FTA Report No. 0270

FTA RESEARCH

FEDERAL TRANSIT ADMINISTRATION

Effectiveness of Wireless Charging for Electric Transit Buses

An Industry Report

PREPARED BY

CALSTART

U.S. Department of Transportation
Federal Transit Administration

DECEMBER
2024

COVER PHOTO

Cover image courtesy of WAVE Charging
Antelope Valley Transit Vehicle Approaching Wireless Charging Pad

DISCLAIMER

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PREPARED BY
Katrina Sutton, Bryan Lee, and Katrina Bayer
CALSTART
48 S Chester Ave.
Pasadena, CA 91106

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U.S. Department of Transportation
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Metric Conversion Table

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
VOLUME				
fl oz	fluid ounces	29.57	millimeters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m^3				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact degrees)				
˚F	Farenheit	5 (F-32)/9 or (f-32)/1.8	Celsius	˚C

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14. ABSTRACT
A study on wireless charging for public transportation revealed that high-powered inductive charging lacks robust standards and is not widely deployed in the U.S., although efforts by the Society of Automotive Engineers (SAE) are underway. Wireless charging shows promise, especially for on-route and depot use where space constraints exist, but faces challenges due to current battery-electric bus range limitations and the need for reliable on-route charging to replace fossil fuel buses. Enhanced standards, data collection, and funding opportunities are needed to advance the technology.

15. SUBJECT TERMS
FTA Research, Wireless charging, Public transit, Battery electric bus, Inductive charging, Wireless charging industry standards, On route charging

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Abstract

As mandated in the FY 2023 House Transportation, Housing, and Urban Development Appropriation Report,[1] the Federal Transit Administration (FTA) directed CALSTART to conduct literature research and qualitative interviews to study the effectiveness of wireless charging as an alternative to wired charging, including recommendations for deploying wireless charging for public transportation.

Wireless charging, also known as inductive charging, is a type of power transfer used to charge a vehicle without a physical connection. While standards for high-power wireless charging do not currently exist, the SAE International standard for high-powered wireless charging (J2954-2) is under development and is expected to be released in late 2025 or early 2026. High-powered wireless charging for transit buses does not currently have a robust standards regime in the U.S., and the technology has yet to be broadly deployed. While standards are being developed by the Society of Automotive Engineers (SAE), they have not been fully adopted or implemented.

The literature review utilized existing published documents, including news articles, press releases, and relevant standards documentation. Semi-structured interviews were conducted with transit agencies, fleet operators, vehicle manufacturers, charging companies, and other industry stakeholders. The semi-structured interviews allowed for new ideas to arise organically during the interview process. The purpose of the interviews was to obtain experiential and anecdotal information regarding challenges faced in deploying wireless and wired charging for transit fleets.

Wireless charging is one option for on route charging and the technology can be deployed at depots where space constraints preclude the installation of plug-in charging. This report outlines the effectiveness of wireless charging as an alternative to wired charging for transit by examining the availability, capability, and limitations of both charging types. Current battery electric bus (BEB) range limitations indicate that reliable on route charging may prove necessary for BEBs to be viable one-to-one replacements for fossil fuel buses.

1 DEPARTMENTS OF TRANSPORTATION, AND HOUSING AND URBAN DEVELOPMENT, AND RELATED AGENCIES APPROPRIATIONS BILL, 2023. Accessed November 2024. HYPERLINK https://www.govinfo.gov/content/pkg/CRPT-117hrpt402/pdf/CRPT-117hrpt402.pdf

Executive Summary

Introduction

The objective of this study is to evaluate the effectiveness of wireless charging for battery electric transit buses as an alternative to traditional plug-in charging. Plug-in chargers are currently the dominant charging technology, transferring power by plugging the charger into a receptacle on the vehicle to establish a physical connection. Most plug-in chargers are deployed in depots and are typically used to charge buses overnight. Unlike plug-in charging, wireless charging occurs without establishing a physical connection between the charger and the vehicle. Instead, wireless charging uses electromagnetic waves to transfer power to vehicles without a physical electrical connection between an in-ground charging pad and an onboard receiver. Wireless charging can facilitate multiple different types of charging, such as on route charging to extend the range of the vehicle, on route charging as the primary source of power, and even depot charging under certain circumstances.

Public transit has emerged as an early adopter of this technology with at least 10 transit agencies already deploying wireless charging to support battery-electric transit buses. Most of these deployments provide on route charging. Public transit is a strong candidate for wireless charging technology because the buses are on a set timetable in which time blocks for on route charging can be scheduled. These deployments have successfully demonstrated the technological viability of wireless charging across real-world conditions in public transit applications. However, despite these successful demonstrations, there are relatively few deployments of this technology. This report explores the effectiveness and barriers to the growth of this technology.

Background

This study was conducted in accordance with the following section of the FY 2023 Transportation, and Housing and Urban Development, and Related Agencies Appropriations Bill[2]:

> The Committee recognizes the potential of wireless charging, also known as inductive charging, for electric buses, which could extend the operating range of buses, shorten charging times, and reduce the size of batteries. The Committee directs the FTA to conduct a study on the effectiveness of wireless charging as an alternative to wired charging, including recommendations for deploying wireless charging to improve

2 DEPARTMENTS OF TRANSPORTATION, AND HOUSING AND URBAN DEVELOPMENT, AND RELATED AGENCIES APPROPRIATIONS BILL, 2023. Accessed November 2024. HYPERLINK https://www.govinfo.gov/content/pkg/CRPT-117hrpt402/pdf/CRPT-117hrpt402.pdf

> public transit. The Committee directs the FTA to complete such a study no later than 1 year after enactment of this Act and to publish the report on the agency's website.

Per the above stipulation, CALSTART conducted a study on the effectiveness of wireless charging as an alternative to wired charging, including recommendations for deploying wireless charging in the public transit sector. Transit agencies have used wireless charging to charge their buses on route, in which the buses partially recharge during short (usually 10–15 minutes) planned breaks in service throughout the day. This charging strategy extends the operating range of buses, shortens depot charging times, and can allow transit agencies to reduce the size of the battery packs needed to maintain daily operations. This technology is in the early stages of commercialization, and there are relatively few deployments. CALSTART's research for this report seeks to uncover lessons learned from these limited deployments and to assess prospects for future technological development and commercialization.

Methodology

CALSTART examined potential barriers to wireless charging technology for public transit and developed recommendations for further research and knowledge sharing. Researchers gathered qualitative data from multiple sources and conducted research and review of literature to understand the current state of the technology and industry standards. Interviews were conducted with multiple stakeholders across different functional capacities within the industry. Interviewees included charging companies and transit vehicle original equipment manufacturers (OEMs). CALSTART also interviewed employees and managers of fleets with and without wireless charging currently deployed. The interviews focused heavily on transit fleets with wireless chargers as they were able to provide information on best practices and lessons learned. Additionally, charging management companies were interviewed to understand the feasibility of integrating wireless charging into charging management systems (CMS), which are commonly used in the transit industry. Interviews were also conducted with industry groups and standards organizations to obtain a company-neutral perspective on the technology. The majority of the supply chain and customer base for wireless charging technology was also captured through these interviews, allowing them to provide insight into the market dynamics and lessons learned from operational deployments. Interviews were semi-structured, providing new ideas to surface during the interview. All interview data was aggregated and anonymized.

This report includes an analysis of:

- Wireless charging including industry standards, advantages, and disadvantages.

- Transit agency feedback including current practices and experiences, lessons learned from deployments, as well as barriers to charging.
- Charging company feedback including market segmentation, barriers to funding, standards and interoperability, and education.
- Vehicle equipment manufacturer feedback including discussion from the point of view of manufacturers experienced with wireless technology compared to those without such experience, standards and interoperability, and the market for wireless technology.
- Research findings and potential actions to reduce barriers to the adoption of wireless charging technology for transit agencies interested in integrating the technology into their fleets.

Research Findings and Recommendations

This study is based upon research to define ongoing efforts to develop a high-power wireless charging standard. The authors conducted interviews with transit agencies and seven major transit vehicle OEMs and held discussions with SAE International committee members to identify key challenges and opportunities for the adoption of high-power (up to 500kW) wireless charging for transit vehicles. While standards for high-power wireless charging do not currently exist, the SAE International standard for high-powered wireless charging (J2954-2) is under development and is expected to be released in late 2025 or early 2026. The lack of published standards and market demand are significant barriers to greater integration of wireless charging technology. Transit providers noted the potential for static inductive charging, i.e., wireless charging when the vehicle is stationary, particularly for on route charging to support (BEBs). However, funding and interoperability issues hinder widespread adoption. Enhanced data collection, funding opportunities, and the development of interoperable standards could accelerate the adoption and efficacy of wireless charging in transit. The research findings are summarized below:

- Potential for Static Inductive Charging: Static inductive charging can significantly enhance the viability of BEBs, particularly for on route charging.
- Lack of Standards and Market Demand: Absence of current standards and an uncertain market as barriers to investing in OEM wireless charging integration. SAE International is working on a high-power wireless charging standard (J2954-2), expected by late 2025 or early 2026.
- Funding Challenges: Funding for wireless charging is less accessible due to the specificity of funding opportunities favoring wired charging infrastructure. Existing funding programs may inadvertently favor wired charging via 1:1 vehicle-to-charger ratios and existing standards requirements.

- Interoperability Needs: Wireless charging equipment must be interoperable across different vehicle and charging systems to advance market development.
- Operational Data and Knowledge Gaps: More transit-specific data collection is required to fill the knowledge gap and support broader wireless charging adoption.
- Recommended Conditions for Effective Deployment: BEBs need a minimum dwell time of 15 minutes for vehicles to receive enough energy. Multiple chargers should be deployed in succession and within painted guidelines to assist operators in properly aligning their vehicles.

