On-Road Medium- and Heavy-Duty Zero-Emission Vehicle Fueling and Charging Standardization Assessment

White Paper

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Glossary of Terms, Abbreviations, and Symbols

A	Ampere
AB	Assembly Bill
AC	Alternating Current
ANSI	American National Standards Institute
APRR	Average Pressure Ramp Rate
ASTM	American Society for Testing and Materials
AQMD	Air Quality Management District
BEB	Battery Electric Bus
BEV	Battery Electric Vehicle
CaFCP	California Fuel Cell Partnership
CAN	Controller Area Network
CARB	California Air Resources Board
CCR	California Code of Regulations
CCS	Combined Charging Standard
CCTS	CharIN Conformance Test System
CEC	California Energy Commission
CEN-CENELEC	European Committee for Electrotechnical Standardization
CEQA	California Environmental Quality Act
CFR	Code of Federal Regulations
CGA	Compressed Gas Association
CharIN	Charging Interface Initiative e. V.
CHSS	Compressed Hydrogen Storage System
CP	Control Pilot
CTEP	California Type Evaluation Program
DC	Direct Current
DCFC	Direct Current Fast Charging

DIN	German Institute for Standardization
DMS	Division of Measurement Standards
DOE	Department of Energy
EIM	External Identification Means
EN	European Standards
EnergIIZE	Energy Infrastructure Incentives for Zero-Emission Commercial Vehicles
E.O.	Executive Order
ETSI	European Telecommunications Standards Institute
EV	Electric Vehicle
EVCS	Electric Vehicle Charging Station
EVSE	Electric Vehicle Supply Equipment
FCEV	Fuel Cell Electric Vehicle
GFO	Grant Funding Opportunity
GH2	Gaseous hydrogen
g/s	grams per second
H2	hydrogen
H2FillS	Hydrogen Filling Simulation
H35	350 bar pressure hydrogen dispensing
H70	700 bar pressure hydrogen dispensing
HB	Handbook
HDHSV	Heavy-Duty Hydrogen Surface Vehicle
HDV	Heavy-Duty Vehicle
HSV	Hydrogen Surface Vehicle
HVIP	Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project
HyRAM+	Hydrogen Risk Assessment Models
HySTEP	Hydrogen Station Equipment Performance
IEC	International Electrotechnical Commission

IEEE	Institute of Electrical and Electronics Engineers
IrDA	Infrared Data Association
IrPHY	Infrared Physical Layer Specification
ISO	International Standards Organization
JH2A	Japanese Hydrogen Association
JPEC	Japan Petroleum Energy Center
kg	Kilogram
kW	Kilowatt
LCFS	Low Carbon Fuel Standard
LD-BEV	Light-Duty Battery Electric Vehicle
LDV	Light-Duty Vehicle
LD-ZEV	Light-Duty Zero-Emission Vehicle
LH2	Liquid Hydrogen
MCS	Megawatt Charging System
MDV	Medium-Duty Vehicle
MD/HD-BEV	Medium- and Heavy-Duty Battery Electric Vehicle
MD/HDV	Medium- and Heavy-Duty Vehicle
MD/HD-FCEV	Medium- and Heavy-Duty Fuel Cell Electric Vehicle
MD/HD-ZEV	Medium- and Heavy-Duty Zero-Emission Vehicle
Min	Minute
MM	Management Message
MPa	Megapascal
MW	Megawatt
NEC	National Electric Code
NEMA	National Electrical Manufacturers Association
NEVI	National Electric Vehicle Infrastructure
NFC	Near Field Communication

NFPA	National Fire Protection Association
NIST	National Institute of Standards and Technology
NRTL	Nationally Recognized Testing Laboratory
NTEP	National Type Evaluation Program
OCPI	Open Charge Point Interface
OCPP	Open Charge Point Protocol
OCTA	Orange County Transportation Authority
OEM	Original Equipment Manufacturer
OpenADR	Open Automated Demand Response
OSHA	Occupational Safety & Health Administration
PKI	Public Key Infrastructure
PLC	Power-Line Communication
PnC	Plug and Charge
PON	Program Opportunity Notice
PP	Proximity Pilot
PRHYDE	Protocol for Heavy-Duty Hydrogen Refueling
Reneg	Renegotiation
RFID	Radio Frequency Identification
SB	Senate Bill
Sched	Schedule
SoC	State of Charge
SAE	Society of Automotive Engineers
STEP	Sustainable Transportation Equity Project
STRIDE	Spoofing, Tampering, Repudiation, Information Disclosure, Denial of Service, and Elevation of Privilege
T20	-20^{o}C
T30	-30^{o}C

T40	-40°C
TIR	Technical Information Report
TLS	Transport Layer Security
UL	Underwriter's Laboratory
U.S.	United States
V	Volt
V2G	Vehicle-to-Grid
V2I	Vehicle-to-Infrastructure
V2L	Vehicle-to-Load
V2X	Vehicle-to-Everything
ViGIL	Vehicle-Grid Innovation Laboratory
WIP	Work-in-Progress
WPT	Wireless Power Transfer
ZANZEFF	Zero- and Near Zero-Emission Freight Facilities
ZEB	Zero-Emission Bus

Executive Summary

Introduction and Background

Broad implementation of zero-emission technologies in the transportation sector is essential for California to meet its long-term air quality and climate protection goals. For on-road medium- and heavy-duty (MD/HD) vehicles with a gross vehicle weight rating of greater than 8,500 lbs., battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs), collectively termed zero-emission vehicles (ZEVs), provide a robust pathway to achieve these goals. To increase MD/HD-ZEV adoption, California requires a comprehensive suite of measures including use of incentives and regulatory measures. Some regulations require that vehicle manufacturers commit to an increasing percentage of ZEV sales, such as the Advanced Clean Trucks regulation. Other regulations require the end users and fleet owners to gradually transition their entire fleets to zero-emission technologies by purchasing ZEVs, such as the Innovative Clean Transit Regulation and the Advanced Clean Fleets regulation.

Broad on-road MD/HD-ZEV deployment requires robust charging and hydrogen fueling networks. A majority of charging and hydrogen fueling stations currently available are designed for light-duty vehicles (LDVs), which generally require lower charging and hydrogen fueling rates and total energy transfer compared to MD/HD-ZEVs. Supporting MD/HD-ZEVs will require new stations, designed to accommodate the greater MD/HD energy demands. These stations require new or revised standards to ensure that charging and hydrogen fueling performance, as well as safety, are appropriately considered.

In contrast to LDV-ZEVs, MD/HD-ZEVs operate for longer periods of time and over longer ranges, both of which require (1) higher charging and hydrogen fueling rates and (2) high levels of availability and reliability on par with the current diesel experience. To facilitate a broader and successful adoption of MD/HDV-ZEVs, the challenges of vehicle supply, station availability and reliability, interoperability, and costs must be proactively addressed. Establishing the codes and standards for charging battery-electric MD/HDVs and fueling fuel cell-electric MD/HDVs is central and foundational to successfully resolving each of the challenges.

Standards Organizations and Standards Development

Codes and standards serve a critical role in optimizing product performance, ensuring safety, and streamlining local deployment. Furthermore, utilizing codes and standards can ensure equipment interoperability between different manufacturers, provide market certainty, reduce risks (e.g., data management risks), and avoid stranded assets. Therefore, establishing codes and standards is crucial in enabling broad MD/HD-ZEV deployment.

To that end, numerous regional and international organizations have developed standards related to zero-emission infrastructure. Key organizations that develop standards for both battery-electric vehicle (BEV) and fuel cell-electric vehicle (FCEV) infrastructure technologies include the Society of Automotive Engineers (SAE) International, Institute of Electrical and Electronics Engineers (IEEE), the International Electrotechnical Commission (IEC), the International Organization for Standardization (ISO), and the National Fire Protection Association (NFPA).

While the standards development process can vary by organization, the process in general consists of multiple stages where a technical committee formed of a diverse set of stakeholders develops a draft document. This draft then proceeds through a series of comment, revision, and approval stages. If the information is urgently needed to inform industry, a report may be issued preceding the full standard. Also, due to the overlapping scope of many standards organizations, standards may be harmonized across multiple organizations. Since standards routinely go through updates, it is important that the harmonization across different, equivalent standards is maintained through these new iterations.

It is the responsibility of industry to adopt standards voluntarily or governments to promulgate standards through the issuance of codes and regulations. Government agencies may also require application-specific codes and standards as a condition of program funding. Agencies typically set certification requirements and may administer testing programs for compliance certification.

Objectives and Methods

The goals of this study were to (1) assess the status of standards for charging MD/HD BEVs and fueling MD/HD FCEVs, and (2) identify gaps that need to be addressed to assure a broad and timely deployment of charging and hydrogen fueling infrastructure. To meet the goals, the following objectives were established:

1. Collaborate with standards organizations
2. Assess the status of standardization and associated activities
3. Convene a program consultatory group
4. Develop an informational resource for standardization processes
5. Provide a White Paper on standardization status, outlook, and priorities

To this end, the research team engaged with standards and testing organizations involved in the development of charging and fueling protocols and technologies for on-road and off-road medium- and heavy-duty vehicles, including direct participation in the SAE J3271 (Megawatt Charging System for Electric Vehicles) committee and ISO 19885 (Gaseous Hydrogen – Fueling protocols for hydrogen fueled vehicles) committee (ISO Technical Committee 197, Work Group 24). Information on other in-development standards was garnered through one-on-one interviews with key participating stakeholders throughout the project, as well as publicly available reports. In addition, a thorough literature review was conducted to gather data on the status of standards and associated activities. Two consultatory meetings were held during the project period, the first on October 19, 2021, and the second on June 14, 2022, in order to facilitate discussion among government, research, and industry stakeholders and solicit feedback on the research findings. A list of attendees is provided in Appendix D. Information compiled through these different pathways was summarized in two interim reports, both of which served as the basis for this document. The salient contributions of each report and the scope of the white paper are summarized here:[1]

Interim Report 1:

- **Current ZEV Market:** what standards are currently implemented for LDV, MDV, and HDV applications?
- **Energy Transfer:** what standards are currently available that specify charging and hydrogen fueling protocols?
- **Physical Interfaces:** what standards define the hardware and physical connections between the charger or hydrogen dispenser and the vehicle?
- **Standardization Efforts:** what current standards organizations, industry groups, and government entities are pursuing standardization efforts related to MD/HD ZEV infrastructure?
- **Current Standards Gaps:** What are the current gaps that need to be addressed in order to enable broad MD/HD ZEV deployment? What standards are in development to address these gaps?

Interim Report 2:

- **Communications:** What current standards are implemented for vehicle, network, and grid communications? How do these standards need to be updated for MD/HD applications?
- **Testing and Certification:** What are the procedures for testing and certifying MD/HD ZEV infrastructure? Are there any gaps related to these procedures that need to be addressed for MD/HD applications?
- **Network and Cybersecurity:** What standards are currently used in ZEV applications? Are there any gaps in security codes and standards to be addressed?
- **Policy Actions:** What actions has the State and federal government taken to standardize MD/HD ZEV infrastructure deployment? What policy actions can be taken to further advance standardization?

White Paper:

- **Summary of approved standards:** What are the current standards adopted within the ZEV market? What is the suitability of existing standards for MD/HD applications?

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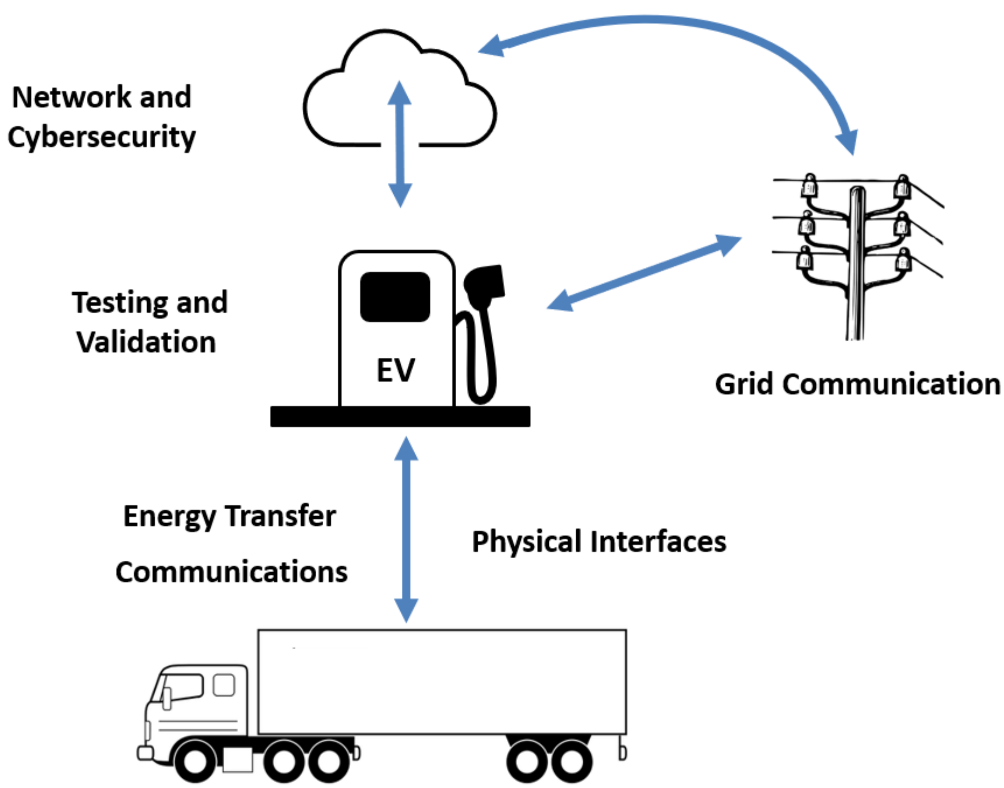
[1] All findings, including this white paper, are to be publicly available online: https://www.apep.uci.edu/mhdv/index.html

- **Summary of current standardization activities:** What standards are in development to support broad MD/HD ZEV deployment?
- **Summary of additional standards need:** What standards gaps persist that need to be addressed? What activities, if any, are addressing these gaps?
- **Recommendations:** What additional work can be done?

This white paper provides an assessment of standardization efforts across all MD/HD BEV charging (e.g., plug-in, overhead conductive, and wireless inductive) and MD/HD FCEV hydrogen fueling, with a focus on on-road MD/HDV needs within the context of State GHG emissions reduction goals. In assessing MD/HD ZEV infrastructure, the paper first provides background on standards organizations and standards development. It then covers how codes and standards are currently utilized in California to support ZEV deployment. Crucial standardization gaps and technology limitations for MD/HD applications are identified from a thoroughly conducted literature review as well as from input from key organizations and stakeholders. From the assessment, standards gaps and priorities are identified. Finally, the overall status of standards for MD/HD ZEV infrastructure are summarized and recommendations are presented.

The standards assessment encompasses standards for physical interfaces and energy transfer, as well as standards covering communications, safety, security, and testing. **Error! Reference source not found.** presents a general overview of the standards categories within scope.

Figure 1. Overview of Standards Areas within Scope of the Current Study



The standards categories are parameterized as follows:

- **Physical interface standards:** protocols that establish the physical and electrical connections between the vehicle and the station for energy and data transfers.
- **Energy transfer standards:** protocols that define the process of transferring energy, either electricity or hydrogen, between the station and the vehicle. Parameters include operating temperatures, voltage and current ranges, related communication requirements, and safety guidelines.
- **Communications standards:** protocols for data transfer between station and vehicle, station and network, or between networks. Standards specify message types, data formats, methods of transfer, session timing, and error handling.
- **Safety standards:** standards related to the design and operation of equipment to minimize environmental and human health risks and hazards, such as fire and electrocution.
- **Security standards:** protocols that specify data protection and encryption protocols to ensure secure data transfer and prevent tampering.
- **Testing standards:** protocols for verifying that the equipment adheres to established standards. These standards include but are not limited to tests for safety, performance, communications, and reliability.

The following criteria are used to characterize current and "in development" standards:

- **Standards Scope:** Hardware, energy transfer, communications, network and cybersecurity, physical interfaces, and testing protocol,
- **Status:** Published, revised, update pending, standard in development, technical report in development, or technical specification in development,
- **Market Location(s):** North America, Asia, Europe, etc.,
- **Current Vehicle Market:** LDV, MDV, HDV,
- **Market Penetration:** Widely adopted, shared market, recently released, in development, and
- **Suitability for Medium- and Heavy-Duty Vehicle Applications:**
    - *Not Suitable:* No specific MD/HD applications are considering the use of the standard,
    - *Low Suitability:* Very limited applications could use standard,
    - *Moderate Suitability:* Select use considered currently, broader adoption possible, depending on market interest,
    - *High Suitability:* Suitable for most or all MD/HD ZEV applications, any caveats are discussed, and
    - *Requires Revision:* for moderate and high suitability categories, standard needs revision to enable MD/HD use.

Leveraging the analysis of standards for MD/HD applications, a gap analysis was conducted. This analysis identified technology and protocol gaps that may need to be addressed for ZEV technologies to satisfy MD/HD-ZEV applications broadly. For each gap identified, the following information was determined:

- **Goal:** The desired functionality that will be achieved once the gap is resolved.
- **Type of Gap:** An explanation of the issue that needs to be addressed. This also indicates whether the gap relates to standards, codes, technology, implementation, or policy.
- **MD/HD ZEV Impact:** This section outlines the consequences of not addressing the current gap in terms of the deployment of MD/HD ZEVs.
- **Recent Activities:** Description of any relevant activities undertaken by stakeholders, government entities, or standard organizations that can contribute to addressing the identified gap.
- **Anticipated Activity Outcomes:** Description of added functionality and any remaining gaps following current activities.

The white paper is divided into two main sections: MD/HD BEV charging and MD/HD FCEV hydrogen fueling. Within each section, standards are identified and categorized based on their area of focus, document status, current market status, and suitability for MD/HDV applications. While the focus of this work is the North American market, international standards are mentioned where relevant. Gaps in standards that will affect the broad deployment of MD/HD-ZEVs are identified, and any activities related to addressing the gaps are discussed, as well as needed outcomes to enable standardized MD/HD-ZEV charging and hydrogen fueling.

Assessment Results

Battery Electric Vehicle Charging

For LDV BEVs, charging standards can vary depending on the regional market. North America, Europe, and Asia have their own charging protocols, spanning from SAE J1772 to Combined Charging Standard (CCS1) in North America, CCS2 in Europe, and GB/T to CHAdeMO in Asia. In recent years, there have been multiple regional efforts to standardize the type of charger used within a region in order to promote broader market interoperability.

There are several standards that govern the different elements of battery electric vehicle charging. This study focuses on the standards for the electric vehicle supply equipment (EVSE) that provide charging and the standards that specify communications requirements between the EVSE, the vehicle, other networks, and the electric grid. For the purposes of this study, EVSE refers to the hardware that enables charging, encompassing the connectors, cables, and related equipment managing power delivery. On-board BEV standards are excluded. Key standards enabling BEV charging in the U.S. are listed in Table 1. Additional relevant standards are covered in the following chapters.

There are several charging standards that are available in the U.S. market. These span plug-in and automatic AC and DC conductive charging systems as well as static inductive (wireless power transfer) charging for LDV applications. In December 2022, SAE International released a specification for wireless charging for HDV applications, covering static and some dynamic use cases with charging rates up to 500 kW and is working towards a standard [1].

BEV charging requires communication between the vehicle and the charger at a minimum to manage charging, including the charging protocol to be used and setting and adjusting charging power levels. The vehicle battery management system communicates charging parameters in order to maintain safe temperature limits and monitor the battery's state-of-charge. Communication between the vehicle and/or the EVSE and a network is also required when payment transactions take place. Furthermore, load management strategies and vehicle-to-grid (V2G) services, where the vehicle discharges back to the electric grid, require communication. The two most common communication standards used with CCS are DIN SPEC 70121 and ISO 15118. ISO 15118 is becoming the key standard for vehicle-EVSE communications moving forward for MD/HD-BEV applications. Load management and V2G communications are further standardized using open protocols, such as Open Charge Point Interface (OCPI), Open Charge Point Protocol (OCPP), and Open Automated Demand Response (OpenADR), which also will be important for MD/HD-BEV deployments.

In addition, charging stations are high voltage systems that require careful design and use to minimize safety risks and hazards, such as electrocution, shock, and fire. Relevant safety codes and standards will vary by region, as requirements are set at federal, state, and local levels. In California, key codes include the National Electric Code section 625, NFPA 70, and Title 24. Overall, equipment testing, and certification of standards compliance is required by the State in the production of different EVSE models and at the commissioning stage of an electric vehicle charging station. There are also cybersecurity concerns, including payment fraud, tracking and data insecurity, damage to vehicle batteries and/or station [2]. In response, efforts at the national and international level, within government agencies and standards organizations, are advancing to improve cybersecurity of EVSE. For example, the most recent update, ISO 15118-20, has added cybersecurity features, including strengthened Transport Layer Security (TLS) encryption requirements. However, a standardized, robust cybersecurity approach has not yet been adopted by the EVSE industry.

Table 1. Overview of Broadly Used Standards for Battery Electric Vehicle Charging

Standards Scope	Standard/ Proprietary Protocol	Description	Status (Year of Update)	Market(s)	U.S. Market Penetration	MD/HD Suitability
Charging Hardware and Protocols	**SAE J1772/CCS1**	Plug-in AC/DC charging	Revised (2017)	North America	Shared market with Tesla	J1772: Low CCS: High
	SAE J3068	Plug-in AC charging	Revised (2022)	North America	Limited	Moderate
	Tesla; SAE J3400	Plug-in AC/DC charging	SAE J3400: WIP (2023)	North America	Shared market with J1772/CCS	Moderate
	CHAdeMO	Plug-in DC charging	Revised (2021)	Asia, Limited in Europe and North America	Phasing out in North America	3.0 (ChaoJi): High
	SAE J3105	Automated overhead DC charging	Revised (2023) Recommended practice	North America	Limited (Transit)	Moderate
	SAE J2954-2	Static and dynamic wireless charging (MD/HDV)	Issued (2022)* Technical information report	North America	Limited (Proprietary solutions)	Moderate
	SAE J2954-3	Dynamic wireless charging for LD and HD	WIP (2023)	North America	Not deployed	Moderate
	SAE J3271	Plug-in DC charging at the megawatt scale	WIP (2023)	North America	Not deployed	High
Communications and Power Quality	**DIN SPEC 70121**	Bi-directional digital communication between the vehicle and DC charger	Issued (2014)	North America	Shared market with ISO 15118 for DC	Moderate
	ISO 15118	Bi-directional communication between the vehicle and the charging station (AC or DC); includes additional features compared to DIN SPEC 70121, such as plug-and-charge	Published: -1 (2019), -2 (2014)*, -20 (2022) Confirmed: -3 (2020), -4 (2023), -5 (2023)	North America, Europe, Asia	Widely adopted (AC and DC)	High
	SAE J2847-2	Communication between vehicle and DC charger	Revised (2023) Recommended practice	North America	Limited to J1772	Low
	SAE J2894	Power quality	Revised (2015)*	North America	Widely adopted	High

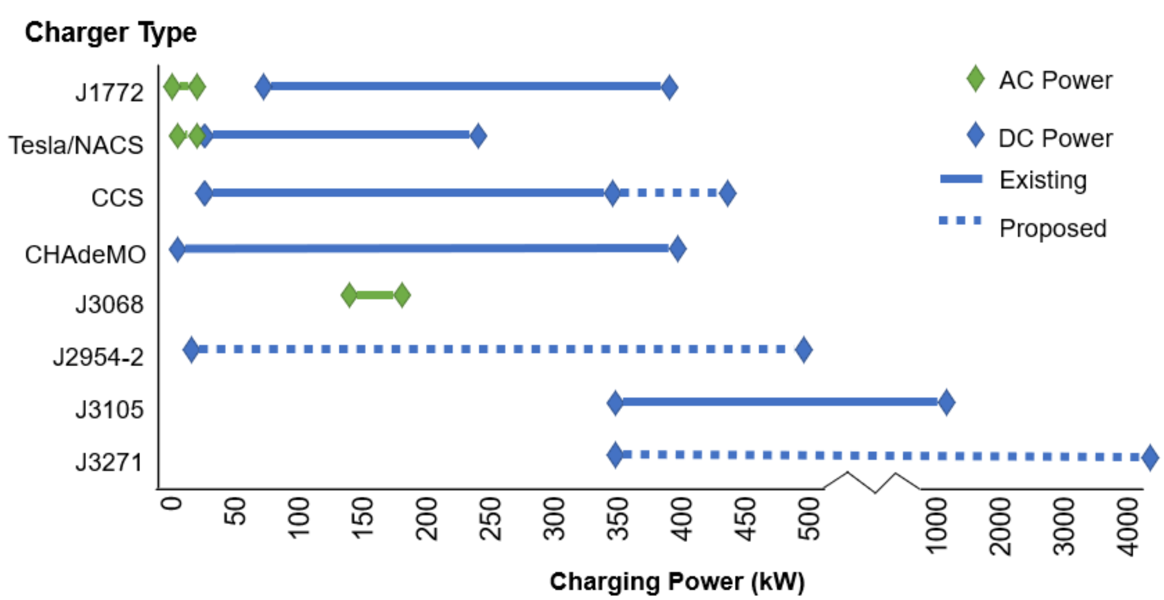
			Recommended practice			
	IEC 63110	Charging and discharging architectures, protocol specifications, and requirements	Published (2022)	Europe, North America	Shared market with OCPP	High
	Open Charge Point Interface (OCPI)	Communication between different network operators	Version 2.2.1 Released (2021)	Europe, North America	Shared with proprietary solutions	High
	Open Charge Point Protocol OCPP	Communication between the EVSE and the network	Versions 2.0.1 Released (2020)	Asia, Europe, North America, South America	Shared with proprietary solutions	High
	Open Automated Demand Response (OpenADR)	Demand response protocol	Version 3.0 Released (2023)	Asia, Europe, North America	Shared with proprietary solutions	High
Safety and Security	**UL 2202**	DC charging equipment for electric vehicles	Edition 3 Approved (2022)	North America	Widely adopted	High
	UL 2251	Testing for plugs, receptacles, and couplers for electric vehicles	Edition 4 Revised (2022)	North America	Widely adopted	High
	UL 2594	Testing for electric vehicle supply equipment; used for AC chargers	Edition 3 Approved (2022)	North America	Widely adopted	Moderate
	NFPA 70	National electric code: electrical safety	Updated (2023)	North America	Widely adopted	High
	SAE J2344	Safety guidelines for operation and charging	Reaffirmed (2020)	North America	Widely adopted	High

* Revision in development

Given the higher charging rates needed to support not only on-road MD/HDVs but also off-road sectors, such as aviation and rail, new and updated standards are being pursued to address the need. Learning from the challenges related to the heterogeneous LDV charger market, there is a push for developing a single charger or limited suite of charger technologies to support the future of MD/HDV electrified transportation. To that end, two major international efforts have been established for higher power (up to megawatt scale) charging—ChaoJi for the Asian market and Megawatt Charging System (MCS) for the North American and European markets. ChaoJi, released under CHAdeMO 3.0 in 2020, has a maximum power rate of 500 kW and updates are planned to enable 900 kW, possibly 1.8 MW. It has been proposed as the single, future DC charger type for China and Japan, with further expansion being considered. SAE J3271, also known as the megawatt charging system, stems from work by the industry consortium, CharIN. SAE J3271 is targeting power levels up to 4.5 MW, possibly greater, with systems supporting up to 3,000 A [3]. A J3271 technical information report (TIR) is in development at SAE International with a planned release sometime in 2024. A full standard for megawatt charging-capable protocols is anticipated within the next two to three years, with commercial deployments starting within the same timeframe.

As shown in Figure 2, a diverse set of charger types is available with charging capabilities that can support MD/HD-BEV charging. Currently, LDVs have J1772/CCS (combo charger), CHAdeMO, or the Tesla proprietary inlets. While CHAdeMO is being used for some LDVs, it is being phased out at the vehicle OEM level. At the same time, several OEMs, including Ford, GM, Honda, Hyundai, Nissan, and Volvo, have announced plans to adopt the North American Charging Standard (NACS) to be defined in SAE J3400 [4].

Figure 2. Charging Power for Current and In Development Charging Standards for the U.S. Market



MD/HD-BEVs on the road today use a variety of charging solutions. Most proprietary MD/HDV charger types that were deployed in early markets already have been phased out and new vehicle models are primarily offering J1772/CCS for plug-in charging, J3105 for automated charging, and in some limited cases, proprietary wireless solutions. J3068 is a newer AC high power charging option that is being offered by some OEMs.

Current limitations in BEV charging affecting MD/HDV deployment include charging rate, interoperability, reliability and resiliency, automation, standardization of payment systems and user interfaces, cybersecurity, tampering, emergency services training, and component standardization and supply security. Several of these limitations, such as reliability and resiliency, remain prevalent in the light-duty space and are therefore expected to persist with the deployment of MD/HD charging systems. In combination, these issues can limit ZEV suitability for different vehicle applications, reduce consumer confidence, and increase operational costs of zero-emission systems. Priority areas for codes and standards development include increased reliability (e.g., greater station uptime and EVSE interoperability), improved ease of use (e.g., automation), and higher charging rates (up to megawatt charging rates).

Hydrogen Fueling

Table 2 presents an overview of the hydrogen fueling standards, encompassing hardware, fueling protocols, communications, safety, and security. Harmonization has occurred over different iterations of the SAE and ISO standards. The SAE standards for each category are primarily referenced in the United States. While hydrogen may be stored as a liquid on-site, hydrogen stations in California dispense gaseous hydrogen. This study, as a result, focuses on gaseous hydrogen fueling protocols. Liquid hydrogen fueling is discussed as it applies to potential future standards.

For gaseous hydrogen fueling, the main fueling standards are SAE J2601 and SAE J2601-2. In addition, a TIR for high flow fueling, J2601-5, was released in February 2024. The main differences between fueling protocols are pressure class (target end pressure during fueling), flow rate calculation method, communications, compressed hydrogen on-board storage capacity, and flow rate. The U.S. currently only uses H35 (350 bar/5,000 psi) and H70 (700 bar/10,000 psi) pressure classes, with light-duty stations moving away from H35. MD/HD hydrogen stations may have either, depending on the fleet(s) supported, as H35 is the predominant pressure used for buses due to the lower cost and providing a sufficient fill to support typical bus routes.

Table 2. Overview of Major Standards for Hydrogen Fueling

Standards Scope	Standard	Description	Status (Year of Update)	Market(s)	U.S. Market Penetration	MD/HD Suitability
Hardware	SAE J2600	Dispenser nozzle design	Revised (2015)	North America	Widely Adopted	Moderate
	ISO 17268	Dispenser nozzle design (harmonized with SAE J2600)	Published (2020)	Asia, Europe	(Deployed under SAE J2600)	Moderate, revision needed for H70 high flow
Fueling Protocols	SAE J2601	Hydrogen fueling protocols (350 and 700 bar)	Revised (2020)	North America	Widely Adopted	Moderate
	SAE J2601-2	Hydrogen fueling guidance for heavy-duty applications	Stabilized (2023)	North America	Limited	Moderate
	SAE J2601-5	High flow fueling protocols	TIR (2024)	North America	In development	High
	ISO 19885-3	High flow fueling protocols	WIP	Asia, Europe, North America	In development	High
Communications	SAE J2799	Communications	Revised (2019)	North America	Widely adopted	High, needs revision
	ISO 19885-2	Communications for high flow fueling	WIP	Asia, Europe, North America	In development	High
Safety and Security	NFPA 2	Hydrogen safety	Revised (2023)	North America	Widely adopted	High

SAE J2601 establishes hydrogen fueling protocols for LDVs, incorporating safety limits and performance targets. The standard categorizes fueling protocols based on temperature, pressure, Compressed Hydrogen Storage System (CHSS) capacity, and communication type. For temperature, SAE J2601 considers three categories: -40^{o}C, -30^{o}C, and -20^{o}C. CHSS capacity is divided into four categories (A, B, C, D) with varying hydrogen storage tank capacities. Communication during fills can be either “non-communications” or “communications.” In the non-communication case, the station relies on ambient temperature and initial tank pressure, while communication fills include additional data like CHSS temperature and volume. The fueling gas flow rate calculation involves two methods: Table-Based Fueling Protocol and Mass and Thermal Capacity (MC) Formula-Based Fueling Protocol. The Table-Based Protocol uses computer modeling, and the MC Formula calculates the pressure ramp rate in real time, considering various parameters. The standard includes detailed look-up tables for both methods, addressing different scenarios and conditions. The maximum fueling rate in SAE J2601 is 60 g/s.

SAE J2601-2 provides a general overview of operational limits for a faster fueling rate for the pressure class H35 but is not a comprehensive fueling protocol. Under the current guidance, there are three fueling options characterized by maximum flow rate: (A) ≤ 120 g/s, (B) ≤ 60 g/s, and (C) ≤ 30 g/s. The high flow rate under option A requires a high flow nozzle (ISO 17268:2012) that is intentionally incompatible with the standard H35 receptacle. Protocols using this guidance are customized to meet a specific fleet's needs and therefore, are not designed for more generalized, public access. They also do not provide faster fueling for the H70 pressure class.

SAE J2799 outlines communication hardware and data transfer requirements for fueling FCEVs. It complements J2600 (hardware) and all J2601 versions. Data are communicated through infrared transmission from the vehicle to the hydrogen dispenser. The communication process begins with nozzle insertion, continuing throughout the fueling session. If the vehicle sensor cannot provide valid data, the station follows a non-communication protocol or terminates the fueling session.

The key standard for ensuring hydrogen safety is NFPA 2, which covers safety measures for the full hydrogen supply chain, including gaseous and liquid hydrogen storage at hydrogen fueling stations. NFPA 2 is updated regularly, so government entities need to identify which version (current or otherwise) should be followed. Safety considerations include planning for both accidental and intentional disruptions. Potential disruptions to stations can result from physical damage, cyberattacks, and tampering with consumer data.

Table 3 provides an overview of the status of the major hydrogen fueling standards in development. These include the high flow standards listed previously, as well as additional standards that are being added or revised to address current gaps in fueling protocols. Two key examples are the update to SAE J2601 that would add a Category D for H35 fueling and the new document SAE J2601-4 that would address ambient temperature fueling, which is not yet covered by a standard.

Table 3. Key Standards in Development for Hydrogen Fueling

Name	Scope	Status
SAE J2601-1	H35 Category D (CHSS >5.97 kg)	WIP
SAE J2601-4	Ambient Temp Fueling	WIP
SAE J2601-5	High Flow Protocols	TIR
ISO 19885-1	Design and development process for fueling protocols	WIP: Committee Draft
ISO 19885-2	High Flow Communications	WIP: Preparatory
ISO 19885-3	High Flow Protocols	WIP: Preparatory
ISO 17268 (Update)	High Flow Components	Current version: ISO 17268:2020 WIP: Preparatory

Much of the recent protocol work has focused on developing an optimized approach that incorporates advanced communications in order to enable higher hydrogen flow rates up to the U.S. Department of Energy's target of an average fueling rate of 10 kg/min.[2] The ISO working group developing ISO 19885 is currently compiling the available data and methods for high flow protocols in order to develop a standard encompassing one or more protocols for use in MD/HD-FCEV fueling applications. High flow standards are leveraging hydrogen research from domestic and international research (e.g., U.S. DOE National Laboratory programs) associated with (1) testing high flow, large on-board storage fills, (2) conducting risk analyses on hydrogen safety in MD/HDV fueling applications, and (3) verifying new and modified hardware for hydrogen fueling stations. Another key resource is the Protocol for Heavy-Duty Hydrogen Refueling (PRHYDE) program in Europe, which concluded in late 2022. The PRHYDE program developed a heavy-duty fueling protocol expected to be incorporated into the ISO 19885 standard. Table 4 provides an overview of how current and in-development protocols (shown in green) align in terms of fueling rates.

