36th International Electric Vehicle Symposium and Exhibition (EVS36)
Sacramento, California, USA, June 11-14, 2023

Reliability of Corridor DC Fast Chargers and the Prevalence of no-Charge Events

Tisura Gamage[1,2], Alan Jenn[1], Gil Tal[1]

[1]*University of California, Davis, Electric Vehicle Research Center*

1605 Tilia Street, Davis, CA 95616,

[2]*PhD Candidate, Transportation Technology and Policy*

Email: tdgamage@ucdavis.edu

Executive Summary

A highly reliable and easy-to-use network of corridor charging stations is necessary for building driver confidence in using battery electric vehicle (BEVs) for long distance trips. This research is an exploratory study to understand the prevalence of no-charge events and the true reliability of corridor DC fast chargers. We propose an overarching framework to understand the reliability of charging stations from the users' perspective and identify many levels and stages of charging failures. Here we propose a new methodology to measure charging station reliability using charging data from corridor charging stations. We distinguish charging failures from recorded charging attempts where issues were successfully resolved and where drivers did not resolve reliability issues. We categorize “point failures” that can prevent drivers from successfully charging their BEVs using DC fast chargers when such chargers are considered to be “online”. Such issues could be stemming from communication failures between the charger and the vehicle, connector/ cable damages, electrical leakages, equipment errors, or errors from the vehicle side. We aim to understand how deep the problem is from the users’ perspective.

Keywords: DC Fast Charging, reliability, interoperability, no-charge events, infrastructure

1. Introduction

The U.S. transportation sector is 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. Just as internal combustion vehicles (ICE) depend on refueling infrastructure, these new energy vehicles are going to be dependent on a national network of energy supply and charging infrastructure across urban centers and major transportation corridors. 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 [1] [2]. National Electric Vehicle Infrastructure Formula Program (NEVI) was created as part of the IIJA to administer $5 Billion dedicated to corridor DC fast charging infrastructure.

In the context of light duty vehicles, both battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) are reliant on charging infrastructure, also known as Electric Vehicle Supply Equipment (EVSE). While PHEVs can continue to operate without being solely dependent on charging, BEVs are reliant on recharging infrastructure after the battery is depleted. However, BEVs can meet the energy needs of most vehicle days across the US, relying primarily on a night-time home charger [3]. Long-distance BEV trips have higher energy requirements than a typical day of driving, making a network of publicly available **convenient and rapid** recharging stations necessary to facilitate long-distance BEV trips. Public corridor chargers that are strategically placed along major highways and transportation corridor are well suited to serve drivers who undertake such trips. It's important that such corridor chargers are highly reliable and dependable. To that end, NEVI formula program funded chargers need to meet a minimum reliability standard of 97% of annul "uptime" [4].

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 [5]. 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 [6]. Therefore, this is evidence to suggest that on the one hand charging station service providers are failing to meet reliability expectation set by policy makers or that they are unaware of the scale of the problem. Uptime is a time-based metric that is calculated as a percentage of time a charger is functional annually on an ongoing basis [5] . Many authors and studies have questioned the validity of this time-based measurement [5] [6]. The original NEVI program Notice of Proposed Rulemaking (NPRM) published in June 2022 did not properly define what is meant by "uptime". However, the final rulemaking made available in February 2023 seems to define uptime beyond "dispense electricity as expected" [7]. The final ruling specifies that chargers should be capable of meeting minimum charging speeds and accommodating output voltages between 250 volts DC and 920 volts DC when they are considered to be at "uptime" [7]. However, it is unclear how uptime is going to be measured. 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 [5, 8]. 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.

Some of the common points of failure in the charging system ecosystem can be categorized into these following overarching buckets, (1) electrical failures, (2) mechanical issues, (3) software/communications issues, and (4) logistical factors. **Electrical points of failure** stem from control systems put in place to reduce the risk of electric shock to users. This type of failure can make the EVSE potentially unsafe to use and unreliable. **Mechanical issues** include damage to external hardware components from various environmental factors. **Communication failures** include configuration errors, power loss, and hardware failures anywhere along the communications network within the charging ecosystem. **Logistical failures** can include anything from payment issues and difficulty in locating chargers to complicated instructions to operate [5] [8].

Typically, most level 2 chargers and nearly all DC fast chargers can communicate with the BEVs attempting to charge using the charger connector. After this direct method of communication between the vehicle and the charger, charging station operators can communicate with the drivers through a membership portal (sometimes a phone app) or a personally identifiable ID that corresponds to the driver's membership information. Chargers communicate with the BEVs and the drivers to (1) process payment information, (2) identify vehicle parameters to optimize the charging process, and (3) monitor electrical leakages, equipment overheating to ensure safety for both the user and vehicle. Charging station operators and EVSE units usually store information from each charging session including personally identifiable information (PII) of drivers. Charging session information is typically collected in the form of energy dispensed (in kWh), output voltage, start and ending state of charge (SOC), session end type, max power (in kW), start and end time of charging session, type of connector, station name and address of EVSE station, among other data points. PII collected can usually include user information, payment methods, membership type, residence addresses and more.

