*33rd Electric Vehicle Symposium (EVS33)*
*Portland, Oregon, June 14 - 17, 2020*

# Project ChaoJi: the background and challenges of harmonising DC charging standards

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**Summary**

Nicknamed ChaoJi, the co-development of a new DC charging standard harmonising two of the three existing international DC fast charging systems, CHAdeMO and GB/T, started in 2018 as a Japan-China bilateral project. This unprecedented work of creating a brand-new plug that handles up to 900kW, while ensuring safety and backward compatibility with the existing systems, evolved into an international technical collaboration platform of experts beyond these two countries. With the sole objective of making a truly excellent new system, the experts voluntarily joined, bringing together their knowledge and market experience from around the world, and marked a turning point from battles for charging technology supremacy to international cooperation for the long-term harmonisation of standards.

*Keywords: standardization, DC fat charging, interoperability, infrastructure, ultra-fast charging*

## 1 Introduction

On 22 August 2018, CHAdeMO Association, the provider of CHAdeMO, the most widely deployed DC charging standard, and the CEC (China Electrical Commission), that of the GB/T standard mostly used in the People's Republic of China, announced their co-development of a new standard[1]. Described as 'almost shocking news[2]' by an e-mobility news site, the story was featured not only in the e-mobility media but also in more general media outlets. It came as a surprise because multiple co-existing standards had become a given in the past decade, and there was no sign of harmonisation visible to the public.

In the relatively short history of the DC fast charging systems, the background of multi-standard charging is well known at least amongst e-mobility stakeholders. In contrast, this CHAdeMO-CEC collaboration is much less documented and therefore almost unknown. This paper aims to review the project's background, describe the process and key challenges they faced, and reflect on the impacts Project ChaoJi could have on the global EV charging infrastructure outlook, through both literature search and interviews with the key stakeholders behind the ChaoJi project.

## 2 Background: DC charging systems and the global market

### 2.1 Three IEC systems, four couplers

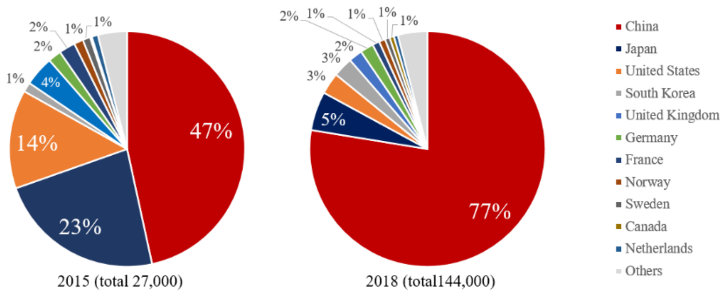
CHAdeMO was the first 'modern' DC fast charging protocol to come to market with mass-produced electric vehicles (EV), with the launch of Mitsubishi i-MiEV in 2009. Here 'modern' means leaving behind the idea of proprietary charging systems and introducing the possibility of (then non-existent) public charger networks for many types and models of vehicles (and their batteries), regardless of manufacturer, by defining a protocol equipped with EV-to-charger real-time power reference with a grid-battery capacity coordination function. Tesla came with their supercharger stations around 2012 for Model S[3], followed by the Combined Charging System (CCS) chargers and EVs in 2013. During the early days, the CHAdeMO leadership solicited key automakers to adopt CHAdeMO, but some European and American automakers announced their intention to use the CCS charging system instead in 2011[4]. Around the same time, China was also developing its own DC charging system (GB/T), which saw over 10,000 EVs on the roads by 2012, with the strong support by the government's Ten Cities, Thousand Vehicles Program[5]. Different systems but following the same 'modern' features of DC charging proposed by CHAdeMO.

The initial proposals for the IEC 61851-23 (DC EV charging station), 61851-24 (digital communication between a DC EV charging station and an EV) and 62196-3 (vehicle couplers) standards were all submitted by the Japanese CHAdeMO group, to which three additional submissions were made: China in 2010 (GB/T 20234.3-2011), Germany (CCS2) and USA (CCS1) in 2011[6]. These four coupler standards were defined in 2014. Today, all of these as well as Tesla's proprietary system are in use in various markets.

## 2.2 Charging infrastructure and EV market

According to the International Energy Agency (IEA), there are 144,000 publicly accessible fast chargers in the world, which is a five-fold increase in a mere three years, mostly owing to China's rapid growth[7]. Today, about three quarters of the publicly accessible fast chargers are in China, followed by Japan and the United States. Almost all chargers in China are GB/T and almost all in Japan are CHAdeMO. In the U.S., the number of CHAdeMO and CCS stations are both over 2,000[8] and in Europe, EAFO counts 10,950 CHAdeMO and 11,461 CCS charge points[9]. While these numbers are not directly comparable since the definition and the way each institution counts such infrastructure are different, they give a rough idea of scale.

