Towards Japan’s Future EV-Friendly Highway Concept with In-motion Road-Embedded Wireless Chargers

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Abstract: This paper proposes a demonstration of the infrastructure concept of electric vehicles-friendly highways. EVs (electric vehicles) are gaining momentum as a bright prospect to replace conventional fuel-dependent ICE (internal combustion engine) 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. The proposed concept is to solve range anxiety issues by wirelessly charging in-motion vehicles, particularly at highways namely DCH (dynamic charging highway).

Key words: Electric vehicles, demonstration, in-motion wireless charging, LabVIEW observation.

1. Introduction

Usage of electric vehicles for long range driving has gained manufactures’ attention and battery developers in recent years. Currently, two of the longest cruising distances for an EV (electric vehicle) in a single charge are the Tesla Model S 90D, astoundingly capable up to 570 km (https://www.tesla.com/jp/models?redirect=no) and Nissan Leaf EV 30 kWh with capability up to 280 km (http://ev.nissan.co.jp/LEAF/PERFORMANCE/battery.html). 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 (on-line electric vehicle) Project (Korea), ZeEus Project (Europe) and Milton Keynes Project (UK) [1]. However, these projects are tested in urban public transportation that are applied for electrical buses, without considering usage for normal passenger EV.

In this paper, the authors present 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 DCH (dynamic charging highway) in Japan for normal passenger EV. Then, the proposed demonstration shows the operation proposal, installation locations and future issues in realizing the project.

2. Highway Charging Infrastructure

In this section, the authors explain current and future EV charging in highways in some countries.

2.1 USA (United States of America)

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 fastest charging station in the world as it could provide 273 km of additional range in as little as 30 minutes. The charging station supplies 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 customers the range confidence to travel anywhere without worrying about battery level. Fig. 1 shows the supercharger network that would be completed in 2016.

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

2.2 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. Fig. 2 shows the highway fast charging network in their project.

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 the biggest highway rest area operator Tank und Rast to initiate multi-standard fast chargers to German highways.

2.3 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 Fig. 3 provided by CHAdeMO [3].

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. Currently, Dongwon OLEV in South Korea are
operating their wireless charging buses, namely OLEV for public transport connecting Gumi station to Indong district, a total route length of 24 km. The OLEV buses have been supplied 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, the UK government organization “highways England”, which is responsible for maintaining and operating England’s motorways and major A roads, recently publishes a feasibility study for their highway-charging project [5]. Fig. 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.

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

In this section, the authors propose the infrastructure of the highway embedded in-motion EV chargers, named as “dynamic charging highway”, abbreviated as DCH. In DCH, underground wireless 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. Fig. 5 shows the DCH proposal design.

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. When a vehicle travels at low speed, only a few transmitters will be turned on. On the other hand, for high-speed vehicles, more coils will be activated in order to increase the certainty of transmitting and receiving power.

Basing on amount of transfer power, the velocity of an EV has been determined. The lower speed of EVs is, the more power they expected to receive. When EVs travel at slow speed, the period passing through each transmitter is longer than the high-speed vehicles. Tables 1 and 2 show an example of coil switching according to the vehicle speed.

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

Fig. 4 Highways England roadway charging topology.

Fig. 5 Dynamic charging highway topology (image).
Table 1  Transmitter activation for low-speed EVs.

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<thead>
<tr>
<th>Position</th>
<th>Sensor</th>
<th>Transmitter</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>OFF</td>
<td>OFF</td>
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<tr>
<td></td>
<td>OFF</td>
<td>OFF</td>
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<tr>
<td></td>
<td>ON</td>
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Table 2  Transmitter activation for high-speed EVs.

<table>
<thead>
<tr>
<th>Position</th>
<th>Sensor</th>
<th>Transmitter</th>
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<tbody>
<tr>
<td></td>
<td>ON</td>
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4.1 Installation Locations

In our project, we determine the best places to install locations based on the traffic volumes of highways. As amount of transferred power is inversely proportional to vehicle speed, this system will have better performance at locations where EV’s speed is relatively low, for example, near SA (service areas), IC (interchange), JCT (junctions), curve roads and traffic jam areas. The author has conducted installation location studies for potential DCH locations, focusing on traffic congestion areas using data from Ministry of Land, Infrastructure, Transport and Tourism of Japan (MLIT) [6]. The provided data rank in term of traffic congestion by “loss of time due to congestion”. We suggest five potential locations to be equipped with in-motion charging capability. Listed below are the locations:

- Worst Traffic Jam Ranking
  - (1) Tomei Expressway Yokohama Machida IC – Ebina JCT (Inbound);
  - (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

The automatic payment system is based on amount of transferred power in the DCH. Each customer has to register their vehicle with DCH operators and each vehicle ID is connected to their credit card or personal bank account. The vehicle ID user authentication employs the RFID tags placed on the vehicle body and on the road (see Fig. 5-green box). Two types of payment are proposed. In the first method, the payment will be conducted once charging process finish (real-time payment), separately with highway usage payment. In the second method, amount of the payment will be charged together with highway toll and the payment is calculated as highway usage payment plus the dynamic charging bill. Fig. 6 shows the flowchart for DCH operations from vehicle detection to the payment process. The author will explain payment price per kWh in the next section.

