



Article

A Universal Electric Vehicle Outlet and Portable Cable for North America

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Abstract: For electric vehicle (EV) charging in North America, three AC connectors are standardized, resulting in a proliferation of charging stations which can only charge one of the three types of EV. We propose a “Universal EV Outlet” that works with an EV “carry along” charging cable—one end of the cable has a connector specific to that user’s EV, the other a plug for the Universal EV Outlet. This proposal does not interfere with, nor require change to, any existing charging stations. It does not require any new types of inlets on EVs. The components are already standardized. Eight use cases are examined to illustrate the advantages, and some limitations, of the Universal EV Outlet. The use cases illustrate how this solution: resolves the problem of multiple AC charging connectors, makes today’s “EV Ready” building codes more adaptable, lowers capital and maintenance costs, creates a solution to curbside and urban charging, increases energy efficiency, enables higher power three-phase AC charging for heavy vehicles, and facilitates use of EVs for building backup power and for vehicle-to-grid. Finally, we propose a standards-based active cable used with the Universal EV Outlet, which would allow fast and secure EV identification for curbside or other shared charging locations, usable today without modifications to current EVs.

Keywords: electric vehicles; charging system; electrical standards; SAE J3068; SAE J3400; connectors; EV outlet; charging use cases; vehicle-to-grid



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1. Introduction

Electric vehicles (EVs) are rapidly becoming significant fractions of the vehicle fleet and are evolving new designs for power electronics and grid interactions [1]. In multiple world areas, the standards and the industry practice for charging electric vehicles is entering a transition; for a successful transition, we must understand the user interactions with EV charging systems and enable technologies that facilitate that interaction. Taking North America as an example, we propose a way of facilitating that transition, while improving the user experience of EV charging and lowering infrastructure, energy and maintenance costs.

For most electric vehicle (EV) charging stations, a driver wanting to charge follows three steps: park beside a charging station, grasp the loose end of a cable attached to the charging station, and plug that cable’s connector into their EV. These three steps are the same for all charging stations in North America, with public stations typically adding a step for identification or payment. However, there are now three AC connectors defined by North American standards, as shown in Figure 1; all three are allowed for public stations under the US DOT National EV Infrastructure Regulations. This analysis concerns alternating current (AC) charging, which is used most frequently and which accounts for the overwhelming volume of energy flow (kWh) into EVs worldwide. AC charging standards have developed little in 15 years, despite their importance—convenient charging at or near one’s residence is a strong determinant of whether one will purchase, use, and

retain an EV [2]. Standards mentioned here are by IEEE, UL, SAE (formerly Society for Automotive Engineers), ISO (International Standards Organization), and IEC (International Electrotechnical Commission), organizations that recruit volunteer experts in the relevant fields to develop, agree upon, and document standards. Standards documents essential to this article are in the references.

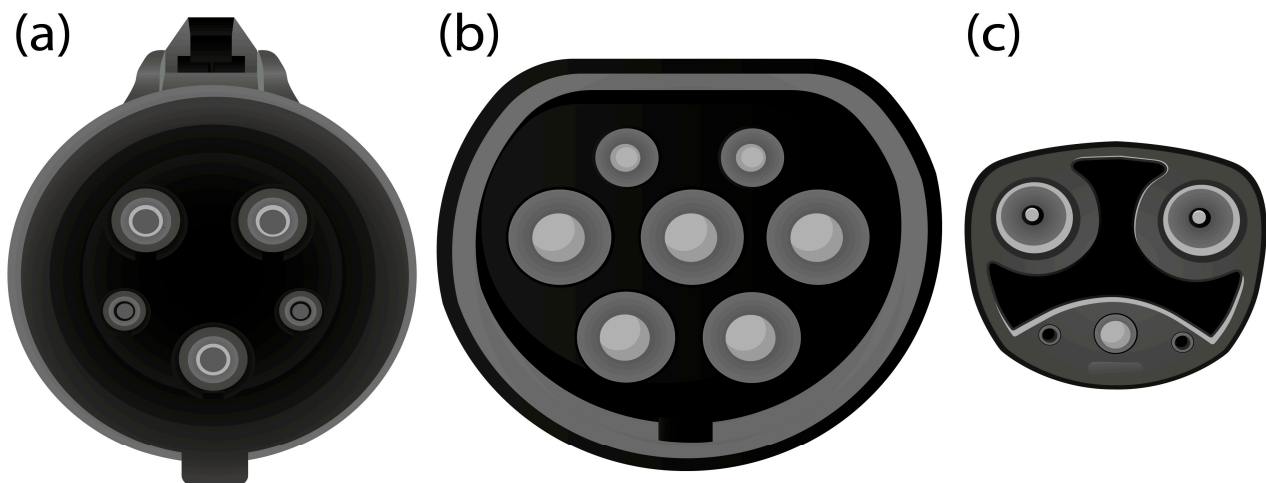


Figure 1. The main three types of AC connectors used to charge North American EVs. (a) Type 1, also called SAE J1772. (b) Type 2, in North America called SAE J3068. (c) Type 5 or SAE J3400, the connector formerly known as Tesla. Images are to scale. Each connector fits one set of cars or trucks in North America, none are interoperable.

Figure 1a is the connector used to charge the largest number of EV models in North America, it supports only single-phase AC charging, and is called “Type 1”. The other two connectors in Figure 1 have advantages over it. Type 2, Figure 1b, can achieve higher power AC charging (including three-phase power—hence 3ϕ), important for medium and heavy vehicles, and potentially useful for faster charging of passenger cars. Type 5, Figure 1c, is lightweight and allows mid-power AC (our numbering skips Type 3 and Type 4 because Type 3 is no longer commonly used, and Type 4 designates the Chinese standard GB/T). The Type 5 connector, previously used only in the Americas and only for Tesla cars, has been standardized for North America by SAE J3400. (The terminology “Type 5” is not yet consistently used in the Americas but is logical and follows Type 4 for GB/T). All three of the connectors in Figure 1 are recognized by the National EV Infrastructure (NEVI) requirements [3] and by SAE or IEC standards. This discussion covers AC charging, although Type 2 and Type 5 connectors are standardized to use DC charging and commonly do so in some regions.

With three types of connectors, for different EVs, how are they managed in North America? Today, for each type of connector, there is a different charging station with a permanently attached cable, and only one type of connector at the loose end of the cable. Unfortunately, no charging station’s connector fits into an EV having an inlet made for any other type, as can be immediately seen by the mismatched pin configurations and dimensions in Figure 1. Consequently, if the right type of charging station is not available where an EV is parked, the EV cannot charge. In some cases, it is possible to secure an adapter, allowing an EV expecting one type of car inlet to charge from a charging station with a mismatched connector. However, adaptors create reliability and safety problems as discussed later.

As we write, in mid-2024, it is urgent to reconsider EV charging connectors due to two factors. The Type 2 connector, Figure 1b, standard in Europe, can provide up to 100 kW of power from a low-cost 3ϕ 480 VAC charging station, thus it is economical and better matched than the Type 1 to the larger batteries of medium- and heavy-duty vehicles (trucks and busses). And Type 5, Figure 1c, fits an inlet now installed only on Tesla EVs in North

America, but it is in the process of being adopted by other brands of EVs in North America (Tesla EVs in Europe and in most of Asia use Type 2, Figure 1b). Thus, all three connectors in Figure 1 are likely to continue to be used in North America for years.

This article draws from industry and user experience and documented problems with current EV charging in North America. Then, we utilize new North American standards plus current practice outside the Americas to propose solutions to these problems.

2. Technologies, Present and Emerging

This section briefly reviews the technologies available, and what must be considered in designing the SE and EV for charging (in EV standards, a charging station is called “Supply Equipment” (SE) or “EV Supply Equipment” (EVSE); we will use the shorter “SE” to refer to the charging station). The purpose of plugging an EV into SE is to draw electric energy from the grid and charge the EV’s battery for subsequent driving. This is very much like a cell phone, laptop computer, or other mobile electronic device, which is charged, unplugged, then run from its battery while in motion. Although conceptually the same as cell phone charging, EVs are different quantitatively by orders of magnitude—compare ~5 watt phone charging at 5 V with EV charging, now available from 1 kW to 350 kW and up to 600 VAC or 1000 VDC. These levels of current require that the conductors and connections have very low resistivity and, therefore, have a larger cross-section. And these voltages require appropriate ratings of insulators and other components for shock protection.