Figure 1: Publicly accessible fast chargers in the world in 2015 (left) and 2018 (right) (IEA Global EV Outlook)




On the vehicle side, the market has been growing at a fast rate for the past decade. China has been the biggest growth driver, led by their strong national policy. Ever since China surpassed the U.S. numbers in 2015, it has been by far the largest EV market in the world, both in terms of annual new plug-in sales (BEV, battery electric vehicles, plus PHEV, plug-in hybrid electric vehicles) and of the EV stock. The result is that today, China represents over half of the global EV market (55% in 2018)[10].

Regarding the EV-side plug-type share, of the 4.3 million fast-chargeable BEVs (54% of the overall plug-in sales), excluding the non-fast chargeable vehicles (20% of BEVs), the largest EV fast-charging inlet share is GB/T (40%), followed by Tesla (19%), CCS (17%), CCS1 and CCS2 combined (includes Tesla Model 3 in Europe) and CHAdeMO (15%)[11]. As Tesla's CHAdeMO adapter allows Tesla vehicles to CHAdeMO-charge, 34% of the fast-chargeable EVs were compatible with CHAdeMO as of the end of 2019.

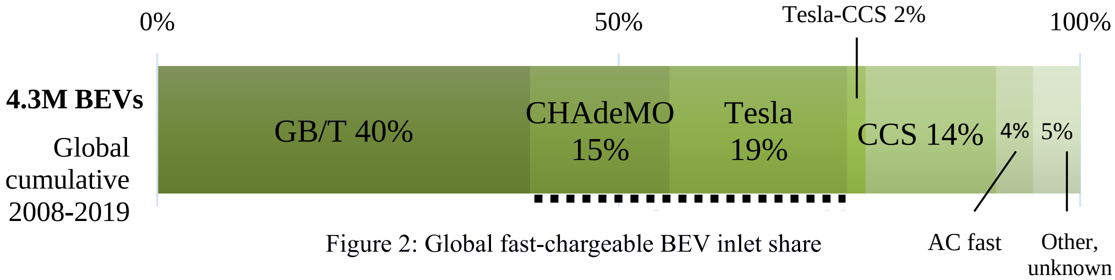



Figure 2: Global fast-chargeable BEV inlet share

While the vehicle sales as well as the charger installation data are favourable for CHAdeMO, the CHAdeMO Association's OEM members seem to have stalled in the number of upcoming models equipped with CHAdeMO inlets outside Japan; a growing concern that came to be a CHAdeMO pain point.

# 3 China: behind the phenomenal EV infrastructure development

The Chinese government provided a strong push for electro-mobility, reflecting its willingness to improve air quality as well as to end its dependence on international technology and upgrade its industrial capability to become a major automobile manufacturer. As a result, the Chinese EV market and charging infrastructure were both expanding at such an incredibly fast pace during the first half of the 2010's that the standardisation work for a single united charging standard across the massive territory was proving to be difficult[12], and collaboration with outside organisations was called for.

## 3.1 GB/T standardisation and international collaboration

A good working standard and efficient certification system to ensure safety and interoperability were missing in China. For example, in 2010, cities such as Beijing, Shenzhen and Hefei had their own standards of EV charging, which did not conform with each other[13]. It was unclear whether the GB/T charging standards were mandatory or recommended (GB/T means 'recommended'[14]), which was perceived to be a barrier by some foreign companies[15]. As the standard was perceived incomplete, not only foreign EVs, but even China's domestic brands brought in their own set of standards[16] and a new, unified version of GB standard was needed. Fast.

Starting from work on an ad-hoc basis with foreign OEMs developing their EVs for the Chinese market and testing with Chinese chargers, collaboration was eventually formalised into more structured and more permanent frameworks, at times through governmental talks, and resulted in bilateral forums for technical exchange between China and Germany and between China and Japan.

### 3.1.1 Sino-German collaboration

The Sino-German collaboration had its start circa 2010[17] and was initially focused on AC charging. More concretely, they established the Sino-German Electric Vehicle Innovation Support Center (SGEC) and implemented the Sino-German EV Charging Project (SGEVCP). In 2014, Chancellor Angela Merkel and Miao Wei, China's Minister of Industry and Information Technology (MIIT) opened the Sino-German project, and a conference series promoting 'the harmonisation of China and Germany's standardisation roadmaps' was launched[18]. A Sino-German EV standardisation working group was formed and organised technical exchanges amongst the experts on charging systems, communication between EVs and chargers, vehicle safety, and interaction with smart grids[19]. However, according to a GIZ report, 'it was soon apparent (…) that while there was significant interest in aligning standards in a general sense, the impulse to establish the predominance of one or other country's specific, existing standards remained strong[15]' and these multiple efforts did not converge on DC fast charging harmonisation. Unlike the GB/T using CAN communication, Germany's CCS uses single-wire PLC communication mandated by the ISO 15118 set of standards. While it is relatively easy to translate from one CAN protocol to another, converting from CAN to PLC is challenging. 'Germany wanted China to use CCS. The Chinese government and the industry wanted something immediately and there was no time for China to migrate to the CCS system, especially if we had to change from CAN to PLC communication,' recalls Ni Feng, NARI Group Corporation, who led the development of GB/T and had sustained close discussions with the German experts[20].

