Towards Japan's Future EV-Friendly Highway Concept With In-Motion Road-Embedded Wireless Chargers

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ABSTRACT

Electric vehicles (EV) are gaining momentum as a bright prospect to replace conventional fuel-dependent internal combustion engine (ICE) as demand of EVs increase year by year in every country. However, due to battery capacity limitation and charging stations availability, EVs are mainly used in urban areas for short-range commuters rather than long-range journeys. This has resulted in EV usage concentrated in town and business areas. It is clear that EV usage for long distance driving is still in minimal priority due to inadequate battery performances and charging infrastructures insufficiency. In this study, we propose an infrastructure concept of EV-friendly highways, solving range anxiety issues by wirelessly charging the vehicle while in-motion, particularly at highways namely Dynamic Charging Highway (DCH).

1. INTRODUCTION

Usage of electric vehicles for long range driving has gained manufactures' attention and battery developers for some time. Currently, two of the longest cruising distance for an EV in a single charge is the Tesla Model S 90D, astoundingly capable up to 570 [km] (Source : teslamotors.com/jp) and Nissan Leaf EV 30kWh with capability up to 280 [km] (Source : Nissan.co.jp). In addition to the plug-in charging, wireless charging mechanism introduced for EVs mainly aimed to eliminate the time wasted during stop and recharge process such as the KAIST OLEV Project (Korea), ZeEus Project (Europe) and Milton Keynes Project (UK) [1]. However, these projects tested in urban public transportation that applied for electrical buses, without considering usage for normal passenger EV.

In this paper, the author presents EV charging infrastructure in few countries in promoting long-range EV usage and conducted a design on dynamic charging infrastructure to promote non-urban driving, namely the Dynamic Charging Highway (DCH) in Japan for normal passenger EV. Its operation proposal, installation locations and future issues in realizing the project were also presented.

2. HIGHWAY CHARGING INFRASTRUCTURE

In this section, the author will explain current and future EV charging in highways in few countries.

1.1 UNITED STATES OF AMERICA (USA)

In USA, EV charging network is expanding day by day. One of the most attention-gaining charging infrastructures is the Tesla Supercharger. Using the Supercharger, Tesla owners could recharge up to 80% of battery capacity in minutes. Tesla claimed that their Superchargers are the world's fastest charging station as it could provide 273 [km] of additional range in as little as 30 minutes. This was made possible through supplying 120 [kW] of DC current directly to the battery. According to Tesla, they aimed that in these 30 minutes, they could supply sufficient power enough to reach the next Supercharger station. Expansion of these stations will give their customer the range confidence to travel anywhere without worrying about battery level. Figure 1 shows the Supercharger network that will be completed in 2016.

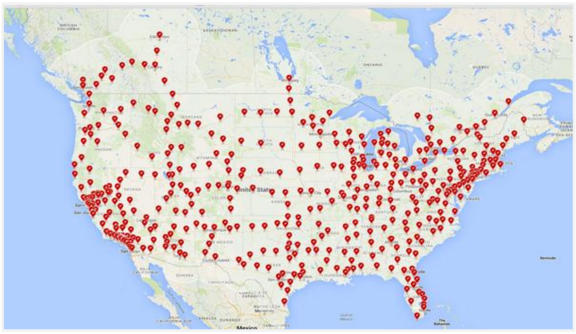

Fig. 1 Tesla Supercharger Network 2016 plan
(Source : Teslamotors.com)

In completion of these charger network plan, Tesla will make history by completing coast-to-coast electric highway for Tesla travelers.

1.2 EUROPE

In December 2014, an European consortium of five partners : the leading partner ABB B.V. (Netherlands), Fastned B.V (Netherland), CLEVER A/S (Denmark), Öresundskraft AB (Sweden) and the VDE Prüf-und Zertifizierungsinstitut GmbH (German), launched a project in an attempt to create an open access of fast charging corridor situated along major highways connecting Sweden, Denmark, Germany and Netherlands. The project, named as European Long-Distance Electric Clean Transport Road Infrastructure

Corridor, abbreviated as ELECTRIC [2]. For a reported project cost of 8.4 million Euros, this project will add 155 ABB Terra Series high-quality fast chargers on major roads connecting Germany, Netherlands, France, and Denmark. The consortium expects this corridor will help accelerate the proliferation of electric vehicle not only in the countries where the network will be created, but also serve as a model for other regions and EU member states. Figure 2 shows the highway fast charging network in their project.