There are three layers of protection from shock when charging an EV. First, the connection is not energized unless the plug and/or connector is fully into the socket, making it impossible to touch live contacts. The second layer of safety is continuously monitoring current to detect a possible flow through a person, and when detected to turn off the voltage source within milliseconds (via a ground fault interrupter, GFI, or a Charge Circuit Interrupting Device, CCID). The third safety layer is that the EV and SE connector shape, insulation, and recessed sleeves ensure that, even if both above protections should fail and an unplugged connector is left energized, the contacts are difficult to touch with a finger (these three are in addition to the standard electrical safety measure of bringing the protective earth connection from the premises to the SE to the EV, in order to ground all user-exposed conductive parts).

Moving from voltage to current, connections can heat up at high current, depending on the resistance of the connections. In particular, both the SE outlet and the EV inlet can be contaminated by abrasives in the environment, or wear for other reasons, leading to loose connections, increased resistance, and thus heat. The traditional solution, arguably the primitive solution, is for the designer to enlarge the contacts until they would rarely fail even under the worst conditions, but at the tradeoff of larger and heavier components. The designer’s other solution is to reduce rated amperes, at the user disadvantage of lower power, and thus a longer charge time. Some advanced EV charging standards, if they have rich SE to EV communication, now specify that for high current, the connectors must have thermal monitoring and must dynamically derate, lowering the power successively until an acceptable temperature is restored (SAE J3068 and J3400). With this design, a failure that could have caused a fault and interruption of charging, a component melt, or in extreme cases a fire, becomes only a slower charge and a diagnostic message about why it is slower.

For any electric device to receive power, its voltage and amperage must be compatible with the supply and branch circuit. Setting aside EVs for a moment, AC appliances’ legacy system to match voltage and maximum current is the NEMA standard. The National Electric Manufacturers Association (NEMA) defines different geometry and pins of the physical plug and outlet to signify the common voltages and currents. This physical plug restriction dates back to the early 20th century. Today, instead of scores of plug and pin shapes, the modern way—just beginning to be used in EV charging—is to have the source and load each electronically transmit an agreed-upon voltage, current, and frequency, then energize only if the two sides are compatible. A familiar modern example is USB-C Power Delivery [4]. For EVs, such signaling is now defined in J3068 [5] for all three connectors

shown in Figure 1, enabling SE and EV to communicate and agree upon an acceptable voltage and maximum current, using the two smaller pins shown on each connector.

SAE J3068 defines connectors as well as communications. This article refers to communications functionality only when needed to understand plug compatibility, use cases, and safety, with references for further reading (for background, J3068 defines communication via LIN signals over the CP line, called LIN-CP, and also defines how, during a charging session, communication can switch from LIN-CP protocol to IEC15118, WiFi, telematics, or older analog signals). This article's focus is the connectors, outlets, and cables, and how users interact with them to achieve needed functions—which, as we found when writing this, requires a whole article.

Another technical factor concerns EVs that are capable of discharging, that is, EVs that can transfer DC power out of the EV battery, convert to AC, and back through the SE. Discharging into a building can be used for backup power during a power failure. Discharging through the building to the power distribution system, first formally described and named “vehicle-to-grid” (V2G) power in [6], is valuable to the electric grid for reliability, load management, and the integration of renewables [7]. A third function of discharging is remote site power, such as at a job site or “car camping”. To enable discharging via AC, small but important adjustments are needed to the EV's charger, along with more sophisticated signaling between EV and SE. This article's proposals, and the referenced standards (especially SAE J3072 [8], SAE J3068 [5], IEEE 1547, and UL 1741-SC), greatly improve AC charging but are also based on careful consideration of AC discharging functions, to make them safe, straightforward, inexpensive, and able to be permitted across jurisdictions.

For public charging, the driver may need to validate their identity or account number to the SE, for authorization or billing. The SE can then either provide charging power to the authorized person, establish billing to a known account number, or deny charging if unauthorized. A different identification is essential to allow discharging for V2G or backup power—in that case, the EV and/or its power conversion equipment (vs. the driver or account) must be securely identified, to confirm that electrical requirements are met to safely discharge. For AC V2G, these requirements are transmitted using SAE J3072 (Section 5.8), with signaling defined for either IEEE 2030.5 or SAE J3068/2.

Today, most North American charging stations identify the driver or EV in clumsy ways, such as by a credit card swipe, a membership card, a charge point operator's mobile app, or if other methods fail, by calling a toll-free number and speaking a credit card number to a support person. It is generally accepted (e.g., [3,9]) that these cumbersome steps increase the frequency of failure to charge and are inconvenient to users. Thus, it is highly desirable to replace them with a simpler means of identification, ideally transmitting ID over the charging cable using what is called “plug and charge”. IEC labels this “Plug&Charge”, whereas in this document we use the term “plug and charge”—lower case and not run together—to mean generically any communications protocol that exchanges unique identifiers, whether EV ID, SE ID, or account number, using signals that are automatically transmitted over the charging cable.

Unique IDs are now defined by two EV communication standards, IEC15118-20 and SAE J3068/1, either of which can uniquely identify an EV and SE to each other. SAE J3068/1 allows for several ID alternatives, including IEC15118-20, VIN, driver ID, serial number, or other formats. For older EVs or drivers without a plug and charge account, the SE may accept a credit card or another identifier token. However, from the user perspective, credit card swipe or insert requires more user time and potential failure, and from the station operator's view, it is more expensive and “requires frequent maintenance” (S. Rafalson quotation in [10]).

3. A Standards-Based Solution to Current Problems

The problem of battery-powered devices with diverse power inlets has been solved for mobile electronics, as shown in Figure 2. The solution for mobile electronics is a charging

cable separate from, rather than permanently connected to, the outlet. These separate cables have diverse connectors on the device end, yet each cable has the same type of plug that fits into the universal outlet.