### 3.1.2 Japan-China collaboration

Although collaborations at the individual company level were already taking place much earlier between Japan and China, a more formalised collaboration scheme was established through the framework of JARI (Japan Automobile Research Institute) and CATARC (China Automotive Technology and Research Center) at the end of 2014, and one of the projects focused on charger interoperability and certification[21]. On DC charging, they conducted large-scale connection tests, worked on the issues and together fed back the results to update the Chinese GB/T standard to the next version GB/T 20234.3-2015, helping make the latter China's first solid national DC standard, which was eventually made mandatory.

Twelve Chinese exerts were invited to Japan in November 2015 to learn about the Japanese system to ensure interoperability, which was lacking in China. In Japan, since 2013 JARI (AC) and CHAdeMO (DC) provided a certification system to guarantee the good working of chargers across manufacturers. In February 2016, further connection tests took place with six EVs and five chargers. Having analysed the errors and evaluated the test items, the Chinese team saw first-hand the importance of certification tests, which led to the creation of a certification system based on the Japanese model and modifications to the Chinese charging standards[21].

## 3.2 China's proposal

China, through its bi-lateral platforms with Germany and Japan, quickly caught on to EV charging technology, which was much needed in order to exploit its full market potential and secure its place as a leader in the EV market. During that time, the market was also evolving very quickly: EV battery size, autonomy, and charging power increased rapidly especially in Europe. In the mid-2010's, China's technology in this area was 'not mature[22]' and soon after the new GB/T (2015) was released, some issues were already spotted. 'Some of the designs were not fully compliant with the IEC safety requirement, the locking system was not functioning very well, and the coupler, when the system was working at high current, was too easily damaged,' recalls Ni from the NARI Group.

China initially tried to modify its GB/T connector with minor revisions, but it soon became evident that in order to achieve all the functionality requested by the market stakeholders, they would be better off developing a brand-new connector. The key issue then was backward compatibility. 'It takes at least one or two years to produce a new plug, that means one or two million chargers using the current GB/T would be deployed during that time in China, and these could not be wasted,[20]' Ni said.

The Chinese team reached out to its partners to ask for help in high-power charging as well as some core technology in safety management. Through many discussions with multiple experts, China further shaped its proposal to create a new plug, taking into account all the best elements from the existing charging systems, and finally asked the same question to both the CHAdeMO and CCS groups: would you be willing to co-develop the next-generation DC charging protocol, and eventually migrate to the new charging system?

The CHAdeMO group has agreed to cooperate with the Chinese with several conditions, among which the most important being that the new plug would ensure backward compatibility with the existing CHAdeMO EVs and chargers. The biggest risk for CHAdeMO as the first mover and the most-widely used protocol in the market was losing trust of the e-mobility stakeholders. Protecting the interest of the CHAdeMO EV users, infrastructure owners, as well as the vehicle and charger manufacturers, who had invested in CHAdeMO, was of utmost importance. This 'waste not' philosophy aligned well with the priority of the Chinese team, who absolutely wanted to ensure backward compatibility with GB/T 2015.

The answer the German CCS group gave was that it was the Chinese who should adopt the CCS system, and not the other way around. While some CCS-member companies agreed to participate in the making of the new plug, as a group they could not align, despite the many solicitations from the Chinese side to join this international endeavour to harmonise DC charging systems.

As such, the GB/T plug modification project became a new plug creation project to ensure backward compatibility with GB/T and CHAdeMO. For CEC, who wished to improve the safety and quality of the Chinese standard, CHAdeMO was an ideal partner, who had the longest in-market experience amongst the exiting DC standards with an impeccable track record of safety. For the CHAdeMO group, with diminishing number of new EV models outside Japan and a stagnating EV market in Japan, access to the gigantic Chinese market was a promise to regain growth momentum. A trusted relationship had been nurtured through previous collaboration projects, and, above all, there was a great deal of affinity between CHAdeMO and GB/T: both used the CAN communication and followed a similar charging sequence.

# 4 Project ChaoJi: members, targets and challenges

The project was nicknamed ChaoJi, deriving from the Chinese word 超级, which means 'super.' The project kicked off in May 2018, prior to the official signing of the MoU in August that same year. The team held monthly conference calls, followed by some face-to-face meetings, and moved quickly to tackle this unprecedented work of harmonisation. As the project progressed, a wider variety of members, not only from China and Japan, joined this initiative from different motives, sharing the same hope for a safe, reliable and unified charging standard that not only functions safely and well for a long period of time, but can also help move the divided world of standards one step further towards unification.

## 4.1 Members

Figure 3: Key ChaoJi participants (CEC side)


From the CHAdeMO side, eleven OEMs from Asia, Europe and the United States, four coupler/adapter manufacturers, over a dozen charger manufacturers, and several other related companies including systems, certification and utility joined this project. From the Chinese side (Figure 3[23]), thirteen OEMs, eight charger manufacturers, another eight connector/cable assembly manufacturers and two battery manufacturers were some of the key participants, from Asia and Europe across categories.