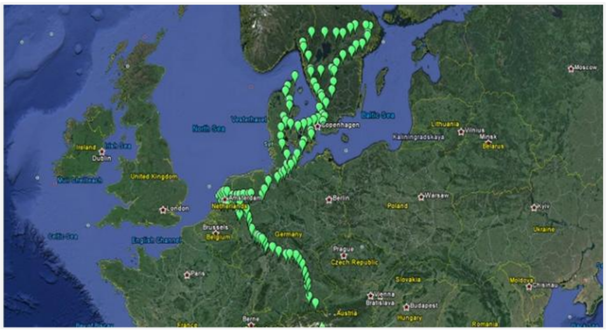

Fig. 2 Europe Cross-border Motorway charger plan (Source : abb-conversations.com)

Additionally, in September 2015, German Transport Minister Alexander Dobindt inaugurates 400 fast charging stations every 30 [km] to be deployed on highways' rest area by 2017 [3]. This project is collaboration between the government and biggest highway rest area operator *Tank und Rast* to initiate multi-standard fast chargers to German highways (Source : chademo.com).

1.3 JAPAN

In February 2015, Nissan Motor Co. officially reported that Japan has more charging spots (40,000) compared to gas stations (34,000), as quoted by Bloomberg [4]. This clearly shows the expanding popularization of EVs in the country. At present, the number of fast charging stations is increasing rapidly in Japan, as shown in Figure 3 provided by CHAdeMO.

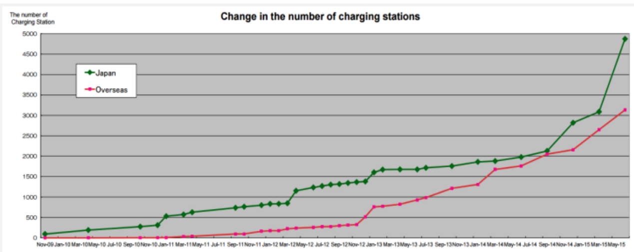

Fig. 3 Number of CHAdeMO's stations in Japan and Overseas (Source : Chademo.com)

3. WIRELESS CHARGING HIGHWAY

As plug-in charging networks are greatly increasing in number day by day, a new groundbreaking charging mechanism for an EV is currently in development. In this part, the author will present a wireless charging project for EVs in Japan in our research project. Currently, Dongwon OLEV in South Korea are operating their wireless charging buses, namely On-Line Electric Vehicle (OLEV) for public transport connecting Gumi Station to Indong District, a total route length of 24 [km], supplying power from underground coils up to 100 [kW]. They claimed that the system was able to reduce battery size to 1/3 to 1/5 of normal size. In their project, they plan to implement mainly for public transports, namely buses, trucks and trains.

In England, "Highways England", the UK Government organization that is responsible for maintaining and operating England's motorways and major A roads recently publishes a feasibility study for their highway-charging project [5]. Figure 4 shows the topology for their project. In their study, they mainly discuss on collaborations with industries, possible design and potential technical problems to current power system.

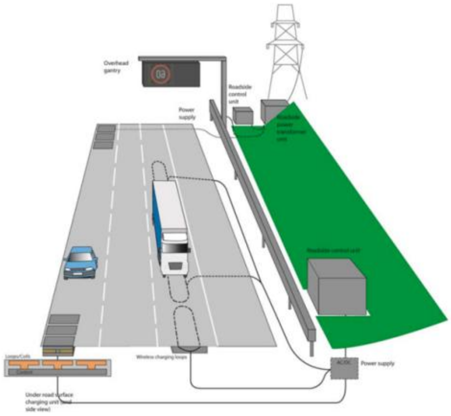

Fig. 4 Highways England roadway charging topology

Conclusively, we can see that many organizations in the world have started practically test the system for electric-powered vehicles. Although further developments are still indeed required, these efforts clearly showed that the mechanism is technically feasible and possesses bright prospect to be realized in future.

