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Optimal Configuration of Dynamic Wireless Charging Infrastructure for eHighway Applications

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Abstract—On-road or dynamic wireless charging systems constitute electrified highways on which electricity from the electric grid is supplied to electric vehicles wirelessly as they travel along the road, rather than the vehicles solely relying on the storage capacity of batteries. Electrification of highways can contribute to decarbonization in the transport sector and provide a solution to range anxiety, high battery costs and long charging times of electric vehicles. However, installing the wireless charging infrastructure along highways is costly. This paper presents a modeling approach that has been developed based on key variables of dynamic wireless charging systems to minimize the infrastructure cost so that the deployment of electrified highways could be economically viable. The overall investment for the dynamic wireless charging systems consists of different types of costs, including those for inverters, road-embedded power transmitter devices, control devices and grid connections. The costs of the different components depend on traffic flows but to different extents, resulting from the amount of energy demanded in a specific section of the electrified highway (i.e. the traffic flows are section-dependent). It is shown that the charging power level that could vary from 165 kW to 400 kW and road coverage ratio of an electrified highway are interrelated with regard to the economic context. Based on the developed model, the configuration and deployment of a proposed electrified highway in Eastern Canada are designed with an optimal charging power level and road coverage ratio or intermittency, thus achieving the best cost effectiveness. Intermittent electrified highways have the potential to reduce overall investment cost over fully electrified highways. In addition, the cost break-up of various components of the dynamic wireless charging system is estimated.

Keywords—electrified highway, wireless power transfer, electric vehicles, cost

I. Introduction

The transportation sector is one of the largest consumers in fossil fuels. Reducing emissions in the transportation sector is essential to achieving the net-zero emissions in the future. Electric vehicles (EVs) are the leading clean technology with low emissions. The adoption of EVs could be a solution to environmental issues. However, the batteries of these vehicles have a limited travel distance per charge and the batteries require significantly more time to recharge compared to refueling a conventional gasoline vehicle. An increase in the size of a battery can increase the driving range, but will greatly increase the price as the battery is the most expensive unit in an EV. As a result, range anxiety, high battery cost, and long charging time lead to certain obstacles in EV's widespread adoption. One approach to overcome the obstacles is to supply electricity from the electric grid to electric vehicles wirelessly while they travel along the road, rather than the vehicles solely relying on the storage capacity of batteries (Figure 1). This method is referred to as dynamic wireless power transfer (DWPT) or charging-while-driving [1-3]. In this approach, highways are electrified and turned into charging infrastructure. DWPT has been shown to be capable of reducing the high initial cost of EV by allowing the battery size to be downsized [4].

In the field of electric vehicles, wireless charging mainly denotes medium-range inductive power transfer, through near-field electromagnetic coupling [5, 6]. There have been various studies on the design, application and future prospects of DWPT for electric vehicles [7-9]. Some automobile companies are working to incorporate wireless charging capabilities in EVs while a number of institutions have conducted researches for developing efficient wireless charging systems for electric vehicles and testing them in a dynamic charging scheme. These institutions include Auckland University [10], HaloIPT [11], Oak Ridge National laboratory [6], MIT (WiTricity) and Delphi [12]. An analysis of the costs associated with the implementation of a DWPT infrastructure and a business model for the development of a new EV infrastructure are reported in [13]. Integrated pricing of electricity in a power network and usage of electrified roads in order to maximize the social welfare are investigated in [14].

Given the effectiveness and advances in dynamic charging technology, optimal configuration and deployment of DWPT infrastructure become more important. This paper presents a modeling approach based on key variables of dynamic wireless charging systems to minimize the infrastructure cost so that the deployment of electrified highways could be economically viable. An intermittent or partial dynamic wireless power transfer (PDWPT) system is proposed to reduce the DWPT eHighway cost. By means of the developed model, an optimal DWPT coverage ratio (or intermittency) and an optimal level of the wireless charging power are sought, at which the total infrastructure cost could be minimized.