We were tasked by California Department of Transportation (Caltrans) to study the infrastructure performance and downtime using the data from the charging stations installed under the Caltrans ZEV 30-30 project. The goal of this project was to fill gaps within California's corridor charging network along key routes of the State Highway System [9]. Caltrans installed 54 corridor DC fast chargers in 36 different locations that belong to them. These chargers were constructed, operated, and maintained by the same agency. Although the construction of these charging stations was successful, previous studies have raised questions about the reliability of similar public open fast charging infrastructure. Here we aim for independently measure the reliability of said charging stations using charger usage data.

The clearest definition for reliability of a system is "the probability that the system will perform it's intended function" [10]. Reliability models should describe the system and its functions as realistically as possible. Other than charger availability (no frequent outages) and access, we think a definition of charger reliability should include some aspects of user experience and interoperability to accommodate a variety of BEV models and charging standards. On top of this, chargers should deliver fast charging consistently meeting advertised speeds and should deliver uninterrupted charging for the expected duration.

Since the U.S. Bipartisan Infrastructure Law (BIL) was signed into law on November 15th, 2021, there is significant interest from electric vehicle stakeholders to replicate versions of California's ZEV 30-30 project to build a national network in the United States. The objective is to build an EV charging infrastructure network that is spaced at a maximum of 50 miles along designated alternative fuel corridors. Therefore, understanding the reliability and defining metrics to capture many aspects of charging station reliability will help us understand the problem better and come up with solutions and ultimately help achieve a smoother transition to ZEVs.

2. Materials and Methods

2.1. Data Overview

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 by early 2021, almost all stations were operational and were open to the public. Charging was available free of charge to the public to the best of our knowledge. Each charger in our analysis were required to have a CHAdeMO connector and a CCS1 (SAE J1772 Combo) connector by design. The chargers were designed to operate at a rated charging speed of 50kW each. Two different EVSE brands available in the market were chosen for the project. Here we will refer to them as brand B and brand C. Other monitoring and ancillary services required for the operation of the charging stations were provided by their respective brands. For example, both brands offered cloud services that recorded and remotely monitored charging sessions.

The data used for this analysis contains charging events between 06-15-2021 and 11-22-2022 with the most up to date information with us. A summary of the data is available in Table *1*. 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. Table *1* provides a summary of the number of recorded charging events for each charger brand and the number of charging stations included in the dataset. The number of generally recorded charging events appears to be low compared to other similar databases for the given time period. This is since the charging stations included in our dataset were corridor chargers located away from urban metropolitan regions. A map of the charging station locations with the selected brans of EVSE is found in Figure 1.

Here we define a no-charge event as a charging event that **does not start, or has a negligible energy transfer, or an event that terminates prematurely**. Based on this definition, an **initial screening** of the charging events is indicated in column 6 of Table *1*. Any recorded charging event that discharged more than 1 kWh of energy were considered a successful event. Any event that did not meet this criterion was considered unsuccessful or a "no-charge event".

Table 1: Summary of data sources collection

Site owned by	Brand	Number of stations	Connectors	Recorded number of events	Percentage of "Successful" events
Caltrans	Brand B	47	CCS, CHAdeMO	59,542	**54%**
Caltrans	Brand C	7	CCS, CHAdeMO	8,664	**76%**
	Total	**54**			

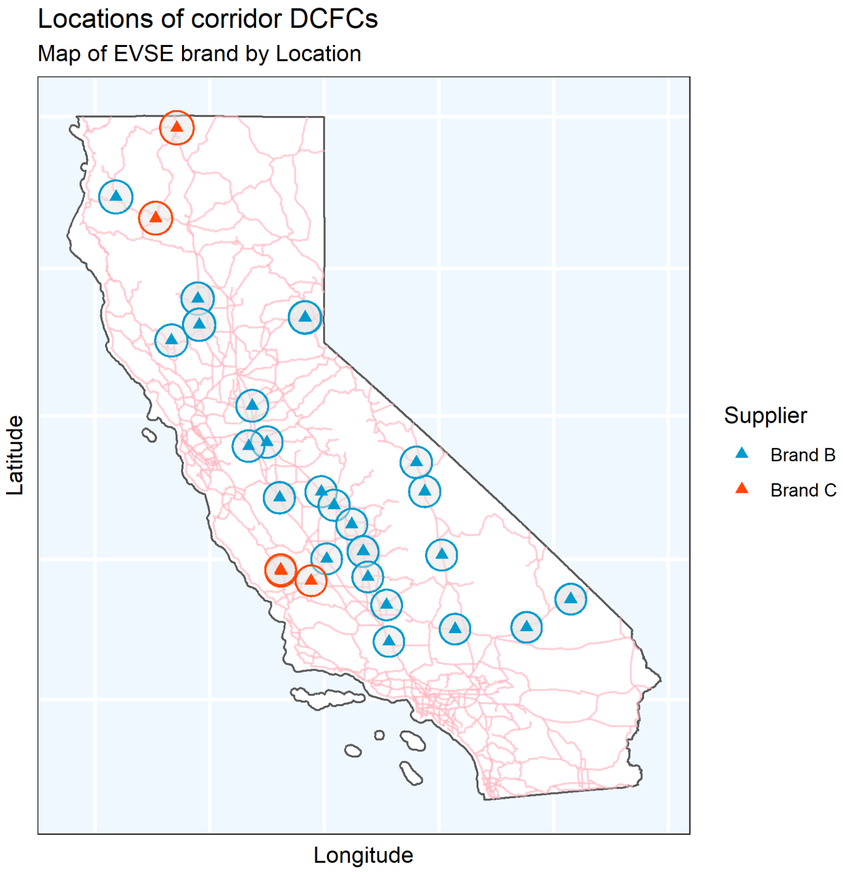

Figure 1: General locations of the charging stations where we received charging event data. Some locations may indicate two different charging stations located on both sides of the freeway. A radius of 15 miles indicated around the chargers.