It is anticipated that the high flow fueling protocols for MD/HD-FCEVs will require updated, advanced communications. ISO 19885-2 is in development in conjunction with ISO 19885-3. Increasing the flow rate to 10 kg/min will also require new hardware. Updated hardware requirements will be added to SAE J2600 and ISO 17268.

As the ISO committee iterates on the final high flow fueling standard, key stakeholders are discussing the potential for an interim protocol in the short-term that can support flow rates greater than the 3.6 kg/min maximum established in J2601. The SAE J2601-5 TIR provides

[2] The U.S. Department of Energy has established a 2030 goal of 8 kg/min and ultimate goal of 10 kg/min achieved by 2050 [229].

information on this protocol. ISO 19885 and SAE J2601-5 are being harmonized through the standards development process.

Table 4. Current and In Development Hydrogen Fueling Protocols and Corresponding Pressures and Flow Rates

Pressure: 350 Bar			
CHSS (kg)	Fueling Rate (kg/min)		
	1.8	3.6	7.2
1.19-2.39	J2601 Category A		
2.39-4.18	J2601 Category B		
4.18-5.97	J2601 Category C		
5.97-10	J2601(Category D)		
10+	J2601-2 Slow Fueling Option C	J2601-2 Normal Fueling Option B	J2601-2 Fast Fueling Option A / J2601-5 MC Formula High Flow

Pressure: 700 Bar					
CHSS (kg)	Fueling Rate (kg/min)				
	<=3.6		7.2	8	10+
2.00-4.00	J2601 Category A				
4.00-7.00	J2601 Category B				
7.00-10.00	J2601 Category C				
10-30	J2601 Category D	J2601-5 Category D High Flow		J2601-5 MC Formula High Flow & ISO 19885	
30+					

Current limitations in hydrogen fueling affecting MD/HDV deployment include lack of fast fueling, challenges related to back-to-back fueling, achieving a high final fill state when fueling, fueling protocol complexity, and HDV-specific equipment and station testing to verify standards compliance. These issues are mainly related to the equipment limitations of existing designs and are being addressed through research on components with low reliability, such as compressors, and standards development and revision. Priority research areas include high flow fueling hardware, communications, protocols, and HDV station testing methods.

Industry and Government Stakeholder Engagement

During the project, one-on-one interviews were conducted with industry stakeholders to garner the most up-to-date information on current market development and standardization efforts within industry groups and standards organizations. In addition, questions were discussed during two consultatory meetings in order to garner additional information on the status of MD/HD-ZEV infrastructure standardization and other related activities. A list of stakeholder participants is provided in Appendix D and the stakeholder questionnaire is in Appendix E.

Overall, the industry stakeholders interviewed demonstrated a strong coordination with other stakeholders and a proactive participation in the various standards development efforts with a particular interest in megawatt charging and ISO 15118 updates for MD/HD-BEVs and the high flow hydrogen fueling standards for MD/HD-FCEVs. Several challenges were identified, including station reliability, charger durability (J3105), long charging and fueling times, high station cost, long commissioning times, and limited MD/HD-ZEV supply. In order to address these issues, the following recommendations for governmental support were suggested:

- Continuing public funding of MD/HD-ZEV infrastructure,
- Streamlining permitting processes,
- Providing guidance on electric utility coordination, such as electric grid interconnection rules, information on the electric grid distribution network to inform depot station siting,
- Providing updated modeling tools for designing MD/HD hydrogen fueling stations and simulating fueling performance, and
- When setting security requirements, considering the use case, e.g., private versus public use (There are concerns that too many added requirements for private stations could unnecessarily increase costs).

In addition, stakeholders discussed actions that industry members are taking to address issues. These include:

- Moving away from proprietary solutions and towards standardized charging and hydrogen fueling approaches,
- Establishing broad stakeholder collaboration in the development of MD/HD charging and hydrogen fueling standards,
- Collaborating with industry and governmental entities to improve testing and interoperability across manufacturers,
- Increasing responsiveness to station outages and increasing preventative maintenance frequency,
- Designing more resilient stations based on a modular design with system redundancy to allow continued operation following an equipment failure while prioritizing safety, and
- Leveraging failure analysis data in order to design and operate more reliable systems.

Multiple stakeholders identified increased reliability and shorter charging and hydrogen fueling times as critical goals for enabling broad, long-term MD/HD charging and hydrogen fueling deployment success.

Conclusions

Based on the MD/HD-ZEV infrastructure standardization assessment and feedback from stakeholders, several conclusions were drawn.

1. Kilowatt-level charging is well established but will not meet all MD/HD-BEV operational use cases. Higher charging rates, up to MW charging, are needed to support many heavy-duty applications.

2. New standards that permit higher charging rates up to MW charging and greater hydrogen flow rates greater than 10 kg/min are needed to meet fully the range of expected MD/HD-ZEV applications.

3. Increased infrastructure reliability is needed to support the broad market utilization of MD/HD-ZEV infrastructure. Light-duty charging stations and hydrogen fueling stations experience outages and other operational challenges, negatively affecting the consumer experience and market development. For LD-ZEV and especially MD/HD-ZEV stations, it is essential to enhance reliability by mitigating issues associated with communication and component failures, and hydrogen supply. While the industry is actively engaged in efforts to tackle these issues, policy and government oversight that assures maintaining an acceptable level of overall performance of charging and hydrogen fueling stations is crucial.

4. The continued improvement and prioritization of cybersecurity for ZEV stations is also a high priority. Charging stations lack a standardized cybersecurity approach, despite various tools in use and government guidance. Hydrogen stations prioritize physical safety but share risk vectors with EVSE. Common advancements in encryption and security standards can enhance cybersecurity for both types of stations.

5. Due to the wide range of vehicle classes and applications within the MD/HD sector, a combination of station configurations is needed to support broad deployment. This includes the deployment of both charging and hydrogen fueling stations, MD/HD stations providing LDV services, and MD/HD stations offering varying charging rates and both H35 and H70 hydrogen fueling pressures.

6. Several challenges, outside the scope of this study on standards, identified by stakeholders to hinder the broad deployment of MD/HD-ZEVs include limited zero-emission vehicle stock, high total cost of ownership, and insufficient trained workforce.

Recommendations

The following policy considerations are recommended.

Policy Recommendation 1: *Policies for MD/HD-ZEV stations should strike a balance between the need for standardization and the promotion of on-going innovation.* Key areas of focus for required codes are safety, security, and reliability (including interoperability). Moving forward, as the market matures, the State should continue to focus on these vital areas. At the same time, the State should continue to promote innovation needed to enable broad MD/HD ZEV deployment, including increased equipment reliability, higher charging rates, and faster hydrogen fueling rates.

Policy Recommendation 2: In public funding solicitations, differentiate station type/configuration, including public versus fleet-only access, when setting codes and standards requirements.

Station designs can vary based on the use case. Private stations can have more design flexibility to cater to the specific needs of the target fleet. In contrast, public stations focus on serving a larger number of vehicles, necessitating higher standards for interoperability, faster charging rates, and hydrogen fueling rates to encourage efficient station throughput, and consecutive fueling events.

Policy Recommendation 3: Promulgate "short term" guidance for charging and fueling protocols employed in MD/HD commercial stations with the goal of facilitating interoperability.

The timeline for advancing MD/HD standardization such as megawatt charging and high flow hydrogen fueling is one to three years. In the interim, the risk of an increase in technological heterogeneity within the marketplace is high, giving rise to a negative impact on market engagement and development. The State can provide guidance on how stations can support continued interoperability in the short-term given the different generations of stations and vehicles.

Policy Recommendation 4: In public funding solicitations, reference Technical Information Report (TIR) documents, namely SAE J3271, SAE J2601-5, and other related documents, pending finalization of formal standards for high power and high flow systems.

TIRs are valuable guidance documents that signal the direction of on-going standards development and have been previously used for this purpose in past State funding solicitations. Megawatt charging and high flow hydrogen fueling standards are anticipated to release TIRs preceding their final standards. Leveraging these documents in station funding initiatives can expedite deployment of stations that will be compatible with anticipated standards.

Overall, transitioning to 100% MD/HD-ZEVs in California requires significant investment and coordinated, regional planning efforts. The State has a responsibility to establish infrastructure requirements that support the rapid deployment of a reliable, interoperable MD/HD-ZEV infrastructure network without hindering technological advancement within the market. To date, federal, state, and regional agencies have played a critical role in supporting technological maturation and standardization of MD/HD-ZEVs and the associated infrastructure through direct funding, program guidance, tools, and policies. Based on the findings from this study and lessons learned from the LDV market deployment, a systematically planned agency strategy is appropriate to assure MD/HD-ZEV charging and fueling stations are designed, constructed, and operated to be:

- ***Compliant*** with industry standards, such as ISO, SAE and IEEE for operability and NFPA for safety, to be
- ***Reliable*** and thereby instill market confidence and accelerate market engagement, at levels (e.g., 98% dispenser availability) commensurate with existing fueling infrastructure, with enforcement to assure maintenance of the reliability over the life of the station, and to
- ***Leverage*** industry innovation, by allowing MD/HD design flexibility to consider future improvements.

1. Introduction

To address the growing threat of climate change, the State of California has established the following ambitious greenhouse gas emissions (GHG) reduction goals under SB 32 (Pavley, Chapter 249, 2016) and AB 1279 (Muratsuchi, Chapter 337, 2022):

- Reduce GHG emissions to 40 percent below 1990 levels by 2030,
- Achieve net zero GHG emissions by 2045, and
- Reduce GHG emission to 85 percent below 1990 levels by 2045.

In support of these overarching GHG reduction goals, as well as regional air quality attainment goals, the State has implemented legislation to support the transition to light duty (LD), medium duty (MD), and heavy duty (HD) zero-emission vehicles (ZEVs):

- **Assembly Bill (AB) 8 (Perea, Chapter 401, 2013):** allocates $20 million annually from 2013 through 2023 to fund hydrogen fueling stations and requires an annual report evaluating the status of fuel cell electric vehicle and hydrogen fueling station deployment [5].
- **Senate Bill (SB) 454 (Corbett, Chapter 418, 2013):** establishes rules for public charging station payments, including prohibiting of subscription fees, allowing payment by credit card or mobile pay, and disclosure of all fees, as well as station location reporting requirements [6].
- **SB 350 (de Leon, Chapter 547, 2015):** directs the California Public Utility Commission to promote the increased deployment of electric vehicle charging infrastructure [7].
- **Executive Order (E.O.) B-48-18 (2018):** sets a goal of 5 million zero-emission vehicles by 2030 and 200 hydrogen stations and 250,000 electric vehicle chargers, including 10,000 DC fast chargers by 2025 [8]. The E.O. does not specify vehicle class.
- **AB 2127 (Ting, Chapter 365, 2018):** requires a statewide assessment of the charging infrastructure needed to support 5 million zero-emission vehicles by 2030, inclusive of MD/HD ZEV deployment [9].
- **Innovative Clean Transit Regulation (2019):** requires increasing adoption of zero-emission buses by transit agencies. Starting 2029, all new transit buses purchased must be zero-emission, with the goal of complete transition to zero-emission bus technologies by 2040 [10], see **Error! Reference source not found.**.
- **Electric Vehicle Supply Equipment (EVSE) Standards Regulation (2019):** authorized by SB 454 (Corbett, Chapter 418, 2013), this CARB regulation establishes a billing standard for network stations, including payment requirements, roaming standards, display of feeing, labeling of fuel dispensed information, and State and federal reporting requirements [11].
- **Zero Emission Powertrain Certification (2019):** requires that all heavy-duty vehicles, excluding transit buses, of model year 2021 and later be certified following the "California Standards and Test Procedures for New 2021 and Subsequent Model Heavy-Duty Zero-Emission Powertrains," section 1956.8, Title 13, California Code of Regulations [12], [13].

- **Zero-Emission Airport Shuttle Regulation (2019):** requires the transition of airport shuttles to zero-emission vehicles starting in 2027 and completing by 2035 [14].
- **E.O. N-79-20 (2020):** directs for all sales of light-duty vehicles be zero-emission by 2035 and all medium- and heavy-duty vehicle sales be zero-emission by 2045, where feasible [15].
- **Advanced Clean Trucks Regulation (2020):** requires the sale of MD/HD-ZEVs within the State starting in 2024 and increasing in the sales percentage up to 40-75%, depending on vehicle type, by 2035 [16].
- **Electric Vehicle Supply Equipment Standards Regulation (2020):** establishes requirements for labeling, payment, roaming agreements, and reporting [17].
- **SB 643 (Archuleta, Chapter 646, Statutes of 2021): r**equires the California Energy Commission (CEC), in consultation with CARB and the CPUC, prepare a statewide assessment of the FCEV fueling infrastructure and fuel production needed to meet state zero-emission goals [18]. The first assessment was released in 2023 [19].
- **AB 2061 (Ting, Chapter 345, 2022):** requires the CEC to assess the availability of charging stations, i.e., "uptime" [20].
- **Advanced Clean Fleets Regulation (2023):** adds 100% ZEV targets for drayage trucks, last-mile delivery, and government fleets by 2035 and refuse trucks, local buses not covered under the ICT regulation, and capable utility fleets by 2040 [21].
- **SB 123 (Committee of Budget and Fiscal Review, Chapter 52, Statutes of 2023):** harmonizes previously established EVSE requirements set under the EVSE Standards regulation with federal rules, updating payment requirements and authorizing the CEC to further update requirements as needed [22].

In concert with these legislative efforts are substantial investments in MD/HD-ZEV and charging and fueling infrastructure through multiple programs, such as the CEC's Clean Transportation Program [23], the Low Carbon Transportation Investments and Air Quality Improvement Program [24], the Carl Moyer Memorial Air Quality Standards Attainment Program [25], and the Volkswagen Environmental Mitigation Trust Fund [26]. In addition, the California Public Utilities Commission has authorized investor-owned utilities to implement programs installing charging infrastructure supported by ratepayer funding [27]. Appendix A provides an overview of the major funding programs for MD/HD ZEVs. Given the fast deployment timeline and the participation of numerous stakeholders, California faces challenges of scale and reliability for electric charging and hydrogen fueling of MD/HD-ZEVs. Infrastructure standardization is crucial in providing market certainty, protecting State investments, streamlining heavy-duty transformation, and accelerating early deployment. Simply stated, the rapid increase in MD/HD-ZEV adoption requires a complementary network of reliable and interoperable fueling infrastructure on a short timeline. Availability of necessary infrastructure preceding vehicle deployment is crucial to market confidence and unconstrained MD/HD-ZEV deployment.

In support of the State's goals to fully transition the on-road MD/HD transportation sector to zero-emission vehicles, this project conducted a comprehensive and holistic assessment of all standards and policies related to MD/HD-ZEV charging and hydrogen fueling in order to identify gaps in standards that need to be addressed for broad infrastructure deployment and ensure an effective approach to broad standardization.

This white paper serves as the final report for the two-year study conducted for the California Air Resources Board under contract 20MSC006. Information presented in this work is sourced from numerous reports and research papers, in-progress standards development within standards and testing organizations, and direct feedback from key stakeholders involved in the development of charging and fueling protocols and technologies for on-road medium- and heavy-duty vehicles. To the extent applicable, light-duty standards and equipment are included, due to their foundational overlap with medium- and heavy-duty standards. This white paper is complemented by a publicly available online resource[3] in order to inform government and stakeholders on MD/HD zero-emission infrastructure standardization and information related to new regulations, vehicle deployment, infrastructure planning, and State support.

[3] Online resource available at: www.apep.uci.edu/mhdv

2. Standards Development and Implementation

A combination of standardization with innovation supports the development and proliferation of new procedures and technologies into the mass market [28]–[30] with the goal of standardization is to ensure technical performance, safety, sustainability, and scalability [31]. Adopting a standardized approach to the development and deployment of MD/HD-ZEV charging and hydrogen fueling infrastructure can provide benefits critical to the evolving MD/HD-ZEV market, including:

- **Improved performance:** Standards development allows for broad sharing of knowledge and data across industry, academic, government, and non-governmental organizations. This coordination can support optimal design of equipment and protocols that reflect state of the art expertise. Example technical performance criteria include reliability, accuracy, and efficiency.
- **Improved safety:** Establishing standardized safety protocols ensures all infrastructure equipment meets minimum safety requirements, protecting users from known safety hazards of charging and hydrogen fueling, such as electric shock and fire.
- **Improved reliability:** Standards establish technical specifications for manufacturers to follow, improving the consistency between individual stations and between different equipment providers.
- **Reduced cost:** Standardizing parts can reduce costs for manufacturing station components and reduce cost for maintenance by increasing ease of repair [32].
- **Reduced risk of stranded assets:** Standardization results in stations being interoperable across multiple OEMs, increasing access and reducing the risk of stations becoming obsolete in the face of an evolving market.
- **Improved ease of maintenance:** Standardized stations can leverage established test methods for troubleshooting errors and utilize standardized replacement parts.
- **More effective workforce training:** Standardized design and operation of charging and hydrogen fueling infrastructure means that the workforce trained to construct and maintain the infrastructure are well-equipped to work for a variety of station providers on diverse projects.
- **Improved user experience:** Standardized labeling, payment steps, as well as charging and hydrogen fueling protocols mean that customers can expect a similar user experience across stations.

A broad spectrum of international and national organizations is driving the development of standards. Standards organization committees drafting and publishing standards consist of a diverse set of stakeholders, ranging from manufacturers to academia, with the goal of receiving satisfactory input from all areas within the technology space to develop an impartial standard supported and approved by a consensus [33], [34]. The scope and impact of standards can vary greatly, depending on the issuing organization and the market adoption of relevant technologies. In general, international organizations can have a broader impact than national organizations by directing standards that can be readily implemented across many countries and markets. Standards are then adopted by manufacturers and government agencies.

2.1 Standards Organizations

Several organizations lead the development of standards to support the advancement of MD/HD-ZEV infrastructure technology deployment. Standards organizations generally focus on a subset of expertise and may be intended for different regional markets. For example, the Compressed Gas Association (CGA) focuses on compressed gas standards for North America, whereas the International Organization for Standardization (ISO) has a broader scope, developing standards for a multitude of subject matters ranging from environmental management to food safety, for the global market. California generally selects standards from North America-centric standards organizations, such as SAE International, CGA, and ASTM International, but there are exceptions, such as the adoption of ISO 15118 for charger communications.

The following standards organizations have issued standards and recommended practices relevant to MD/HD-ZEV infrastructure within the scope of this work:

- **American National Standards Institute (ANSI):** is an American non-profit organization that oversees standards development in standards organizations within the U.S. It does not develop its own standards; rather, it coordinates conformance efforts across other standards organizations and provides accreditation programs [35]. Several standards from CSA are cross listed with ANSI, including ANSI/CSA HGV 4.3 and ANSI/CSA HGV 4.9.

- **ASTM (American Society for Testing and Materials) International**: develops and publishes international standards related to materials and chemical/fuel testing [36]. Relevant standards include those that provide test methods for different contaminants in hydrogen fuel.

- **Compressed Gas Association (CGA):** is a North American trade association and ANSI-accredited standards organization that develops safety and technical standards and best practices in the transport, storage, use, and disposal of compressed gases. Its members further participate in standards development in other, international standards committees [37]. The main CGA technical specification used in MD/HD-ZEV infrastructure is CGA G-5.3: "Commodity Specification for Hydrogen," which classifies hydrogen by quality (impurity levels) [38].

- **CSA (Canadian Standards Association) Group:** is an ANSI-accredited standards organization specializing in electrical, electronic, compressed gas and occupational health and safety standards [39]. CSA Group also provides standards and certification training and serves as an OSHA-accredited nationally recognized testing laboratory [40]. The main CSA standards deployed for MD/HD-ZEV fueling infrastructure are CSA/ANSI HGV 4.3: test methods for hydrogen fueling parameter evaluation and CSA/ANSI HGV 4.9: hydrogen fueling stations.

- **European Committee for Electrotechnical Standardization (CEN-CENELEC):** is a separate organization from CEN that specializes in electrical and electronic standards for Europe [41]. CEN and CEN-CENELEC were tasked with overseeing which charger standards are adopted in Europe [42].

- **European Telecommunications Standards Institute (ETSI):** develops and publishes standards for the European market. Relevant work includes cybersecurity standards for Europe.

- **European Committee for Standardization (CEN):** develops and publishes European standards for its 34 member countries spanning everything from energy to healthcare [43]. An example standard within the scope of the current study is EN 17127: "Outdoor hydrogen refuelling points dispensing gaseous hydrogen and incorporating filling protocols" [44].

- **International Organization for Standardization (ISO):** develops international standards through the collaboration of national standards organization members. Standards span a broad range of technical and non-technical fields [45]. For MH/HD-ZEV infrastructure, standards encompass both charging and hydrogen fueling, including ISO 15118: "Road Vehicles Grid Communication Interface" [46] and ISO 19880: "Gaseous Hydrogen – Fuelling Stations" [47].

- **International Electrotechnical Commission (IEC):** develops and publishes international electrical and electronic standards. Relevant standards include IEC 62196: Plugs, socket-outlets, vehicle connectors and vehicle inlets - Conductive charging of electric vehicles and IEC PAS 62804: electric vehicle battery swapping system.

- **Institute of Electrical and Electronics Engineers (IEEE):** is a standards developing organization that publishes standards within the area of electronics [48]. IEEE standards for MH/HD-ZEV infrastructure include those that govern grid interconnection (e.g., IEEE 1547, IEEE 2030.5) and IEEE P2030.13: Guide for Electric Transportation Fast Charging Station Management System Functional Specification.

- **Japan Petroleum Energy Center (JPEC):** is a Japanese foundation that conducts research and development for the advancement of energy technologies [49]. Its focus in the area of MD/HD-ZEVs is hydrogen. A key standard is JPEC-S 0003 for hydrogen fueling.

- **National Fire Protection Association (NFPA):** is an international non-profit organization that provides codes and standards as well as other educational resources, such as data analysis research, handbooks, and training within the area of fire safety [50]. Key standards within the scope of this study include NFPA 2: Hydrogen Technologies Code, NFPA 55: Compressed Gases and Cryogenic Fluids Code, and NFPA 70: National Electrical Code.

- **National Institute of Standards and Technology (NIST):** is a U.S. government agency with a broad focus on promoting industrial competition through technology research and standards development [51]. Key areas include cybersecurity and safety standards, such as Handbook 44 [52].

- **Payment Card Industry Security Standards Council:** is a consortium of major credit card companies that establishes data security standards [53]. A major standard relevant to this study is PCI-DSS [54].

- **SAE International:** focuses on automotive standards encompassing aerospace, ground vehicles, and systems management [55]. Important zero-emission vehicle standards from SAE International include those detailing AC and megawatt DC charging (architecture and protocols), wireless charging, conductive charging, hydrogen fueling components, hydrogen fueling protocols, power quality, gas quality, and safety. Example standards include SAE J2600: Compressed Hydrogen Surface Vehicle Fueling Connection Devices and SAE J1772: Electric Vehicle and Plug in Hybrid Electric Vehicle Conductive Charge Coupler.

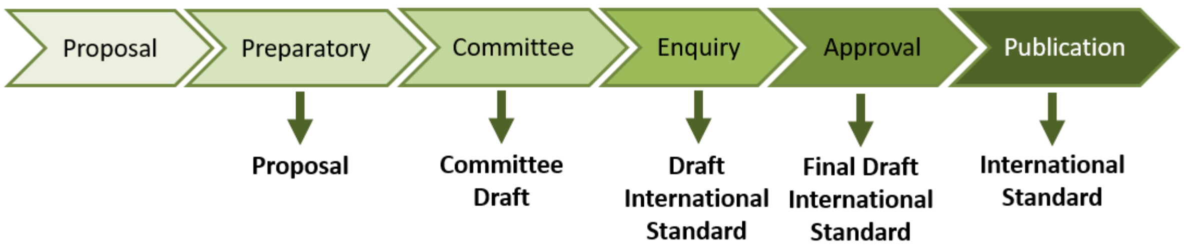
- **Underwriters Laboratory (UL):** develops standards centered on equipment performance and safety testing, focusing on applications within the U.S. and Canada regions. UL also coordinates international standards harmonization across multiple standards organizations, such as CSA Group [56]. Example standards relevant to this study are UL 2251 and UL 2594.

Several standards organizations have formal agreements to coordinate on standards and “harmonize” across standards with similar scope. For example, SAE International and ISO have harmonized standards for hydrogen fueling, such as SAE J2600 and ISO 17268, which both define hydrogen fueling hardware. By harmonizing standards across standards organizations, it ensures broader standardization across multiple markets.

2.2 Standards Development

Standards organizations have established procedures for developing new standards which, in general, consist of several stages including the establishment of a technical committee, creation of a draft document, revision and comment periods, and approval stages, the last of which is for the publication of the final document. Figure 3 illustrates the standards development stages and resulting documents for ISO as an example.

Figure 3. ISO Stages and Documents



Standards organizations may publish documents that provide guidance on standardization methods prior to, or in leu of establishing a full, prescriptive standard. Key examples include a technical specification (TS), a technical (information) report (TIR/TR), and a recommended practice. A TS provides requirement information within the scope of larger, in-progress international standards development, with the goal of disseminating guidance for immediate use and to garner feedback. A TIR/TR provides industry agreed upon technical guidelines or guidance without establishing requirements. A recommended practice provides guidance on preferred technology, configurations, performance, procedures, etc. for a specified industry practice [57].

Generally, organization documents are subject to review after a set number of years (e.g., every 5 or 10 years) at which time the document must be reaffirmed, stabilized, revised, or canceled [58]. For example, SAE J2601 was first issued in 2010, and has been revised three times: in 2014, 2016, and 2020. Another example is ISO 15118-1, which was first issued in 2013 and has since been revised in 2019. Due to the evolution of standards over time, it is important to reference the most recent version of a standard to ensure proper conformance.

Given the technological differences between battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs), different standards are necessary to dictate the charging and fueling requirements for each. In the following sections, standards are divided into BEV charging and FCEV hydrogen fueling subsections.

2.3 Standards Implementation and Certification of Compliance

Standards organizations do not have the power to require that standards be followed, rather the manufacturers have the responsibility to adopt and follow standards and, when appropriate, governmental agencies can require standards be followed and verify compliance. For charging and hydrogen fueling, the U.S. Weights and Measures Division and the California Division of Measurement Standards (DMS) set and utilize methods for testing compliance with government codes, such as hydrogen dispensing accuracy, energy transfer accuracy, efficiency, fuel quality (for hydrogen) and power quality (for electricity).

Compliance can be tested at two levels: the equipment level and the project level. At the equipment level, individual components or a system of related components are tested and certified for use by the relevant test program. There are several testing programs administered at the national and state level that provide testing and certification. Most relevant to this study are the Occupational Safety & Health Administration (OSHA)'s Nationally Recognized Testing Laboratory (NRTL) program, which certifies product compliance with OSHA safety standards [59]; the National Conference on Weights and Measures' National Type Evaluation Program (NTEP), which certifies weighing devices [60]; and the California Type Evaluation Program (CTEP), overseen by DMS, which participates in the larger NTEP program and certifies weighing and measuring devices corresponding to California laws [61]. For relevant products, companies are required to complete the certification process(es) before making the products commercially available. NIST Handbook 44 serves as a guidance document for test methods and procedures associated with certifying devices and equipment for charging and hydrogen fueling [52].

At the project level, general standards, and other technical specifications for charging and hydrogen fueling stations have been codified in the California Code of Regulations. Compliance of a particular project is, in part, verified by local authorities that have jurisdiction [62], [63]. This verification may include ensuring other local ordinances are also followed. In addition, DMS oversees codes and standards compliance related to weights and measures. Verification is usually handled at the local level by county weights and measures officials. In California, the adopted codes and standards overseen by DMS include:

<u>For Hydrogen,</u>

- **Hydrogen Quality:** Chapter 14, California Business and Professions Code; California Code of Regulations (CCR) Title 4, Division 9, Chapter 6, Article 8, Section 4181; and SAE J2719– DMS is required to enforce hydrogen quality specifications. It periodically tests hydrogen samples from hydrogen fueling stations to ensure dispensed hydrogen meets hydrogen purity requirements specified in SAE J2719 as adopted by Section 4181, CCR Title 4 [64].
- **Hydrogen Dispensing:** CSA HGV 4.3, SAE J2601, and SAE J2799 – Stations must be tested for compliance before they are commissioned. DMS tests hydrogen fueling performance as specified in SAE J2601 and communications in SAE J2799 using the HyStEP device. Test methods are defined in CSA HGV 4.3. HyStEP device tests include validating safety and performance, which is assessed by collecting communications and dispensing

parameter data, including hydrogen dispensed, temperature, and tank pressure [65]. Communications and non-communications protocols are tested.

- **Hydrogen Gas-Measuring Devices:** CCR Title 4, Division 9, Chapter 1 – Revised Section 3.39, NIST Handbook 44 – This code establishes specifications for hydrogen dispensing devices, including measurement units, flow rates, and accuracy tolerances [66].
- **Hydrogen Fuel Advertising and Labeling Requirements:** NIST Handbook 130 Chapter 13 and Chapter 5 of the California Business and Professions Code – The California codes specify requirements for signage, displayed pricing information, and other labeling, including delivery pressure [64].

<u>For Charging,</u>

- **Electric Vehicle Fueling Systems:** Title 4, CCR, which includes the revised Section 3.40 of Handbook 44, specifies measuring units, temperature limits, accuracy tolerances, and voltage. In California, EVSE need to be certified by the CTEP that they adhere to these requirements.
- **Electric Vehicle Supply Equipment Labeling, Payment, and Reporting Requirements:** Under California's 2020 Electric Vehicle Supply Equipment Standards regulation, the State established EVSE requirements for labeling, payment, roaming agreements, and reporting, which were further updated in SB 123 to harmonize with federal requirements [17]. The EVSE Standards regulation updated Title 13, CCR.

Besides codes and standards that are required for all projects, public funding programs may have additional codes, standards, and reporting requirements that awardees must follow as a condition of funding. Through funding solicitations, the State can also signal future standards support by referencing technical reports and standards in development. For example, Table 5 provides a list of codes and standards for the 2022-2023 MD/HD-ZEV hydrogen fueling funding under the infrastructure incentive funding program, EnergIIZE. Highlighted are the referenced standards that are in development (orange) and being revised for HD applications (yellow).

In general, additional requirements are designed to facilitate broader coordination regarding technology standardization and interoperability. In that manner, public funding can shape the technologies and standards that are used in the market. In addition, funding programs can set benchmarks and performance thresholds which can drive industry priorities. For example, the National Electric Vehicle Infrastructure (NEVI) Formula Program proposes a minimum uptime of at least 97% for chargers, where uptime is a function of outage hours excluding outages caused by third-party interruptions (i.e., outages due to network service providers, utility providers, and vehicle-side disruptions.) [67]. This new requirement could provide similar data to those currently reported by hydrogen fueling stations through the Station Operational Status System (SOSS).

Table 5. Hydrogen Infrastructure Codes and Standards Guidance for California's EnergIIZE Funding Program

Standards Organization/Entity	Category	Standard or Code	Status
SAE International Standards	**Fueling protocol** - One or more of the listed fueling protocols or equivalent standard	J2601 – 1 Category D (greater than 10 kg tank sizes)	Revised (2020); under review
		J2601 – 2 HD fueling	Stabilized (2023)
		J2601 – 4 Ambient Temperature refueling	**WIP**
		J2601 – 5 MC Method for HD fueling	**WIP**
		JPEC-S 0003 Japanese Bus fueling protocol	Published
	Nozzle hardware	J2600 or an equivalently accepted industry standard, e.g., ISO 172	Revised (2015); ISO 17268 under review
	Fuel quality	J2719 – hydrogen fuel quality for fuel cell vehicles	Revised (2020)
	Communications	Open retail hydrogen refueling station shall conform to the most recent version of SAE J2799, verified through the most recent version of CSA HGV 4.3. Or an equivalent standard	Revised (2019)
National Fire Protection Association (NFPA)	**Safety**	NFPA 2	Latest edition (2023)
American National Standards Institute (ANSI)	**Hydrogen storage**	Hydrogen Gas Vehicle (HGV) 2-2021 Compressed hydrogen gas vehicle fuel containers	Old version; Revised (2023)
		HPRD 1:21 Thermally activated pressure relief devices for compressed hydrogen vehicle (HGV) fuel containers	Revised (2021)
		CGA S1.1 Guides Cylinder Pressure Relief Device Selection and Sizing	Revised (2022)
	Fueling system	HGV 4.1 Hydrogen-dispensing systems	Revised (2020)
		HGV 3.1 Fuel system components for compressed hydrogen gas powered vehicles	Revised (2022)
	Safety	G 095A Guide to safety of hydrogen and hydrogen systems	Published (2017)
International Organization for Standardization (ISO) Standards	**Fueling system**	19880-3 Valves	Revised (2018); Under review
		19880-4 Compressors	**Proposed**
		19880-5 Dispenser hoses and hose assemblies	Revised (2019); Under review
		19880-6 Fittings	Deleted (2023)
California Code of Regulations	**Building Codes**	California Building Code, Part 2, Title 24	Revised (2022)
		California Electrical Code, Part 3, Title 24	Revised (2022)
		California Energy Code, Part 6, Title 24	Revised (2022)
		California Fire Code, Part 9, Title 24	Revised (2022)
CA Department of Food and Agriculture, Division of Measurement Standards (DMS)	**Testing**	Handbook 44 Section 3.34 Cryogenic Liquid-Measuring Devices	Latest Edition (2023)
		Handbook 44 Section 3.39 Hydrogen Gas Measuring Devices	Latest Edition (2023)
		NIST Handbook 130 Uniform laws and regulations in the areas of legal metrology and fuel quality	Latest Edition (2023)

3. Assessment Methodology

For this study, standards are identified and evaluated based on their function and suitability for MD/HD-ZEV infrastructure deployment. The following criteria were developed to characterize standards:

- **Standards Scope:** Hardware, energy transfer, communications, network and cybersecurity, physical interfaces, and testing protocols,
- **Status:** Mature, update pending, standard in development, technical report, or specification in development,
- **Market Location(s):** North America, Asia, Europe, etc.,
- **Current Vehicle Market:** LDV, MDV, HDV,
- **Market Penetration:** Widely adopted, shared market, recently released, or in development, and
- **Suitability for Medium- and Heavy-Duty Vehicle Applications:** identification of applications that are best suited to utilize standards, if applicable. The following categories are also applied:
    - *Not Suitable:* No specific MD/HD applications are currently considering the use of the standard,
    - *Low suitability:* Very limited applications could use standard,
    - *Moderate Suitability:* Select use currently considered, broader adoption possible with the standard as written, depending on market interest,
    - *Moderate Suitability, requires revision*: potential use of the standard is possible for MD/HD applications, if it is updated to add or expand MD/HD considerations, and
    - *High Suitability:* Suitable for most or all MD/HD ZEV applications, any caveats are discussed.

