles along designated routes or alternative fuel corridors (AFCs). While addressing “range anxiety” was a critical problem many years ago, **“charge anxiety”** appears to be becoming a predominant barrier for BEV adoption. It is characterized as the feeling of uncertainty about the ability to use chargers while on a trip, as opposed to locating a charging station. This fear derives from unreliable charging stations that may potentially have one or more reasons that can prevent a driver from successfully charging their BEVs.

Chapter 3 of my dissertation focuses on identifying critical corridor DC fast chargers in California’s network through a comprehensive modeling approach considering various attributes of the existing corridor charging network in the United States. The objective is to develop a tool to measure the relative importance of different chargers for the resiliency of the whole network to ensure efficient and uninterrupted travel for BEV highway users. The methodology involves data collection, geospatial analysis, demand modeling (approximation), and the development of mitigation strategies via different maintenance strategies. We believe that higher levels of reliability can be attained through increased maintenance and better equipment, but this may come at a higher cost. It's worth noting that not all charging stations need to meet the same standards of reliability and evaluating them based on the same criteria can divert resources away from where they are most needed. A charging station located in a remote area with few other options should prioritize achieving a higher level of reliability to ensure that drivers can complete their trips without issues.

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Dissertation:

Introduction and Motivation

Transportation is the largest contributor to greenhouse gas (GHG) emissions in the United States (US) among major economic sectors. That is due to the widespread reliance on petroleum-based vehicles that result in direct emissions [1] [2]. However, the U.S. transportation sector is undergoing a transition to zero-emissions vehicles with electric vehicles having the most promise of wide adoption. That is partly a result of financial and other incentives introduced by policymakers to nurture the growth of plug-in electric vehicles (PEV) [3] [4]. There are also other trends such as the declining costs, PEV technology maturity, decarbonization of the electricity grid and increased charging opportunities that fuel this trend [5]. By 2035 and beyond we can expect our passenger mobility and logistics services dependent on electric vehicles. In 2018 California established a target of five million zero emission vehicles (ZEVs) by 2030 and 250,000 public EV charging stations to be installed [6]. In 2020 California established a goal for all in-State sale of passenger vehicles to be ZEVs by 2035 [6]. Studies have suggested that PEVs are being adopted not only by high income families, but they continue to be adopted by other income groups across various socio-demographic groups [7]. Overall PEVs are seeing a growth in adoption fueling the need for other support services such as charging infrastructure.

Just as internal combustion vehicles (ICE) depend on refueling infrastructure, these new energy vehicles are going to be dependent charging solutions. Studies have indicated that the most important location for PEV charging is at home, followed by work, and then public locations [8]. Studies have found that charging behavior can differ among PEV owners based on their travel patterns, preferences and access to infrastructure and that cost differences in charging options play an important role in the demand for different charging options/ locations [9] [10]. While studies suggest that PEV charging may not impact electricity grids in the short term, charging needs to be managed as PEV adoption increases long term [8]. Studies have also identified that a high adoption scenario of 6 million electric vehicles in California will require upgrades to nearly

20% of all circuits in PG&E service territory, and less than one fourth of them have planned upgrades [11]. More recent studies find the need to upgrade 50% of the feeders in California's distribution grid by 2035, and 67% the feeders by 2045 costing between $6 to $20 billion [12].

A network of publicly available, reliable, convenient, and rapid recharging stations is necessary to facilitate long-distance BEV trips [13]. Such a national network is beginning to take shape with infrastructure funding made available by the Infrastructure Investment and Jobs Act of 2021 (IIJA) and other State and local initiatives [8] [14]. While most Battery Electric Vehicles (BEVs) can meet the energy needs of typical vehicle use in the US with a night-time home charger, long-distance BEV trips require a higher amount of energy [15]. While plug-in hybrid electric vehicles (PHEVs) can continue to operate without being solely dependent on charging, BEVs are reliant on recharging infrastructure after the battery is depleted. Public direct current (DC) Fast chargers can also support routine charging for BEV drivers who cannot charge at home and support irregular charging for drivers who miss charging and/or have unplanned trips [16].

The electrification of transportation and the decarbonization of the electrical grid in California are the result of a carefully planned regulatory regime. In 1990, California adopted the ZEV rule for the first time. While there were many issues in its implementation at the time, it is credited with launching a shift in clean automotive technology [17] [18]. The California ZEV regulations have evolved over time and regulators have introduced more complex and comprehensive laws such as the 2012 Advanced Clean Cars I and 2022 Advanced Clean Cars II regulations [18]. They were also the basis for many executive actions such as Governor's Executive Order B-16-12 for promoting goals for increasing PEVs on the road and ZEV infrastructure funding [18]. In 2006 California also passed the AB 32 Global Warming Solutions Act to require in law a sharp reduction in GHG emissions [19]. Again in 2018 California approved SB 100 that requires publicly owned electric utilities in the state to dramatically reduce GHG emissions over the next few years [20]. While these are the basis and rationale for ZEV investments in California, there's been other regulations that specifically target coordinating and promoting investments in charging infrastructure. California's AB 2127, AB 2061, SB 1000 are some examples [6].

A brief overview of DC fast charging station technology

Electrical engineers categorize EV chargers as on-board chargers and off-board chargers. Level 1 and Level 2 chargers fall under on-board chargers. The ac-dc conversion takes place in the onboard charger in the vehicle. Such onboard chargers typically have restricted power because of weight, space, and cost constraints [21] [22]. DC Fast Chargers are what is considered off-board chargers, and they are not design constrained by weight and space as the charger lies outside the vehicle (i.e., DC Fast Charger (50kW-350kW)). DC Fast chargers have various topologies that typically have an ac-dc rectifier and dc-dc converter and feed power directly to the EV battery for charging [23]. A rectifier converts alternating current (AC) to direct current (DC) which flows in one direction. The dc-dc converter converts a DC supply from one voltage to another voltage based on the optimum requirements of the EV battery.

Many new EV models have been introduced to the market by vehicle manufacturers to be competitive in this growing market. Their battery voltage levels can also vary greatly (i.e., 323V – 450V) [23]. The actual voltage also varies during the charging cycle. Some automakers have been introducing BEV models with battery voltage as high as 800V. The advantage of this design is being able to deliver higher a power (kW) at a lower ampere of current. Chargers that can support up to 800V batteries have many advantages as well as disadvantages. Although charger hardware design is not in the scope of this study, it is relevant to have some basic introduction here.

The design of a typical charger has many technical requirements such as a ac-dc converter and a dc-dc stage to regulate the voltage and current during charging stage to secure the durability of the battery [23]. Outside this basic technical architecture, manufacturers have their own characterizes and technical designs and are not publicly available. A summary is available in Table 1.

Table 1: Charger classifications and their inbuilt protections [23]

Charging Station Type	Charger Location	Charger Power level	Protection Type
Level 1 (AC)	On-board	From 1.44 kW - 1.92 kW	Breaker in cable
Level 2 (AC)	On-board	From 3.1 kW - 19.2 kW	Pilot function and breaker in cable
DC Fast	Off-board (Charger located in a public place like a gas station)	From 50 kW – 350 kW	Monitoring and communication between charging station and EV
Next generation – Ultra fast DC charging	Off-board	400 kW and higher	Monitoring and communication between charging station and EV, liquid cable

Study [23] considers the technical specifications of currently available models of DC fast chargers from different manufacturers in detail. The difference output voltages, operating temperatures and electronic component architectures considers some merit.

What happens before successful charge initialization?

Every charging event using a DCFC involved several initialization steps before any power is transferred. Once the EVSE connector is physically connected, the charging station (EVSE equipment) and the EV negotiate the charging session. The EV and charging stations “talk to each other” via Power-Line Communication (PLC) [23].

Each vehicle battery has its own set of restraints and conditions. This is governed by a charging controller or charging regime. The battery management system communicates safe operating voltages, charging stages where the charger can make changes to rates and voltages. The connection also goes through some initial safety checks. If there is a leakage current beyond safe limits to the user, then immediately charging station will signal operations to cease. Any failures in this local communication can prevent charge initialization [23].

What is the reliability of EV chargers?

"Reliability is the ability of a system to perform its intended function" [24]. Reliability planning must be considered at the design stages of any project to achieve the desired level of reliability. This consists of elements such as (1) a definition of system reliability, (2) an overall reliability target and allocation to subsystems, (3) reliability modeling and evaluation, (4) testing and data collection and (5) reporting [25]. Reliability definitions for a given system should not be restrictive. Many complex systems can have several levels of failure [24] [25]. Therefore, it is appropriate to define system reliability measures that contain many numbers of system states.

A broad definition that captures the nuances of issues mentioned before is found here: "From the perspective of an EV driver, a reliable charger successfully charges their EV, for the expected duration, at an expected rate, after accepting an appropriate payment method"[1].

The Charging Eco-system

California has multiple charging network providers, while some chargers are installed independently. The rollout of these chargers been followed by multiple incentives at the Federal and state level, and it appears this might be the case in the future. The well-functioning of the charger-EV user eco system requires many other stakeholders, and Table 2 provides a good summary of all the different stakeholders and their definitions.

Table 2: EV Charging Ecosystem Stakeholder Descriptions [26]

Charging Stakeholder	**Description**
EV user	A person who owns/drives an EV. In order to charge their EVs at a public charging station,

[1] Public Comment from Gil Tal on August 22, 2022, in response to the NEVI proposed rulemaking published by the Federal Highway Administration (FHWA) on June 22, 2022. ref: FHWA-2022-0008-0317

	the EV user typically must be subscribed to a CSO via their eMSP.
E-Mobility Service Provider (eMSP) or the Electric vehicle Service Provider (EVSP)	The eMSP or EVSP is a company that offers EV charging services to EV users. The eMSP is responsible for all communication and billing processes involving the EV users. They grant EV users access to charging infrastructure by issuing UIDs.
Navigation Service Provider (NSP)	The NSP aids EV users to locate and/or reserve public charging stations. The NSP usually belongs to the eMSP.
Charging Station or EVSE	A device equipped with charging connectors to supply energy to EVs from the electrical grid.
Charging Station Operator (CSO)	CSOs are responsible for installing and operating charging stations that they own. They can also maintain charging stations owned by eMSPs. CSOs typically manage charging stations remotely using communication protocols such as Open Charge Point Protocol.
Clearing House Operator (CHO)	The CHO enables roaming services i.e., they allow EV users to charge at CSO that they aren't subscribed to via the eMSP. They run a software platform to facilitate the exchange

	of information between eMSPs. NSPs and CSOs.
Energy Supplier	The energy supplier is contracted by the CSO to deliver electricity to charging stations, according to contracted tariffs.
Distribution System Operator (DSO)	The DSO provides the connection to the distribution power grid and provides the CSO with key information about the grid status.

There are multiple business models and revenue streams to support the capital costs and operational expenses of charging stations. However, this is an ongoing area of research with limited data and access to real world sales information. The consensus is that charging network providers are not directly able to cover their expenses directly from sales. Therefore, many networks have opted to different business models and revenue streams other than the traditional “gas station model” where you’re billed for the gallons of gasoline purchased. Even in the context of gas stations, it appears that most profits are raked in by the convenient stores and the sale of other goods and services to customers according to a recent study [27].

In 2020, the UC Davis-ITS Electric Vehicle Research Center was tasked by the California Department of Transportation (Caltrans) to study the construction and operations of such a network of publicly available corridor DCFCs. The project consisted of 54 different DC Fast Charger installation projects in 36 different locations. These sites were selected under the Caltrans ZEV 30-30 project along priority highways, such as Interstate 5, State Route 99, and U.S. Highway 101. The objective of the “30-30” project was to “fill the gaps within California’s DC Fast Corridor Network along key routes of the State Highway System where sufficient commercial zero-emissions vehicle (ZEV) fueling opportunities do not currently exist”. Uniquely, these sites are at remote or underserved locations that other commercial networks likely did not consider to be economically viable in their business model but were found to be necessary to support long distance travel using BEVs [28]. This was a great opportunity for us to study a futuristic network of corridor DCFC here in California. Even in 2020, this project had the makings of an infrastructure project that had the potential to be replicated nationally. The passage of the Infrastructure Investment and Jobs Act (IIJA) in 2021 has made the learning outcomes of this project even more relevant and timely. Therefore, the **first chapter** of my study focuses on the complex nature of the cost drivers of corridor DCFCs along major transportation corridors.

While the construction of these charging stations was successful, recent issues have arisen regarding the reliability of this infrastructure. A new study found that public open-access charging stations in the Greater Bay area are far less reliable than what station operating companies have reported. Out of a random survey of public, open access DC fast charging stations, only 72.5% were found to be functional [29]. A survey conducted by the California Air Resources Board (CARB) found out that many drivers cite 'charging station operability issues' as a top barrier to using charging stations and many drivers contacted customers services because charging station unit was not working [30]. One common measure used to understand charging station reliability is called "uptime". This time-based metric is calculated as a percentage of time a charger is functional based on a 24-hour, 7-day week [29]. Many authors and studies have questioned the validity of this time-based measurement [29] [30]. This is because (1) there is no standard definition of "uptime", (2) because many studies have findings that are at odds with 95-98% uptime reported by charging station operators, and (3) it is unclear who is responsible for maintaining and measuring the uptime of stations [29, 26]. The new California Assembly Bill 2061 passed in 2022 also aims to understand this issue by encouraging the development of additional reliability metrics. Whichever metric is used to measure this issue, unless resolved, low charger reliability has the potential to derail the State's goals to achieving a cleaner passenger transportation system.

Chapter 2 will focus on developing better metrics to understand charger reliability in the context of DCFCs and aim to first (1) measure the real-world operational reliability of corridor charging stations and secondly (2) understand the factors that determine better operational reliability of public fast charging stations. The Caltrans ZEV 30-30 project is a unique source of charging behavior data from charging stations. When chapter 2 aims to understand reliability of individual charging stations, Chapter 3 aims to explore the level of reliability that is desirable in the context of drivers who are taking trips.

The National Electric Vehicle Infrastructure (NEVI) Formula Program created as part of the IIJA aims to have public fast recharging stations at least every 50 miles along designated routes or alternative fuel corridors (AFCs)[2]. While addressing "range anxiety" was a critical problem many years ago, **"charge anxiety"** appears to be becoming a predominant barrier for BEV adoption. It is characterized as the feeling of uncertainty about the ability to use chargers while on a trip, as opposed to locating a charging station. This fear derives from unreliable charging stations that may potentially have one or more reasons that can prevent a driver from successfully charging their BEVs [31].

Chapter 3 of my dissertation focuses on identifying critical corridor DC fast chargers in California's network through a comprehensive modeling approach considering various attributes of the existing corridor charging network in the United States. The objective is to develop a tool to measure the relative importance of different chargers for the resiliency of the whole network to ensure efficient and uninterrupted travel for BEV highway users. The methodology involves data collection, geospatial analysis, demand modeling (approximation), and the development of mitigation strategies via different maintenance strategies. We believe that higher levels of reliability can be attained through increased maintenance and better equipment, but this may come at a higher cost. It's worth noting that not all charging stations need to meet the same standards of reliability and evaluating them based on the same criteria can divert resources away from where they are most needed. A charging station located in a remote area with few other options should prioritize achieving a higher level of reliability to ensure that drivers can complete their trips without issues.

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[2] National Electric Vehicle Infrastructure Formula Program (2022) available online: https://www.federalregister.gov/documents/2022/06/22/2022-12704/national-electric-vehicle-infrastructure-formula-program

Chapter 1: Costs and challenges of installing corridor DC Fast Chargers in California

1. Costs and challenges of installing corridor DC Fast Chargers in California

Introduction

Electrification of transportation is generally considered a major pathway to shift the current fossil-fuel dominant surface transportation system towards a more energy efficient and less polluting future. In the context of light duty vehicles, this means adopting plug-in electric vehicles (PEVs) which include both battery electric vehicles (BEVs) and plug in hybrid electric vehicles (PHEVs) that are considered more energy efficient and less polluting than most internal combustion engine vehicles (ICEVs). Some studies indicate that most of the global light-duty vehicles fleet should be BEVs by 2050 to meet climate mitigation goals [32]. For these reasons and more, many governments, including the State of California have supported the adoption of BEVs through various incentive mechanisms [8] [14].

The success of large-scale BEV adoption is partly reliant on the development of recharging infrastructure. There are different modes and levels of charging for these BEVs including slower AC chargers known as Level 1 and 2, which provide power ranging from 1-20 kW. DC Fast Chargers are the fastest option for BEV charging and have very high-power demands on the grid. They have an AC/DC converter outside the vehicle to deliver DC power directly (DCFC) to the BEV battery typically at 50 kW or greater. These chargers are considerably more expensive than level 2. Usually, level 2 and DC Fast Chargers can communicate with the BEV, and charging can be controlled allowing the charging station (or electric vehicle supply equipment, EVSE) to optimize the charging process based on available software and information. The charge time depends on the state of charge in the battery, and other physical constraints such as ability of the battery to accept higher charge rate, the charging cable used and the charging station or EVSE. Due to inconsistencies in definitions of charging infrastructure across reports and studies within the topic area, we provide a comprehensive set of definitions for terms used in this paper in Table 3 [8] [33] [34] [35] [36].

This study focuses on DC Fast Charging infrastructure, specifically on corridor charging stations. We were tasked by the California Department of Transportation (Caltrans) to study the construction and launch of 49 different DC Fast Charger installation projects in 36 different locations. These sites were selected under the "30-30" project along priority highways, such as Interstate 5, State Route 99, and U.S. Highway 101. The objective of the "30-30" project was to "fill the gaps within California's DC Fast Corridor Network along key routes of the State Highway System where sufficient commercial zero-emissions vehicle (ZEV) fueling opportunities do not currently exist". Uniquely, these sites are at remote or underserved locations that other commercial networks likely did not consider to be economically viable in their business model but were found to be necessary to support long distance travel using BEVs [28].

The U.S. Department of Energy's (DOEs) 'EV project' identified that DCFCs are more effective when located close to inter-metro major transportation corridors [33]. However, such optimal corridor charging locations across major transportation corridors sometimes lie in rural areas. Fast chargers enable using BEVs on journeys above their single-charge range that would have been impractical using standard chargers. Studies have found that customers strongly prefer BEVs with longer range and higher battery capacities. Charging time and overall driving range are usually identified as the strongest barriers to BEV adoption in customer surveys. As the battery size of electric vehicles grows (and their driving range with it), demand for charging at DC Fast Charging located in long distance corridors outside metropolitan areas are expected to grow substantially [37] [38] [8] [39].

Table 3: Some Charging infrastructure nomenclature and definitions

Word	**Definition**

Charger	The above-ground appliance or the EVSE[3] unit that delivers electricity to charge the BEV[4]
Connector	A charger may have one or more connectors. It is the physical socket that connects to the BEV
Charging Station/ Electric Vehicle Charging Station	Synonymous to "gas station", a charging station is a physical address where one or more chargers are available for use. They can be public, private, or shared private
Make-ready infrastructure	All necessary on-site electrical infrastructure in between the utility connection and chargers, including all conduit, electrical service panels and concrete work
EV ARC	Photovoltaic (PV) power supply on a motorized sun tracking, structure. Includes PV panels, batteries, wireless communications, emergency panel, lighting, and transformers.
EVSE	Electric Vehicle Supply Equipment (EVSE) is the above ground electric Vehicle charging station hardware, including, but not limited to, Level 1, Level 2, and DC Fast Charge.

While most drivers will charge from residential EVSE, there is considerable need for non-residential charging stations in workplace and public settings. Like any other infrastructure investment, understanding the costs is an important starting point to making policy decisions such as (1) choosing which investments to make, (2) who should pay and (3) how to balance risk and reward for stakeholders while aiming to achieve climate mitigation goals. After all infrastructure investments are known to have long lead times and BEV charging is a good example for needing critical mass for widespread BEV adoption in time to achieve long term climate goals [40].

[3] Electric Vehicle Supply Equipment (EVSE) is the above ground electric Vehicle charging station hardware, including, but not limited to, Level 1, Level 2, and DC Fast Charge.

[4] Plug-in Electric Vehicles: Includes Battery Electric vehicles and Plug-in Hybrid Vehicles

It is generally understood that DC Fast Charging (DCFC) infrastructure entails very high costs for construction. However, for a variety of reasons, the cost of DCFC infrastructure is not readily available to the public. Whenever such costs are known, such information is guarded as proprietary information with charging network companies. Furthermore, the available examples for DCFCs construction cost studies are limited to attain a generalized understanding of the cost factors. General attempts at modelling the costs of DCFC do not go beyond including the cost of the EVSE unit and some estimate of labor and material costs for total construction. This is an oversimplification. Reputable qualitative studies indicate that DCFCs will require significant upgrades to the electrical distribution grid infrastructure along with the high costs of on-site wiring [41] and civil construction support for BEV parking spots [42]. These costs are referred to as "make-ready infrastructure" by industry stakeholders. The cost factors that mostly contribute to final costs can help determine whether economies of scale influence the cost per charger and if choice of technology/ site design changes the final costs. These questions and their answers can help planers and policymakers optimize the rollout of a national DCFC network across the United States and achieve the most output from limited resources.

One of the first planned attempts to understand the costs of EVSE installations in the United States was called the "EV Project". Initially it started as a project proposed by the Electric Transportation Engineering Corporation (ETEC, a subsidiary of ECOtality Inc.) to spend funding made available by the American Recovery and Reinvestment Act's (ARRA) on EVSE stations in 10 cities across the United States. The EV Project had a budget of $229.6 million with funds equally contributed by federal funds and ETEC partners. The U.S. Department of Energy (DOE) was tasked with capturing lessons learnt from the initial projects. The EV Project from 2009 to 2013 deployed more than 12,500 Level 2 charging stations and 110 dual connector DCFCs at publicly accessible locations. While ECOtality filed for bankruptcy in 2013, some of the initial EVSE investments survives in the Blink electric vehicle charging network. The DCFCs selected for these projects had a capacity of 60kW and sites were in metropolitan areas. The EV Project's initial data identified that cost of installing a DCFC ranged between $8,500 – $50,820. However, the total cost of installations included only the costs paid to the electrical contractors to install Blink DCFCs. The contractor's costs typically would have included permit costs, engineering drawings (usually required), contractor's installation and administration labor, subcontracted construction labor or equipment (e.g., concrete, asphalt, trenching, boring, etc.), and materials other than the DCFC itself, which was provided by The EV Project. Installation costs did not include the cost of any AC Level 2 EVSE units that may have been simultaneously installed at the same site [34]. Later studies by the DOE that were informed by the EV Project attempted to model the full costs of DCFC installation by agglomerating together many chargers into a given site as a "charger complex". This study included the costs of additional components. However, in this design, some make-ready infrastructure capacities were shared amongst several DCFCs preventing all the chargers from achieving maximum capacity if chargers were used in unison. The new installation costs ranged from $ 385,500 - 392,000 for the installation of 6 DCFCs with a rated 50 kW charger capacity. However, the total combined electrical service capacity of the 6 chargers together was 160 kW. [38].

The study by Rocky Mountain Institute [43] obtained cost information from interviews with various charging networks. Information were obtained under non-disclosure agreements with the assurance that the data would be anonymized and aggregated. A whitepaper by Nicholas M. published in 2019 [44] cites the previous RMI study as a primary source of information. RMI estimated a cost range of about $ 20,000 - $150,000 per 50kW DCFC station. The CALeVIP (2021) cost data are self-reported by site applicants who wish to obtain a rebate from the California Energy Commission (CEC). Their data indicated a $75,841 – $118,131 total project cost per DC fast charger [45].

Below is a summary of the available studies conducted by government organizations and non-profit organizations that have researched and modelled the costs of installing DC Fast Chargers. All the studies are subject to substantial modelling assumptions that vary amongst the authors. A summary of the costs is available in *Table 4*.

Table 4: Summary of the final cost information of installing DC Fast Chargers from available literature and studies funded by public and private agencies. Notice the vast range of cost information and the way this information was presented, such as the number of chargers and what is included in final costs.

Study	Conducted by	Cost Range	Other remarks
California Energy Commissions CALeVIP Cost Data	California Energy Commission (2021)	$75,841 – 118,131 total project cost per DC fast charger	Further inquiry revealed that CALeVIP cost data may not reflect the full costs of DC fast charging station construction.
Estimating electric vehicle charging infrastructure costs across major U.S. metropolitan areas	Nicholas M. (2019), ICCT	$ 45,506 - 65,984 (50kW - 350 kW) one charger per site	$17,692 - 25,694 per charger. 6x(50 kW - 350 kW) per site
Reducing EV Charging Infrastructure Costs	RMI (2019)	$ 20,000 - 150,000 (50kW - 350 kW)	
Costs Associated with Non-Residential Electric Vehicle Supply Equipment	DOE EV Everywhere (2015)	$ 31,000 - 61,000 single port	$10K - 40K EVSE unit cost + 21K average installation cost
Electrification of Transportation Strategic Roadmap (Conducted for the Hawaii Public Utilities Commission)	EThree (2018)	$128,094	
Considerations for Corridor and Community	Idaho National Labs (2017)	$64,250 - 65,333 ($ 385,500 - 392,000 for 6x50 kW units)	

DC Fast Charging Complex System Design			
What were the Cost Drivers for the Direct Current Fast Charging Installations? The EV Project	Idaho National Labs (2015)	$8,500 – 50,820 (for 60kW chargers and includes only contractor's costs)	

Comparing the information in these cost studies were challenging for many reasons. The first being, different studies used DC Fast Chargers with different charging speeds as the baseline for study. For example, the EV project used 60kW charging speeds, whereas Idaho National Labs (2017) study used a charger complex design that has 6 of 50kW chargers that ultimately had a ceiling capacity of 160 kW for the charger complex. RMI's (2019) study used 3 different charging speeds, 50kW, 150kW and 350kW DCFCs as the baseline. The second is that some studies did not include all the cost segments in the final cost calculations. For example, the EV Project only included contractor's installation costs and did not include EVSE costs or the cost of new service connection from utilities. The third reason is the apparent lack of openness to share information. Studies that opted to gather cost information from interviews explicitly mention in their reports that sources they interviewed "were hesitant to share full-cost data or to share information at the component level" [43] because doing so could reduce their competitive advantage in an industry that is only in the early stages of market maturity. While the California Electric Vehicle Infrastructure Project (CALeVIP) database has the most realistic cost information, our interviews with the program administrators suggests that the cost data indicated may not reflect the full construction costs for the same reasons. It is a program funded by the California Energy Commission and other co-funding partners to the tune of $203 million where selected DCFC projects are given rebates for a fraction of the project costs. Since each individual application for funding has an upper limit, the applicants are under no obligation to share full costs of DCFC installations projects after the upper limit for obtaining rebate funding [38] [34] [33] [46].