We found initial evidence to suggest that unsuccessful events were over-represented in our dataset. That is because a successful charging attempt will be recorded as one charging event, whereas a user may attempt multiple attempts to charge following a no-charge event. Although such events are recorded as multiple events, in reality, they should be considered as part of the same unsuccessful attempt. We came up with a methodology to define a **visit ID** to identify all charging events made by a user during a single visit to a charging station.

2.2. Differentiating charging attempts by the same user for a given visit

Brand C maintained a system of anonymized unique user identifiers (UIDs) and they were included in the recorded charging events. However, brand B did not maintain such a UID system. For Brand C, with UIDs we can differentiate consecutive charging events from the same user as opposed to a different user.

Therefore, our approach here is to identify a time threshold between consecutive charging events from brand C to inform our classification for brand B.

Using data from brand C, we analyzed the distribution of time interval between two charging events by the same user and different users. This distribution is found in Figure 2. We did this to understand if we have recorded events by the same user attempting multiple charging attempts to connect their vehicle to the charger. As expected, the time interval between charging events by different drivers at a given station is spread out, whereas charging events by the same user are within a few minutes. Both successful and unsuccessful events were taken for this analysis from brand C. In Figure 2 charging events by the same user are indicated in blue, whereas events by different users are indicated by pale red. The distribution in the top graph is a subset of the data to highlight events that had a time interval of 15 minutes between them. We observed that most events that take place after 5 minutes of each other involves a different user, whereas events within 5 minutes are more likely to be from the same user at a given charging station.

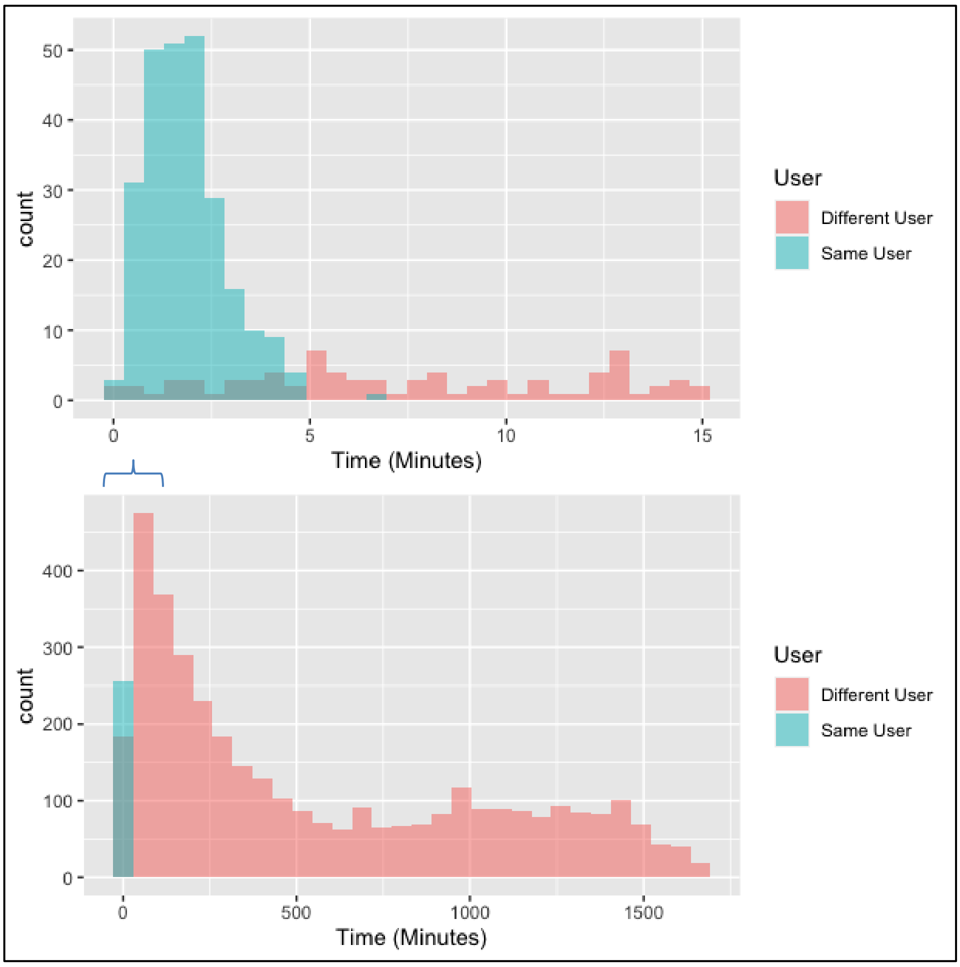

Figure 2: Distribution of time interval between recorded charging events at the same charging station between the same user and a different user. (Top) distribution is a subset of the data for 15 minutes.