Figure 4 and Figure 5 illustrate the types of codes and standards that are within scope of the current analysis.

Figure 4. Types of BEV Charging Codes and Standards within Scope

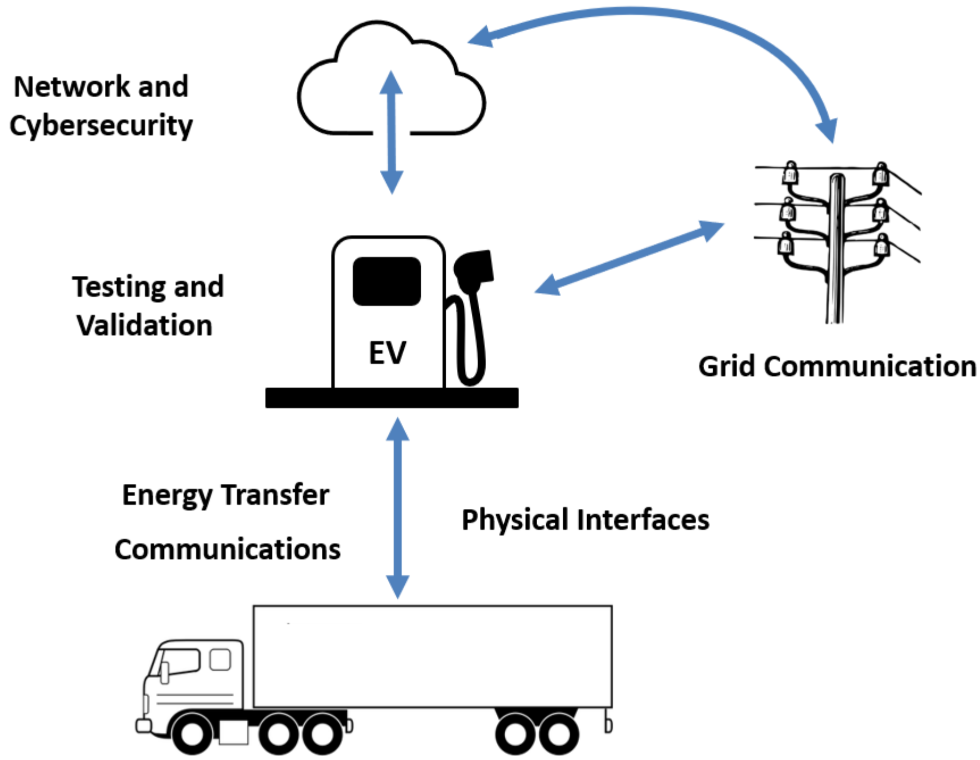
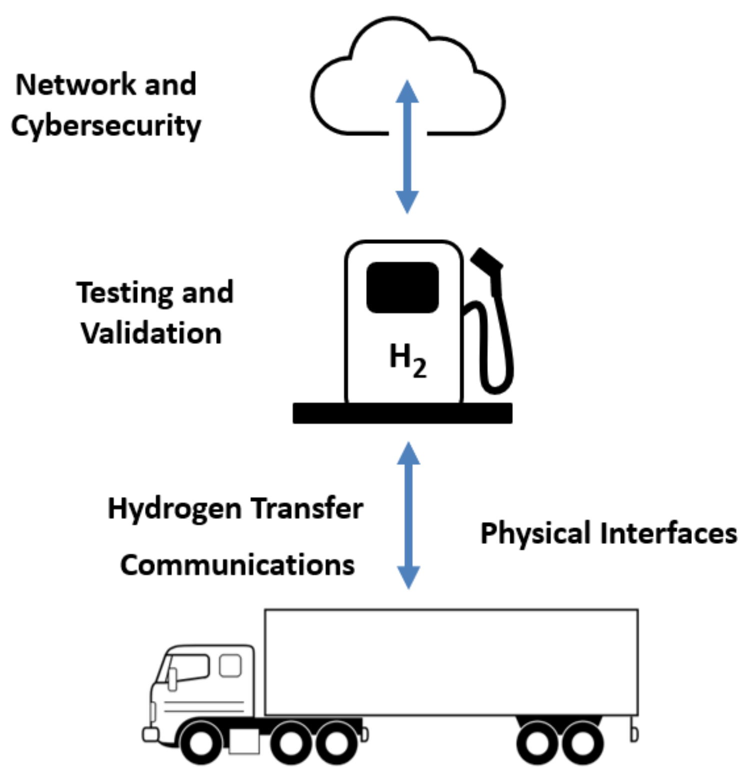


Figure 5. Types of FCEV Hydrogen Fueling Codes and Standards within Scope



The standards assessment encompasses standards for physical interfaces and energy transfer, as well as standards covering communications, safety, security, and testing. These standards categories are parameterized as follows:

- **Physical interface standards:** protocols that establish the physical and electrical connections between the vehicle and the station for energy and data transfers.
- **Energy transfer standards:** protocols that define the process of transferring energy, either electricity or hydrogen, between the station and the vehicle. Parameters include operating temperatures, voltage and current ranges, related communication requirements, and safety guidelines.
- **Communications standards:** protocols for data transfer between the station and vehicle, station and network, or between networks. Standards specify message types, data formats, methods of transfer, session timing, and error handling.
- **Safety standards:** standards related to the design and operation of equipment to minimize environmental and human health risks and hazards, such as fire and electrocution.
- **Security standards:** protocols that specify data protection and encryption protocols to ensure secure data transfer and prevent tampering.
- **Testing standards:** protocols for verifying that the equipment adheres to established standards. These standards include but are not limited to tests for safety, performance, communications, and reliability.

Standards may encompass multiple categories and are often intended to be used in conjunction with other standards.

In order to assess the suitability for MD/HD-ZEV applications, a gap analysis was conducted. The gap analysis identified technology and protocol gaps that may need to be addressed in order for ZEV technologies to satisfy MD/HD vehicle applications broadly (Note, key MD/HD considerations are summarized in Appendix B). For each gap identified, the following information was determined:

- **Gap Description:** Overview of the issue that needs to be addressed.
- **Type of Gap:** Standards, codes, technology, implementation, and policy.
- **MD/HD-ZEV Impact:** Implications of not addressing the current gap on MD/HD-ZEV deployment.
- **Recent Activities:** Description of relevant activities being conducted by stakeholders, government entities, and/or standard organizations that can contribute to MD/HD infrastructure standardization.
- **Goal:** Functionality achieved if gap is addressed.

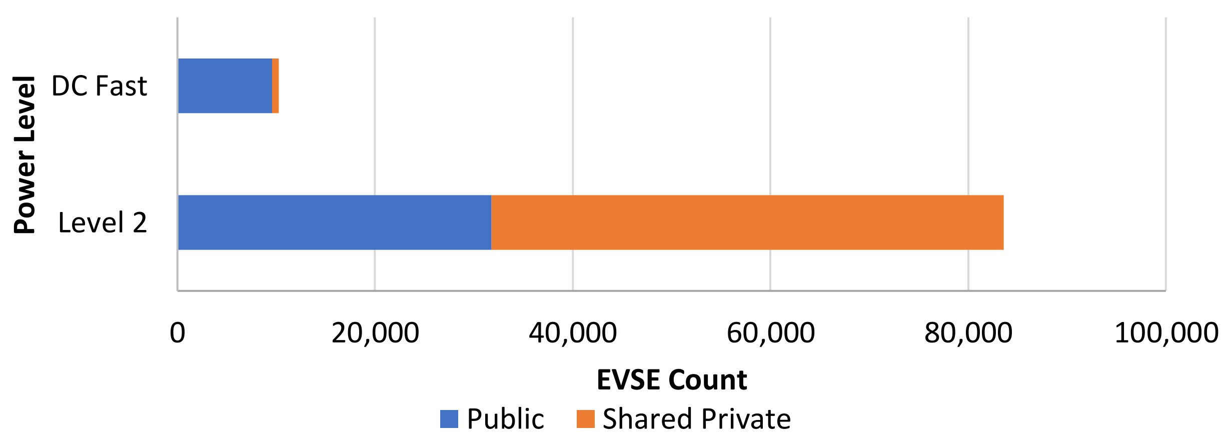
4. Battery Electric Vehicle Charging Codes and Standards

An expansive list of codes and standards are related to the development and operation of battery electric vehicles and charging stations. For this study, the focus is directed to those standards related to the charging of medium- and heavy-duty battery electric vehicles (MD/HD-BEVs) as well related to communications between electric vehicle supply equipment (EVSE) and the charging network.

4.1 Battery Electric Vehicle Charging Market Status and Goals for Medium- and Heavy-Duty Vehicles

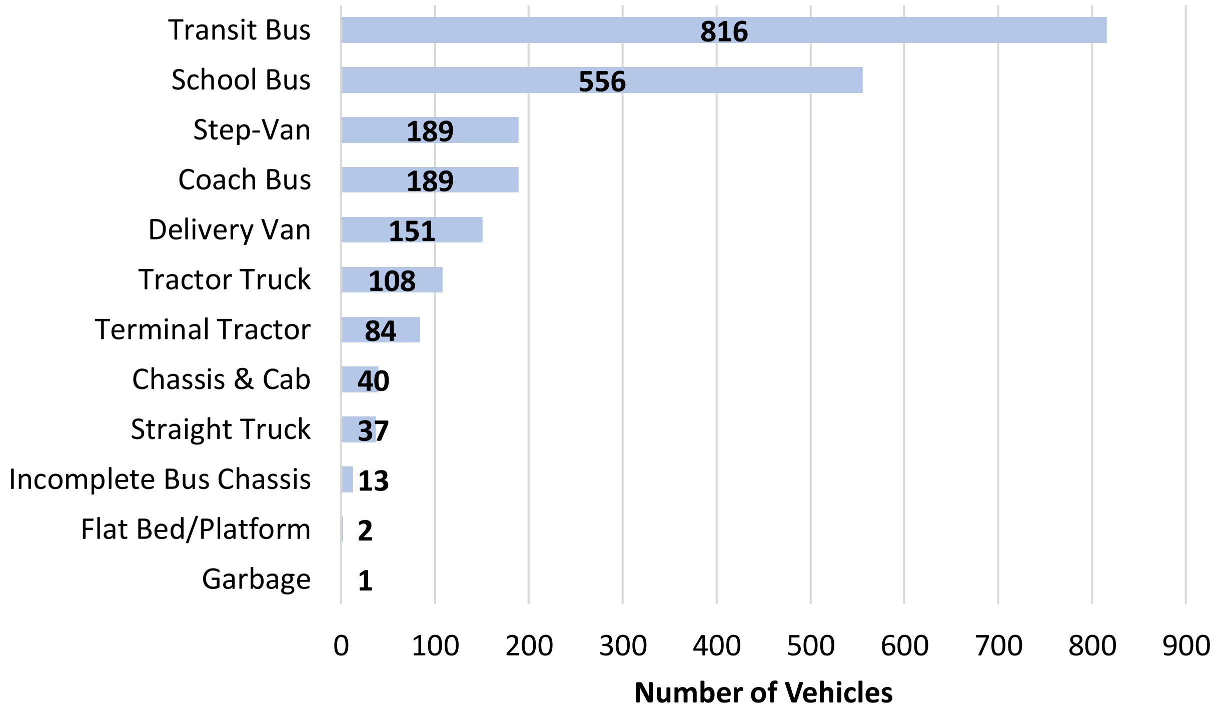
The LD BEV market has accelerated in recent years with over 1.3 million LD BEV sales on the road in California as of 2023 and over 93 thousand public and shared private chargers, see Figure 6. In comparison, the MD/HD BEV population in California was slightly above two thousand as of 2023 [68]. Early markets for MD/HD-BEVs have focused on short-distance, relatively consistent duty cycles such as last-mile delivery and fixed-route transit [69], [70]. Figure 7 presents the current number of MD/HD-BEVs in California at the time of this report. Most MD/HD-ZEVs are buses, with transit buses making up the largest category and school buses representing the second largest type.

Figure 6. California Public and Shared Private EVSE by Charging Rate



Source: California Energy Commission (2024). Electric Vehicle Chargers in California. Data last updated 2023. Retrieved February 2, 2024, from https://www.energy.ca.gov/zevstats

Figure 7. Current California Medium- and Heavy-Duty Battery Electric Vehicle Deployment by Type



Data from California Energy Commission (2023). Medium- and Heavy-Duty ZEV Population in California. Data as of Q4 2022. https://www.energy.ca.gov/data-reports/energy-almanac/zero-emission-vehicle-and-infrastructure-statistics/medium-and-heavy

Early adopters of MD/HD-BEVs can provide significant insight into early challenges and successes, as well as best practices moving forward. For example, in transit deployments, agencies deploying battery electric buses have prioritized deploying them on shorter routes with ready access to charging [69], [71]–[73]. A report from the Electrification Coalition determined that existing electrical infrastructure must be upgraded, more technicians for vehicles and charging and fueling infrastructure are needed, and the current supply of MD/HD-ZEVs is too low, despite high pre-order counts [74]. In addition, multiple studies have found that there is a need for increased reliability and standardization of charging technologies to address interoperability issues [69], [75], [76] New and updated standards are also needed to standardize high power systems and ensure their safe deployment [77].

Looking forward, CALSTART has projected that the MD/HD-ZEV marketplace will grow to include new vehicle types over time as ZEV technologies mature and supply chains expand. From this study's interviews, it was found that stakeholders are already deploying BEVs that range from class 3 to class 8. Therefore, BEV charging technologies and standards will need to evolve to meet the operational requirements of the full spectrum of MD/HDV applications.

Broad MD/HD charging station deployment will require standardized, reliable charging that is fast, safe, and secure. The light-duty charging network and early MD/HD charging deployments have experienced several challenges that will need to be resolved in order to sustain a MD/HD charging network. These challenges include low reliability and high technology heterogeneity. Reliability is being addressed through several strategies. For example, the light-duty market seems to be converging on the North American Charging Standard (NACS) in development, based on the Tesla proprietary charger. In addition, improved reliability requirements for light-duty publicly funded charging stations are emerging with compliance based on monitoring and reporting. Lastly, a broad, coordinated effort to increase interoperability testing and develop more systematic testing tools has been established. These approaches—a standardized charger, systematic testing, and monitoring—can be applied in the MD/HD space and support a highly reliable charging network.

The goal of fast BEV charging is to achieve operational parity to equivalent diesel vehicles, where feasible. The charging rate needed to achieve this parity for a given vehicle or fleet will depend on several factors, including vehicle class, operating hours, dwell times, and dwell locations [78], [79]. Heavier vehicle classes with long shifts will require higher charging rates compared to lighter vehicle classes that operate only a few hours a day. Vehicles that do not have a dedicated fleet facility to charge may rely on public high powered charging stations that can provide fast turnaround.

The goal of safe and secure MD/HD charging is accomplished through the adoption of codes and standards that minimize hazards and risks of injury from high power systems, as well as minimize risk for charging session disruption, tampering, and data insecurity. With higher powered systems that can provide power rates up to multiple MW, safety standards will need to be updated. This task is already underway by the relevant standards organizations, such as NFPA and UL. In addition, as the MD/HD charging market grows, security risks will need to be re-evaluated especially related to protected fleet data and vehicle-grid communications.

The following sections provide an overview of the status and suitability of codes and standards for MD/HD charging. Ongoing efforts and areas that need attention are examined. A summary of persisting gaps and suggested actions is provided at the end of this chapter.

4.2 Charging Hardware and Protocols

The two main categories of charging technologies are conductive and inductive (wireless). Conductive charging can be further classified by the type of current being used within the charger: alternating current (AC) and direct current (DC). Conductive charging is currently the dominant type of charging used globally for BEVs. However, interest in standards for wireless charging is growing, such as J2954-2 (HDVs) [80]–[82]. For conductive charging, the global market currently uses a mix of AC and DC standards for BEV charging, see Tables 6-8. Charging standards, such as J1772, describe the physical interface of the connector and the charging protocol(s). Connector diagrams and descriptions can be found in Appendix C.

AC charging is split into two power levels: Level 1 and Level 2 [83]. AC level 1 chargers typically deliver under 2 kW of power, in some cases about 3 kW depending on the standard voltage and current. In North America, AC level 1 charging uses 120V and up to 16A, or occasionally 24A. AC level 2 charging delivers up to 19.2 kW of power, with 240V and up to 80A. Three-phase AC charging can deliver higher power up to 166 kW, depending on the standard configuration described in SAE J3068.

DC charging is generally called Direct Current Fast Charging (DCFC). While no official power levels are defined for DC charging, those that are marketed to residential LDV charging provide power up to about 7 to 10 kW. Maximum power supply per charger for LDV public stations and commercial MD/HDV charging facilities range between 30 kW to 350 kW. The higher power levels are generally achieved by stacking several power modules (each subunit is usually capable of providing 30-50 kW charging power). Newer standards are expected to exceed the 350 kW mark.

Table 6. BEV Charging Hardware and Protocol Standards

Standard/ Proprietary Protocol	**Description**	**Status (Year of Update)**	**Market(s)**	**U.S. Market Penetration**	**MD/HD Suitability**
SAE J1772/ CCS	Plug-in AC and DC charging	Revised (2017)	North America	Shared market with Tesla	J1772: Low CCS: High
SAE J3068	Plug-in AC and DC charging	Revised (2022) RP	North America	Limited	Moderate
Tesla; SAE J3400	Plug-in AC and DC charging	SAE J3400: WIP (2023)	North America	Shared market with J1772/CCS	Moderate
CHAdeMO	Plug-in DC charging	Revised (2021)	Asia, Limited in Europe and North America	Phasing out in North America	Low
SAE J3105	Automated overhead DC charging	Revised (2023) Recommended practice	North America	Limited (Transit)	Moderate
SAE J2954-2	Static and dynamic wireless charging (MD/HDV)	Issued (2022) TIR	North America	Limited (Proprietary solutions)	Moderate
SAE J2954-3	Dynamic wireless charging for LD and HD	WIP (2023)	North America	Not deployed	Moderate
SAE J3271	Plug-in DC charging at the megawatt scale	WIP (2023)	North America	Not deployed	High

Table 7. Predominantly AC BEV Charging Connector Specifications

Current Standards								
Connector	GB/T 20234.2	IEC 60309	IEC 62196-2 (Type 2 - Mennekes)	IEC 62196-2 (Type 3 Scame)	SAE J1772 (Type 1)	SAE J3068	SAE J2954	SAE J2954-2 (Recommended Practice)
Current Type	AC	AC	AC*	AC	AC and DC	AC and DC	AC (Inductive)	AC (Inductive)
Power (kW)	14	10	Up to 33-43	Type 3A – 19.2 Type 3C – 43.6	AC: Up to 19.2 DC: Level 1- 80 Level 2 – 400	Up to 133-166	3.7, 7.7, 11, & 22	Up to 500
Voltage (V)	250/440	230	400/480 3/1ϕ	Type 3A – 230/240 Type 3C – 400	120/240 1ϕ, 208 3ϕ DC: 1000 maximum	480/600	N/A	N/A
Current (A)	16/32 (Rated 63)	15	63/70 3/1ϕ (Rated 300)	Type 3A – 32 1ϕ Type 3C – 63 3ϕ	AC: Up to 16 DC: Up to 80	160 3ϕ (Rated 300)	N/A	N/A
V2X				✓	WIP	✓		
Markets	China	India	Europe	Europe (Now Deprecated)	North America, Japan	North America	North America	North America

✓ Vehicle-to-Grid Capable
*DC power transfer mode only implemented in Europe at Tesla Supercharger stations.

Table 8. Predominantly DC BEV Charging Connector Specifications and Standards in Development

	Current Standards							In Development	
Connector	CHAdeMO	GB/T 20234.3	CCS1	CCS2	Tesla (Proprietary, See SAE J3400)	SAE J3105 (Recommended Practice)	ChaoJi (CHAdeMO 3.0)	SAE J3271 (MCS)	SAE J3400 North American Charging Standard (NACS)
Current Type	DC	DC	DC*	DC*	AC and DC	DC	DC	DC	AC and DC
Power (kW)	6 – 400	187.5	Up to 350, Planned 450	Up to 350, Planned 450	AC: up to 19.2 DC: 250, 350 Planned	Level 1: 350 kW Level 2: 1.2 MW	50-900 kW (Expandable)	Up to 4.5 MW	AC: up to 19.2 DC: 250, 350 Planned
Voltage (V)	1000	750	920, Planned 1000	920, Planned 1000	AC: 240 DC: 1000	Up to 1000	1500	1500	AC: 240 DC: 1000
Current (A)	400	250	380 (Rated 500)	380 (Rated 500)	AC: 80A DC: 250, 350 Planned	Up to 1200	600	3,000	AC: 80A DC: 250, 350 Planned
V2X	✓		✓	WIP			✓	WIP	
Markets	Japan, Sporadic	China	North America	Europe	North America	North America, Europe	China, Japan	North America, Europe	North America

✓Vehicle-to-Grid Capable, WIP = Work in Progress, MCS = Megawatt Charging System

* CCS1 and CCS2 ports accept Type 1 and 2 AC chargers, respectively.

Note: NACS, which is a standard modeled after the Tesla proprietary hardware, is in development

Countries worldwide use different standard voltages and currents, causing the supply of power to BEV chargers to be significantly different between regions. These differences are one of the many factors contributing to the wide variety of BEV charging standards. SAE J1772, CHAdeMO, Tesla, and CCS1 are prominent in North America while IEC 62196 Type 2 and CCS2 are the dominant standards in Europe. Japan uses CHAdeMO and J1772 while China uses its own standards for electric vehicle charging. In North America, the SAE J3068 standard was developed for the region but has limited adoption in the marketplace. The SAE J3105 standard for bus charging is used for on-route charging applications across North America and Europe as well. The CHAdeMO standard is being phased out slowly for newer technologies in most markets, excluding Japan.

In most cases, DC charging options support a greater power output than AC charging as they supply power at higher voltage and current. The trade-off is that they tend to be more expensive. The onboard energy storage system on all electric vehicles uses direct current, so alternating current chargers require onboard converters—(1) AC/DC and (2) DC/DC—within the vehicle to convert the power to direct current [83]–[85]. A DC charging station consists of multiple components: an AC/DC converter, a power control unit, and a DC/DC converter. DC chargers place the AC/DC converter outside the vehicle because the high-power output requires a larger and heavier converter, too large and heavy to be placed in a vehicle efficiently [83]–[85]. For a DC charging station, the power control unit regulates voltage and current through a DC/DC converter to provide electricity to the vehicle [84].

Charging standards have changed over time to reflect improvements in technology development and lessons learned, see Figure 8 and Figure 9.

Figure 8. Inductive and Wireless Charging Standards Evolution

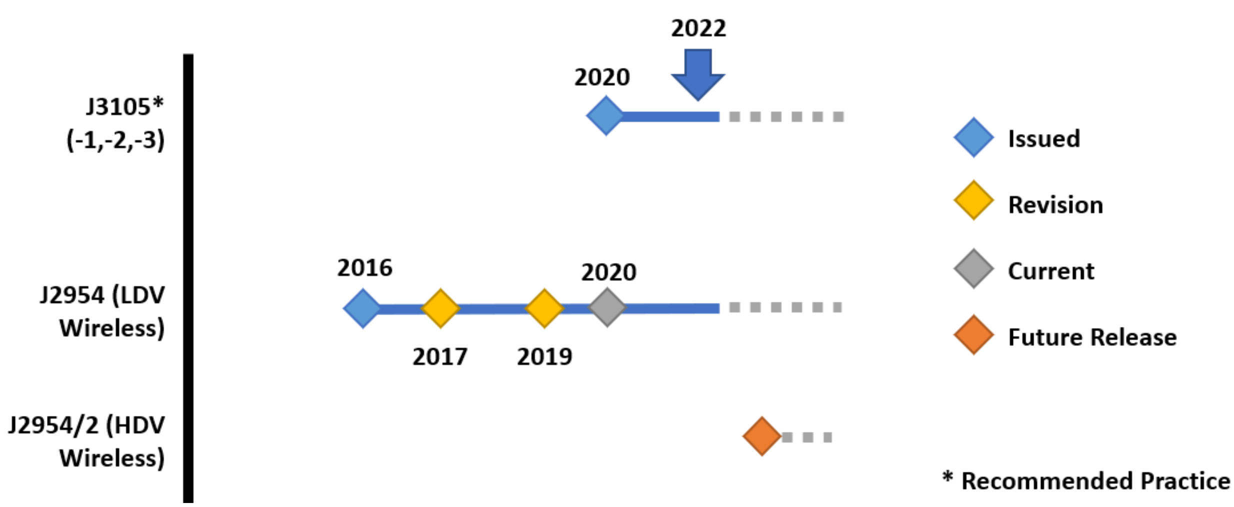
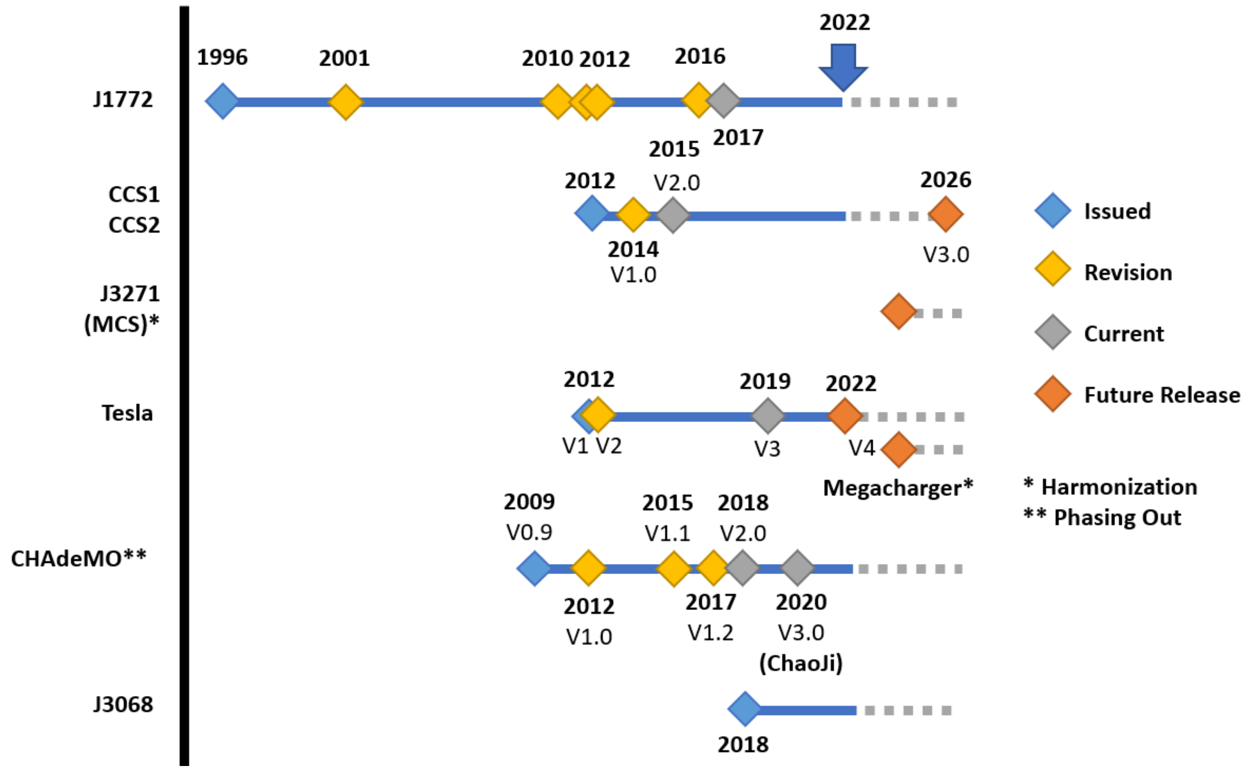


Figure 9. Conductive (Plug-In) Charging Standards Evolution

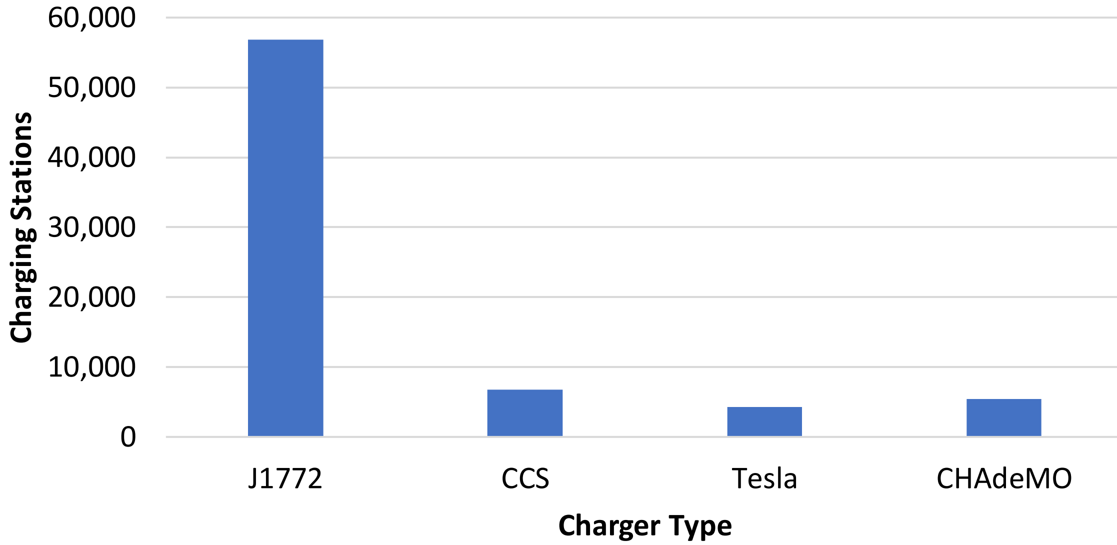


As BEVs with larger battery capacities have entered the market, charging systems have also been adapted in order to increase power levels to minimize charge times. Currently, standardization organizations are working to increase the maximum power of existing standards and develop new, high-powered DC charging standards. For example, CCS power levels have increased from 100 kW to 350 kW, and now 450 kW is proposed [85], [86].

Of the 4.3 million BEVs globally, approximately 40% of BEVs have the GB/T connector option, 19% have Tesla, 15% have CHAdeMO, 17% have either CCS 1 or CCS 2, 4% is higher power AC charging (e.g., J3068, IEC 62196-2), and 5% is other/unknown [87]. The vast majority of these vehicles are LD-BEVs. As of 2023, several vehicle OEMs have announced that they will be adopting the planned Tesla NACS charging system.

Figure 10 presents the distribution of connector types within the U.S., including level 1-2 AC charging and DC charging. As the figure shows, the U.S. does not use the GB/T and CCS 2 connectors. The most common type of EVSE is the J1772 connector that provides AC level 2 charging.

Figure 10. U.S. Market Share of EVSE at Charging Stations by Connector Type



Data Extracted from US DOE Alternative Fueling Station Locator Feb 2, 2024. * Some stations offer more than one connector type and are counted multiple times.

4.2.1 Charging Protocols in Current Medium- and Heavy-Duty Markets

Most chargers in the U.S. were first developed to support light-duty applications and have been adapted for MD/HDV use cases, see Table 9. Diagrams of the charger plugs are provided in Appendix A. SAE International established a Task Force to develop a charger standard that focused on MD/HD applications. Some charging standards that have emerged for MD/HD applications include SAE J3068 and J3105, which is currently implemented for buses and can be directly applied to other MD/HDV use cases in the future, if desired [88].

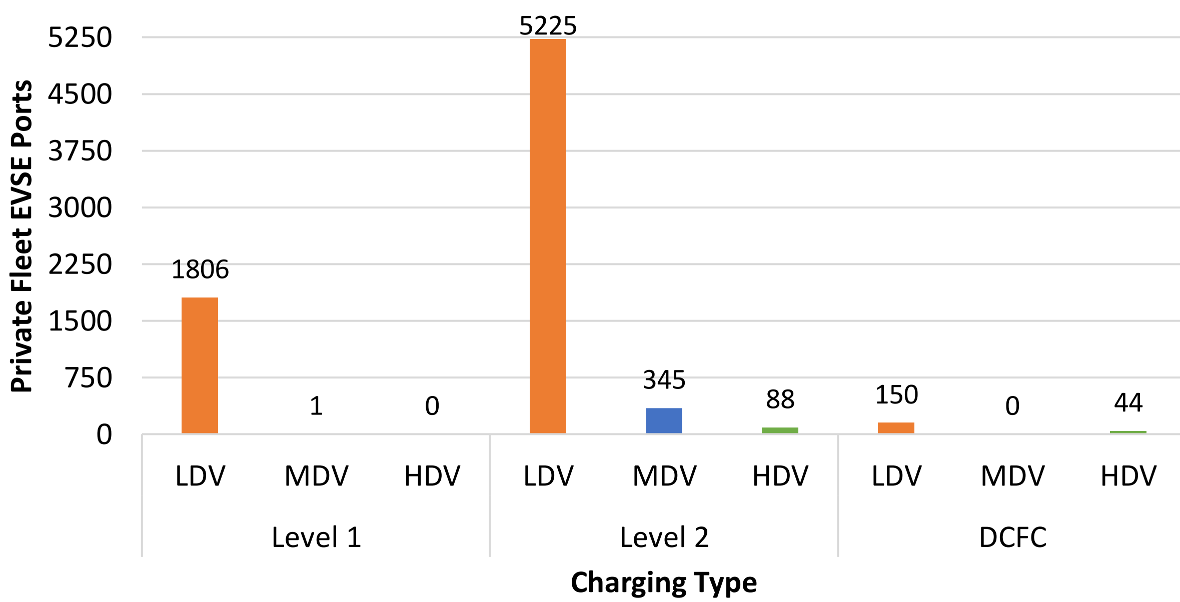
Figure 11 presents the current distribution of charger types (AC level 1, AC level 2, and DCFC) for fleets in the U.S. [89]. AC level 2 charging has been demonstrated to meet the BEV charging demands for some early MD/HD-ZEV use cases, such as last mile delivery. A fleet's selection between charging standards—in particular, between AC level 2 (J1772) and DCFC (CCS1)—is dependent on fleet operations and cost constraints. DCFC tends to be significantly more expensive, so if AC level 2 charging is sufficient for the fleet's needs, it is the preferred EVSE. J3068 is a more recent charging standard (2018) compared to J1772 and CCS1, and has some benefits compared to the two other standards. In general, J3068 can provide higher charging rates compared to J1772 and cost less than DCFC [90]. However, adding a J3068 charging option in public charging may increase market heterogeneity and silo utilization of public infrastructure.