Through the barriers and opportunities discussed above, the following recommendations would reduce barriers faced by transit agencies interested in adopting wireless charging technology.

- Standards: High-power inductive charging standards are necessary for interoperability, while also protecting vehicle OEMs and transit agencies from fluctuations in the market.
- Funding: Ensure wireless charging receives equitable funding opportunities, which includes funding opportunity language that supports both vehicle and ground-mounted equipment.
- Safety: Adoption of charging-related safety standards and third-party certifications would increase confidence in wireless charging technology.
- Nascent Technology: Address concerns about the potential long-term reliability of wireless charger purveyors. Moving to adopt wireless charging at scale would serve to reassure investment-related concerns.
- Education: Widespread dissemination of wireless charging case studies and reports on best practices would help transit agencies make informed decisions.

Section 1

Introduction

This study evaluates the effectiveness of wireless charging as an alternative to traditional plug-in charging for battery electric buses (BEBs). Plug-in chargers are currently the standard charging technology, and they transfer power by plugging the charger into a receptacle on the vehicle to establish a physical connection. Most plug-in chargers are deployed in depots and are typically used to charge buses overnight. Unlike plug-in charging, wireless charging occurs without establishing a physical connection between the charger and the vehicle. Instead, wireless charging uses electromagnetic waves to transfer power to vehicles through an airgap between an in-ground charging pad and an onboard receiver. Wireless charging can facilitate different types of charging, such as on route charging to extend the range of the vehicle, on route charging as the primary source of power, and even depot charging under certain circumstances.

Public transit is a strong use candidate for wireless charging technology because bus timetables make it easier to schedule on route charging. At least ten transit agencies are already deploying wireless charging to support BEBs. These deployments have successfully demonstrated the technological viability of wireless charging across real-world conditions in public transit applications, although there are relatively few deployments of this technology. This raises questions about the barriers to the growth of this technology.

Background

The FY 2023 Transportation, and Housing and Urban Development Appropriations Bill called for further research into adapting wireless charging technology for public transit:

> The Committee recognizes the potential of wireless charging, also known as inductive charging, for electric buses, which could extend the operating range of buses, shorten charging times, and reduce the size of batteries. The Committee directs the FTA to conduct a study on the effectiveness of wireless charging as an alternative to wired charging, including recommendations for deploying wireless charging to improve public transit. The Committee directs the FTA to complete such a study no later than 1 year after enactment of this Act and to publish the report on the agency's website.[3]

Per the stipulation, CALSTART conducted a study on the effectiveness of wireless charging as an alternative to wired charging, offering recommendations

3 DEPARTMENTS OF TRANSPORTATION, AND HOUSING AND URBAN DEVELOPMENT, AND RELATED AGENCIES APPROPRIATIONS BILL, 2023. Accessed November 2024. HYPERLINK https://www.govinfo.gov/content/pkg/CRPT-117hrpt402/pdf/CRPT-117hrpt402.pdf

for its deployment in public transit. Transit agencies have used wireless charging to charge their buses on route, in which the buses partially recharge during short (usually 10–15 minutes) planned breaks in service throughout the day. This charging strategy extends the operating range of buses, shortens depot charging times, and can allow transit agencies to reduce the size of the battery packs needed to maintain daily operations. This technology is in the earlier stages of commercialization as there are relatively few deployments. CALSTART's research seeks to uncover lessons learned from these limited deployments and to assess prospects for future technological development and commercialization.

Methodology

CALSTART examined potential barriers to wireless charging in public transit and developed recommendations for further research and knowledge sharing. Researchers used a literature search and stakeholder interviews to gather qualitative data.

Literature Review

Research on the current state of the technology and existing industry standards included a review of technical documents about wireless technology from the following sources:

- International Commission on Non-Ionizing Radiation Protection
- International Electrotechnical Commission
- International Organization for Standardization
- Society of Automotive Engineers
- Standardization Administration of China
- Underwriters Laboratory
- United Nations Economic Commission for Europe

Interviews

CALSTART interviewed stakeholders to gain perspective on the best practices and lessons learned related to the wireless charging systems:

- Charging companies provided insight into the feasibility of integrating wireless charging into charging management systems (CMS) commonly used in the transit industry
- Transit vehicle original equipment manufacturers (OEMs),
- Representatives of transit and non-transit fleets provided insight about the majority of the supply chain and customer base for wireless charging technology, the market dynamics, and lessons learned from operational deployments.

- Industry groups and Standards organizations offered a company-neutral perspective on the technology

The goal of the interviews was to gather information on best practices and lessons learned.

Protocols were semi-structured to enable new ideas to surface during the interview. The prepared interview questions are in Appendix A. Interview data was aggregated and anonymized.

Section 2

Wireless Charging Overview

Wireless charging, also known as inductive charging, is a type of wireless power transfer (WPT). Traditional plug-in charging infrastructure uses conductors in wires to transfer electricity to the vehicle. Wireless charging uses electromagnetic waves to transfer energy through a process called induction. Unlike plug-in charging, wireless chargers do not need to establish physical contact with the vehicle to transfer power. To enable wireless charging, a vehicle needs a charging plate aligned with a ground-mounted (or embedded) charging pad. The vehicle charging plate is mounted on the underside of the BEB and integrated with the vehicle's high-voltage battery and battery management system (BMS). Figure 2-1 is an example of the in-ground infrastructure, while Figure 2-2 shows a schematic of an inductive wireless charging system. Charging occurs through a magnetic field between the ground assembly and vehicle assembly.

Figure 2-1. WAVE Inductive Charging System, Source: Bryan Lee, CALSTART

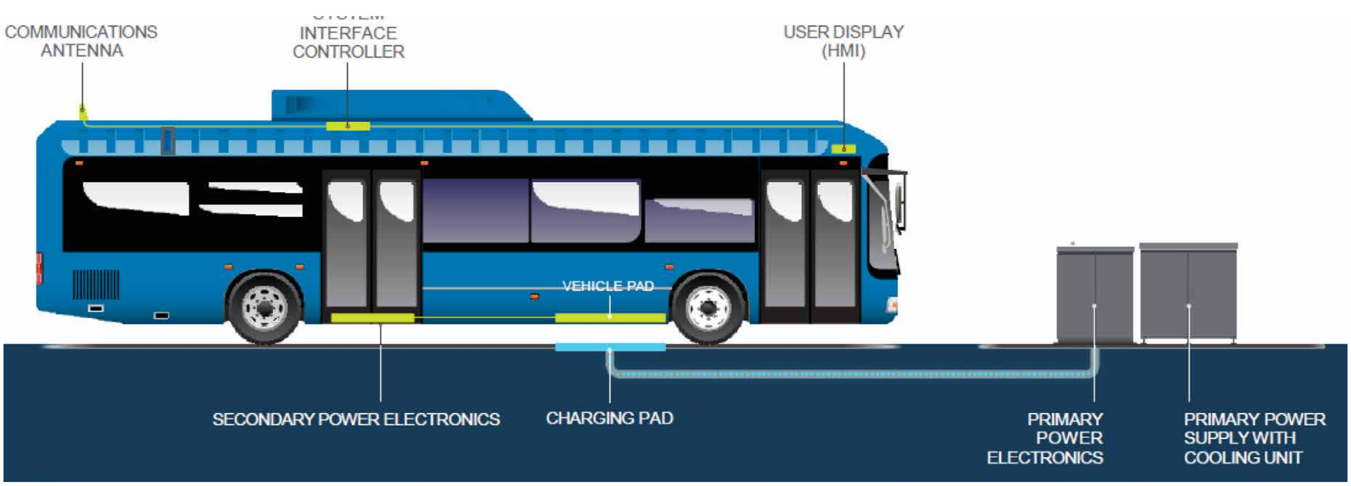

Figure 2-2. Inductive Charging Schematic Source: WAVE Charging

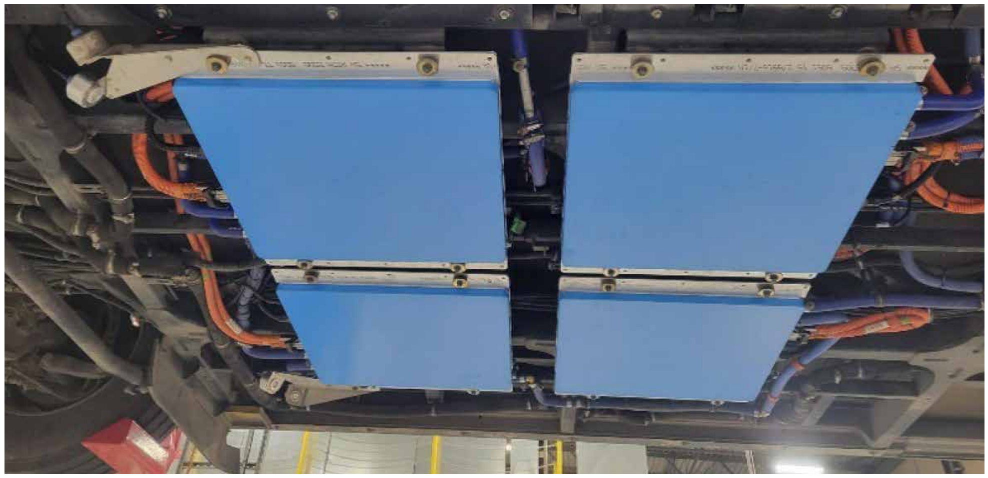

Figure 2-3. InductEV Vehicle Mounted Receivers, Source: InductEV

There are two types of wireless charging—static and dynamic. Static wireless charging occurs when a vehicle is stationary or parked. Dynamic charging occurs while the vehicle is in motion. Dynamic charging involves outfitting a vehicle with one or more receivers so that it can receive energy through charging coils embedded in the roadway.