One of the OEMs that joined the ChaoJi initiative and took an active part in its development is a Japanese commercial vehicle manufacturer that made their first prototype EV through this project. This automaker, despite much pressure to electrify its product offering, had not dared to launch an EV until ChaoJi. The engineer in charge of the R&D explained that the company was not convinced by the existing DC charging protocols because their vehicles are typically used for over 20 years by several generations of users quite often in different parts of the world before their end of life, and they wanted a durable solution. ChaoJi was the first to show this company promise for entering the EV market as it was 'a protocol that has sufficiently large market coverage, which shall allow cost reduction and longer expected technology life time, with safety ensured through years of scrutiny by CHAdeMO.[24]'

Almost a year into the project, Project ChaoJi reached another level: the development was extended to a broader multinational work group with companies from various countries and regions joining at their own will, from beyond China and Japan[25], for a timely resolution of technical issues and for adopting the best-in-class technology. To this effect, the first international conference was called for in Tokyo in July 2019, in which over 40 companies joined. In the most recent tele-conference, close to 100 participants called in, representing over 60 companies. For Ni, it was a natural extension of China's 'step-by-step' approach. 'Through private and public discussions, we came to a point where we agreed to expand our discussion to one ChaoJi interfacing with multiple other systems.[20]' For Utaka Kamishima, Co-Lead of the project and Head of High-Power SWG at CHAdeMO, it was no surprise to see many automakers in this new team: 'Any automaker would want to avoid adopting different EV charging systems for different markets.[26]'

## 4.2 Targets: specs and timeline

At the outset of the project in 2018, ambitious specification targets and a timeline were drawn: up to 900kW (600A), achieved within two years.

### 4.2.1 Target specs

The initial target specs were for the ChaoJi coupler to deliver up to 900kW (600A x 1,500V), which could go up to 1,800 kW with additional pins. With this, additional target characteristics/requirements were defined:

- Simple, light and compact new connector
- Liquid-cooling future proof cable that can handle up to 600A
- V2X (vehicle-to-everything, or VGI, vehicle-grid-integration) and PnC (plug-and-charge) ready

As there were some key European industry partners that joined the initiative, not on behalf of CCS but as individual companies through the Sino-German platform, certain specs were defined in hopes of appealing to the proponents of CCS:

- Use of a control pilot circuit similar to that of CCS
- Optional combo-style inlet that can integrate various AC connectors
- Backward compatibility: guaranteed with current CHAdeMO and GB/T, and potentially with CCS

### 4.2.2 Target schedule

An ambitious timeline was drawn: a CHAdeMO-side new version of the draft protocol (CHAdeMO 3.0) was to be finalised by Q1/2020, and the final specifications, charger certification tests and the performance test criteria for connector and cable assembly by Q1/2021. On the Chinese side, the timeline is for both the new GB/T charging protocol and certification test standards to be completed in 2021. In order to achieve this timeline, both sides advanced at lightning speed, in parallel, keeping each other updated through monthly joint teleconferences.

The Chinese side's initial prototypes were developed in 2018 and went through various tests. Some prototypes were revealed to the CHAdeMO members at large at CHAdeMO's General Assembly in May 2019[27].

By the beginning of 2019, several demonstration projects (field tests) kicked off in China. For the tests run during the first half of 2019, for example, prototype vehicles were provided by six automakers, testing with chargers provided by four manufactures, using various connectors/inlets and voltage/amperage parameters, as shown on Table 1[23]. Numerous tests including high-power charging, control pilot circuit, communication protocol, charging sequence, temperature rise, compatibility and efficiency, etc., were conducted through these demo projects.

Table 1: ChaoJi demo projects in China

工作回顾 Review- ChaoJi Demonstration

| 时间 TIME | 地点 SITE | 桩企 Charger manufacture | 车企 Vehicle manufacture | 插头/插座 Vehicle connector /inlet | 充电参数 Charge parameters |
|---|---|---|---|---|---|
| Jan. | Beijing | Xuji | BAIC | Huber Suhner , AVIC /Kangni | 600V，300A |
| | Changzhou | Star Change | FAW | Woer/Woer | 600V，360A |
| Feb. | Nanjing | NARI | Audi | Kangni/Woer | 500V，350A |
| | Shenzhen | ATC | BYD | Kangni, Woer/Woer | 650V，200A |
| | Shenzhen | ATC | Audi | Kangni, Woer/Woer | 500V，350A |
| Apr. | Xuchang | Xuji | Daimler | Huber Suhner , AVIC /Kangni | 400V，300A |
| | Nanjing | NARI | Daimler | Kangni/Kangni | 400V，300A |
| | Changzhou | Star Change | Daimler | Woer/Kangni | 400V，300A |
| | Shenzhen | ATC | Daimler | Kangni, Woer/Kangni | 400V，300A |
| May. | Nanjing | NARI | BMW | Kangni/Kangni | 400V，125A |
| Jun. | Xuchang | Xuji | Audi | Huber Suhner , AVIC /Woer | 500V，350A |
| | Changzhou | Starcharge | Audi | Woer/Woer | 500V，350A |
| | Changchun | Starcharge | FAW | Woer/Woer | 600V，360A |

During the testing event in October 2019 in Shanghai, ultra-high power connection tests were demonstrated to the participants of the charge-related IEC TC meetings (Figure 4[28]).