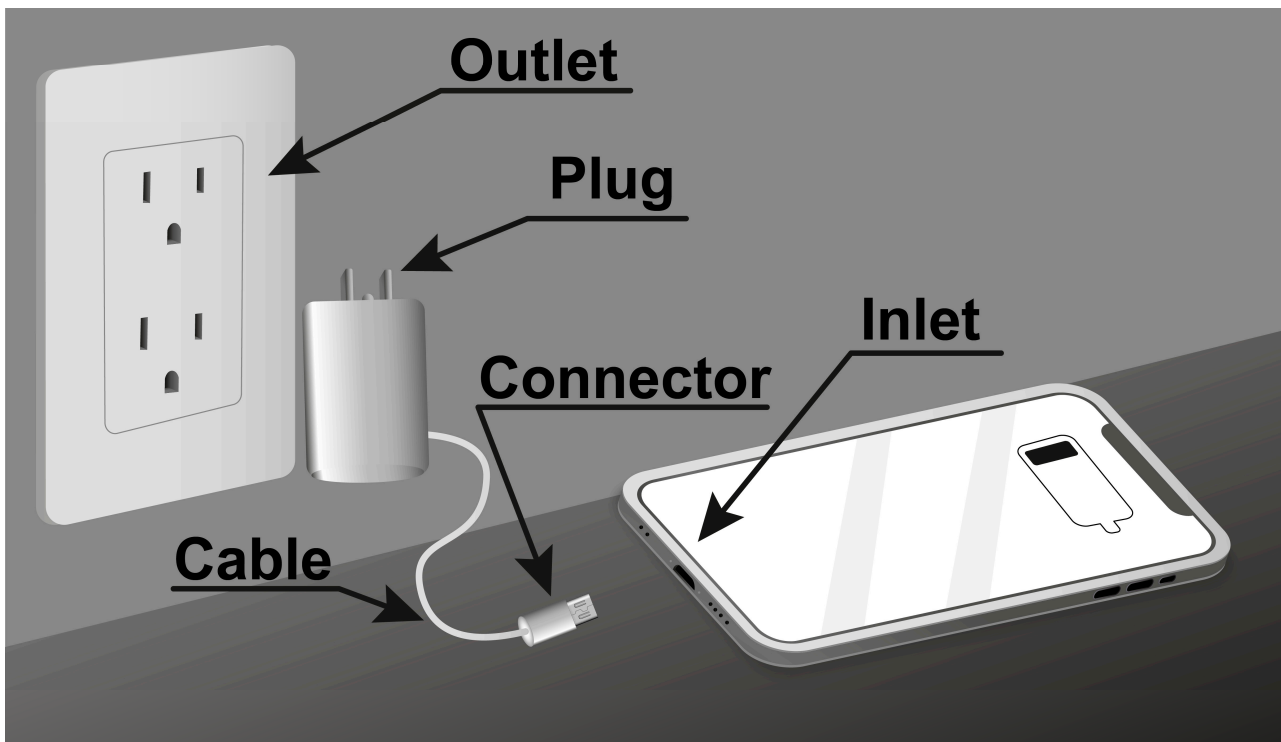


Figure 2. An existing solution to incompatible electrical inlets and connectors. Power flows from a universal outlet into a plug, through a cable, to a device-specific connector that plugs into the correct device-specific inlet. Power outlets are standardized (per country), but inlets for portable electronic devices are diverse and change over time. The problem is parallel to the emerging North American diversity of EV inlets and connectors, and we here propose a similar solution.

To implement this solution for EV charging, the cables could be included with new EVs by the manufacturer. They would likely also become a low-cost commodity item available at retail outlets, for older EVs, and when the manufacturer-supplied EV cable is lost or damaged. The terms we underline in the caption of Figure 2—outlet, plug, connector, and inlet—are standard for their EV analogs and will be used in this article. And, the familiar mobile charging cable solution of Figure 2 parallels our proposal for EV charging.

Analogous to the wall outlet shown in Figure 2, we propose a “Universal EV Outlet” as shown in Figure 3b. For AC charging, any EV would be able to plug into a charging station with a Universal EV Outlet, using a cable appropriate for their EV—exactly as one now buys the cable and connectors appropriate for one’s specific mobile device, per Figure 2. The Universal EV Outlet need not replace today’s single-connector-type charging stations, nor need it be required for new stations—we propose only that regulations allow it, and that it be given equal availability of incentives. We will show why the market will often prefer it, once allowed and equally funded, with reference to the common use cases described in the following analysis.

The analogy of Figure 2 is not perfect. First, for mobile devices, there is typically power conversion in a small box on one end of the cable (seen in Figure 2), whereas for the AC charging of an EV, there is no power conversion in SE, cable or connector; AC is passed from the electric system through to the EV and power conversion is performed in the EV. Second, EVs have higher power and voltage than mobile electronics, thus EV cables must be heavier and bulkier, so potentially there is more handling inconvenience for an EV cable than for the cable required for a mobile device.

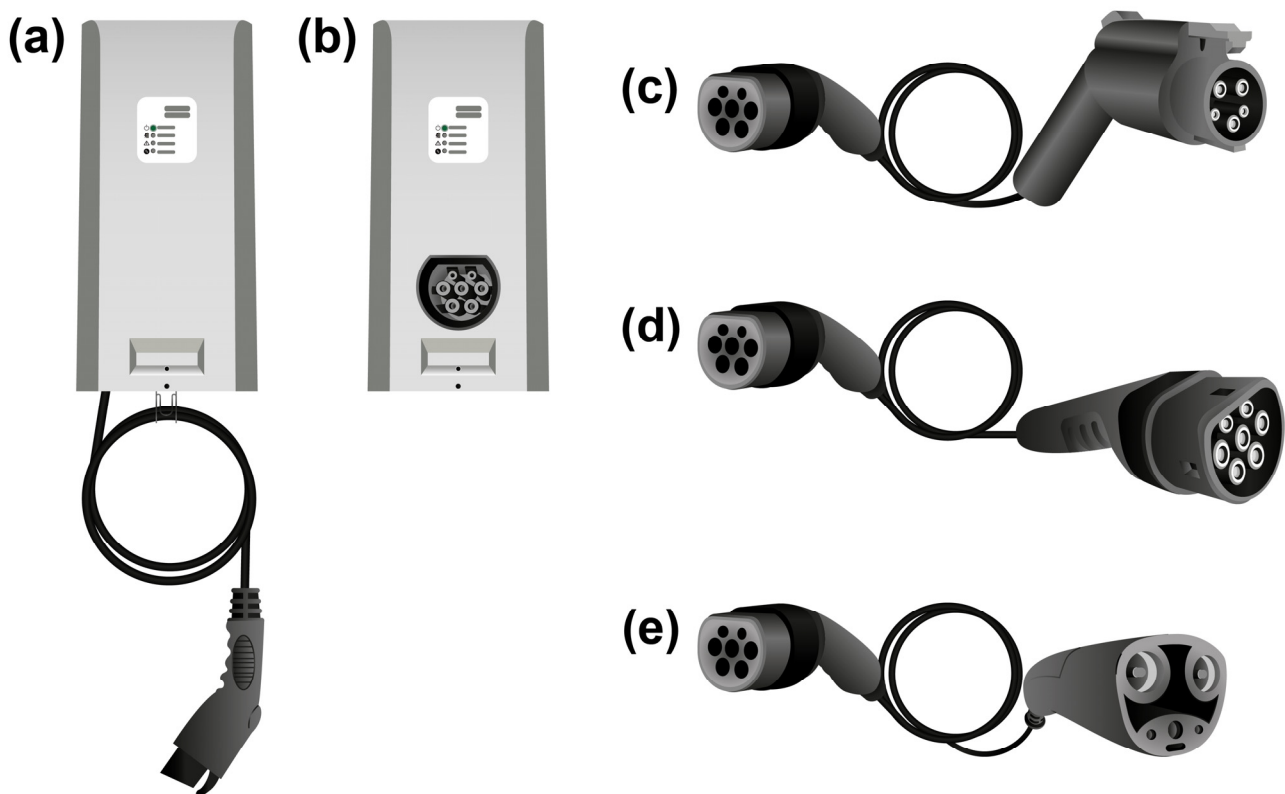


Figure 3. Charging stations and cables. (a) Example of North American charging station today, with the cable and connector permanently attached. (b) The proposed charging station with Universal EV Outlet. (c) Portable charging cable with Universal EV Plug on the left, Type 1 connector on the right. (d) Portable cable with EV plug to Type 2 connector. (e) Portable cable with EV plug to Type 4 connector.

Our proposed candidate for a Universal EV Outlet for North America, Figure 3b, and the carry-along EV cables in Figure 3c–e, are the most common connection for charging stations in Europe and are used in many other countries. The mechanical specifications of the outlet and connectors are defined by the international standard IEC 62196-2 [11], and in that standard, the Universal EV Outlet is called a “socket-outlet” or “Type 2 outlet”. Prior to ratification of SAE J3068, no outlet has been defined for, nor used in, North America, Japan, or Korea, where only the SAE J1772 standard has been applied to AC charging. SAE J1772 defines no outlet and requires a permanently attached cable. Now, SAE J3068 defines the electric system specifications of the outlet and the connectors in Figure 3 needed to meet North American electrical standards, including the maximum electrical quantities of Table 1.

To show how the Universal EV Outlet in Figure 3b works with all connectors shown in Figure 1, Figure 3c through Figure 3e illustrate three carry-along cables, each with one of the Figure 1 connectors on the right of the cable, and the Universal EV Plug on the left.

Returning to the question of handling the carry-along cable, in Europe we see that in cars, they are often stored in the hatchback or trunk, either loose or in a simple bag; for work trucks, there may be a small built-in cabinet near the charging inlet designed for the carry-along cable. Weight varies by ampacity, length, and phase; an approximate range of weights would be from 2 kg for a low-amp 1 ϕ car cable to 7 kg for a high-amp 3 ϕ truck with a long cable.