4. HIGHWAY DESIGN PROPOSAL

Next, the author will present about the EV-charging highway in this paper, named as "Dynamic Charging Highway", abbreviated as DCH. In DCH, wireless underground chargers embedded in highway roads in few locations of major highways in Japan will provide sufficient power enough to 'top-up' few percentage of power to the vehicles' battery. Basically, this system will be installed on most left lane in highways because vehicles that will be charged need to slow down their vehicle as this will improve power transfer efficiency. We aim to install the system in places where congestion mostly occurs. Figure 5 shows the DCH proposal design.

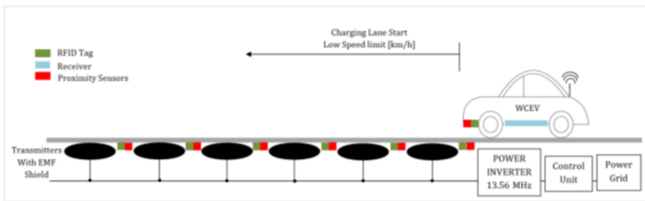

Fig. 5 Dynamic Charging Highway topology (Image)

Proximity sensors (red) are vital components in the on-road system, as they will not only utilized for vehicle detection but also for sending rapid signals to transmitter coils to turn it on. When vehicles with dynamic charging ID are detected, a number of transmitter coils will be turned on according to the vehicle cruising speed. Therefore, for a vehicle that is travelling at lower speed, only few of the transmitters will be turned on. On the other hand, for higher speed vehicle, more coils will be activated in order to increase the certainty of transmitting and receiving power. However, it needs to be justified that slower vehicles are expected to receive more amount of power as power transfer efficiency increase with lower vehicle speed. This is mainly due to the fact that lower speed vehicle will pass through each transmitter for longer periods than higher speed vehicle. The table below shows example of coil switching according to vehicle speed.

Table 1 Transmitter activation for low-speed EV

Position							EV
Sensor							
Transmitter							

Table 2 Transmitter activation for high-speed EV

Position							EV
Sensor							
Transmitter							

Therefore, by linking the switching process with vehicle speed sensors, we are able to respond the power transfer process to be able to operate at any vehicle speed, accordingly.

4.1 Installation Locations

In our project, we consider the installation locations based on the traffic volume. Thus, highway traffic volumes are considered in determining where the best place to install the system is. As amount of power transfer are inversely proportional to vehicle speed, this system will have better performance at locations where EV's speed are relatively low, for example, near service area (SA), interchange (IC), junctions (JCT), curve roads and traffic jam areas. The author has conducted installation location studies for potential DCH location, focusing on traffic congestion areas using data from Ministry of Land, Infrastructure, Transport and Tourism of Japan (MLIT) [6]. They provided a data ranking in term of traffic congestion by 'Lost of time due to congestion'. I have determined that five locations are potential to be equipped with on-the-move charging capability. Listed below are the locations.

- Worst Traffic Jam Ranking
  1. Tomei Expressway Yokohama Machida IC – Ebina JCT (Inbound)
     Tomei Expressway Ebina JCT – Yokohama Machida IC (Outbound)
  2. Tomei Expressway Hadano Nakai IC – Atsugi IC (Inbound)
  3. Chugoku Expressway Nishinomiya Yamaguchi JCT – Takarazuka IC
- Morning Peak
  4. Chuo Expressway Inagi IC – Chofu IC (Inbound)
- Evening Peak
  5. Kan-Etsu Expressway Oizumi JCT – Nerima IC (Inbound)

4.2 User Payment System

Automatic payment system based on amount of power received will be implemented in the DCH. Each user will have to register their vehicle with DCH operators and each vehicle ID are linked with their credit card or personal bank account. The vehicle ID user authentication uses the RFID tags placed on the vehicle body and on the road (see Figure 5-green box). Two types of payment are proposed. In the first method, payment will be conducted once charging process finish (real-time payment), separately with highway usage payment. In the second method, amount of payment will be charged together with highway toll and payment is calculated as highway usage payment plus dynamic charging bill. Figure 7 shows the flowchart for DCH operations from vehicle detection to payment process. The author will explain payment price per kWh in the next section.