Figure 4: ChaoJi demo in China

On the Japanese side, the first prototype testing event attended by the CHAdeMO Regular members took place in February 2020 at UL's lab in Kashima, Japan, where CHAdeMO 3.0 charging was tested with success using ABB's prototype charger[29]. Lars Bech, Global R&D Interop Manager for EVI, ABB, says that the development of the prototype was 'relatively easy using our existing CHAdeMO and GB/T hardware, and helpful in advancing the development of the standard, as it identified some discrepancies within the flow diagrams between the CHAdeMO- and GB/T-based ChaoJi versions to be rectified.[30]' For Bech, the biggest challenge was the very strict timeline, which he hopes does not compromise the quality of the standard.

Kamishima saw excellent synergy in the working relationship between the Chinese and Japanese teams: 'While the Japanese companies excel in their basic knowledge and know-how, their Chinese counterparts were extremely fast in actually making prototypes and testing them. The Chinese team's speedy actions stimulated the scrupulous and cautious Japanese engineers in a positive manner.[26]'

The CHAdeMO 3.0 protocol draft will be published around Q1/ 2020 to all CHAdeMO Regular members, meeting the initial deadline. On 1 April 2020, exactly ten years after CHAdeMO Association was established, the CHAdeMO group planned a public event to announce the completion of CHAdeMO 3.0 (ChaoJi) to members of the press, which has now been postponed to a later date as a COVID-19 precaution.

## 4.3 Technical challenges

The ChaoJi core team identified a fair number of challenges to overcome, including:

Hardware challenges:

- Coupler's structural design: to achieve good mechanical strength
- Inlet adapters: currently prohibited by the IEC, adapters are to be used for backward compatibility
- Safety: measures against electric shock and fire, including short-circuit protection
- Control pilot circuit: balancing safety, electromagnetic interference and backward compatibility
- Cable assembly: thermal management and temperature sensor configuration

Software challenges:

- Long-term unification and transition of communication protocol
- Plug-and-charge (PnC) and V2X (vehicle-to-everything) capabilities to be included by default

In the first international conference held in 2019, the core team proposed to set up a number of small work groups (SWGs) to tackle these tasks in parallel: **SWG1** (coupler & adapter), **SWG1-1** (automated / robotised charging), **SWG2** (system & safety) and **SWG3** (communication protocol). Each of these international SWGs met on a monthly basis to push forward the work, in some cases feeding directly to/from the IEC discussions. In the next sections, selected technical challenges are discussed in further detail: the coupler (mechanical strength, size and safety measures), adapters, and communication options.

### 4.3.1 Coupler: mechanical strength and safety

The reports of current plugs' weak structures and lack of safety led to an ISO warning in the end of 2017[31]. Achieving the mechanical strength of the connector that was at least equivalent to that of the CHAdeMO connector was a goal that the SWG1 members did not want to compromise. Several connector models were proposed and tested, but the mechanical strength did not improve as they had wished, until the Japanese experts came in. Keiji Yahagi, Fujikura Ltd., recalls the tough requirements: 'The Chinese side had already pretty much finalised the design of the coupler when they consulted for improving its strength, which meant we had to keep all the key dimensions such as the pin diameters and layout.[32]' Several hundred micrometres to a few millimetres of modifications in the thickness of the outer wall within the stringent constraints of the connector dimensions were made, which led to 'an improvement of up to 70% in the mechanical strength[26],' praises Kamishima, The Japanese 'Modify 2' proposal was retained, which passed the strict requirement of the ball-impact test of 10J as shown on Figure 5[33] and cleared the criterion that was set to at least three times more severe than the IEC requirement (3J), consequently avoiding risk of electrical shock by direct contact with the power terminals, double-checked by the test results from China and Japan.