To accommodate 3 ϕ as well as 1 ϕ charging, the Universal EV Outlet in Figure 3b, like the Type 2 connector in Figure 1, has five large power pins and two small signal pins. Three phases can transfer higher AC power. The carry-along cable shown in Figure 3d also carries 3 ϕ power, from the Universal outlet it can provide 52 kW AC at 480 V 3 ϕ ; when permanently attached, it can transfer 100 kW (Table 1). The user receives 1 ϕ or 3 ϕ from

this outlet simply by using the appropriate carry-along cable—when the user plugs their cable into the Universal EV Outlet, the correct voltage and phases at the connector are automatic—e.g., a user can plug in either a Figure 3c cable for a 1 ϕ car or a Figure 3d cable for a 3 ϕ truck. This dramatically increases the versatility of the Universal EV Outlet over what is currently available in North America, yet at a lower station cost. The Chinese GB/T standard GB/T 20234.2-2015 [12] uses a connector like the one on the right in Figure 3d but with reverse gender—although this connector is not shown in Figure 3, it is also easily accommodated by the same Universal EV Outlet and an appropriate cable, as currently used in China.

Table 1. Electrical characteristics of the AC charging components in Figure 3. Values are from standards unless otherwise noted; some require LIN-CP signaling. The “Attached” columns are for a cable and connector permanently attached to the SE, like Figure 3a. “Removable” columns are carry-along cables like Figure 3c through Figure 3e, for which the rated amperes will be the minimum of outlet/plug and connector.

Type	Outlet or Connector	ϕ	Max VAC ¹	Max Amperes		Max kW	
				Attached	Removable	Attached	Removable
2	Universal EV Outlet	1	277	--	70	--	19
		3	480	--	63	--	52
1	SAE J1772 connector	1	240	80	70	19	17
2	SAE J3068 connector ²	1	277	120 ³	70	33	19
		3	480	120 ³	63	100	52
5	SAE J3400 connector ²	1	277	150 ⁴	70	42 ⁴	19

¹For 3 ϕ connections, line-to-line voltage is given. Some Canadian 3 ϕ electric supply is 600/347 V, primarily for industrial and off-road vehicles. J3068 permits 600/347V on SE and EV with communication, but compliance with each standard shown requires no more than the voltages shown under “Max VAC”. ²DC charging is also defined for Type 2 and Type 5 connectors; DC ratings are not shown here. ³For the Type 2 connector, amperes are an inferred but conservative AC maximum based on learning from Tesla’s use of Type 2 for DC charging in Europe, and assuming no liquid cooling in the cable. Not yet specified in any standard. ⁴Inferred from measured J3400 contact sizes, not yet specified in any standard.

As a practical matter greatly affecting the speed and cost of implementation, all outlets, connectors, and cables shown in Figure 3 are already in use in most of the world. All cables shown, except Figure 3e, are already mass manufactured, and the cable in Figure 3e is now standardized in SAE J3068 and, by reference, in SAE J3400. Because appropriate standards, specifications, and test procedures, as well as existing manufacturing, are already available (a rarity for new ideas), rapid deployment of our proposal for North America is possible.

4. Materials and Methods

Diverse use cases are analyzed in this section to illustrate how the Universal EV Outlet and the separate carry-along cable would solve many of today’s EV charging problems. The description of each case is based on problems identified in the EV literature [2,9,13–15], as well as problems identified during our participation in UL and SAE committee discussions, which included multiple industry and government EV actors. Additionally, this article and our proposed solutions are informed by the authors’ two decades of experience with EV communications protocols, charging power, vehicle-to-grid power, and standards, all kept realistic by our ongoing designing, fabricating, using and maintaining of SE and EV equipment. As shown by the use cases below, our proposed solution will: use one charging station for multiple types of EVs, lower SE costs, increase energy efficiency, improve the user experience, and solve several problems now blocking wide deployment of EV charging in urban and on-street parking areas.

5. Results

Eight use cases are analyzed in each of the following subsections, followed by a ninth subsection listing cases for which the Universal EV Outlet is not a solution.

5.1. A Region Where EVs Have Different Types of AC Inlets

North America is a compelling example. North America has never had a single AC connector. For many years, it has had Type 1 (standardized as J1772) and “Tesla” (originally a one-company non-standard connector, now SAE J3400 or Type 5). Until SAE J3068, Type 1 and Tesla connector standards required the cable and connector to be permanently connected to the SE, a restriction that often leaves EV drivers parked at an SE but unable to charge due to connector-car mismatch.

By comparison, diverse AC inlets have always been present in Europe, because EVs have always varied among Type 1 and Type 2 inlets (and other types). The most common AC charging station in Europe has a Universal EV Outlet, per Figure 3b, and European EV drivers carry cables like those shown in Figure 3c,d. Note that each EV need only carry one cable. The Universal EV Outlet enables all cables to use the same plug on the charging station side, yet on the EV side, the connector matches their one particular EV. This existing European use case is our suggestion for North America—additional standardized refinements add signaling and qualification for North American voltages, but this European outlet is identical in physical form to what we call the Universal EV Outlet for North America.

5.2. EV-Ready Building Codes for New Construction

The ICC 2021 recommended building code [16] and many US state building codes require that new residential buildings with parking space (garage or driveway) must be EV capable, or EV ready. “EV capable” means that sufficient power is available on the main panel to provide power to a defined number of EV chargers, and a raceway or conduit has been installed for future wire runs from panel to parking location [16]. “EV Ready” means EV capable plus a dedicated branch circuit being run to the parking space, with breaker of at least 40 A, terminated at a junction box.

California’s definition of EV ready requires the circuit to be terminated in a receptacle or EVSE (required for some or all parking [17]). We believe that the CA code provision of a 40-amp receptacle was intended to simplify installation of 40-amp SE, for example, by buying an SE powered from a NEMA 14–50 plug. However, codes like California’s create a post-installation problem—meeting the EV ready requirement via a receptacle will require the electrician to install a branch circuit GFI and require receptacles to trip at 5 ma, likely via a GFI integrated with the panel breaker. But for SE, which detects ground continuity, the trip level is allowed to be 20 mA and typically integrated in the SE. If a California building is EV ready with a NEMA 14–50 outlet, and EVSE is subsequently installed, the allowed 20 mA CCID in the EVSE will be preempted by the existing panel breaker with 5 mA GFI protection. This will cause many nuisance trips and may be very difficult to diagnose without an SE specialist. From the user’s perspective, they might report, for example, “my EV won’t charge whenever it rains” and they will have trouble finding a person who can diagnose the problem (the fix being to replace the GFI-breaker in the panel with a simple overcurrent breaker). Such stories in communities increase the reluctance to adopt EVs and may reduce trust in “EV Ready” codes.

A simple code modification can fix this problem. An EV-ready charging location should meet code by installing either a junction box without GFI or a Universal EV Outlet—but a NEMA outlet with GFI should not qualify. Because no cord is installed for the EV outlet, an EV Ready integrated SE with GFI is a minimal cost above the current code’s NEMA 14–50 outlet plus GFI panel breaker (in NEC terminology, the Universal EV Outlet is listed equipment rather than an outlet, so, this allows installing three-phase EVSE equipment in premises with split-phase supply). If a new building met such a code requirement via installing a Universal EV Outlet, that would also in fact be a legitimate,

working EVSE as originally installed, and thus would not only fit the building code category “EV Ready Space” but for a user would in fact be a preinstalled charging station—a new resident with an EV and appropriate charge cable (per Figure 3c,d,e) could plug in their EV the first day they arrive, with no need for any building installation or upgrade. Also note that a visitor with a carry-along cable could immediately charge their EV at a friend’s home in a qualified EV-ready space, even if the homeowner has no EV and has performed no preparation. For rental apartments, the Universal EV Outlet eliminates the lessor’s problem of sequential EV-owning tenants with EVs requiring different connectors.