1.1. Materials and methods:

The data used for this project is unique. We had access to full cost data from the Caltrans ZEV "30-30" project. Caltrans had asked our help for data collection and reporting, and since it was a publicly funded project, all costs are publicly disclosed.

History of the Caltrans "30-30" project

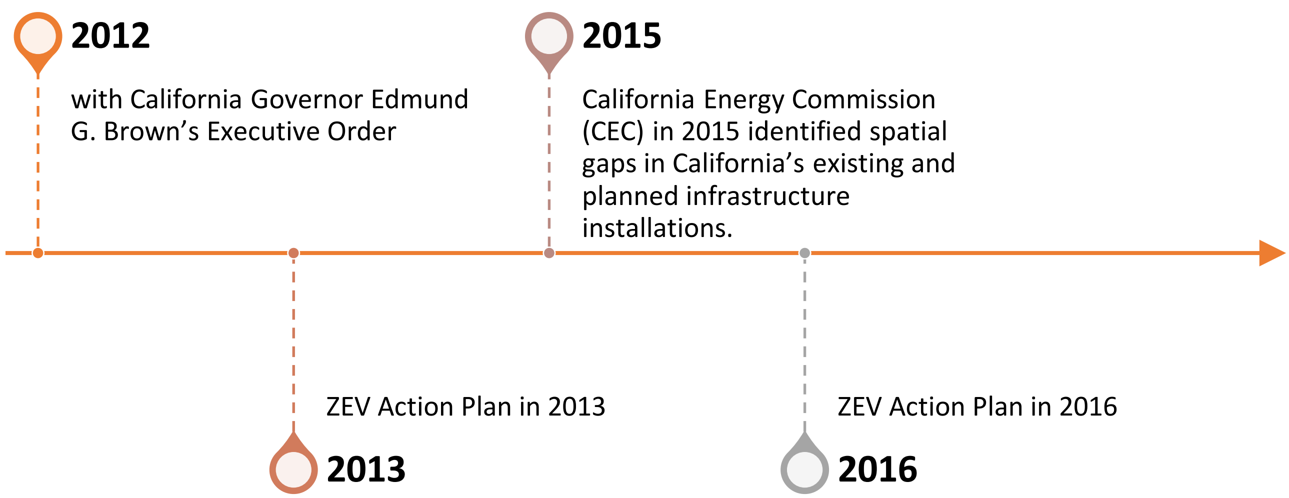

Figure 1: Project timeline history [47]

The California Governor's ZEV Action plan of 2013 put into actionable goals the need for PEV infrastructure in public places. The ZEV Action plan released in 2016, further homed in on the ZEV 30-30 project that specifically directed the State to install public DC Fast Chargers at a minimum of 30 locations [48]. The project was originally proposed to be completed in 2018 with a budget of $25.3 million USD. However, due to legal obstacles, the project implementation delayed till early 2020. Since the project was originally planned in 2016, the DC Fast chargers in the original plan had an output up to 50 kW capacity. This charger capacity was considered very high at the time. By 2020 the maximum capacities of DCFCs had expanded beyond 50 kW to 150 kW and more. However, when the project was finally implemented in 2020, the scoping and original design did not change to reflect the changes in the market DCFC technology from 2016 to 2020.

Figure 2 is a map from Caltrans project memorandum. The site selection process was informed by a consultation report published by the California Energy Commission (CEC) in 2015 that identified spatial gaps in California's existing and planned infrastructure installations [28] and a study that identified high demand and high congestion rest areas in the future [49] [50]. The chosen 36 sites for DCFC installation were distributed between 27 highway Safety Roadside Rest Areas (SRRAs), 5 Maintenance Stations, 2 District Offices, and 2 Park and Ride Lots along priority transportation corridors, including Interstate 5, State Route 99, and U.S. Highway 101 in the State of California. [28].

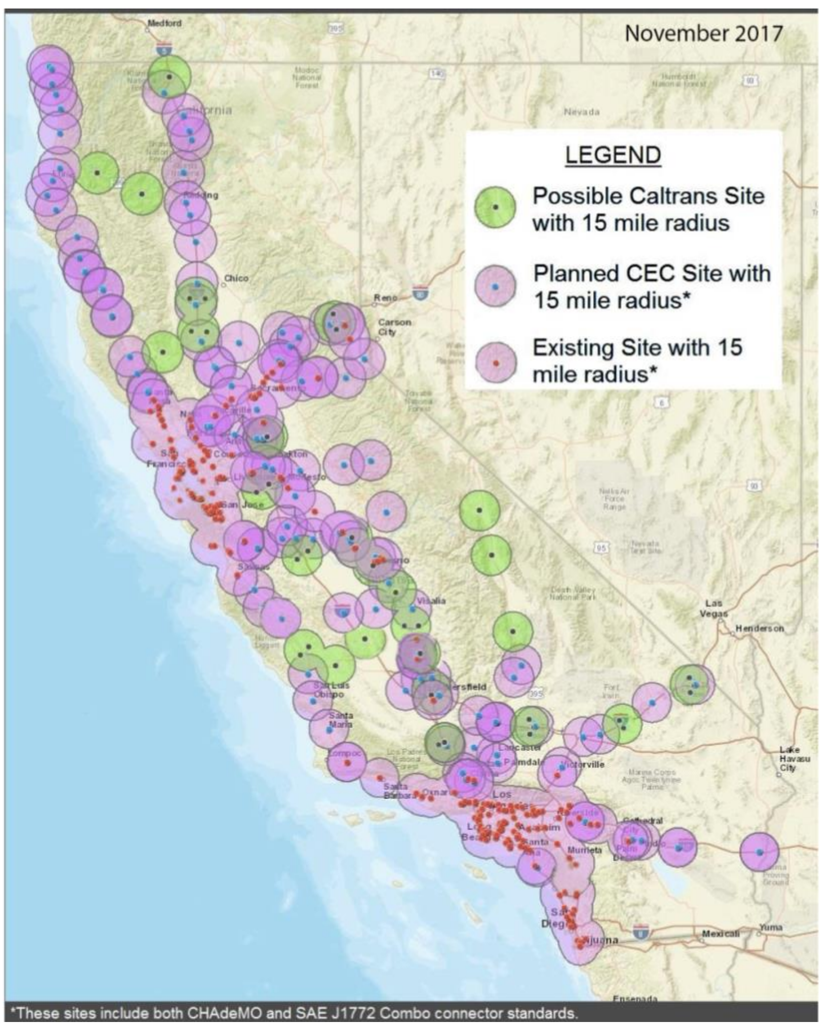

Figure 2: Map identifying possible Caltrans sites for DCFC installation based on CEC study [28]

What is a Safety Roadside Rest Stop (SRRA)?

According to Caltrans:

> "Caltrans provides Safety Roadside Rest Areas as a part of the State Highway System pursuant to Streets and Highways Code, Sections 218-226.5. Safety Roadside Rest Areas provide opportunities for travelers to safely stop, stretch, take a nap, use the restroom, get water, check maps, place telephone calls, switch drivers, check vehicles and loads, and exercise pets. Rest areas reduce drowsy and distracted driving and provide a safe and convenient alternative to unsafe parking along the roadside." [5]

SRRAs are an important feature of the nation's highway system, and they are used every day by travelers using the highway system. Some rest areas along busier highways have two separate rest areas in tandem next to each other on opposite sides of the highway to service traffic traveling in opposite directions. Out of the 27 SRRAs selected for this project, 22 were such a location that had a twin rest stop next to each other. That is, 11 locations with twin rest stops that were servicing traffic traveling in opposite directions. Because such twin rest areas had their own dedicated facilities, such rest stops were considered unique sites, even though they were alongside the freeway on opposite sites. For example, Boron Westbound (WB) SRRA and Boron Eastbound (EB) SRRA (Figure *3*) were located on opposite sides of the freeway but were considered as two unique rest stops.

[5] Caltrans (2022), "Safety Roadside Rest Areas" https://dot.ca.gov/programs/design/lap-landscape-architecture-and-community-livability/lap-liv-h-safety-roadside-rest-areas

Figure 3: Map of Boron Rest areas servicing westbound and eastbound traffic (From Google Maps used under fair use).

Interviews and data collection

We initially interviewed Caltrans engineers and project managers who were tasked with the DCFC construction. A sample interview question matrix can be found in Appendix 1 and 2. Then, project cost data were collected from contractor's bid documents and utility interconnection bills. In addition, we analyzed information from detailed civil/ electric design plans to further understand the costs information obtained from winning bid documents. We also interviewed engineers from private charging networks to understand their project design and implementation process. A summary of the initial data collection process is indicated in *Figure 4* below.

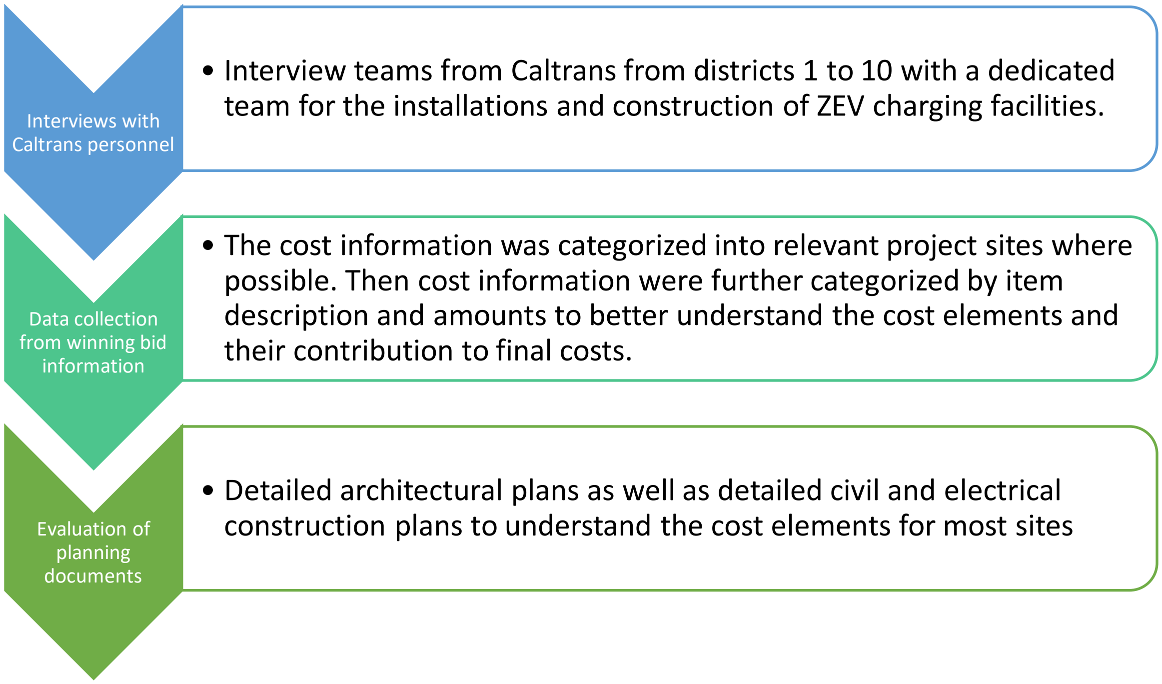

Figure 4: Summary of data collection and evaluation

1.2. Analysis

Planning and early states of project implementation

Caltrans would initially create a working unit with a project manager and a project engineer (also referred as the design engineer) for a given Caltrans district. The project manager is responsible for scoping, scheduling, and costing for the project and the project engineer is responsible for the design and technical guidance of the project.

We spoke to project managers and design engineers to understand the early stages of the project implementation process. At this point, they considered 3 main issues. (1) purchasing EVSE unit(s), (2) getting adequate power supply for the PEV parking spot (EVSE unit) and (3) designing and construction of necessary on-site make-ready infrastructure. This early design and planning stage is important for understanding cost variables in the project.

Purchase of the EVSE unit was done through the Department of General Services which administers all California State contracts with suppliers. Then design engineers survey the proposed construction site to understand initial conditions. At this level they estimate the existing capacity of the electrical supply connection and assess the necessary civil and electrical work to make the EVSE units operational. From our interviews, we identified that design engineers must finalize the engineering design for the site, which has a detailed project plan for building civil/ electrical construction for all sites. This plan includes a detailed site plan, with detailed parking spots, their layout, and existing and modified electrical works plan. They also included other plans such as tamper protection designs for EVSE.

A significant piece of the initial stages is about getting power to the remote locations and then getting power from the utility drop site to the designated PEV parking spot. From our interviews we understood that there are two ways to obtain a utility connection. Either (1) the existing electrical connection and panel can be modified to handle the higher electricity load required by the DCFC or (2) opt for a completely new service connection. Caltrans opted for a new utility connection in almost every location. The observation of project engineers was that previous electrical loads were very small that they were only adequate for lighting and other needs in rest areas. This decision makes a significant cost difference in these remote sites compared to most urban sites selected by other private networks.

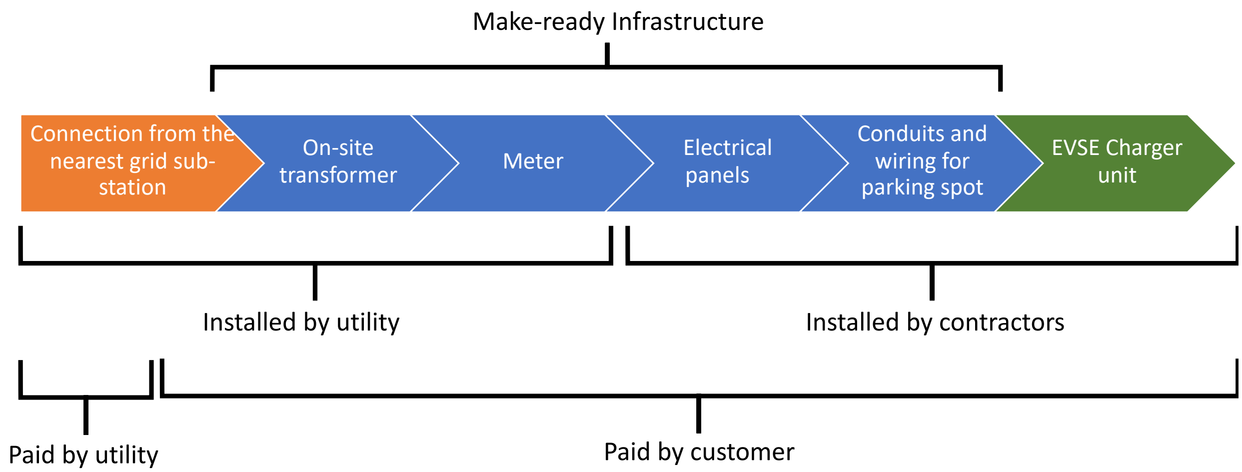

Figure 5: Summary of infrastructure required for a working DCFC and who is involved with what. The blue indicates the make-ready infrastructure, the green indicates the above ground EVSE unit and orange indicates all utility infrastructure leading to the work site.

In most locations, utilities needed to upgrade their infrastructure with new electrical cabinets and brand-new panels on site. In addition, new infrastructure must be built to supply adequate power to a new location. Figure 6 includes two maps, the first is the modified electrical design to accommodate the EVSE unit and the second is a google satellite map of the rest area for greater clarity. As seen in Figure 6, there is a considerable distance between the utility service drop site to the PEV parking spot which needs to be connected by PVC (Polyvinyl chloride) insulated copper conduit wire that is buried under 30’’ inches in this design. The conduit sizes, insulation requirements and undergrounding and safety requirements are guided by the National Fire Protection Association standards or NFPA 70, National Electrical Code (NEC) and Caltrans safety requirements.

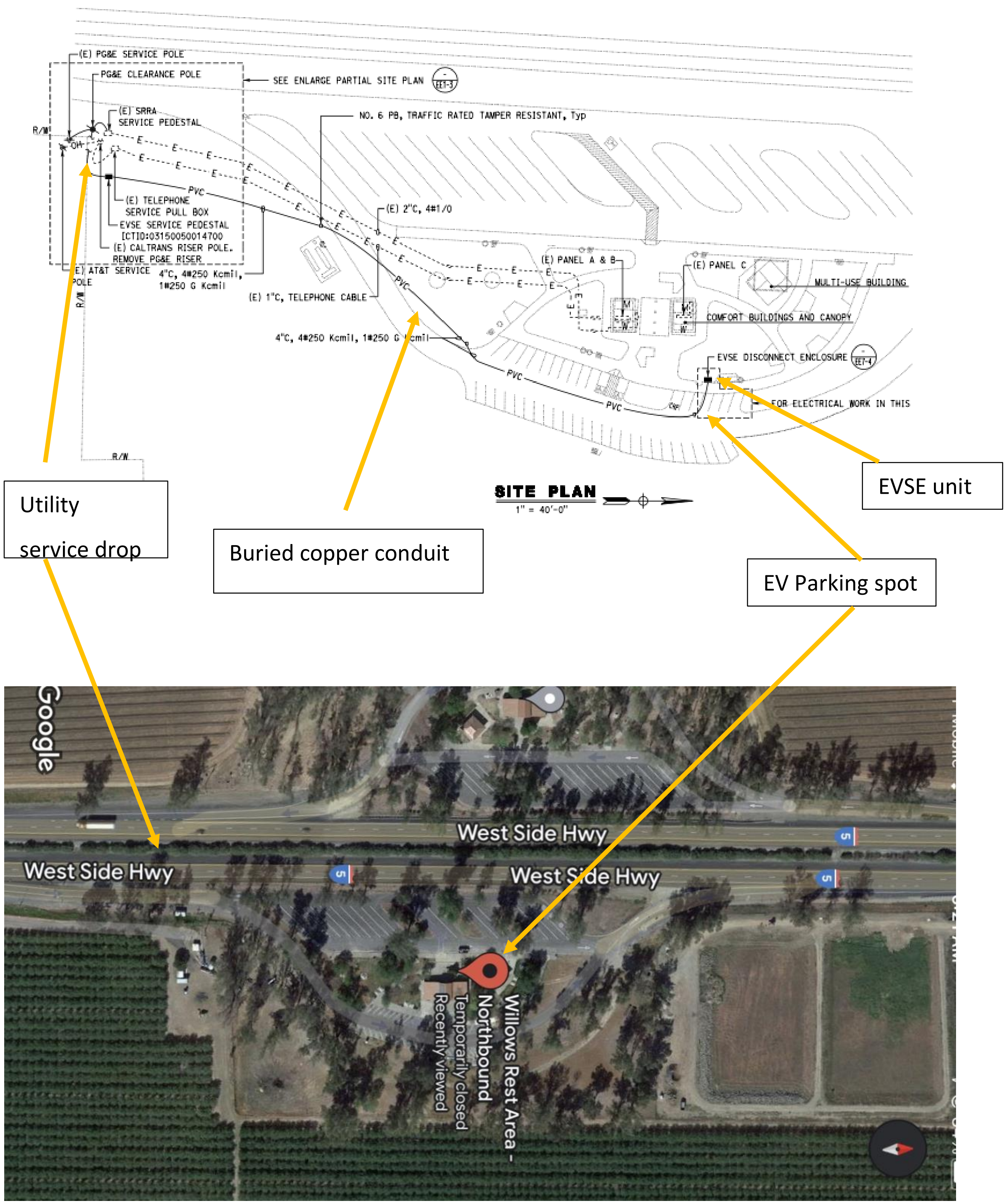
(E) PG&E SERVICE POLE
PG&E CLEARANCE POLE
SEE ENLARGE PARTIAL SITE PLAN
(E) SRRA SERVICE PEDESTAL
NO. 6 PB, TRAFFIC RATED TAMPER RESISTANT, Typ
R/W
(E) TELEPHONE SERVICE PULL BOX
EVSE SERVICE PEDESTAL
[CTID:03150050014700
(E) CALTRANS RISER POLE.
REMOVE PG&E RISER
(E) AT&T SERVICE POLE
4"C, 4#250 Kcmil, 1#250 G Kcmil
(E) 2"C, 4#1/0
(E) 1"C, TELEPHONE CABLE
PVC
(E) PANEL A & B
(E) PANEL C
MULTI-USE BUILDING
COMFORT BUILDINGS AND CANOPY
4"C, 4#250 Kcmil, 1#250 G Kcmil
EVSE DISCONNECT ENCLOSURE
FOR ELECTRICAL WORK IN THIS
SITE PLAN
1" = 40'-0"
Utility service drop
Buried copper conduit
EVSE unit
EV Parking spot
Google
West Side Hwy
West Side Hwy
West Side Hwy
5
Willows Rest Area - Northbound
Temporarily closed
Recently viewed

Figure 6: Brief overview of the on-site make-ready infrastructure in a rest area (from Caltrans)

Figure 6 is a good case study to analyze cost factors involved because we were able to obtain electrical and civil design plans for the site upgrades and map them to real cost information. Figure 6 represents the Willows Northbound rest area (SRRA) alongside highway 5 in California.

Case Study 1: Willows Safety Roadside Rest Area (SRRA) vs. Maxwell SRRA

We will also use this example to compare the costs between two twin SRRAs along highway 5, Willows SRRAs and Maxwell SRRAs in case study 1. The two locations had cost variations because of different design decisions at the planning stages. The previous example of Willows Northbound and Southbound SRRAs opted for two different utility connections, thereby receiving two different utility interconnection bills as indicated by the utility fee column in Table 5.

Maxwell Northbound and Southbound SRRAs are similar rest stops along highway 5 that have a very different construction cost than Willows SRRAs. In many ways the rest areas are very similar and are located only 5 miles apart. But the different design implications have led to almost $540,000 differences in costs as seen in Table 5.

Table 5: Project costs of Willows Safety Roadside Rest Area (SRRA) vs. Maxwell SRRA. The conduit and conductor costs are a sub-cost of the make ready infrastructure costs. They are indicated in parathesis not to be confused as a new cost element.

Description	Utility fee ($)	Make-ready infra. Cost	Conduit & Conductor (Sitework) costs	EVSE
Willows Safety Roadside Rest	$14,918.30	$321,300	($123,951)	$26,000.00

Area (Northbound)				
Willows Safety Roadside Rest Area (Southbound)	$22,673.09			$26,000.00
Maxwell Safety Roadside Rest Area (Northbound)	$24,211.72	$878,900	($516,983)	$26,000.00
Maxwell Safety Roadside Rest Area (Southbound)				$26,000.00

A systematic cost comparison between the above locations is necessary to understand the significant cost differences. They both have "twin" rest areas servicing northbound and southbound traffic on opposite sides of the highway 5. Willows SRRAs have two different utility service connections for the two sites, whereas Maxwell only received one service connection to the Southbound SRRA. Everything else about the 2 locations (or 4 SRRAs) are the same. They have the same contractor, relatively similar geography, and the same equipment. However, the make-ready infrastructure cost is more than twice in Maxwell compared to Willows.

A further examination of engineering drawings and engineer's cost calculations explains this cost difference from having to extend a special conduit from the Maxwell SRRA (Southbound) to the Maxwell SRRA (Northbound) under the freeway for electricity connection. The cost material and labor cost for "Conduit & Conductor (Sitework)" for Willows and Maxwell were a significant portion of the make-ready costs. For Willows it was about 38% of the make-ready costs whereas, it was about 58% for Maxwell as seen in Table 5. Such additional costs included cost of directional drilling under the highway to connect the conduit from one side of the highway, the cost of standard copper wire insulated by PVC conduits and additional trenching costs. The design engineer said they arrived at this design after initial negotiating with the local electric utility with the best available information to them at the time.

Make-ready cost components:

We were able to analyze the make-ready infrastructure costs from the construction related winning bid documents for Caltrans. They included the costs of setting up the site, trenching for conduits, laying concrete pads and construction of switchboards and transformer vault. Different local construction groups had won the contract from Caltrans at different locations across the State. Some groups had only one project undertaken by them, such as the Moon Lim Lee Safety Roadside rest stop. Therefore, the make-ready costs of that site can be directly ascertained from the winning bid document. Some contracts were awarded for multiple sites together and unfortunately the winning bid documents had lumped together cost for the multiple sites. In such locations, we were only able to identify an average cost for make ready infrastructure. We were able to find a few unique winning bid documents that encompass different cost segments. *Figure* 7 is a summary of those costs of what constitutes the construction costs per DC Fast Charger.