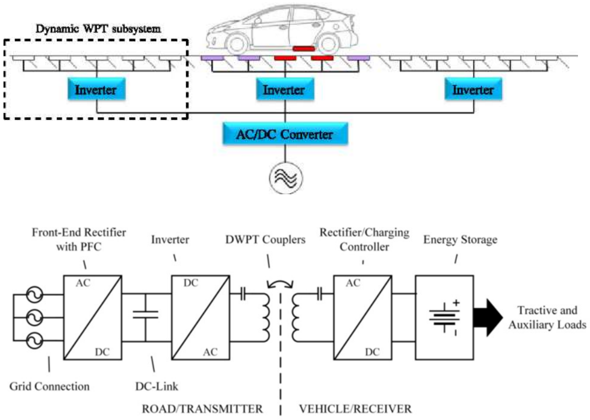

Figure 1. Dynamic wireless power transfer system [15]

II. METHOD

A. Description

The development of eHighways has focused on the equipment and infrastructure that allows electrical power to be provided to the EVs wirelessly while they are driving so that the EVs are capable of running longer distances with small battery capacities. Less reliance on batteries could also alleviate the need and environmental impacts associated with the mining of critical metals. The major challenge for eHighways is considered not to be technological; instead, it is an implementation issue. Initial infrastructure investment is often seen as a limit to real-scale deployment. When compared with other low emission options, DWPT technology offers many advantages. The objective of the study is to explore the application of the eHighway technology to a Canada's major transportation corridor that links Montreal, Toronto and U.S. border, as illustrated in Figure 2.

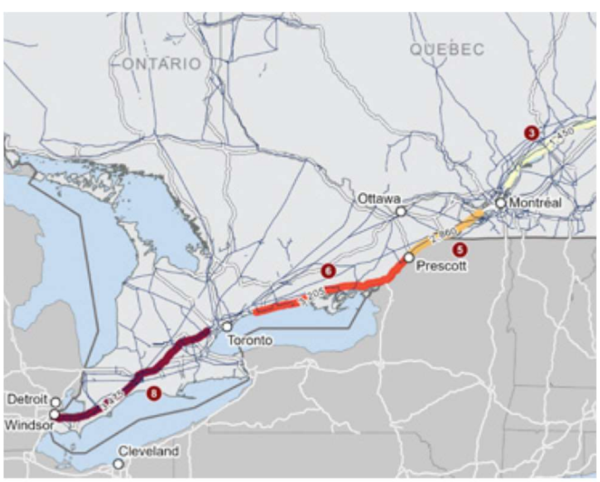

Figure 2. Canada's major highway transportation corridor that links Montreal, Toronto and the U.S. border

B. Model

A suitable design procedure should consider the service provider's need to minimize the installation and maintenance costs and the users' acceptance of the time required for a proper charging on an eHighway. A balance between the energy consumed for vehicle motion and the energy provided by the DWPT should be taken into account.

The average power consumed is calculated by applying driving conditions to an expression from [16]:

$$p_{el} = \frac{(\mu_f + \sin\alpha)Mg}{\eta_{eq}} + \frac{C_d A v(t)^3 \rho}{2\eta_{eq}} + \frac{\delta M a(t) v(t)}{\eta_{eq}} \qquad (1)$$

The terms in Eq. 1 account for rolling resistance and elevation change (first term), form drag (second term) and acceleration effects (last term). The power consumption rate of an EV required on eHighways is a function of the vehicle's weight and velocity when all other parameters are given. For sake of simplicity, the power consumption rate can be expressed as [4]:

$$p_{el}(v, M) = C_1 v^3 + C_2 v M + p_{aux} \qquad (2)$$

where v is the velocity, M is the gross weight, p_{aux} is the auxiliary power, C_1 and C_2 are two coefficients whose values were given in the reference [4]. The energy consumed by the vehicle over time is obtained by multiplying the power being consumed by the duration. It is assumed that the highway is partially equipped with the dynamic charging technology in an intermittent way or segment by segment. The overall route is divided by m number of segments (i=1, 2, 3, …, m). Thus, the electrified highway coverage ratio is defined as:

$$\alpha = \frac{\sum_{i=1}^{m} l_s(i)x(i)}{L_t} \qquad (3)$$

where L_t is the total highway length and $l_s(i)$ is the length of the i^{th} segment along the highway. $x(i)$ is the binary decision variable for each segment (i) to represent whether it is covered by a DWPT facility:

$$x(i) = \begin{cases} 1, & if\ segment\ (i)\ is\ covered\ by\ a\ DWPT\ facility \\ 0, & otherwise \end{cases} \qquad (4)$$