This research focuses on static charging in transit bus applications as static charging is more established and closer to market adoption than dynamic charging. Unless stated otherwise, the reference to wireless or inductive charging in this report refers to one-directional static high-power wireless charging, up to 500kW, and compliant with SAE J2954-2. Refer to Industry Standards Development for more details about this standard.

Wireless charging has undergone significant technological development but is not yet considered to be a commercialized product. Technology development is assessed through a metric called technology readiness level (TRL). TRL is measured on a scale of 1 to 9. A score of 1 means there is scientific evidence for a potential innovation or technology. A score of 9 indicates the technology is a commercialized product generally available for use, has begun serial production, and has been operated successfully in an uncontrolled commercial environment3. The Society of Automotive Engineers (SAE) International, a leading standards organization, and Advancing Sustainability through Powered Infrastructure for Roadway Electrification (ASPIRE), a leading research center focusing on wireless charging, agree wireless charging has currently achieved a TRL of at least 7, which is the early pilot/late demonstration stage. This means the technology is successfully operating in real-world conditions at a pre-commercial scale. The scoring rubric is presented in Table 2-1.

Table 2-1. TRL Scoring Rubric[4]

TRL Level	General Technology Level	TRL Definition	Example Technology
9	Early Market	Full commercial application; Technology in general availability for users. Manufacturing phase. Successfully operated in uncontrolled commercial environment.	Low NOx Engine 8.9L; Battery-Electric Bus; FCEV Forklift
8	Large Scale Pilot	Pre-production. First of its kind commerical system. Technology ready to support commercial activity. In limited release assessment numbers. Vehicle succeeds in uncontrolled environment.	Battery-Electric Harbor Craft Vessels; Battery-Electric Mobile Power Unit
7	Early Pilot/Late Demonstration	Demonstration system. Operating in intended environment at pre-commercial scale. Units succeeds in relevant environment.	FCEV Drayage; FCEV Harbor Craft Vessels
6	Early Demonstration (Advanced Prototype System)	Tested in intended environment at close to expected perfromance. Limited vehicle builds. Behicle succeeds in first real world scenarios.	0.02 NOx Diesel Engine; FCEV Automated Guided Vehicle
5	Prototype	Large scale prototypes. Tested in intended environment; tested well enough to validate in real world scenarios.	John Deere Gridcon Autonomous Tractor
4	Technology Developement	Small scale (ugly) prototypes. First prototypes built, tested to perform under specific conditions.	Fully Autonomous Long-Haul Trucks
3	Research	Benefits and viability of technology confirmed in lab. (Pre-Prototype)	
2	Research	Early invention stage. Concept and application have been finalized.	
1	Research	Scientific evidence for potential innovation.	

Wireless charging requires further development to achieve a TRL of 9. According to SAE International, foreign object detection and living organism detection technologies are vital to ensure the safety of wireless charging. These technologies will address safety concerns by preventing wireless chargers from operating when they detect foreign objects or live organisms in the electromagnetic field. Because metals exposed to these frequencies can heat up rapidly. there is a safety risk if foreign objects, particularly metals, enter the electromagnetic field between the ground pad and the receiver. This heat can damage the road surface and/or the ground pad. The heated metal poses several risks to people and systems, including igniting nearby flammable

4 CALSTART (2002) Methods for Assessing Technology and Market Readiness for Clean Commerical Transportation. Retrieved from: https://calstart.org/wp-content/uploads/2022/04/Assessing-Technology-and-Market-Readiness_Final.pdf

materials, causing burns if touched,[5] and adverse health impacts from exposure to electromagnetic waves.[6] [7] SAE International states that a testing program for foreign object detection and live organism detection technologies should be established to provide a greater level of safety for this technology.[8]

Wireless charging technology is being tested for other types of vehicles beyond transit including medium- and heavy-duty (MHD) vehicle segments such as port equipment, yard tractors, and semi-trucks. Wireless charging companies are researching how wireless charging technology could be used in light duty vehicles, such as taxis, rideshare vehicles, and personal EVs. Two wireless charging companies interviewed expressed potentially developing bidirectional wireless charging capabilities in the future, which would allow for the vehicle to wirelessly export power from their battery back to the grid.

Industry Standards Development

Standards are critical to the advancement of BEBs because they establish interoperability across manufacturers and ensure safe and reliable products. Additionally, they allow a market in which a product purchased from any manufacturer will be compatible with all the fleet's vehicles, keeping transit buses operating regardless of whether the original wireless charger manufacturer remains solvent. Standards help markets competitively accommodate multiple manufacturers, which is critical for market growth. Traditional plug-in charging infrastructure has undergone standardization; the connector for direct current fast charging (DCFC) plug-in chargers adheres to standards such as the Combined Charging System (CCS) or the North American Charging Standard (NACS).

The U.S. Standards for wireless chargers are not fully developed. CALSTART's research interviews with various stakeholders indicate the upcoming SAE International standard is needed to bring the high-power wireless charging industry to scale.

An industry standard, SAE J2954-1, has been developed for low-power (up to 11 kW) wireless charging; however, there are no standards for the high-power wireless charging required for MHD vehicles (up to 500kW). The lack of standards for high-power wireless chargers is problematic for both safety and funding reasons. SAE International has made progress toward developing a standard for

5 SAE International (2022). Wireless Power Transfer for Light-Duty Plug-in/Electric Vehicles and Alignment Methodology. Retrieved from: https://www.sae.org/standards/content/j2954_202208/

6 Possible Effects of Radiofrequency Electromagnetic Field Exposure on Central Nerve System. Accessed April 2024. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6513191/

7 International Commission on Non-Ionizing Radiation Protection (2020). ICNIRP Guidelines for Limiting Exposure to Electromagnetic Fields (100 kHz to 300 GHz). Retrieved from: https://www.icnirp.org/cms/upload/publications/ICNIRPrfgdl2020.pdf

8 Interview with SAE International

high-power wireless charging, which is expected to be released as SAE J2954-2. In 2022, SAE International released the SAE Technical Information Report (TIR) J2954-2, which detailed power transfer levels for high-power stationary wireless charging up to 500 kW and the technical requirements for these power levels. The TIR will be used as the basis for the future standard. SAE J2954-2 is expected to be released in late 2025 or early 2026. SAE International is also developing SAE J2954-3, which would address industry standards for dynamic wireless charging.

SAE International is also working on other topics relating to wireless charging standards. SAE International plans to address the alignment between the ground pad and the onboard receiver. SAE J2954-1 has been revised to include vehicle-ground equipment alignment methodology, and this update should be released by the end of 2024. This alignment methodology will be included in J2954-2 is unknown, but it appears likely. SAE International is also holding discussions with the Standardization Administration of the People's Republic of China (SAC), the International Organization for Standardization (ISO), and Underwriters Laboratories (UL) to ensure that SAE J2954-2 aligns with other international wireless charging standards. The technical committee for SAE J2954 states that interoperability between SAE J2954-1, J2954-2, and J2954-3 is anticipated.

There are other wireless charging standards beyond those developed by SAE. Table 2-2 has a list of relevant industry standards. Some standards are not directly related to BEB high-power wireless charging in the U.S. but are worth mentioning for reference.

Table 2-2. Industry Charging Standards

Org.	Standard	Title	Status
SAE	J2847-6[9]	Communication for Wireless Power Transfer Between Light-Duty Plug-in Electric Vehicles and Wireless EV Charging Stations	Published
	J2954-1[10]	Wireless Power Transfer for Light-Duty Plug-in/Electric Vehicles and Alighment Methodolgy	Published

9 SAE International (2020). Communication for Wireless Power Transfer Between Light-Duty Plug-in Electric Vehicles and Wireless EV Charging Stations J2847/6_202009. Retrieved from: https://www.sae.org/standards/content/j2847/6_202009/

10 SAE International (2022). Wireless Power Transfer for Light-Duty Plug-in/Electric Vehicles and Alignment Methodology. Retrieved from: https://www.sae.org/standards/content/j2954_202208/

Org.	Standard	Title	Status
	J2954-2[11]	Wireless Power Transfer for Heavy-Duty Electric Vehicles	In-progress (likely late 2025/early 2026)
	J2954-3[12]	Dynamic Wireless Power Transfer for both Light and Heavy-Duty Vehicles	TBD
SAC	GB/T 38775[13]	Electric vehicle wireless power transfer	Published
IEC	61851-1[14]	Electric vehicle conductive charging system–Part 1: General requirements	Published
	61851-21-1[15]	Electric vehicle conductive charging system–Part 21-1: Electric vehicle on-board charger EMC requirements for conductive connection to an AC/DC supply	Published
	61851-21-2[16]	Electric vehicle conductive charging system–Part 21-2: Electric vehicle requirements for conductive connection to an AC/DC supply-EMC requrements for off board electric vehicle charging system	Published
	61980-1[17]	Electric vehicle wireless power transfer (WPT) systems–Part 1: General requirements	Published

11 SAE International (2022). Wireless Power Transfer for Heavy-Duty Electric Vehicles. Retrieved from: https://www.sae.org/standards/content/j2954/2_202212/

12 SAE International (2023). Dynamic Wireless Power Transfer for both Light and Heavy-Duty Vehicles. Retrieved from: https://www.sae.org/standards/content/j2954/3/