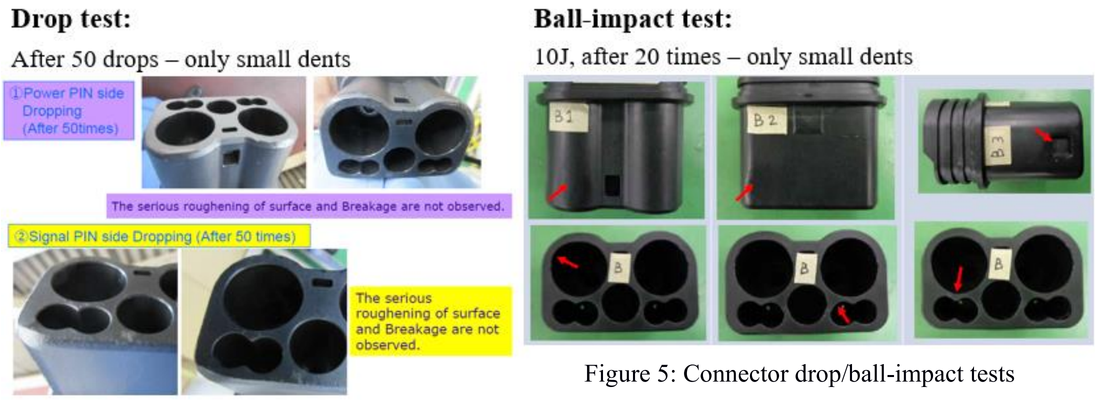



Figure 5: Connector drop/ball-impact tests

Coordinating the development of the new coupler with the relevant discussions at the IEC in parallel was another advantage of this project. While the ChaoJi team discussed the design of the coupler, the experts at the IEC were also having discussions on safety measures and standardisation, including avoiding risks stemming from damage to the connector when dropped; protecting consumers from potential hazards caused by direct contact with the power terminals; short-circuit due to water penetration; etc. The ChaoJi team 'adopted such best-in-class standards directly and helped build common safety models for the IEC in return,[20]' Ni says with pride. Lars Bech from ABB also emphasises the importance of establishing the safety standards. For ABB, one of the objectives of actively participating in the ChaoJi work group was a way to rectify many of the issues existing standards encountered, especially the lack of conformity to a high level of safety standards, which were yet to be established[30].

Having tests in Japan, China and elsewhere led to a strong culture of data-oriented decision-making. 'The Chinese Team placed much importance in the Japan-side test results, and we sensed it. We were able to cross-reference our data, which led to our mutual trust based on data,[26]" confides Kamishima. Bech from ABB also saw a great deal of testing and simulation results performed and shared by a number of parties 'to answer the same question of whether or not this standard was producible and robust,' and confirms that 'the efforts of all involved parties were commendable[30]'.

### 4.3.2 Coupler: high-power yet light and compact

Making the new connector high-power yet compact and light was one of the key items on the wish list. When picking up a ChaoJi connector, one is surprised by how light and compact it is, compared to the current high-power CHAdeMO connector, as shown on Figure 6[29]. There are two key factors for this: liquid cooling and the locking mechanism that was moved to the vehicle side.


Figure 6: ChaoJi vs. CHAdeMO

According to Yahagi from Fujikura, liquid-cooling inside the cable enables the cooling of the connector terminals, but cooling and keeping the cable safe and durable, as the EV drivers ‘pull and twist’ those connector cables all the time, is the fine balance they needed to strike[32].

### 4.3.3 Adapter: dealing with weight and usability

Backward compatibility being the starting point of the project, the task of developing adapters was critical. Incidentally, IEC 61851-1 prohibits any use of adapters for high power charging today. It was ChaoJi Team’s first task at the IEC to submit an amendment proposal to change this clause in October 2019.

The first CHAdeMO-ChaoJi adapter was prototyped by Fujikura and demonstrated at the CHAdeMO demo event in Kashima[29]. Unlike the CHAdeMO-Tesla adapter offered by Tesla, no protocol translation function is in the adapter, which eases many aspects e.g. cost, weight, durability, interoperability and testing. However, there remain challenges to overcome.


Figure 7: Adapter prototype

Key challenges included how to make the adapter compact and easy to use. For now, the sheer weight (3.5kg) of the adapter and the inflexible cable make its handling not easy. This is largely because it is not cooled, and the cable needs to have thick conductors for safety reasons. Yahagi’s team chose to make the cable longer to avoid scratching the EV body in use, which in return made the cable part alone weigh almost 2kg. ‘We need to make it shorter and improve further the coupler design to reduce the overall weight as well.[32]’

### 4.3.4 Communication: unification of the communication protocol

The hardware harmonisation still allows for different communication protocols (GB/T and CHAdeMO). Unification of the communication protocols would be a natural next step. As most stakeholders want to move in the direction of harmonisation rather than having to deal with multiple regional standards, the ChaoJi group took a long-term view and initiated discussions involving multiple stakeholders for a unified protocol. As some key regional legislative bodies, including the European Union, the State of California (USA) and India, are looking into mandating some standards concerning smart charging and other value-added services (e.g. plug-and-charge), it became crucial that the ChaoJi group take into consideration such regional legislative movements in setting its direction.

NARI’s Ni Feng, who leads ChaoJi’s SWG3 activities thinks that the ChaoJi group should propose a new common communication standard that can be acceptable for all international stakeholders. ‘In a world that is becoming more and more IP based, CAN is not the final answer. Of course, this shall remain the legacy system for a while, but we need to think about what the world in 5-10 years will be like, how to achieve a smooth transition to the future system, and finally to reduce the cost of transition,[20]’ says Ni. The thinking of the SWG3 at the time of writing this article is that Ethernet-based, 2-wire (and wireless) communication are the most likely direction.