These use cases and the low cost could also justify code or regulation to require a Universal EV Outlet, rather than also allowing a NEMA outlet, to qualify as EV ready.

5.3. Automatic Plug and Charge, for Legacy EVs Plus New EVs

Plug and charge speeds up user interaction and improves the reliability of any paid charging scheme. It also enables any scheme such as V2G requiring positive vehicle identification. However, automatic identification is not available for AC charging today. This section’s use case addresses how a region can implement plug and charge widely without requiring the retrofit of existing EVs.

We propose that when new SE with plug and charge is installed in an area with EVs lacking plug and charge, it uses the Universal EV Outlet and an active carry-along cable. The active cable would be like those in Figure 3, but with an added signaling module with coded ID in the cable as in Figure 4. Adding J3068 signals via LIN-CP to a carry-along cable (for example, a module within a connector) would be a very low added cost (under USD 10 for a module and housing, with the processor alone <USD 1), and it draws so little power (160 mW) that it can be powered by the existing 12 V power drawn from the EV side of the proximity signal line—as defined in J3068/2, Section A.3.3, this is 1.2 to 2.4 watts at 12 VDC. Alternatively, the digital signal could be IEC15118 via PLC, but the higher power draw of a 15118 translator (tens of watts to 100 W) would require a substantial battery or other power supply added to the cable. (This use case of the cable enabling plug and charge favors J3068 signaling because of its low power, low cost, and ability to embed in a connector without adding a power supply. The same argument would apply to an electrical outlet box used for remote site power from an EV. The other use cases discussed in the Results section are neutral to what signaling is used, as the outlet and cable merely pass the signals received along the CP line.)

Figure 4 gives a simplified but illustrative example of how signaling would work between a modern SE and a legacy EV, via an active cable. The legacy EV has only analog signaling as defined in J1772, but an analog-to-digital module in the EV side connector housing translates the old analog signal to digital and adds the account ID. All three (SE, EV, and cable module) use the control pilot signal line (CP).

A locking mechanism is available in the Universal EV Outlet as well as in the inlets on many EVs. These allow locking the cable to the EV and/or SE. Even if the cable were stolen, the theft could be reported to disassociate the built-in cable identifier from the owner’s account.

Thus, any region or city could provide Universal EV Outlets with plug and charge, allowing all EVs to immediately participate. In addition to new EVs with built-in digital plug and charge, also older EVs can participate by simply buying the appropriate cable and registering its identification number. This is only possible because the carry-along cable is stored in the vehicle and possessed by the owner, so the cable becomes a registered identity token (impossible with legacy standards requiring the cable attached to the SE). In sum, the Universal EV Outlet with a carry-along cable makes possible the widespread availability of plug and charge on AC chargers, even for EVs with older protocols or without built-in plug and charge.

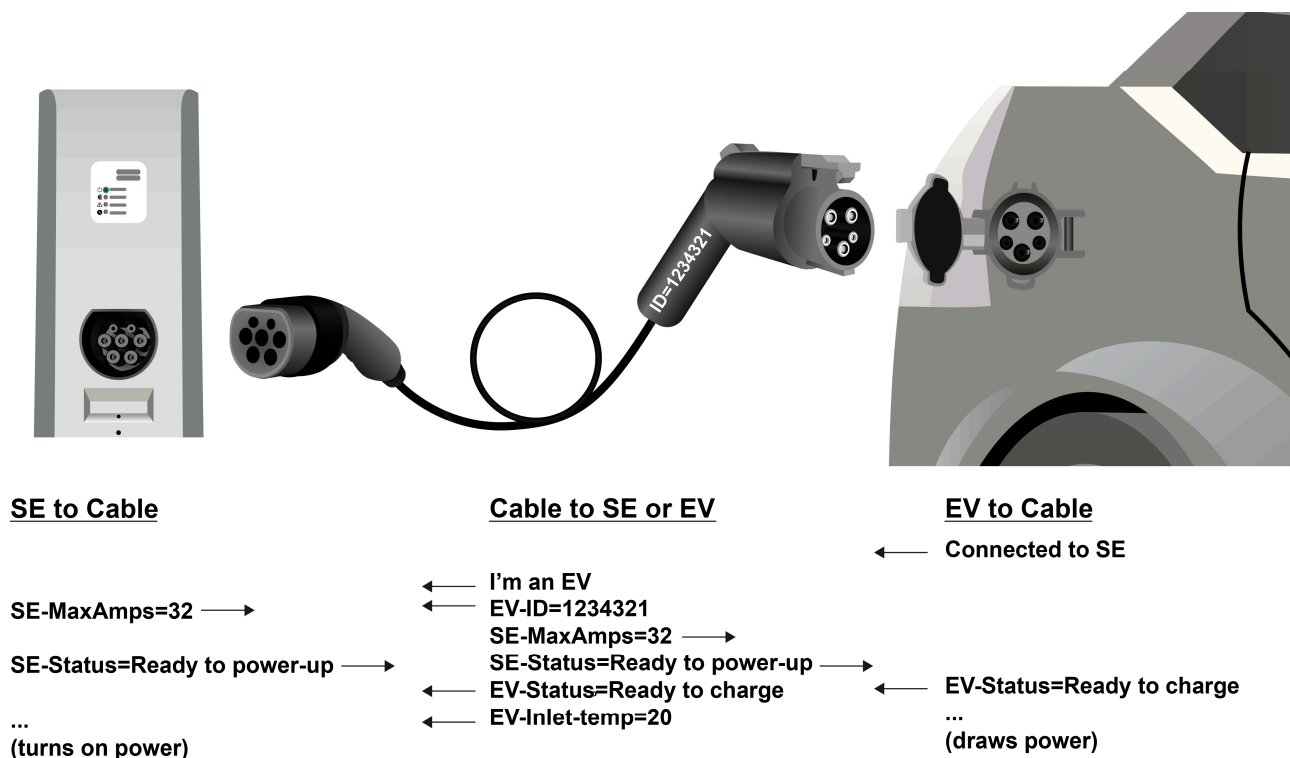


Figure 4. An active cable used between the EV and the Universal EV Outlet, to enable plug and charge over AC for legacy EVs. The analog signal from the EV is translated to a digital signal for the SE, and the cable can use its embedded unique ID to identify the account and/or car. Excerpts of a startup sequence are shown. Arrows show the direction that each communication is sent. For readability, the signals are shown as key-value pairs, although a legacy EV communicates to the cable via analog voltage and pulse width.

5.4. Minimizing Capital Cost and Maintenance Cost of Charging Stations

Cost minimization helps meet many goals: widespread deployment, rapid EV rollout, buyer confidence that a new EV can find a matching charging station, accommodating low-income users, and being well suited for areas of parking space scarcity where reserving some parking spaces for only EV charging is impractical.

The cable and connector are the most common maintenance replacement parts on AC charging stations. Our solution shifts cable repair from being a service call requiring a specialized electrician who opens the SE, to instead being a user-replaceable commodity that an EV driver can purchase at retail and “install” themselves, a substantial cost reduction. Thus, the cost to society is substantially lowered, which may in turn lower the total cost to consumers even if the consumer must buy the cable.

In dense street parking, reaching a charging station from every parking spot will require placing more charging stations than there are EVs parked nearby. That means buying more SE than there are EVs. Needed extra SEs will be more affordable if the cable and connector need not be purchased for each. Equally important, care in plugging the connector into the EV, a frequent point of damage or failure, becomes the responsibility of the EV owner, the person who actually handles it. In sum, both capital cost and maintenance costs of the charging station are lowered, reducing the financial barriers to installing many charging stations in an area. (To approximate cost savings, we draw on 10 years of hands-on maintenance of six stations used 40 h per week in employee parking with frequent use of adapters. We also draw from our consulting experience regarding a thousand stations of our design repaired by others. We find that roughly one cable replacement is needed per one to two years. We find approximately one charging station internal repair about every 4 years. Based on these estimates, having a Universal EV Outlet rather than attached cable

and connector would reduce first cost by about USD 150 and reduce maintenance costs by about USD 200/year.)