If the vehicle's speed over the highway is assumed to constant, the electrified highway coverage ratio can also be expressed as:

$$\alpha = \frac{E_{ot} u v}{P_e E_v \eta} \qquad (5)$$

where E_{ot} is the total amount of electricity charged during the operation time on the eHighway, u is the energy consumption per km, v is the vehicle speed, P_e is the wireless or inductive charging power, E_v is the electricity consumption of the vehicle during the operation time on the eHighway and η is the charging efficiency. η can be calculated from [4]:

$$\eta = \frac{k^2 Q_t Q_r}{\left(1+\sqrt{1+k^2 Q_t Q_r}\right)^2} \qquad (6)$$

where k is the coupling coefficient, Q_t is the quality factor of the transmitter coils and Q_r is the quality factor of the receiver coils. The minimum required coverage ratio can be calculated at the energy equilibrium where the energy consumed by the vehicle is equal to the energy received from the DWPT.

The investment cost for the entire eHighway can be calculated from:

$$C_{Invest} = F(P_e)\left[C_{grid} \sum_{i=1}^{m} f_g^i z(i)\, l_s(i) + C_{invert} \sum_{i=1}^{m} y(i)\, l_s(i) n(i) + \sum_{i=1}^{m} f_d^i C_{dwpt} l_s(i)\, x(i)\right] \quad (7)$$

where $F(P_e)$ is the factor as a function of wireless charging power, C_{grid} is the cost for grid connection per km, f_g^i is the coefficient of grid connection concerning traffic flow impact, C_{invert} is the cost for an inverter, $n(i)$ is the number of inverters per km at the i^{th} segment, C_{dwpt} is the DWPT components cost per km including road-embedded power transmitter devices and control devices, and f_d^i is the coefficient of DWPT components concerning traffic flow impact. Note these costs include installation. $z(i)$ is the binary decision variable which has value of 1 when there is grid connection at the i^{th} segment; otherwise, it has value of 0. $y(i)$ is the binary decision variable which has value of 1 when the inverters are allocated at the i^{th} segment; otherwise, it has value of 0. $F(P_e)$ is given by an empirical formula:

$$F(P_e) = 0.0181 P_e^{0.65} + 0.309(0.6e)^{\frac{p_e}{165}} \quad (8)$$

The Equation (7) is subject to:

$$E_e(i-1) - e_v(i) + e_{ot}(i)x(i) \geq E_e(i) \quad (9)$$

where $E_e(i)$ is the battery charging level after passing the i^{th} segment, $e_v(i)$ is the amount of consumed electricity at the i^{th} segment, $e_{ot}(i)$ is the amount of supplied electricity at the i^{th} segment. Equation (9) indicates that in addition to the electrified highway coverage ratio, the length of a segment, which is not covered by the DWPT, needs to be considered since this influences the battery charging level (or the state of charge) of an EV. In other words, when the EV exits a segment that is equipped with DWPT, its state of charge should ensure it can drive and complete the next segment without DWPT.

TABLE 1. COMPONENT COSTS AND RELATED SYSTEM PARAMETERS

Parameter	Description	Value
C_{invert}	Unit inverter cost, $	6,000
C_{grid}	Grid connection cost, M$/km	0.35
C_{dwpt}	Cost for DWPT components, M$/km	1.35
f_w^i	Coefficient for DWPT components concerning traffic flow impact	1 for 3,000 vehicles or less per day 1.25 for 3,001~4,500 vehicles per day 1.38 for 4,501~5,500 vehicles per day
$n(i)$	Number of inverters per km	3 for 3,000 vehicles or less per day 4 for 3,001~4,500 vehicles per day 5 for 4,501~5,500 vehicles per day

The equivalent annual cost is calculated as follows

$$EAC = \frac{C_{Invest} \times d}{1-(1+d)^{-N}} + C_{O\&M} \quad (10)$$

where C_{Invest} is the total investment cost of the eHighway infrastructure for DWPT, $C_{O\&M}$ is the cost of operation and maintenance, N is the lifetime and d is the discount rate or the cost of capital which is the required return necessary to make a capital budgeting project worthwhile. The cost of operation and maintenance is assumed to 15% of annual investment cost in this study.

At present, the cost data for DWPT components and related system parameters can only be estimated from the design point of view and obtainable material prices due to the fact that the technology is still in its emerging stage and market data are not yet available. Table 1 shows the estimated component costs and related system parameters.