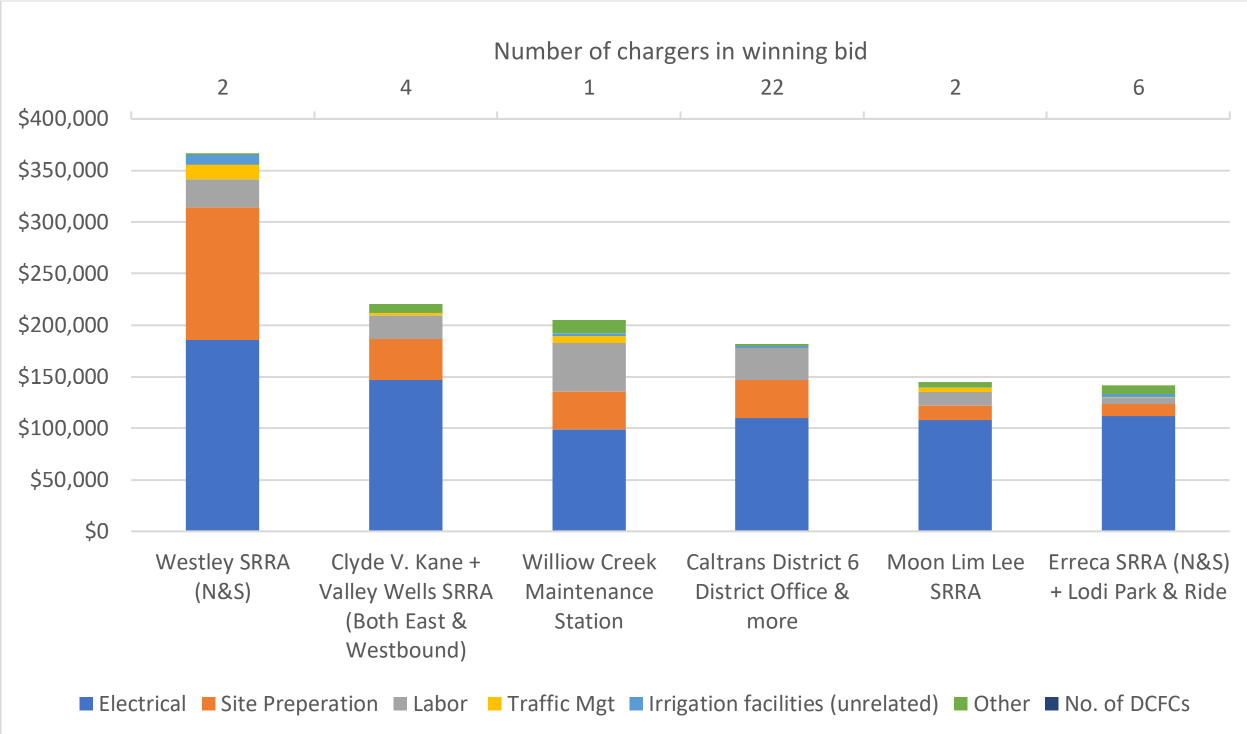

Figure 7: Per DCFC cost breakdown of make-ready costs

We compiled all the cost items in winning bid documents into six categories: electrical, labor, site preparation, traffic management, irrigation facilities and other costs. The electrical and labor costs included conduit trenching, boring costs, and costs of other wires and conduits. Site preparation costs included all other non-electrical civil construction costs such as charging station foundation, barrier post costs, concrete costs, and cost to backfill trenched areas and restore rest stop surfaces, sidewalks, and pavements as before. This also included the cost of making EV parking spots ADA accessible as seen in *Figure 8*. All state funded designs need to have minimum ADA accessibility to be compliant with the Americans with Disabilities (ADA) Act of 1990. Traffic management costs are incurred during construction phase in managing traffic around the construction site. Costs of irrigation facilities maintenance are a Caltrans specific cost.

Parking spots

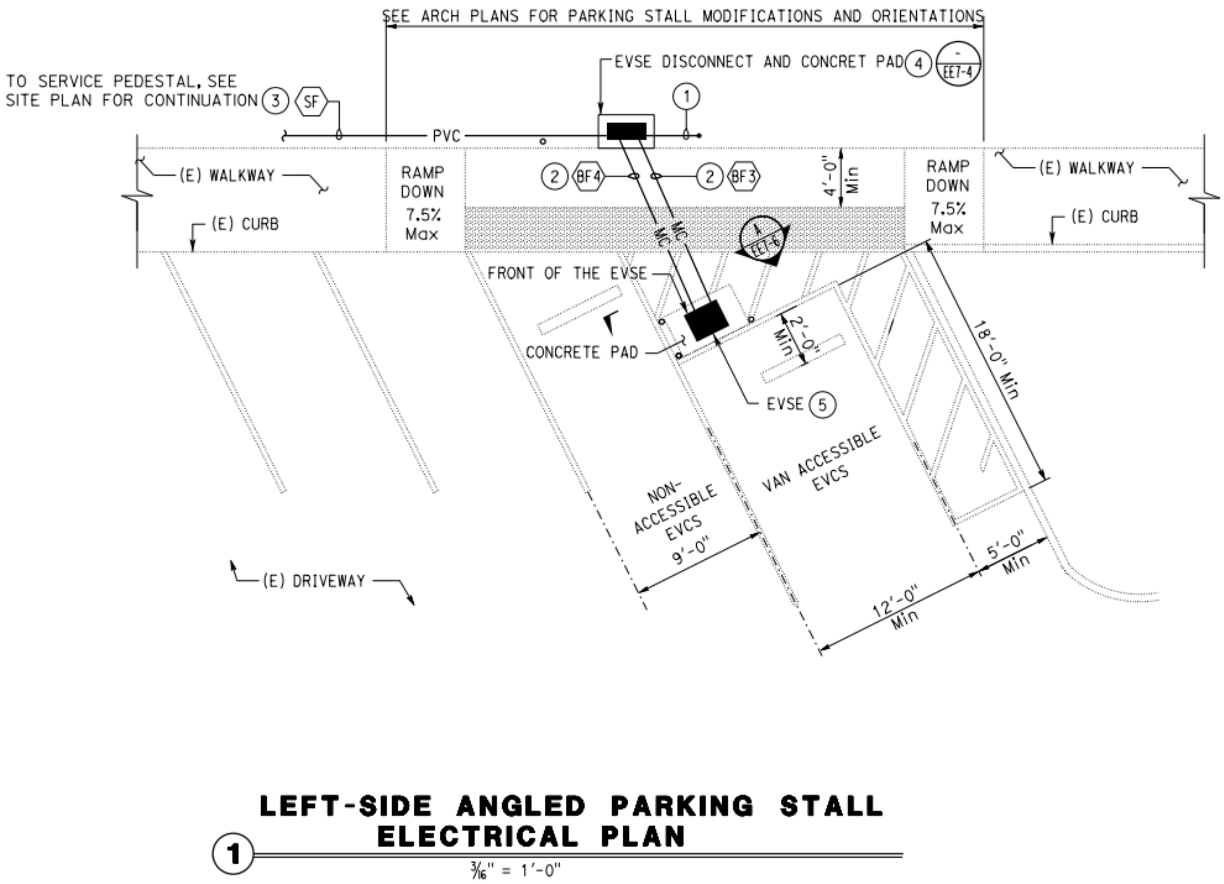

Figure 8: Example of an ADA compliant PEV parking spot (from Caltrans designs)

Utility Interconnection costs

Figure 9 is a summary of the utility costs passed onto Caltrans at different sites. For our analysis, the costs were allocated per DCFC and some sites such as Maxwell had only one utility connection for Northbound and southbound rest areas, whereas sites such as Willows rest areas had two different utility interconnections for each rest stop servicing northbound (NB) and southbound (SB) traffic as seen in Figure 9. Maintenance Stations are indicated as MS.

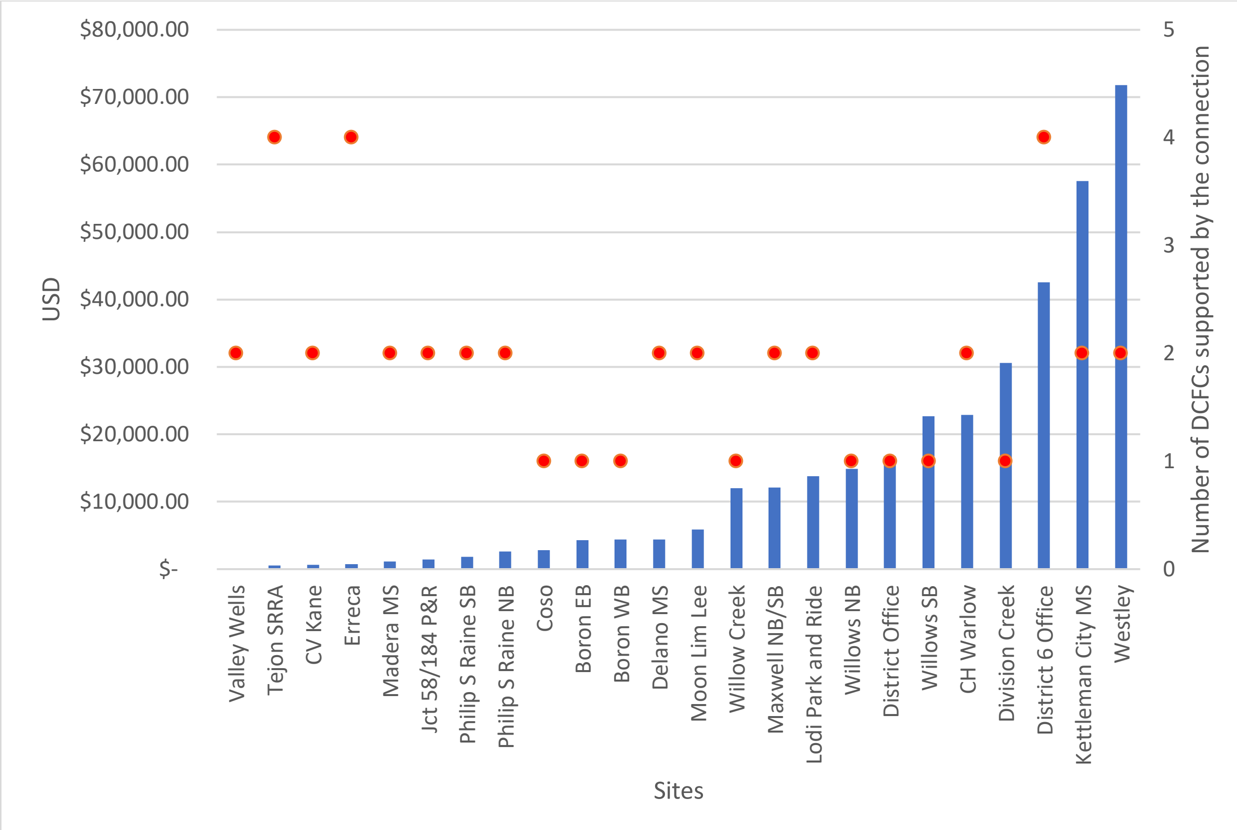

Figure 9: Cost of utility service connection per DCFC passed onto the customer.

Utilities will determine the necessary upgrades to their network based on two factors to upgrade their costs. They look at other neighbors in the vicinity of the site and plan their infrastructure based on how much upgrades they anticipate in the future. If your charging station site is the only anticipated customer, then the utility network upgrades are done solely for your benefit and as such, much of the distribution line extension costs will be passed onto the customer. It is the responsibility of the utility customer (i.e., Caltrans) to provide on-site space for necessary substations and transformers on customer's premises. Figure 9 indicates how much utility cost expenses were passed on and billed to Caltrans at different sites.

A major learning experience from almost all our interviewees was how project engineers have underestimated the timelines and costs of working with major utilities. Given the remoteness of most of the sites, power utilities needed to expand the energy supply capacity of the local distribution grid and plan to procure other electrical equipment such as transformers and other utility side make-ready infrastructure. Almost all interviewees suggested a 4 to 6-month precautionary lead-time to begin working with electric utilities.

Alternative Solar off-grid DCFC installation design

Out of the 36 sites, Caltrans had opted to try an experimental off-grid Solar arc DCFC design in 3 remote sites where the electrical grid-extensions would have been very expensive. Here the EVSE charger directly connects to four solar tracking stations with attached storage. The solar photovoltaics (PVs) are called solar EV ARC (trademark) in the Caltrans bid documents because they have some sun tracking features. The design of this charging station is straightforward. Four solar stations with attached battery storage would feed a single DC Fast Charger unit on the site located almost next to the solar units. As seen in the engineering drawing Figure 10 and Figure 11, the EVSE unit is connected by underground conduits to the four solar and battery stations located almost next to each other. This design does helps bring down on-site make ready costs and incurs almost no electrical utility costs. While the solar PV units and attached storage units add extra costs to the design, they avoid the need to have expensive on-site conduits bringing power from the grid to the EVSE units.

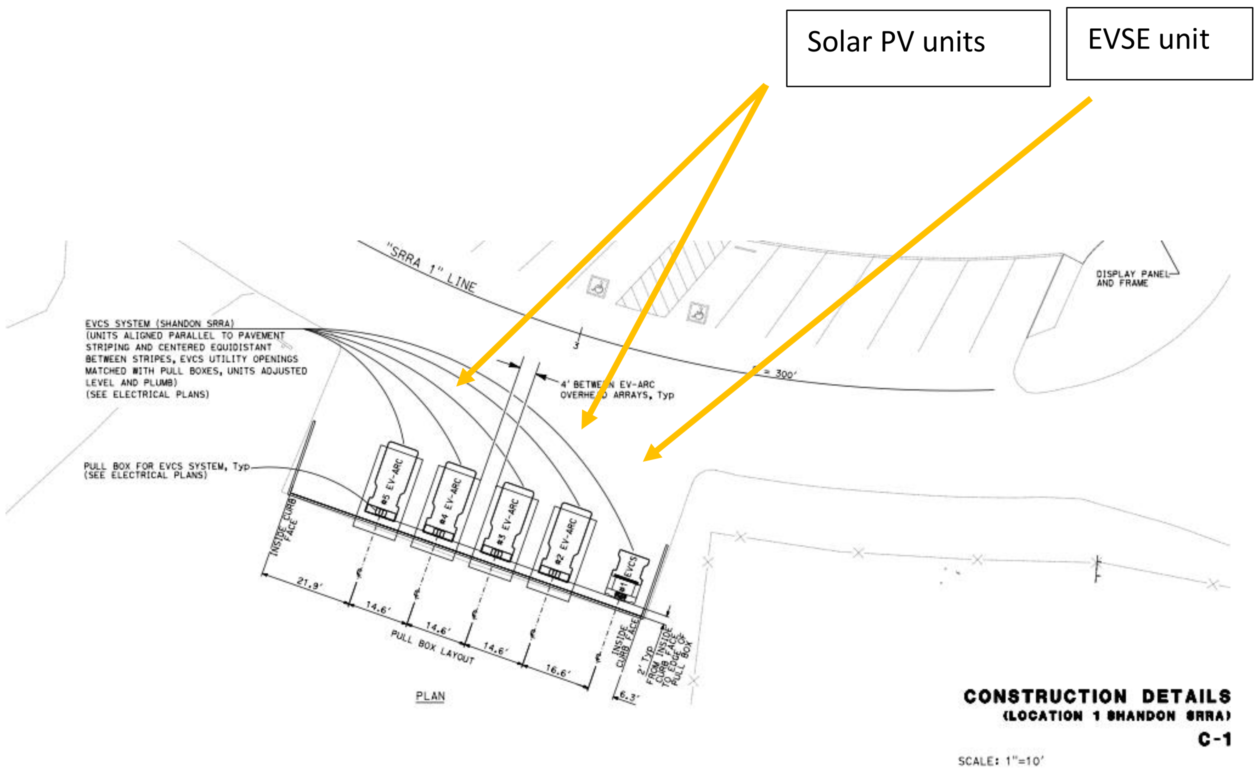

Figure 10: Site design for on-site solar EV ARC + attached storage design of DCFC (from Caltrans)

Figure 11: Shandon Rest Area (Images from Google under fair use)

Case Study 2: Shandon Safety Roadside Rest Area (solar)

Shandon SRRA is located alongside route 46 in Caltrans district 5. The engineers chose the unique solar powered DC Fast charger design for this location. Below is a breakdown of all the costs incurred for the 50kW DC Fast Charger installed.

Main cost components of the off-grid EV Charging System:

Table 6: Cost breakdown of the Shandon safety roadside rest area charging system with necessary components that enable the operation of the off grid DCFC charging station.

Item	Unit Price
4 EV ARC (Sun-tracking PV array with battery storage)	($420,545)

DC Fast Charging Station	($51,150)
Additional Battery Storage	($60,132)
5-year monitoring and maintenance plan	($31,221)
Taxes, training, and testing	($51,150)
Other	($13,588)
Total of EVSE system	$627,786
Electrical Trenching and Backfill	$24,000
Site Specific other costs	$66,873
Contractor's other costs averaged for this site	$138,900
Total	$857,559

This unique design of DC Fast Charger complex supported by on-site solar and extended storage capacity does not require a dedicated utility service connection. The cost breakdown for installing the DC Fast Charger in SRRA is shown Table 6. The shaded items contain the costs of the Solar EV ARC system and the direct costs of the charging system whereas the other items in Table 6 incorporates the labor costs as well as compliance and site preparation costs incurred from the project.

The total cost for this project is indicated above as $857,560 per DC Fast Charging unit with solar and storage capabilities.

Cost of installing DCFC of higher powers

What lessons can we take from this project to charging stations with higher powers? We can simulate the costs of installing a DCFC with a higher power by comparing the full project costs of a rest area that opted to build four 50kW DCFCs on one site on side of the highway. This is a close approximation to constructing a 200 kW DCFC in each site.

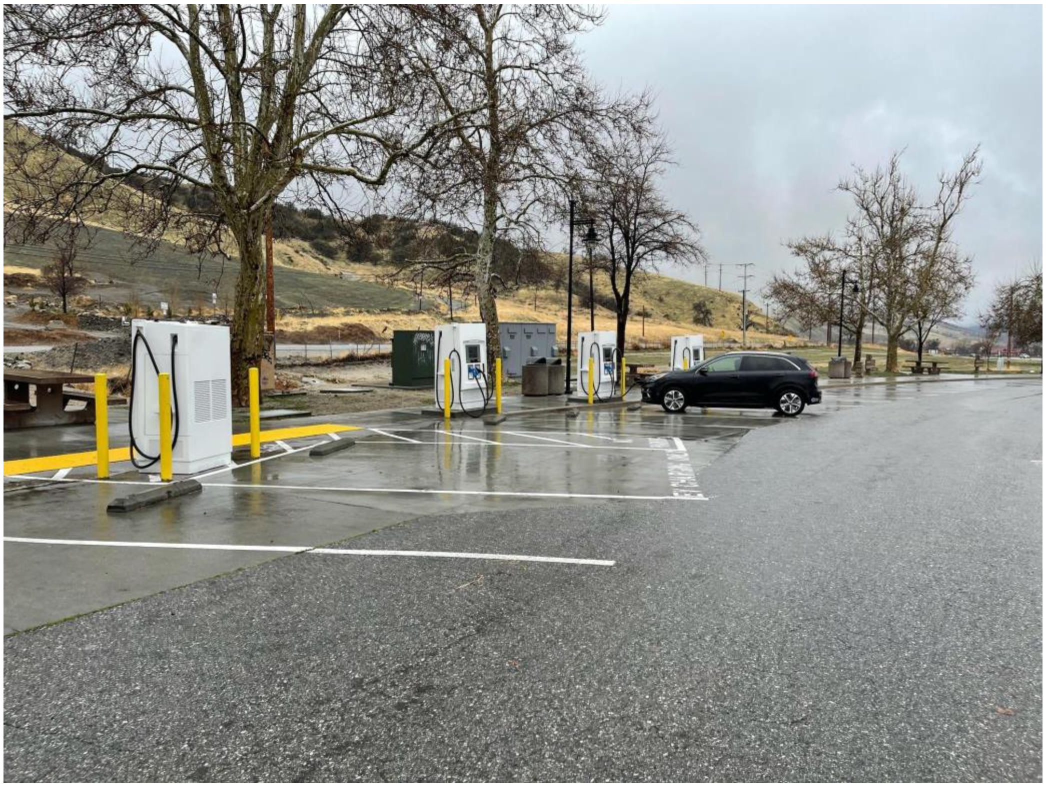

Figure 12: El Tejon SRRA has 4 DCFC on one side of the highway (from Plugshare used under fair use)

El Tejon SRRA cost of installing one 50 kW was roughly $208,355. So, we can estimate the cost of a 200 kW DCFC around $833,420 per DCFC. This is also in line with the judgement from our interviews.

Economy of scale in DCFC installation in one location

Tesla Superchargers tends to install many DCFCs together (40-80) in one location. This is also true of other private charging networks. From our analysis, we find some indication of economy of scale in the installation of DCFC. Figure *13* is the outcome of our findings. When 2 or more DCFCs were installed in on location sharing on site "make-ready infrastructure", they can save some costs. However, this is not as significant because more DCFCs will require more utility supply capacity and upgrade to other onsite make-ready infrastructure. Furthermore, out dataset is not large enough to conclusively identify any potential benefits from economy of scale.

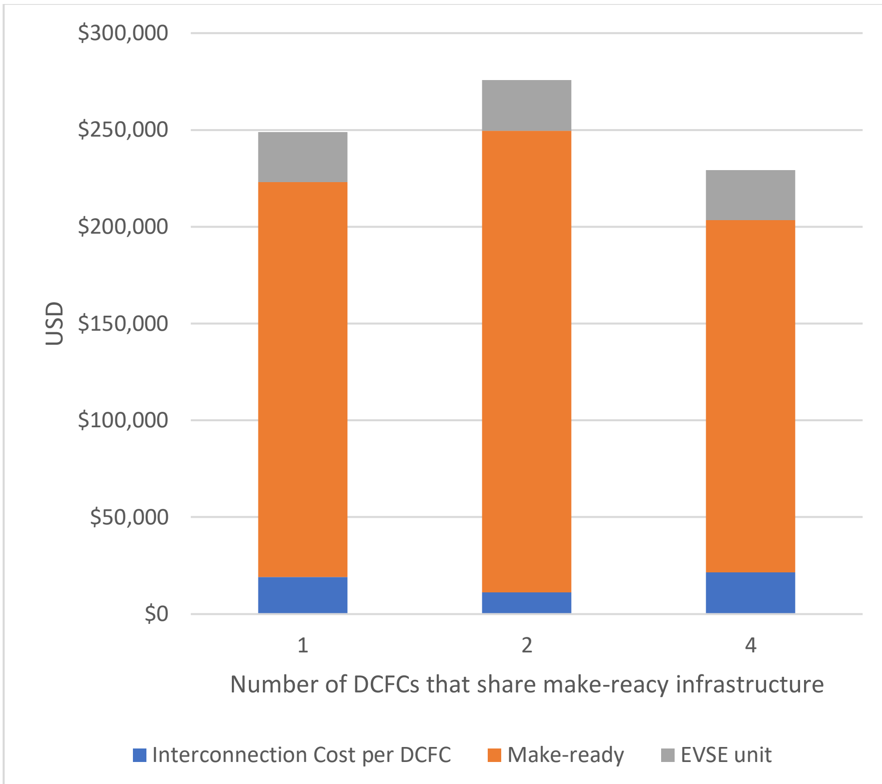

Figure 13: Average construction and installations costs per DC Fast Charger at sites that had shared make-ready infrastructure between multiple DCFCs.

There is some evidence to suggest that Tesla is minimizing construction and installation costs by prefabricating make-ready infrastructure in a shared pre-cast concrete foundation with multiple EVSE units. According to unverified reports, these prefabricated units are then transported to the final location of interest and installed. This strategy can help reduce construction costs and timelines. However, the authors are unable to verify this claim independently [51] [52].

Project Execution:

While the design phase of the project started in 2019, implementation of the construction projects began only in 2020 and were impacted by the Covid-19 crisis. The California Governor's stay at home orders were issued on March 15, 2020. That some impact on the projects. The Covid-19 impacts ranged from implementation delays as contractors tested positive for Covid-19, delays in getting supplies to some cost overruns as the prices of primary construction materials such as concrete increased in the State of California [53]. All the project was completed by March of 2022.

1.3. Discussion

Based on our study we find that the installation of corridor DC Fast chargers requires more effort and funding than cost information available in the literature review. There are added challenges for corridor DCFC installations along major transportation corridors. Regular DCFC installation requires significant onsite make-ready infrastructure for the operation of chargers at maximum rated power following National Electrical Code and NFPA guidelines. The infrastructure must undergo substantial planning and administrative processing, and requires engineering designs, architectural designs, planning for labor mobilization, planning for safety and coordinating with local stakeholders such as electrical utilities and local suppliers for the successful construction and launch of DCFCs.

While existing studies indicate that DCFC construction and installation costs ranging from $20,000 - $150,000, the project we analyzed had total costs ranging anywhere between $122,000 – $440,000 for grid connected corridor DCFCs. For off-grid systems, the costs were found to be even higher. We believe that this is due to the following reasons:

- The nature of the sites selected have additional stresses that drive costs higher. On the one hand It is difficult to mobilize labor and materials for a construction project in a remote site such as a Caltrans safety rest area. On the other hand, it was necessary to take adequate precautions to manage the traffic and safety during construction in a location that usually has a daily high foot traffic.

- Most DCFC construction projects in an urban dense location would benefit from existing local infrastructure already invested by cities and local utilities. Although we take this for granted, such shared infrastructure creates a complimentary eco-system that brings down costs for construction in an urban setting. The selected remote sites did not have this advantage of complimentary infrastructure.
- The co-location of DCFC stations on both sides of a freeway adds significant costs and challenges especially if the local electrical grid infrastructure is only accessible from one side of the freeway. Significant challenges were faced in extending make-ready electrical infrastructure from one side of the freeway to the other side to make sure that the DCFCs in both sides of such "twin" rest areas have adequate power supply to support PEV charging at maximum rated speeds.

What can be done to bring down costs?

Based on our findings, we suggest that design engineers and contractors in the future can reduce costs by adopting some flexibility with the on-site architectural and engineering design plans. A flexible design that allows PEV parking spots to be moved closer to the utility drop site can save on costs such as pavement repairs, buried copper conduits, trenching and borings costs. It is also a prudent choice to receive a dedicated utility service connection for every corridor charging station site wherever possible.

Given the nature of corridor charging sites, always select sites to install DCFC in locations where adequate distribution grid capacity and infrastructure is available from both sites of the freeway. When it is necessary to lay conduit under the freeway, it is cheaper for the utility to do it before the meter at a higher voltage than at a lower voltage for the contractor. At low voltage, the electrical design needs more conducting materials to compensate for higher resistance leading to additional boring, trenching, and ultimately higher costs. We recommend closely working with local utilities to obtain separate service connections for corridor charging sites when possible. Planning corridor DCFC installations should be an ongoing process before and during the construction phase. Some advanced planning before the construction phase can save significant resources. Moreover, as the DCFC technologies are improving rapidly, it helps for planners to be up-to date about new EVSE designs, speeds, and technologies.

We also observe that most civil construction groups have limited experience with installation of DCFCs. A step in the right direction was made by the California Assembly Bill 841 and CA Public Utilities Code 740.20 that requires the presence of at least one electrician who hold an Electric Vehicle Infrastructure Training Program (EVITP) certification on site for DCFC installations from September 2021 onwards to be eligible for CALeVIP rebates in California[6]. Certification and training programs should be expanded to train electricians and new programs should be dedicated for civil engineers and civil contractors who want to work in installation of DCFCs. The insights of trained electricians and civil construction partners in DCFC installations can help reduce missteps, bring down costs in construction, and help expedite the construction process.