Table 9. Current U.S. Vehicle Markets for Charging Connectors

	Vehicle Category				
Connector Type	**Light-Duty**	**Bus**	**Class 3-5 Trucks**	**Class 6-7 Trucks**	**Class 8 Trucks**
Current					
J1772/CCS	✓	✓	✓	✓	✓
J3068		✓	✓	✓	✓
Tesla (SAE J3400)	✓				*
CHAdeMO	^	^	^		
J3105		✓	*	*	*
J2954 (LDV Wireless)	+*				
J2954-2 (HDV Wireless)		*	+*	+*	+*
In Development					
J3271 (MCS)		*	*	*	*

^Phasing Out
*Potential Future Market
+Recently Released

Figure 11. 2022 Q1 U.S. Private Fleet Charging by EVSE Port Type



Source: Brown et al. National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy22osti/82987.pdf

There are three main technologies high power charging technologies that are undergoing standardization: MCS, ChaoJi, and wireless charging (J2954-2 and J2954-3). MCS and ChaoJi are both standards planned for conductive DC high powered charging. In the case of the MCS, it is planned to deliver 1500V and 3000A for 4.5 MW, while ChaoJi is said to be capable of delivering

1500V and 600A for 900 kW. MCS is planned to roll out in North America and Europe while the ChaoJi system will be implemented in China and Japan. The wireless charging recommended practice for heavy-duty applications is currently considered for power levels up to 500 kW with the potential for future iterations to consider higher levels [1].

The ChaoJi design was released under CHAdeMO 3.0 in 2020, with a maximum power rate of 500 kW. The expectation is that further updates will increase the maximum charging rate to 900 kW, possibly 1.8 MW [87], [91]. The new design is harmonized with previous CHAdeMO designs and GB/T, and it is envisioned as the ultimate DC fasting charging for China and Japan, possibly beyond.

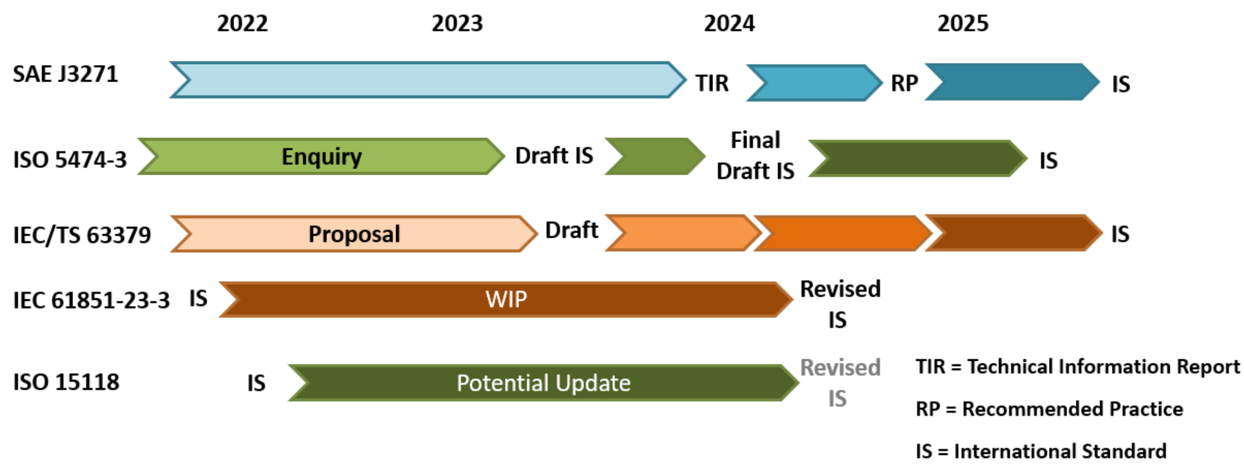
The initial market for MCS is expected to be MD/HDV applications, but CharIN has stated that it is intended to serve as a universal plug for anything that “rolls, flies, or floats,” signaling its applicability for off-road transportation [92]. MCS is currently a WIP within SAE under J3271 and its contents are being coordinated with the CharIN industry consortium [93], [94]. It is anticipated that MCS will adopt the ISO 15118 standard with the intention of enabling V2X capabilities. The current focus on the SAE J3271 megawatt charging committee is to publish a TIR. The TIR is anticipated to include documentation on couplers/inlets, cables, communication (EV-EVSE-Grid), and interoperability/testing [93]. To achieve the full capabilities of a megawatt charging system, several standards are being updated and/or created, as listed in Table 10. The timeline for standards development is outlined in Figure 12, with the SAE J3271 standard anticipated for 2025.

Table 10. Status of Standards Related to Megawatt Charging Systems

Standard	Description	Status	Anticipated Future Publication
SAE J3271	Plug-in DC charging at the megawatt scale	WIP (2023)	TIR anticipated early 2024, RP in 2024
ISO 5474-3	Safety and functional requirements for power transfer	Draft International Standard (DIS) (2022)	Final DIS to be published 2024
IEC/TS 63379	Plugs, socket-outlets, vehicle connectors, and vehicle inlets	Committee Draft (CD) (2023)	Standard to be published Dec. 2025
IEC 61851-23-3	Electric vehicle supply equipment for Megawatt charging systems	CD (2023)	Standard to be published Dec. 2024
ISO 15118	Bi-directional communication between the vehicle and the charging station (AC or DC)	Published: -1 (2019), -2 (2014)*, -20 (2022) Confirmed: -3 (2020), -4 (2023), -5 (2023)	Revision possible
UL 2202	DC charging equipment for electric vehicles	Edition 3 Approved (2022)*	Revision for MCS underway
UL 2251	Testing for plugs, receptacles, and couplers for electric vehicles	Edition 4 Revised (2022)*	Revision for MCS underway

*Revision in development

Figure 12. Megawatt Charging Standards Roadmap



Timelines are estimates.
Source: Argonne National Laboratory, U.S. Department of Energy

Standards for wireless power transfer (WPT) for heavy-duty applications are also in development. J2954-2 [1] is the MD/HDV expansion of J2954, which was released in 2016 and most recently updated in 2020 [95]. The J2954-2 standard will account for differences between LDV and MD/HDV charging requirements including vehicle geometry, vehicle suspension systems, vehicle electrical considerations (voltage, phase, power levels – potentially, between 50-500 kW) [96]. SAE J2954-2 is currently a TIR. The heavy-duty TIR covers static and dynamic wireless charging, i.e., charging while the vehicle is stationary and while driving, respectively, for a range of charging rates between 20 and 500 kW [97].

With the deployment of high-powered charging solutions, automated charging strategies are becoming increasingly of interest. Automated charging can reduce safety risks and streamline the charging process. Current standards that incorporate automatic charging approaches include SAE J2954-2 and SAE J3105. ISO 15118-20 provides communication specifications for automated charging. See Section 4.3 for more information. It is anticipated that SAE J3271 will consider automated charging use cases, leveraging ISO 15118-20. It is uncertain whether ISO 15118-20 will need additional revisions to accommodate MCS. An alternative to higher power charging is battery swapping, where vehicles can exchange their depleted batteries for fully charged batteries. There are no standards on battery swapping, but there is one publicly available specification, IEC PAS 62840 (-1,-2,-3):2021 that provides specifications to inform physical layers, safety, power transfer, etc. [98]. China has deployed over 700 battery swapping stations for light-duty vehicles, and Norway is testing the same technology [99]. Wu (2022) found that current limitations for battery swapping stations include:

- Limited station capacity — surveyed LDV battery swapping stations were designed to service one vehicle at a time with each swap taking approximately five minutes.

- Battery heterogeneity — even for the same vehicle model and year, there may be multiple battery capacity options. If the station is designed to service multiple vehicle makes and models, it will need to carry all the appropriate batteries [100].

As of 2023, there is limited interest in developing a public battery swapping network in California, mostly start-up led projects in the Bay Area. However, should these initial projects spur expanded interest, the State should consider to what extent standards could support accessibility, safety, and reliability of these types of stations.

4.2.2 Standardization Mandates

In 2010, the European Union mandated the standardization of chargers for plug-in electric vehicles, directing the E.U.'s standards organizations CEN, CENELEC and ETSI to identify the standards (existing or future) to be implemented in the European market [42]. In 2014, the DIRECTIVE 2014/94/EU selected Mennekes Type 2 for level 2 charging and CCS 2 for DCFC, with allowances for pre-existing infrastructure and the possibility of any solutions compatible with the selected standards [101]. The resulting legislation within E.U. member states has led to Tesla implementing DC Type 2 and CCS2 standards within their European charging network [102].

Historically, the U.S. did not limit the charging standards that can be utilized in public and private EVCS for light-duty vehicles. Instead, the market has driven which connectors are most widely used. This has led to a more heterogeneous market, as was shown in Section 4.2.1. Adapters have been developed to support charging compatibility between some charger types. Examples include Tesla's adapters for National Electrical Manufacturers Association (NEMA), CCS, and CHAdeMO [103]. There is no adapter between CHAdeMO and CCS.

Recently, federal and state governments have opted to be more prescriptive in the standards required for public stations. The NEVI Formula program has established several codes and standards requirements, including charging protocols. In California, the California Public Utility Commission under Rulemaking 18-12-006 approved a submetering protocol that requires all ratepayer-funded EVSE for LDVs to follow the following standards by July 2023: AC-conductive EVSE use SAE J1772, DC-conductive use CCS, all are capable of operating OCA OCPP 1.6 or later, and all are ISO 15118 ready (i.e., have the required hardware such as powerline carrier, secure data management, remote connectivity capabilities). It further clarifies that these requirements do not apply to MD/HD BEVs as they are in an earlier developmental phase than LDVs [104]. The California Energy Commission's charger rebate programs have the same requirements [105].

Based on the current status of charging hardware and protocols, the following gaps were identified: new standards for high powered charging up to the multi-megawatt scale and new standards for wireless and other automated charging technologies. A significant amount of research is being conducted to develop the technologies to support MCS. The hardware and protocols for MCS are in development, with protypes being tested now and standardized options being available within the next few years. With the release of standards for high powered charging, vehicle OEMs will need to consider the subsequent requirements on the vehicle-side to support charging up to the multi-megawatt level.

4.3 Communications

Communications are required between the EV and EVSE, and between the EVSE and the charging network and/or the electric grid, see Figure 13. EV-EVSE communication is required to manage energy flow to the vehicle. Network communication can be required for payment, load management, management of membership permissions in the case of a membership-based EVSE network, and control of power discharge in the case of vehicle-to-grid (V2G) services. A summary of standards related to charging communications is presented in Table 11.

Figure 13. Overview of Protocols Covering EV-EVSE-Network Communications

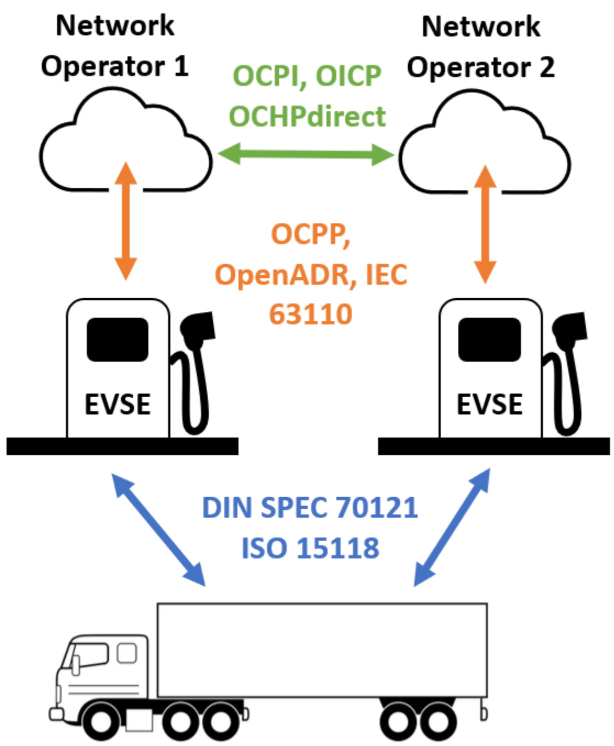


Table 11. Communication Standards and Protocols

Standard/ Protocol	Description	Status (Year of Update)	Market(s)	U.S. Market Penetration	MD/HD Suitability
DIN SPEC 70121	Bi-directional digital communication between the vehicle and DC charger	Issued (2014)	North America	Shared market with ISO 15118 for DC	Moderate
ISO 15118	Bi-directional communication between the vehicle and the charging station (AC or DC); includes more features compared to DIN SPEC 70121, such as plug-and-charge	Published: -1 (2019), -2 (2014), -20 (2022) Confirmed: -3 (2020), -4 (2023), -5 (2023)	North America, Europe, Asia	Widely adopted (AC and DC)	High
SAE J2847-2	Communication between vehicle and DC charger	Revised (2023), RP	North America	Limited to J1772	Low
SAE J2894	Power quality	Revised (2015), RP	North America	Widely adopted	High
IEC 63110	Charging and discharging architectures, protocol specifications, and requirements	Published (2022)	Europe, North America	Shared market with OCPP	High
Open Charge Point Interface (OCPI)	Communication between different network operators	Version 2.2.1 Released (2021)	Europe, North America	Shared with proprietary solutions	High
Open Charge Point Protocol OCPP	Communication between the EVSE and the network	Versions 2.0.1 Released (2020)	Asia, Europe, North America, South America	Shared with proprietary solutions	High
Open Automated Demand Response (OpenADR)	Demand response protocol	Version 3.0 Released (2023)	Asia, Europe, North America	Shared with proprietary solutions	High

4.3.1 EV-EVSE Communications

Two main methods are employed for wired digital communications between the EV and EVSE: Power-Line Communication (PLC) and Controller Area Network (CAN) bus. Less common methods are Local Interconnect Network (LIN) and analog. J1772 and CCS1 rely on PLC, CHAdeMO relies on CAN, and J3068 relies on LIN [83], [91]. J1772 also supports basic, non-digital charging communication for AC charging, where the EVSE communicates to the vehicle using an analog pulse width modulation (PWM) signal.[4] Communication signals are sent across

[4] Other relevant communications standards include those referenced in SAE J1772; IEC 61851-1: Electric Vehicle Conductive Charging System; SAE J2847/2: Communication Between Plug-in Vehicles and Off-Board DC Chargers, SAE J2931/1 & 4: PLC Communication for Plug-in Electric Vehicles, and SAE J2953: Plug-In Electric Vehicle (PEV) Interoperability with Electric Vehicle Supply Equipment (EVSE).

two pins: the proximity pilot (AKA Plug Present: PP) and the control pilot (CP) pin. The PP pin detects when the charger latch is engaged (signaling connecting/disconnecting the charger and the vehicle). In IEC 62196, which specifics the Type 2 connector, as well as CCS 1 and CCS 2, the PP pin also sets cable current limits [106], [107]. The CP pin controls the EVSE charge to the vehicle and communicates the station status. The charger sends a pilot signal through the CP pin to inform the vehicle of the station status. The possible station states are defined within the standard and are listed in Table 12. The pilot signal voltage denotes the station status, and the percentage of the signal that is positive determines the amps the vehicle is allowed to charge [108].

Table 12. Station States Communicated through the CP Signal (J1772)

State	Station Status	EVSE Ready	EV Ready
A	Vehicle Not Connected	N/A	N/A
B1	Vehicle Connected	No	No
B2	Vehicle Connected	Yes	No
C	Vehicle Connected, ventilation not needed	Yes	Yes
D	Vehicle Connected, ventilation needed	Yes	Yes
E	Disconnection (signal from PP)	N/A	N/A
F	Other EVSE problem (fault in device)	N/A	N/A

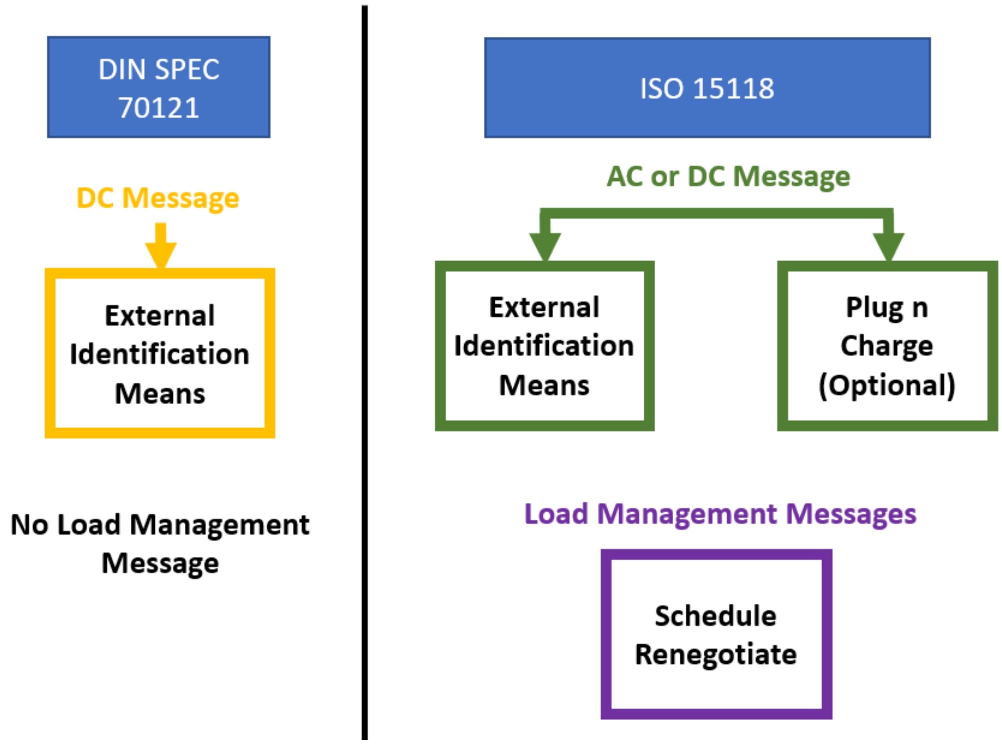
The most common communication standards used with CCS are DIN SPEC 70121 and ISO 15118. First published in 2012 and revised in 2014, DIN SPEC 70121 details the communication for DC charging between an EV and an EVSE. DIN SPEC 70121 was a precursor to ISO 15118, and as such, is simpler and has fewer use cases and cybersecurity provisions compared to ISO 15118, see Figure 14. Some of the functions that are included in ISO 15118 but are not in DIN 70121 are: (1) scheduled charging based on grid signals such as electricity cost, (2) plug and charge (covered in Section 5.2.3), and (3) secure communication methods including transport layer security (TLS) encryption [46], [109].

The ISO 15118 series consists of nine documents and covers both AC and DC charging:

- ISO 15118-1: General information and use-case definition
- ISO 15118-2: Network and application protocol requirements
- ISO 15118-3: Physical and data link layer requirements
- ISO 15118-4: Network and application protocol conformance test
- ISO 15118-5: Physical layer and data link layer conformance test
- ISO 15118-6: General information and use-case definition for wireless communication
- ISO 15118-7: Network and application protocol requirements for wireless communication
- ISO 15118-8: Physical layer and data link layer requirements for wireless communication
- ISO 15118-20: 2nd generation network layer and application layer requirements

Part 1 provides general definitions, Part 2 covers the application layer and communication messages requirements over the network to support energy transfer (conductive and wireless), Part 3 covers high-level communication, Parts 4 and 5 provide conformance testing information, Parts 6 through 8 cover wireless communication, and Part 20 serves as the second generation of ISO 15118-2, adding new and expanded features not covered in part 2. These features include bidirectional power transfer, conductive and wireless communication.

Figure 14. Comparison between DIN SPEC 70121 and ISO 15118-2



Adapted from data in DIN SPEC 70121 and ISO 15118

The general steps for charging communication are as follows:

1. Customer plugs in;
2. Vehicle cable signals the EVSE, which signals the network to start the transaction;
3. Identification of the vehicle is verified;
4. Network authorizes vehicle access;
5. Charge parameters for the session are established; and
6. Charging begins.

Initiation communication steps for using an EVSE can vary among different suppliers. Some EVSE have the customer initiate the payment before the charger plug-in step, whereas others have the steps reversed. It is common for a customer to pay by tapping an RFID chip (e.g., from a credit card or membership card) or near field communications (NFC) card for mobile payment. Note, in the case of public charging, chargers are required to include chip readers. In the case that smart charging or V2G is enabled, after Step 4, the network can provide charging profiles to the EVSE, which passes it through to the vehicle. The vehicle then determines the charging profile it will follow and sends it back through the EVSE to the network, which must approve the profile. Step 5 then begins [110].

4.3.2 Network Communication and Grid Interconnection

Requirements (and restrictions) to EVSE network communication with the electric grid are defined by codes and regulations established at the federal and state levels as well as at the utility level. In California, the relevant codes and standards include the National Electric Code section 625 that covers safety requirements specific to EVSE and charging; Electric Rule 21, which covers distributed energy resource interconnections; and several IEEE and SAE standards that cover communications, network architecture, and testing and certification, see Table 13.

Several open protocols are also used to control communications between the EVSE, the EVSE network, and the electric grid (illustrated in Figure 13). CARB has adopted several communication standards required for public stations, such as Open Charge Point Interface (OCPI), along with minimum test procedures under "California Open Charge Point Interface Interim Test Procedures for Networked Electric Vehicle Supply Equipment for Level 2 and Direct Current Fast Charge Classes." OCPI is a protocol that allows communication between different network operators, called "roaming" [111]. Open Charge Point Protocol (OCPP) is a protocol for communication between the EVSE and the network. It can be used to for smart charging control and supports interoperability between EVSE and networks [112]. Open Automated Demand Response (OpenADR) protocol is an open protocol for demand response. It can be used in conjunction with OCPP to enable secure control of connected vehicles as grid resources [113].

Table 13. Codes, Standards, and Open Protocols for Communications and Vehicle-Grid Integration

Standard/ Open Protocol	Description	Status (Year of Update)	Market(s)	U.S. Market Penetration	MD/HD Suitability
NFPA 70	National electric code: covers all EVSE and related devices as well as components on the station and vehicle sides. Refers to UL 2594 and UL 2202.	Revised (2023)	North America	Widely adopted	High
CPUC Electric Rule 21	Tariff covers interconnection rules between individual facilities and utilities. It excludes facilities participating in Federal Energy Regulatory Commission wholesale markets.	Revised (2020)	California	California, widely adopted	High
ISO 15118 series	Bi-directional communication between the vehicle and the charging station (AC or DC)	Published: -1 (2019), -2 (2014)*, -20 (2022) Confirmed: -3 (2020), -4 (2023), -5 (2023)	North America, Europe, Asia	Widely adopted (AC and DC)	High
SAE J3072	Grid interconnection requirements for an inverter-based system; configurations to allow vehicle discharge	Revised (2021)	North America	Widely adopted	Moderate, V2G applications
UL 1741	Safety tests for inverter-based devices, including those for V2G, for distributed generation	Edition 3 Revised (2023)	North America	Widely adopted	Moderate, referenced in UL 9741
UL 9741	Power export equipment for the discharge of an EV battery from the vehicle to the grid	Edition 1 Published (2023)	North America	Recently released	Moderate, V2G applications
SAE J2894	Specifies power quality requirements for maintaining power quality during discharge	Revised (2015)* Recommended practice	North America	Widely adopted	High
IEC 63110	Charging and discharging architectures, protocol specifications, and requirements	Published (2022)	Europe, North America	Shared market with OCPP	High
IEEE 1547	Interconnection standard used with SAE J3072 and IEEE 1547.1 (conformance testing)	Revised (2018)	Global	Widely adopted	Moderate, V2G applications
IEEE 2030.5	Internet communication protocol that allows utilities to communicate with DERs	Revised (2023)	Global	Widely adopted	Moderate, V2G applications
IEEE P2030.13	Utility interconnection for fast charging management	Draft Specification (2023)	Global	Widely adopted	High, MCS revision
IEEE 802 series	Physical and control specifications of various communication methods (e.g., wireless and ethernet)	Revised (2020)	Global	Widely adopted	High
OCPI	Communication between different network operators	Version 2.2.1 Released (2021)	Europe, North America	Shared with proprietary solutions	High
OCPP	Communication between the EVSE and the network	Versions 2.0.1 Released (2020)	Global	Shared with proprietary solutions	High
OpenADR	Demand response protocol	Version 3.0 Released (2023)	Asia, Europe, North America	Shared with proprietary solutions	High

*Revision in development

4.3.3 Payment Systems

For paid electric vehicle charging stations (EVCS), a payment method must be provided by the user to the EVSE, which then needs to complete the transaction through the network. Standards associated with payment systems are listed in Table 14. Payment approaches can vary, depending on the region and EVSE network. In the U.S., several major LDV EVSE networks are available, all with their own subscription plans and payment systems, along with their own apps to guide users to stations and communicate data such as charging status. This network design leads to unnecessary complexity and limits vehicle access and customer ease-of-use.

Table 14. Standards Related to Payment Systems

Standard	Scope
ISO/IEC 14443	Identification/Contactless/RFID Cards Standard
ISO/IEC 15961	Data protocol for radio frequency identification (RFID) for item management
ISO/IEC 15963	Information technology — Radio frequency identification for item management
ISO 15118	Plug and Charge
ISO/IEC 18000-3	Radio Frequency Identification for Item Management (Parameters for Air Interface Communications)
ISO/IEC 18046	Test Methods for RFID Performance

To address these issues, California passed SB 454, the Electric Vehicle Charging Stations Open Access Act (2013), which encompasses transparency and consumer choice requirements, including station location, pricing, and interoperable payment methods across networks. DC EVSE commissioned before January 1, 2022 and level 2 EVSE commissioned before July 1, 2023 are not subject to compliance until July 1, 2033. Minimum payment options for public EVCS under SB 454 are RFID chip readers for credit cards, EMV (Eurocard, Mastercard, and Visa) card readers, and NFC readers for mobile devices [11], [114]. The regulation further specifies additional security standards, including compliance with "Payment Card Industry Data Security Standard Level 1 (PCI-DSS Level 1)" [114]. PCI-DSS establishes data security requirements to ensure secure e-commerce payments. Level 1 is the highest level of compliance, which applies to merchants with over 6 million transactions per year and requires proof of compliance at a quarterly and annual basis [54]. The final NEVI rules for LDV charging require a wireless payment option, but individual methods are not specified [115].

In addition to digital card and mobile readers, ISO 15118 specifies a "Plug and Charge" (PnC) option. Under the PnC use case, the payment process is automated, i.e., the customer plugs in the vehicle and the payment transaction occurs through that communication process without additional input from the customer. PnC is possible for AC, DC, and wireless charging [46]. The objective of PnC is to improve ease of use; however, this process requires previous set-up with the network provider [116].

4.4 Safety and Security

The U.S. has detailed safety code requirements that apply to EVCS, see Table 15. Of key importance is the National Electric Code (NFPA 70), which covers EVSE safety requirements and equipment checks including specifications, labeling, and placement on-site [117] and California Code of Regulations (CCR) Title 24, which focuses on building design and construction requirements to ensure safety [118]. EVSE contain high voltage circuits that can cause injury or death if mishandled. Standard placement and design of charging stations ensure that emergency services can easily identify equipment and enact safety protocols in a timely manner.

Table 15. Safety and Security Standards for BEV Charging

Standard	Description	Status (Year of Update)	Market(s)	U.S. Market Penetration	MD/HD Suitability
UL 2202	DC charging equipment for electric vehicles	Edition 3 Approved (2022)	North America	Widely adopted	High, revision in development for MCS
UL 2251	Testing for plugs, receptacles, and couplers for electric vehicles	Edition 4 Revised (2022)	North America	Widely adopted	High, revision in development for MCS
UL 2594	Testing for electric vehicle supply equipment; used for AC chargers	Edition 3 Approved (2022)	North America	Widely adopted	Moderate
NFPA 70	National electric code: electrical safety	Updated (2023)	North America	Widely adopted, amendments by state	High
SAE J2344	Safety guidelines for operation and charging	Reaffirmed (2020)	North America	Widely adopted	High

In addition to codes and standards requirements, industry best practices for safety measures are available that can be implemented to minimize risks (both physical damage and use as access points for software tampering). The components most commonly at risk of accidental damage are cabling and the charging connector. Establishing locking mechanisms can help to prevent accidental damage and tampering of the EVSE charging connector by
(1) locking the charging connector to the EVSE unit until payment initiation confirmed and
(2) having a locking mechanism when connected to the vehicle (can be released by the user). Most LDV EVSE have charging cables that can touch the ground and risk getting run over. With higher power systems (e.g., MCS) it is especially important to design the positioning of cables in such a way that cables cannot be accidentally damaged as vehicles traverse the station.

In addition to physical damage, EVSE have cyber risks. Cybersecurity risks exist at physical and virtual access points where the vehicle and EVSE communicate and where the EVSE communicate with the network, affecting multiple parties including the vehicle operator, charging station operator, grid operator and payment company [119], [120]. Potential access points for cyberattacks include the payment system/user interface, cabling, and EVSE units themselves, as well as any other on-site equipment (e.g., power conversion systems). Some issues associated with these access points include payment fraud, tracking and data insecurity, damage to vehicle batteries and/or station by affecting charging/discharging load, and malware affecting connected parties [121].

While numerous steps have been established to ensure cybersecurity, EVSE charging networks have not yet adopted a standardized, robust approach. In particular, the U.S. federal government found a lack of encryption across inter-module communications, as well as a lack of cybersecurity testing and best practices [121], [122]. In response to cybersecurity concerns, new security measures have been added to communication standards. For example, SB 454 introduced PCI-DSS level 1 as a requirement for California EVSE, and OCPP added Public Key Infrastructure (PKI) encryption in its V1.8 update. OCPP 2.0.1 has also improved monitoring capabilities in order to resolve errors. Updates to 15118 (15118-20) also have added features to promote cybersecurity, such as mandatory TLS encryption [110].

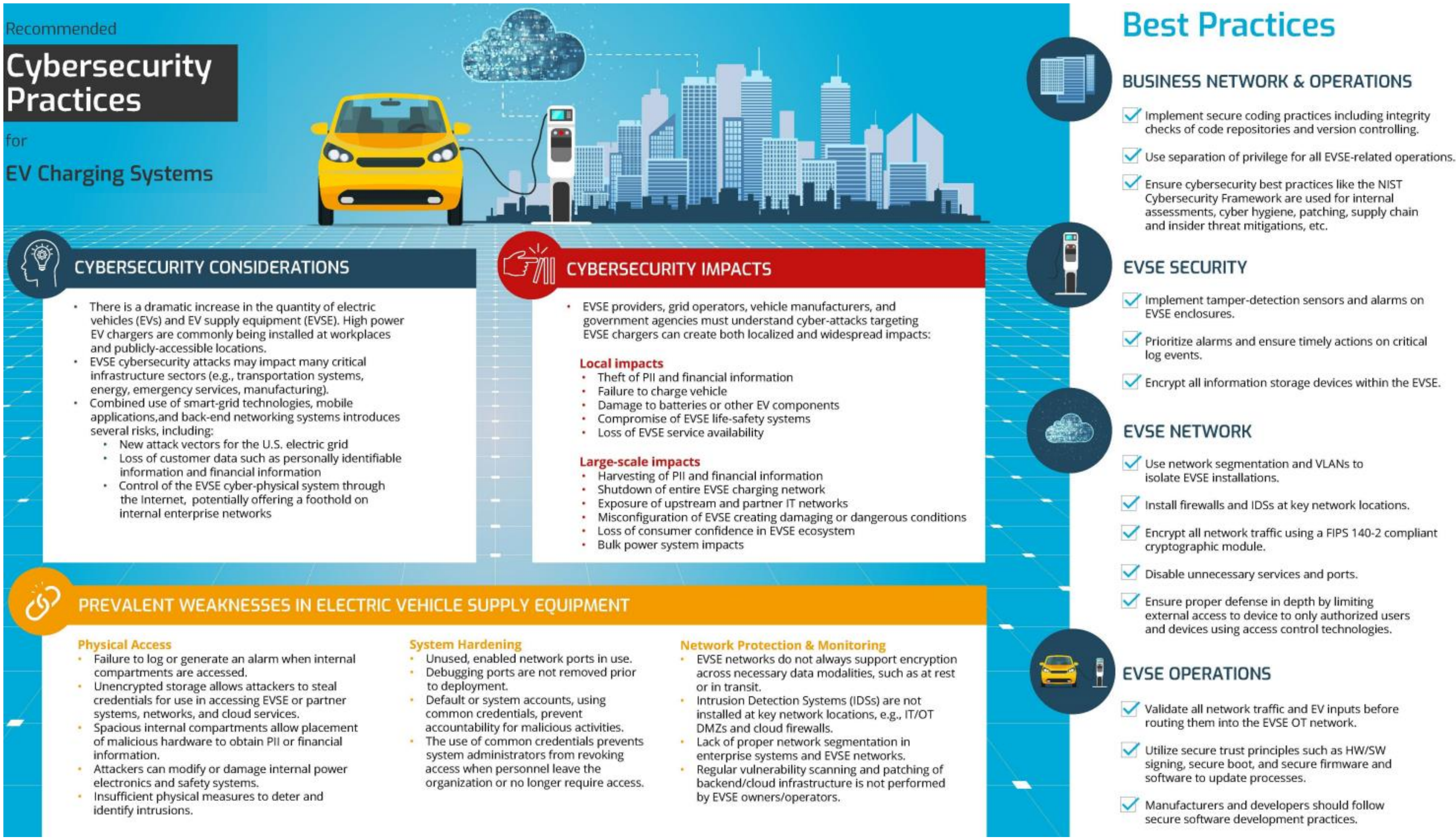
A significant amount of research and policy development focuses on cybersecurity for EVSE systems. Recently, Sandia National Laboratory has developed a "Best Practices" guide for securing EVSE (see Figure 15) and has designed a risk assessment tool,[5] based on the STRIDE cybersecurity threat model framework[6] [122]. The National Institute of Standards and Technology (NIST) also offers a cybersecurity risk assessment tool and a general Cybersecurity Framework, which can be applied to EVSE systems [123]. There are also several on-going efforts in Europe to expand cybersecurity requirements for EVSE, like in the U.K. where future EVSE will have to comply with cybersecurity standard ETSI EN 303 645 [124]. Another effort by ElaadNL, a smart charging research foundation in the Netherlands, and the European Network for Cybersecurity has developed an initial set of cybersecurity requirements for charging stations [125].

In summary, standards organizations are also actively updating safety standards to correspond with the risks of high-powered charging up to the multi-megawatt scale. Also, there has been significant improvement in the security of charging with the addition of enhanced encryption requirements in communication standards. Government agencies have provided more detailed guidance and requirements for industry implementation further advancing charging security. While Industry is moving towards a broad, standardized approach but more work is needed, as cybersecurity threats continue to evolve.

[5] The general framework of a cybersecurity risk assessment is to 1) define the scope of the system, access points, and information flows, 2) identify potential threats at each point of the system, 3) determine risk and impact of potential threats, 4) analyze the adequacy of system controls, 5) rank risks, and 6) calculate risk.

[6] STRIDE stands for "Spoofing, Tampering, Repudiation, Information disclosure, Denial of service, and Elevation of privilege."

Figure 15. Recommended and Best Cybersecurity Practices as identified by Sandia National Laboratory



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4.5 Codes, Testing, and Certification

Multiple certifications of standards compliance are required in the production of EVSE and the commissioning of an EVCS. A list of codes and standards relevant to BEV charging testing and certification are presented in Table 16.