Adding to today's SE maintenance cost, there is sufficient metal, often copper, in the cable that it may be a target for petty theft. A traditional attached cable is always there, 24/7, as a target. The carry-along cable is only there when the owner is using the charger. It is always latched to the SE when charging and the car side can be locked at the driver's option (typically using the car's key fob.). When no cable is in use, only the EV outlet is present, which is difficult to remove intact and has minimal salvage value.

Why not solve connector mismatch problems with adapters? Physically, an adapter is a cylinder, typically 15 to 25 cm long with a connector that plugs into the EV and an inlet on the side away from the EV to receive the charging station's different type of connector. However, adapters also increase failures and maintenance costs. When a cable is pulled perpendicular to the adapter, the leverage risks breaking the inlet; adapters also become two more sets of contacts in the circuit, subject to wear and breakdown. Also, for safety derating, temperature should be measured on both the SE's outlet and on the EV's inlet, but it is difficult to measure temperatures in an adaptor and communicate those to the EV or SE for derating. The carry-along cable obviates the need for adaptors, leaving the SE plus EV able to measure all potential thermal failure connections, and reducing the frequency and severity of failures. All of these contribute to a lower capital cost and lower maintenance cost.

In short, using charging stations with Universal EV Outlets rather than with attached cable lowers capital cost, lowers the frequency and cost of repairs, and facilitates the installation and maintenance of charging points over a wide area.

5.5. On-Street Charging and Other Shared Parking Locations

Most charging events, and most charging energy, are transacted at locations where EV drivers park for long periods. This is especially at home and work but also at schools, shopping areas, and entertainment and social venues [15]. In shared public parking—locations including row houses, apartment buildings, and some workplaces—the charging points will have to be accessible to cars that must compete for parking spaces. On-street parking is the only home parking for 9% of US car owners and users, and off-street but without any plug availability for another 34% of cars, a total of 43% [18]. When surveyed, about one-third of those earning under USD 30,000/year perceive a barrier to EVs as “they had no place to charge an EV where they lived” [14]. Owners of plug-in vehicles are significantly more likely to replace that vehicle with a combustion vehicle if they do not have home charging [2]. A thorough statistical study of New York City's distribution of EV charging stations concludes “The current distribution is heavily skewed against low-income, Black-identifying, and disadvantaged neighborhoods” [13]. Although discrimination based on race, class, and income surely plays a part in these discrepancies, there is also a more subtle bias in that currently available charging stations are not designed for the urban environment, and worse, today's underlying technologies and legacy standards could not be efficiently used to create such a charging station.

Based on legacy SE standards, the only solution for urban locations is to reserve a subset of parking spaces to have an SE, those spaces restricted and marked with signage “EV charging only”. That is an inefficient allocation of valuable curb or parking space. The cost of city parking spaces is roughly twice the cost of charging equipment plus electricity. The need to efficiently allocate charging equipment to parking spaces especially applies to street parking but also to parking lots that do not reserve each space individually for specific employees or residents. The current North American standards situation, requiring separate SE and a reserved space for each type of connector, significantly exacerbates these problems. (Calculation of cost of space vs. cost of charging is as follows: The US median urban parking fee is USD 10/day or about USD 200/month [19]. Assuming serial installation of simple EV outlets installed along streets or parking lots at USD 5000 for installed dual outlet units, using simple payback over an 8-year life, the amortized cost

of chargers is USD 26/month. Assuming 1000 mi/month driving, a 3.5 mi/kWh EV, and 0.111 USD/kWh median retail electric price (from EIA [20]), the electricity cost is USD 32/month. Thus, the monthly parking cost (USD 200) is over three times the monthly cost of charging (USD 26 + USD 32 = USD 58).

The ideal SE for shared parking environments would be compact, low-cost, and not require an attached cable. If based on the Universal EV Outlet, there are many ways to reduce the cost and installation effort of the SE. The Universal EV Outlet already starts without the cost of a cable, and adding plug and charge could make optional or eliminate credit card or other validation components. Five LEDs can provide the essential user information, obviating the need for a screen, thus there is a lower cost and less maintenance. (The authors and the UD EV team have designed similar LED panels and EV charging stations, and both we and our commercial licensee, Nuvve Corp, have deployed over a thousand of them. From this experience, we believe the user can obtain all the information needed from five LED indicators: power on, authentication/identity confirmed, charging active, unrecoverable error, and server is connected).

Additionally, appropriate locations can use a simple waist-height pole supporting a two-outlet SE design fed by only a single branch circuit and the SE intelligently power sharing across the two outlets (see Figure 5). A single branch circuit with intelligent power sharing significantly reduces installation cost with minimal impact on charging speed. Another possible cost reduction in selected locations would use existing street-side structures, for example, using a flush-mount Universal EV Outlet in existing streetlight poles or using wall mounting for parking spaces adjacent to buildings. In high-pedestrian areas, wall mounting may have a gap to the roadway curb, creating a walkway trip hazard; thus, lamp poles, for example, may be better than walls as existing near-curb infrastructure.

Curbside charging and shared parking are important to thoughtfully place and design, since many cars park for long durations in those areas, making them suitable for low-cost AC charging. Of those areas, residential zones would be the highest priority, to enable the essential case of nightly charging while sleeping [15].

Another user advantage of the carry-along cable in shared parking is that if an EV driver finds that the only open parking space is often too far from the nearest EV outlet, the driver can adapt by simply buying their own longer EV carry-along cable.

For near-curb locations, snow removal and street cleaning are accomplished in many places by rules restricting parking to just one side of the street for a period of time, or on alternative days. In such locations, the user-owned carry-along cable will inherently also be moved away from the cleaning or snow removal. By comparison, today's SE with attached cables continues to obstruct plowing and cleaning, whether a car is there or not. Additionally, an always-present cable may present a trip hazard or ADA access issues (some AC connected-cable charging stations spool up the cable when in use, incurring the initial and maintenance cost of added mechanical spooling systems on each SE). A related issue is that attached cables causing trip or other hazards are a liability to the station owner or operator (e.g., municipality and charge point operator), whereas if the cable is brought by the user, they are responsible for their own cable.

This discussion of Universal EV Outlets for shared and urban street parking also inherits benefits discussed in the above subsections. Reiterating these for the urban and shared parking use case, our solution provides AC charging for all EVs from each SE despite a variety of EV inlets, minimizes the first cost and maintenance cost, reduces the susceptibility to cable theft and vandalism, provides an early path to AC plug and charge before it is available on all EVs, and, via low cost, makes charging stations more practical to install widely.

The many advantages of this solution, compared with the lack of current options for urban charging and the consequent lack of installed urban infrastructure, seem compelling if we are to make EVs accessible in a socially equitable way.