Regulatory guidance and oversight over electric utilities

Based on the sites we analyzed, it costs the customer between $100 to $71,700 per site to bring adequate power to the charging stations from the local grid. We do not have enough information to calculate how utilities determine the cost of utility fees for a new connection and upgrades. But some factors that influence this are (1) existing feeder capacity, (2) distribution grid infrastructure availability in the vicinity, and (3) projected future demand from neighboring customers of the site.

Not all costs of grid upgrades are passed onto the customers. Some costs are rate-based, and that amount is determined by a complex web of rules that are enforced by the CPUC. A new

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[6] CALeVIP (2021), "How do I comply with the Electric Vehicle Infrastructure Training Program (EVITP) certified electrician requirement?" https://calevip.org/faq/how-do-i-comply-electric-vehicle-infrastructure-training-program-evitp-certified-electrician-0

resolution issued by the CPUC in October 2021 is an attempt at clarifying such rules on how to recover line extension costs and utility side make ready costs for PEV chargers. These rules will come into force in California from 2022 for the general rate case (GRC) of that year and will be monitored by the CPUC on a rolling basis. Before this CPUC resolution, only customers participating in dedicated utility programs were allowed to fully rate base their utility side costs. Progressive action will help alleviate uncertainties about utility side costs and help make a better business case for DCFC installations. Further research is necessary to understand and compare the regulatory action of other States and their respective public utility commissions.

Infrastructure Investment and Jobs Act of 2021-2022

In 2021, the U.S. Federal Government passed into law a comprehensive funding package to upend America's infrastructure. Amongst other things, this bill aims to build a nationwide network of 500,000 PEV chargers across the United States. We believe there are many insights from our study to help the planning and infrastructure investment of $7.5 Billion for this effort[7].

According to our calculations, the necessary investment for a national robust and reliable network of 500,000 DCFCs requires much higher funding than what is allocated from the federal government. However, the federal bill does not seem to specify if all the 500,000 chargers are to be DCFCs. Our calculation for a network of 500,000 DCFCs across rural America can be as expensive as $74 Billion. Therefore, we observe the need to fill this gap in funding from other sources. Ratepayers funding for utility side make-ready costs can help alleviate some cost burden.

1.4. Conclusions

This study focuses on publicly available corridor DCFC construction in locations that belong to the California Department of Transportation. All the 49 DC Fast Charger installations in 36 different

[7] The White House (2021), "Fact Sheet: The Bipartisan Infrastructure Deal" https://www.whitehouse.gov/briefing-room/statements-releases/2021/11/06/fact-sheet-the-bipartisan-infrastructure-deal/

locations we analyzed are now operational and accessible along priority highways such as Interstate 5, State Route 99, and U.S. Highway 101. Installing DCFCs in transportation corridors will always be a challenging task for the reasons mentioned before. Strategies mentioned above in site selection and advanced planning can bring down costs. But because the United States highway network go through a diverse terrain with very diverse physical features and sometimes sparsely populated regions, there will be the need to invest in public charging infrastructure in very isolated and costly locations to fill the gaps in the charging network. These sites will incur higher than average costs and private networks will have limited incentives to build infrastructure in such locations.

A key objective of the Caltrans "30-30" project was to identify the learning experiences and sharing that information publicly. We think such publicly funded infrastructure projects can help advance our understanding of the challenges and costs of installing corridor DCFCs. In this study, we want to emphasize the need to analyze more corridor DCFC case studies in the future to advance our understanding of them. Such information needs to capture the full costs of installations such as utility costs, make-ready infrastructure costs and EVSE costs. While we think private partners should also be incentivized by public funding, we have limited information of construction costs that can be independently verified where private changing networks are concerned.

We think that a broader analysis of the business case for public DCFCs is necessary to understand the different revenue streams for investments. The business case for DCFCs can be very different based on location, charging speeds and ownership structure. We have identified in our study that DCFC installations capable of higher charging speeds incur higher costs and DCFC installations in transportation corridors will incur above average costs. Further research into public charging behavior at different prices and at different locations might shed light on how to optimize much needed public funds to locations and sites where public funding is most necessary.

Chapter 2: Novel Methodology to Measure the Reliability of Public DC Fast Charging Stations

ABSTRACT

A network of reliable corridor charging stations is essential to building driver confidence in long-distance Battery Electric Vehicle (BEV) trips. Here, we propose a detailed methodology to measure station reliability based on charging infrastructure data. By assigning charging events to unique charging visits, our methodology can capture a holistic overview of the driver's charging experience. We use real world charging data collected between 2019 and 2022 from 54 DC fast chargers in 36 corridor charging stations across California to demonstrate that our overarching reliability framework is closer to the experience of users. Our analysis of two different charging networks shows that users of these networks have an average chance of 83% and 77% generally successful outcomes after one or more tries at a charging station location. We also find significant variation in station performance within the same network (i.e., 79% - 87% and 13% - 95% respectively). Furthermore, we observe that at least 3% of users are facing unexpected charging interruptions. Additionally, we demonstrate a practical application of our framework for deep diagnostics of the charging eco-system using error codes to identify common issues such as vehicle/ charger communication issues, safety issues, payment issues and cable/ connector issues. We compare how error codes alone are not a good proxy to diagnose charging failures. As more data from DCFCs becomes available, our methodology can become a mainstream tool for evaluating station reliability.

Keywords: reliability, error codes, interoperability, corridor chargers

2. Novel Methodology to Measure the Reliability of Public DC Fast Charging Stations

2.1. Introduction

The U.S. transportation sector is rapidly undergoing a transition to zero-emissions vehicles with electric vehicles having the most promise of wide adoption. By 2035 and beyond we can expect our passenger mobility and logistics services dependent on electric vehicles [54]. As with internal combustion vehicles (ICE) relying on refueling infrastructure, the success of these new energy vehicles will hinge on the development of a robust and reliable network for energy supply and charging infrastructure to meet their transportation energy requirements [55]. Such a national network is beginning to take shape with the infrastructure funding made available by the Infrastructure Investment and Jobs Act of 2021 (IIJA) and other State and local initiatives [8] [56]. A total of $7.5 Billion is made available by the IIJA for electric vehicle charging infrastructure. The National Electric Vehicle Infrastructure Formula Program (NEVI) was created as part of the IIJA to administer $7.5 Billion of public funds dedicated to corridor DC fast charging infrastructure. And $2.5 Billion will be disbursed as a Charging and Fueling Infrastructure (CFI) discretionary grant. There is increasingly evidence that the biggest hurdle to EV adoption maybe the unreliable public charging system [57] [58].

Battery Electric Vehicles (BEVs) can typically meet the energy needs of most vehicle days across the US, relying primarily on a night-time home charger [15]. However, long-distance BEV trips have higher energy requirements than a typical day of driving, making a network of convenient and rapid recharging stations necessary to facilitate such trips. Public corridor chargers that are strategically placed along major highways are well suited to serve such trips. With improved range of new BEVs and better BEV route planning tools such as ABetterRoutePlanner and Plugshare trip planner, range anxiety is becoming less common with drivers. However, charge anxiety appears to be becoming a predominant barrier for EV adoption. It is characterized as the feeling of uncertainty about the ability to use chargers while on a trip, as opposed to locating a charging station [31]. It encompasses a larger set of issues such as availability/ presence of stations, characteristics of vehicles (i.e., range) and reliability of charging stations. This paper will use real world charging data to study the reliability of public DCFCs using data from the chargers but focusing on the perspective of the users.

At its core, reliability of a system can be defined as "the probability that the system will perform it's intended function" [24]. Reliability models should describe the system and its functions as realistically as possible. Several studies consider the reliability of power electronics in fast charging stations as their components are exposed to extreme high-power stresses [22] [23] [59]. However, these studies typically define the system in terms of its components and operations within the charger. This framework falls short in considering the user's interactions with the charging station. To ensure that NEVI program funded chargers are reliable, they proposed a proxy measurement to reliability as "uptime". They are required to meet a minimum annual uptime of 97% according to the latest rules issued in 2023. According to the NEVI definition "A charging port is considered "up" when its hardware and software are both online and available for use, or in use, and the charging port successfully dispenses electricity in accordance with requirements for minimum power level (see § 680.106(d) of NEVI guidelines) [60]. The final ruling also specifies that each DCFC "must simultaneously deliver up to 150kW, as requested by the EV" [60] so as "to ensure a consistent and satisfying customer experience regardless of which charging port a customer selects and how many other ports are currently in use" [60]. The uptime rule overlooks important aspects of the charging experience. That is because (1) hardware and software being online do not always ensure successful charging, (2) it overlooks the many interoperability challenges with different vehicle and charger models in the charging eco-system, and (3) it does not provide guidance on charging interruptions and emergency stops that can be observed from the charging data. Moreover, the rules relevant to minimum power level do not provide enforcement guidance nor provide guidance for relevant data collection, such as disparities in the power levels requested by the EV and what is provided by the changer. Overall, we think uptime as a reliability measurement falls short of capturing many aspects of reliability that are important for driver experience and oversimplifies the operations of a charging stations.

Many authors have questioned the validity of this time-based metric to measure reliability of DCFCs [29] [30] [60]. Other reliability studies have findings that are at odds with 95-98% uptime reported by charging station operators. A recent study found that public open-access charging stations in the Greater Bay area are far less reliable than what station operating companies have reported. Out of a random sample of public, open access DC fast charging stations, only 72.5% were found to be functional [29]. A survey conducted by the California Air Resources Board (CARB) found that out of the 1,290 drivers that responded, 439 drivers cite 'charging station operability issues' as a barrier to using charging stations. In the same survey, out of the 617 drivers that contacted customers services, 261 cite they did so because charging station unit was not working [30]. Therefore, this is evidence of the discrepancy between uptime and reliability. It appears that driver's perception of charger reliability is different from the various aspects that can be measured by "uptime". We believe uptime will offer limited value in rectifying negative charging experiences of drivers [29, 26]. We fear that substandard industry incentives could develop around ensuring high uptime, rather than prioritizing meaningful reliability from the user's perspective. In anticipating this disparity, the new California Assembly Bill 2061 passed in 2022 encourages the development of additional reliability metrics. Unless resolved, low charger reliability has the potential to derail the State's goals to achieving a cleaner passenger transportation system.

In the rest of the paper, we propose a new methodology to calculate the reliability of public DC fast charging station from real world charging data. Here we also define charger reliability holistically based on different levels of charging failure and partial successes that have been observed in the data. And finally, we include an analysis of the common error codes and what they mean in this context.

A broad framework of reliability

In our reliability analysis, we define the system more broadly considering the broad charger eco-system with respect to the user and the BEV. **Figure 14** provides a summary of the various levels of reliability failures a driver may experience when they arrive at a charging station with the intent of charging their vehicle. We have attempted to make this list as comprehensive as possible. The shaded region marked by the blue indicates the focus of our study that directly analyses data from the charging events. We have limited information on situations where access to the charging station may be physically blocked or when the station is offline. Some definitions of different charging errors indicated in **Figure 14** are found below.

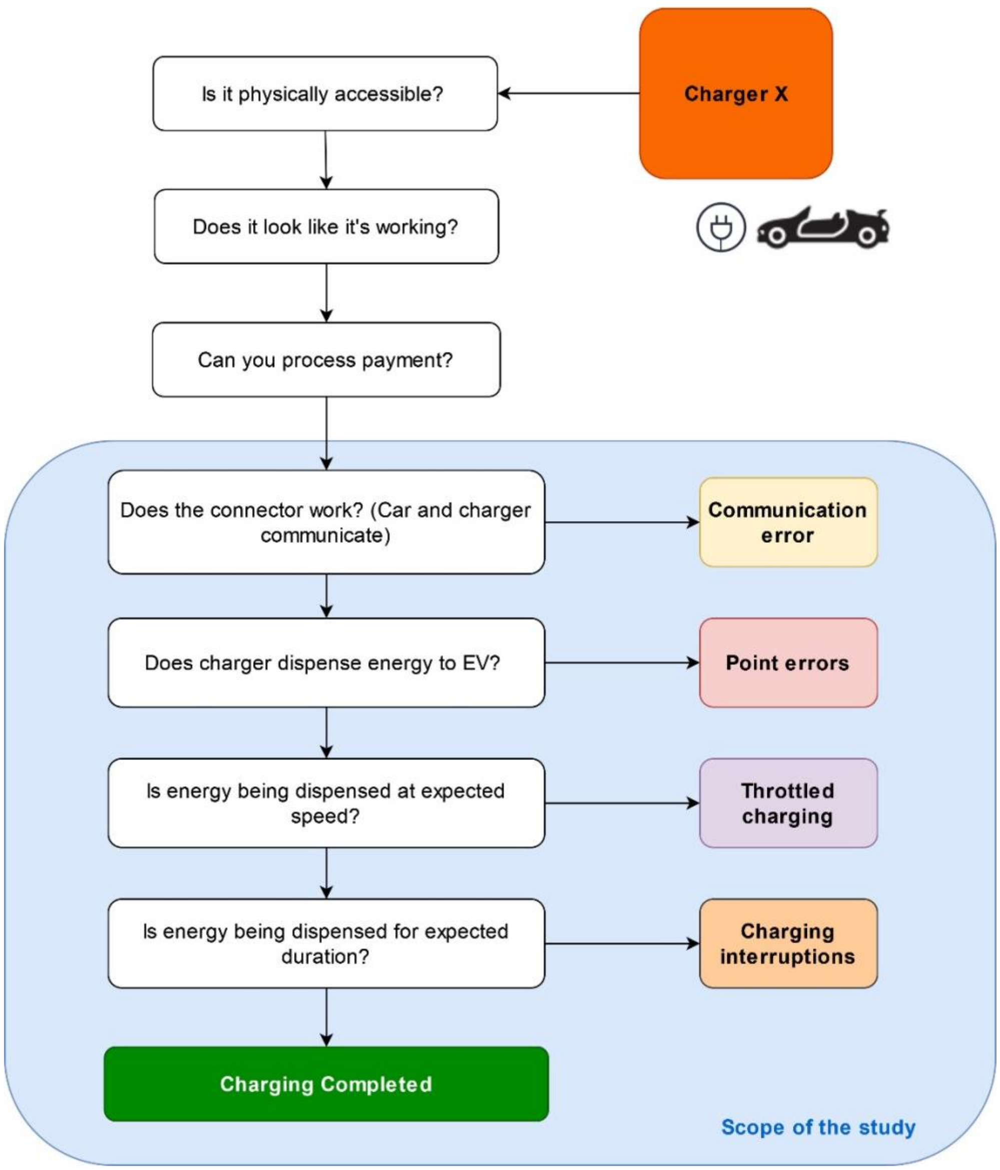

Figure 14: Possible levels of reliable failures at a charging station from the perspective of the driver (user). Our focus in this study is highlighted in blue.

Some definitions of charging failures as described in **Figure 14**:

- **Point errors** refer to no-charge events when the charger is online but still fails to initiate a charging session, or a charging session is initiated and immediately interrupted in an infinitesimal amount of time, such that the failure occurs at a brief point in time and cannot be captured in a time-based metric like uptime.
- **Throttled charge** refers to the situation where the charging speed or power in kW was much lower than the advertised speed. It is most likely that the speed was reduced or limited during a charging session intentionally by the battery management system or the charging station.
- **Charge interruptions** refer to the situation where the charging of the BEV battery is stopped or interrupted during a charging session. Charge interruptions can result in incomplete charging, longer charging times, and inconvenience to the EV driver.

From the point of view of charging station users (i.e., drivers), a successfully completed charging event is an uninterrupted charging event that delivered fast charging consistently meeting advertised speeds for the desired duration of time.

2.2. Methods

This study analyses data from the 54 corridor DC fast chargers installed in 36 different locations by the Caltrans ZEV 30-30 project. These chargers were constructed during 2020 and almost all stations were operational and were open to the public by early 2021. Major features of the charging stations can be found in **Table 7**. Two popular charging providers available in the market were chosen for the project. Here we will refer to them as brand A and brand B. Other monitoring and ancillary services such as cloud services that recorded and remotely monitored charging sessions were provided by their respective brands.

Table 7: Features of the charging stations

Site features	
Charger site(s)	Highway rest areas, some maintenance stations

Geographic region	California
Station characteristics	
Charger model	Two popular brands available in North America
Charger type	DC Fast – 50 kW
Station host	California Department of Transportation (Caltrans)
Access	Open to the public - highway users
Plug type	CCS and CHAdeMO
Pricing	
Pricing type	Free of charge
Payment platform	One brand needed membership info to initiate
Parking cost	Free

Data preparation:

The charging data was shared with us by Caltrans personnel in the form of a downloaded excel file. The original datapoints contains different aspects of the recorded charging events as 32 variables. We filtered the following variables expanded in **Table 8** for our study as they were the most relevant:

Table 8: Data Dictionary

Attribute	Description
EVSE ID	A unique ID to identify the charger unit used.
Connector Type	This describes which connector was used between CCS or CHAdeMO
Energy Delivered in kWh	Energy dispensed by the charging session in kWh
User ID	A unique user identifier
Charger Start date-time	Charging event starting date and time
Charger End date-time	Charging event end date and time
OCPP Session ID	Unique identifier for a charging event within the network
Start SoC in %	Starting State of charge of the battery

End SoC in %	Ending State of Charge of the battery
Ending Voltage	Recorded ending Voltage of the battery
Session End Type	Reason for ending the charging event

As part of data preparation, we created a 'Station ID' combining different EVSE IDs that were in the same charging station. Only chargers within proximity to each other on the same side of the freeway were considered as part of the same station.

A charging event consists of an attempt by the user to connect the charger plug to the EV charger socket in the vehicle. The charger records such attempts irrespective of whether energy was dispensed or whether charger was able to communicate with the vehicle. When the charger did not communicate with the vehicle, certain attributes such as starting and ending state of charge (SOC) and ending voltage were not captured in the data and remained as missing values.

Step 1: Initial screening of charging events:

Here we differentiate charging events based on the energy output of the event. Any event that dispensed more than 1 kWh is considered as a successful event. All events that do not meet this criterion are considered unsuccessful events or no-charge events. A separate column was created to indicate if the event was a success or not. (This is an initial definition to screen charging events. A more comprehensive definition of a successful charging event is introduced in Figure 14)

In this step, we attempt to filter events that have negligible energy transfer. We think 1 kWh is a good cut-off point to make this distinction. The equivalent electric range added by 1 kWh is about 3-4 miles. This does not make a significant difference in outcome for long distance BEV trips. A distribution of the energy output of events that fall under these criteria are found in Figure 15 as an example. According to Figure 15 most of the no-charge events have an energy output less than 0.1 kWh.

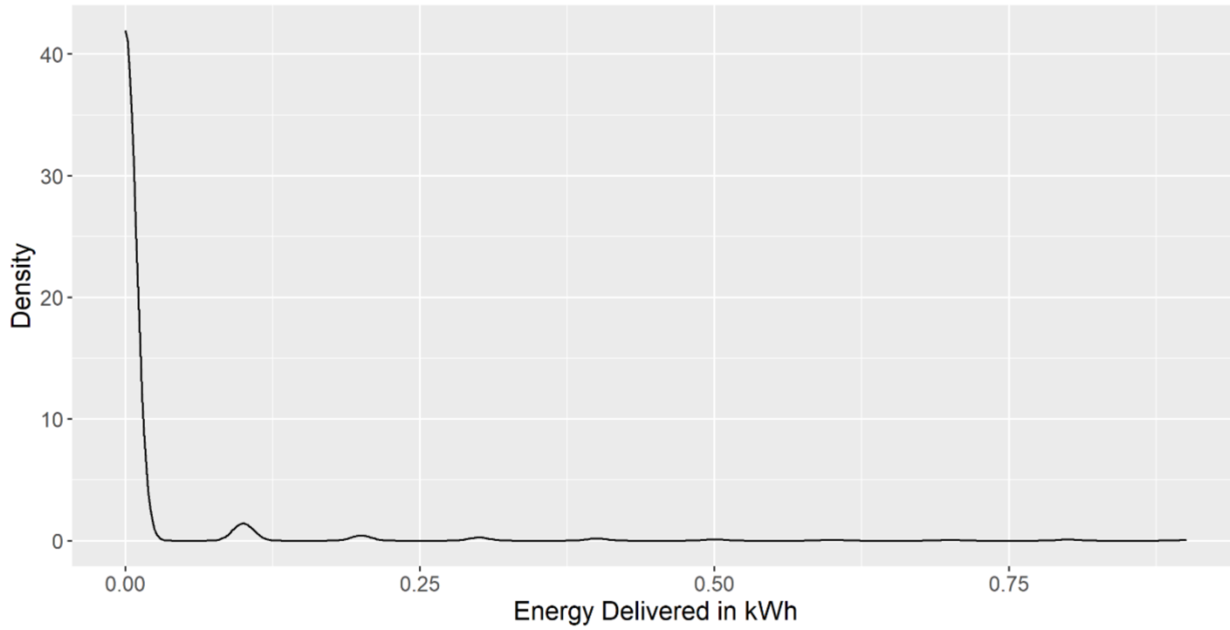

Figure 15: Distribution of Energy output of charging events that dispensed less than 1 kWh.

Step 2: Determining visit threshold and Defining Visit ID

We needed to establish a time threshold to differentiate different charging visits from the same user. This threshold represents the minimum time gap required to differentiate two charging sessions whether they are part of the same visit or distinct visits. Initially we selected a time threshold of 5 minutes intuitively. After careful analysis of the data (found in Figure 16), we identified that the time threshold for 5 minutes agrees with the evidence.

Figure 16 draws charging data that included unique User IDs. We were able to group charging data by station location and arrange by chronological order to plot the time difference between consecutive charging events. According to Figure 16, we identified that if there are multiple charging events recorded by the same user, almost all such charging events by the same user at a given station takes place within 5 minutes of each other. We observed that attempts from different users are usually recoded after 5 minutes of the end of the previous event. This trend might change with corridor chargers as more EVs are driven for long distance trips. But using User ID information, such events can be differentiated. Intuitively multiple attempts by users within the visit threshold indicates some difficulties in successfully initiating charging.

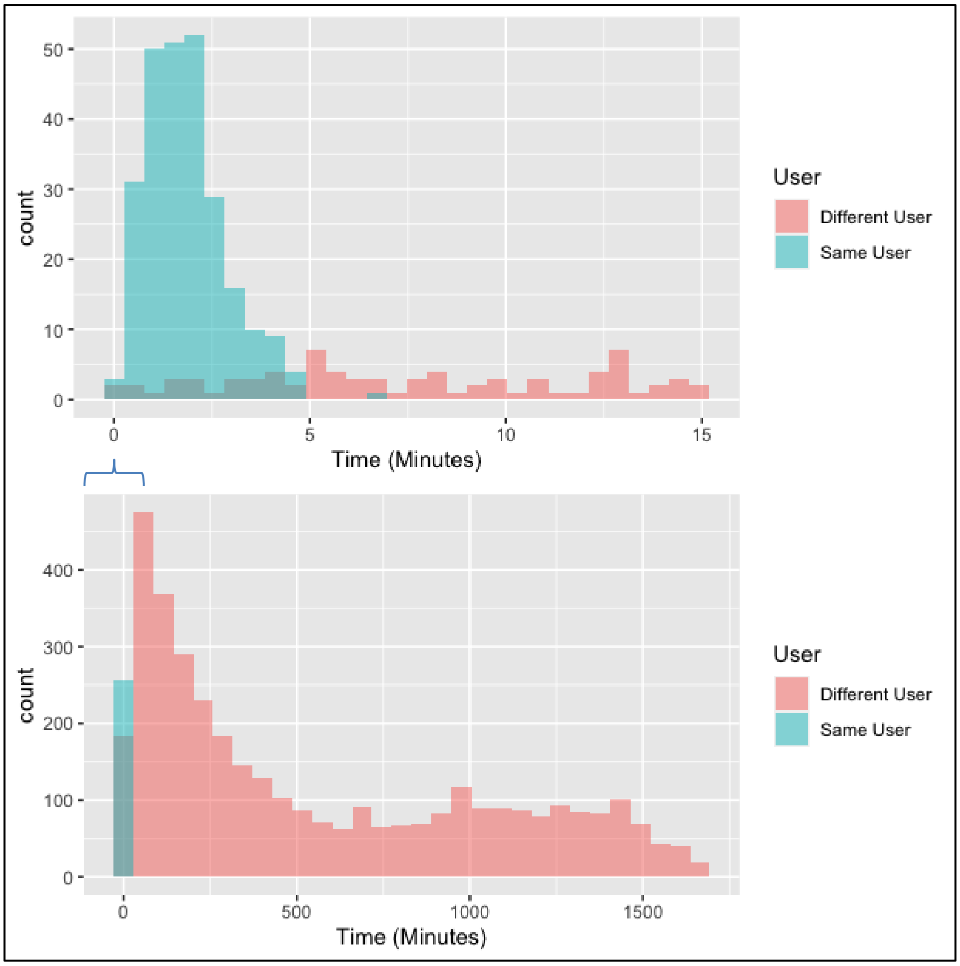

Figure 16: Distribution of time interval between recorded charging events at the same charging station between the same user and a different user. (Top) distribution is a subset of the data for 15 minutes.

Visit identification.

Based on visit threshold determined before, we group all charging events recorded by a user during a single visit to a charging station by defining a Visit ID. First, we arranged all the charging events in the dataset by Station ID and Charger start date-time to ensure chronological order. Then we grouped the data by Station ID and User ID to process each charging station separately.

Step 3: group events by Visit ID.

In this step, we created a new summary dataset from the previous dataset that had Visit ID information. We grouped data by User ID, by the success/ failures of the event, Station ID and Visit ID. This dataset gives more information of how many successful and unsuccessful attempts were made by a user for a given visit.

In the next step, we further summarize the previous data by summarizing the count of successful as well as unsuccessful attempts grouped in the same row by User ID, Station ID and Visit ID. This summary table provides a more comprehensive grasp of the events that transpired in a visit to the charging station.