Another global movement consisting of prominent EV OEMs, EV charger manufacturers, and charging network/service providers also supports the idea of new communication standards in this direction: a collaborative research project launched by SAE International, with the aim of developing a worldwide Public Key Infrastructure (PKI) for EV charging system cybersecurity[34]. ‘This is essential for properly securing implementations of advanced applications like plug-and-charge (PnC) and energy management for ISO 15118 and CHAdeMO protocols,’ says Craig Rodine, Director of Standards at ChargePoint, a U.S.-based EV infrastructure company and a key member of this industry-led initiative. ‘CAN bus-based protocols like

CHAdeMO and GB/T will also have to evolve to support PnC and other advanced services beyond charging control. For this, EV-charging systems need state-of-the-art end-to-end cybersecurity, which strongly indicates a TCP/IP connection between EV and charging station,' continues Rodine, who supports ChaoJi's approach of using Ethernet and a TCP/IP stack, 'as many experts think that future connectors should be able to use inexpensive and widely-supported Ethernet technologies on this link, which would also allow the exchange of much higher volumes of data.' Rodine hopes, like Ni, that in the long term, all key charging standards can unify, or at least harmonise, their communication protocols[35].

As the harmonisation of ChaoJi hardware was the defined initial step of the project, the work for unification of communication shall continue. Along the way, it may potentially converge and increase momentum with other movements like those of SAE or the CCS group, and eventually be accepted as a new unified communication standard.

# 5 Non-technical challenges and implications

Once the new standard is developed, the question will move to the development and deployment of new systems (EV and EV charging infrastructure) as well as how the markets will transition to the new regime. What are the potential scenarios and implications of this work on the global EV-charging market? How is the actual productisation (which products, when and where?) expected to happen and evolve?

## 5.1 Transition to the new systems and ensuring backward compatibility

The ChaoJi development team's primary concern and the starting point was 'backward compatibility': how to keep using current systems as long as possible, even when the new systems are introduced to the market, to solicit the most organic and optimised transition to the new systems.

Table 2: Backward compatibility matrix proposed by ChaoJi core team

| | | Vehicle | | | |
|---|---|---|---|---|---|
| | | CHAdeMO ~2.x | GB/T-2011 or 2015 | CHAdeMO 3.0 (ChaoJi) | New GB/T (ChaoJi) |
| Charger | CHAdeMO ~2.x | Compatible | | Via adapter | Via adapter |
| | GB/T-2011 or 2015 | | Compatible | Via adapter | Via adapter |
| | CHAdeMO 3.0 (ChaoJi) | CHAdeMO-ChaoJi dual charger | | Compatible | Compatible |
| | New GB/T (ChaoJi) | | GB/T-ChaoJi dual charger | Compatibe | Compatible |

As discussed briefly above (4.3.3) investors in EVs and charging infrastructure can promote and proceed with deployment of the new system, while supporting current devices and systems, with the use of adapters or dual chargers to make the transition as natural and smooth as possible.

Consequently, the ChaoJi team proposes a matrix of ensuring interoperability and backward compatibility (Table 2[36]). Roughly speaking, it suggests the use of an adapter or conversion box for charging new vehicles with existing chargers. For charging current vehicles with new chargers, it suggests a multi-standard charger equipped with both the current and new connectors. Ni thinks this transition process shall take fifteen to twenty years in China, depending on the speed and scale of e-mobility evolution in each region. 'It's a long time. It's normal, when considering the typical 10-year life cycle of vehicles, and what's important is to minimise the cost of transition and not waste or rebuild current chargers.[20]'

## 5.2 New charging stations and vehicles

The first ChaoJi EVs are expected to be launched in the market a few years after the standards are published, or around 2023. The deployment of new chargers can wait until the initial EVs' specifications become known, especially if the use of adapters can already ensure some comfort for the beginning of transition. Adapters and multi-standard chargers can precede, before the mass market picks up with the new systems.

Since product development plans are among the most confidential type of information, concrete launch plans of ChaoJi OEMs are unknown to the author. Some expect the initial ChaoJi vehicles to be commercial vehicles (e.g. delivery trucks and buses). If the initial vehicles aim for ultra-high-power charging, the new chargers are going to be significantly more expensive as compared to the current systems. In order to cope with the ultra-high power, ChaoJi uses liquid cooling, which requires a dedicated system for heat transfer, e.g. radiator, fan, and/or chiller. As the power level is higher than the current systems, a high-voltage power conversion facility (e.g. separate cabinet and possibly a fenced area) will also be needed, both of which will contribute to making the new infrastructure larger and more expensive.