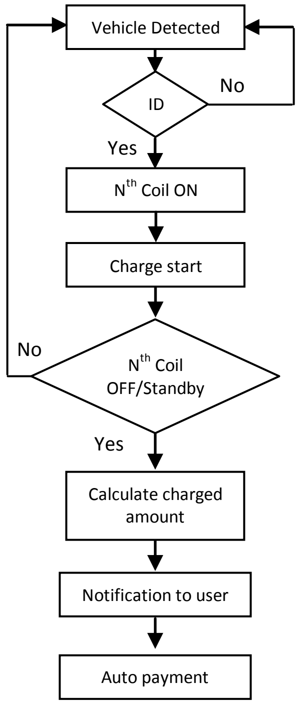

Fig. 7 System flowchart

4.3 Plug-In Charging vs. DCH Charging

Next, I have conducted comparison of plug-in charging with DCH charging in terms of the relative one-liter consumption of fuel with electricity tariff per kWh (plug-in charging); units are in [km/l]. Calculation results are as in Table 1 only for Location 1. Here, I have set the DCH Charging price at ¥50/kWh during peak-time and ¥25 during off-peak time. Gasoline price assumption is ¥130/liter, an average price considering MLIT's data on regular gasoline price from April 2014 to December 2015 [7].

Table 1 Comparison of plug-in and DCH charging for Nissan Leaf (135Wh/km)

<table>
<tr><th>Charging Place</th><th>Home</th><th>Public</th></tr>
<tr><td>Relativity with gasoline usage [km/l]
(Daytime Charging ¥30/kWh)</td><td>33.8</td><td rowspan="2">36</td></tr>
<tr><td>Relativity with gasoline usage [km/l]
(Nighttime Charging ¥13/kWh)</td><td>78</td></tr>
<tr><td colspan="3">With DCH (Example : Location 1-Inbound)
Expected power transfer (Eff. 90%) : 0.702 [kWh]
Extendable cruising distance : 5.2 [km]</td></tr>
<tr><td>Relativity with gasoline usage [km/l]
(Peak price ¥50/kWh)</td><td colspan="2">19.5</td></tr>
<tr><td>Relativity with gasoline usage [km/l]
(Off- Peak price ¥25/kWh)</td><td colspan="2">39</td></tr>
</table>

Therefore, we can see that EV charging through DCH during off-peak time (39) would offer better benefits compared to daytime plug-in charging at home (33.8) and public (36) in terms of relative price of gasoline to DCH payment price. Consequently, we can expect more wireless charging EVs to use DCH during off-peak time and as a result, DCH could also contribute in reducing peak time congestion.

5. CONCLUSION

The author has presented a proposal of constructing wireless charging highway in Japan, namely Dynamic Charging Highway (DCH) in this paper, its topology example, operational proposal, and its payment and billing system. Calculation results has shown that charging using DCH could give better benefits to users in terms of relativity to gasoline price and benefits to highway operators as it could reduce peak time congestion. Therefore, I can conclude that realization of DCH will offer better range to current and potential EV users and additionally complement current plug-in charging infrastructure. It is clear that EV usage is getting worldwide attention to replace current gasoline vehicles and EV manufacturers. In future, more EV will be having the capability of long distance driving.

6. FUTURE ISSUES

Nevertheless, it is clear that many future issues arise in our efforts to realize this concept. Listed below are few issues that need to be cleared in commencing the DCH project.

1. <u>DCH Construction and R&D cost</u>
   It is clear that a large amount of funding are needed in developing this WPT system in highways. Government funding, as made by South Korea government in the OLEV project, can further accelerate the R&D process.
2. <u>Standardization of WPT system</u>
   In terms of operational frequency, the SAE International has suggested that 85 kHz is considered to be the best candidate for kW-class WPT for passenger EV.
3. <u>Collaboration with electric power company</u>
   Connecting DCH system to current power system could impose interference to power system, especially during DCH's high load time as rapid switching could give voltage or frequency fluctuations.

7. REFERENCES

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Authors Profile

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