Variation 2 for datasets without unique user ID information:

Some data sets may not contain User ID information. Until industry wide charging data collection best practices are adopted, some charging databases may have data without User IDs to differentiate events by users. In such a situation, we can approximation the previous rigorous visit identification process by differentiating events by a 5-minute time threshold by Stations. We had to use this methodology for data collected from one EVSE provider as they did not include User ID.

Step 4: Identifying Failure/ Success Categories:

Based on the summary database created from Step 3, we're able to classify outcomes from charging visits as follows:

a) Identifying Persistent failures (Failures > 0 & Success == 0)

We define persistent failures as visits where either (1) the users could not successfully have the chargers working as intended even after multiple attempts (multiple failed attempts with no success) or (2) users did not attempt to try again after first failed attempt. In both instances, the users leave the charging station not having received any energy.

We can filter such persistent failures using visits where the outcome follows the criteria mentioned above.

b) Identifying Troubled success (Failures > 0 & Success == 1)

These are charging visits where users had some initial difficulties in initiating the charger but managed to get the charger working after some attempts. We can filter such visits using the criteria here.

c) Identifying Charging interruptions (Success > 1)

Here we identify a unique situation where the charging event was stopped or interrupted during a charging session. We hypothesize that the charging station or vehicle ended the charging event as part of a safety feature that prompted an emergency stop. This is a necessary feature built into the charger eco-system to protect damaging the equipment or prevent harm to the user. However, charge interruptions can result in incomplete charging, longer charging times, and inconvenience to the EV driver if they were not notified real time of the charge interruption.

Charging interruptions can happen at any point of the charging process. Therefore, to better capture such events, we can expand the visit threshold previously defined from 5 minutes to 2 hours. Unfortunately, that means only datasets with user IDs can be able to fully capture interruptions using this method.

We filter out visits where 2 or more 'successful' events were recorded back-to-back. We hypothesize that this is an indication of forcing the driver to re-start the charging process to achieve a desirable level of state-of-charge.

d) Identifying Throttled Charging

We refer to a situation where the charging speed or output power in kW was much lower than the advertised speed as a throttled charging event. There are many factors that can limit the charging speeds such as SOC of the battery, limitations set by the vehicle. Conceptually this is a situation where charger is failing to meet the desirable speed by the vehicle considering limitations in the power rating.

Step 5: Identifying Successful events and measuring performance.

A successful outcome in the first charging attempt should be the aim of charging service providers and can greatly enhance the charging experience of users. Here we use the following criteria to identify first time success.

First time success (Failures == 0 & Success == 1)

A simple probability can be calculated for every level of success/ failure based on charging visits as follows:

$$Probability\ of\ first\ time\ success = \frac{Visits\ with\ first\ time\ success}{Total\ number\ of\ visits} \quad (1)$$

Practically, we think troubled success should also be considered as part of overall successful outcomes. In our analysis we aim to include (1) first time success, (2) troubled success, and even (3) interrupted charging in the first layer of success. Then we can identify the probability of throttled charging out of the generally successful visits.

Criteria for **Generally Successful visits (Failures >=0 & Success > 0)**

$$\text{Gen}erally\ succesful\ visit = First\ time\ success + Troubled\ success\ visits + Charging\ interuptipns$$

Holistically, we use equation (2) to calculate the probability of a successful visit with no throttled charging and no interruptions.

$$Probability\ of\ holistically\ succesful\ visits = P(generally\ succesful\ visit) * P(no\ throttled\ charge) * P(no\ charge\ interuptions) \quad (2)$$

Summary of the Data collected:

The data in our database starts from August 2019 starting from brand B. The Stations from brand A were finished in January 2021. We have data collected until 11-22-2022 used for this study. Figure 17 is a summary of the number of charging events ordered by charging station and network provider.

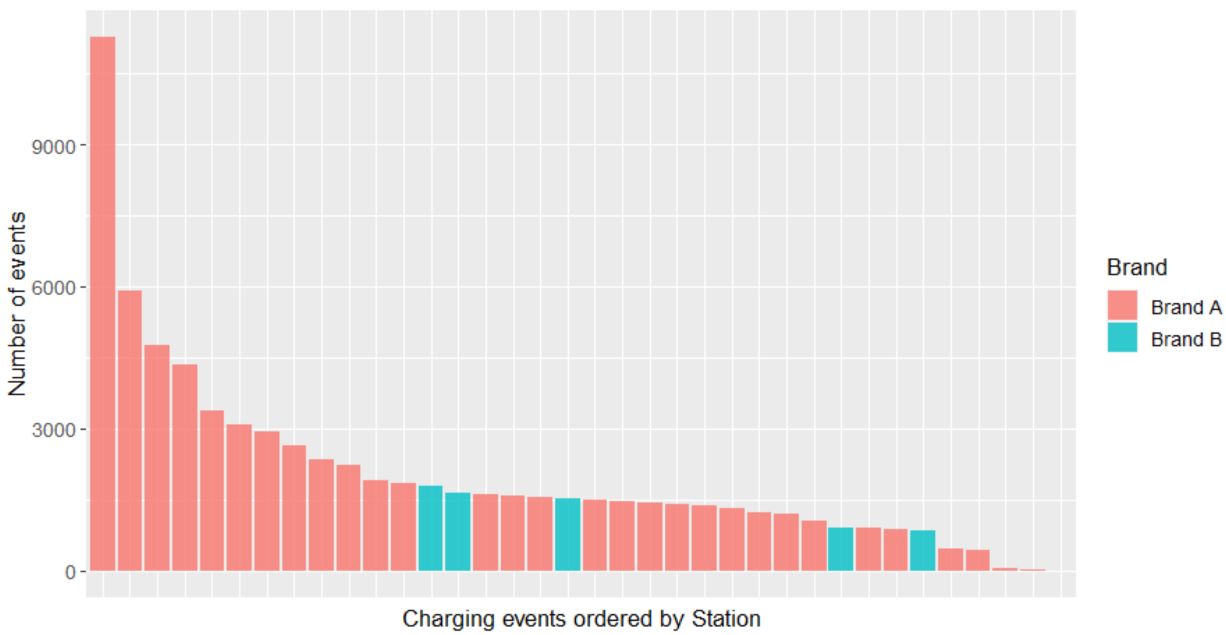

Figure 17: Summary of the data by Station and Brand of EVSE (Station names in the x-axis are muted here to protect the EVSE brand identities)

Table 9 provides a summary of the number of recorded charging events from each charger brand and the number of chargers included in the dataset. (Some stations included 2 chargers and few stations had 4 co-located chargers). The generally recorded number charging events appears to be low compared to other similar databases for the given period. We believe this is because this data is from en-route corridor chargers selected for this project by CALTRANS because of the lower BEV traffic volumes as opposed to destination chargers installed in high traffic long-dwell locations such as department stores or workplaces. A map of the charging station locations is found in Figure 18.

Table 9: Summary of data sources collection

Site owned by	Brand	Number of chargers	Connectors	Recorded number of events	User ID available	Percentage of Successful events*
Caltrans	Brand A	47	CCS, CHAdeMO	59,542	**No**	**54%**
Caltrans	Brand B	7	CCS, CHAdeMO	6,726	**Yes**	**71%**
	Total	**54**				

**Refers to the preliminary definition of success used to screen charging events.*

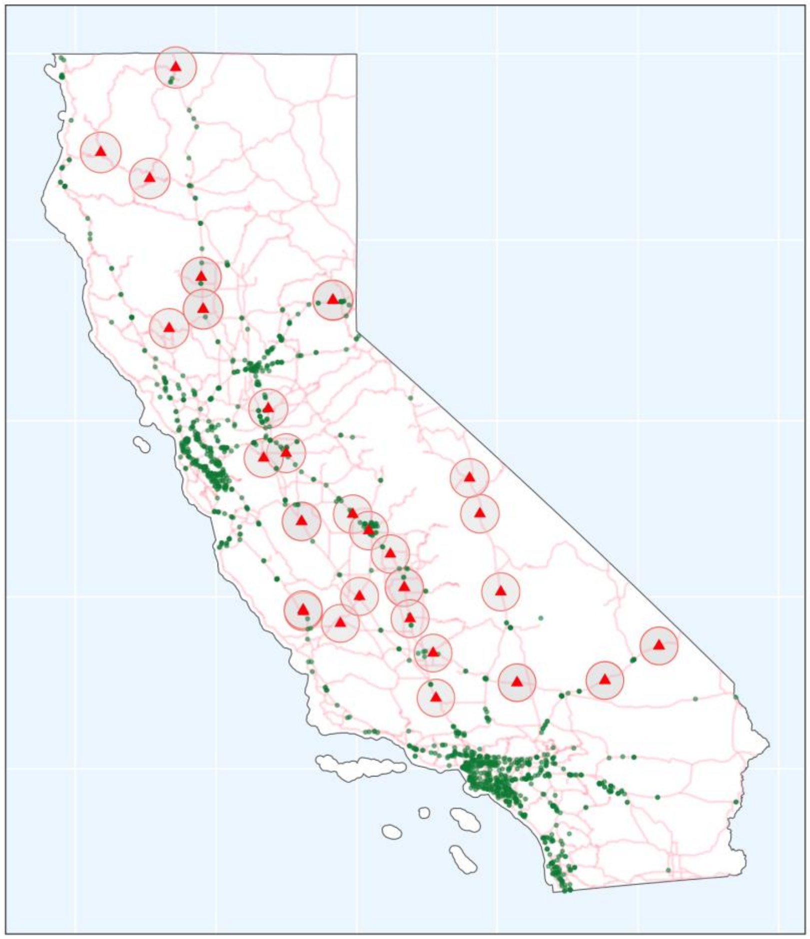

Figure 18: Location of the ZEV 30_30 charging stations (in red) with respect to other public DCFCs in California (in green)

2.3. Results

This section covers the results of the reliability calculations from the dataset described above. We show this as a practical application of the methodology section for a network as a whole and individual stations. In this section, we also use the methodology to identify causes of persistent failures.

Overall Probabilistic Reliability results for Brand B network

A summary of the analysis for brand B data is provided in ***Figure 19***. For Brand B, the total number of 6,726 recorded events from the DCFCs in our analysis maps to 5,761 unique visits where multiple charging events are assigned to the same charging visit. With this information, we can determine the failed visits with no successful outcome. Figure 19 includes the summary of this information for all the charging stations that installed brand B in the network. About 25% of the visits experience first time failure. But 8% of them try again and manage to get the charger started. We then add these visits in the overall success. About 17% of the drivers experience failed visits. That's comprised of 14% of the drivers who didn't try again and 3% who experience persistent failures despite trying again. Overall, we identify an 83% probability of generally successful visits in this network of chargers.

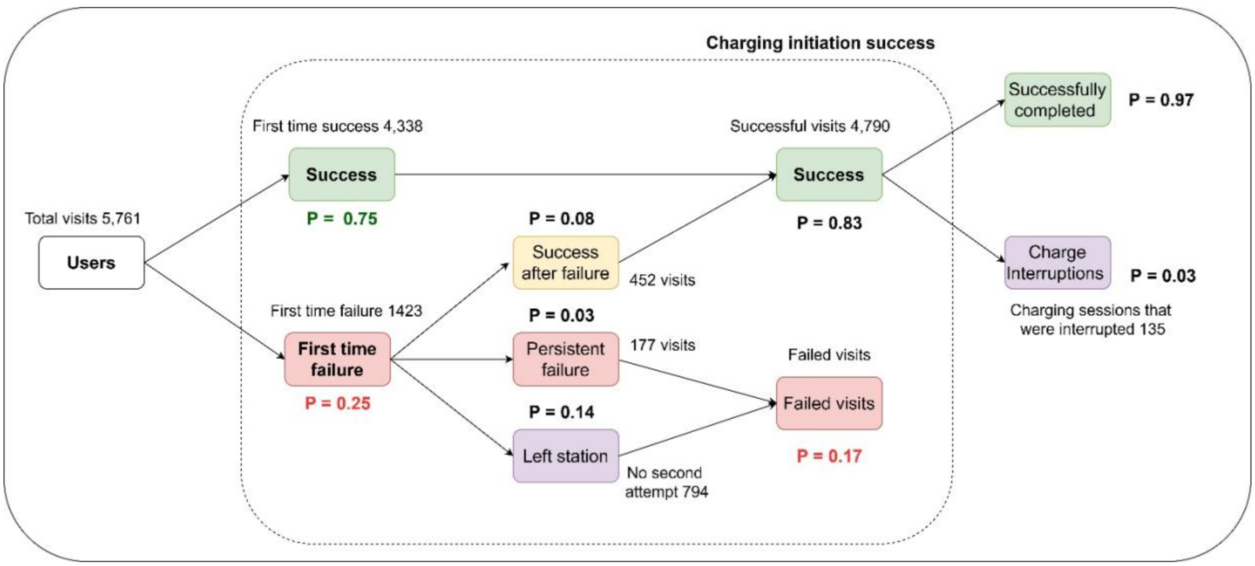

Figure 19: Summary of reliability probabilities for brand B

We identify that out of the 4,790 successful visits, at least 3% of the drivers experienced charging interruptions based on our methodology. Therefore, we can calculate the probability of holistically successful outcomes for the network as follows using the previous equation (2):

$$\begin{aligned} &Holistic\ reliability\ metric\ based\ on\ probability \\ &\qquad = P(generally\ succesful\ outcomes) * P(no\ throttled\ charge) \\ &\qquad * P(no\ charge\ interuptions) \ldots \end{aligned}$$

$$Holistic\ reliability\ metric\ based\ on\ probability = 0.83 * 0.97 = 0.81$$

Brand A network

Using our methodology, the total of 59,542 recorded events at brand A charging stations converts to 42,014 visits as summarized in Figure 20. As the brand A network data did not collect User ID information, we're approximating charging events recorded by different users. To do this, we're using our methodology and grouping charging events by connector type to further separate data by different users. As indicated, about 24.5% of the users did not have a successful outcome from the charging visits. About 8.5% of the drivers experienced troubled success (had some initial trouble charging but managed to have a successful charging at the end). So overall we can assign a 75.5% probability of success at the brand A network.

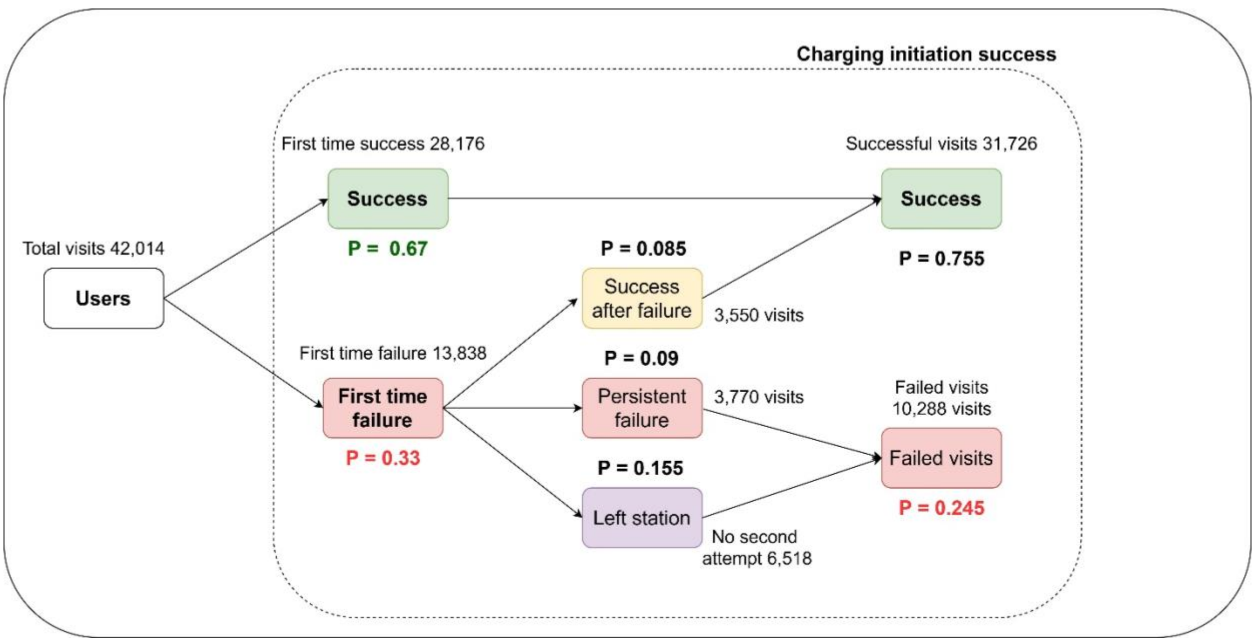

Figure 20: Summary of reliability probabilities for brand A

As the brand A network data did not collect User ID information, we are unable to holistically calculate charging interruptions.

Probability of generally successful visits by Station level

To better understand station-based reliability, we can separate the charging visits by stations and calculate a probabilistic reliability value by stations. Such a distribution is available in Figure 21. The color legend is as follows. Stations that have 0.9 probabilities or higher are represented in green, stations with 0.8-0.9 probabilities of general success are represented in orange and stations with probabilities less than 0.8 are represented in red.

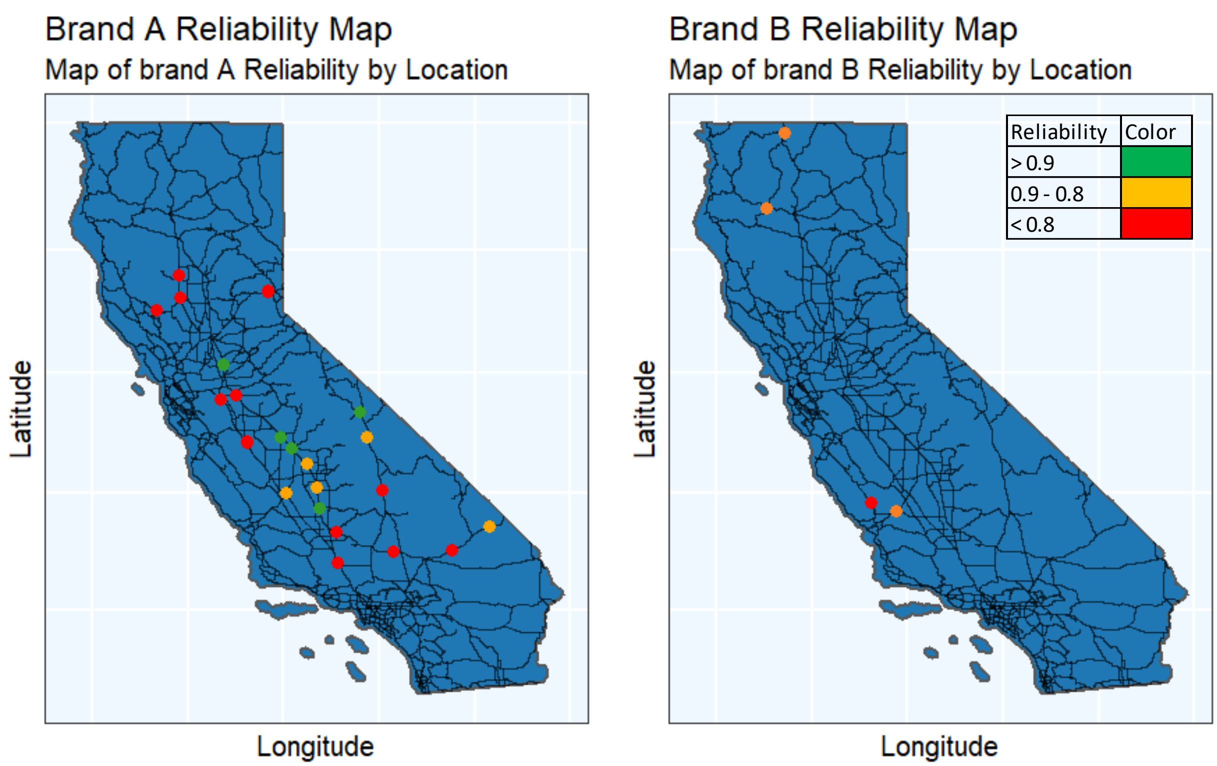

Figure 21: Probabilistic reliability of charging stations with Brand A (left) and Brand B (right)

*It is important to note that one charging station (A Caltrans maintenance station far north of Sacramento) is missing from the map. We have no usage data from that charger. However, upon further investigation, based on public comments from Plugshare for that station, we think the charger is working properly. There can be several reasons why the charger is not communicating charging data to the server such as (1) limited cellular signal in the vicinity or (2) malfunction in the charger's cellular communication system.

Diagnostic analysis based on persistent failures based on charger error codes.

Using the classification made with Visit IDs, we're able to filter **persistent failures** using the criteria described in the methodology. These are visits (1) where the users could not successfully have the chargers working as intended even after multiple attempts or (2) did not attempt to try again after first failed attempt. Then we can reverse our strategy in converting charging events to visits by mapping visits back to individual charging events. This is because successive errors considered in the same charging visits can have different reasons. Furthermore, errors are assigned in the dataset to a specific charging event, not visits. Here we conduct a deeper diagnostic analysis of the charger eco-system of the causes of persistent failures.

Error codes

We derive error codes from the session end type information that is recoded in the dataset. Error codes are typically a subset of the session end types which can also include information of successful charging and normal shutdown of the charging stations. For our analysis an error code is an indication of a failed charging session. These include issues like communication errors, over-current errors, temperature related errors, connector/ cable issues and system errors. These codes are not consistent across different EVSE brands and there is an ongoing effort by the National Charging Experience Consortium to standardize diagnostic and testing tools such as error codes [61].

Types of error codes and sub-categories

With brand A we were able to identify 39 distinct error codes from the recorded charging events that map to persistent errors. We have attempted to group together the 39 charging error codes into larger error categories to the best of our understanding using publicly available information and information provided in EVSE user manuals. Brand B only had 11 distinct error codes for the persistent errors, and we have summarized how we grouped error codes in Table 10.

Table 10: Error categories used for analysis.

Category	Error codes
None	No indication of errors
EVSE electrical safety	Indication of charger stop due to risk of electrical safety to the user or vehicle
EVSE cable connector	Indication of problems in the charger cable
Authorization payment	Errors in payment authorization
Vehicle connection communication	Indication of communication errors between the EVSE and vehicle
Emergency stop	STOP button from the user or vehicle forced emergency stop
other	other

Brand A

Figure 22 represents the causes of persistent reasons out of 40,724 total charging visits. We identified unique error codes pertaining to the CCS and CHAdeMO connectors. We identified overall 12,874 events mapped from persistent failures. A summary is found in **Figure 22**.

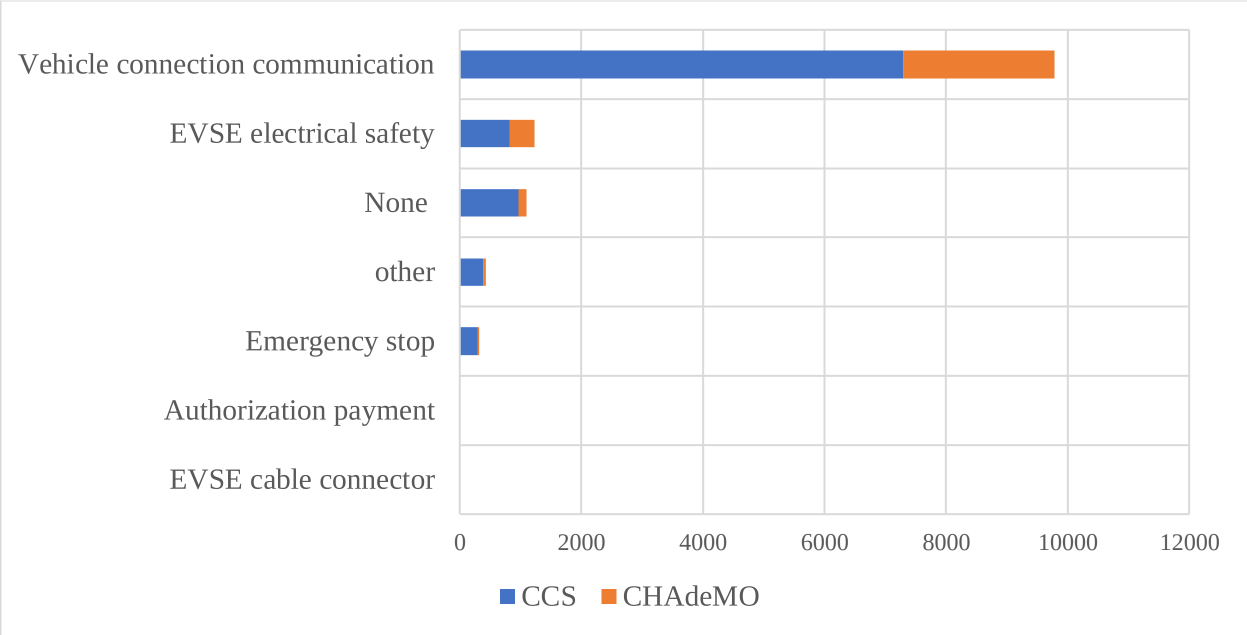

Figure 22: Causes of persistent errors for brand A

Brand B

Figure 23 represents errors out of 5,760 total visits. A total of 1,116 events are mapped from persistent failures. Here we observe that some events are not able to identify the connector used by the user and are listed as NA. Brand B had far less distinctive error codes by their design. Although we could not find a manual that describes the meaning behind brand B error codes, they were descriptive enough to infer some meaning.