13 Standardization Administration of China (2023). Interim Provisions on Radio Management of Wireless Charging (Power Transmission) Equipment. Retrieved from: https://mp.weixin.qq.com/s/Tp64eq1u-m-yws2QMhe5SA

14 International Electrotechnical Commission (2017). Electric vehicle conductive charging system - Part 1: General requirements. Retrieved from: https://webstore.iec.ch/publication/33644

15 International Electrotechnical Commission (2017). Electric vehicle conductive charging system – Part 21-1: Electric vehicle on-board charger EMC requirements for conductive connection to an AC/DC supply. Retrieved from: https://webstore.iec.ch/publication/32045

16 International Electrotechnical Commission (2018). Electric vehicle conductive charging system - Part 21-2: Electric vehicle requirements for conductive connection to an AC/DC supply - EMC requirements for off board electric vehicle charging systems. Retrieved from: https://webstore.iec.ch/publication/31282

17 International Electrotechnical Commission (2020). Electric vehicle wireless power transfer (WPT) systems - Part 1: General requirements. Retrieved from: https://webstore.iec.ch/publication/31657

Org.	Standard	Title	Status
	61980-4[18]	Interoperability and safety of high-power wireless power transfer (H-WPT) for electric vehicles	In-process
	61980-5[19]	Dynamic electric vehicle wireless power transfer systems (formally IEC 63243)	In-process
	61980-6[20]	Dynamic wireless power transfer (formally IEC 63381)	In-process
ISO	15118-20[21]	Vehicle to grid communication interface	Published
UNECE	R10[22]	Concerning the Adoption of Harmonized Technical United Nations Regulations for Wheeled Vehicles, Equipment and Parts which can be Fitted and/or be Used on Wheeled Vehicles and the Conditions for Reciprocal Recognition of Approvals Granted on the Basis of these United Nations Regulations	Published
	R100[23]	Concerning the Adoption of Harmonized Technical United Nations Regulations for Wheeled Vehicles, Equipment and Parts which can be Fitted and/or be Used on Wheeled Vehicles and the Conditions for Reciprocal Recognition of Approvals GRanted on the Basis of these United Nations Regulations	Published

18 International Electrotechnical Commission. Interoperability and safety of high-power wireless power transfer (H-WPT) for electric vehicle. Retrieved from: https://www.iec.ch/ords/f?p=103:14:18596444030514::::FSP_ORG_ID:27229

19 International Electrotechnical Commission. Dynamic electric vehicle wireless power transfer systems (formally IEC 63243). Retrieved from: https://www.iec.ch/ords/f?p=103:14:200002670289147::::FSP_ORG_ID:23149

20 International Electrotechnical Commission. Dynamic wireless power transfer (formally IEC 63381). Retrieved from: https://www.iec.ch/ords/f?p=103:14:17084134954331::::FSP_ORG_ID:27462

21 International Organization for Standardization (2022). Vehicle to grid communication interface. Retrieved from: https://www.iso.org/standard/77845.html

22 United Nations Economic Commission for Europe (2022). Framework Document for Automated/Autonomous Vehicles (UPDATED). Retrieved from: https://unece.org/transport/publications/framework-document-automatedautonomous-vehicles-updated

23 United Nations Economic Commission for Europe (2022). Concerning the Adoption of Harmonized Technical United Nations Regulations for Wheeled Vehicles, Equipment and Parts which can be Fitted and/or be Used on Wheeled Vehicles and the Conditions for Reciprocal Recognition of Approvals Granted on the Basis of these United Nations Regulations. Retrieved from: https://unece.org/sites/default/files/2022-07/R100r3e.pdf

Org.	Standard	Title	Status
	R121[24]	Uniform provisions concerning the approval of vehicles with regard to the location and identification of hand controls, tell-tales, and indicators	Published
UL	2750[25]	Investigation For Wireless Power Transfer Equipment for Electric Vehicles	Published

Wireless Charging Advantages and Disadvantages

The benefit of wireless charging is the ability to charge a vehicle without making physical contact, eliminating the need for personnel to connect requiring a heavy charging cable. Wireless charging can serve a variety of use cases, including depot charging, on route static charging, and on-road dynamic charging, allowing for significant changes to charging operations.

How Wireless Charging Compares to Wired Charging

Below is a non-exhaustive list of the technological advantages and disadvantages found through the research and raised by the entities interviewed. Note that different interviewees may perceive the same facts as either an advantage or a disadvantage and facts should not be perceived as a consensus of those interviewed.

The following advantages were among the favorable aspects identified in CALSTART's research:

- **Right Sizing BEB Battery Capacity** – Wireless charging allows for quick charging on route throughout the day. Thus, the transit agency does not have to size the battery for all-day operations because a smaller, more frequently charged battery will suffice. A smaller battery would be less expensive to purchase and would weigh less, and as lighter vehicles are more energy efficient, this would allow for savings in operating costs, as well as lessening the wear and tear on public infrastructure.
- **Cleaner Charging** – Daytime charging, especially in areas with higher levels of solar energy penetration, typically has a higher renewable

24 United Nations Economic Commission for Europe (2016). Uniform provisions concerning the approval of vehicles with regard to the location and identification of hand controls, tell-tales and indicators. Retrieved from: https://op.europa.eu/en/publication-detail/-/publication/0ba565c5-b5cd-11e5-8d3c-01aa75ed71a1

25 Underwriters' Laboratory (2023). Outline Of Investigation for Wireless Power Transfer Equipment for Electric Vehicles. Retrieved from: https://webstore.ansi.org/standards/ul/ul2750ed2023

energy content, so the buses could potentially be powered by cleaner, less expensive energy. Transit agencies traditionally charge their buses overnight and in the evening hours, which generally offers lower renewable energy content than daytime charging. Charging throughout the day also means less overnight charging which can lead to load shifting. Figure 2-4 below illustrates how renewable content is highest during the middle of the day on the California Independent System Operator grid.

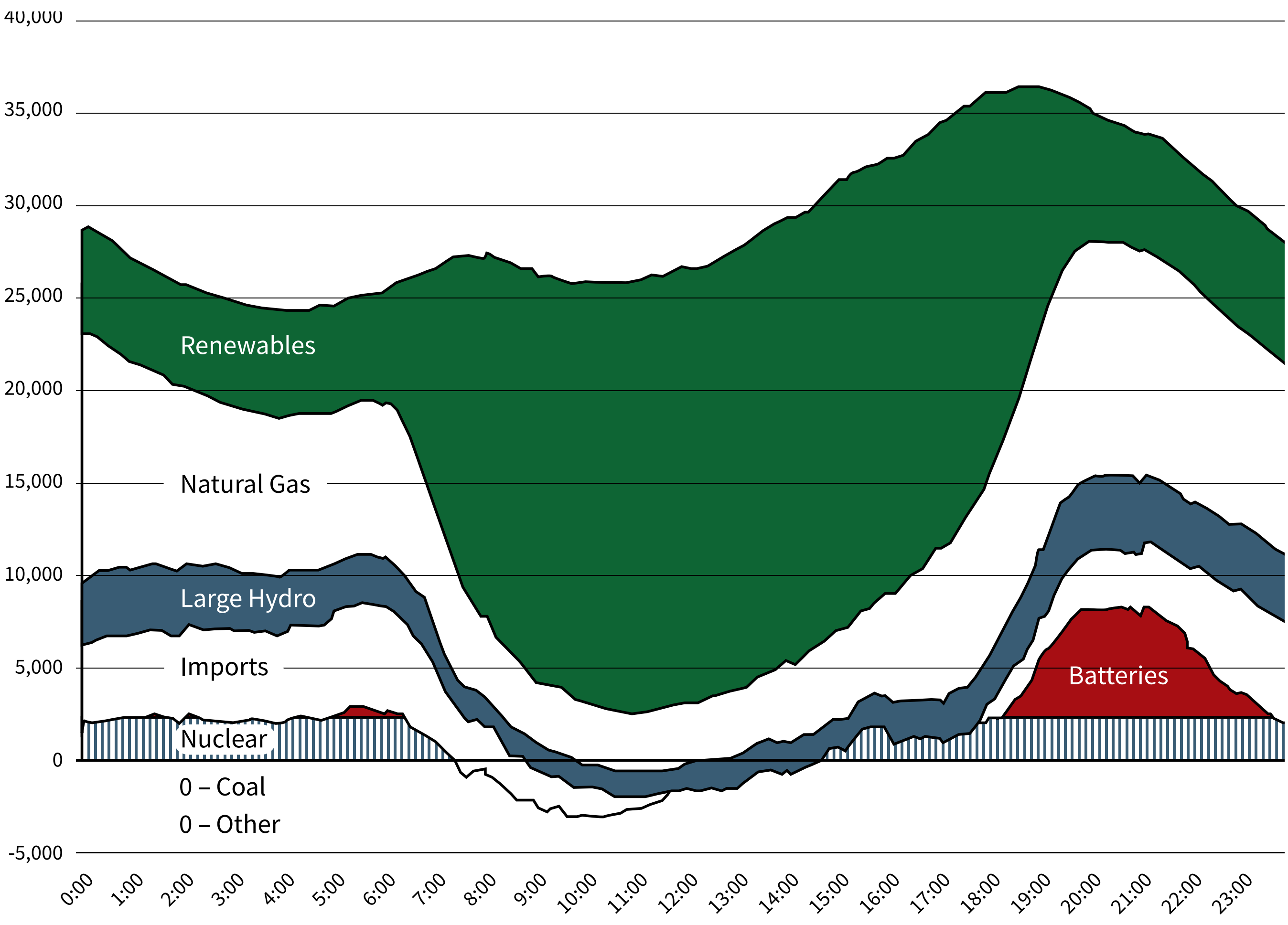

Figure 2-4. California Energy Source Graph, June 26, 2024 *Source: Compiled from data of a California Independent System Operator*

- **Diminished Likelihood of Charger Damage from Vehicular Collision** – Wireless charging equipment is generally unobtrusive and integrated into the roadway, minimizing the likelihood of accidental impact to the charging equipment.
- **Space** – Transit agencies are often space-constrained. Wireless charging equipment's footprint is unobtrusive and either does not require the installation of fixed surface infrastructure that prohibits vehicle parking and movement or requires minimal surface infrastructure.
- **Safety (no cords)** – Bulky and unwieldy charging cords could be a tripping hazard for personnel, and water-insulated cords are heavy and difficult to maneuver. Bus tires can damage cords in the garage, leading to costly and time-consuming repairs.
- **Labor Considerations** – Wireless charging circumvents the need to physically involve staff in-vehicle charging, reducing potential harm to the driver as well as human error in charging. No human interaction with the charging infrastructure means that technicians will not forget to charge the vehicle. Three transit agencies reported that existing collective bargaining agreements with bus drivers define the bus driver's role in a manner that precludes drivers from plugging in BEBs.