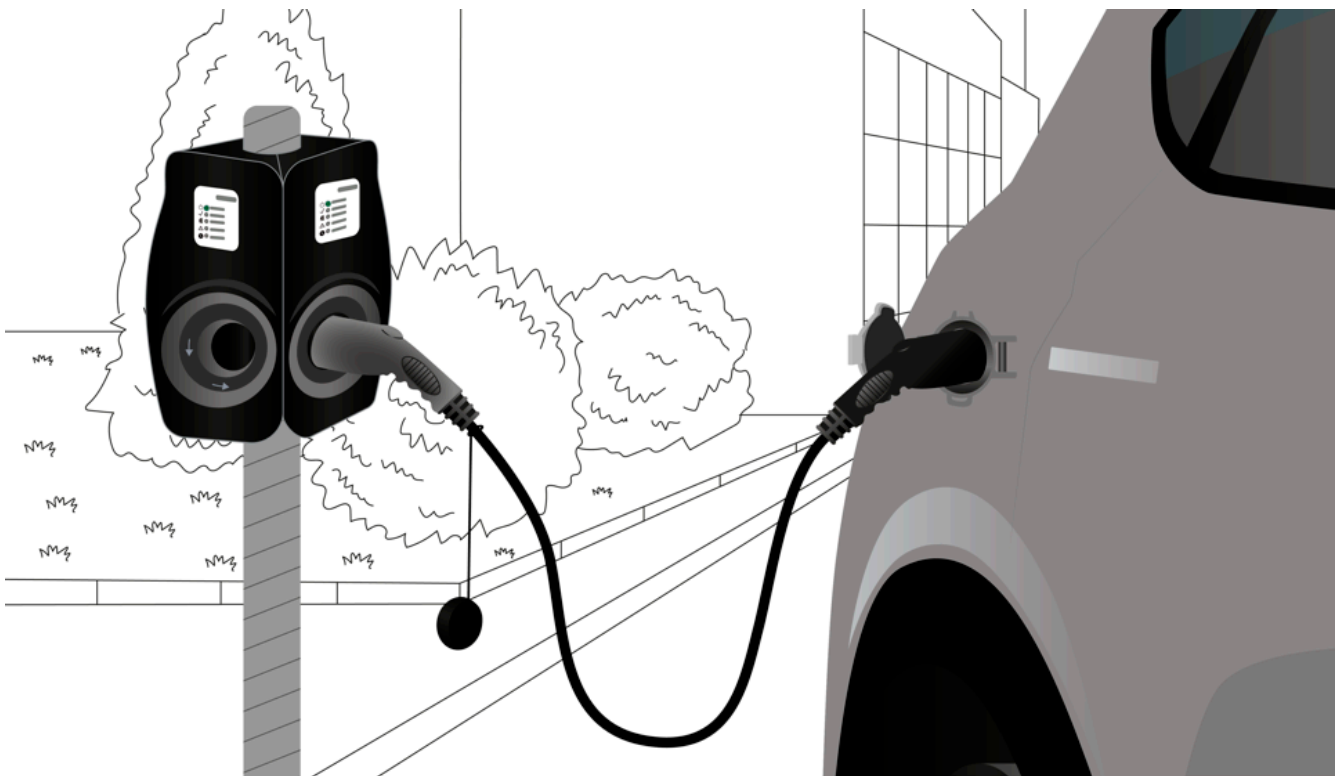


Figure 5. Example of low-cost, low-maintenance urban charging. The figure shows a curbside pedestal with dual Universal EV Outlets and a carry-along cable connecting one of the outlets to an EV. Identification is via the charging cable, eliminating the requirement for a credit card swipe, display screen, or keypad. The user inserts the plug into the Universal EV Outlet, then the ID and charging are automatic. The user can confirm startup, authentication, and the beginning of charging via five LEDs.

5.6. A Mix of EVs, Some Single-Phase, Some Three-Phase

A number of fleet parking facilities have both medium-duty vehicles (light trucks and vans), which can be cost-effectively charged from 3 ϕ AC Type 2 connectors, as well as passenger cars that only accept 1 ϕ charging. This is true of many government and company fleet lots. The Universal EV Outlet can be used for either light-duty vehicles with standard 1 ϕ charging, or for heavier vehicles with 3 ϕ charging, simply by each vehicle using the appropriate carry-along cable.

Three-phase is of value for medium-weight or heavy vehicles because it provides relatively high power from low-cost AC SEs. The Universal EV Outlet allows plugging in 3 ϕ charging for drivers with the appropriate cable (Figure 3d) which can be rated up to 63-Amp and 480 V 3 ϕ to allow 52 KW (Table 1). This power level is comparable in speed to some DC charging, but with a dramatically lower first cost and less maintenance. The lower cost of 3 ϕ AC charging in turn makes it more practical to install a separate charging outlet for every 3 ϕ EV truck or bus in the fleet, thus obviating the need to swap around the fleet's heavy vehicles as their batteries fill up during overnight parking.

Using the same Universal EV Outlet, a passenger car with a 1 ϕ carry-along cable and Type 5 connector (like Figure 3e) could plug into the same outlet used by trucks and be provided 1 ϕ 277 V up to 70 A, thus able to charge a 1 ϕ passenger car at 19.4 kW (Table 1). Note that for an SE location where EVs will never require 3 ϕ charging, the SE provider can save electrical installation cost by connecting power only to the Universal EV Outlet's neutral and L1, which will work perfectly for a single-phase car. In the converse case, if a 3 ϕ EV plugs into an EV outlet wired only for single-phase, it would typically charge but at the slower single-phase rate—in either case, both 1 ϕ and 3 ϕ EVs can charge via the

Universal EV Outlet regardless of wiring, a substantial benefit and an additional reason for the label “Universal”.

5.7. Energy Efficiency

For single-phase charging, the Universal EV Outlet can provide voltages 100 V up through 277 V (or up to 347 V with communication), whereas J1772 is capped at 240 V (Table 1). Because 277 V is higher voltage, the power transfer can be more efficient. At commercial locations, the available 1 ϕ voltages are often 208 V or 277 V. Since the power transferred is $V \times I$, increasing from 208 to 277 V will allow 33% more power transfer through the same charging equipment and cable. The higher voltage would also allow for reducing the current and reduce the resistive losses in the cable, making the charging system more energy-efficient. Since loss is equal to I^2R , increasing from 208 V to 277 V with the same cables and same power, the system would lose half (56%) as much energy.

With today's J1772 specifications, 480 V sites now require an added transformer to step down from the site's 480 V/277 V to today's J1772 maximum voltage of 240 V. The added 240 V transformer incurs added capital cost and more electrical losses. By standardizing all EVs and SEs to accept voltages up to 277 V (as is done in SAE J3400 and J3068), the Universal EV Outlet will enable more efficient and faster EV charging in so-equipped buildings and parking lots with little or no change in equipment or capital cost (Of course if the vehicle is able to use the same outlet's 480 V 3 ϕ power, that further substantially increases both charging speed and energy efficiency.). Lower electric losses and fewer required transformers both have environmental benefits as well, of course.

5.8. EV Exporting Power for Backup Power or Vehicle-to-Grid

First, we briefly consider safety for an EV exporting power. For power export, an SE with either the Universal EV Outlet or an attached cable can be used. For both charging and exporting, the cable is not energized unless both SE and EV confirm being plugged in (by J1772, J3068, or J3400 standards), thus a loose connector cannot ever be energized. All the EV and SE safety measures, described in Section 2, apply fully for charging as well as power export from the EV. Therefore, from a safety perspective, both SE with the Universal EV Outlet and SE with an attached cable are fully suitable for power export.

Lower-cost AC equipment makes it practical to have an SE near most every EV-using home and to let the EV continue to be plugged-in for the entire duration of parking. This makes the EV available most of the time for V2G or backup power. In comparison, higher-cost equipment typically means more rotation of EVs attached, and thus in the aggregate will have a lower power export capacity (e.g., DC chargers for a fleet, with EVs swapped serially as each becomes full). The rotation of vehicles is undesirable both for labor cost and because V2G revenue is in part proportional to the length of time the EV is connected [6,21].

Considering multiple electrical environments for backup power, the Universal EV Outlet allows an EV to export whatever form of power is appropriate for the building: single-phase to back up only some branch circuits, split phase to back up an entire North American residence, or 3 ϕ as is typical in industrial, commercial, and multi-family buildings. The current North American use of single-phase-only SEs at home precludes the EV from directly producing split-phase power for full-house backup power, even though today's EVs increasingly have sufficient battery capacity and power for full-house backup. Split-phase power for whole-house backup could be provided by an EV's 3 ϕ charger inverters, adjusted for two 180° phases, connected to the building via the Type 2 connector and Universal EV Outlet. (Alternatively, export could flow from an EV capable of only single-phase 240 V export, if the building side has added either a single-to-split-phase isolation transformer, an autotransformer, or similar. The transformer would be installed in the premises, connected into building circuits by a transfer switch, and tailored to the EV's export power specifications.) Creation of split-phase power is not needed for the grid-connected (V2G) split phase, as the utility-side step-down transformer remains connected

during V2G and serves as a split-phase balancing transformer without any added premises equipment.