Table 16. Codes and Standards Relevant to BEV Charging Testing and Certification

Code, Standard, or Regulation	Description	Status (Update)	Market(s)	U.S. Market Penetration	MD/HD Suitability
UL 1741	Safety tests for inverter-based devices, including those for V2G	Edition 3 Revised (2023)	North America	Widely adopted for distributed generation	Moderate, referenced in UL 9741
UL 2231-1, -2	Testing for compliance with NFPA 70; covers components that reduce risk of electric shock during charging	Edition 2 Revised (2021)	North America	Widely adopted	High
UL 2251	Testing for plugs, receptacles, and couplers for electric vehicles	Edition 4 Revised (2022)	North America	Widely adopted	High, revision needed for MCS
UL 2594	Testing for electric vehicle supply equipment; used for AC chargers	Edition 3 Revised (2022)	North America	Widely adopted	Moderate
UL 9741	Power export equipment involved in the discharge of an EV battery from the vehicle to the electric grid	Edition 1 Published (2023)	North America	Recently released	Moderate, V2G applications
SAE J1113-21	Testing for electromagnetic compatibility of EVSE components	Revised (2023)	North America	Widely adopted	High
SAE J2953-1, -2, -4	Test procedures for interoperable EV-EVSE pairs (-1), for multiple suppliers (-2), and for nominal conditions (-4)	Reaffirmed (2023): -1, -2; Revised (-4)	North America	Widely adopted	High
NIST Handbook 44 (Sec.3.40)	Specifications, Tolerances, and Other Technical Requirements for Weighing and Measuring Devices	Revised (2024)	U.S.	Widely adopted, states may adopt amendments	High, revisions may be needed
NFPA 70	National electric code: electrical safety	Updated (2023)	North America	Widely adopted	High
ISO 15118-4, -5	Conformance testing for network and application protocol (-4), and physical layer data link (-4)	Confirmed (2023)	North America, Europe, Asia	Widely adopted (AC and DC)	High, revisions may be needed
California Public Utilities	EVSE installation requires a minimum number of contractors with Electric	Revised (2022)	California	California	High

Code section 740.20	Vehicle Infrastructure Training Program certification				
CCR, Title 4, Division 9, Chapter 1	Includes amended Section 3.40 of Handbook 44, specifies measuring units, temperature limits, accuracy tolerances, and voltage	Revised (2022)	California	Widely adopted as Handbook 44, states may adopt amendments	High, revisions may be needed
CCR Title 13, Division 3, Chapter 8.3 2360.3	Requires OCPI test procedures, updated by EVSE Standards regulation	Revised (2020)	California	California, code is harmonized with federal code	High
CCR Title 24 (multiple parts)	Building/Construction Codes, incorporates and amends NFPA codes	Revised (2022)	California	Shared market, varies by state	High

4.5.1 Equipment and Interoperability Testing

Many of the standards covering BEV charging equipment testing are developed by the Underwriters Laboratory (UL) Solutions, which specializes in the development of standards for the testing and certification of electrical and electronic equipment. For example, UL 2251 covers charger (plug/receptacle/inlet/connecter) testing up to 800 A and 600 V (AC and DC). UL 2594 covers the EVSE unit (up to 600 V AC) testing. UL 9741 covers power export equipment involved in the discharge of an EV battery from the vehicle to the electric grid (V2G). UL 1741 covers numerous safety tests for inverter-based devices, including those deployed in V2G use cases [126]. Additional testing procedures, specifications, and certification procedures are defined in SAE standards, as well as national and state codes for the commissioning of an EVCS.

Communications protocols provide general guidelines for signaling between the EV and EVSE. There is sufficient design heterogeneity at the commercial product level that interoperability testing is required to ensure performance across multiple platforms and products. Interoperability testing between different manufacturers and platforms is conducted, following the applicable standard(s), e.g., J2953-2, ISO 15118-4, and/or ISO 15118-5.

Interoperability testing occurs through collaboration between vehicle OEMs and EVSE manufacturers and can also take place at company test facilities or at broader in-person testing events where several companies come together and conduct multiple cross-platform tests. The limitations to this approach include (a) time spent organizing the event/collaboration, transporting equipment and people to the event/testing facility, and the actual testing and (b) space available to house and power equipment. Depending on the number of different solutions entering the marketplace, this solution may not be manageable at a larger scale. More permanent test facilities may be beneficial.

Automated conformance testing is an alternative testing approach to in-person testing. Automated conformance testing has been developed to test a product against a simulated (versus real) EVSE or EV. The CharIN Conformance Test System (CCTS) is currently available to test CCS1 and CCS2 compliance and uses a rigorous set of test cases [127]. This system can augment the current physical testing approach [128]. In-person testing remains critical for testing edge-cases and features not fully captured in simulated test cases. The DEKRA Vehicle-Grid Innovation Lab (ViGIL) offers test procedures and systems for a wide variety of standards, including but not limited to: ISO 15118, DIN SPEC 70121, OCPP , SAE J1772, SAE J2593, and SAE J2894 [129]. ViGIL will also offer CharIN CCTS conformance testing as test cases and procedures become finalized.

4.5.2 Station Design, Construction, and Commissioning

As discussed in the previous section, EVCS must comply with the National Electric Code (NFPA 70) and other national codes that stipulate required safety standards and technical specifications (e.g., cable sizing, ventilation, spacing). In addition, California has its own codes that apply to EVCS installations, including Title 4, Division 9, Article 1 and Title 24 (multiple parts), which both incorporate national codes (e.g., NIST HB 44 and NFPA 70, respectively) with amendments and additional, California-specific requirements. Furthermore, California agencies set codes relevant to the scope of their jurisdiction. For example, the California Department of Food and Agriculture, Division of Measurement and Standards oversees accurate accounting of electricity dispensed by EVSE through CTEP. The California Public Utilities Code section 740.20 stipulates requirements for installation of EVSE and associated infrastructure, including that at least one electrician on-site has completed the Electric Vehicle Infrastructure Training Program certification [130]. Lastly, local jurisdictions may have additional ordinances that need to be followed before a station can be commissioned.

Codes for EVSE and EVCS are continuing to evolve, with changes to HB 44 regarding EVSE testing tolerances for electricity delivered already scheduled [131]. With the introduction of megawatt charging systems, it is anticipated that these new systems will need to adhere to existing codes and additional tests may be required. For that reason, MCS standardization efforts already are incorporating testing data and test procedures.

4.6 BEV Charging Industry and Government Stakeholders

4.6.1 BEV Charging Industry and Government Collaborations

Several industry and government collaborations focus on the development of MD/HD charging technologies and standards. Some efforts include:

- **Charging Interface Initiative e. V. (CharIN):** CharIN is an international organization responsible for the development of the CCS standards [132]. It has multiple focus groups that are working on different aspects of EV charging standardization, including improved communications, grid integration, and interoperability [133]. It was also the leader in developing the megawatt charging system now being standardized under SAE J3271 [94]. In addition, CharIN hosts testing events or "Testivals," where companies can verify charger and vehicle interoperability [134].

- **CHAdeMO:** The CHAdeMO Association developed the CHAdeMO charging standard, and most recently ChaoJi, a high power charging system [91]. CHAdeMO continues to advance high power charging standardization under IEC (e.g., IEC 62196-3) with plans for higher-power systems in the near future [135].

- **ANSI Electric Vehicles Standards Panel (EVSP):** EVSP is a group organized by ANSI that brings together different stakeholders to coordinate on electric vehicle and infrastructure standardization [136]. In 2023, the group published an updated Standardization Roadmap on EV Charging identifying gaps and priorities for standardization [137]. The previous version was published in 2012.

- **Electric Vehicles at Scale (EVs@Scale) Lab Consortium:** EVs@Scale Lab Consortium is a collaborative group that includes national laboratories and other stakeholders that conduct research in the areas of high-power charging, smart charging management, codes and standards vehicle-grid integration, and cyber-physical security [138].

- **Run on Less:** Run on Less was a program organized by the North American Council for Freight Efficiency that demonstrated MD/HD depot charging, including level 2 and DC fast charging solutions [139]. The program concluded in 2023.

The U.S. DOE funds numerous projects within the scope of MD/HD ZEV infrastructure. Table 17 presents an overview of MD/HD charging projects funded by the U.S. DOE. Current research projects span wireless charging, megawatt charging, vehicle-grid integration, and cyber-physical security.

Table 17. U.S. Department of Energy Funded EV Charging Projects related to Charging Safety, Codes, and Standards for MD/HD-ZEV Infrastructure

Project Lead	**Project Title**	**Relevant Topic Area(s)**	**Relevant Codes and Standards**	**Years**
Office of Energy Efficiency and Renewable Energy	Electric Vehicles at Scale (EVs@Scale) Lab Consortium	Wireless charging, Vehicle-Grid Integration, Cyber-Physical security, Megawatt charging, codes and standards	SAE J3271, SAE J2954/2, SAE J2954/3, OCPP, ISO 15118, DIN 70121, OpenADR, SAE J2847-2	2022-2027
Oak Ridge National Laboratory	High Power and Dynamic Wireless Charging of Electric Vehicles (EVs)	Wireless charging	SAE J2954/2, SAE J2954/3	2019-2022
Volvo Group North America	Volvo SuperTruck 3 A Zero Emission Freight Future	Megawatt charging	SAE J3271	2022-2026
PACCAR	Development and Demonstration of Zero-Emission Technologies for Commercial Fleets (SuperTruck 3)	High power charging, vehicle-grid integration	ISO 15118	2022-2027
CALSTART	Bi-directional Wireless Power Flow for Medium-Duty Vehicle-to-Grid Connectivity	Wireless charging, vehicle-to-grid	ISO 15118-20, future standard related to J2954 possible	2017-2023
Kenworth Truck Company	Long-Range Battery Electric Vehicle with Megawatt Wireless Charging	Megawatt charging	SAE J3271	2019-2024
National Renewable Energy Laboratory	High-Power Electric Vehicle Charging Hub Integration Platform (eCHIP)	Hardware, Communication, Grid Integration, Standardization	SAE J3271, ISO 15118, IEEE P2030.13	2022-2027

4.6.2 Industry and Government Stakeholder Engagement

As an integral component of this study, industry and government stakeholders were engaged to inform the research on current market conditions and standardization/technology gaps, and to gather information on other standardization efforts within industry. This engagement included two consultatory meetings, one-on-one interviews, and participation in the ANSI EV Roadmap update and SAE J3271 committee. The results from individual interviews and the consultatory meetings are summarized in this section. Table 18 lists the stakeholders that were interviewed during this period.

Table 18. Participating Industry and Government Stakeholders

Industry Stakeholders		
ABB	Hubbell	Proterra
ChargePoint	Motiv Power Systems	Rhombus
CharIN	Nikola	Volvo
CTE	Nuvve	WallBox
EVBox	Rivian	XOS Trucks
Government Stakeholders		
Argonne National Laboratory	California Air Resources Board	California Energy Commission
CA Governor's Office of Business and Economic Development	National Renewable Energy Laboratory	U.S. Environmental Protection Agency

Overall, a strong industry coordination has evolved to support the development of MD/HD-ZEV charging standards with several concurrent national and international projects investigating the development of new technologies, methods, and procedures. There is a general move away from proprietary solutions and towards a standardized charging approach. These standards include MCS (SAE J2) MCS, with the TIR anticipated in 2024 and the standard within a 2 to 3-year timeline.

Several challenges identified are related to reliability, charging time, cost, commissioning time, and policy that could be addressed to help accelerate MD/HD-ZEV deployment. A summary of the comments received from key stakeholders during the consultatory meetings and one-on-one interviews is presented in Appendix F.

4.7 Summary of Current Gaps and Medium- and Heavy-Duty Vehicle-Specific Needs

Many activities are addressing current gaps in MD/HD charging systems to achieve the goal of standardized, reliable charging that is fast, safe, and secure. Current standards result in long charging times that are manageable to support early MD/HD vehicle use cases but insufficient for broad adoption. These developments include new hardware, charging protocols, and advanced communications. In addition, charging system performance improvements could provide additional benefits to these markets and bring ZEV operations closer to conventional vehicle expectations. Based on the literature review and feedback from stakeholders, the following gaps and improvement goals have been identified:

- **Lack of High-Powered Charging**

  Goal: The potential benefits of faster charging include improved uptime and greater operational flexibility. For example, a fleet may be able to use a BEV that requires overnight charging for a single shift per day. However, with a faster charging rate, the fleet may be able to either reduce the space and time required to accommodate EVSE and/or switch the BEV to two shifts per day, which is common for some fleets, such as drayage.

  Type of Gap: Standards and Technology

  Currently, the highest charging rates are between 300-500 kW, depending on the technology. These rates are insufficient to achieve broad operational parity with conventional MD/HD vehicles. The constraints on charging rate include rate limits on the EVSE side and vehicle battery side. Charging rates are limited by the technical capabilities of the EVSE to transfer electricity and the vehicle's battery to receive the charge. In particular, the vehicle battery and the EVSE are limited by thermal constraints to ensure safety and protect the useful life of the vehicle's battery [140]. Potential limiting factors to high power charging deployment will include the timing of product/standard availability, market need, and cost.

  Gap Impact on MD/HD-ZEVs

  BEV charging takes considerably longer than fueling internal combustion vehicles (ICVs). Paired with shorter vehicle ranges, BEV charging at low power level can take a significant amount of time away from vehicle operating time. For MD/HD vehicles that travel over 300 miles per day, current charging options result in charging times between two to eight hours, which may be too long for some fleets, especially those that do not have the ability to charge over night at a dedicated facility.

  Recent Activities

  Specifications in existing standards are being updated to allow for higher charging rates. For example, the next CCS update is expected to allow for 450 kW systems, whereas the current standard specifies a maximum of 350 kW. Additionally, there are new charging technologies in testing and new standards in development to achieve higher charging rates including SAE J3271 Megawatt Charging Systems [93].

  At the same time, vehicle battery systems must be able to tolerate high charging rates, as currently, charging rates are limited to ensure safety and protect battery health [141]. As charging rates have been increasing in the marketplace, battery and EVSE advanced cooling architectures have been developed utilizing a variety of cooling methods such as air-cooled, indirect or direct liquid cooled, or heat-pipe cooled [142]. The new MCS standard development also includes cooling requirements on the EVSE side to ensure performance and safety.

Anticipated Activity Outcomes

MCS and high-power wireless charging options are currently being developed and standardized. Adoption of these new standards will depend on market demand for multi-megawatt charging. The anticipated timeline for standard implementation is two to five years. In the interim, TIRs can provide guidance to developing MW charging systems.

- **Insufficient Reliability, Interoperability**

Goal: Improve error resolution and achieve overall higher reliability.

Type of Gap: Standards and Codes

Charging stations (level 2 and DCFC) have lower reliability than desired. A major issue is interoperability between different EV-EVSE. As of 2022, according to SAE International, 30-40% of charging sessions fail [143]. A charging session "fails" when charging cannot be initiated or charging halts unexpectedly at any point during the session. Charging failure can result from hardware or software incompatibility. These include interoperability issues, challenges with payment systems, hardware failure, and communication failures (e.g., failed start-up sequence). Surveys of current, public charging stations (level 2 and DCFC) have found that there are repeated issues related to communications between EVSE, the vehicle, and/or station network.

Gap Impact on MD/HD-ZEVs:

Commercial MD/HDVs demand higher reliability rates. Failed charging sessions can lead to reduced vehicle availability, increased operating costs, and lower consumer confidence in the technology.

Recent Activities:

Industry groups are discussing a more standardized approach for testing (e.g., the CharIN Conformance Test System). A standardized, industry-level approach to report errors is important to better understand and address frequent issues. Addressing reliability is another high priority. Improved reliability has been a frequent discussion topic in several standard committees, such as SAE J3271, which is currently reviewing communications protocols and needs for MCS. Potential improvement areas include improved error detection and resolution, which can be achieved through adopting OCPP 2.0.1 [144]. This could include allowing the EVSE to auto-restart the charging session in case of an error. Also, resolving inconsistencies between EVSE network software and payment systems can increase operability.

The NEVI guidelines require a 97% up time for LD chargers funded through the program, which is significantly higher than current averages reported for existing systems [145]. In addition, the CEC is developing real-time monitoring and reporting standards related to AB 2061, which would potentially track causes for charging sessions failing.

Anticipated Activity Outcomes

Analysis of operational data associated with uptime and failure modes can inform updates to technology improvements or best practices for operating charging stations. Currently, CTEP certifies stations for dispensing accuracy and labeling. The State should investigate expanding CTEP's conformance testing requirements under Title 4 based on these failure data.

- **Lack of Automation**

Goal: Automated charging can improve ease of use and safety. Automated charging management can increase charging flexibility, minimize negative grid impacts, and potentially supports the deployment of connected vehicles as grid resources.

Type of Gap: Standards, Technology

Currently, automated charging devices and charging management systems lack sufficient standardization. Automated charging devices (ACDs) are an area of interest for high power charging. ACDs can reduce the burden/safety risk to employees to handle/manage bulky, high voltage equipment by automating the connecting and disconnecting of the charger. A second type of automation is automated load management strategies, often controlled by software in the EVSE. Automated load management can help balance high charging rates anticipated with MD/HD-ZEV electrification. For example, load management can allow planning the charging time of vehicles to avoid peak demand periods. It can also decide how to split power between two or more vehicles connected to the same power unit, such as prioritizing vehicles that need to disconnect sooner.

Gap Impact on MD/HD-ZEVs:

High power systems can be a safety risk, as unsafe handling can result in injury and death. Lack of charging flexibility can result in greater impacts on the electric grid. Potential negative grid impacts of uncoordinated charging include higher electricity consumption during peak demand periods (4 pm – 9 pm) and more frequent transformer upgrades [146], [147].

Recent Activities

ISO 15118-20, released in 2022, considered automated charging management and automated connection devices. SAE J3271-2 (MCS) is under development, and it is expected to delineate communication needs, including automated charging management, for MCS. The California Public Utilities Commission is funding V2G pilots in its efforts to advance V2G technology and regulations surrounding the integration of electric vehicles on the grid as required by SB 676 (Bradford, Chapter 484, Statute of 2019) [148]. J3105 overhead charging and wireless charging are other options to increase automation and improve ease of use. SAE J2954-2 HDV wireless charging is in development with a TIR anticipated for late 2022/early 2023.

Anticipated Activity Outcomes

J2954-2 and ISO 15118-20 are steps toward more standardized automated charging. Automated charging devices continue to advance through proprietary solutions, with the option of later standardization. Bi-directional charging is not yet covered under automated charging systems but could be added in future revisions.

- **Insufficient Cybersecurity**

Goals: More robust cybersecurity can improve station uptime, safety, and security. Gap:

Type of Gap: Standards

As BEV charging expands, the quantity and type of data communicated across networks is expected to grow. These data can include payment information, charging session data, vehicle data, trip data, and other fleet logistics. Fleet logistical software tends to require a significant amount of data to function. These data can be used to coordinate charging across multiple vehicles and/or implement smart charging strategies, including V2G. Any data communicated between the vehicle and the network is vulnerable to hacking, as well as any data stored at any point within the system (vehicle, EVSE, the cloud) that could be accessed physically or remotely.

Gap Impact on MD/HD-ZEVs:

It is critical to provide robust cybersecurity when it comes to vehicle-EVSE interactions and EVSE-charging network interactions. Without enough protection, payment information and sensitive fleet data are at risk, as is overall station reliability.

Recent Activities:

As the EVSE markets mature, new security measures are being added to existing standards and new codes and regulations are being introduced to enforce robust cybersecurity. Some examples include TLS encryption now required under ISO 15118-20 and PKI encryption now included in OCPP.

Anticipated Activity Outcomes

Charging security has greatly improved through incorporating heightened encryption requirements within communication standards. Government agencies have contributed to this progress by issuing more comprehensive guidelines and mandates for the industry to implement, further improving charging security. Despite strides toward a comprehensive and standardized approach within the industry, there is still more work to be done, especially given the ever-evolving cybersecurity threats.

- **Lack of Standardization of Payment Systems and User Interfaces**

<u>Goal:</u> Standardized payment increases ease of use and utilization of a public charging network.

<u>Type of Gap: Policy and Implementation</u>

A lack of standardized payment systems and use interfaces lead to interoperability issue, as well as a perceived barrier to public charging access and use.SB 454 (Corbett, Chapter 418, Statue of 2013), which standardizes payment systems for charging in California, is not yet fully implemented. There remain issues around EVSE network membership requirements, variation in payment requirements—some require pre-registration and/or require payment through a specific app, and overall complexity [149]. In general, there remains a heterogenous approach to payment systems, which especially compounded by reliability issues, creates a barrier to public charging access. As new EVSE expand and older EVSE are replaced, the standardized payment system will become more widely available.

<u>Gap Impact on MD/HD-ZEVs</u>

It is unclear what portion of MD/HDV charging stations will be public versus private (fleet). However, it will be important that public stations are readily accessible to potential users. Since new EVSE will be required to follow SB 454, issues surrounding heterogeneous payment systems are expected to lessen.

<u>Recent Activities:</u>

In February 2022, CARB released findings from a standards technology review required by SB 454 [149]. They found that perceived challenges to EVSE access still exist, including interoperability, payment methods, and membership requirements. As of the start of 2022, all new DC EVSE must follow SB 454 requirements [11]. The availability of PnC, which automates the payment process, is also expanding, with CharIN now offering a PnC certification process [150].

As previous noted, the CEC is developing uptime reporting standards related to AB 2061. As a part of these reporting requirements, more data on session failure causes will be collected. These data will in turn provide needed insight into failures related to payment systems, which can be used to update system requirements to improve reliability.

Anticipated Activity Outcomes:

Interoperability is anticipated to improve with the adoption of State requirements and guidance. Uptime reporting standards will provide real-world data to help identify failure frequency and causes, which in turn can support more robust system design.

Additional considerations include:

- **Emergency Services Training**

  As the charging rates continue to increase, the appropriate safety measures need to be reassessed and updated. These updates will most likely be specified in NFPA documents and adopted in federal and state codes. This includes vehicle and EVSE design considerations to disconnect power and ensure ready access by emergency services. It also includes training considerations to ensure that there is widespread understanding of how to respond to emergencies, especially given high voltage concerns.

- **Tampering prevention**

  Light duty BEV charging deployments have reported incidents of bystanders unplugging chargers and even blocking charger access. This type of tampering is less likely for private, limited access charging but could be a risk for public MD/HDV charging stations. Potential strategies for protecting against tampering include added locking mechanisms and station/EVSE design to guard against malicious actions such as destruction of property. Other physical security considerations include cameras and lighting, which may be covered by building codes or local ordinances.

- **Component Standardization and Supply Security**

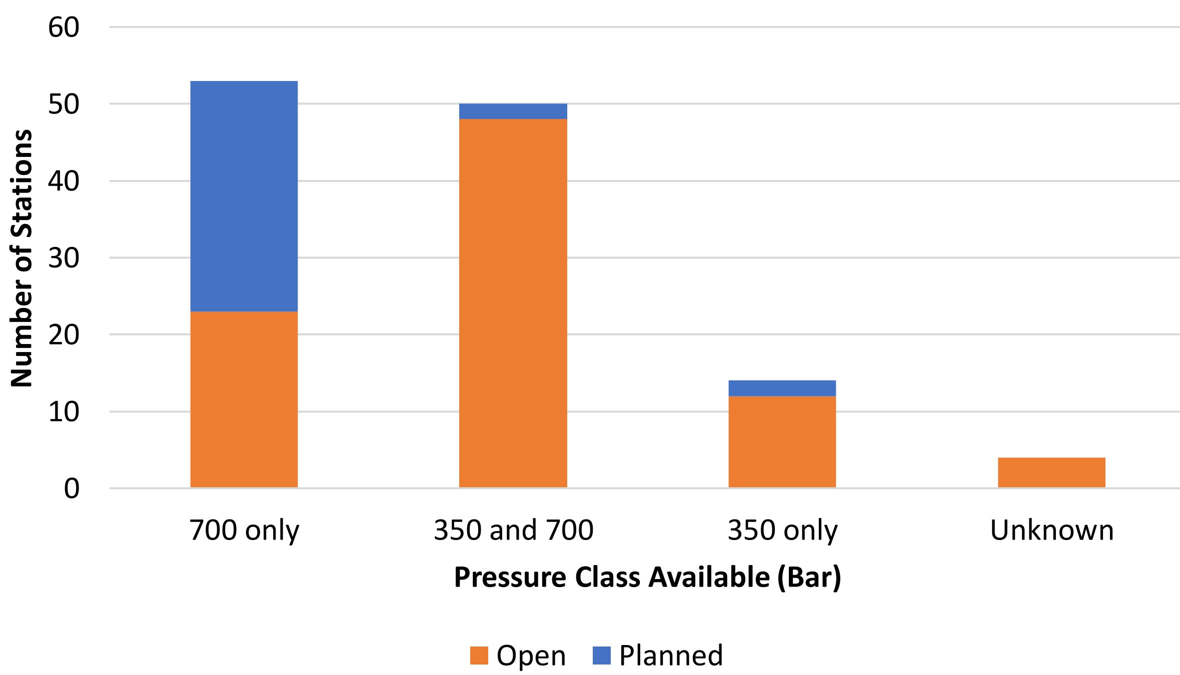
  Due to the new and experimental nature of early BEVs and EVSE, suppliers in some cases have created their own solutions to meet desired performance. In the early generations of battery electric buses, this included proprietary charging solutions, novel components, and limited supply. This has led to some maintenance issues. Moving forward, component standardization and improved planning for replacement parts should support the long-term success of charging infrastructure and BEV deployment.

5. Fuel Cell Electric Vehicle Hydrogen Fueling Codes and Standards

5.1 Hydrogen Fueling Market Status and Goals for Medium- and Heavy-Duty Vehicles

As of 2023 over 1,000 hydrogen fueling stations were deployed globally [151]. China has the largest hydrogen fueling network with over 250 stations, followed by Japan with over 160 stations [152]. While California and Hawaii are the only states that currently have public retail hydrogen stations in the U.S., several states have one or two private or non-retail hydrogen stations, including Colorado, Connecticut, Delaware, Massachusetts, Michigan, New York, Ohio, Pennsylvania, Texas, Virginia, and Washington. Public stations are also planned in Massachusetts, Ohio, Rhode Island, New York, Massachusetts, and Connecticut [153]. In the U.S., most open stations offer 700 bar (70 MPa) and 350 bar (35 MPa) fueling, while most planned stations are focused on 700 bar only. Figure 16 presents the distribution of U.S. hydrogen fueling by rated fill pressure.

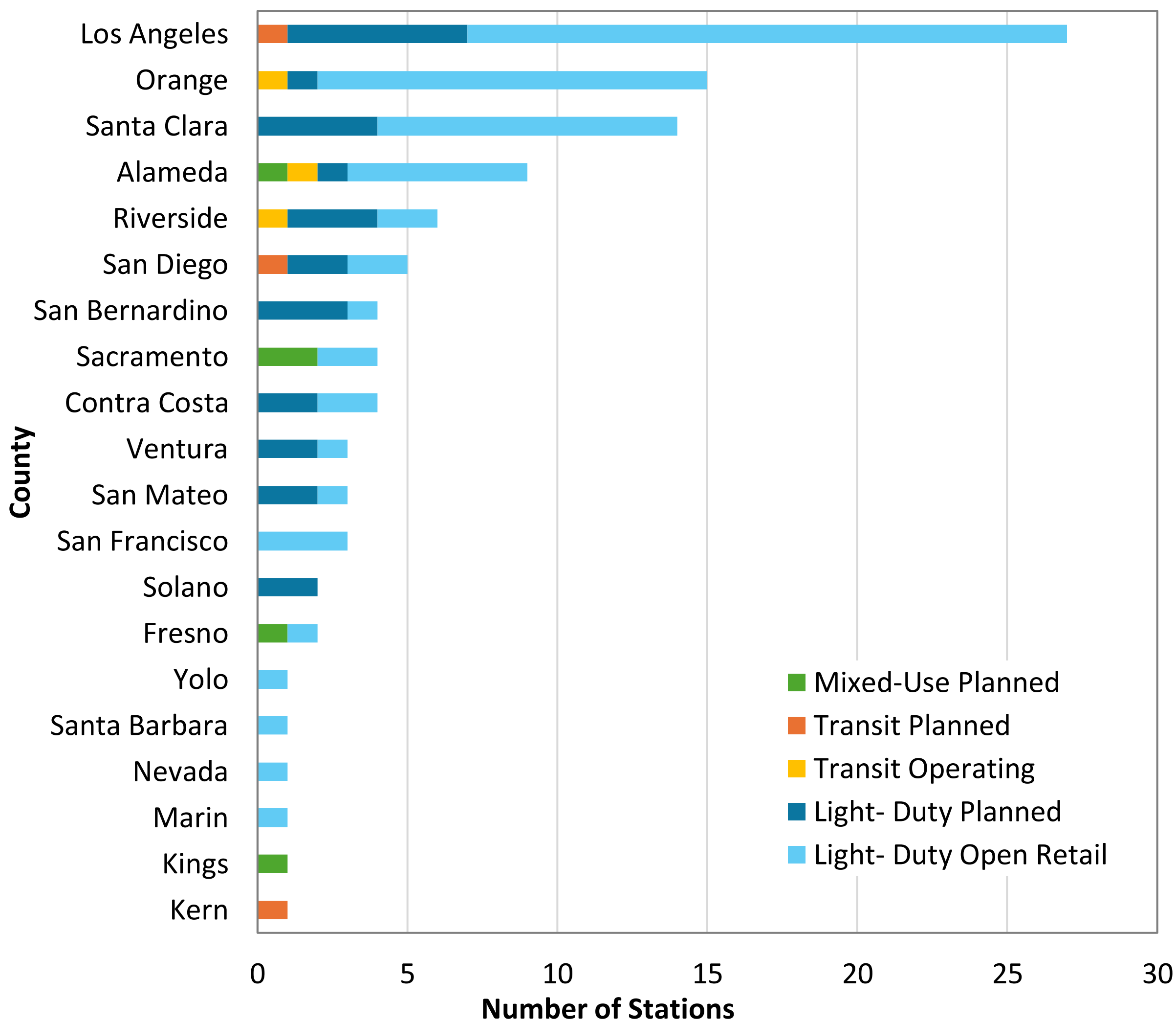
Figure 16. U.S. Stations by Rated Fill Pressure



Data extracted from US DOE Alternative Fueling Station Locator Oct 24th, 2023.

As of this report (January 2024), the CEC counts 94 current and planned publicly funded LDV stations and 7 privately funded LDV stations in California [154]. There are seven operating heavy-duty hydrogen stations in California and four more planned. Of the operating stations, at least three service transit buses [AC (Alameda-Contra Costa) Transit, Sunline Transit, and Orange County Transit Authority] [153]. Of those planned, three additional stations are planned for transit [154]. The number of stations is expected to grow significantly between now and 2045, in line with the California ZEV goals. The current location and operating status of hydrogen fueling stations in California is consistently updated by the Hydrogen Fuel Cell Partnership [155]. Figure 17 presents the current and planned hydrogen stations in California [156].

Figure 17. California Hydrogen Fueling Stations by County



Source: California Energy Commission (2022). Hydrogen Refueling Stations in California. Data last updated December 31, 2023. Retrieved April 19, 2024. From https://www.energy.ca.gov/data-reports/energy-almanac/zero-emission-vehicle-and-infrastructure-statistics/hydrogen-refueling

Applicable standards for heavy-duty hydrogen fueling include those that define fueling protocols for large on-board storage capacity. For reference, on-board hydrogen storage capacity ranges between 30 and 50 kg for transit buses and 50-70 kg for class 8 trucks [157]. In comparison, light-duty FCEVs store about 5 kg of hydrogen. SAE J2601 Category D and SAE

J2601-2 provide specifications for large capacity on-board storage within the range of HD vehicle requirements for H70 and H35, respectively.

At present, all commercial FCEVs store hydrogen on-board as a compressed gas, although fuel systems for on-board liquid storage are starting to become available, with ISO 13985 covering liquid hydrogen storage for mobile applications. The current analysis focuses on fueling for on-board compressed hydrogen storage using existing Type III and Type IV tanks. The requirements for these tanks are specified in ISO 19881 and SAE J2579. Type III and Type IV are lined composite tanks, both of which are suitable for on-board hydrogen storage with a maximum pressure of 700 bar. Type III is metal lined, whereas Type IV is plastic lined.

Currently, HD stations operate with a variety of different fueling protocols and pressures. For example, the heavy-duty hydrogen fueling stations at the ports (Port of Los Angeles and Port of Long Beach) are rated for 350 and 700 bar in order to service multiple vehicle types, such as drayage trucks and other demonstration vehicles, and provide a test bed for emerging fueling strategies [158]. The transit hydrogen fueling stations are rated for 350 bar and rely on customized protocols based the guidance document J2601-2 [153]. There are several caveats of applying current standards documents in HD applications, which are described in more detail in Section 6.2.1. In brief, current protocols lack a standardized approach to provide fast fueling on-par with HD diesel fueling.

Broad MD/HD hydrogen fueling station deployment will require standardized, reliable hydrogen fueling that is fast, safe, and secure. High reliability has been identified as critical to achieving market success [159]. The goal of a mature MD/HD hydrogen fueling station network is to maintain high reliability while minimizing cost (e.g., due to redundancy measures and maintenance) [160]. The light-duty hydrogen station network in California has experienced low reliability due to a variety of issues including component failures and low hydrogen supply [160]. Given the significant overlap of the technologies used in light duty stations and MD/HD stations, it is probable that similar reliability issues will affect MD/HD deployment, if issues are not addressed [161].

The goal of fast hydrogen fueling is to achieve parity with diesel fueling. To that end, the U.S. DOE has established the following hydrogen fueling goals: average hydrogen flow rate of 8 kg/min by 2030 and average hydrogen flow rate of 10 kg/min by 2050 [162]. At present, SAE J2601 Category D specifies hydrogen flow rates up to 3.6 kg/min and SAE J2601-2 specifies rates up to 7.2 kg/min.