The following elements were among the unfavorable aspects identified in CALSTART's research:

- **Not Standardized** – Charging equipment is not interoperable among wireless charging companies. The industry standard for high-power wireless charging, SAE J2954-2, will address interoperability, however, it has been in development since 2012 with an expected release in late 2025 or early 2026.

- **Perceived Safety Risks** –Wireless charging standards have provisions restricting electromagnetic exposure intensity to safe levels based on the International Commission on Non-Ionizing Radiation Protection (ICNIRP) guidelines.[26] Despite this, stakeholders continue to voice safety concerns which leads to a hesitancy to adopt wireless charging.

- **Weight Increases** – Adding equipment to the bus adds weight and a heavier bus is less energy efficient. However, a bus that is charged on route will rely less on battery size for range, there is potential for the weight added by the receiver to be more than offset by the weight removed by decreasing the battery size since a bus that is charged on route will rely less on battery size for range.

26 SAE International (2022). Wireless Power Transfer for Light-Duty Plug-in/Electric Vehicles and Alignment Methodology. Retrieved from: https://www.sae.org/standards/content/j2954_202208/

- **Cost** – The installation of wireless charging equipment on-bus and in-ground is an additional cost. While some of this cost may be offset by the presence of a smaller battery pack, it is not clear that the costs required for wireless charging technology will decrease at the same rate as the anticipated decreases in battery costs.
- **Nascent Technology** – In the event of a parts failure, the downtime of the equipment while awaiting maintenance may strain transit agency resources. The economies of scale do not appear to be large enough at present to have spare parts and technicians on standby in case of a failure, resulting in longer downtimes thus adversely affecting transit operations.

Section 3

Transit Agency Feedback

CALSTART interviewed transit and non-transit fleet employees to understand perceptions about wireless charging and willingness to adopt the technology. Anonymity was promised to all to promote candid and actionable feedback. Between November 14 and December 8, 2023, CALSTART interviewed seven transit agency representatives and two non-transit fleet employees. The employees of the non-transit fleets were interviewed to understand if there was a difference in perception of wireless charging of transit versus non-transit fleet operators. After preliminary analysis of the data, CALSTART determined focusing on the transit fleets was the most constructive feedback. As such, this section is based on interviews conducted with seven transit agency employees.

One of the transit providers interviewed has an entirely BEB fleet in operation (100+ BEBs), and the other six have mixed fuel fleets with between 5-30 BEBs currently in operation. The mixed fleets include diesel, compressed natural gas (CNG), hybrid diesel-electric buses, and gasoline-powered cutaways. Two of the transit providers currently utilize inductive charging, and one used inductive charging in the past.

Of the seven transit providers interviewed, four expressed an intention to pivot to fuel-cell electric buses (FCEBs) and hydrogen fuel in the longer term. It was reported that the BEBs did not have enough range to complete the daily demands, so the transit agency representative felt FCEBs were able to handle the demands. The price of electricity and the ability to get more power to their depot was highlighted as another reason to switch to FCEBs. Three indicated that they intend to continue expanding their BEB fleet; one transit fleet employee noted that hydrogen will also be necessary for the longest routes.

Current Charging Practices and Experience

All the transit provider representatives interviewed reported that most of their charging occurs in-depot with four having some capacity for on route charging to increase range.

The employees of fleets utilizing inductive charging reported that it takes 10 minutes on average to complete an inductive charging session (note: these sessions do not fully charge the bus; they partially refill the battery to extend the range); all fleets utilizing on route charging had to rework their schedules significantly to accommodate this charging technique. Some transit agency representatives modified the schedule to accommodate wired depot charging.

Wired charging is the more established technology and there is more information and charging companies for the transit agency employees to choose from. However, two transit provider representatives called out component failures and difficulty sourcing parts as significant issues they faced with wired charging.

Many transit agency representatives were concerned about the small number of companies in the wireless charging industry. At least two had experience with the now-defunct blade charging technology; there was concern about how to maintain the infrastructure if a company were to go out of business.

One transit agency executive noted their primary concern is that insufficient capital is being invested in inductive charging. Some transit providers expressed that jurisdictional hurdles, such as the need to coordinate with external agencies and/or acquire right of way for on route charging, may ultimately be insurmountable for some service providers.

Overall experiences with charger dependability varied greatly; however, all but one transit provider operating BEBs reported that vendors issuing unannounced over-the-air software updates had repeatedly caused communication issues between the vehicles and the chargers. Two transit providers called out component failures and difficulty sourcing parts as significant issues they faced with wired charging.

Two of the three transit providers interviewed observed no notable difference in charging efficiency between the wired and inductive chargers. However, the third transit provider found plug-in charging substantially more dependable and considered inductive charging useful only as a range booster and not reliable as the primary charging mechanism.

Table 3-1 offers a non-exhaustive list of current wireless charging deployments in the U.S. that serve transit buses.

Table 3-1. Current Wireless Charging Deployments Serving Transit Buses[27]

OEM	Deployments
WAVE Charging[28]	• Twin Transit, Centrailia, WA • Central Contra Costa Transit Authority, Concord, CA • Antelope Valley Transit Authority, Lancaster, CA • Metro McAllen, McAllen, TX • Pinellas-Suncoast, St. Petersburg, FL

27 Listed deployments compiled based on publicly available information and are not an exhaustive list.

28 Source: https://wavecharging.com/products/wireless/mass-transit/ Accessed 2024.

OEM	Deployments
Induct EV[29]	• IndyGo, Indianapolis, IN • Kansas City International Airport, Kansas City, MO[30] • Link Transit, Wenatchee, WA[31] • Martha's Vineyard Transit, Martha's Vineyard, MA • Chattanooga Area REgional Transportation Authority, Chattanooga, TN

BEB Charging Infrastructure

Every transit agency representative interviewed had BEBs deployed in their fleet. Deploying the BEBs and managing the charging infrastructure required reorganizing the route schedule, planning a charging schedule, and educating the workforce to minimize operational disruptions.

Transit agencies reported issues with charging the buses whether they used wired or wireless charging infrastructure. Some transit agencies reported having chargers failing after the initial warranty period was over and had to scramble for coverage. Running power out to other locations for on route charging was also brought up as a concern. One transit agency brought up that each wireless charging location would need a separate meter; based on their calculations, the interconnection fees and additional demand charges outweighed any advantages it could bring.

Installation location is also important. Wired charging has a large footprint, and the charging infrastructure is often placed in inconvenient locations. Installing wireless charging in a public area requires other stakeholder engagement, and the transit agency representatives interviewed were hesitant to start that process. Wireless charging requires the BEB to line up accurately with the in-ground pads. To aid the drivers, painted guidance strips are highly recommended. One transit interviewee noted that more than one inductive charger per location was very efficient in allowing multiple buses to charge at once and maintain the schedule.

Interviewees mentioned concerns about the wear and tear to wired chargers from the repeated plugging and unplugging of the vehicles; wired chargers offer too many opportunities for operator error. Technician education may provide some mitigation, but not requiring physical contact for charging limits concerns about charger wear and tear.

29 Source: https://www.inductev.com/public-private-transit Accessed January 2024.

30 Source: https://www.aviationpros.com/airports/buildings-maintenance/people-movers/article/21281274/airport-wireless-charging-for-electric-buses Accessed January 2024.

31 Source: https://www.linktransit.com/services_and_programs/electric_bus_project.php Accessed January 2024.

Potential and Limitations of Inductive Charging

The majority of transit agency respondents noted that, while presently imperfect, inductive charging could be a valuable tool for transit providers. As one interviewee stated:

> *"Yes, 100%, yes. … It would be wonderful to be able to use inductive for depot charging in the future, while on route chargers are critical to obtaining BEB range comparable to diesel."*

Two of the eight transit providers noted that transit vehicle OEM's willingness to incorporate inductive charging is crucial to the development and deployment of this technology. Of the four full-size transit bus OEMs in North America at the time of the study, three have vehicles in service utilizing inductive charging or are currently working through engineering adjustments to support inductive charging. Interviewees expressed a desire for inductive charging safety standards and third-party verification.

Section 4

Charging Company Feedback

CALSTART interviewed representatives from companies currently manufacturing wireless chargers or considering doing so in the future to understand their perspective on the market for wireless charging. CALSTART investigated topics such as the state of the technology, expected technological developments, and barriers to deploying this technology. CALSTART interviewed representatives from the following companies:

- ABB
- eLeapPower
- Electreon
- ENRX
- Induct EV
- WAVE Charging
- WiTricity

The selected companies are prominent providers of charging infrastructure The companies represent multiple use cases and applications of both low-power and high-power wireless charging, spanning various stages of technological development.