Using this insight, we define a **visit ID** to identify all charging events made by a user during a single visit to a charging station. For example, if a user had trouble connecting the charger few times, but eventually managed to figure it out in the same visit, all such recorded attempts will fall under the same visit ID. (For example, user A, station 1, visit ID - 1, failures – 2, success – 1). All chargers located in the same charging station were considered together given the proximity to each other. A time threshold of 5 minutes was used to distinguish returning drivers to charger at the same charging station.

2.3. Overarching framework for analysis:

Figure 3 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 rectangle 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 3 are found below.

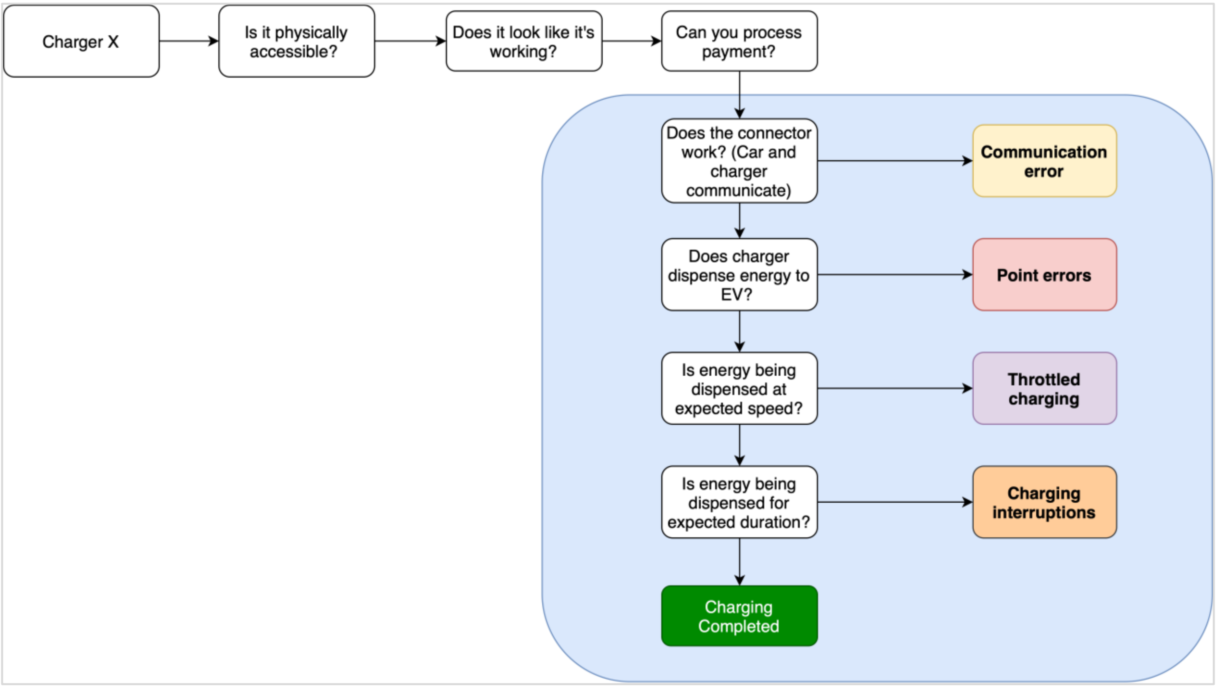

Figure 3: Possible levels of reliable failures at a charging station from the perspective of the driver (user). Our focus in this study is highlighted in blue.

Some definitions to charging failures:

- **Point failures** refers to no-charge events when the charger is online but still fails to provide a charge to vehicle.
- **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.