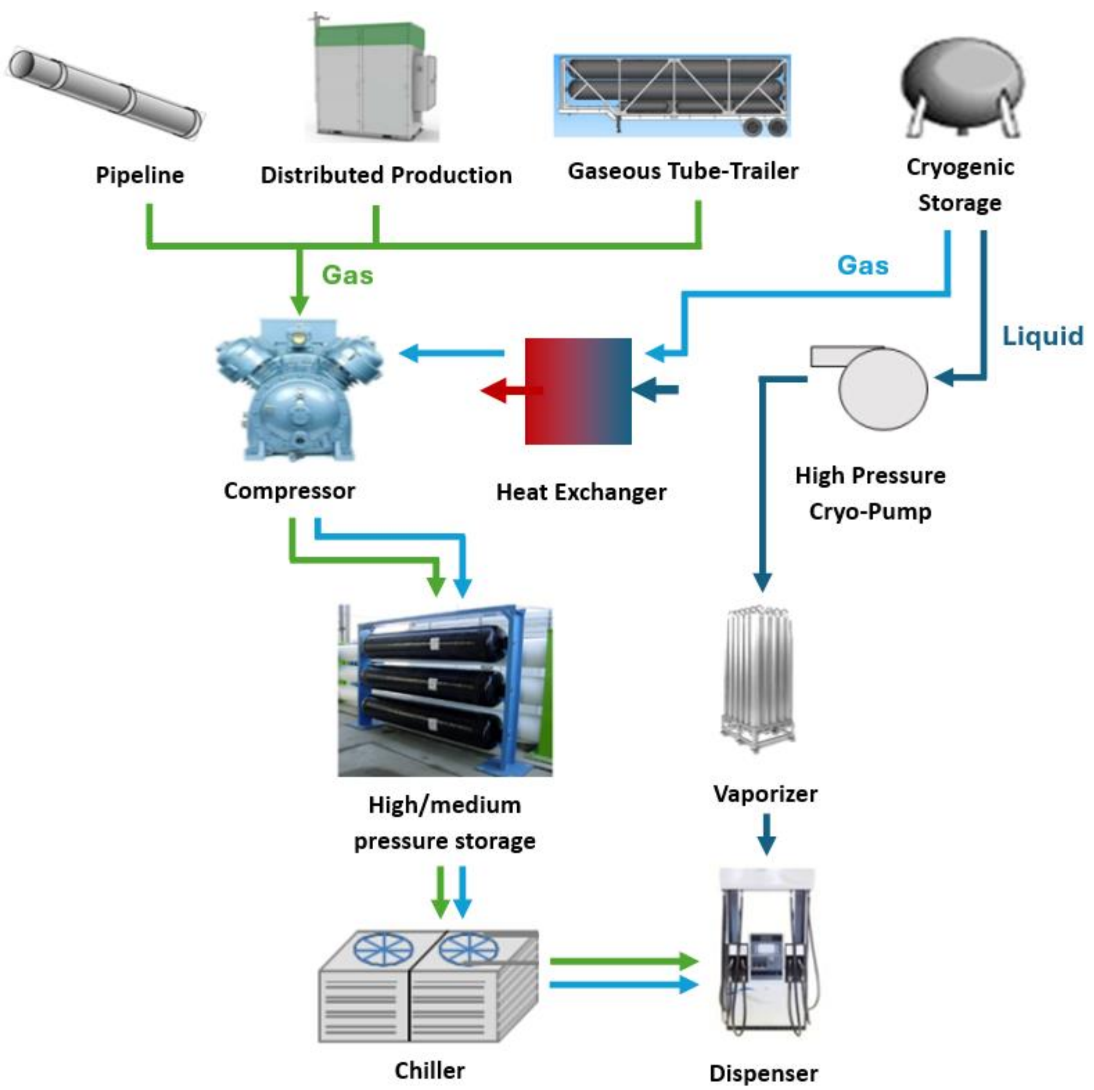
The goal of safe and secure fueling is achieved through the adoption of standards and best practices that minimize hazards and risks of injury from hydrogen storage and dispensing systems and minimize risk for fueling disruption, tampering, and data insecurity. As HD hydrogen fueling stations grow in size and number, safety and security standards will need to be re-evaluated to ensure continued accuracy in risk assessments. Current standards are geared towards light-duty, small capacity (less than 4,000 kg) stations, whereas new HD stations greater than 10,000 kg hydrogen are planned.

The following sections provide an overview of the status and suitability of codes and standards for MD/HD hydrogen fueling. On-going work and gaps are discussed. The last section of the chapter provides a summary of identified gaps as well as anticipated outcomes of new standards based on current research and standards development efforts.

5.2 Hydrogen Fueling Hardware

Hydrogen fueling stations have several different configurations, see Figure 18 [163]. In general, hydrogen can be produced either on-site or delivered (via pipeline or truck).

Figure 18. Hydrogen Fueling Station Configurations



Adapted from Argonne National Laboratory. Hydrogen Refueling Station Analysis Model (HRSAM) https://hdsam.es.anl.gov/index.php?content=hrsam

Hydrogen can be stored at a refueling station as a liquid ("sub-cooled"), a compressed gas, or a cryo-compressed gas (typically 35 MPa, -253^{o}C) [164]. Other proposed storage methods include sorbents, chemical hydrides, and metal hydrides [165]. Table 19 presents an overview of the codes and standards specifying hydrogen fueling station requirements. The scope of relevant documents includes general station requirements and the dispenser.

Table 19. Hydrogen Fueling Hardware General Requirements and Dispenser Standards

Category	Standard	Description	Status (Year of Update)	Market(s)	U.S. Market Penetration	MD/HD Suitability
Dispenser	**SAE J2600**	Dispenser nozzle design	Revised (2015)	North America	Widely Adopted	Moderate, revision needed for high flow
	ISO 17268	LD Dispenser nozzle design (harmonized with SAE J2600) HD nozzle for J2601-2 implementation specified in ISO 17268: 2012	Published (2020)	North America, Europe, Asia	LD: deployed under SAE J2600 HD: Limited fast fueling (J2601-2)	High, revision needed for high flow
	ISO 19880	Series covers dispensers up to H70. -2 Covers requirements and testing of gaseous hydrogen dispensers, -3 Covers valves -4 Compressors -5 Covers hoses -7 Covers O-rings	-2: DIS (2023) -3: Published (2018) -4: CD (2024) -5: Published (2019) -7: DIS (2023)	North America, Europe, Asia	Not adopted, NFPA and NIST documents used	High, revision needed for high flow
General Requirements	**NFPA 2**	Covers all design, construction, and operational aspects of hydrogen fueling stations	Published (2023)	U.S.	Widely adopted, amendments by state	High, routinely revised to reflect updated research and priorities
	NFPA 55	Covers hydrogen storage placement, including separation distances, labeling and safety systems	Published (2023)	U.S.	Widely adopted	High, routinely revised to reflect updated research and priorities
	NFPA 70	Covers electrical systems	Published (2023)	U.S.	Widely adopted, amendments by state	High, routinely revised to reflect updated research and priorities
	ISO 19880-1	General requirements for gaseous hydrogen dispensers	Published (2020)	North America, Europe, Asia	Referenced in SAE documents	High, revision needed

A key focal point of high flow fueling hardware development is the dispenser. The dispenser houses the dispenser hose, breakaway and nozzle, as well as the point-of-sale (POS) system. Dispenser nozzles for hydrogen dispensing are defined in SAE J2600 "Compressed Hydrogen Surface Vehicle Fueling Connection Devices" and ISO 17268: "Gaseous hydrogen land vehicle refuelling connection devices" [166]. The nozzle specifications permit vehicles can fuel with nozzle rated for pressure equal to or less than vehicle tank rating. In addition, the 2012 version of ISO 17268, a "fast fueling" nozzle is specified with the intention that it is used with SAE J2601-2 Option A rate of 7.2 kg/min for H35.

For the U.S. market, a limited number of commercial nozzle products are available for H35 and H70 [167]. While other pressure classes are mentioned in the J2600 standard (H11, 25, and 50), they are seldomly used in the North American market given that (1) there is no need, and (2) to avoid fueling complexity. The nozzle and receptacle specifications are designed for specific ambient and gas process temperature ranges: -40°C to 65°C (ambient) and -45°C to 85°C (gas).

Available data show that component failures, particularly the dispenser and compressor, are a leading cause of station downtime at light-duty stations [168]. Given the significant overlap between the components for light-duty stations and MD/HD stations, similar risks can be anticipated. Several stakeholders, including station providers, national laboratories, and academic researchers, are actively working to assess and improve component reliability [160], [169], [170].

Key differences between LD and MD/HD stations include the scale of the system and the anticipated higher fueling rates. The changes from light duty stations will require new dispenser technologies, specifically nozzles that can support the higher flow of hydrogen. To that end, several industrial consortia and DOE National Laboratory projects are working on the development of new hardware (nozzle, breakaway, hose, etc.). For example, the DOE National Laboratories are currently testing the design of a high flow nozzle that will support the deployment of high flow fueling under ISO 19885 (WIP): "Gaseous hydrogen — Fuelling protocols for hydrogen-fuelled vehicles" [171].

In summary, the following hardware gaps were identified:

- Low reliability of station hardware, and
- Need for new hardware for high flow fueling.

Improving the reliability of station hardware requires additional research and technology development, building upon on-going work. Dispensing hardware for high flow protocols is in development, and standards are planned within the next few years. Following the release of standards for high flow nozzles, vehicle OEMs will need to also deploy the appropriate receptacles on vehicles to support faster fueling.

5.3 Fueling Protocols

Industry has developed and adopted essentially one standard for LDV hydrogen fueling, SAE J2601, which was harmonized for the European market as ISO 19880-1 [47] and adapted for the Japanese Market as JPEC-S 0003 [172]. EN 17127 was then created based on ISO 19880-1 and adding the pressure class H50 [44], [173]. Since the original issuance of the standards, there has been a series of updates and harmonization across the different standards organizations. For example, JPEC-S 0003 introduced filling protocol for larger fills (up to 30 kg), which was then harmonized with J2601 as Category D (>10 kg fill, H70). Several hydrogen fueling protocols are in development to address current fueling gaps. These include ambient fueling and high flow fueling. See Table 20 for a summary of North American fueling protocols.

Table 20. Hydrogen Fueling Protocol Standards

Standard	Description	Status (Year of Update)	Market(s)	U.S. Market Penetration	MD/HD Suitability
SAE J2601*	Hydrogen fueling protocols (350 and 700 bar)	Revised (2020)	North America	Widely Adopted	Moderate (Category D)
SAE J2601-2	Hydrogen fueling guidance for heavy-duty applications	Stabilized (2023)	North America	Limited	Moderate
SAE J2601-3	Hydrogen fueling for hydrogen powered industrial trucks	Reaffirmed (2022)	North America	Limited to forklifts	Low
SAE J2601-4	LD ambient temperature fueling	WIP (2016)	North America	In development	Moderate, if HD scope added
SAE J2601-5	High flow fueling protocols	TIR (2024)	North America	In development	High
ISO 19885-3	High flow fueling protocols	WIP (2023)	Asia, Europe, North America	In development	High

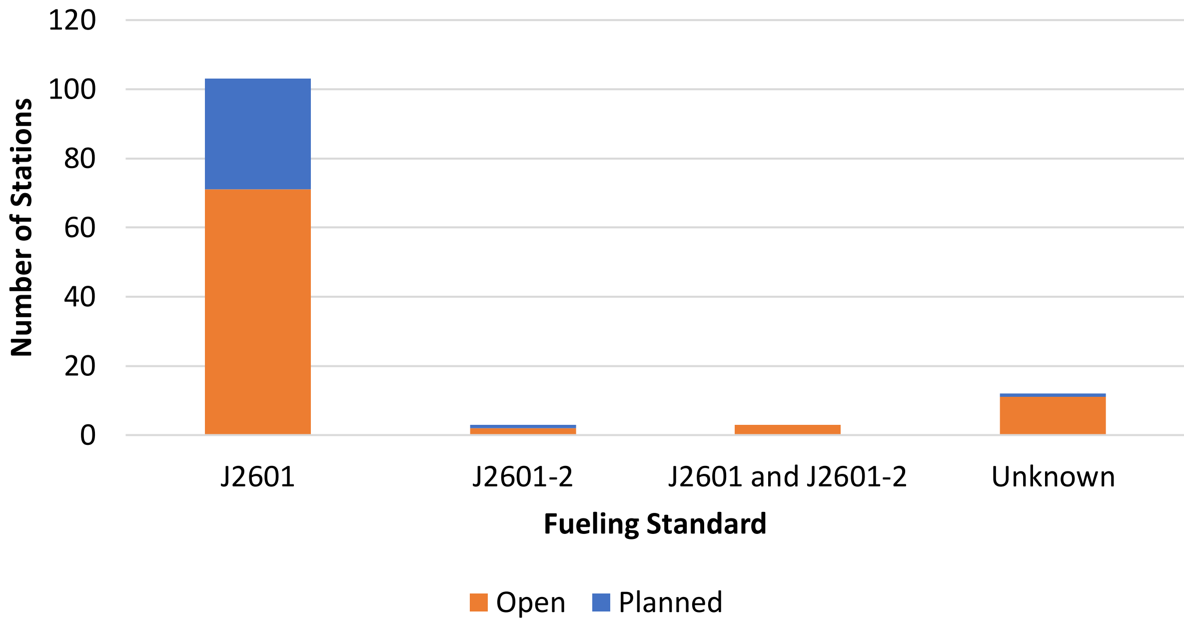
*Revision in development

5.3.1 SAE J2601 and J2601-2

The CEC and CARB funded a set of LDV hydrogen station demonstration projects in the 2000s. Following the first round of demonstrations, the CEC, in coordination with CARB, established standards and performance requirements for funded hydrogen fueling stations moving forward [174]. Early LDV hydrogen fueling stations funded by the CEC, such as PON-12-606, required awardees to follow the SAE J2601 TIR, which has since been upgraded to the codified standard

J2601 [174], [175]. As Figure 19 shows, there is strong uniformity in the fueling protocols for LDVs being used in California.

Figure 19. California Hydrogen Stations by Fueling Protocol



Data extracted from US DOE Alternative Fueling Station Locator Oct. 24, 2023. Transit hydrogen stations operating with SAE J2601-2 were verified through [176], [177].

SAE standard J2601 defines hydrogen fueling protocols for LDVs, based on safety limits and defined performance targets. The standard outlines different temperature and pressure classes as well as maximum flow rates for dispensing hydrogen. It is critical that the fueling protocol correctly accounts for temperature and pressure conditions of the fueling event session, due to the safety risks of overheating and over pressurizing of the on-board compressed hydrogen storage system (CHSS). J2601 characterizes its fueling protocols by different station and vehicle/hydrogen storage parameters [175], [178]:

- **Tank rated pressure** – In the U.S., two pressures are available for fueling: 350 bar (H35) and 700 bar (H70), as defined in SAE J2601.
- **Hydrogen fueling delivery temperature** – In the standard, there are three fuel delivery temperature categories: -40ºC (T40), -30ºC (T30), and -20ºC (T20). It does mention that other (higher) delivery temperatures could be the basis of future work. The lower the temperature, the faster the anticipated fueling. However, the trade-off is an increased energy cost of achieving the lower fueling temperature [179].
- **CHSS capacity** – There are four categories of CHSS Capacity, which are divided by maximum stored hydrogen (kg) at a full state-of-charge: Category A, B, C, and D, as provided in Table 21 [175]. The different categories delineate different hydrogen storage tank capacities. These categories have varying target pressures. The lower

pressure class of H35 has a lower stored hydrogen amount for all categories and does not have an equivalent Category D. However, it should be expected in the next SAE J2601 revision. Therefore, the maximum stored hydrogen for H35 under SAE J2601 is 5.97 kg. H70's Category D has an open-ended upper limit, with the range defined as greater than 10 kg.

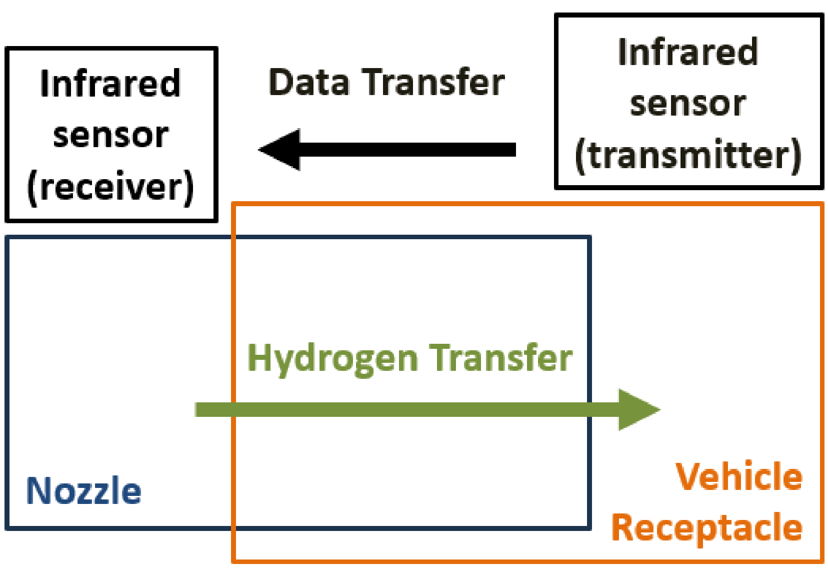
Table 21. SAE J2601 CHSS Capacity Categories

	Max Hydrogen Stored in CHSS (kg)	
Category	**H35**	**H70**
A	1.19 – 2.39	2.00 – 4.00
B	2.39 – 4.18	4.00 – 7.00
C	4.18 – 5.97	7.00 – 10.00
D	-	>10.00

Data from SAE J2601

- **Vehicle-station communications** – Fills can be characterized by "non-communications" or "communications." The type of fill is determined at the beginning of the fill session by the station based on whether it receives wireless infrared data signals and whether they meet the defined requirements in SAE J2799 [180]. See Figure 20 for a simplified diagram. Collected data are described under the flow rate calculation method bullet below.

Figure 20. Hydrogen Fueling Communications and Physical Interface Diagram



Adapted from SAE J2799

At a minimum, all stations shall be able to complete a fill without vehicle communications. Under this "non-communication" scenario, the station measures ambient temperature at the dispenser and initial tank pressure, which are used to determine the average pressure ramp rate (APRR) and target pressure using one of the fueling protocol methods described below. The vehicle also needs to communicate the CHSS pressure class (H35 or H70). Vehicles with H35 rated tanks cannot fuel at H70, but vehicles with H70 tanks can fuel at either H35 or H70. For a communications fill, additional data are provided by the vehicle, including CHSS temperature and volume. If a station cannot determine the CHSS volume to an accuracy of -/+ 15%, it shall fuel at the most conservative APRR and end fueling at the most conservative target pressure. Furthermore, if a station does not fuel vehicles with the most conservative APRR and target pressure, it shall calculate the CHSS volume for non-communication fueling.

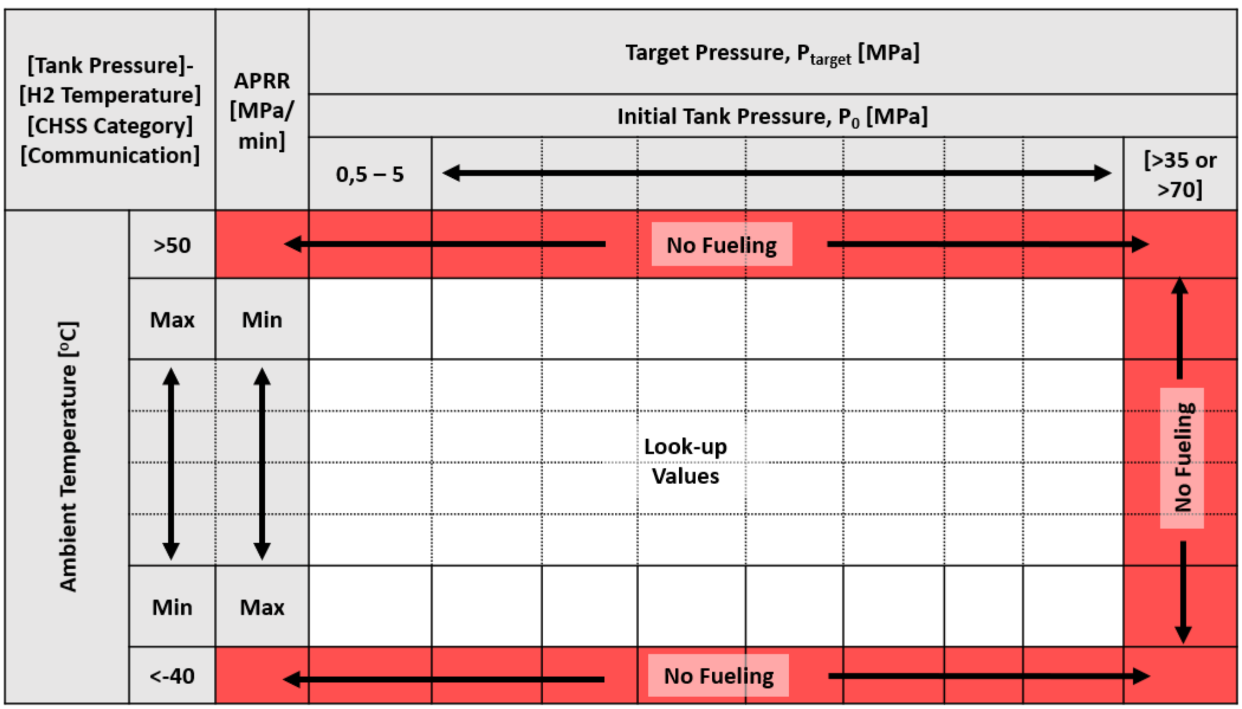
- **Fueling gas flow rate calculation method** – Two main methods are used for calculating APRR: Table-Based Fueling Protocol and Mass and Thermal Capacity (MC) Formula Based Fueling Protocol.[7] In all cases, the maximum fueling rate in the latest update is 60 g/s (3.6 kg/min), and the maximum allowable tank pressures are 87.5 MPa (for H70) and 43.8 MPa (for H35). In addition, the minimum and maximum fuel temperatures are -40^{o}C and 85^{o}C, respectively.
    - The **Table-Based Fueling Protocol** uses look-up tables included in the standard that are based on computer modeling. The appropriate table is determined by the vehicle and station conditions measured at the start of the fill session. The data used to determine the appropriate look-up table are hydrogen delivery temperature and CHSS capacity category (the dispenser will not initiate the fill if the CHSS pressure rating is less than the dispenser rating). The look-up tables are further divided into a communication fill or non-communication fill. Fueling parameters of a given session are ambient temperature and initial CHSS pressure, which are used to determine the appropriate APRR and target final pressure. The look-up tables are considered conservative, as the provided APRR ensures that the pressure/temperature limits will not be exceeded in any instance, thus, preventing over-pressurizing/overheating the CHSS [175]. There is also a "top-off" category under the H70 communications fills when a vehicle starts fueling at a low initial CHSS pressure (0.5 – 5 MPa) and ambient temperature above 0^{o}C. This approach assumes the non-communications APRR for the initial fill period (until the target pressure achieved) then the APRR is reduced to meet the top-off target pressure [175], [181].
    - The Mass and Thermal Capacity (**MC) Formula**-**Based Fueling Protocol** (MC Formula) uses a dynamic, analytical approach to calculate the Pressure Ramp Rate (PRR) in real time–once at initiation, then after 30 seconds, and then 1 measurement per second to update the pressure ramp rate for the fill session duration. "MC" stands

[7] "MC" is a reference to the formula for heat rate: $q = mC\Delta T$, where q = heat transferred, m = mass, c = specific heat capacity, and ΔT = change in temperature

for “Mass and thermal Capacity” (i.e., total heat capacity) [179], [182]. The MC Formula uses a regression equation to calculate the appropriate PRR at a frequency of once every second, considering ambient temperature, initial CHSS pressure, mass flow, and gas pressure and temperature measured at the nozzle outlet. The MC Formula also has non-communications and communications options, which differ in how the pressure endpoint is calculated, with the non-communications method assuming “Worst Case” conditions, which are provided in the look-up tables [175].

Pre-determined look-up tables are provided in J2601 for both the Table-Based Fueling Protocol and the MC Formula. The general format of the look-up tables for the Table-Based Fueling Protocol is illustrated in Figure 21 for non-communications fills and Figure 22 for communications fills. All look-up tables include the parameters described above in order for the user to determine the correct look-up table and table line to use for a given fill session. The “No Top-Off” and “See Top-Off” sections are dependent on the specific look-up table. Also, some look-up tables have more extensive “No Fueling” sections [175].

Figure 21. Look-up Table Format, Non-Communications

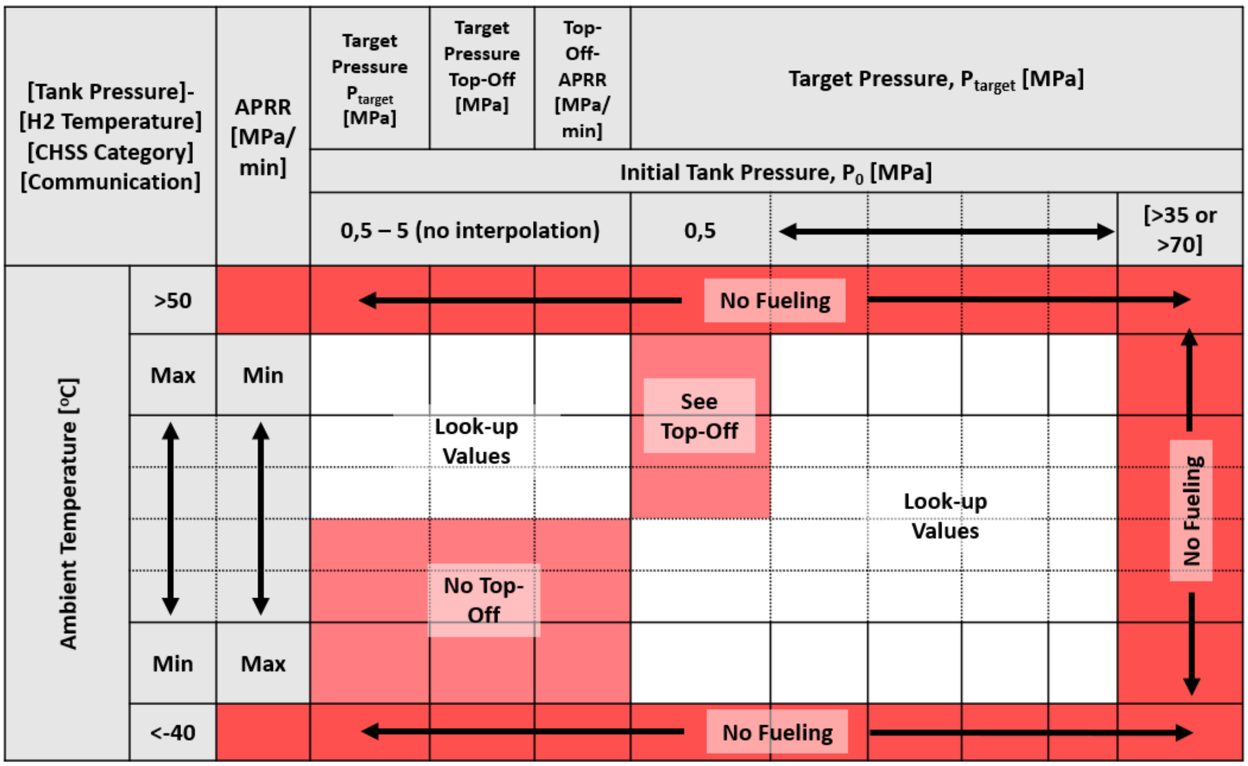


Data from SAE J2601

Figure 23 presents the general format of the MC Formula tables. The tables provide the session pressure target for the non-communication case and the pressure limit for the communication case. The “No Fueling” sections vary based on whether there are communications. For communications, this pressure limit services as a secondary limit, representing 115% State of Charge (SoC) of the tank.

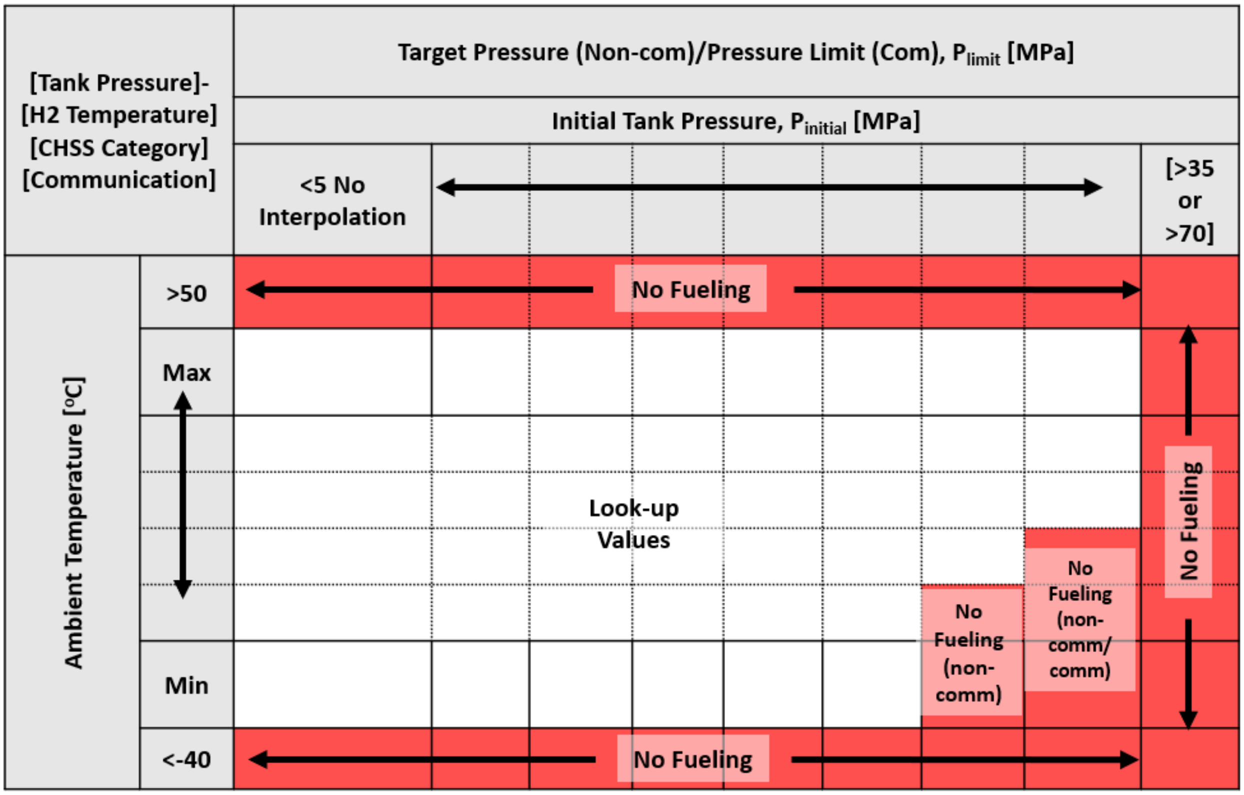
SAE International has released a short guidance document for MD/HDV fueling: SAE J2601-2 Fueling Protocol for Gaseous Hydrogen Powered Heavy Duty Vehicles [183]. This document provides a general overview of operational limits for H35 but is not a comprehensive fueling protocol. Under the current guidance, there are three fueling options characterized by maximum flow rate: (A) ≤ 120 g/s, (B) ≤ 60 g/s, and (C) ≤ 30 g/s. The high flow rate under option A requires a high flow nozzle (ISO 17268:2012) that is intentionally incompatible with the standard H35 receptacle. SAE International has also released a fueling protocol for industrial heavy-duty vehicles, namely used for forklifts, SAE J2601-3 Fueling Protocol For Gaseous Hydrogen Powered Industrial Trucks [184].

Figure 22. Look-Up Table Format, Communications (H70 for Top-Off Sections)



Data from SAE J2601

Figure 23. MC Formula Table Format, Communications/Non-Communications



Data from SAE J2601

5.3.2 Development of Medium- and Heavy-Duty Fueling Protocols

Current heavy-duty, high-fill vehicles (>30 kg) are being fueled using a variety of methods (e.g., J2601 Category D, J2601-2, JPEC-S 0003, custom APRR-based protocol) [185]. Several heavy-duty vehicle protocols are in development to provide faster, standardized fueling [185]–[187]. The standardization of these protocols is being coordinated between ISO and SAE International.

5.3.2.1 H35 Fueling Protocols

SAE J2601 provides a standardized protocol for H35 for CHSS capacity between 1.19 – 5.97 kg. J2601 currently does not have a Category D (CHSS >6 kg) for the H35 pressure class. Instead, J2601-2, which is recommended practice, provides guidance on fueling heavy-duty vehicles and buses at 350 bar [183]. The primary application of J2601-2 is fuel cell electric buses, which generally have H35 tanks with a capacity greater than 6 kg. For this application, the flow rate guidance in J2601-2 is paired with a customized protocol to provide hydrogen fueling to the buses at private hydrogen refueling stations. The protocol can vary across different hydrogen refueling stations as J2601-2 does not specify a required fueling method (Table-based or MC formula), only boundary conditions. If future fleets with similar hydrogen tank specification wish to use public stations, a standardized protocol is needed. It is anticipated that the next J2601 will provide a new "Category D" for H35 effectively addressing the current gap, see Table 22.

Table 22. Hydrogen Fueling Standards Scope and Future Updates for H35

CURRENT

CHSS (kg)	Fueling Rate (kg/min)		
	1.8	3.6	7.2
1.19-2.39	J2601 Category A		
2.39-4.18	J2601 Category B		
4.18-5.97	J2601 Category C		
5.97-10			
10+	J2601-2 Slow Fueling Option C	J2601-2 Normal Fueling Option B	J2601-2 Fast Fueling Option A

PLANNED

CHSS (kg)	Fueling Rate (kg/min)		
	1.8	3.6	7.2
1.19-2.39	J2601 Category A		
2.39-4.18	J2601 Category B		
4.18-5.97	J2601 Category C		
5.97-10	J2601 Update Category D		
10+			J2601-5 MC Formula High Flow

Connection Type
SAE J2600/ISO 17268
ISO 17268:2012 HDHSV
Future connection (SAE J2600/ ISO 17268 Revision)

Note: J2601-2 is a recommended practice and not a full standard

5.3.2.2 H70 Fueling Protocols

A major focus of the international community is the development of a high flow H70 HDV fueling standard within ISO. Several standards are under development within ISO. The main two are high flow HDV fueling, updating ISO 17268 and establishing a new standard—ISO 19885 (-1,-2,-3) [186]. The scope of ISO 17268 is the design of the nozzle and corresponding receptacle, operational characteristics including safety guidelines, and communication hardware [166].

ISO 19885-1, currently in the committee draft stage, is intended to provide information on the design and development process for fueling protocols. ISO 19885-2 is intended to address communications requirements. Lastly, the scope of ISO 19885-3 is expected to include fueling protocol(s) for high flow H70 fueling for heavy duty road vehicles. The target average flow rate under the new standard of 80 kg in 10 minutes is consistent with U.S. DOE targets (8-10 kg/min)**Error! Reference source not found.**. The current timeline for standard development is completion by 2025. There is a plan to harmonize the completed ISO standards with SAE International standards [187]. The upcoming ISO 19885-3 standard is purported to include multiple fueling protocol options, including those based on the PRHYDE work and the MC Formula method used in J2601.

However, given the immediate need for a standardized high flow fueling protocol, there is discussion to accelerate dissemination of high flow fueling data and methods through the development of a SAE TIR that would precede the ISO 19885-3 publication [187]. This TIR “SAE J2601-5” will describe high flow fueling protocols using the MC Formula in combination with nozzles having similar specifications to the current standard but a larger bore size to allow for higher flow. The timeline for completion of the TIR is 2024. Table 23 presents a summary of the standards available to meet different compressed hydrogen storage capacities and fueling rates.