- CALSTART also interviewed representatives from two charging software companies, bp pulse, and EO Charging, because charging infrastructure is typically integrated into charging and energy management systems to simplify operations for transit agencies and optimize charging behavior. CALSTART investigated whether wireless charging is compatible with their existing platforms.

Market Segmentation

The market for wireless charging is segmented between low-power wireless charging (maximum of 19 kW) and high-power wireless charging (50 kW or above). As noted earlier, the current SAE J2954-1 standard only goes up to 11kW, but one company reported they had plans to provide products up to 19kW. These low-power and high-power wireless charging levels are analogous to Level 2 and DCFC, respectively. The low-power wireless charging market will primarily serve light-duty vehicles as a substitute for traditional plug-in charging infrastructure. The high-power wireless charging segment will primarily be used by MHD vehicles. Most wireless charging companies focus on one of these segments, as they serve distinctly different clientele.

There are far more light-duty vehicles than MHD vehicles. Nationally, in 2023, there were a reported 3.3 million LD EVs[32] on the road and an estimated 36,000[33] [34] electric MHDVs deployed. Due to the generous size of this market, they believe that the light-duty segment is more financially lucrative and more likely to benefit from economies of scale. While low-power wireless charging companies have not ruled out entering the high-power segment, it is unlikely that they will do so soon. because light-duty vehicles typically charge at a low power level, their product will likely not be appropriate for that market. One charging company has an 11kW offering that has a heavy-duty (HD) wireless charging solution ready and anticipates late 2025 or early 2026 is the earliest the standards and market for MHD charging will be ready for that product.

CALSTART discussed the potential for future wireless charging with companies that manufacture traditional charging infrastructure such as plug-in chargers and overhead pantograph chargers. These companies stated that they do not have immediate plans to develop a wireless charger but are monitoring the market and may do so in the future.

Currently, there are only a few companies that provide high-power wireless charging. BEBs have large battery packs, requiring high-power wireless chargers. CALSTART does not expect new entrants to the high-power wireless charging market in the near future because of the lack of standards funding opportunities. Additionally, the interviewees reported the backlog volume of the transit vehicle OEMs has stifled the ability to demonstrate new technologies and the attrition of transit vehicle OEMs makes the U.S. market less desirable for new technology entrants.

Funding Barriers

All levels of government and utilities have historically supported charging infrastructure deployments with funding. This support comes in the form of incentive funding or grant solicitation funding. To date, funding from these programs has predominantly been used for traditional plug-in charging infrastructure.

Several states and utilities have incentive funding programs to fund charging infrastructure. These programs are structured such that they provide a subsidy to a particular charging infrastructure project. The funding can be allocated as a fixed cost per charger or as a percentage of the project cost. These programs

32 Source: https://www.edmunds.com/electric-car/articles/how-many-electric-cars-in-us.html

33 Source: https://calstart.org/zio-zets/

34 Source: https://calstart.org/zeroing-in-on-zebs-2024/

can also be administered by different sources. The EnergIIZE program[35] is funded by the California Energy Commission. Utility companies in California also offer utility make-ready programs such as Southern California Edison's (SCE) Charge Ready Transport[36] and Pacific Gas & Electric's (PG&E) EV Fleet program.[37] These programs have played a key role in accelerating infrastructure deployment by reducing equipment costs.

Because there are no standards for wireless charging, they are not eligible for incentive funding through major utility incentive programs, such as SCE's Charge Ready program and PG&E's EV Fleet program.

EnergIIZE includes wireless charging in its program as an innovative technology, where the wireless charging system meets industry technical standards. The description for projects eligible for funding from EnergIIZE states "For EV chargers using conductive connectors, only Level 2 and direct current (DC) chargers are eligible for EnergIIZE funding. Innovative technologies such as inductive charging systems and bidirectional chargers are also permitted."[38] Some of the technical requirements that must be met include complying with SAE J2954-2 TIR, ISO 15118, OCPP 1.6 (minimum), and being safety certified by Nationally Recognized Testing Laboratory (NRTL). At the time of writing, at least one wireless charging manufacturer is going through the process to meet EnergIIZE requirements. To date, the Approved Products List for EnergIIZE is limited to systems that meet the low-power standard absent a completed high-power standard.[39]

Wireless charger companies noted, based on their understanding, that the structure of existing funding programs creates barriers to funding wireless charging systems because the system uses one charger shared among vehicles. This structure is not aligned with the program funding allocations where funding is allocated per charger which is typical of state programs. Under this funding structure, a plug-in charging installation where each bus has its own charger would receive more funding than one wireless charger shared between

35 CALSTART (2023). Implementation Manual for Energy Infrastructure Incentives for Zero-Emission Commercial Vehicles Project (EnergIIZE). Retrieved from: https://energiize.org/implementationmanual/EnergIIZE_Implementation%20Manual_%20Q1%202023.pdf

36 More information about SCE's Charge Ready Program can be found at: https://crt.sce.com/overview

37 More information about PG&E's EV Fleet Program can be found at: https://www.pge.com/en/clean-energy/electric-vehicles/ev-fleet-program.html

38 CALSTART (2023). Implementation Manual for Energy Infrastructure Incentives for Zero-Emission Commercial Vehicles Project (EnergIIZE). Retrieved from: https://energiize.org/implementationmanual/EnergIIZE_Implementation%20Manual_%20Q1%202023.pdf

39 Electric Power Research Institute (2024). EPRI's Vetted Product List – A Comprehensive Resource of Vetted Products for the Electric Vehicle Equipment Industry. Retrieved from: https://www.epri.com/vpl

multiple buses. This criticism is not true of Federal funding programs such as the Low or No Emission Grant Program.

Inductive charging requires both an in-ground power transmitter that can serve multiple vehicles and receivers on each vehicle. In EnergIIZE, the funding is structured in the form of a project cap and maximum percentage of a total project cost but is limited to the physical permanent infrastructure up to the “port” (i.e., the charging pad) and does not include the requisite vehicle-mounted receivers. Funding programs traditionally have data reporting requirements such as reliability and uptime; the reporting process may look different for wireless charging, considering that inductive chargers do not have a physical display.

Wireless charging infrastructure is also at a disadvantage where funding eligibility requires a minimum number of chargers per site. Because wireless chargers are typically shared between multiple buses, it is unusual to deploy large numbers of chargers at one site. It is not known if the vehicle receiver equipment would qualify as charging infrastructure, or if its eligibility would vary between funding opportunities. California’s Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project (HVIP), one of the leading zero-emission (ZE) vehicle incentive programs, is not able to include the cost of the vehicle assembly equipment under the program, and there are no plans to change this in future funding cycles. Future alternative funding scenarios to consider wireless charging should include elements such as removing the minimum number of chargers per site or measuring the number of vehicles supported by one charger as part of the charging infrastructure requirements.

Standards and Interoperability

All wireless charging manufacturers in the interviews brought up the need for industry standards for high power wireless charging to push the industry forward. Standards ensure that charging products are safe, and interoperable, and grow the market by allowing it to competitively accommodate multiple manufacturers. The wireless charging companies state that without standards the market is severely hindered; the lack of standards prevents wireless chargers from accessing many funding opportunities, and it was noted that the transit vehicle OEMs are not interested in spending resources on integration until the standard is complete.

Industry representatives expressed concern that standards may push some inductive charging companies out of the market if they are unable to pivot to the standard’s requirements quickly enough to remain competitive. SAE International stated the market is flexible enough for inductive charging companies to adapt.

Transit agencies are also concerned about interoperability. The high-power wireless charging products currently on the market are not interoperable, meaning the onboard receivers and the ground pads are not compatible across manufacturers, introducing a potential risk for transit agencies. If a transit agency deploys a wireless charger that is not interoperable, they are tied to that manufacturer for the useful life of that equipment. If the transit agency deploys a different manufacturer's product in the future, it will not be compatible with the original manufacturer's equipment. Additionally, if the charging manufacturer exits the market, the agency loses infrastructure support, and additional compatible equipment purchases are precluded. Both possibilities result in stranded assets. The development of SAE J2954-2 will be vital for addressing interoperability issues and mitigating the risk of stranded assets.

Integration with Charging Management Software

Many fleets use CMS to control charging for their vehicles. This software analyzes bus charging needs in real-time and controls charging behavior to minimize peak power demand and lower charging costs for the fleet. Due to these benefits, most transit agencies utilize CMS. Discussions with charging software companies indicate that wireless chargers can be integrated into these systems if they are Open Charge Point Protocol (OCPP) compliant. Because every high-power wireless charger company interviewed states that their wireless chargers can be OCPP compliant, CALSTART does not anticipate CMS integration will be a barrier to wireless charging adoption.

Right of Way

The wireless charging companies state that one of the barriers to deploying wireless chargers on route is site control and right of way. When used for on route charging applications, wireless chargers in the United States are typically installed in public places, such as streetside bus stops, transit centers, and parks. In these situations, transit agencies must install a wireless charger in a location that they do not own. Deploying wireless chargers requires installing a ground pad and a power electronic cabinet at the site. This requires obtaining the right of way at the site; without this, transit agencies cannot install the wireless charger.

Education

Transit fleets are increasingly familiar with plug-in charging technology; however, some transit fleets are unwilling to consider adopting wireless charging due to a lack of familiarity with the technology. The wireless charging companies interviewed suggested an education campaign about the capabilities, efficacy, and safety of inductive charging technology would help increase transit agency awareness and encourage acceptance of this technology.