2.4. Methodology Overview:

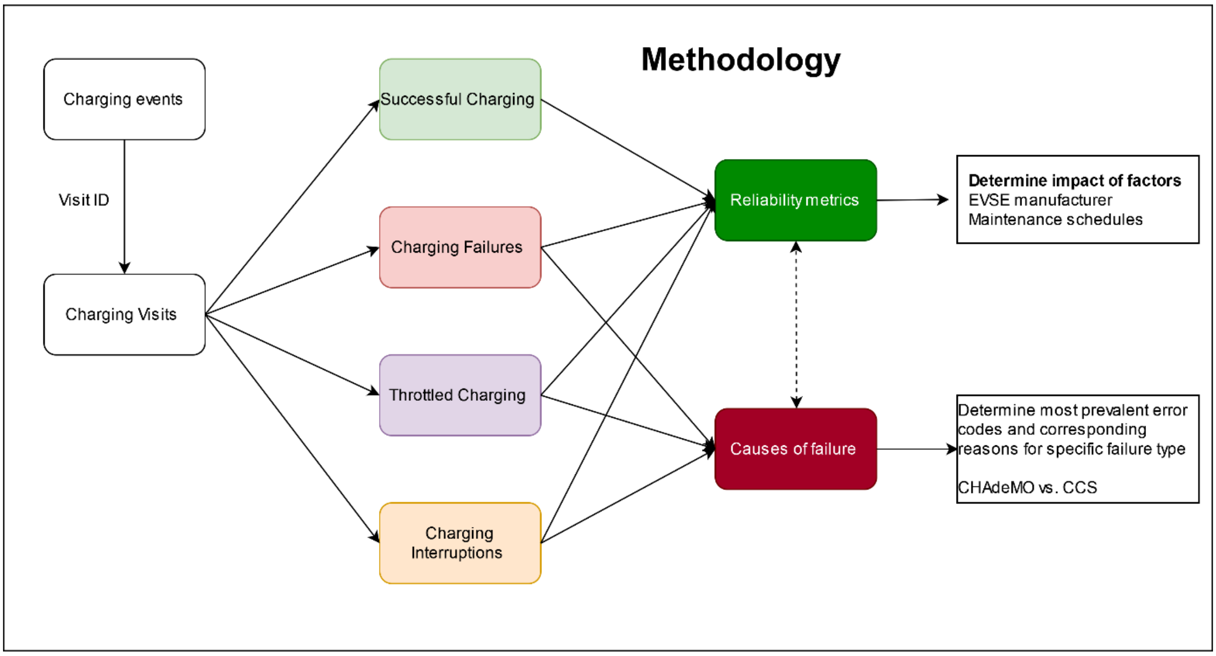

Figure 4: Summary of methodology

As a first step, all charging events are given a unique visit ID and then classified to charging visits. With this method, we are able better to understand the real outcome of the charging visit from the perspective of the user. Then we can classify events that had a successful outcome. We are also able to classify charging failures and have some indication of the errors that prevented the charger from successfully initiating charger based on error codes in the dataset. We use a different methodology to identify throttled events and interruptions where possible. Using the methodology summarized in Figure 4 we're able to (1) come up with a probabilistic metric of charging station reliability based on true charging failures and (2) identify corresponding reasons for failures. Holistic probability of charging station reliability can be calculated using the function below.

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

A simple probability is calculated at every level based on the charging data as follows:

$$Probability\ of\ failure = \frac{Real\ number\ no\ charge\ visits}{Total\ number\ of\ visits}$$

Determining Charging interruptions:

We observed a different kind of reliability failure in the form of charging interruptions. If a charging session was successfully initiated but was interrupted without the user ending the charging session, we consider this charging interruptions. Here, we consider a longer time threshold ~ 2 hours to differentiate events by the same user at a given charging station. If we see two or more "successful" charging events back-to-back during the same visit, we think this issue is arising from charger interruptions. Figure 5 includes details of the events where out of the total successful visits, about 2% of the charging sessions resulted in charger interruptions where the user has to initiate the charger within the span of 2 hours.

3. Results

An example is provided in Figure 5 using the complete dataset of brand C to identify point errors and charging interruptions. For Brand C, the total number of 8,664 recorded events shrink to 7,654 unique visits with more information about the visit. With this information, we can make a determination of the true “no charge” visits where drivers failed to successfully charge at brand C charging stations. Figure 5 includes the summary of this information for all the charging stations. About 14% of the drivers failed to charge from brand C stations. About 6% of the users had some trouble charging at first but managed to get that resolved in consecutive attempts to charge.

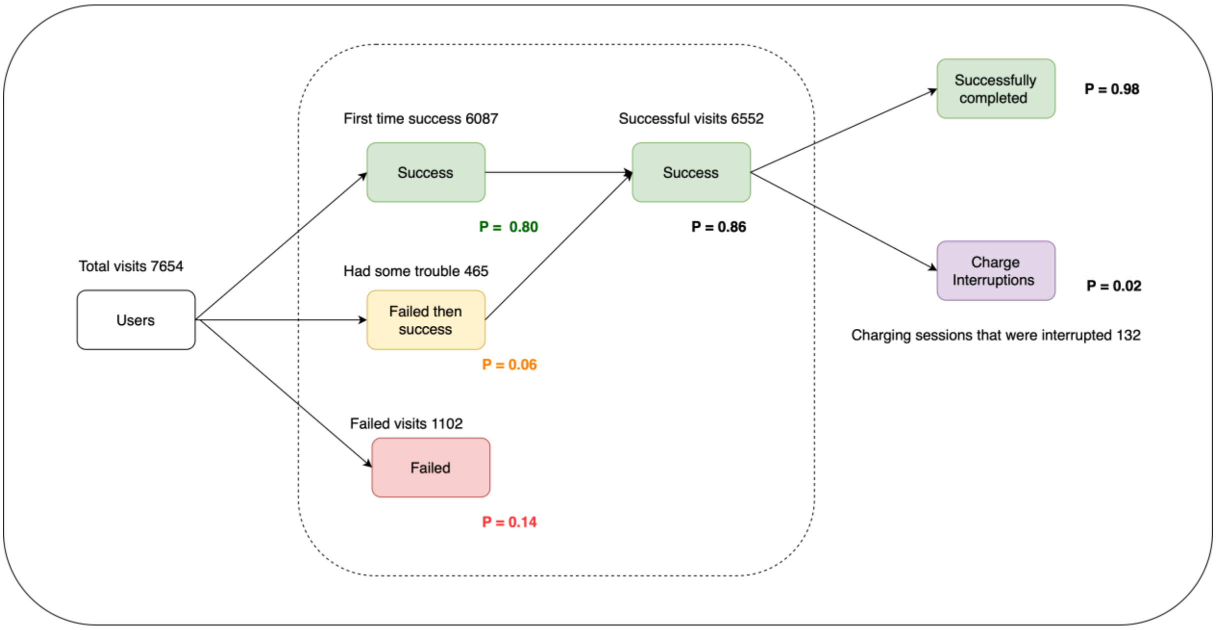

Figure 5: Summary of reliability probabilities for brand C

Using our methodology, the total of 59,542 recorded events at brand B charging stations converts to 40.724 visit as summarized in Figure 6. As indicated, about 23% of the users did not have a favorable outcome from the charging visit.