5.9. Cases for Which an EV Outlet Is Not Appropriate

If one or more of the following are true in the location or region considering a Universal EV Outlet on their charging stations, the case for using it is less strong:

- All EVs in the country or region, or all EVs in one fleet, use the same charging inlet, and the region has no electric trucks that can accept 3 ϕ power. In this case, 1 ϕ SEs with an attached cable, plus en-route DC stations, may be sufficient.
- Over 52 kW power transfer is needed. Per J3068, 52.4 kW (63 A at 480 V 3 ϕ) is the maximum for the EV outlet. For more AC charging power, an SE with attached cable and Type 2 connector can be used, permitting 100 kW AC power transfer (120 A at 480 V 3 ϕ). This is seen in Table 1.
- If over 100 kW charging is needed, only DC is standardized at that power, and DC charging has no approved outlet, only the permanently connected cable and DC connector such as CCS or J3400/Type 5.
- For areas with no street or shared parking, today's SEs with an attached cable and connector may be appropriate.

The above situations each remove one argument for the Universal EV Outlet. Nevertheless, almost all world areas have some of the conditions motivating Universal EV Outlet use. In areas with many of the inappropriate cases above, the argument for Universal EV Outlets may be less compelling.

6. User Perspectives

The above considerations and above-cited standards are complex but achieve high functionality and make user actions simple and understandable for the EV driver. User simplicity may not be conveyed clearly in our technical and use case analysis above. How the proposed design works for users may be more fully understood via the perspectives from two example EV drivers: Bill, a potential future case, and Latasha, an actual present case. The examples show how specific user needs and requirements would be met in a country allowing Universal EV Outlets.

Bill owns a new 2028 EV sedan with a Type 5 inlet and J3068 LIN-CP communication. At work, Bill drives a delivery truck that charges overnight at the warehouse with a three-phase Type 2 inlet. Because his workplace uses all low-cost Universal EV Outlets, Bill's employer installed a 52 kW outlet for every truck parking space (52 kW could fill the truck battery in 2 h, so the business sells V2G grid services the remainder of the night). The employer also lets employees with personal EVs charge during the day as a perk. Bill does not know the names of different EV inlets and he does not understand single phase versus three phase, but he has a cable in the car and another cable in the truck and knows he can plug either vehicle into any EV outlet at work, or any Universal EV Outlet anywhere, and it always just works (if he gets the cables mixed up, it is obvious because the vehicle side connector does not fit the car's inlet). For example, when he unplugs his truck at work in the morning, he can plug his EV in to the same outlet, using the EV's cable, and his car charges while he drives his route. When driving his car, he also knows that he can charge at old Tesla chargers using the attached cable on the charging station (his carry-along cable is not needed, as the older chargers have an attached cable). In his home garage, Bill has a simple AC charging station with a permanently attached cable and connector, not a Universal EV outlet. Bill likes that because at home he does not need to pull out his carry-along cable; he charges most frequently at home and his one car only uses that one type of connector. There is no need for authentication at home or at work, but he knows that when he parks at public stations, the station starts charging a couple of seconds after plugging in, like it does at home, but the electric cost at public stations appears on the bill from his charging service provider. In all these locations, he never has to think about plug compatibility, volts, amps, phases, or billing. If he sees any Universal EV Outlet, he can

plug in with his cable. If he sees a station with an attached cable, he can charge there only if the charging station connector looks like, and fits into, the inlet on his car.

We see in Bill's example that many low-cost charging connections are available, they are easy to understand and use, and although there may be a variety of types of charging equipment, users are rarely unable to charge due to being at the wrong type of station.

A second example is from interviews with EV users [15]. The example is Latasha (a pseudonym), who lives in a large Eastern US city and 2 or 3 days a week commutes 194 miles round trip to work. She lives in a row house, with parking on the adjacent street, but street parking spaces are first come first served, not reserved for residents. She evaluated an EV with 240-mile range, reporting that her EV purchase motivations were both environmental and to save money on gasoline. Before the EV purchase, Latasha located high-power DC charging, finding two charging stations at her regular grocery store, and two locations along her route to work. She also inspected the trickle charger (about 1 kW) that came with the car, finding she could string the cord from an upstairs window to a tree next to the curb, reaching either of two parking spaces on the street adjacent to her house. She noted that she could always find parking on the street within a block or two of home, but rarely adjacent to her house. She judged these combined charging options sufficient and bought the EV. However, she found over time that she could rarely park within extension cord range of her house—she even tried paying a neighbor to watch for a space within cable reach, so the neighbor could park her car there and swap when Latasha returned home, but this rarely worked. With curbside charging unsuccessful, she had to rely on the neighborhood grocery and en-route to work chargers. But sometimes, both grocery chargers were occupied, broken, blocked by gasoline cars, or required an inconvenient wait. En-route charging added to her commute time. And DC charging filled only to 80%, making it risky to rely on an EV with an 80% round-trip range of 200 miles to meet a 194-mile need. Disappointed, she found that, as for most people, AC charging at or near home is essential to having an EV [15]. After a year of the above and many other attempts to make her EV charging work, she reported selling the new EV back to the dealer, trading it in for a gasoline SUV.

Our solution to these problems is described in Section 5.5 “On-street charging” and shown in Figure 5. This type of low-cost, low-maintenance charging is designed for curbside and these design characteristics make it more likely to be widely deployed in cities. The problem for many people like Latasha is no longer that the standards do not exist, it is not that the equipment is not already mass-produced, nor that it is costly or difficult to install or use. The problem is that the appropriate US Federal agencies do not yet sanction a reasonable urban charging station, thus it is not yet eligible for Federal funding, and thus there is no market demand to manufacture and install them in North America. A charge point operator installing in Latasha's city today would be qualified to install only attached-cable charging stations [3], not the curbside design shown in Figure 5. Thus, such products are not installed in North America, preventing AC home charging and perpetuating Kahn's [14] finding that the availability of EV charging is “heavily skewed against low-income, Black-identifying, and disadvantaged neighborhoods”.

7. Conclusions

North America now recognizes and uses three types of EV connectors for AC charging, all mutually incompatible. We propose a solution analogous to that for mobile electronic devices with diverse inlets—plug into a single type of power outlet, and different cables match the EV. Our solution has two physical components, what we call the Universal EV Outlet and the carry-along cable. We propose that new charging stations with the Universal EV Outlet be allowed and authorized for Federal programs. There is no need to replace, modify, or discontinue installing the existing types of charging stations; indeed, we identify several situations where existing stations with an attached cable and connector are preferred or equally useful. We only suggest that for new charging stations, this solution should be eligible equally with legacy standards for state and Federal programs and funding.

The needed components for this EV solution have been recently standardized for North America (in SAE J3068 and J3400); they are all mass-produced and in use by consumers in other regions. Therefore, our proposed solution could be rapidly implemented in North America. We have shown how our proposed physical components are also compatible with advanced signaling between EV and SE and compatible with power export from the EV, as used for backup power or V2G (signaling for all these use cases are defined in SAE J3068 and J3400 via LIN-CP).

We analyzed diverse use cases, finding that the Universal EV Outlet solves many existing problems. Those existing problems slow the adoption of EVs, raise costs, and inconvenience EV users. Importantly, the Universal EV Outlet is a simple to use solution to AC charging for today's world of diverse EVs with three mutually incompatible EV connectors. The current approach has been to build a separate type of charging station for each type of connector. Our solution makes possible an alternative; if implemented, a single station can charge any type of EV, since users carry in their car a cable matching their EV.

This is not a hypothetical or untested solution—in Europe, the most common SE has this outlet, and EVs are sold and rented with matched carry-along cables. The new standards SAE J3068 and J3400 adapt the European outlet so it can be used with North American-appropriate signaling and voltages.

This article has reviewed salient additional benefits: reducing capital cost and maintenance costs, making AC plug and charge available for new and legacy EVs, increasing energy efficiency, providing a means for building codes to be truly “EV Ready” at minimal cost, and allowing simple user identification and billing without any credit card swipe or app, for any EV type. By including the advanced signaling such as LIN-CP in these standards, we would additionally gain V2G, backup power, and job-site power. To our knowledge, this is also the only North American solution that will make EV charging cost-effective and practical for urban street parking or shared lots.

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