Table 23. Hydrogen Fueling Standards Scope and Future Updates for H70

CURRENT

CHSS (kg)	Fueling Rate (kg/min)	
	<=3.6	7.2
2.00-4.00	J2601 Category A	
4.00-7.00	J2601 Category B	
7.00-10.00	J2601 Category C	
10-30	J2601 Category D	
30+		

PLANNED

CHSS (kg)	Fueling Rate (kg/min)				
	<=3.6		7.2	8	10+
2.00-4.00	J2601 Category A				
4.00-7.00	J2601 Category B				
7.00-10.00	J2601 Category C				
10-30	J2601 Category D	J2601-5 Category D High Flow		J2601-5 MC Formula High Flow & ISO 19885-3*	
30+					

Connection Type
SAE J2600/ISO 17268 (green)
Future connection (SAE J2600/ ISO 17268 Revision) (red)

*ISO 19885-3 may also cover liquid fueling

At the time of this report, a faster (>3.6 kg/min) standardized protocol for HD vehicles is still under development. In the interim, SAE J2601-5 is anticipated to inform market deployment. With the release of ISO 19885-3, multiple protocols may be available, which has the risk of increasing protocol heterogeneity in the future MD/HD market. Ensuring interoperability will become a greater focus as the market matures.

5.4 Communications

In the early transit fuel cell electric bus market, variability in communication approaches, particularly wireless versus physical connection, resulted in interoperability issues between different HD hydrogen fueling stations [188]. The market appears to be moving towards wireless communications, with current standards focused on wireless communications and the advanced protocols in development also focused on wireless methods, see Table 24. SAE J2799 specifies the wireless communications hardware and communication requirements for fueling hydrogen vehicles with compressed hydrogen storage. [180]. This standard is paired with SAE J2600 and the SAE J2601 document series.

Table 24. Hydrogen Fueling Communications Standards

Standard	Description	Status (Year of Update)	Market(s)	U.S. Market Penetration	MD/HD Suitability
SAE J2799	Communications	Revised (2019)	North America	Widely adopted	High, revision needed
ISO 19885-2	Communications for high flow fueling	WIP (2023)	Asia, Europe, North America	In development	High

SAE 2799 data communications are based on infrared transmission from the vehicle to the hydrogen dispenser (one-way transfer of data). The infrared optical physical layer is defined in the Infrared Data Association (IrDA) Serial Infrared Physical Layer Specification (IrPHY) 1.4. The data link layer protocol ensures valid data transfer and is based on IrDA infrared link access protocol (IrLAP) 1.1. The data transferred are those required to follow the communication-based protocols as defined in SAE J2601: pressure, temperature, pressure class/receptacle type, CHSS temperature, and CHSS volume. [180].

Data transfer begins once the dispenser nozzle is inserted into the vehicle inlet and continues throughout the fueling session. If the vehicle sensor is unable to provide valid data to the dispenser, the hydrogen fueling station will follow the available non-communication protocol. In addition, if communications are lost during fueling, the fueling session will either be aborted or the protocol will switch to non-communications [180].

Current standards development efforts anticipate that advanced communications will be needed to improve fueling rates and achieve parity with diesel fueling. The PRHYDE project found that advanced communications can lead to more dynamic control, and possibly higher pre-cooling temperature and improved end state-of-charge (SOC) [185]. This may include bidirectional communication, whereas SAE J2799 currently covers unidirectional communication. Advanced communications are an active area of research, with multiple organizations testing new techniques and technologies [189], [190]. For example, in 2020, Nikola Corporation patented an advanced communications protocol, which could be used in coordination with a high flow hydrogen fueling protocol as well as for battery electric vehicle charging protocols [190]. Standardization for high flow communications is being developed in coordination with ISO 19885-3, with plans to harmonize with SAE.

5.5 Safety and Security

Safety requirements are regulated at the federal and state levels, with the U.S. and California governments establishing codes and regulations to ensure that hydrogen fueling stations maintain a high assurance of safety. Table 25 presents an overview of hydrogen fueling station safety codes and regulations from [62].

Table 25. Safety Codes and Standards Relevant to Hydrogen Refueling Stations

California Code, Standard, or Regulation	Description	Status (Update)	Market(s)	U.S. Market Penetration	MD/HD Suitability
NFPA 1	Fire Code, safety requirements	Revised (2024)	North America	Widely adopted	High
NFPA 2	Hydrogen fueling station design and safety	Revised (2023)	North America	Widely adopted	High
NFPA 30A	Guidelines for storage and handling motor fuels at fueling stations	Revised (2024)	North America	Widely adopted	High
NFPA 55	Hydrogen storage and safety	Revised (2023)	North America	Widely adopted	High
NFPA 70	National Electrical Code, safety requirements	Revised (2023)	North America	Widely Adopted	High
OSHA Reg. 29 CFR 1910 Subpart H (1910.103)	Hazardous Materials: Hydrogen, safety requirements related to worker protection	Revised (2007)	United States	Widely Adopted	High
40 CFR Part 68, subpart G	Risk Management Plan, includes plan requirements for hydrogen facilities	Revised (2019)	California	Shared market, varies by state	High
California Health and Safety Code Section 25510(a)	Hazardous Materials Release Response Plans and Inventory: Business and Area Plans	Revised (2020)	California	Shared market, varies by state	High
CCR Title 24 (multiple parts)	Building/Construction Codes, incorporates and amends NFPA codes	Revised (2022)	California	Shared market, varies by state	High

Safety codes and standards include general building considerations, electrical systems, energy systems, fire safety, hazardous materials, and accurate accounting of hydrogen dispensed. A key safety standard referenced is NFPA 2, which defines primary safeguards needed across the hydrogen supply chain, spanning generation, storage and handling, delivery, and use [191]. NFPA 2 covers gaseous and liquid hydrogen systems, describing safety considerations when planning the design of a station (e.g., ventilation, spacing) to address health and safety risks of handling and storage of hydrogen. Compliance with NFPA 2 is required for all hydrogen fueling stations within California [62]. The updates to NFPA 2 in 2023 included revised set back distances for liquid hydrogen storage based on new modeling using Hydrogen Risk Assessment Models (HyRAM+), a toolkit for quantitative risk assessment and consequence analysis for hydrogen infrastructure [192].

Additional standards and codes required that address safety include OSHA's Reg. 29 CFR 1910 Subpart H (1910.103), which covers safety requirements during hydrogen delivery, storage, and use with a focus on worker safety [118] and California's Health and Safety Code Section 25510(a), which covers hazardous materials release. CCR Title 24 covers building and construction codes, including amended versions of NFPA documents, such as NFPA 1 and NFPA 70. California routinely updates its Code of Regulations to reflect revisions at the national level and new State rulemakings, allowing for revised guidance on hydrogen fueling stations as the technologies evolve.

Safety planning includes not only design considerations to minimize the risk of unintentional malfunctions but also to minimize the risk of intentional tampering. Tampering vectors include physical damage that harms the performance of the station, risking hydrogen release, fire, or other incident, or sends the station offline. It also includes cyberattacks that can steal payment data and risk site security.

The two main paths for cyber-access to a station are the nozzle infrared sensor and the payment system. In the first case, there is a risk that safety protocols can be bypassed to initiate an unapproved fill. In the second case, the risk is stealing consumer payment data. More detail on cybersecurity risks associated with payment systems is presented in Section 4.4. A secure hydrogen fueling station requires a robust framework for receiving, vetting, and utilizing communication data.

In addition to codes, standards, and regulations, government-developed tools are available to support the safe and secure deployment of hydrogen as a transportation fuel. Some examples include H2Tools, a suite of tools to promote hydrogen best practices [193], HyRAM+ and Hydrogen Filling Simulation (H2FillS), a simulation tool for modeling hydrogen flow behavior during fueling to support safety and compliance with codes and standards [194]. More information on station testing and standards compliance certification is covered in the next section.

5.6 Testing and Certification

Commissioning of a hydrogen fueling station requires compliance testing, DMS certification, and verification that the station adheres to all prescribed regulations, codes, and standards. Several federal and state codes and regulations, as well as local ordinances are used in concert to define specific requirements of a given hydrogen fueling station. Testing can include assessing interoperability across multiple, comparable standards (e.g., ISO versus SAE). Proof of compliance generally occurs right after construction during the station commissioning stage [62].

Table 26 lists relevant codes and standards related to the testing and certification of hydrogen fueling stations in California. Safety codes covered in the previous section are also applicable under the current section. CSA/ANSI HGV 4.9 provides an overarching specification that encompasses requirements for the design, construction, operation, and maintenance of hydrogen fueling stations (gaseous) [195]. Elements of a station that require testing include hydrogen fuel quality, communications, fault detection, and fueling accuracy. CGA G-5.3 serves as a specification for hydrogen quality verification at a hydrogen fueling station [38]. Hydrogen fuel quality requirements, as defined in SAE J2719, include the minimum molar hydrogen content required (≥ 99.97%), as well as the maximum concentrations of contaminants of concern [196]. Potential contaminants include, but are not limited to, water, hydrocarbons, oxygen, and nitrogen, and can be tested using methods defined by ASTM.[8] CSA/ANSI HGV 4.3 defines testing methods for evaluating hydrogen fueling dispenser compliance against J2601 (fueling) and J2799 (communications) [197]. CCR Title 4, Division 9, Chapter 1 includes national definitions (NIST Handbook 44), exceptions, and additional technical requirements for commercial weighing and measuring devices [66]. ISO 18000 and 18046 are related to payment systems at stations, which were previously covered in Section 5.2.3.

To expedite the certification process, the Department of Energy commissioned the development of Hydrogen Station Equipment Performance (HyStEP) device that is being used at publicly and privately funded hydrogen fueling stations to validate that the hydrogen dispensers operate within the tolerance limits defined within the relevant codes and standards [198]. HyStEP was designed for and is currently being used at light-duty hydrogen fueling stations. New methods for testing HDV high flow fueling protocols are under development.

CARB recently awarded a contract for the development of a new HyStEP 2.0 device [199]. The HyStEP 2.0 device will include new hardware and capabilities that enable testing of fueling protocols for larger vehicle tank sizes, and testing of back-to-back fill performance. Once developed, both the original HyStEP and HyStEP 2.0 devices would be used to perform testing

[8] Test methods for different contaminant species are defined in ASTM D5466, D6228, D7607, D7649, D7650, D7651, D7652, D7653, D7675, D7676, D7833, D7892, D7941, D7941M.

at stations across the state. Simultaneously, the U.S. DOE and the State are funding the design of a high flow testing device [200]. The device is being designed to test for adherence to medium- and heavy-duty hydrogen fueling protocols. This effort is part of a larger project testing and modeling high flow fueling systems at NREL [201].

Table 26. Codes and Standards for Hydrogen Fueling Station Testing and Certification

Code or Standard	Description	Status (Update)	Market(s)	U.S. Market Penetration	MD/HD Suitability
California Code of Regulations (CCR) Title 4, Division 9, Chapter 1	Tolerances and Specifications for Commercial Weighing and Measuring Devices	Latest version (2022)	California	Shared market, varies by state	High
CSA/ANSI HGV 4.3	Test Methods for Hydrogen Fueling	Revised (2022)	North America	Widely adopted	High, may need revision
CSA/ANSI HGV 4.9	Hydrogen Fueling Stations	Revised (2020)	North America	Widely adopted	High, revision may be needed
CGA G-5.3	Commodity Specification for Hydrogen	Revised (2017)	North America	Widely adopted	High
ISO/IEC 18000-3	Conformance Tests for Air Interface Communications	Confirmed (2022)	Asia, Europe, North America	Widely adopted	High, HDV communications TBD
ISO/IEC 18046-3	Test methods for RFID tag performance	Published (2020)	Asia, Europe, North America	Widely adopted	High, HDV communications TBD
NIST Handbook 44	Specifications, Tolerances, and Other Technical Requirements for Weighing and Measuring Devices	Revised (2024)	U.S.	Widely adopted, states may adopt amendments	High, revisions may be needed
Title 24, (Parts 2, 3, 6, 9)	California Codes related to fire, building, and electrical safety, including testing requirements	Revised (2022)	California	Shared market, varies by state	High, revisions may be needed
UL 2075	Standard for Safety Gas and Vapor Detectors and Sensors	Revised (2023)	North America	Widely Adopted	High

DMS is also developing a proposed rulemaking that would require all stations in the state to ensure ongoing compliance with SAE J2601 via the test method CSA HGV 4.3 that is used by the HyStEP device. This requirement would apply to all stations regardless of funding source and require proof of compliance periodically, the frequency of which is still undetermined. These requirements may also facilitate the development of a third-party testing industry to help address the expected increase in workload for testing hydrogen fueling stations. CARB staff is collaborating with DMS to develop the proposed rule to update Section 3.39 of NIST Handbook

44 [202]. A pre-rulemaking workshop was held on August 11, 2022, and a final rule may become effective within the next couple years.

5.7 Industry and Government Stakeholders

Several industry consortia and business/government collaborations have focused on the development of technology and protocols in support of medium- and heavy-duty FCEV (MD/HD-FCEV) fueling, and other standards development activities are occurring at the regional level, such as a new Japanese protocol under JPEC [203] and a European protocol—PRHYDE ("Protocol for Heavy-Duty Hydrogen Refueling"). Examples include:

- **Hydrogen Fuel Cell Partnership:** is a collaboration between 71 companies, academic institutions, and government agencies focused on the advancement of FCEV and hydrogen station deployment through stakeholder engagement and collaboration [204].

- **Consortium of Hyundai, Toyota, Nel, NIKOLA, Air Liquide, and Shell:** the goal is to develop and standardize MD/HD-FCEV hydrogen inlet receptacle, dispenser hose, breakaway, and nozzle [205].

- **HyConnect:** led by Shell, Bosch, and Hochschule Aalen (University of Applied Science) with support from other OEMs. The goal is to develop advanced communications for fueling MD/HD-FCEVs [189].

- **Japan Hydrogen Association (JH2A):** consists of over 80 companies and focuses on the areas of hydrogen research, development of a global hydrogen supply chain, and policy [206].

- **Clean Hydrogen Joint Undertaking, previously the Fuel Cells and Hydrogen Joint Undertaking:** public-private partnership under the Europe Union, which developed a heavy-duty vehicle hydrogen fueling protocol under the PRHYDE project, concluded in 2022 [173]. The goals of this project were to (1) collect information on anticipated MD/HDV hydrogen on-board storage requirements; scope of existing MD/HDV fueling protocols, and if applicable identify any gaps; anticipated requirements for future fueling protocols; and existing fueling hardware, and if applicable, identify development gaps and (2) define future fueling protocol with high performance [173].

The U.S. Department of Energy's National Laboratories are conducting several research projects within the areas of hydrogen safety, codes, and standards related to MD/HD-ZEV infrastructure standardization. Table 27 presents a summary of relevant U.S. DOE projects from the 2022 Hydrogen Annual Merit Review. Current programs are eligible for renewal on an annual basis [207].

Table 27. U.S. Department of Energy Funded Hydrogen Projects related to Hydrogen Safety, Codes, and Standards for MD/HD-ZEV Infrastructure

National Laboratory	Project Title	Relevant Topic Area(s)	Relevant Codes and Standards	Years
Los Alamos National Laboratory	Fuel Quality Assurance R&D and Impurity Testing in Support of Codes & Standards	Fuel Quality, Testing	SAE J3219, SAE J2719	2006-2023
National Renewable Energy Laboratory	Assessment of Heavy-Duty Fueling Methods and Components	Fueling Protocols, Fueling Components	SAE J2600, ISO 17268, SAE J2601, SAE J2601-5	2022-2024
	Component Failure R&D	Reliability, Fueling Components	NFPA 2, ISO 19880-1, ISO 9300	2018-2023*
	High Pressure, High Flow Rate Dispenser and Nozzle Assembly for Heavy Duty Vehicles (Electricore, Inc.)	Fueling Components	ISO 17268, ISO 19880-3, -5 SAE J2601-5, SAE J2799, CSA HGV 4.1, 4.3, 4.4, 4.9, NFPA 2 ASME B31.2 ISA 12.13.03 CSA C22.1	2019-2023
	MC Formula Protocol for H35HF Fueling	Fueling Protocols	SAE J2601-2	2021-2023
	NREL Hydrogen Sensor Testing Laboratory	Safety, Fueling Protocols	NFPA 2, ISO TC 197	2010-2023*
Pacific Northwest National Laboratory	Hydrogen Safety Outreach to Expedite H_2 Fueling and Energy Project Deployment and Promote Public Acceptance for Zero Emission Vehicles and Reliable Distributed Power Generation	Safety	NFPA 2	2019-2022*
	Hydrogen Safety Panel, Safety Knowledge Tools, and First Responder Training Resources	Safety	NFPA 2	2003-2023*
Sandia National Laboratories	Hydrogen Quantitative Risk Assessment	Safety	NFPA 2, NFPA 55	2003-2023*
	R&D for Safety, Codes and Standards: Hydrogen Behavior	Safety	NFPA 2, CGA G-5.5	2003-2023*
	R&D for Safety, Codes and Standards: Materials and Components Compatibility	Infrastructure, Fuel quality	ISO 15916, ISO/TC 164/SC 1/WG 9, SAE J2719	2003-2023*

*Project continuation beyond stated year is dependent on annual U.S. DOE review.

Research topics span hydrogen safety, fuel quality, hydrogen fueling protocols for H35 and H70, and component material and design testing. These projects are providing important data and guidance for the development of HDV fueling infrastructure. For example, the National

Renewable Energy Laboratory (NREL) is conducting testing of the high flow nozzle design and parameterization of high flow fueling performance and safety [208]. It is expected that work under these different initiatives will be considered, and where possible, integrated with the on-going ISO standards development. As a part of assessing HDV hydrogen fueling protocols and components, NREL has built and demonstrated an HDV hydrogen fueling testing system at its Energy Systems Integration Facility. As of 2022, it has demonstrated hydrogen flow rates up to 21 kg/min peak. The system will be available for further testing of fueling protocols and components needed to establish a new, standardized method for high flow hydrogen fueling [201].

5.7.1 Hydrogen Fueling Industry and Government Stakeholder Engagement

This project involved engaging with standards and testing organizations involved in the development of hydrogen fueling standards and technologies for medium- and heavy-duty vehicles. This involvement included active participation in the ISO 19885 committee, which focuses on fueling protocols for hydrogen-fueled vehicles and falls under ISO Technical Committee 197, Work Group 24. The team also conducted one-on-one interviews and two consultatory group meetings to gather input on the standards assessment. Table 28 presents the list of stakeholders that participated in the consultatory process.

Table 28. Participating Industry and Government Stakeholders

Industry Stakeholders		
Air Liquide	Hydrogen Fuel Cell Partnership	New Flyer
Air Products	Hyundai	Nikola
Chevron	Hyzon	Shell
FirstElement Fuel	Kenworth	Toyota
Government Stakeholders		
Argonne National Laboratory	California Air Resources Board	California Energy Commission
California Governor's Office of Business and Economic Development	National Renewable Energy Laboratory	Orange County Transportation Authority

From stakeholder interviews, several challenges to broad deployment of hydrogen fueling for MD/HD FCEV were identified. These include low reliability, long hydrogen fueling times, high cost, long commissioning time, and varying local permitting processes. Overall, there is strong industry coordination regarding the development of MD/HD-ZEV hydrogen fueling standards with several concurrent national and international projects investigating the development of new technologies, methods, and procedures. Both high flow hydrogen fueling standards development are in the committee writing stage with a 3 to 5-year timeline. A TIR for SAE J2601-5 was released in February 2024, and an equivalent report from ISO is planned to provide interim guidance preceding the release of a full standard. Appendix G presents a summary of takeaways from the consultatory meetings and one-on-one interviews.

5.8 Summary of Current Gaps and Medium- and Heavy-Duty Vehicle-Specific Needs

Significant work is on-going to achieve the goal of standardized, reliable hydrogen fueling that is fast, safe, and secure. These activities seek to improve hydrogen fueling performance through new technology and standards development. These developments include new hardware, hydrogen fueling protocols, and advanced communications. In addition, new testing devices and methods are needed to verify new, large capacity, high flow systems. Based on the literature review and feedback from stakeholders, the following is a summary of current gaps and desired improvements that have been identified:

- **Fueling Hardware for High Flow Fueling**

  Goal: The goal of implementing faster, reliable fueling technologies is to achieve parity with diesel fueling, with HD hydrogen fueling rates averaging 10 kg/min. This rate would allow class 8 trucks to fuel under 10 minutes.

  Type of Gap: Standards, Technology

  Faster fueling is currently limited by the dispenser design, component reliability, and fueling protocol standards, which were originally designed for LDVs and limited transit applications. Fueling hardware prototypes are currently being tested but not yet standardized for fueling rates above 7.2 kg/min with ISO 17268 (2012) and above 3.6 kg/min for SAE J2600. At the same time, the reliability of key fueling systems, such as the dispenser and compressor, is low.

  Gap Impact on MD/HD-ZEVs

  SAE J2601-2 and ISO 17268 (2012) allow for hydrogen flow rates up to 7.2 kg/min for H35 fueling, which have been deemed insufficient for HD large hydrogen capacity vehicles. (Note: protocols specify rates *up to* the defined values and average flow rates are significantly lower, see [209]). Low reliability of components can result in low station uptime.

  Recent Activities

  As discussed in previous sections, several industrial consortia and national laboratory projects are working on the development of new hardware (nozzle, breakaway, hose, etc.), modeling and experimentation of high flow fueling, and development of new test equipment and methods. Currently, these advancements are being integrated into new standards (e.g., ISO 17268 updates; ISO 19885-1, -2, -3) that can be utilized for widespread MD/HD-ZEV deployment. In addition, research into improving station component reliability is being conducted by multiple stakeholder groups, including station providers and national laboratories.

Anticipated Activity Outcomes

In the near term, the updated nozzle design that is in the process of being standardized may be used to support higher flows under TIR J2601-5. While component reliability remains an issue, HD stations should incorporate system redundancy measures that allow for continued operation in the case of a non-critical component failure. In the long term, it is anticipated that reliability issues will be addressed through research and development. Station providers are at the forefront of ensuring that stations are designed with high reliability. The State can provide guidance to station providers to facilitate compatibility between different generations of stations.

- **High Flow Fueling Protocols**

Goal: The goal of updating and developing new protocols is to improve fueling performance and reduce fueling times.

Type of Gap: Standards

Overall, current high-fill (>10 kg) vehicles are being fueled using a variety of methods, including J2601 Category D, SAE J2601-2, and JPEC-S 0003 [185]. Current protocols have been reported to be overly complex and restrictive to implement and in general, too conservative. While safety should remain the priority, the future protocols should also consider reducing the difficulty in implementation. Several private-public partnerships are working to develop optimized approaches, building on recent technological innovations, and utilizing updated computer modeling and experimental testing. The new protocols will also need advanced communications.

Gap Impact on MD/HD-ZEVs

SAE J2601 Category D results in slow fueling due to low flow rates and conservative fueling assumptions [185]. SAE J2601-2 requires custom protocol development which hinders interoperability across different stations [183]. Also, protocols can result in lower end state of “charge” due to the more conservative assumptions of end target pressures. Examples include non-communication protocols and H35 fueling which result in lower hydrogen transfer capacity compared to the higher H70 pressure class.

Recent Activities

High flow fueling protocol standards are under development through new and revised standards, e.g., SAE J2601-5, ISO 19885, and ISO 17268 (hardware). On-going research activities, including updated computer modeling, experimental testing, and new hardware development, are expected to inform these standards. Standardization for high flow communications is being developed under ISO 19885-2 in coordination with ISO and SAE protocol standardization.

Anticipated Activity Outcomes

Harmonized SAE and ISO standards for high flow hydrogen fueling, with a target hydrogen flow rate of 10 kg/min, are anticipated within the next few years. A SAE J2601-5 TIR was released in February 2024 and can inform near term HD station development. With the release of ISO 19885-3, multiple protocols may be available, based on the work done in Europe and Asia. The potential of multiple protocols may pose a risk of increased heterogeneity in the MD/HD vehicle market. This can create challenges, particularly in terms of interoperability. As the market for MD/HD vehicles matures, ensuring interoperability between different protocols becomes more crucial.

- **Lack of Standardized H35 Fueling Protocol for Larger (>6 kg) Fill**

  Goal: The goal is to standardize the current implementation and ensure an H35 option for MD/HD-ZEVs with CHSS capacities greater than 6 kg that may be deployed in the future.

  Type of Gap: Standards

  Fueling for H35, greater than 6 kg fills is described in SAE J2601-2. However, SAE J2601-2 is a guidance document that requires a custom protocol that considers specific vehicles that fuel at the station, causing heterogeneous deployment across stations, impacting station interoperability.

  Gap Impact on MD/HD-ZEVs

  H35 stations are generally less expensive than H70 due to less intensive demands for compression, chilling, and maintenance. The trade-off is that on-board hydrogen storage capacity is half that of H70. This vehicle range trade-off may be acceptable for some MD/HD applications, as demonstrated by transit early adopters. Currently, J2601-2 is utilized for the private stations that fuel these buses. The current J2601-2 document is not prescriptive and requires custom implementation and is not suitable for public stations. A comprehensive, standardized protocol is needed to support deployment of public H35 hydrogen refueling stations for medium- and heavy-duty buses and other future use cases.

Recent Activities

Full protocols are in development under two standards. It is anticipated that the next SAE J2601 update will include a new H35 category D for flow rates up to 3.6 kg/min. SAE J2601-5 is anticipated to include a high flow protocol covering the scope previously addressed in SAE J2601-2.

Anticipated Activity Outcomes

This gap should be considered addressed in the next J2601 update, where it is anticipated to fall under a new H35 "Category D" for normal fueling and J2601-5 for MC formula high flow. An outstanding issue is to what degree existing stations that use J2601-2 guidance can or should be compatible with these new protocols.

- **Lack of Standardized Process for HDV Station Certification and Testing**

  Goal: Safe and reliable performance of hydrogen refueling stations for MD/HD-FCEV fueling.

  Type of Gap: Standards, Codes, Policy, and Technology
  Current procedures for commissioning hydrogen refueling stations are designed for light-duty vehicle stations. It is probable that new procedures and devices are needed to accommodate differences in MD/HD fueling protocols, station equipment, and vehicle design. These new specifications could benefit from the development of a type approval certification process, possibly administered by NRTLs, as well as new test procedures to verify fueling protocol compliance and back-to-back fueling performance.

  Gap Impact on MD/HD-ZEVs

  Methods for testing LDV stations have limited applicability to HDV stations, especially when high flow equipment and fueling protocols are released. Testing of high flow equipment will require flow meters that can monitor the higher flow rates (10 kg/min average versus the previous maximum of 3.6 kg/min for J2601-1 or 7.2 kg/min for J2601-2). It is important that testing equipment and measurement instruments have a high degree of accuracy to ensure safe and accurate reporting of the station and vehicle conditions [185]. In addition, accuracy tolerance of measured hydrogen dispensed should be assessed within the scope of commercial vehicles. Fleet operators may desire a lower tolerance (i.e., greater dispensing accuracy), because accurate accounting of hydrogen dispensed is directly tied to how far a vehicle can travel and the cost of fueling.

  Recent Activities

  Several concurrent efforts are developing devices, test methods, and validation procedures for HDV fueling, such as the current industry efforts and the U.S. DOE programs mentioned in Section 6.7. These efforts include the development of new test devices for large capacity fills and high flow fueling protocols.

<u>Anticipated Activity Outcomes</u>

New testing devices and procedures will be standardized within new ISO and SAE standards once documents for high flow protocols (ISO 19885-3, SAE J2601-5) are finalized. In advance of formal standards, California and U.S. DOE can coordinate with HD station providers to provide access to these new testing devices and procedures, which are being funded in part by the State and federal government.

Additional considerations include:

- **Emergency Services Education and Training**

  Similar to BEV charging, emergency response teams have limited experience with designing and operating hydrogen refueling stations. As the number and capacity of hydrogen stations increase, it is important that testing and safety guidelines (e.g., NFPA 2) are more broadly understood and incorporated in regional planning. Local and regional variability in station permitting, understanding of hydrogen properties and safety, and emergency response training leads to longer commissioning times and a slower growth of MD/HD-FCEV deployment. Lead times can also affect project costs and overall feasibility. While there have been several state initiatives on the EVSE-side to streamline the permitting process (e.g., through AB 1236), there has been less progress on streamlining hydrogen refueling station permitting. However, several tools and guidance documents are available to assist in hydrogen refueling station design and deployment, such as H2Tools and the Governor's Office of Business and Economic Development (GO-Biz) "Hydrogen Station Permitting Guidebook" [62], [193].

6. Summary, Conclusions, and Recommendations

Zero-emission vehicle technologies, including charging and hydrogen fueling infrastructure, have advanced over the last decade in response to State climate and air quality policies. The initial growth in the LDV sector has established foundational codes and standards that can either be adapted to MD/HD vehicle applications or can inform new codes and standards to meet MD/HD vehicle applications and beyond. Available codes and standards span hardware, charging and hydrogen fueling protocols, communications, safety, security, testing, and certification.

This assessment analyzed the status of charging and fueling standardization efforts across electric vehicle charging technologies (e.g., plug-in, overhead conductive, and wireless inductive) and hydrogen fueling technology within the context of the transition of on-road MD/HDVs to ZEVs in California. To that end, crucial standardization gaps and technology limitations were identified and priorities for policy actions discussed.

Several gaps and areas of improvement that, once addressed, can facilitate and accelerate mass market adoption of ZEVs within the on-road MD/HD market. MD/HD BEV charging gaps include the need for power charging at the megawatt scale, robust reliability, and increased automation. MD/HD FCEV hydrogen fueling gaps include the need for fast fueling protocols, a standardized H35 protocol for larger fills, consistency in achieving a complete fill, and an absence of standardized heavy-duty specific certification and testing procedures.

Based on the assessment, the following conclusions were drawn:

1. **Kilowatt-level charging is well established but will not meet all MD/HD-BEV operational use cases.** Mature standards provide options up to 350-450 kW. However, available charging rates are insufficient for fleets that operate larger vehicle classes, have longer routes, and/or have little downtime between shifts. While higher charging rates are needed to support many heavy-duty applications, fleets may find a trade-off between installing higher power systems and cost.

2. **New standards that permit higher charging rates and greater flow rates for hydrogen fueling are needed to meet fully the range of expected MD/HD-ZEV applications.** Several standards in development are focused on supporting increased charging power and faster hydrogen fueling rates in order to achieve reasonable MD/HD-ZEV charging and hydrogen fueling times. Not only will these new standards support on-road MD/HD-ZEV deployment, but they will also become the foundation for other applications, such as larger off-road equipment, aviation, rail, and shipping, which will all need to be addressed to meet the state's 2045 emissions reduction targets.

3. **Increased reliability is needed to support the broad market utilization of MD/HD-ZEV infrastructure.** Electric LDV charging and hydrogen fueling stations have experienced outages and other operational challenges that interfere with the consumer experience. For LD-ZEV and especially MD/HD-ZEV stations, it is essential to enhance reliability by mitigating issues associated with communication and component failures, and hydrogen supply. While the industry is actively engaged in efforts to tackle these issues, policy and government oversight that assures maintaining an acceptable level of overall performance of charging and hydrogen fueling stations is priority one.

4. **The continued improvement and prioritization of cybersecurity for ZEV stations is also a high priority.** Station providers are leveraging several tools, including updated standards and best practice recommendations, to strengthen station cybersecurity. However, a standardized, robust cybersecurity approach across the ZEV infrastructure markets is lacking. State and federal governments have directed action on cybersecurity for charging stations, including California mandating security standard PCI-DSS for payment systems at public stations (SB 454) and the federal NEVI formula program requirements, including compliance with OCPP and 15118. Hydrogen stations have similar risk vectors and advancements in encryption and security standards can be equally applied across both station types.

5. **Due to the wide range of vehicle classes and applications within the MD/HD sector, a combination of station configurations is needed to meet MD/HDV needs.** MD/HD ZEV adoption necessitates the deployment of both charging and hydrogen fueling stations. While for BEV charging, AC level 2 charging may be sufficient for some medium-duty applications (e.g., shorter route applications and last mile delivery), DC fast charging up to megawatt level charging will be required to support larger vehicle classes and longer-range vehicle applications (e.g., long haul).

   For hydrogen fueling, current station configurations in California include two pressure classes: 350 and 700 bar. Future hydrogen station sizing will vary depending on the number of vehicles with access, and station hydrogen storage will be either gaseous or liquid depending on the hydrogen supply and station size.

   Furthermore, fleets using either BEVs or FCEVs may require a combination of private (fleet-based) and public infrastructure to ensure a resilient fueling network. These station variations will need to be appropriately considered in code requirements and public funding solicitations.

6. **Several challenges, outside the scope of this study on standards, hinder the broad deployment of MD/HD-ZEVs.** These challenges include vehicle and fuel supply constraints, cost, and training. Limited ZEV options are currently available for a range of

vehicle applications and potential station locations are hindered by a lack of sufficient electric grid capacity and the need for utility upgrades. Similarly, the supply of renewable hydrogen will need to significantly increase to meet future MD/HD-FCEV demands. Capital costs for ZEVs and their associated infrastructure remain prohibitive for many fleets. Lastly, the expansion of ZEVs and infrastructure requires that technicians and emergency services are trained in new, high voltage systems as well as hydrogen-specific systems to ensure station safety.

Based on the conclusions of this study, the following policy considerations are recommended:

1. *Policies for MD/HD-ZEV stations should strike a balance between the need for standardization and the promotion of on-going innovation.*
While key areas of focus for required codes and standards are safety, security, and reliability (including interoperability), policies should provide a flexible framework that establishes effective codes and standards but promotes innovation and allows for the integration of new technology advancements.

2. *In public funding solicitations, differentiate station type and configuration, including public versus fleet-only access, when setting codes and standards requirements.*
For example, private stations may be allotted additional flexibility in design to meet the specific requirements of the target fleet. On the other hand, public stations are oriented towards providing services to the greatest number of vehicles as possible, which will require a higher standard for interoperability as well as faster charging rates and hydrogen fueling rates to promote high station throughput.

3. *Promulgate "short term" guidance for charging and fueling protocols employed in MD/HD commercial stations with the goal of facilitating interoperability*.
Technologies and standards are in development (e.g., SAE J2601-5) with timelines for completion between one and three years, and stakeholders will need to determine the manner in which to adapt in near-term station development. The government can (1) encourage and support technology development efforts conducted through public-private partnerships (e.g., U.S. DOE National Laboratory research and industry consortia) already testing new technologies and methods to inform the new generation of stations, (2) monitor the status of standards, and (3) provide guidance on how stations can support continued interoperability in the short-term given the different generations of stations and vehicles. Given the need for State agencies to closely monitor the evolution of MD/HD charging and fueling industry standards, it may be prudent to consider direct observation of relevant standards committees. Furthermore, a State committee administered by the Office of the Governor (e.g., GoBiz) could coordinate an effectual exchange of observations and oversee the assignment of agency observers.

4. *Require compliance with TIR documents that are pending finalization of formal standards for high power and high flow systems in public funding solicitations.* TIRs are valuable guidance documents that signal the direction of on-going standards development and have been previously used for this purpose. At the time of this report, SAE J2601-5 TIR was recently released and a TIR for SAE J3271 is in draft. These TIRs are available in advance of planned full standards. Referencing these documents can prepare stations to be compatible with upcoming standards.