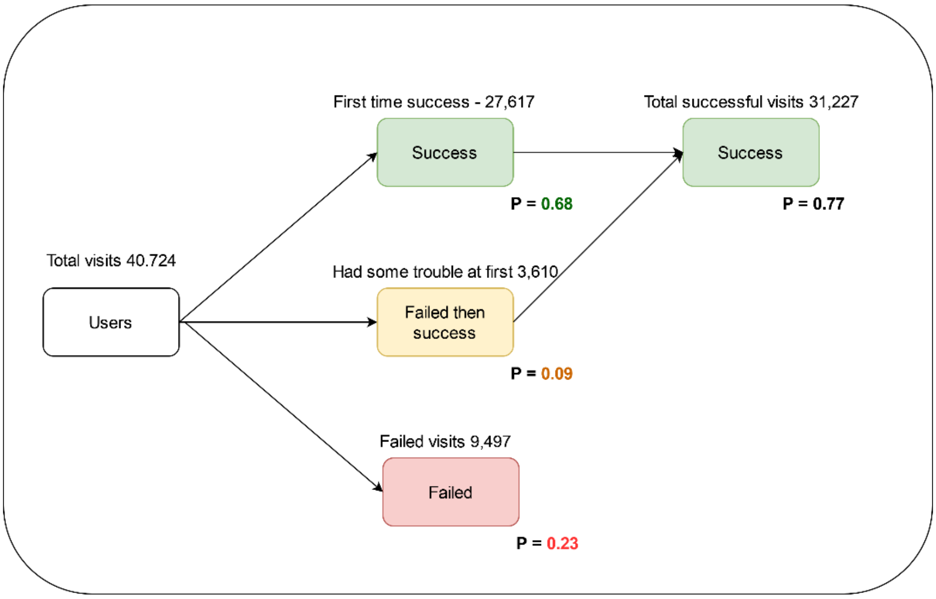

Figure 6: Summary of reliability for brand B

Reliability by Station (Brand B):

To better understand **station-based reliability** using the probabilistic value, we can separate the visits by stations and calculate a probabilistic reliability value by stations. Such a distribution is available in Figure 7. The colors legend are as follows. Stations that have 0.9 reliability or higher are represented in green, stations with 0.8-0.9 reliabilities are represented in orange and stations with reliabilities less than 0.8 are represented in red.

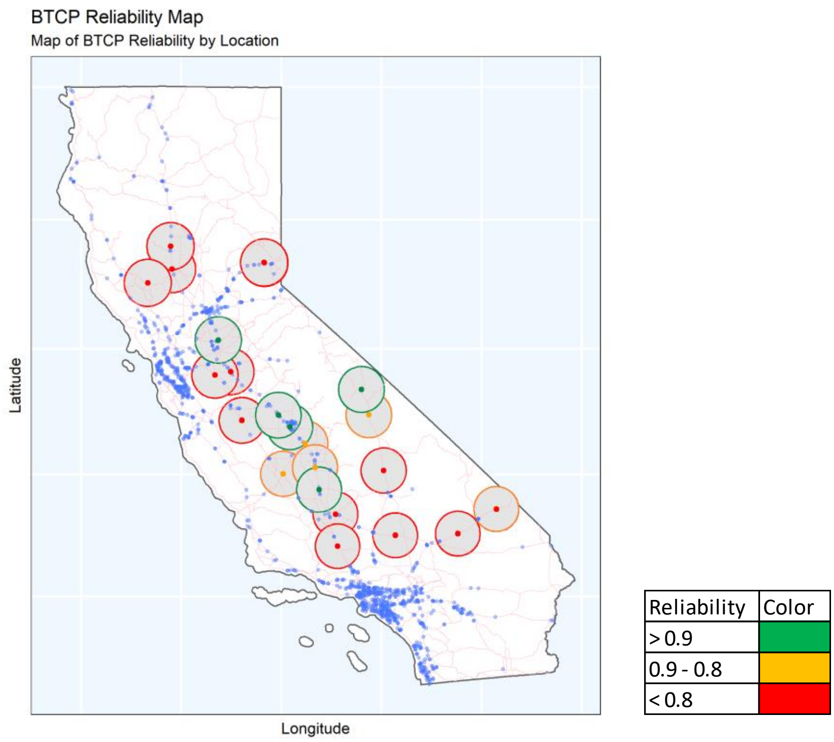

Figure 7: Probabilistic reliability of the Brand B charging stations. A radius of 25 miles is indicated around the Caltrans charging stations. Non-Caltrans public DC fast stations are indicated in light blue in the background.