III. Results.

In this study, the minimum required DWPT coverage ratio is defined as an energy equilibrium to be reached where the energy consumed by the vehicle is equal to the energy received from the DWPT. Figure 3 shows the modeling results of the minimum coverage ratio for various energy consumptions of electric vehicles on the assumption that the vehicle speed is 100 km/h. The areas above the curves represent that the energy received by the electric vehicle from the DWPT will be more than the energy consumed by the vehicle. It is shown that the required road coverage ratio decrease considerably as the wireless charging power increases. For instance, for an electric vehicle consuming 1.65 kWh/km, the required DWPT coverage ratio is 1 at a wireless charging power of 165 kW whereas the ratio reduces to 0.413 at a wireless charging power of 400 kW. This could reduce initial infrastructure investment for the eHighway but there is a trade-off between the charging power level and road coverage ratio.

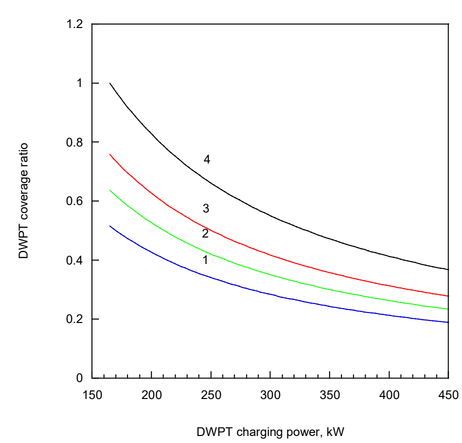

Figure 3. Minimum required coverage ratio for various energy consumption values of electric vehicles at energy equilibrium. Vehicle's energy consumption: 1: 0.85 kWh/km; 2: 1.05 kWh/km; 3: 1.25 kWh/km; 4: 1.65 kWh/km.

Figure 4 shows the variations of the investment cost per km with DWPT charging power for different traffic volumes when the DWPT coverage ratio is equal to 1. It is shown that the investment cost increases with rising level of the charging power. For instance, at a coverage ratio of 1, the investment cost is 1.718 M$/km at a charging power of 165 kW and the cost rises to 3.546 M$/km at a charging power of 400 kW for a daily traffic volume of 3,000 vehicles. For a daily traffic volume of 4,501~5,500 vehicles, the investment cost is 2.243 M$/km at a charging power of 165 kW and the cost rises to 4.63 M$/km at a charging power of 400 kW. Obviously, Figures 3 and 4 indicate that the road coverage ratio and the charging power level are interrelated with regard to the economic context. In other words, there exist an optimal road coverage ratio or intermittency and an optimal level of the wireless charging power where the infrastructure cost could be minimized. The minimized infrastructure cost is sought using the objective function Equation (7) with the restrictions of Equations (5) and (9). The resulting infrastructure costs (M$/100km) are presented in Figure 5. Figure 5 shows that the minimized infrastructure costs are achieved at an eHighway coverage ratio of 0.46 and a charging power of 358 kW for various travel volumes being considered. The obtained minimized costs are 189.8, 174.42, 145.37 M$/100km for the daily traffic volumes of 4,501~5,500, 3,501-4,500 and 3,000 or less, respectively. These results are then applied to the case study on the highway corridor as shown in Figure 2. It is noted that a coverage ratio of 0.6 is used in this case study so that the amount of electricity charged on the eHighway is securely more than the electricity consumption by electric vehicles. Also, the intermittent segments are determined to be 12/8 km on/off, i.e. 12 km with DWPT coverage and 8 km without the coverage alternately. Table 2 lists the calculated investment costs for the eHighway from Winsor to Montreal section by section. At the configuration conditions of 0.6 coverage ratio and 358 kW wireless charging power, the total investment cost is 1,643.4 M$, which would otherwise cost 3,918.62 M$ if 100% electrification of highway were to be used.

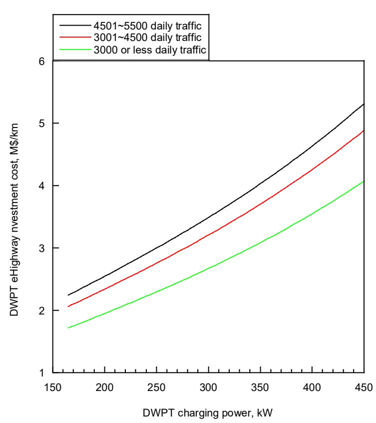

Figure 4. Variations of the investment cost with DWPT charging power for fully electrified highways for different traffic volumes.