Section 5

Vehicle Manufacturing Feedback

CALSTART interviewed seven OEMs of BEBs, both full-sized and cutaway, to understand their perspective on wireless charging technology. The companies interviewed were:

- BYD/RIDE
- Gillig
- GreenPower Motor Company
- Motiv Power Systems
- New Flyer Industries
- Phoenix Motorcars
- Van Hool

Some of these BEB OEMs have previous experience with wireless charging integration, while others are aware of the technology but have not integrated it into their vehicles. The complete list of questions discussed with BEB OEMs can be found in Appendix A: Interview Questions. Please note that not all OEM representatives interviewed answered the questions in such a way that added value to the report. The results are a summary of relevant information collected.

See Table 5-1 below for the breakdown of OEMs that focus on medium-duty vehicles (MDVs) and heavy-duty vehicles (HDVs) as they relate to being experienced with wireless charging. Two-thirds of the MDV OEMs had experience with wireless charging and three-fourths of the HDV OEMs had experience with wireless charging.

Table 5-1. Current Wireless Charging Deployments Serving Transit Buses

	MDV OEMS	HDV OEMS
Experienced	2	3
Inexperienced	1	1

Experienced Wireless Charging BEB OEMs

The experienced wireless charging BEB OEM representative interviewed have vehicles in service or are currently working through engineering adjustments for the vehicle to support wireless charging. Five of the seven (71%) of the OEMs the CALSTART interviewed are experienced with wireless charging based on the above description.

Partnerships

All of the OEM representatives highlighted the importance of choosing a high-quality wireless charging company to work with. Each of the experienced OEMs conversed with multiple wireless charging companies, but usually only chose to integrate one company's wireless charging hardware. Engineering investments are intensive, and there is little interest in repeating the integration process with another company. The consensus is that the hardware, specifically the onboard wireless receiver, was straightforward to integrate, but the associated software and BMS required careful updating. One company reported that the entire integration process took a year and several hundred thousand dollars to finalize.

Equipment and Systems Integration

The experienced vehicle OEMs noted integrating wireless chargers into their vehicles would involve integrating two key items: the hardware, which consists of the onboard receiver; and the software that controls charging. Integration of the hardware involves redesigning the bus to accommodate the onboard receiver. The MDV OEMs noted the size of the onboard receiver as an important factor in integration. The HDV OEM reported they needed to remove a battery pack to free up space for the wireless charging equipment which would likely increase the frequency of charging and mitigate the loss of range from the battery pack removal. OEM representatives noted different approaches for incorporating the equipment: One stated they use a separate chassis when installing the wireless charging equipment; while another OEM did not use another chassis to the added step of getting the BEB tested by Altoona a second time. There were no concerns that the factory installation of the equipment would slow down the time it took to produce the BEB. All OEMs reported that there is no delay in receiving wireless charging equipment and the installation of the equipment takes a maximum of one day. Although there is no standardized location on vehicles for mounting the charging plate, all OEMs interviewed reported installing it behind the front axle was the most convenient and least obtrusive location.

Software integration was also important to the OEMs. Chargers must establish communication, or "handshake," with the vehicle and follow the vehicle's charging protocol. This process allows the charger to work with the vehicle's BMS. Both plug-in chargers and wireless chargers need to handshake before they can operate. The handshake process for wireless charging is more complex than for plug-in charging because wireless chargers have more steps that need to be taken before charging can begin. For example, wireless chargers have foreign object detectors that prevent charging if there are objects between the ground pad and the onboard receiver. Furthermore, for static wireless chargers, charging will not commence if the vehicle is not completely at rest. These extra steps increase the complexity of the handshake process, making software integration a more intensive process and increasing the time and resources required to complete integration.

Standards/Interoperability

CALSTART's research found that the industry needs and wants wireless charging standards. Bus OEMs cannot lead the development of the standards; those need to be developed by the wireless charging companies to ensure integration between a charging manufacturer and a vehicle OEM.

Neither passenger nor driver safety was brought up as a concerning aspect of wireless charging during discussion with the vehicle OEMs, nor was cybersecurity raised as a concern. The OEMs indicated that they would follow the charging companies' lead on safety and standards development. None of the vehicle OEMs indicated that they would be responsible for developing additional safety equipment on the vehicle unless requested by the wireless charging company or the transit fleet. Only one vehicle manufacturer reported installing additional insulation and a steel plate between the passengers and charging equipment to the bus because of wireless charging.

Market

Opinions among the OEMs varied concerning market outlook: one OEM stated the belief that this technology would remain a niche product; another anticipated that inductive charging would gain traction following expansion in the light-duty and semi-truck markets, driven by their larger purchasing power. None of the OEMs reported that they highlight wireless charging as an option, but they are open to discussing it if prompted. They reported that they do not feel that it is their responsibility to educate customers about this charging option.

An OEM that offers both charging systems reported that sales for pantograph equipment are double the demand for wireless charging. On route, inductive charging (pantograph + wireless charging) is only requested by the transit customer in half of the vehicles built by this OEM.

Inexperienced Wireless Charging OEMS

Two of the seven BEB OEMs (29%) interviewed are inexperienced, which is defined as having no engineering hours or equipment testing of wireless charging systems on their vehicles. Feedback from inexperienced OEMs is important to understand a variety of perspectives on this technology. For example, the reasoning behind why OEMs are not interested in integrating or what changes would need to change in the industry to encourage OEMs to begin incorporating wireless charging into their vehicles.

Partnerships

One of these OEMs had been approached by a few of the wireless charging companies but had not yet decided whether they wanted to partner. Another, quoted below, succinctly described its reasoning for not entering the market:

“We will not move forward until there are wireless charging standards, and a solvent company to work with. Until then, why bother?”

Equipment and Systems Integration

One of the inexperienced, as defined above, OEMs noted a concern about the location of wireless charging equipment underneath the vehicle. Their apprehension was that the equipment might block access to other important components on the bus needing to be serviced or accessed in the event of an emergency. Another OEM mentioned that pantograph technology seemed sufficient and that they were unsure how wireless charging could be an asset to transit agencies. Public charging installations entail taking on significant paperwork and bureaucracy, and there was concern that the cost may outweigh the benefit.

One inexperienced OEM brought up integration as a concern. Specifically, their concern focused on the software integration with the BMS. The hardware integration, however, did not seem to be considered a challenge.

Standards/Interoperability

One OEM was adamantly against spending any time on engineering or integration into their vehicles until the high-power inductive charging standard was finalized. Another stated that standards would help with interoperability in shared-use charging locations.

Safety was also a key concern, and one OEM was hesitant to take on the risk without standardized technology. The other inexperienced OEM had not thought about safety specific to wireless charging, although they did mention that safety is one of the company’s core values.

Market

The OEMs were of mixed opinion on the wireless charging market. Pantograph charging was broadly seen as a solid reliable choice for on route charging. One interviewee said they would consider integrating wireless charging if they see a viable market and appropriate demand from their customer base. None of the companies reported that they bring up wireless charging in sales pitches, and the sales teams reportedly steer potential customers away from wireless charging.

Section 6

Research Finding and Recommendations

This research found that high-powered inductive charging can effectively fulfill certain specific use cases. While some fleets might be able to use it as the primary source of charging, most fleets will use it for on route charging to extend the range of a BEB. However, there are still hurdles that hinder the technology's development and adoption. None of the three transit operators with deployed wireless charging technology observed any difference in charging efficiency (defined as power loss from meter to bus) between wired and wireless charging. Two of the three transit operators with inductive charging experience reported the uptime of wired and wireless charging as being comparable; one transit agency representative, however, reported their inductive charging still functions inconsistently due to difficulties integrating the inductive charging equipment with the BEB OEM's systems. Transit providers using wired chargers similarly report vastly different uptime experiences, depending upon the systems and equipment installed. The reliability of both wired and wireless charging depends on the charging systems procured with some equipment manufacturers outperforming others.

CALSTART's research indicates that high-power wireless charging has the potential to resolve space constraints by minimizing the ground-level infrastructure footprint in bus depots and transit facilities. However, existing facilities reported struggling with space constraints and disruptions to operations at their on route charging site during the installation of in-ground charging equipment.

Concerning safety, SAE J2954-1 sets electromagnetic field exposure limits to safe levels as outlined by ICNIRP. Despite these standards, some transit providers and OEMs have continued to express concerns over potential harm.

Respondents reported that high-power inductive charging standards are needed to push the market forward. Efforts in conjunction with other standards committees nationally or internationally can accelerate the process and drive the market closer to a standard. Standards for interoperability across equipment providers can reduce the risk of stranded assets if a wireless charging manufacturer goes out of business. As a result, until standards are developed by both the BEB OEMs and the wireless charging manufacturers, transit agencies are generally unwilling to invest significantly in high-power wireless charging technology. The publication of SAE J2954-2 is expected to address many of these concerns.

Based on CALSTART's literature review and industry interviews, the study identifies several recommendations that can be implemented to reduce barriers to the adoption of wireless charging technology for transit agencies interested in integrating it into their operational charging plans. Overall, there is interest in the system, but more data and research are needed to fill the gaps. Key points highlighted by multiple interviewees—across different facets of the industry — focus on funding, fledging technology concerns, and education.