3.1. Causes of Charging failure:

Using the classification made with Visit IDs, we're able to separate out the charging visits that could not successfully complete a charging session. These are visits where after multiple attempts the users could not successfully have the chargers working as intended or did not attempt to try again after first failed attempt. We will refer to them as **persistent errors**. A deeper analysis of reasons to understand such no-charge events reveals interesting reasons for their cause. We were able to identify 39 distinct error codes from the recorded charging event that map to persistent errors. The 39 charging error codes can be combined together into larger error theme such as communication errors, vehicle errors, cable/ connector errors and electrical insulation errors as indicated in Figure 8. While some errors do not neatly fit into such classifications, we used our best judgement to categorize the error codes referring to technical manuals published by the EVSE manufacturers and other publicly available information. Based on this information, we hope a deeper analysis can be conducted by the corresponding EVSE manufacturers.

The **communication errors** in Figure 8 can be stemming from multiple reasons. They are (1) charger is not able to complete initiate communications with vehicle, (2) vehicle is not connecter properly to the connector, or (3) vehicle not communicating with the charger. **Vehicle side errors** suggest that charging is not initiated from because vehicle is not permitting the charger to do so. Errors are categorized into cable/ connector issues because vehicle did not give any communication back to the charger within the allocated time. Insulation errors indicate the prevalence of leakage current or safety issues where the charger will not initiate charger for the safety of the user and the vehicle.

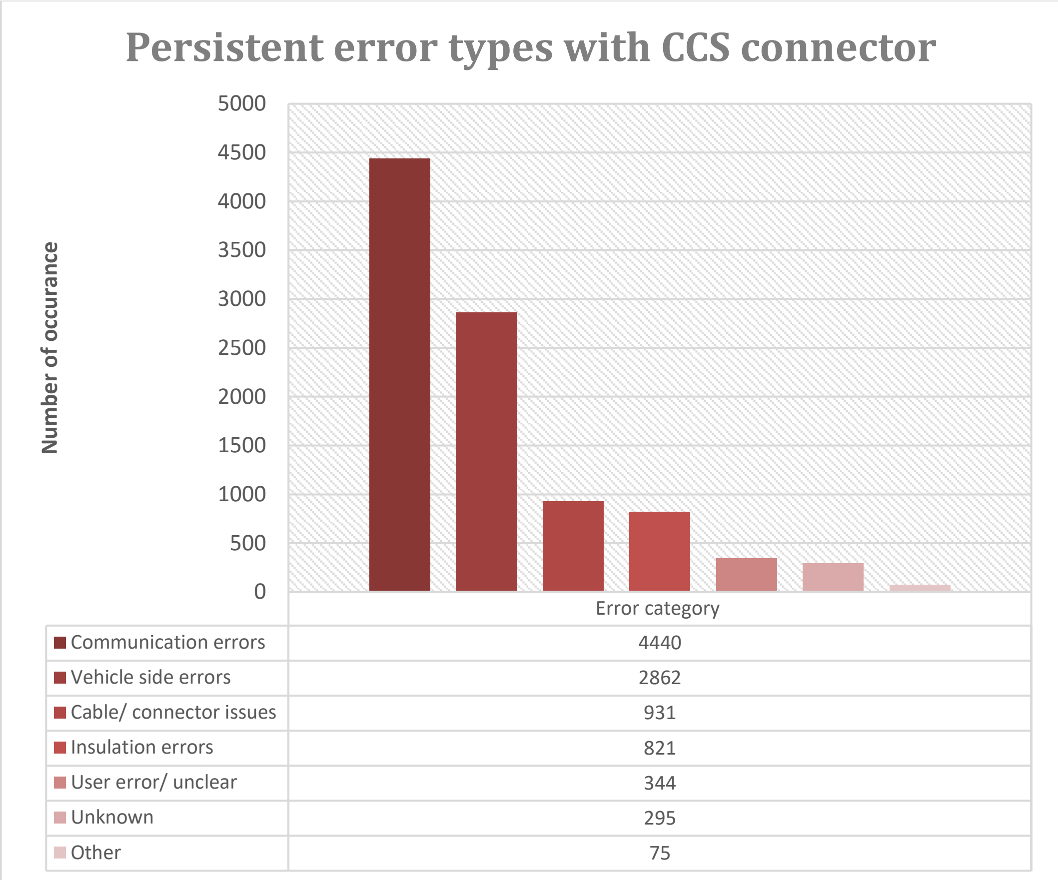

Figure 8: Summary of persistent errors from CCS connectors at Brand B

4. Discussion

4.1. Framework for determining charger reliability.

From the results we can determine that these corridor charging stations are not meeting our reliability expectations. Brand C chargers had a reliability of 86% whereas brand B chargers had 77%, not considering other levels of charging failures such as throttled charging and charging interruptions and other invisible charging failures that are potentially missing from the data (such as physically being blocked from accessing the chargers). That is to say the true reliability of charging stations is less than these metrics suggest. As found in Figure 7 some individual charging stations have a reliability number below 80%. This means that at least 20% of drivers who come to charge their vehicles may not be able to do so as expected. If we compare this to the current gas station model, this kind of reliability failures would be unacceptable.