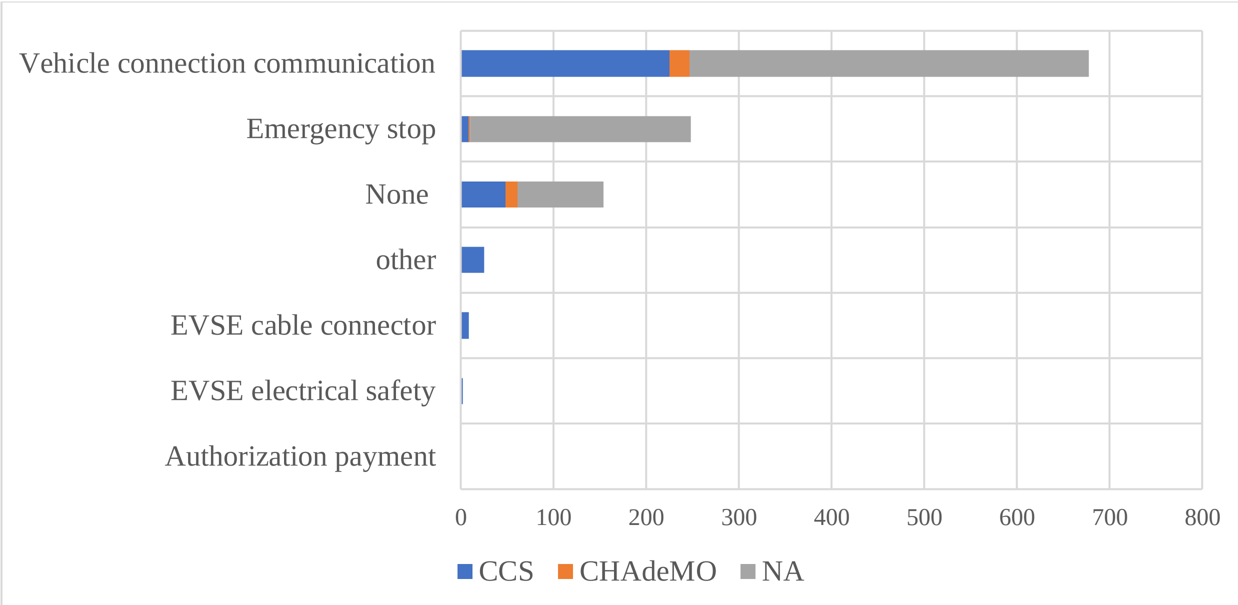

Figure 23: Causes of persistent errors for brand B.

Comparing EVSE networks

Data from **Figure 22** and **Figure 23** were not comparable because the total number of visits and charging events that lead to the error counts were vastly different. Also, the same network may have different hardware models by the same manufacturer. To rectify this, we created a plot to count errors per 1000 charging visits in **Figure 24**. The purpose is not to compare the two brands but identify common trends. It's clear that communication failures between the vehicles and EVSE is a major cause of persistent errors.

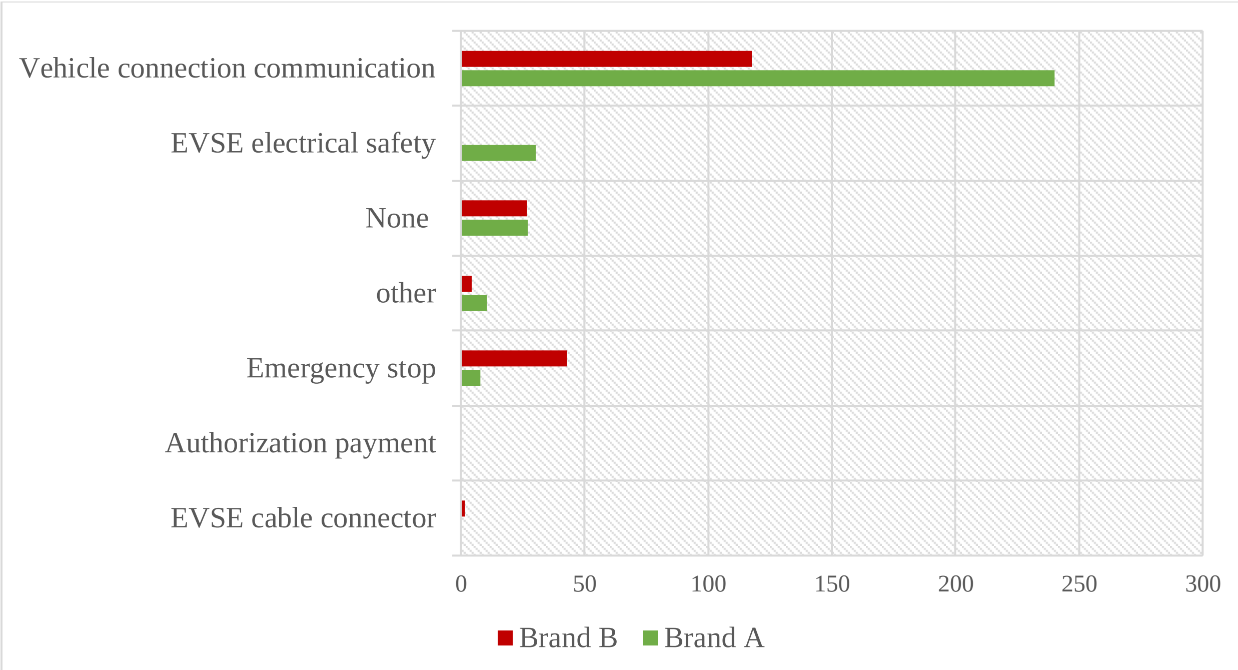

Figure 24: Errors counts by both brands per 1000 charging visits (error counts are in events, and therefore not an indication of outcome of charging visits)

2.4. Discussion

Deeper diagnostics

The most prevalent reason for persistent charging errors was communication errors. This indicates the inability of the charger and the vehicle to communicate with each other. When this error is identified, we see that charging events only record minimum information such as attempted time, OCPP ID and plug type that can be recorded from the charger sensors. Information that is communicated from the vehicle such as starting SOC and battery voltage are not recorded as expected. The communication errors in Figure 24 can be stemming from multiple reasons. They are (1) charger is not able to initiate communications with vehicle, (2) connector is not properly connected to the vehicle, or (3) vehicle is not communicating with the charger. Based on some informal interviews we conducted with industry partners, this type of error is largely caused by problems that may prevent physical contact between connector pins and the vehicle charger port (i.e., having some dirt in the connector pins, damaged connector pins or misaligned connector preventing communication). When physical contact is established, this error can be caused by interoperability issues of digital communication between the vehicle and the charger [62]. The assumption is that charging is not initiated because communication cannot be established. The common industry standard for DC fast chargers is the ISO/ IEC 15118 which includes a whole subset of standards for plugs, charging topologies, communication, security, and safety [63]. ISO 15118-2 is the vehicle-to-grid communication interface that's commonly used right now. But other communication standards such as DIN SPEC 70121 exist with the new ISO 15118-20 standard promising to be an advancement to the ISO15118-2 standard. CEC analysis suggested that DC Fast chargers in the market are already ISO 15118 ready [64]. Therefore, any interoperability challenges suggest a gap in testing and compliance of these chargers. More recently automakers have made announcements supporting the North America Charging Standard (NACS) as they move forward. While NACS is the design of the physical connector, it is unclear what communication interface is going to be used to support NACS.

As 8-9% of users experienced troubled success in both networks, we hypothesize that this is due to challenges of maneuvering the cumbersome plugs designs. Adopting the NACS connector may alleviate some of these challenges as it is smaller and easier to use [65]. Some customer education and outreach may also help alleviate frustration at the charging stations.

DC Fast chargers are essentially operating in a complicated eco-system of physical infrastructure, standards (also called public key infrastructure), users, and vehicles. In this eco-system both physical infrastructure and vehicles are supplied by many different market actors (brands) for users who have very different education and experience with charging station usage. When setting reliability expectation to such a complicated techno-economic user ecosystem, regulators should consider the broadest possible understanding of the full eco-system. Furthermore, trying to achieve very high reliability without fixing major design problems within the eco-system may even cause more problems. For example, throttled charging and charger interruptions can occur due to several reasons, such as protecting the battery from overheating, charging cable overheating, ensuring safety to the vehicle and user and general faults in the charging equipment. In trying to fix such nuanced problems, it is important to have an open dialogue with EVSE manufacturers, designers and charging standards and protocols planners to get to the bottom of existing design faults. Federal and State government agencies are well placed to initiate such discussions. The ChargeX consortium initiated by the Joint Office of Energy and Transportation is a step in the right direction.

Policy Implications

The aim of this study is to demonstrate the effectiveness of our proposed methodology in assessing the reliability of charging stations, providing insights into the actual experiences of drivers at these stations. We can employ certain metrics outlined in this study to gauge industry progress, such as achieving consistently successful visits in the short term and first-time success (every time) in the long run. Our approach to reliability is outcome based placing more emphasis on customer experience compared to uptime. **Figure 14** illustrates how uptime is missing a comprehensive range of errors and customer pain points. While high uptime is a necessary precursor to high reliability, first-time charging success when chargers are online should be the definitive goal of the industry and policymakers. Nearly all metrics suggested in the paper dependent on accuracy of visit identification. Here we want to emphasize the importance of capturing User ID or some form of anonymized personally identifiable information (PII) such as vehicle identification number (VIN) that can be used to differentiate multiple attempts to charge the same vehicle at a given visit.

From the results we can determine that the corridor charging stations we analyzed are not meeting our reliability expectations. Brand A and B networks respectively have an average of 77% and 83% chance of a generally successful visit. We also find significant variation in performance in different charging stations. Individual stations in network A had a chance of a general success between 13% to 95% whereas network B stations had a range of 79% - 87%. While the quality of the EVSE brand appears to have some impact on the station performance, we believe other factors such as frequency of maintenance and frequency of usage impact the reliability of charging stations. As found in Figure 21 some charging stations had less than 80% of successful visits. This means that at least 20% of visits to the charging station may result in failures. In comparison to the current gas station business model, this level of reliability is unacceptable. We also think that a high count of usage data per station will improve the accuracy of the probabilistic reliability indicator proposed in this study. As more charging data is made available with higher EV adoption, our methodology can be modified to measure the reliability over time.

The broader goal of our study was to evaluate the scale of the reliability failures in California's network of corridor fast chargers. This is an exploratory study to identify the depth of the problem. The results are very clear, and the problem is severe. Unless resolved, current reliability numbers will hinder the further adoption of electric vehicles and might slow down California's ambitions plans. The urgency of this problem cannot be understated, and we need all stakeholders to prioritize their efforts and focus on addressing the reliability of public DC fast charging stations. California legislation, such as AB 2127 and AB 2061, have focused on improving public charger reliability. The Federally funded NEVI program also has a strong focus on ensuring reliability. The reliability indicator proposed in this study help measure and achieve high reliability better from a customer focus.

As suggested in AB 2061, further reliability metrics should be encouraged. We present our probability-based reliability metric here as one possible measure. As more usage data from DCFCs become available, our methodology can be a mainstream method for evaluating the reliability of charging stations that closely represents the true outcome at a charging station. We are optimistic that the Electric Vehicle Charging Analytics and Reporting Tool (EV-ChART) that is being developed by the Joint Office will facilitate further research to that end. We recommend further research into developing metrics and performance indicators to measure other aspects of customer satisfaction such as (1) ease of use, (2) accessibility, and (3) real-time information availability. The ChargeX consortium is in the process of developing key performance indicators (KPIs) at the time of writing this document. Another interesting study relating to reliability is exploring the causes of throttled or slow charging when it appears both the vehicle and charger are capable of higher speeds. We believe having access to more detailed charging session information can help us understand this problem.

Chapter 3: Are all Charging Stations Created Equal? Identifying location-critical corridor chargers and the need for location-based reliability metrics.

3. Identifying location-critical EV corridor chargers and the need for location-based reliability metrics.

3.1. Introduction:

Modern society is heavily reliant on key infrastructure systems such as electricity, transportation and telecommunication, among others. They serve an essential role in sustaining daily operations, enabling economic activity, and ensuring public safety [66]. With the wide adoption of battery electric vehicles (BEVs), charging infrastructure to support BEVs is becoming an increasingly vital infrastructure network. While home charging can be the backbone of charging for BEVs, public chargers can support routine charging for BEV drivers who cannot charge at home and support irregular charging for drivers who miss charging and/or have unplanned trips [16]. Furthermore, a network of reliable fast-charging stations can facilitate long-distance BEV trips, as they have higher energy needs and a preference for low dwell times.

The U.S. Bipartisan Infrastructure Law (BIL) signed into law in 2021, aims to build such a network of reliable fast chargers across selected alternative fuel corridors (AFCs) under the National Electric Vehicle Infrastructure (NEVI) formula program. In this context, DC fast chargers installed along roads and highways called corridor chargers are expected to support inter-regional and interstate EV driving trips [13]. Before the NEVI program was introduced, the State of California has been in the forefront of building out an initial network of public chargers with publicly funded programs. Such programs include the Caltrans ZEV 30_30 and the CALeVIP program funded by the California Energy Commission. California is also the State with the highest number of BEV ownership. While NEVI program and other California programs have clear guidelines on planning and rules on site selection, it is often unclear how many more chargers are required to support the future growth of BEVs. Moreover, the final NEVI rules establishes that each charging port must have an average of annual uptime greater than 97 percent uptime [60]. It is widely recognized that achieving a high level of reliability and performance necessitates proactive maintenance activities [67]. This involves continuously managing large maintenance crews, and the adherence to scheduled service of equipment in strict time intervals. From a resource allocation perspective, this introduces significant costs to an already challenging business environment.

Furthermore, the inequity of the spatial distribution of charging stations is clear along many factors such as the urban-rural divide, the wealthy and underserved communities and across different types of home ownership [68]. More recently studies have begun to shed light on the inequity of charging stations that has often been ignored by planners. The inequities highlight not only the lack of chargers in isolated locations, but not having enough chargers in high demand locations. This question is often made complicated by unreliable charging stations. While addressing "range anxiety" was a problem to solve many years ago, **"charging anxiety"** appears to be becoming a predominant barrier for BEV adoption right now. It is characterized as the feeling of uncertainty about the ability to use chargers while on a trip, as opposed to locating a charging station [31]. It encompasses a larger set of issues such as availability/presence of stations, characteristics of vehicles (i.e., range) and reliability of charging stations. Range anxiety can transform into charge anxiety with heightened concerns with unreliable or inconvenient charging station. BEV drivers arriving at a station with low state of charge (SOC) might be faced with many levels of travel disruption with unreliable/ inconvenient chargers. Even if the chargers appear to be working, slow chargers can disrupt travel plans, as do charging stations that are occupied by multiple other EVs [16]. As we transition to a more electrified transportation system, the seamless functioning of these systems is critical, as disruptions can have effects across multiple sectors, highlighting the importance of resilience and reliability of the network of charging infrastructure. In many ways, the function of a charger is to charge the battery of a BEV to keep the vehicle in motion [69]. A broad definition that captures the nuances of BEV drivers is: "From the perspective of a BEV driver, a reliable charger successfully charges their EV, for the expected duration, at an expected rate, after accepting an appropriate payment method"[8].

[8] Public Comment from Gil Tal on August 22, 2022, in response to the NEVI proposed rulemaking published by the Federal Highway Administration (FHWA) on June 22, 2022. ref: FHWA-2022-0008-0317

How charging disruptions affect drivers? (Measuring inconvenience)

The level of disruption from a charging failure for BEV drivers is a measure of disruption from the driver's perspective. It attempts to understand "inconvenience" and the hassle of finding alternative charging options so that the driver may continue their trips to their intended destination. In extreme cases, the driver may have to change travel behavior based on charging session failures or can be completely stranded because of a charging failure.

A study by UC Davis modelled the possible level of travel disruption for BEV drivers based on the hassle drivers would face. The researchers considered hypothetical charging disruptions based on recorded charging and travel data. They came up with different levels of disruptions. If the next trip cannot be completed due to a failed charging session, then that charging failure is considered "trip disruptive". If the next charging location cannot be reached after a failed charging session, it is called "charge disruptive". If all trips that occur after charging session failure cannot be completed, this situation was called "day disruptive" [26]. While this framework attempts to understand an individual driver's inconvenience, a complete framework should measure how many drivers were affected. Moreover, this research sheds light on what drivers may face in hypothetical charging disruptions, detailed trip and charging data is necessary for this methodology. Depending on travel conditions, road conditions and broad environmental factors, some failed charging sessions are more prone to disruption than others. Some conditions are inherent to the vehicle, such as (1) vehicle battery capacity, (2) battery age and (3) remaining battery state of charge prior to the charging session [26]. Environmental factors such as cold weather can reduce BEV fuel economy, aggravating the charging disruption [70].

Our study focuses on identifying critical corridor DC fast chargers in that network through a comprehensive modeling approach considering various attributes of the existing corridor charging network in the United States. The objective is to develop a tool to measure the relative importance of different chargers for the resiliency of the whole network to ensure efficient and uninterrupted travel for BEV highway users. The methodology involves data collection, geospatial analysis, demand modeling (approximation), and the development of mitigation strategies via different maintenance strategies. We believe that higher levels of reliability can be attained through increased maintenance and better equipment. But this may come at a higher cost. It's worth noting that not all charging stations need to meet the same standards of reliability and evaluating them based on the same criteria can divert resources away from where they are most needed.

Current research on charging station reliability focuses on reliability from a technical perspective. Such studies dive deep into charging station topologies and components [21] [23] and tend to focus on identifying issues at charging stations. These studies do not focus on resilience of the whole infrastructure network and identify which stations should be more or less reliable. Complex infrastructure systems such as the electrical grid follows three broad maintenances scheduled as listed below. They are determined based on the need (criticality of components) and available resources [67]. (1) Condition-based maintenance (CBM) initiates a maintenance activity when data from equipment monitors indicate a need, (2) reliability centered maintenance (RCM) prioritizes maintenance activities based on the quantification of the likelihood and consequence of equipment failures, and (3) optimization techniques offer methods for maximizing the effectiveness of maintenance activities subject to constraints on economic resources, available maintenance crews, and restricted time intervals [67]. While this is a useful and holistic classification, this work focuses on the reliability of electrical grid components and does not focus on EV chargers. Nor does the study inform how to choose differentiated maintenance techniques based on location and the required charger reliability. Ideally, such a study may use real-world reliability information to optimize maintenance resources and identify critical charging stations.

From an infrastructure network perspective, "resilience is the ability of a system to prepare for, absorb, recover from, and adapt to disturbances [71]". Researchers are increasingly interested in "Complex networks" that usually describe complex interconnected systems involving many users and infrastructure systems such as transportation, communication technology to name a few. Network resilience of such a system requires the understanding of how such a network respond to change, revealing their characteristics and underlying structure [72]. Such networks can be analyzed with graph-structured data that includes node attributes (node name, number, node weight), edge attributes and other information.

The concept of resilience has different interpretations for specialized infrastructure networks, and this is still an evolving concept for charging networks. We think resilience involves the ability of the local and regional charging network to function after the disruption of a charging station. Most studies conducted on charging station reliability relies on a single definition of charging failure and does not consider potential levels of different charging failures and travel disruption [26]. Other studies focus on the spike in demand at some stations during emergencies and extreme weather indicating the complexity of studying network resilience [73]. Therefore, any study of charging network resilience should start with understanding the scale and scope of drivers impacted by a charging station breakdown (i.e. metric of unmet charging demand).

One common method used in understanding business demand within an urban region is called "Point of Interest (POI)" demand modelling. It is commonly used in urban regions for business site selection and real estate investment. This method exploits daily needs of people via large scale mobility data with respect to the business of interest. More specifically, such models would exploit urban geography data (i.e. road networks, other point of interests (POIs)) and human mobility data (i.e. GPS traces from vehicles, traffic measurement data) [74]. Such human mobility data usually benefits from fine-grained location information and time information. This is considered more systematic compared to survey data and is colloquially referred to as "*people vote with their feet"* [75]. In the context of charging stations, emerging studies have found a relationship between traffic volumes and charging demand at corridor stations in California [13]. While the study found daily time-of-day pattern differences between weekdays and weekends, the hourly recorded number of charging events corelate to hourly traffic volumes indicating a high relationship and requires further study. It is important to mention here that this study was conducted for corridor charging stations that are mostly located in rural areas. It remains to be seen if the same relationship holds for charging stations located in urban congested city centers.

In the context of gas stations, other methods include analytical hierarchy process (AHP) and ordered weights based on surveys to come up with a hierarchy of potential locations [76]. According to other studies, availability of data is a limiting factor in fully utilizing the full potential of available methods. This method has been explored for ranking gas station in Beijing to evaluate business performance between sites. Information collected from taxicab refueling event detection and GPS data for dwell times were used to identify gas station crowdedness. Other geographic information and feature extraction of gas stations such as price of gas to come up with a ranking for gas stations in Beijing to evaluate their business performance [76].

3.2. **Data and Methods**

Analysis framework:

We propose a framework below to identify the most critical charging stations from the perspective of the resilience of the whole complex eco-system of charging stations and their users. Criticality of a station is broadly measured how well the users of the network can respond to a change in the network, and how many users were affected, and level of disruption to users in the context of their desired trips. Below we aim to measure five different aspects of this complex infrastructure system as follows. (1) Initially, we aim to measure the number of users who would be disrupted if a charging station were hypothetically unavailable. We calculate this metric based on the foregone demand at a charging station. (2) Secondly, we aim to measure how users can respond to an unavailable charging station by measuring the redundancy of the network by considering alternative stations within the remaining driving range at the time. (3) Next, we identify which charging stations are more likely to require a high degree of maintenance considering the age of their hardware and likelihood of being exposed to environmental factors. (We currently use the opening date of a charging station as a proxy to age of the equipment, assuming the equipment haven't been replaced. While this assumption may not hold for a few chargers that have been replaced, we believe with better data, this can be resolved). (4) Then we assess the level of disruption for users by identifying the expected power performance (charging speed) when drivers arrive at a charging station. Here we hypothesize that users will arrive at a charging station capable of higher speed with a high degree of expectation and service. And next (5) we identify the redundancy within a charging station by the number of fallback chargers within a station in the event one or more charging hardware fails. More details of the methodology are explained in the methodology section.

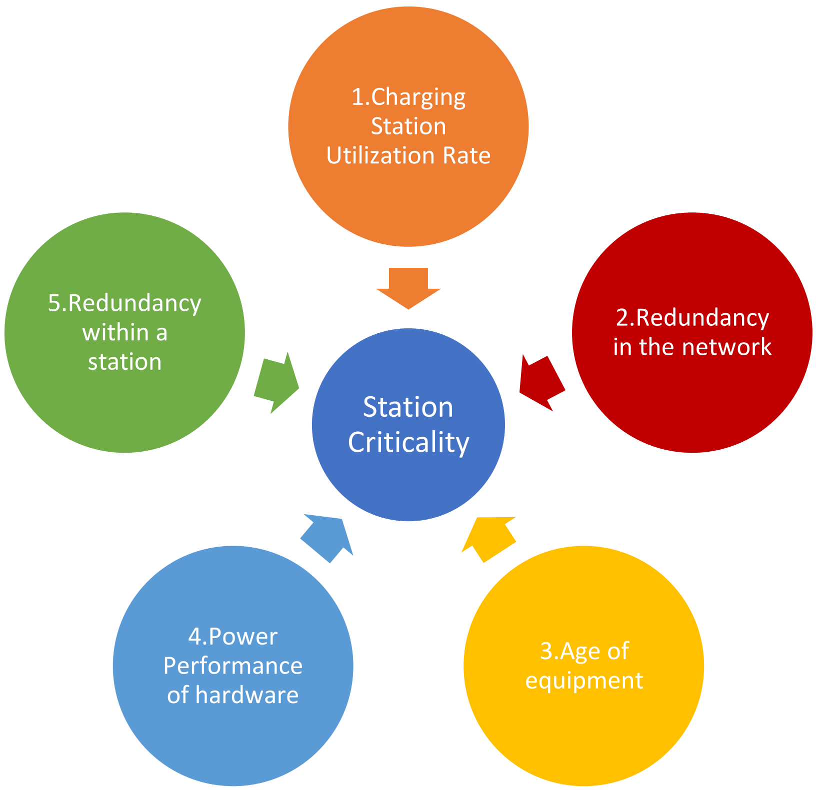

Figure 25: Framework for measuring charging station criticality

While we think the five categories proposed before captures the characteristics and underlying structure of the charging station network, we think it can be further expanded to include other aspects such as equity considerations in the future. However, at this point in time, such equity and justice considerations are outside the scope of this study. Here we aim to model the resilience of the network solely based on the functional characteristics of the existing infrastructure network.

Attribute 1: Measuring Charging Station Utilization Rate:

The first step involves collecting information on corridor DC fast chargers across California, with Table 11 presenting key features of the studied charging stations. These features include charger site characteristics (public access, geographic region), station characteristics (charger model, type, access, plug types), and pricing details. This comprehensive dataset serves as the foundation for subsequent analyses.

Table 11: Features of the charging stations studies

Site features	
Charger site(s)	Public DC fast charging station with each access
Geographic region	California
Station characteristics	
Charger model	All brands that do not restrict any BEV brand
Charger type	DC Fast – 50 kW and above
Access	Open to the public - highway users
Plug type	CCS, CHAdeMO and publicly available NACS
Pricing	
Pricing type	Free or priced

The data of the charging stations were extracted in May 2024 from the Alternative Fuels Data Center (AFDC) hosted by the Department of Energy. The following information were extracted along with the charging stations.

- Geographical information including the city, latitude and longitude.
- The date of opening
- The status of the station (operational, planned or removed)
- Who has access to the station (public or private)
- Number of level 2 and DC Fast chargers in the station
- EV network or if they're not networked
- Connector types in the station (NACS, CHAdeMO, CCS)

- Facility type
- A unique identifier for each station
- Additional pricing information.

These parameters were used in the analysis of attribute 1.

Additional data Sources:

Attribute	Data type	Source:
Traffic flow in proximity	**Traffic counts**	**Caltrans traffic data**
Road Network data	**Shape file**	**Caltrans**

Characteristics of the Charging Stations:

To analyze the distribution of DC fast charging (DCFC) stations in California, we utilized the geographical information of the charging station to map them in relation to the road network in California. This map was crucial for understanding the spatial relationship between existing road infrastructure and charging stations. Additionally, the California state boundary was delineated. This boundary data was used to ensure all subsequent spatial operations and visualizations were restricted to California.

Subgrouping Charging Networks

To analyze network-specific trends, the dataset was further divided into proprietary Tesla only access chargers and non-Tesla public access charging stations. This distinction was made to compare the spatial distribution of Tesla's proprietary charging network against the broader network of publicly accessible charging stations operated by other entities.