Overall, transitioning to 100% MD/HD-ZEVs in California requires significant investment and coordinated, regional planning efforts. The State has a responsibility to establish infrastructure requirements that support the rapid deployment of a reliable, interoperable MD/HD-ZEV infrastructure network without hindering technological advancement within the market. To date, federal, state, and regional agencies have played a critical role in supporting technological maturation and standardization of MD/HD-ZEVs and the associated infrastructure through direct funding, program guidance, tools, and policies.

Based on the findings from this study and lessons learned from the LDV market deployment, a systematically planned agency strategy is appropriate to assure MD/HD-ZEV charging and fueling stations are designed, constructed, and operated to be:

- ***Compliant*** with industry standards, such as ISO, SAE and IEEE for operability and NFPA for safety, to be
- ***Reliable*** and thereby instill market confidence and accelerate market engagement, at levels (e.g., 98% dispenser availability) commensurate with existing fueling infrastructure, with enforcement to assure maintenance of the reliability over the life of the station, and to
- ***Leverage*** industry innovation, by allowing MD/HD design flexibility to consider future improvements.

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Appendix A. Funding Programs

Investing in zero-emission vehicles is a considerable cost and requires coordinated planning with long lead times for both the procurement of vehicles and setting up the necessary charging and/or fueling infrastructure. Direct funding for MD/HD-ZEVs and infrastructure can help offset the higher capital costs of alternative fueled vehicle adoption and drive market growth, as well as technology advancement. It also provides an opportunity for broader coordination regarding technology standardization and interoperability. Funding programs often dictate codes and standards required for eligibility. In that way, public funding can significantly shape the technologies and standards that are used in the broader market. In addition, funding programs can set benchmarks and performance thresholds which can drive industry priorities. For example, the National Electric Vehicle Infrastructure (NEVI) Formula Program proposes a minimum uptime of at least 97% for chargers, where uptime is a function of outage hours excluding outages caused by third-party interruptions (i.e., outages due to network service providers, utility providers, and vehicle-side disruptions.) [67].

There are several federal, state, and regional funding programs that provide funding for MD/HD-ZEVs as well as their fueling infrastructure.

- **Carl Moyer Memorial Air Quality Standards Attainment Program**: Moyer Program is a grant program for projects that reduce emissions ahead of regulatory requirements from heavy-duty on-road vehicles with gross vehicle weight rating greater than 14,000 lbs. to replace, repower or retrofit older, higher-emitting engines [25].

- **Clean School Bus Program:** funded by the Bipartisan Infrastructure Bill, this program is administered by the U.S. EPA and provides rebates and grant funding to transition school buses to zero-emission and low carbon vehicles between 2022-2026 [210].

- **Clean Heavy-Duty Vehicles Program:** funded by the Inflation Reduction Act and administered by the U.S. EPA, this federal grant program focuses on replacing Class 6 and Class 7 vehicles with ZEVs, as well as workforce development and training [211].

- **Discretionary Grant Program for Charging and Fueling Infrastructure:** Established under the Bipartisan Infrastructure Bill, this program focuses on deploying zero-emission vehicle fueling infrastructure along identified corridors, with a focus on benefits (at least 50%) for low- and moderate-income communities [212].

- **Energy Infrastructure Incentives for Zero-Emission Commercial Vehicles (EnergIIZE Commercial Vehicles):** Newly launched CEC program provides reimbursement style incentives to fund fueling equipment for medium- and heavy-duty battery electric and hydrogen fuel cell electric vehicles. The program offers four “funding lanes,” including a fast-track lane for fleets that already have purchased a zero-emission vehicle, in addition to “set-aside funding lanes” specific to drayage, transit, and school bus that will complement HVIP [213].

- **Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project (HVIP)**: Funded by the California Climate Investments, this program provides point-of-sale vouchers for eligible vehicles from approved vendors. Eligible vehicles include medium-duty vans, medium- and heavy-duty trucks (including refuse), buses (including school buses), refuse trucks, and electric power take-off [214].

- **Low Carbon Fuel Standard (LCFS)**: CARB created the LCFS tradeable credits program through regulation with the goal of reducing GHG emissions and providing California’s transportation sector an increasing range of low-carbon and renewable alternative fuels including hydrogen and electricity. The LCFS sets annual carbon intensity (CI) standards, or benchmarks, which reduce over time, for gasoline, diesel, and the fuels that replace them. CI takes into account the GHG emissions associated with a complete life cycle of a fuel. Fuels and fuel blend stocks introduced into the California fuel system that have a CI higher than the benchmark generate deficits. On the other hand, fuels and fuel blend stocks with CIs below the benchmark, such as renewable fuels, generate credits. Annual compliance is achieved when a regulated party uses credits to match its deficits [215]. The 2018 amendment of this regulation also provided support for the deployment of zero-emission infrastructure. The LCFS provides credits for installing ZEV infrastructure based on the capacity of the hydrogen station or EV fast charging site [216].

- **On-Road Voucher Incentive Program**: The on-road VIP provides a streamlined approach to replace older, high-polluting heavy-duty on-road vehicles with vehicles equipped with a motor or powertrain that is certified to the zero-emission standard for fleets of ten or fewer vehicles [217].

- **Sustainable Transportation Equity Project (STEP):** Program funded under the California Climate Investments, focuses on community-level investment in sustainable transportation, encompassing public transit and other clean mobility initiatives [218].

- **Targeted Airshed Grants program:** Program by U.S. Environmental Protection Agency to address degraded air quality within communities [219].

- **Volkswagen Diesel Emissions Environmental Mitigation Trust**: CARB’s California’s Beneficiary Mitigation Plan outlines the eligible mitigation actions for the trust [220]. The funded programs are administered by Air Quality Management/Control Districts, with the trust funding both zero-emission vehicle and infrastructure deployments, spanning light-duty to heavy-duty applications [26].

There are also several past programs and one-time solicitations that have supported MD/HD-ZEV infrastructure deployments:

- **Zero and Near Zero-Emission Freight Facilities:** Provides funding for “pre-commercial” deployments that demonstrate emerging, zero- and near-zero emission technologies [221].

- **Zero-Emission Truck and Bus Pilot Projects:** Subprogram under the California Climate Investments, administered by the California Air Resources Board [221].

- **Awarded California Energy Commission Grant Funding Opportunities:**
    - **GFO-20-304** – Evaluating Bi-Directional Energy Transfers and Distributed Energy Resource Integration for Medium- and Heavy-Duty Fleet Electrification
    - **GFO-20-306** – Research Hub for Electric Technologies in Truck Applications (RHETTA)
    - **GFO-20-601** – Blueprints for Medium- and Heavy-Duty Zero-Emission Vehicle Infrastructure
    - **GFO-20-602** – Zero-Emission Transit Fleet Infrastructure Deployment
    - **GFO-20-603** – Block Grant for Medium-Duty and Heavy-Duty Zero-Emission Vehicle Refueling Infrastructure Incentive Projects
    - **GFO-20-605** – BESTFIT Innovative Charging Solutions *(LDV and MD/HDV)*
    - **GFO-20-606** – Zero-Emission Drayage Truck and Infrastructure Pilot Project
    - **GFO-20-610** – Vehicle-Grid Innovation Lab (ViGIL) *(LDV and MD/HDV)*
    - **GFO-21-501** – Hydrogen Fuel Cell Truck and Bus Technology Integration and Demonstration

Funding for pilots and other “pre-commercial” deployments is important for proof-of-concept designs that will inform broader deployment of zero-emission vehicle infrastructure to meet State goals. For example, the Zero- and Near Zero-Emission Freight Facilities (ZANZEFF) projects underway or completed at the Ports created a test bed for the development of the next generation of heavy-duty fuel cell electric trucks and hydrogen refueling stations [222]–[224] and in several cases, the heavy duty trucks developed under ZANZEFF are now commercially available and eligible for HVIP point-of-sale vouchers. This test bed has provided important data on fueling performance which in turn is informing new standards currently in development for MD/HD-ZEVs.

The major California investor-owned utilities—in response to California Assembly Bill No. 841 (Ting, Chapter 372, 2020) have also implemented charging infrastructure funding programs to assist fleets with planning and funding for charging infrastructure. For example, Southern

California Edison's Charge Ready Transport program helps fleets design, install, and maintain charging infrastructure, including transformer upgrades, as well as covers some of the costs [225].

Each funding program has its own list of requirements for eligibility, including entity type, project scope, vehicle type(s), and/or what codes and standards are mandatory or preferred. Table A provides a list of codes and standards for three recent MD/HD-ZEV infrastructure funding programs.

Table A. Codes and Standards Guidance for Federal and State Zero-Emission Infrastructure Funding Programs

NEVI Formula Program [145]
Proposed Codes and Standards
CCS (at or above 150 kW) SAE J1772 23 CFR 650 Subpart A 23 CFR par 655 23 CFR part 750 EVSE ENERGY STAR certification EVSE must be certified by OSHA recognized testing laboratory Electricians must be certified through EVITP ISO 15118 Plug and Charge Payment (ISO 15118) OCPP 2.0.1 Open Charge Point Interface (OCPI) 2.2.1 Open Charge Point Interface 2.2 Chapter 1 of title 23, United States Code 2 CFR part 200 23 CFR parts 35 and 36 ADA Compliant
Energy Infrastructure Incentives for Zero-Emission Commercial Vehicles (EnergIIZE Commercial Vehicles) [213]
Required Codes and Standards
NFPA 2 NFPA 55 NFPA 70 California Health and Safety Code Section 25510(a) California Public Utilities Code (PUC) section 740.20 California Building Code, Part 2, Title 24 California Electrical Code, Part 3, Title 24 California Energy Code, Part 6, Title 24 California Fire Code. Part 9, Title 24 CCR Title 4, Division 9, Chapter 1 SAE J1715 SAE J2719 SAE J2799 UL 9741 UL 1741

ANSI/CSA HGV 4.3 CSA HGV 4.9 CGA G-5.3
Hydrogen Refueling Infrastructure
Required Codes and Standards
NFPA 2 CCR Title 4, Division 9, Chapters 1 & 6 California Building Code, Part 2, Vol. I, Chapter 11B California Health and Safety Code Section 25510(a) Code of Federal Regulations 225 ISO/IEC 14443 ISO/IEC 15961-1, -2, -3, -4 ISO/IEC 15963-1, -2 ISO/IEC 18000 ISO/IEC 18046 CSA HGV 4.3 CSA HGV 4.9 CGA G-5.3 SAE J2600 SAE J2601 SAE J2719 SAE J2799

Appendix B. Medium- and Heavy-Duty Vehicle Characteristics

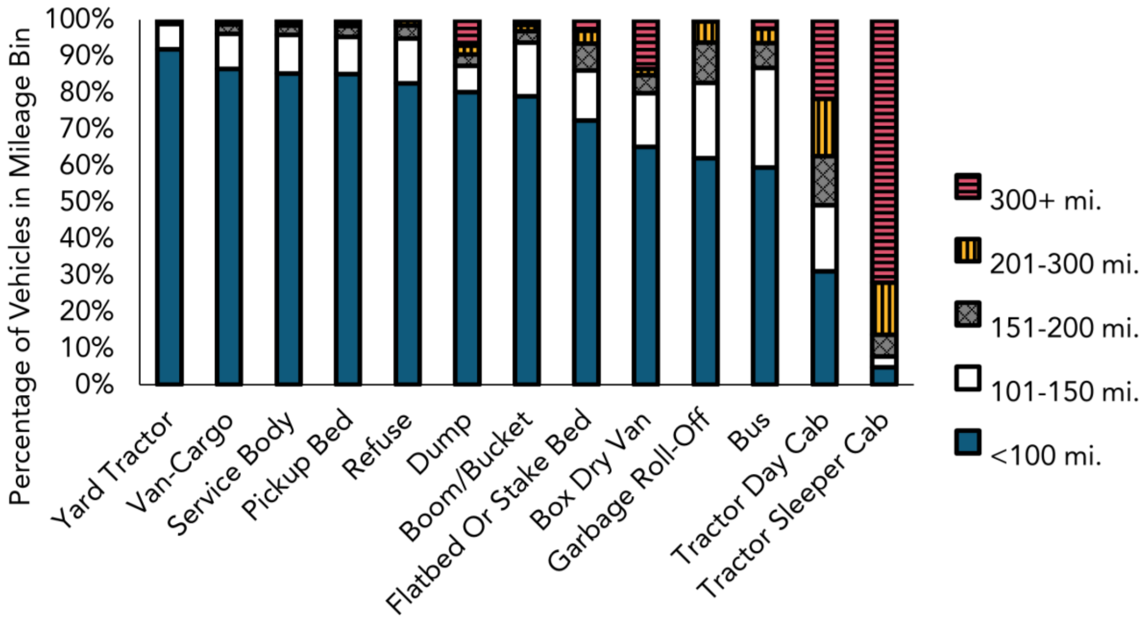
Table B. Vehicle Weight Classifications

Gross Vehicle Weight Rating (lbs.)		Vehicle Classifications				Example Vehicles [226]
	Vehicle Class	U.S. Federal Highway Administration [226]	California Air Resources Board (EMFAC2021) [227]			
0-6,000	1	Light truck	Light duty cars and trucks			Compact car, SUV
6,001 – 8,500	2a		Medium duty cars and trucks			Pick-up truck, minivan
8,501-10,000	2B	Light/Medium duty truck	Light-heavy duty trucks		Buses	Step van
10,001 – 14,000	3	Medium duty truck	Light-heavy duty trucks			Mini bus, Walk-in van
14,001 – 16,000	4		Medium-heavy duty	Class 4		van-cargo, school bus
16,001 – 19,500	5			Class 5		
19,501 – 26,000	6			Class 6		
26,001 – 33,000	7	Heavy duty truck		Class 7		Tow truck, city transit bus
33,001 – 60,000		8a	Class 8			Dump truck, yard tractor, tractor cab, refrigerated van, tour bus
>60,000		8b				

Charging and hydrogen fueling demands can vary significantly. Demand is determined by vehicle fuel efficiency and miles traveled. MD/HD vehicle fuel efficiency ranges significantly depending on vehicle weight, payload, and driving patterns. In addition, daily vehicle travel can vary based on vehicle type and application, as well as by fleet. For example, **Error! Reference source not found.** shows daily travel demand statistics for different vehicle types that were gathered from the Large Entity Reporting effort under the ACT regulation in 2020. From this mandatory survey, the State was able to compile vehicle travel statistics for different MD/HD vehicle types operated by “Large Entities,” i.e., those businesses with $50 million or more annual revenue or 50 or more MD/HD vehicles, and all government agencies within California [228]. As the data shows, average daily travel varies across vehicle categories. Therefore, suitable ZEV solutions may vary depending on the application and fleet. For example, MD/HD-BEVs that travel less than 100 miles per day would need to charge for about 5-10 hours at 19.2

kW, which is achievable if they can charge overnight. If the vehicle can charge at 150 kW, the charging time drops below two hours. For vehicles that travel 300 miles or more per day, charging 19.2 kW would be infeasible, and 150 kW would require 3 or more hours of charging. Alternatively, with today's hydrogen fueling rates, vehicles traveling less than 100 miles per day could refuel in less than five minutes and vehicles traveling 300 miles per day can still refuel in less than 15 minutes.

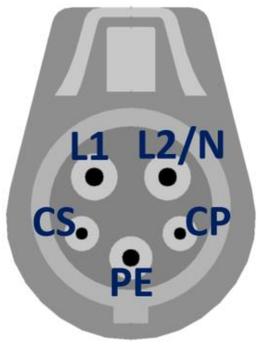
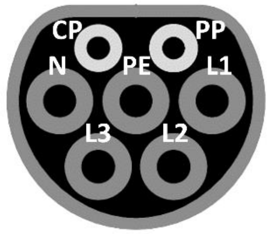
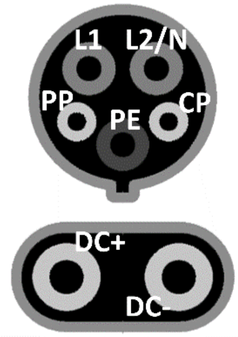
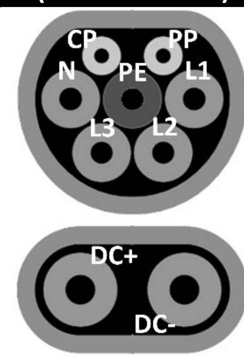
Figure B. Average Daily Vehicle Miles Traveled per Vehicle Categories

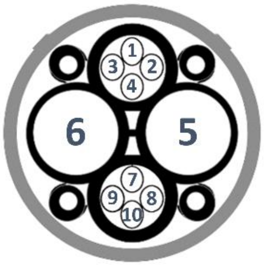
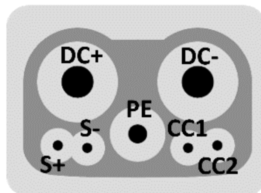
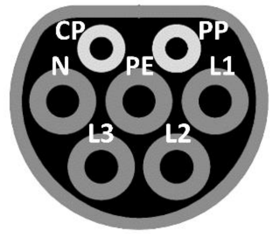
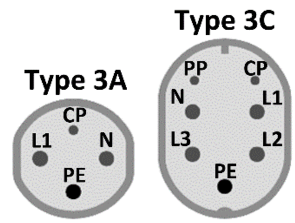


Reproduced from California Air Resources Board, Advanced Clean Fleets Regulation Summary
https://ww2.arb.ca.gov/resources/fact-sheets/advanced-clean-fleets-regulation-summary

Appendix C. Charging Connector Diagrams and Descriptions

Table C. Various BEV Charging Connector Pin Diagrams

SAE 1772 (Type 1)	IEC 62196-2 (Type 2 - Mennekes)	CCS1 (IEC 62916-3 EE)	CCS2 (IEC 62916-3 FF)
			
Power Supply Lines: L1 – Power Supply, Single Phase AC L2/N – Neutral or Power Supply, Single Phase AC	Power Supply Lines: Denoted L1, L2, L3, & N (Neutral) Single Phase – L1 & N Three Phase – L1, L2, & L3 supply one phase of current with N active	Power Supply Lines: Denoted DC (+/-)	Power Supply Lines: Denoted DC (+/-)
Control Lines: CS (AKA PP) – Contact Signal (Proximity Pilot), connected to insertion latch, ensures power transfer does not start until connected CP – Control Pilot, Post Insertion Signaling PE – Protective Earth (Ground)	Control Lines: PP – Proximity Pilot CP – Control Pilot PE – Protective Earth (Ground)	Control Lines: PP CP PE	Control Lines: PP CP PE
CAN BUS Lines: N/A	CAN BUS Lines: N/A	CAN BUS Lines: N/A	CAN BUS Lines: N/A
Notes: CP uses PWM to determine amount of current flowing PE uses full-current system	Notes: In DC Charging Configurations, L1 and L2 become the negative pins while L3 and N become the positive pins	Notes: L1/N sit idle for DC charging as neutrals	Notes: BEV Inlets contain ALL Pins CCS2 connectors do not contain the L1, L2, L3, or N Pins

CHAdeMO (IEC 62916-3 AA)	ChaoJi	SAE J3068	IEC 62916-2 (Type 3)
			
Power Supply Lines: Pin 5: DC- Pin 6: DC+	Power Supply Lines: Denoted DC-/DC+	Power Supply Lines: Denoted L1, L2, L3, & N Single Phase – L1 & N Three Phase – L1, L2 and L3 all supply a single phase of current with N	Power Supply Lines: Denoted L1, L2, L3, & N Single Phase – L1 & N Three Phase – L1, L2 and L3 all supply a single phase of current with N
Control Lines: Pin 1 – Ground Pin 2 – Charge Sequence Signal 1 Pin 4 – Vehicle Charge Permission/Readiness for Charge Pin 7 – Proximity Detection (AKA PP) Pin 10 – Charge Sequence Signal 2	Control Lines: Denoted CC1 and CC2 CC1 – EV Checking cable connection CCS2 – EVSE checking cable connection	Control Lines: PP – Proximity Pilot CP – Control Pilot PE – Protective Earth (Ground)	Control Lines: PP – Proximity Pilot CP – Control Pilot PE – Protective Earth (Ground)
CAN BUS Lines: Pin 8 – CAN High Pin 9 – CAN Low	CAN BUS Lines: Denoted S S (-/+) – CAN Low/High	CAN BUS Lines: N/A	CAN BUS Lines: N/A
Notes: Pin 3 – Unallocated	Notes: May be added to the CCS inlet for interoperability	Notes: Not common	Notes: Used in the EU, now deprecated, not included in spec sheet

Appendix D. Consultatory Meeting Attendance

Table D. Attendance List for Consultatory Meetings

First Consultatory Meeting **October 2021**	**Second Consultatory Meeting** **June 2022**
2050 Partners	AC Transit
AC Transit	Air Liquide
Air Products	Air Products
Argonne National Laboratory	Argonne National Laboratory
BYD	BYD
California Energy Commission	California Energy Commission
California Fuel Cell Partnership	California Fuel Cell Partnership
CARB	California Public Utility Commission
CDFA	CARB
ChargePoint, Inc.	CDFA
CTE	Daimler
Department of Energy	First Element Fuel
EPRI	Flex Power
First Element Fuel	GM
Governor’s Office of Business	Governor’s Office of Business
Hyzon Motors	GTI
Iwatani	Hyzon Motors
National Renewable Energy Laboratory	National Renewable Energy Laboratory
New Flyer	Nikola Motors
Nikola Motors	Nuvve
Nuvve	Proterra
PG&E	Rhombus Energy Solutions
Port of LA	SCAQMD
Port of Long Beach	SFMTA
Proterra	Siemens
Rhombus Energy Solutions	Southern California Edison
SCAQMD	Toyota
SFMTA	U.S. EPA
Shell	Veloce Energy
Siemens	Zen Energy Solutions
Southern California Edison	
Sunline Transit	
Toyota	
U.S. EPA	
Veloce Energy	
WAVE	
XOS	
Zen Energy Solutions	

Appendix E. Stakeholder Questionnaire

The following is a list of general questions that were asked during the interviews:

- What standards/protocols are you using in your current deployments?
- Which vehicle class(es) are you focused on?
- What challenges/limitations are you facing with existing standards?
- What would you like to see in terms of improvements/additions in standardization?
- What standardization committees/activities are you involved in?
- What guidance should be provided for current early deployment?
- Do you see the market moving towards a consensus?
- How important is achieving international consensus, or consensus beyond the US?
- What is the likely market outcome in terms of standards deployed?
- What action(s) can the State or federal government take to support smooth rollout?

The following are the questions asked to stakeholders during the second consultatory meeting:

- What additional charging and hydrogen fueling infrastructure standards gaps and/or performance gaps need to be addressed to support large-scale deployment for MD/HD-ZEVs?
- What specifications are appropriate to guide those applying for charging station grant awards?
    - Are there any ambiguity or issues with current funding solicitations?
    - Listing standards/certification/testing requirements?
    - Referencing a TIR (Technical Information Report) pre-standard
    - Guidance for demonstrations
- Should public funding requirements vary for fleet (private) versus public charging stations?
    - Codes and standards
    - LDV and HDV shared access
- What are the current limitations holding back the widescale deployment of a MD/HDV charging network?
- Are there additional topics/issues that you would like to see in the second interim report?

Appendix F. MD/HD BEV Charging Stakeholder Responses

1. What standards/protocols are you using in your current deployments?

   From the interviews, the most common standards referenced were CCS, J1772, and J3105, in that order. All respondents who previously had proprietary chargers have transitioned to J1772 and/or CCS. For communications, ISO 15118 and DIN SPEC 70121, OCPP are common communications protocols.

2. Which vehicle class(es) are you focused on?

   A range of vehicle classes were given. Classes 3-8 trucks were mentioned as well as buses.

3. What challenges/limitations are you facing with existing standards?

   Several stakeholders mentioned ISO 15118 issues. There are enough gray areas in the standard that results in diverse implementation, which in turn can inhibit interoperability. If ISO 15118 is required for level 2, it would add cost with low benefit. J3105 has some durability issues, communications issues through the pantograph.

4. What would you like to see in terms of improvements or additions in standardization?

   Multiple stakeholders mentioned increased reliability and interoperability. A few mentioned improved durability.

5. What standardization committees/activities are you involved in?

   Stakeholders had varying degrees of participation in committees and other standardization activities. Most referenced committees/activities include CharIN, Megawatt Charging Systems. IEEE P2030.13 – utility interconnection is being updated in coordination with MCS was also brought up.

6. What guidance should be provided for current early deployment?

   The timeline for the deployment of infrastructure and vehicles needs to be synchronized. There is a long lead time for locations that need utility upgrades. In addition, some stakeholders noted that it is challenging to task busy OEMs with new standards.

7. Do you see the market moving towards a consensus?

   Many respondents said that J1772 and CCS adoption is becoming the standard in many use cases. There is a risk that at the regional level, individuals will go in different directions and select a combination of protocols, which is not ideal for interoperability.

Many respondents were aware of MCS but were not sure how/when/if they would deploy MCS.

8. How important is achieving international consensus, or consensus beyond the US?

   Internationally, CCS1, CCS2, and ChaoJi are likely to be implemented in different regions.

9. What is the likely market outcome in terms of standards deployed?

   Again, there is a transition towards J1772 and CCS for medium-duty and away from proprietary solutions. Multiple stakeholders expressed a preference for one coupler/one protocol for all equipment independent of scale. Developers expect a combination of CCS and MCS meeting the needs for all transportation modes, including larger on-road and off-road vehicles. One stakeholder mentioned that ChaoJi (900 kW) does not meet U.S. requirements for charging, and there is a concern that ChaoJi may gain a foothold in U.S. for aviation as it is cheaper. Currently, some demonstrations and early commercial MCS deployments have occurred including Daimler in Portland, which is the first to have public access; Frito Lay in Modesto, in direct agreement with Tesla; and another in Texas with Tesla having 6 stalls. Multiple stakeholders mentioned that vehicle-to-grid is not a good fit for all fleets but there will be a future for it. Vehicle-to-infrastructure and vehicle-to-load are more near term than vehicle-to-grid.

10. What action(s) can the state or federal government take to support smooth rollout?

    Stakeholders mentioned a couple ways in which the government can support MD/HD infrastructure rollout. These include providing more funding opportunities, providing updated rules on grid integration to support charging station deployment and vehicle-to-grid services. In addition, the U.S. DOE serves a neutral and valuable role in providing data and modeling. Utility-related suggestions included better mapping of the distribution system to identify infrastructure constraints and more guidance on site assessments, steps to electrify depot (utility guide, permitting, etc.).

11. What additional charging infrastructure standards gaps and/or performance gaps need to be addressed to support large-scale deployment for MD/HD-ZEVs?

    Stakeholders should avoid proprietary solutions. There is a need for updated standards and protocols for vehicle-to-grid and bi-directional charging Try to avoid proprietary infrastructure. Additional Input from utilities would be ideal.

12. What specifications are appropriate to guide those applying for charging station grant awards? Are there any ambiguity or issues with current funding solicitations?

    Listing standards/certification/testing requirements. A couple stakeholders recommended referencing a TIR (Technical Information Report) pre-standard and provide guidance on standards and deployment for demonstrations.

13. Should public funding requirements vary for (private) fleet versus public charging stations? (Codes and standards, LDV and HDV shared access)

    Public versus private stations: Allowing open access depends on cost-effectiveness and whether higher utilization is desired. Traffic through a station may increase/require different design if a station is public. There are also different insurance and O&M considerations between fleet and public stations, and differences in security requirements between public and private stations. Public stations need additional security to protect payment information. Payment standards may not be relevant to fleet (private) deployments. Not all EVSE providers use ISO 15118. Some use DIN SPEC 70121. Too many added requirements for private stations could unnecessarily increase costs. If ISO 15118 is required for level 2, there would be added cost with low benefit.

    Mixed use stations: Multiple stakeholders expressed a preference for separate dispensers for light-duty versus heavy-duty, and for the option for shared use among a limited number of users, such as a few different fleets. For example, if the is fleet gone for the day, the charging station could be utilized by the public during the day.

14. What are the current limitations holding back the widescale deployment of a MD/HDV charging network?

    First is a lack of vehicles (and infrastructure). The current focus is directed to depot charging, where locations already have appropriate grid infrastructure to support the added load. Considerations include site proximity to resources, transformer capacity, etc. Fleets are looking at standardizing a modular approach to speed up the permitting process. Currently (general example): 2 units – 1 month approval, 10 units – 6 months, 11 units – suddenly looking at 2-year process – disconnect as hubs grow in size. Fleets are also concerned about stranded assets as the technology evolves.

    Second are issues of interoperability. Factors causing charging session failure include: EVSE issue, failure to authorize (network/payment), and component failure. A time window is needed for completing certain initiation steps, and the communication may timeout, causing the session to fail. Firmware updates are also very important. Also, each time a new vehicle is released, additional interoperability testing is needed. One stakeholder mentioned that “random charger” testing by automakers is a bad practice. CharIN proposed automated platform for interoperability testing to expedite troubleshooting interoperability problems.

    Third, most manufacturers are not yet ready for deploying MCS. It will take time for them to ensure their systems conform to standards for MCS. In addition, the max charging rate is dictated by the vehicle, not the charger. Vehicle OEMs may limit charging rate below the peak MCS rates to protect the vehicle’s battery life.

Finally, when looking at the case of an incident at a charging station, the law should revisit liability between the car and the station. There are three scenarios: the car is completely at fault, the station is completely at fault, and somewhere in the middle where each has some culpability. The current concern is that too much liability is on the station side.

Appendix G. MD/HD Hydrogen Fueling Stakeholder Responses

1. What standards/protocols are you using in your current deployments?

   A variety of fueling protocols are being used in deployments, most commonly J2601 category D and J2601-2. Pressure selection is dependent on the customer. Transit uses 350 bar as it is less expensive and sufficient for a transit duty cycle. The total cost of ownership of the station is very important to the customers, as well as the availability of components, which can affect the timeline for construction.

2. Which vehicle class(es) are you focused on?

   Buses and Class 8 trucks are the major focus.

3. What challenges/limitations are you facing with existing standards?

   While some level of continuous performance (back-to-back refueling) is already required, limited data are available on how stations are performing. The current HDV penetration is low, resulting in time available to improve back-to-back refueling performance.

4. What would you like to see in terms of improvements/additions in standardization?

   Current testing methods may not be usable with high flow equipment, and the timeline for new methods of testing for HD fast refueling may not be ready for first high flow station deployments. Stakeholders are not certain how do new protocols affect station testing and certification.

5. What standardization committees/activities are you involved in?

   Several stakeholders verified their participation in standards development committees and industry collaborations. These include but are not limited to: TC 197 - WG 24; PRHYDE; Hyundai, Toyota, Nel, NIKOLA, Air Liquide, and Shell collaboration; and SAE J2601-5.

6. What guidance should be provided for current early deployment of hydrogen stations?

   Multiple stakeholders expressed that it is too early for mandating heavy duty fueling protocols as they are still being developed. Unknowns make hydrogen a challenging investment, as well as cost and lack of experience in constructing HD stations. Guidance that supports more streamlined deployment.

7. Do you see the market moving towards a consensus?

   Overall, there is a strong drive to move towards a consensus. However, there is acknowledgment of multiple, disparate protocols being considered within the ISO high flow standard being developed.

8. How important is achieving international consensus, or consensus beyond the US?

   Multiple stakeholders voiced the importance of having an international standard and, for that reason, the focus is on ISO standard. To accelerate deployment, SAE is developing a TIR, which will then be harmonized with the ISO standard.

9. What is the likely market outcome in terms of standards deployed?

   Multiple stakeholders acknowledged that while, in the long term, the goal is standardized protocols for H35, H70, a transition period will occur wherein interim protocols or sets of fleets will be promulgated that rely on different generations of standards. In.

10. What action(s) can the state or federal government take to support smooth rollout?

    Government roles include ensuring safety codes and standards are implemented (e.g., H2 quality, sensor standards) and directing funding. The scope of federal hydrogen programs span safety, risk assessment, technology development, and testing. One stakeholder emphasized the recommendation that the State should focus on the general environment for the business case for zero-emission MHDV. They suggested that over-conservative guidelines do not necessarily increase safety but can create additional deployment constraints. Two additional inhibitors were identified: high hydrogen pricing and inconsistent rules/regulations between hydrogen and other motor fuels. For example, oil and gas have exemptions (e.g., some provisions in the Clean Water Act and Clean Air Act) that hydrogen must follow.

11. What additional fueling infrastructure standards gaps and/or performance gaps need to be addressed to support large-scale deployment for MD/HD-ZEVs?

    Stakeholders identified three gaps to consider for standards development: technical components, performance, and safety. In terms of hardware, for example, the breakaway hose, nozzle, receptacle design could be the same across stations while offering flexibility in other elements (e.g., system design). Secondly, the HDV protocol requires managing the thermodynamics of larger tanks with a current tank temperature limit of 85 °C. Future research could investigate the potential for higher end temperatures. Thirdly, the stress on multiple components results in premature failure and low reliability. Improvements can be made to these components based on failure analyses to support improved performance. Finally, stakeholders argued that data communication methods could be advanced.

12. What specifications are appropriate to guide those applying for charging station grant awards?
    Multiple stakeholders expressed that general guidelines and safety standards are appropriate. One stakeholder expressed concern regarding entities bidding on fueling projects without sufficient hydrogen understanding and the State should implement a procedure that minimizes, if not avoids, accepting no-experience bids.
13. Should public funding requirements vary for fleet (private) versus public fueling stations? (Codes and standards, LDV and HDV shared access)

    One stakeholder expressed that public stations require standardized approach for a variety of vehicle types, but that private stations should have more flexibility in station design to meet the demands of the specific fleet. Another stakeholder expressed that while private stations may focus on a specific fleet, having the capability to fuel other vehicles would be very beneficial and a minimum level of compatibility across stations is desirable.
14. What are the current limitations holding back the widescale deployment of a MD/HDV fueling network?

    Several stakeholders expressed that unknowns surrounding the future MD/HD FCEV market make it a challenging investment. Hydrogen cost, limited hydrogen supply, and lack of experience were identified as barriers. Multiple stakeholders communicated that streamlining permitting would be good (mentioned multiple times). One stakeholder cited that it is difficult to roll out large stations due to California Environment Quality Act (CEQA). A stakeholder described legacy stations as already outgrowing their useful life and new stations need to have longer lifetimes. There were mixed opinions on co-locating LDV and HDV infrastructure. The main concerns brought up were safety and liability. Overlapping hardware between LDV and HDV was a concern (e.g., same nozzles). Multiple stakeholders subscribed to the approach of LDV and HDV using the same site but not the same dispensers, similar to truck stops today. While mobile refueling can provide an interim solution for infrastructure deployment, only a limited number of options are available for mobile refuelers. Lastly, multiple stakeholders were interested in improving back-to-back refueling, but more data are needed.

15. Are there additional topics/issues that you would like to see addressed?

    Multiple stakeholders expressed that the future of liquid hydrogen on-board is uncertain, but if it comes to market, stations will need to manage different generations of stations.