- **Funding** – Adding wireless charging equipment is an expensive undertaking with the primary cost drivers being the necessary software integration and any additional land purchase or right of way permitting related to installing the charging infrastructure on route. Ensuring that all ZEB technology, including wireless charging, has a level playing field for adoption is vital to enabling transit agencies and OEMs to be responsive to market needs. It is recommended that the language in funding proposals includes both vehicle- and ground-mounted equipment and that inductive chargers intended to serve multiple vehicles are not precluded by 1:1 charger-to-vehicle ratio requirements intended for wired chargers.
- **Nascent Technology** – Wireless charging needs to be adopted at scale to realize the benefits of reliable wireless charging. Transit vehicle OEMs and fleets have reported concerns regarding the potential dissolution of wireless charger purveyors, which could result in stranded assets. This concern is based on past experiences in the early pantograph market. High-power wireless charging is considered to have a TRL of 7 by industry experts. According to transit providers, inductive charging has advantages as a space-efficient tool that minimizes human involvement. These providers believe that if reliability can be ensured, it would be preferable to wired charging. By supporting further research and development to improve reliability and the performance of wireless charging the TRL can be improved and increase confidence in the technology among transit providers.
- **Education** – Additional research, including more case studies and best practice reports, can help the industry make informed decisions about the benefits of wireless vehicle charging options, such as the potential space efficiency provided by wireless charging systems and reduced human involvement in charging. Some stakeholders noted wireless charging could be an effective solution for transit agencies, once agencies are made aware and have more information about the technology. Information about the safety of wireless charging can also help transit agencies effectively compare charging options. Transit agencies have expressed that ZEB focus groups can prevent multiple agencies from repeating the same mistakes.

Appendix A

Interview Questions

OEM Interview Questions

- What has your experience been with wireless charging?
- How much market demand do you see for wireless charging?
  - Do you bring up wireless charging in sales pitches?
- Do you have a preferred wireless charging company?
  - Are you willing to integrate with others, or do you have an exclusive relationship?
- What, if any, barriers do you or your customers have to implementing wireless charging?
- What is your opinion on wireless charging standardization? What is your level of involvement?
- How many engineering hours does it take to successfully integrate a new wireless charging product?
- What is the lead time for the wireless chargers and receivers?
- In what quantities can you purchase the wireless chargers?
- How do wireless chargers affect the manufacturing process?
  - Do the wireless chargers take up space and displace other components?
- Are there any challenges for integrating the wireless charging plate/receiver into the vehicle?
  - If so, is there anything the wireless charger manufacturer can do to address this?
- Does using wireless charging increase the cost of the bus as compared to regular wired charging?
  - If so, by how much?
- If wireless charging becomes more popular, will economies of scale decrease the cost of integrating it?
- Do the different inductive charging companies place the wireless charging plate/receiver into the same place in the vehicle? Does this location need to be standardized?
- Do you have to make any other modifications to the bus to protect other components from EMI or other radiation from the wireless charger?
- Do you think the Federal Transit Administration should support wireless charging for BEBs?
  - What type of support would you like to see from the Federal Transit Administration?

Wireless Charging Company Questions

General Questions

- Tell us more about your deployments.
- What are the biggest challenges you face with wireless charging deployments?
- Do you recommend we reach out to any fleets in particular?

Maintenance Questions

- What annual/preventative maintenance is required for your systems?
- How quickly can you respond to problems with a charger?
- Do you have software that can remotely detect problems with a charger?
- What are the most common repair/maintenance problems encountered?

Manufacturing Questions

- Do you have any barriers to manufacturing?
- Have you had any supply chain problems?
- How do you feel about Buy America requirements?
- How long does it take to manufacture a charger?

Installation Questions

- How long does it take to install?
- What are the challenges for installing?
- Are there any non-technological challenges (i.e., permitting, regulatory, etc.) to installation?

Vehicle Integration

- Are there any challenges for integrating the wireless charging plate/receiver into the vehicle?
  - If so, is there anything the wireless charger manufacturer can do to address this?
- Does using wireless charging increase the cost of the bus as compared to regular wired charging?
  - If so, by how much?
  - If wireless charging becomes more popular, will economies of scale decrease the cost of integrating it?
- Do the different inductive charging companies place the wireless charging plate/receiver into the same place in the vehicle? Does this location need to be standardized?

- Do you have to make any other modifications to the bus to protect other components from EMI or other radiation from the wireless charger?

Forward Looking Questions

- What policy or technology advancements need to happen to keep moving forward?
- What is the outlook for your business for wireless charging?
- What type of market do you see for this?

Transit Agency Questions

- Tell us about your fleet operations.
- Current and future plans? (Re: composition, fueling, operations)
- If inductive charging was considered but not utilized, why did you decide not to utilize it?
- How is your BEB charging set up? (In-depot or on route)?
- How long do your buses spend on average at the (wireless) charger?
- Did you have to rework your bus schedules/blocks to accommodate wireless/on route charging?
- How has your experience been using (wireless) chargers?
  - How dependable have the (wireless) chargers been?
  - How efficient have the wireless chargers been vis a vis wired chargers?
- How do your drivers feel about the (wireless) chargers?
- If you use inductive charging, is the wireless charger shared by multiple fleets (transit, municipal, or private)?
  - Is this something of interest in the future?
  - What challenges would you need to overcome to be able to implement this?
- One key difference between wired and wireless chargers is that the wireless chargers are typically installed in a public place or in the road, rather than in the depot where it is not in public. Have you faced any challenges getting city or local approval for installing the wireless chargers in public places?
- Have you experienced or observed any public opposition to installing the wireless chargers?
- What do you think are the biggest barriers to BEB charging?
  - Wireless:
  - Wired:
- What do you think are the biggest benefits to BEB charging?
  - Wireless:
  - Wired:

- Have you had any safety concerns related to BEB charging?
- If you could start from scratch or plan to expand, what would change? Would you go with wireless/wired again?
- Is there any data you can share?
- Do you think the FTA should support the deployment and development of inductive charging for BEBs?
- Do you have any concerns regarding inductive charging that have not been discussed yet?
- Do you have any thoughts or comments that you would like to add?

Fleet Questions

- Tell us about your current fleet operations and your future plans.
- Tell us about the EV composition of your fleet and what types of charging you use.
- If inductive charging was considered but ultimately not utilized, why did you decide not to utilize it?
- How is your (wireless) charging set up?
- What has your experience been with charger reliability generally?
- Have you seen differences between wired and wireless charging efficacy and uptime?
- Why wireless vs. wired?
- Cost?
- Maintenance?
- What are the biggest barriers?
  - Wireless:
  - Wired:
- What are the biggest benefits?
  - Wireless:
  - Wired:
- Any safety concerns?
- If you could do it again or plan to expand, would you go with wireless again?
- Any data you could share?
- Do you think the FTA should support the development and deployment of inductive charging for BEBs?
- Do you have any concerns regarding inductive charging that have not been discussed yet?
- Do you have any thoughts or comments that you would like to add?

Appendix B

Fleet Feedback, Leon County, FL

Of the two fleets that were interviewed, one is a county fleet based out of Florida (Leon County), the composition of which is 487 law enforcement and emergency vehicles. In 2022, this fleet began a three-year acquisition plan to catch up with their fleet replacement. The light-duty part of this fleet is a mix of gasoline (230), hybrid (100), and electric (3) vehicles. The county has focused on evaluating the relative cost per mile of the fueling alternatives and has found that EVs have the potential to be very cost-effective choices for law enforcement fleets with the hybrids averaging 8.5¢ per mile (50 mpg) and the EVs averaging 2.5¢-6¢ per mile depending on driver behavior (13¢/kWh). The interviewee noted "The math tells the story. … Those who recognize the paradigm shift by which everything trends toward battery electric and who position themselves early stand to benefit the most when reaping the total cost of ownership savings."

The law enforcement fleet does not currently utilize inductive charging, as on route is not readily compatible with their typical use cases with detainee transfer being virtually the only use case in which the law enforcement vehicles are reliably at a single location regularly. That said, according to their feedback, they would love for inductive charging to become available for F-150s, Silverados, Teslas, and the other vehicles constituting their fleet. They expressed that a future in which these vehicles charge wirelessly at intersections could be easily envisioned. Like the transit providers, the fleet manager noted that it is best to minimize user/driver involvement in the charging process wherever possible.

Acronyms and Abbreviations

ASPIRE	Advancing Sustainability through Powered Infrastructure for Roadway Electrification
AVTA	Antelope Valley Transit Authority
BEB	Battery-Electric Bus
BMS	Battery Management System
CARB	California Air Resource Board
CCS	Combined Charging System
CMS	Charge Management System
CNG	Compressed Natural Gas
DC	Direct Current
DCFC	Direct Current Fast Charging
EV	Electric Vehicle
FCEB	Fuel Cell Electric Bus
FTA	Federal Transit Administration
HD	Heavy-Duty
HDV	Heavy-Duty Vehicle
HVIP	Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project
ICCT	International Council on Clean Transportation
ICE	Internal Combustion Engine
ICNIRP	International Commission on Non-Ionizing Radiation Protection
IEC	International Electrotechnical Commission
ISO	International Organization for Standardization
MD	Medium-Duty
MDV	Medium-Duty Vehicle
MHD	Medium- and Heavy-Duty
NACS	North American Charging Standard
NRTL	Nationally Recognized Testing Laboratory
OEM	Original Equipment Manufacturer

PG&E	Pacific Gas & Electric
SAC	Standardization Administration of the People's Republic of China
SAE	Society of Automotive Engineers
SCE	Southern California Edison
TIR	Technical Information Report
TRL	Technology Readiness Level
UL	Underwriters Laboratories
UNECE	United Nations Economic Commission for Europe
WPT	Wireless Power Transfer
ZEB	Zero-Emissions Bus
ZET	Zero-Emissions Truck

U.S. Department of Transportation
Federal Transit Administration

U.S. Department of Transportation
Federal Transit Administration
East Building
1200 New Jersey Avenue, SE
Washington, DC 20590
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