The objective is to analyze all the 2,361 public corridor DC fast charging stations installed in California at the time of this analysis. Out of this 1902 are non-Tesla charging stations with at least one CCS connector. Here we describe model attribute to analyze what makes a charging station more critical than others. Figure 26 is a map of the Tesla proprietary charging networks and the non-proprietary charging networks available to all types of BEVs. Figure 27 includes the distribution of chargers within the two networks.

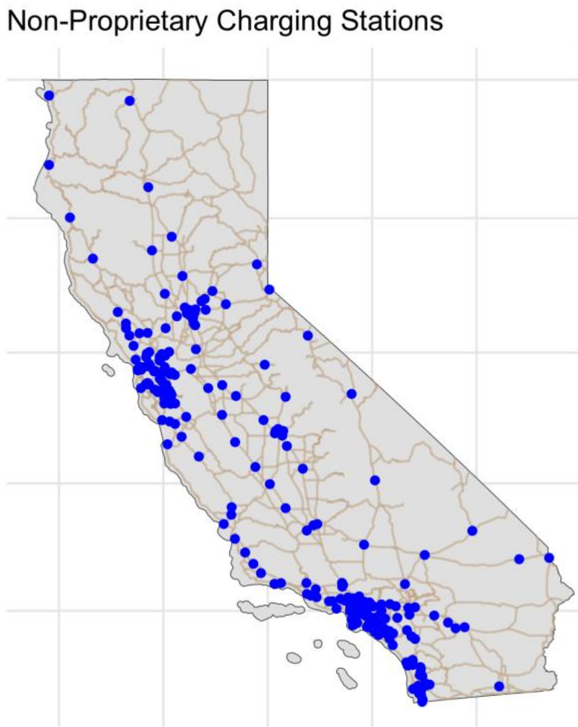

Figure 26: Charging networks in relation to the road network

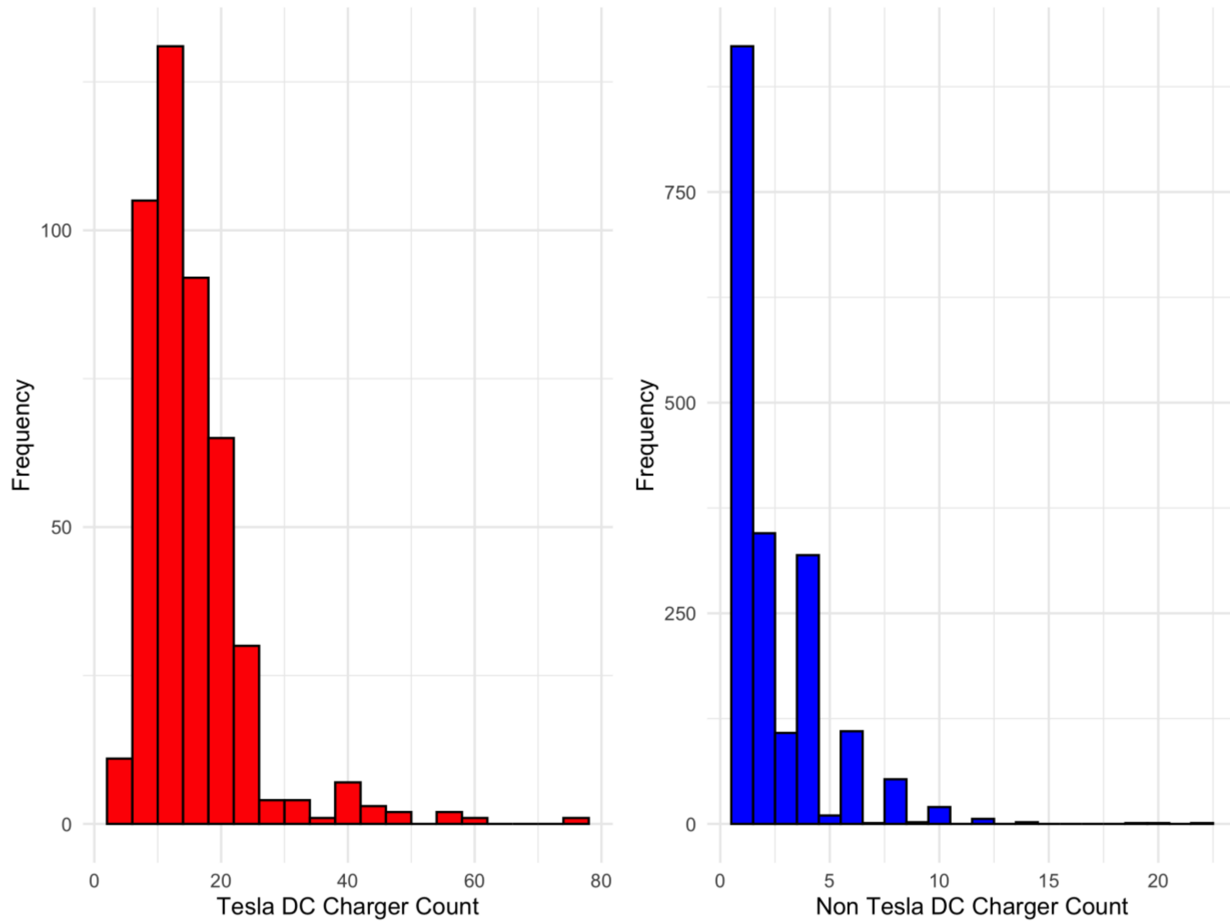

Figure 27: Charging Stations Design by network. We identify more chargers by site in the Tesla network whereas other networks have less chargers by site/ station.

The Caltrans traffic volume data was also included in this study to provide insights into traffic patterns and volumes on California highways. Traffic volume information included observations made from 7,114 locations and traffic volume was available as Annual Average Daily Traffic (Annual ADT) and Peak Hour traffic. Annual ADT is the traffic volume for the year divided by 365 days. Annual traffic count is usually calculated from October 1st through September 30th of the following year [77].

Attribute 1: High Demand Stations

In this step, we conducted a spatial analysis to examine the proximity of electric vehicle (EV) charging stations to traffic count stations managed by the California Department of Transportation (Caltrans).

Here we identified the nearest road network segment that is closest to the Caltrans traffic monitoring stations. Then we independently identify the nearest road network segment closest to each EV charging station in our dataset. Then keeping the road network segment as the common element, we assign each traffic monitoring station (and its traffic data) to each EV charging station.

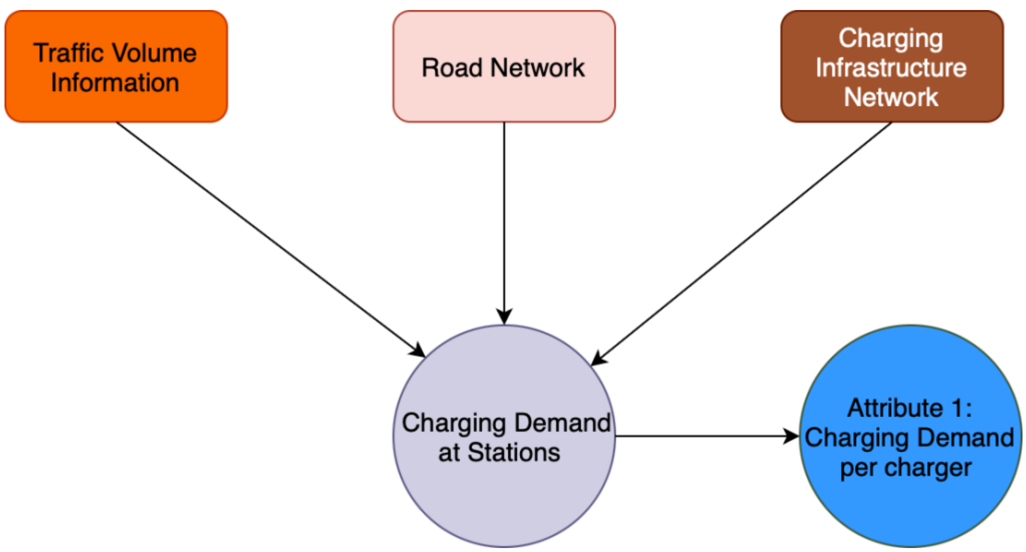

Figure 28: Overview of how traffic data is used to calculate potential demand at charging stations

Filtering for Non-Tesla Charging Stations

Given the distinctive network characteristics of Tesla charging stations, we filtered out these stations to focus our analysis on non-Tesla networks.

To effectively integrate many aspects of the traffic data into the analysis of electric vehicle (EV) charging station utilization, a weighted and scaled traffic metric was developed. This approach began with the assignment of weights to both **peak hour traffic** and **average annual daily traffic** (AADT) to reflect their relative importance in influencing charging station demand. Specifically, peak hour traffic was assigned a weight of 0.3, given its significance during periods of high demand, while AADT was assigned a weight of 0.7, emphasizing its overall relevance across the entire day. To adjust for the number of DC fast chargers at each location, the combined traffic count metric was normalized by dividing it by the number of chargers at a station. This normalization step ensured that the metric accurately reflected traffic demand relative to the available charging hardware.

Subsequently, the normalized traffic metric was rescaled to a standardized range of 0 to 100 using the rescale function. The scaling process allowed for a consistent comparison across different locations, providing a weighted, normalized, and standardized measure of traffic demand in relation to the EV charging infrastructure. This comprehensive metric is essential for evaluating the utilization and potential strain on charging stations. In this analysis we are not accounting for travel distances and inferring demand at charging stations from traffic data. This relationship has been identified in an early study conducted on rural corridor chargers [13].

Attribute 2: External Redundancy

Data:

For this attribute, the data of the charging stations were extracted in May 2024 from the Alternative Fuels Data Center (AFDC) hosted by the Department of Energy. The following information were extracted along with the charging stations as before.

- Geographical information including the city, latitude and longitude.
- The status of the station (operational, planned or removed)
- Who has access to the station (public or private)
- Connector types in the station (NACS, CHAdeMO, CCS)
- A unique identifier for each station

First, we filtered charging station to include only non-proprietary public access stations. (i.e. Tesla stations were removed). Then, we used the road network information from Caltrans to map the charging stations with respect to the existing road network. Then we conducted a comprehensive distance analysis between each pair of stations.

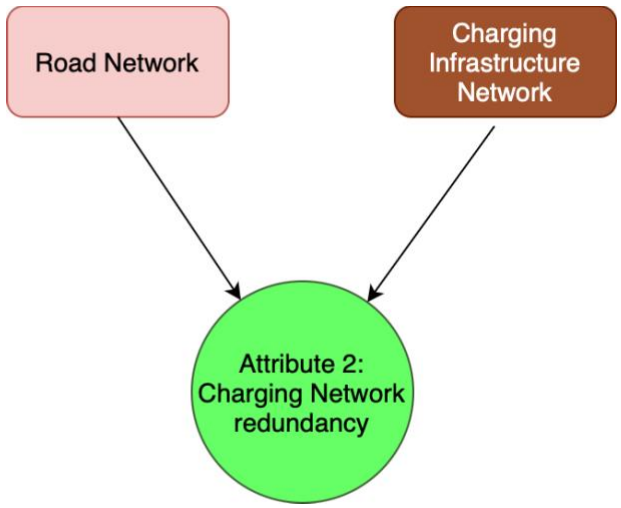

Figure 29: How Road network characteristics and charging network data is used to identify the external redundancy of the charging station network for attribute 2

With this information, we were able to count the number of stations within a specified radius around each EV charging station. The objective was to calculate all the fallback charging stations if a given charging station wasn't operational. To gain a more nuanced understanding of station density, we repeated the proximity analysis for multiple radii (e.g., 5 miles, 10 miles, 15 miles, 20 miles, and 30 miles) of driving distance. Based on data collected from a previous study we identified that 98.5% of BEV drivers will have at least 5 miles worth of remaining range when they drive into a charging station [78]. Therefore, we identified that alternative Stations within 5 miles of driving distance as the benchmark for our analysis.

To standardize the analysis of DC fast charging stations (DCFCs) across different locations, the number of DCFCs was scaled to a consistent range. This process involved rescaling the raw count of EV DC fast charging stations within the 5 miles benchmark to a standardized scale of 100 to 0. The intent is assigning a criticality scale of 100 if there were no chargers within 5 miles and 0 if there were many options within 5 miles. That is, higher the count of charging stations, the score would be lower and vice versa.

Attribute 3: Age of Hardware

This attribute identifies charging stations with the oldest equipment that needs critical attention.

Data:

For this attribute, the data of the charging stations were extracted in May 2024 from the Alternative Fuels Data Center (AFDC) hosted by the Department of Energy. The following information were extracted along with the charging stations as before.

- Geographical information including the city, latitude and longitude.
- The date of opening
- The status of the station (operational, planned or removed)
- Who has access to the station (public or private)
- Connector types in the station (NACS, CHAdeMO, CCS)
- A unique identifier for each station

To standardize the analysis of the age of EV charging stations, a multi-step process was implemented. The age was determined by computing the difference in days between the current date and the station's opening date.

The next step involved rescaling the age data to a standardized range of 0 to 100. Therefore, the stations with the oldest equipment will receive a criticality score of 100, whereas the stations opened most recently will receive a score of 0. Here we use the opening date of the station as a proxy for age, if not upgraded.

Attribute 4: Power Performance of Hardware

Here we calculate the potential level of disruption for users by identifying the expected power performance (charging speed) when drivers arrive at a charging station. Here we hypothesize that users will arrive at a charging station capable of higher speed with a high degree of expectation and service.

Data:

For this attribute, the data of the charging stations were extracted in May 2024 from the Alternative Fuels Data Center (AFDC) hosted by the Department of Energy. The following information were extracted along with the charging stations as before.

- Geographical information including the city, latitude and longitude.
- The status of the station (operational, planned or removed)
- Who has access to the station (public or private)
- Connector types in the station (NACS, CHAdeMO, CCS)
- A unique identifier for each station
- Charging port count with > 150 kW capacity

While we do not have information of exact charging speeds supported by all the hardware in each station, we have the number of ports in a station that have the capacity to support charging speeds of up to 150 kW or more. We decided to base this as a metric to understand the relative disruption to drivers who might be targeting such stations to minimize the charging time. We assume that a disruption to a station with higher speeds of charging could result in high degree disruption to many drivers as well as disruption to a different class of customers who are looking for a higher level of service.

In this method, we calculate the number of ports in a station that can support 150 kW speeds and scale them as before to normalize the information. A station with 0 150 kW ports will receive a criticality score of 0, whereas stations with the most 150 kW enabled ports will receive a criticality score of 100. The station with the greatest number of 150 kW ports is an Electrify American station based in San Francisco with a total of 20 ports at the time of this study. We then provide a score between 0 and 100 for every station accordingly.

Attribute 5: Internal Redundancy

Here we measure the redundancy of chargers within a given station. The following data were used:

Data:

For this attribute, the data of the charging stations were extracted in May 2024 from the Alternative Fuels Data Center (AFDC) hosted by the Department of Energy. The following information were extracted along with the charging stations as before.

- Geographical information including the city, latitude and longitude.
- The status of the station (operational, planned or removed)
- Who has access to the station (public or private)
- Number of DC Fast chargers in the station
- Connector types in the station (NACS, CHAdeMO, CCS)

As before, the number of DC fast chargers within a station were rescaled from 100 to 0. Stations with highest number of chargers received 0 and stations with only one charger received a score of 100 indicating the criticality of that one single charger being operational.

Overall Ranking Across multiple models:

Previously we calculated normalized criticality scores for five different metrics/ attributes of charging stations. Now we create a combined criticality score for the charging stations in our study.

$$Combined\ Criticality\ Score = a * Attribute_1 + b * Attribute_2 + c * Attribite_3 + d * Attribute_4 + e * Attribite_5$$

The equation before can calculate the combined criticality score of a given station. However different weights of *a*, *b*, *c*, *d*, *e* can change the relative importance of different attributes to the final score of charging stations. Therefore, creating one set of weights to calculate the critically score will bias the results based on what we think are the most critical attributes in this study. To make sure that we remove the potential biases from the metric, we created multiple scores based on different weights. We ranged the values of the weights between 0.1 and 1 by a sequence of 0.4. This means we created about 250 different criticality score based on the relative importance of the attributes to identify if we see some charging stations being identified across the models.

To do this, we created a ranking for each model. The station with the highest criticality score would be ranked as the most critical station. Then we combined the ranking across different models into one ranking.

$$Combined\ Ranking = \sum_{model\ 1}^{250} Criticality\ ranking\ of\ a\ given\ station$$

Based on this value, the stations were then ranked again. The stations with the lowest value are identified as stations that would be identified across different criticality models. The results section will discuss the finds in more detail.

Results

In the results section, we focus on the non-proprietary charging stations in California that can be accessed by all BEV users. While the same approach can be used for proprietary networks such as the Tesla Supercharger network, we have limited information about who can access them at this point in time.

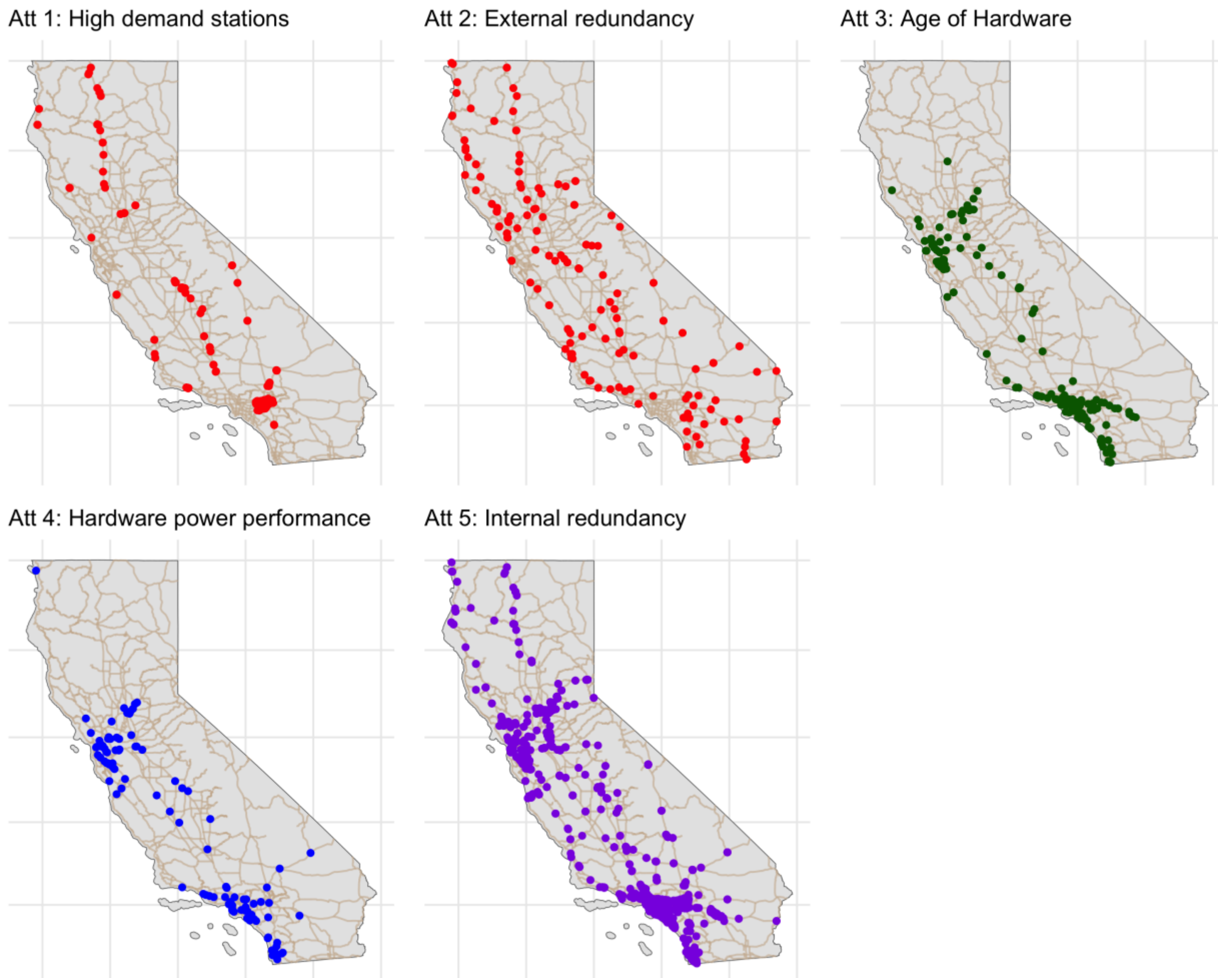

Figure 30: Visual summary of the most critical stations identified by the different attributes. Note that different stations are identified by the attributes in accordance with what they measure, and their spatial distribution patterns are different.

Figure 30 provides a summary of most critical stations identified by each metric. This is followed by a more detailed description below.

Based on attribute 1: High Demand Stations, we see that the most critical chargers are where there is more charging demand per charger. Usually, stations along high traffic corridors with a limited number of chargers or ports per station have been identified here. For example, many stations along California 99 highway have been identified as critical. Usually, corridor charging stations tend to have a limited number of charging ports/ hardware per station given the added challenges of constructing them. The route 99 is a major north-south highway that runs along California that is oriented more toward local and regional traffic within the Central Valley. Route 99 offers more urban access points, whereas the highway-5 is streamlined for continuous, high-speed trave such as San Diego, Los Angeles, Bakersfield, Sacramento. The 99 generally has more exits, connecting with local streets, which makes it accessible for local travel but also more susceptible to congestion. This is a crucial corridor for commerce and international trade while crossing a vast agricultural zone in California's central valley. It's interesting how stations along the 99 have been identified as critical as opposed to highway 5 which is one of the longest interstates in the U.S. Our metric of traffic per charger measures hardware availability and therefore diverts the criticality away from major metropolitan areas such as downtown Los Angeles or San Francisco towards rural corridor chargers. Our analysis identified that 46% of the critical chargers in this attribute were part of the ChargePoint network and 31% were non-networked stand-alone chargers. 10% of the identified stations were part of the Rivian adventure network and only 6% were part of EVgo. Clearly the critical stations identified with this attribute were not part of major charge point operators (CPOs). We believe this is partly because of (1) major CPOs stations design strategies and (2) location selection strategies. Major CPOs would opt to install multiple charging hardware per stations, especially along high demand locations, whereas small business and local governments would opt to install less hardware because of incentives structures. Despite that fact that AFDC data base refers to ChargePoint installed stations as "ChargePoint Network", in reality ChargePoint is not known for operating their own charging network. Their business model is catered towards individual businesses and agencies to own and operate their own hardware. Therefore, we see that identified charging stations from this attribute reflect the station design choices of individual businesses and agencies here as opposed to major CPOs.

The map also indicates the most critical stations identified by Attribute 2: External Redundancy. We can observe a clear spatial distribution of the stations here as opposed to attribute 1 High Demand Stations. We observe stations that are most likely to be isolated from other stations in the network. About 24% of the critical chargers were part of the ChargePoint network followed by 21% being part of Electrify America and 15% managed by the EVgo network. We see that more stations managed by major CPOs are identified by this attribute highlighting their station design features to support long distance travel and fill the gaps in the network. We also see that these stations are installed along some urban centers as opposed to transportation corridors. This fits in with the business model of major CPOs and their target user preferences.

With Attribute 3: Age of Hardware, we identify the oldest stations that are more likely in need of repair. From the results we observe that the stations are more concentrated in urban centers in California as expected. These are the locations that the first charging stations were installed in the early days. We observe that 59% of the critical stations in this attribute are non-networked.

With attribute 4: Hardware Power Performance, we identify the charging stations with ports that can support up to or more than 150 kW speeds. This metric identified the latest developments in charging hardware technology and how many ports can support up to 150 kW speeds. We believe a unique class of customers are willing to focus on these unique locations as they expect a higher level of service and faster charging options. Almost 96% of the identified critical stations by this attribute were operated by Electrify America and the EVgo network. These two CPOs basically dominate this attribute indicating where the industry might be heading in the future. These major network operators might be focused more on supporting fasters charging for their customers and a better charging experience for customers with high end BEVs. This could be in line with their business models and their capacity to invest more in higher quality hardware with faster capabilities.

With attribute 5: Internal Redundancy, we identified the charging stations with no redundancy within the station. Therefore, this metric identified all charging stations with only one single charging hardware in the station. 67% of the critical stations here are part of the ChargePoint network and 11% are non-networked. We see that major CPOs do not even make it to the list indicating that their stations were designed with more internal redundancy. This indicated design preferences of the major networks to have more fallback options and capacity to support more vehicles within a station. There are also economies of scale dynamics when designing a station in this manner. This observation also shows how fragile our charging network is across California indicating stations with only one DC fast charging hardware in them.

We initially aimed to identify the top 10% of critical charging stations based on each attribute. However, we realized that the scores of these attributes are not always uniformly distributed. For example, Attribute 5, which measures internal redundancy of a station by counting the number of chargers, exhibits a stepwise distribution, with many stations having exactly one charger, according to the AFDC database. As a result, the cutoff score for the top 10% may include a large number of stations, and the number of chargers selected in Figure 30 for each attribute varies across the five attributes. Nevertheless, this does not affect the final rankings in the next step.

The Final Ranking

The overall critically score objectively captures the common charging stations identified across 250 different models. All these models capture the essence of these 5 different metrics in varying degrees. Figure 31 indicates the common charging stations identified by the metric proposed in the methodology section. We indicate the top 10% of critical stations highlighted in red and the top 10% - 30% of stations are indicated in orange colors. The top 30% - 50% of stations are identified in grey.