4.3 Comparison between Plug-in Charging and DCH Charging

In this part, we have conducted the comparison of plug-in charging and 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 3 only for the way from Tomei expressway Yokohama Machida IC to Ebina JCT (Inbound). We have estimated the DCH Charging price at ¥50/kWh during peak-time and ¥25 during off-peak time. Gasoline price assumption is ¥130/liter. This is the average price considering MLIT’s data on regular gasoline price from April 2014 to December 2015 [7].
According to Table 1, 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 expect more wireless charging EVs to use DCH during off-peak time and as a result, DCH could also contribute to reducing peak time congestion.

5. Demonstration Device of In-motion Wireless Charging

In this study, simulation of in-motion wireless charging is carried out by using a demonstration device. The demonstration device is divided into two parts. The first part is the vehicle part that simulates electric car and the other is the module part that simulates the transmission side system. In order to monitor power supply status from the coil and to carry out the switching operation, a pair of wireless communication equipment called TWE Lite is installed to the demonstration device as illustrated in Fig. 7. By the means of this equipment, measurement data from the vehicle part can be transmitted wirelessly to the LabVIEW program installed on PC. Figs. 8-10 show the demonstration device diagram, the LabVIEW observation monitor, and, the receiver circuit diagram, respectively.

<table>
<thead>
<tr>
<th>Charging place</th>
<th>Home</th>
<th>Public</th>
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<tr>
<td>Relativity with gasoline usage [km/L] (Daytime charging ¥30/kWh)</td>
<td>33.8</td>
<td>36</td>
</tr>
<tr>
<td>Relativity with gasoline usage [km/L] (Nighttime charging ¥13/kWh)</td>
<td>78</td>
<td></td>
</tr>
<tr>
<td>With DCH (example: Tomei expressway Yokohama Machida IC-Ebina JCT-inbound)</td>
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<tr>
<td>Expected power transfer (Eff. 90%): 0.702 kWh</td>
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<tr>
<td>Extendable cruising distance: 5.2 km</td>
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<tr>
<td>Relativity with gasoline usage [km/L] (Peak price ¥50/kWh)</td>
<td>19.5</td>
<td></td>
</tr>
<tr>
<td>Relativity with gasoline usage [km/L] (Off-peak price ¥25/kWh)</td>
<td>39</td>
<td></td>
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</tbody>
</table>
5.1 Experiment

Using the demonstration device, the in-motion wireless charging is carried out by letting the vehicle with a receiving coil pass through a transmitting coil. The purpose of this experiment is to consider the most stable power and the longest transmission by changing the combination of the shape and arrangement of the coils. In this measurement, three measured parameters are the EDLC voltage, the receiving voltage and the receiving current. The received power is derived from this measurement results.

The experiment circuit includes two middle elliptical coils (30 mm × 61 mm) for transmitter side and a round coil (28 mm × 28 mm) for receiver side, and the result is shown in Fig. 11. In this experiment, the inductance values of each middle elliptical coil and the round coil are 9.0 μH and 12.3 μH, respectively. This experiment result should be considered when carrying out the simulation during the real implementation of in-motion wireless power charging.

According to Fig. 11, the power is successfully supplied from the wireless power charger that includes two transmitting coils. The received power is stable while the maximum power that can be transmitted is about 1 W.

5.2 Summary

Based on the result shown in Fig. 11, the simulation of in-motion wireless charging using the
demonstration device is successful. However, it is also necessary to carry out experiment for another shape and combination of coil, as the best combination still needs to be consider.

In this experiment, the condition of the power fluctuation for the receiving side was confirmed, hence, in the near future the study about power fluctuation for the transmitter side will be continued.

On the other hand, it is compulsory to estimate the inductance and needed capacity when this system is implemented.

Needless to say, simulation of the power system needs to be done and necessary elements need to be decided in order to implement this infrastructure.

6. Conclusions

The authors have presented the proposal of constructing wireless charging highway in Japan, namely DCH. The authors have also proposed the topology example, the proposal operation, the payment and billing system. Calculation results have shown that charging using DCH could give better benefits to customers in terms of relativity to gasoline price and benefits to highway operators as it could reduce peak time congestion. Therefore, we 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.

7. 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) DCH construction and R&D cost

It is clear that a large amount of funding is 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) Standardization of WPT system

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) Collaboration with electric power company

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.

(4) Consideration of power system

Calculating the necessary capacity for infrastructure installation, and checking the influence on the power system due to load fluctuation of the system.

References