Ni, on the other hand explains that ChaoJi was not designed exclusively for ultra-high-power commercial vehicles. 'Such a small and compact plug [as ChaoJi] is still suitable for passenger cars, and might not be optimal for some applications such as buses that can use much bigger systems like pantographs and may not even require public chargers.[20]' Almost all the interviewees for this article hint at a lower maximum power level initially than the targeted 900kW, in order to contain costs for commercial vehicles or for passenger car applications. Commercial vehicles typically run pre-determined routes, which allow for the fleet owners to optimise the life cycle costs of their vehicles, including charging options. 'The total life cycle cost of the commercial vehicles needs to be economically competitive with those of diesel cars,' explains the R&D manager for a commercial vehicle manufacturer, 'ultra-high-power charging such as 900kW might not be economically viable for some of our customers.[24]' Therefore, even if the infrastructure side is prepared for liquid cooling, whether (or not) the actual EVs will adopt high power levels requiring liquid cooling is another question the investors need to keep in mind.

Another potential scenario is DC-only charging at all levels. For passenger cars, as is widely known, the great majority of EV charging takes place at a low power level (below 10kW) at home or the workplace, today typically using AC chargers. The new system will likely not change such basic charging behaviours, but if the price level of low-power DC chargers comes down as low as, if not lower than, today's AC chargers, which is quite possible at high volumes, future EVs could be equipped with a DC port only. Under such a scenario, many future users of ChaoJi would mostly charge with low- to medium-power DC chargers and use fast or ultra-fast chargers at key terminal hubs and motorways occasionally, when going on a long trip, using the one ChaoJi DC interface for all their charging needs.

## 5.3 Target markets

The markets for ChaoJi EVs and ChaoJi infrastructure deployment remain largely speculative at this time. The Chinese and Japanese governments support the extension of the CEC-CHAdeMO collaboration to third countries, i.e. outside of China and Japan[37]. Aggregating stakeholder interviews, Asia (South-East, East, South and Central), Middle East, Africa and Central America were mentioned as the initial markets after China and Japan. Others were more cautious and simply wanted to concentrate on the Chinese market.

In any case, since the current CHAdeMO markets are outside of China and the current GB/T systems are mostly in China, there is very little overlap between the areas where each system is adopted, and both can transition to ChaoJi at a different pace in a different manner depending on their situation and requirements.

Europe and U.S. markets, where the great majority (90%[38]) of global CCS vehicle sales are concentrated, are a different story. As in the case of the EU Directive that 'mandated' the CCS2 plugs in 2014[39], the regional legislation may become a barrier to ChaoJi standard deployment in certain markets. Considering the amount of investments that have already gone into the existing systems and designs, it might be difficult to shift quickly to a new system. However, the ChaoJi core team members remain hopeful, as Ni puts it, 'if the EU/US automakers produce ChaoJi vehicles to introduce first to the Chinese market, and if 30-50% of their EVs go to the Chinese market, the OEMs may ask to sell the same EVs in EU/US.[20]'

## 5.4 Other implications and conclusion

Harmonisation of charging standards is something all EV-charging stakeholders have been asking for, and something the history of DC fast charging protocol development did not deliver, as described in Section 2.1. As a consequence, the market has had to accept the co-existence of a handful of charging standards, to the chagrin of all, EV drivers being the most affected stakeholders.

ChaoJi, regardless of the team's initial intentions, has certainly evolved in its scale and engaged external stakeholders with the conviction of making this an open platform for collaboration for a global unified plug. In this sense, it has proven to be a model case of 'international collaboration with the common aim of making the best-possible product and, as a consequence, advancing electro-mobility,[32]' as described by Fujikura's Yahagi. Some political and economic factors may not have allowed all groups to join this initiative, but when you look at the list of companies that joined in the end, most prominent stakeholders from key markets (Asia, Europe, the Americas, Oceania) have either actively and directly participated in the making of this new protocol, or followed its discussions sufficiently so that they shall have the capability and option of using it. Achieving this level of global scale was an indispensable step for the ChaoJi core team to 'make ChaoJi ready to be a global universal plug, when one is needed,[20]' according to Ni.

Depending on how the stakeholders manage the intricate set of political and strategic options, ChaoJi may or may not become the global standard. However, China for one, which represents the biggest share of the global EV market, is considering to mandate the new standard on a national level, which will require all the OEMs and charger manufacturers who want to participate in the Chinese EV charging market to adopt ChaoJi. For other regions and countries, it is up to the local market players and policy makers to decide what they wish to adopt, but it is the ChaoJi team's hope that all regional standards can move in the direction of harmonisation, rather than closing markets for short-sighted protectionism. As Kamishima puts it: 'Any engineer evaluating purely on the technology merit would know the quality of ChaoJi. In order to accelerate the electrification of the automobile industry, a fair competition and international cooperation should be encouraged through open mind and mutual respect.[26]'

## Acknowledgments

The author wishes to extend her special thanks to the interviewees who took time to share their passion and experience, particularly to Utaka Kamishima and Craig Rodine, who answered queries with infinite patience and painstakingly reviewed my drafts. My thanks to Marie Raude, who undertook the literature search for the Chinese section.

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