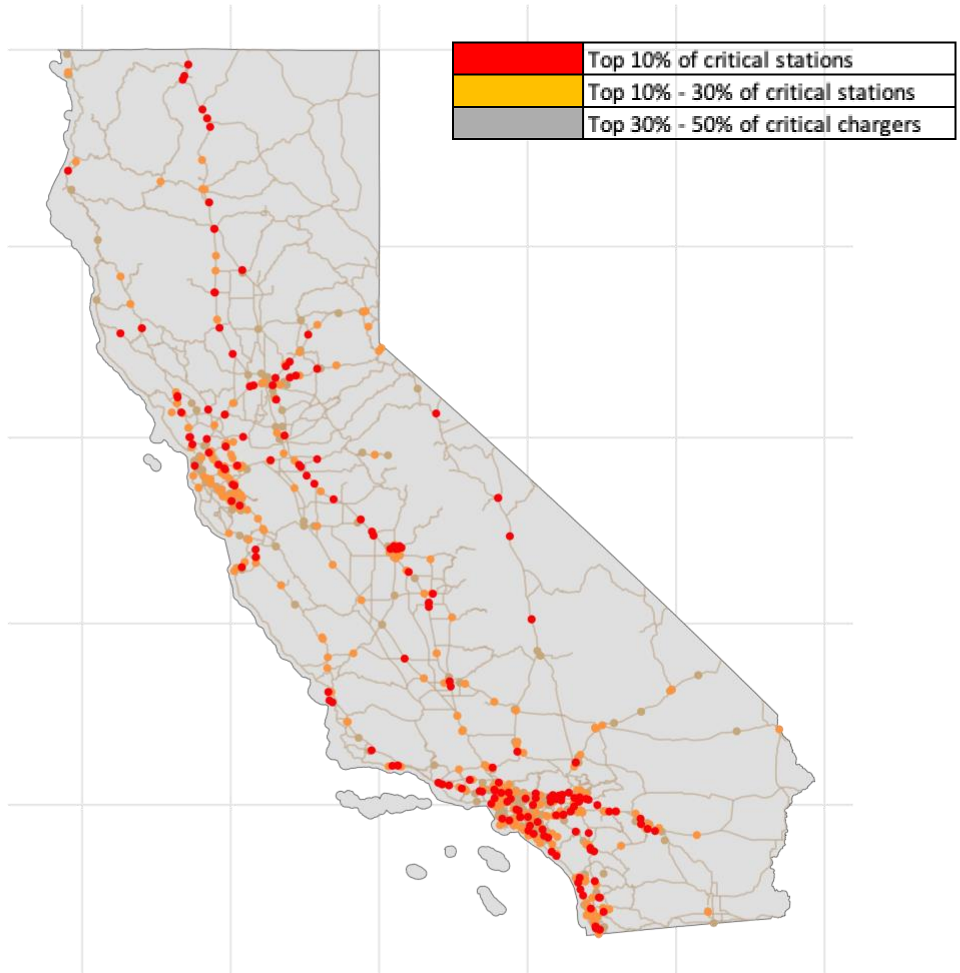

Figure 31: Critical charging stations indicated in this map. We indicate the top 10% of critical stations highlighted in red and the top 10% - 30% of stations are indicated in orange colors. The top 30% - 50% of stations are identified in grey. We observe corridor chargers identified as more critical compared to the stations in urban centers.

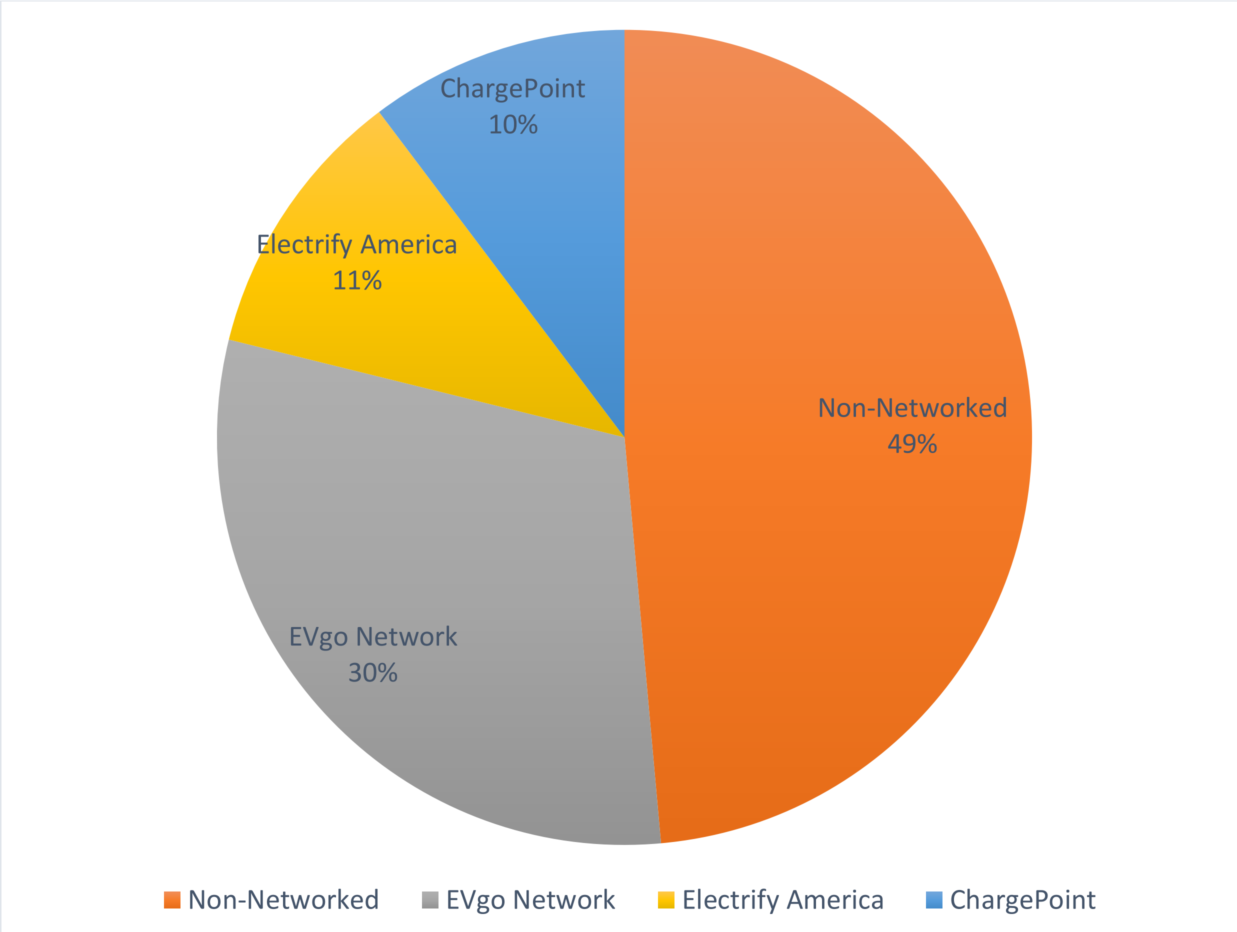

Figure 32: Breakdown of the top 10% of critical stations by network

While Figure 31 indicates the critical chargers spatially, Figure 32 helps identify the most critical chargers by popular CPO network. We see that most identified stations are non-networked indicating that perhaps the most critical chargers are installed in rural and isolated communities or as part of corridor chargers along highways. This is followed by EVgo network, the Electrify America network and the ChargePoint network. How these attributes impact their business models and strategies are discussed in detail in the next section.

3.3. Discussion:

Here we discuss the characteristics of corridor DC fast charging stations with five different attributes. They measure different characteristics of this complex, evolving and interconnected infrastructure system in relation to how it is being used by EV drivers and its network resilience.

Our objective was to be as comprehensive as possible to model different parameters and characteristics of the network and preferences of user as broadly as possible. But we are aware that we did not include other social justice and equity considerations in our modelling effort. We think this is an important and paramount task that future researchers will attempt to better understand. Furthermore, many new EV models have been introduced by vehicle manufacturers to be competitive in a growing market of EVs. Their battery voltage levels can also vary greatly [34] and some automakers have been introducing BEV models with battery voltage as high as 800 – 900 Volts that are capable of faster charging speeds. Many automakers have announced they will switch to the North American Charging Standard (NACS) and many charging networks have made similar announcement to convert their existing chargers to NACS. This is only a few examples how California's public charging network is constantly evolving and faced with multiple challenges to ensure its well-functioning to users with not only diverse travel needs, but diverse EV models.

Realistically we believe that each model we employed out of the 250 different models can be a unique metric in identifying critical chargers according to the values and priorities of an organization. Therefore, we aim to create an online tool based on this research so that anyone can change the weights and importance of the five different attributes to identify the most critical chargers according to their unique needs. We believe the chargers we identified provides a more balanced perspective based on criticality identified across multiple attributes.

Based on our results, we identified that more rural charging stations along California route 99 towards north of Redding and almost all stations along US route 395 gets flagged as critical. This is to be expected. We also identify that popular charger in central California route 99 also gets flagged as critical. While rural and remote chargers are critical because they have more demand per charging dispenser, and to ensure that EVs can travel along that corridor, it is also important not to forget the more urban charging stations that have more demand overall. Furthermore, not all hardware installed in charging stations have the same capabilities. We think this study will be useful in the near to medium term until we have more charging stations installed. Our study helps to prioritize critical chargers that can in-tern help alleviate charging network companies optimize their resources. They are already facing multiple challenges trying to maintain a reliable network. We understand that charge point operators are working with limited resources and limited crew to do the best they can. And it is a monumental task to make sure a network coast-to-coast of chargers are maintained and reliable, especially for the charging companies with the most charging stations to manage. Figure 33 shows how many chargers are managed by the different networks in California, the top 3 (not including Tesla) being EVgo, Electrify America and the ChargePoint network. Our framework aims to minimize the inconvenience while maximizing the utility of the limited operating resources of charging network companies.

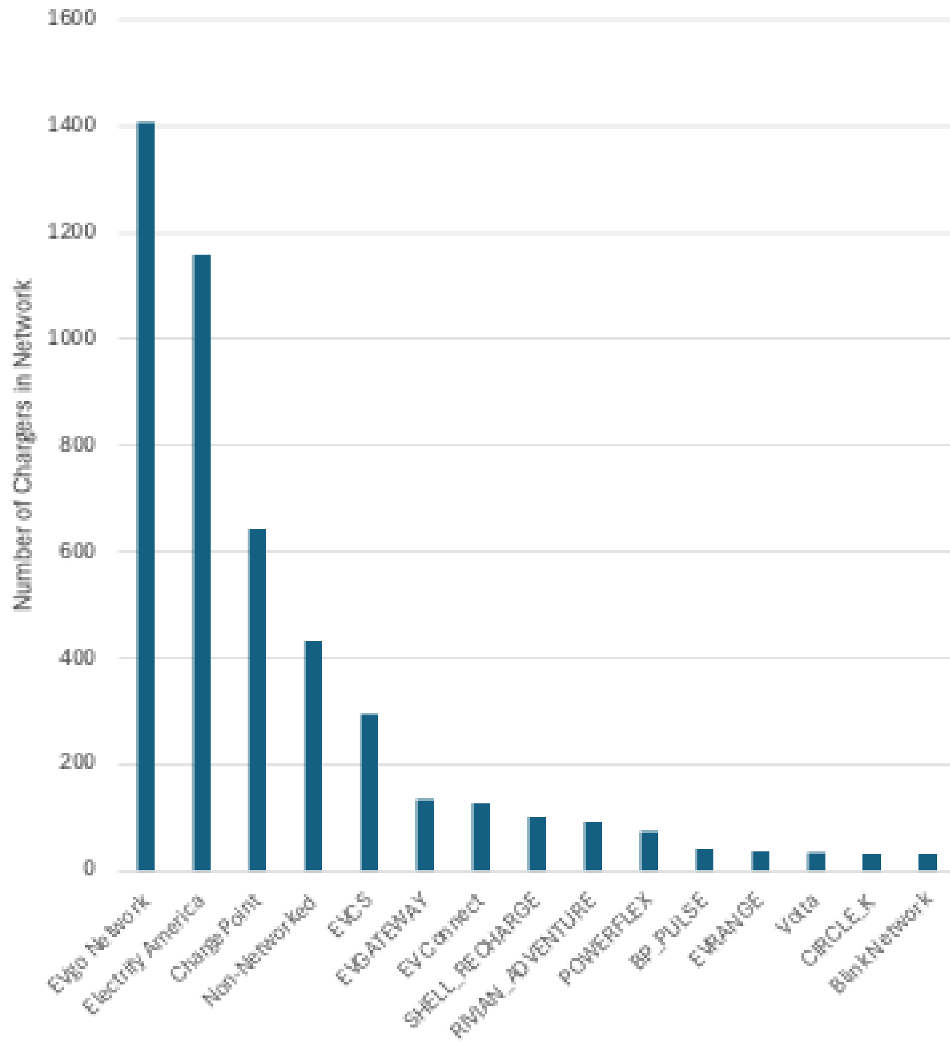

Figure 33: Top charge point operators/ networks in California (not including Tesla).

Overall, our study aims to identify the most critical charging stations of whole charging network to ensure resilience of the whole network. Realistically individual drivers might have their own critically score based on their own driving behavior and type of BEV they drive. It is also important not to forget important social justice and equity consideration in identifying critical chargers in the future as underserved communities or rural communities or tribal communities might have a very different set of charging stations that are critical for their own communities. While this is outside the scope of this study, we identify that this is a critical area of research in the future.

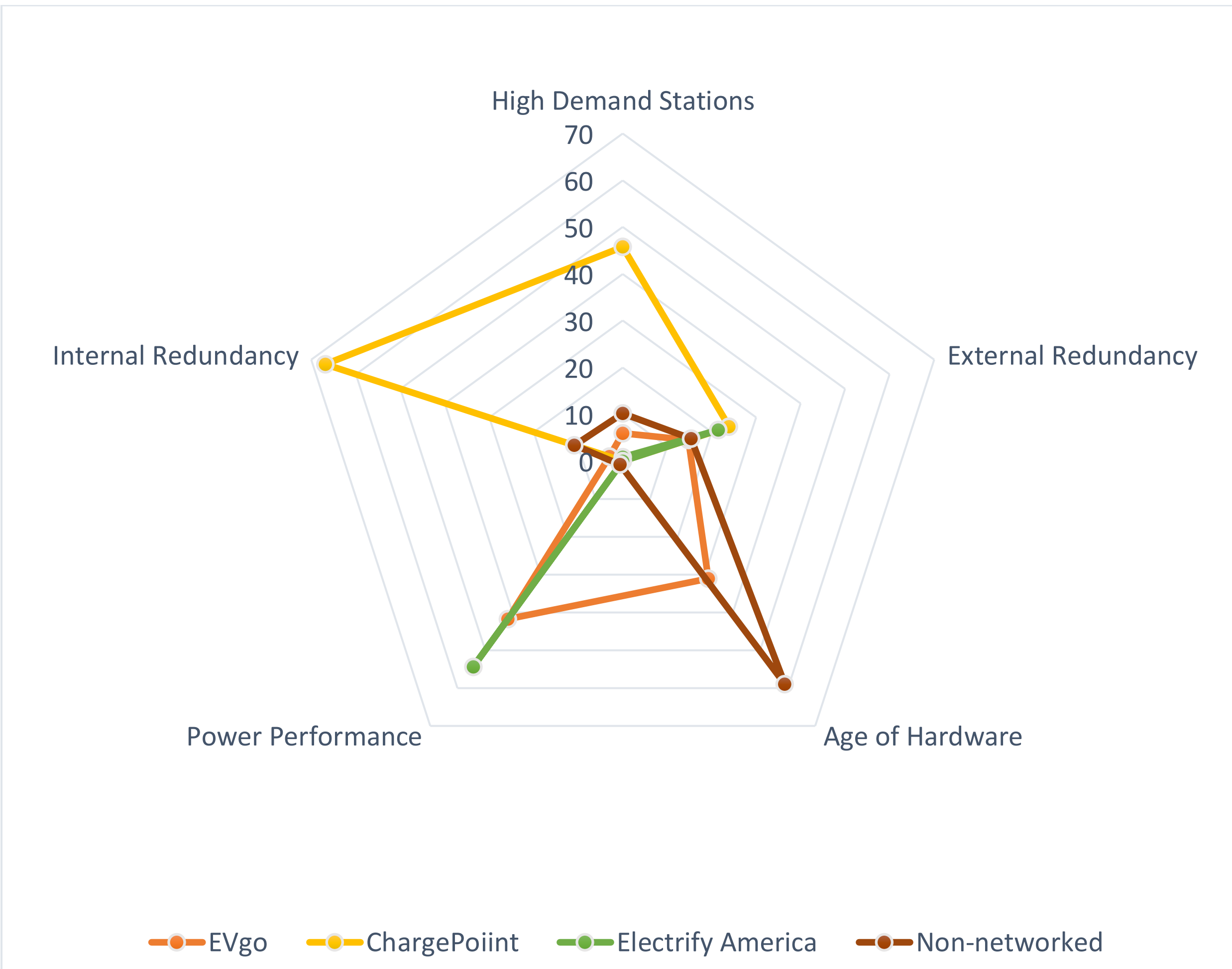

Figure 34: Facet Grid of the top CPOs in California listed by how often their network is identified by the 5 different attributes in our analysis. We see that EVgo and ChargePoint is identified across multiple attributes whereas, Electrify America is identified across attributes such as

power performance and external redundancy. Most non-networked chargers tend to be identified for hardware age. This measures which network has more stations that needs critical attention, and this is not a measure of the performance or resilience of CPOs.

Figure 34 summarizes how often the big 4 networks gets identified by our 5 different attributes. We see that Electrify America gets criticality measure by network redundancy score and for having more 150kW capable ports. ChargePoint network gets identified across most attributes, along with having more demand per charger and less internal redundancy. Given than ChargePoint equipment is purchased independently by small business and local agencies, it makes sense that their stations do not have a lot of hardware of redundancy built-in. EVgo network also gets critical scores for having more 150 kW enabled ports as well as old equipment. While these attributes are measuring different attributes of the network it is not a measure of the performance or quality of the network. What makes a charging station critical can be a positive attribute as well as an indicator that some stations are going to be congested or critical because they might be in need of repairs soon. Therefore, it's not a reflect of the network as opposed to a tool that identifies criticality across the network.

While we think these 5 attributes can be useful in measuring the criticality of stations, we do not believe this is an exhaustive list of attributes. We leave it open for future researchers and agencies to come up with their own metrics and measurements based on person and agency-oriented objectives.

Chapter 4: Conclusions

4. Conclusions:

My dissertation aims to explore some of the challenges of rolling out and managing a complex network of corridor DC Fast charging stations to support long distance travel using BEVs. The State of California has been a good case study for this endeavor as the State has been a leader in supporting BEV adoption and charging infrastructure rollout.

Based on Chapter 1, we find that the installation of corridor DC Fast chargers is more challenging than previously assumed. They require longer timelines and will cost more than the cost information available in the literature made by common assumptions. There are added challenges to corridor DCFC installations along major transportation corridors. Regular DCFC installation requires significant onsite make-ready infrastructure for the operation of chargers at maximum rated power following National Electrical Code and NFPA guidelines. The infrastructure must undergo substantial planning and administrative processing, and requires engineering designs, architectural designs, planning for labor mobilization, planning for safety and coordinating with local stakeholders such as electrical utilities and local suppliers for the successful construction and launch of DCFCs. As, we prepare to electrify medium to heavy duty vehicles such as trucks and buses with Mega-Watt Charging Stations, these challenges are only going to amplify.

My study did not incorporate the economics of different station design options. In could be an interesting study to identify various site design options such as load sharing options between different chargers and the economies of scale for larger stations with 20, 40 or 80 chargers. We did not consider the economics of faster charging hardware such as chargers capable of 350 kW chargers. We also did not consider other theoretical station design choices that can directly receive medium to high voltage interconnections. As any other technology or infrastructure rollout, we're observing a learning curve where charging network companies are learning and adopting best practices to bring down costs. Advanced planning before the construction phase can save significant resources. Moreover, the DCFC technologies are improving rapidly, with new EVSE designs, better speeds, and better cooling specifications. Workforce training programs such as the Electric Vehicle Infrastructure Training Program (EVITP) certification in California[9] and certification and training programs such as ChargerHelp can help train electricians, planners, civil engineers and civil contractors to be better trained on charging stations installations, and help expedite the construction process. As more CPOs plan to adopt NACS in their networks, it might present interesting challenges in their own right to be on the lookout.

In Chapter 2, we used charging data made available to us to identify reliability challenges and objectively measure infrastructure performance. Here we introduced a new methodology measure the reliability of DC fast charging stations identifying different levels of charging success. Our study has gone on to inform policymakers develop new key performance metrics to gauge charging station performance and customer satisfaction. Our study also helped define the full charging station experience of users (EV drivers) by grouping recorded charging data (events) to unique charging visits. This subtle framework can change how we measure the full experience of users at charging stations on an outcome basis. We also proposed a deep diagnostics framework to identify the causes of charging failures using different types of failure modes such as consistent charging errors and troubled charging sessions followed by a successful charge. Error codes and charge session end type information was used to potentially identify the causes of the issues. We also showcase how error codes might have false positive and false negatives in identifying failures.

The most prevalent reason for persistent charging errors was communication errors. This indicates the inability of the charger and the vehicle to communicate with each other. When this error is identified, we see that charging events only record minimum information such as attempted time, OCPP ID and plug type that can be recorded from the charger sensors. Information that is communicated from the vehicle such as starting SOC and battery voltage are not recorded as expected. The communication errors in Figure 24 can be stemming from multiple

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reasons. They are (1) charger is not able to initiate communications with vehicle, (2) connector is not properly connected to the vehicle, or (3) vehicle is not communicating with the charger. Based on some informal interviews we conducted with industry partners, this type of error is largely caused by problems that may prevent physical contact between connector pins and the vehicle charger port (i.e., having some dirt in the connector pins, damaged connector pins or misaligned connector preventing communication). When physical contact is established, this error can be caused by interoperability issues of digital communication between the vehicle and the charger [62]. The assumption is that charging is not initiated because communication cannot be established. The common industry standard for DC fast chargers is the ISO/ IEC 15118 which includes a whole subset of standards for plugs, charging topologies, communication, security, and safety [63]. ISO 15118-2 is the vehicle-to-grid communication interface that's commonly used right now. But other communication standards such as DIN SPEC 70121 exist with the new ISO 15118-20 standard promising to be an advancement to the ISO15118-2 standard. CEC analysis suggested that DC Fast chargers in the market are already ISO 15118 ready [64]. Therefore, any interoperability challenges suggest a gap in testing and compliance of these chargers. More recently automakers have made announcements supporting the North America Charging Standard (NACS) as they move forward. While NACS is the design of the physical connector, it is unclear what communication interface is going to be used to support NACS.

My study attempts to measure charging reliability failures. To that end, I have successfully measured charging start failures and charging interruptions. However, a comprehensive analysis of throttled charging experiences or derated charging is a gap in my analysis. It is my hope that a future study will (1) comprehensively measure the prevalence of throttled/ derated charging and (2) measure the scale of throttling, (3) measure the impact of throttling on the charging experience and (4) explore the causes of throttled charging. We know that this is a common charging experience with BEV drivers. There is a lot of room to identify data sources and measure this suboptimal charging experience.

DC Fast chargers are essentially operating in a complicated eco-system of physical infrastructure, standards (also called public key infrastructure), users, and vehicles. In this eco-system both physical infrastructure and vehicles are supplied by many different market actors (brands) for users who have very different education and experience with charging station usage. When setting reliability expectation to such a complicated techno-economic user ecosystem, regulators should consider the broadest possible understanding of the full eco-system. Furthermore, trying to achieve very high reliability without fixing major design problems within the eco-system may even cause more problems. For example, throttled charging and charger interruptions can occur due to several reasons, such as protecting the battery from overheating, charging cable overheating, ensuring safety to the vehicle and user and general faults in the charging equipment. In trying to fix such nuanced problems, it is important to have an open dialogue with EVSE manufacturers, designers and charging standards and protocols planners to get to the bottom of existing design faults. Federal and State government agencies are well placed to initiate such discussions. The ChargeX consortium initiated by the Joint Office of Energy and Transportation is a step in the right direction.

In Chapter 3, my study aims to identify the most critical charging stations of the whole charging network to ensure resilience of the whole network. Realistically individual drivers might have their own critically score based on their own driving behavior and type of BEV they drive. It is also important not to forget important social justice and equity consideration in identifying critical chargers in the future as underserved communities or rural communities or tribal communities might have a very different set of charging stations that are critical for their own communities. While this is outside the scope of this study, we identify that this is a critical area of research in the future. Our objective was to be as comprehensive as possible to model different parameters and characteristics of the network and preferences of user as broadly as possible.

Topics for further research

I conducted this analysis for public open access charging stations that as of right now support CCS charging standards. However, as Tesla superchargers open their network to other automakers, this analysis can be conducted considering the Tesla network and non-proprietary networks in different combinations. While many automakers have announced they will switch to the North American Charging Standard (NACS) and many charging networks have made similar announcement to convert their existing chargers to NACS, this is not without its challenges. It remains to be seen how automakers navigate the market for adopters for their fleet. This adds an additional complexity and modelling challenge to my analysis. Future studies can also focus on the interoperability of networks between NACS and non-NACS enabled CPOs as the BEV fleet continues to evolve. This is only a few examples how California’s public charging network is constantly evolving and faced with multiple challenges to ensure its well-functioning to users with not only diverse travel needs, but diverse EV models.

In recent years, there has been a trend where charge point operators (CPOs) have made agreements with automakers to provide free charging. While there are variations of the details, some of the agreement vary between free unlimited free charging for two years to free charging up to a certain ceiling of kWh or dollars ($) of credit to free charging for two years for the first 30 minutes. While the exact details of such arrangements can change regularly, this provides an interesting spike in demand at DC Fast charging stations from the regular expected demand. With access to real world charging demand information, it remains to be seen how charging demand is split between paying customers and free charging users. This presents an interesting challenges for the profitability of charging networks in the future.

In conclusion, California’s network of corridor charging stations is evolving rapidly. The technology and business models are evolving as well as the BEV models. Overall, we found that designing, constructing and managing a network of reliable Charging Stations requires a lot more work than previously thought. While gas stations are the closest analogy to fast charging stations, the design aspects of charging stations and usage characterizes have been different from that of gas stations. In this dissertation, my objective was to capture the learnings, and findings so that it may benefit Californians as well as other States and countries who are still behind in building out such a network. Due to the high number of EVs, California has its own challenges, and it is important not to forgot that California's network is also not perfect. However, it presents a blueprint of the issues and challenges that others might face in the future.

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