The standards set by the Notice of Proposed Rulemaking (NPRM) and the final rules for the National Electric Vehicle Infrastructure (NEVI) program attempts to address issues of reliability by requiring NEVI funded charging infrastructure to maintain a minimum of a 97% "uptime" status [4]. As can be seen in Figure 3, this requirement is missing an entire grouping of "no charge" events when the charger is considered online. (i.e., point failures). Thus, a critical reliability question (as it pertains to NEVI) is the ratio of "no charge" events to total charging visits.

We initially created a framework categorizing charging stations as either being online (or considered as "uptime" by NEVI) and offline (as "downtime"). In such a framework, no-charge events during charger "uptime" would be defined as point failures. However, as our research progressed, we realized that this framework is too limiting and does not capture the full complexities and different ways a driver might be prevented from charging or how an intended charging sessions can fail. DC Fast chargers are essentially operating in a complicated eco-system of regulations and standards such as ISO 15118 and IEC 61851 that continue to evolve. We believe it is limiting to think of charging failures and success as a binary outcome of a charging attempt. The reliability of a complicated technological eco-system that comprise of charging stations, BEVs and charging system operators should considered with a broad understanding of possible points of failure in the charging eco-system. For example, we believe a throttled charging can occur for several reasons, such as to protect the battery from overheating or to maintain a stable charging session. Charger interruptions can occur due to various reasons such as, charging cable overheating, communication errors between the charging station and the EV, or faults in the charging equipment. Trying to rectify such errors without fixing major design problems within the eco-system may even cause safety problems. While it is hard to classify such nuances at this point in time, it is important to have an open dialogue with charging EVSE manufacturers, designers and charging standards and protocols planners to get to the bottom of the problem. We think Federal and State government agencies are well placed to initiate such discussions and facilitate further research.

Acknowledgments

The authors want to thank the California Department of Transportation (Caltrans) for sponsoring this study and sharing data and other information with the authors.

References

[1] S. Hardman, A. Jenn, G. Tal and e. al, “A review of consumer preferences of and interactions with electric vehicle charging infrastructure,” *Transport Research Part D,* 2018.

[2] M. Wolinetz and J. Axsen, “How policy can build the plug-in electric vehicle market: Insights from the REspondent-based Preference And Constraints (REPAC) model,” *Technoligical Forecasting and Social Change,* pp. 238-250, 2017.

[3] Z. A. Needell, J. McNerney, M. T. Chang and J. E. Trancik, “Potential for widespread electrification of personal vehicle travel in the United States,” *Nature Energy,* 2016.

[4] Federal Highway Administration, “National Electric Vehicle Infrastructure Formula Program,” 22 June 2022. [Online]. Available: https://www.federalregister.gov/documents/2022/06/22/2022-12704/national-electric-vehicle-infrastructure-formula-program.

[5] D. Rampel, C. Cullen, M. M. Bryan and G. V. Cezar , “Reliability of Open Public Electric Vehicle Direct Current Fast Chargers,” 2022.

[6] California Air Resources Board , “Electric Vehicle Supply Equipment Standards Technical Review,” CARB, 2022.

[7] Federal Highway Administration, “National Electric Vehicle Infrastructure Standards and Requirements,” Federal Highway Administration, 2023.

[8] V. Karanam and G. Tal, “How Disruptive are Unreliable Electric Vehicle Chargers? Empirically Evaluating the Impact of Charger Reliability on Driver Experience [Manuscript submitted for publication],” 2022.

[9] California Public Utilities Commission , “Transportation Electrification,” CPUC, 2021. [Online]. Available: https://www.cpuc.ca.gov/industries-and-topics/electrical-energy/infrastructure/transportation-electrification. [Accessed 16 November 2022].

[10] C. Singh and R. Billinton, “System Reliability Modeling and Evaluation, Hutchinson Educational,” London, Hutchinson Educational, 1977.

[11] D. Rempel, C. Cullen, M. M. Bryan and G. V. Cezar, “Reliability of Open Public Electric Vehicle Direct Current Fast Chargers,” UC Berkeley , 2022.

[12] U.S. Department of Transportation, Federal Highway Administration, “The National Electric Vehicle Infrastructure (NEVI) Formula Program Guidance,” 12 February 2022. [Online]. Available: https://www.fhwa.dot.gov/environment/alternative_fuel_corridors/nominations/90d_nevi_formula_program_guidance.pdf.

[13] M. Yilmaz and P. T. Krein , “Review of Battery Charger Topologies, Charging Power Levels, and Infrastructure for Plug-In Electric and Hybrid Vehicles,” *IEEE Transactions on Power Electronics,* vol. 28, no. 5, pp. 2151-2169, 2013.

[14] C. S. a. R. Billinton, System Reliability Modelling and Evaluation, London: Hutchinson Educational Publishers , 1977.

Presenter Biography

Tisura Gamage is a Ph.D. candidate at the University of California, Davis. Before starting his Ph.D. program, he earned a master’s degree from the Johns Hopkins University School of Advanced International Studies (SAIS) with a concentration in Energy Policy and International Economics. His current research focuses on understanding the reliability of DC fast chargers and the challenges and costs associated with installing corridor DC fast chargers. He holds a bachelor’s degree in mechanical engineering from the University of Moratuwa in Sri Lanka.