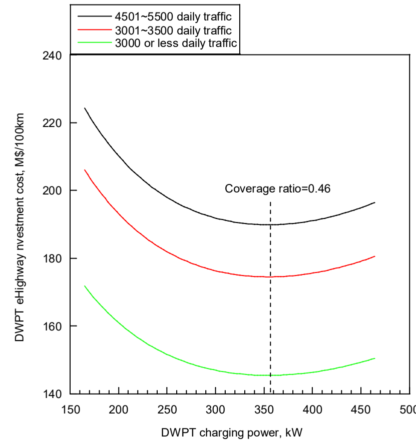

Figure 5. Investment cost as a function of DWPT charging power at varying eHighway coverage ratio.

TABLE 2. SECTION LENGTHS OF THE HIGHWAY CORRIDOR AND MINIMIZED INVESTMENT COSTS FOR VARIOUS TRAFFIC VOLUMES OF ELECTRIC VEHICLES

Highway section	**Section length**	**Traffic volume (1-way)**	**Investment cost**	**Equivalent annual cost***
Winsor - Toronto	370 km	5000/day	718.43 M$	85.07 M$
Toronto - Prescott	360 km	3500/day	642.38 M$	76.07 M$
Prescott - Montreal	190 km	3000 or less /day	282.59 M$	33.46 M$
Winsor - Toronto	920 km		1643.4 M$	194.6 M$

*Lifetime = 15 years; Discount rate = 6%

The theory presented above describes how to minimize the eHighway infrastructure costs based on the DWPT design parameters and configuration. Here, it is noted that the users' acceptance of the time required for a proper charging should also be considered. In other words, electric vehicle's speeds play an important role in reaching a balance between the energy consumed for vehicle motion and the energy provided by the DWPT or featuring an energy plus. In addition, on-board battery capacity is an important factor as there is a trade-off between the savings achieved by the battery weight reduction and thus the increase in transport efficiency and the eHighway investment cost. In our previous work [4], it was shown that the battery of the heavy-duty electric truck could be downsized by 65% with the battery capacity being 304 kWh when using the eHighway technology.

IV. CONCLUSION

DWPT eHighway is an innovative means of transportation. It can reduce the battery capacity and the so-called range anxiety by using the wireless charging technology, but it requires significant capital costs to install the dynamic wireless charging infrastructure. In this study, an intermittent eHighway system is proposed and a mathematical model is built to optimize the DWPT design configuration with the objective of minimizing the total investment cost. It is proven that there are an optimal DWPT coverage ratio and an optimal wireless charging power level at which the infrastructure cost is minimized. Modeling results show that the minimized infrastructure cost is achieved at a road coverage ratio of 0.46 and a charging power level of 358 kW for the travel volumes being investigated. The minimized costs are 189.80, 174.42, 145.37 M$/100km for daily traffic volumes of 4,501~5,500, 3,501-4,500 and 3,000 or less, respectively. In this study, a coverage ratio of 0.6 is employed so that the amount of electricity charged on the eHighway can to a certain degree be more than the electricity consumption by electric vehicles. Thus, the intermittency is determined to be 12/8 km on/off alternately. The modeling results are applied to a major transportation corridor in Canada that is 920km long and links Montreal, Toronto and the U.S. border with varying traffic flows. For the proposed configuration of dynamic wireless charging infrastructure, the total investment cost is obtained to be 1,643.4 M$ for the investigated case, which would otherwise cost much more if 100% electrification of highway were to be used. The results of this study will be useful to support decision-making on how to implement eHighways.

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References

[1] R Vaka and RK Keshri, "Review on contactless power transfer for electric vehicle charging", Energies, vol.10 (5), p.636, 2017.

[2] L. Hutchinson, B. Waterson, B. Anvari and D. Naberezhnykh, "Potential of wireless power transfer for dynamic charging of electric vehicles," IET Intell. Transp. Syst., vol.13 (1), pp. 3-12, 2019.

[3] T.-E. Stamati and P. Bauer, "On-road charging of electric vehicles," In Proceedings of the 2013 IEEE Transportation Electrification Conference and Expo (ITEC), Detroit, MI, USA, 16–19 June 2013, pp. 1–8.

[4] K. Qiu, H Ribberink and E. Entchev, "Advantage and feasibility of wireless charging electric bus systems," Applied Energy Symposium: MIT A+B August 12-14, 2020 Cambridge, USA.

[5] K. Afridi, "Wireless Charging of Electric Vehicles," Frontiers of Engineering, vol.47(4), pp.17-22, 2017.

[6] Oak Ridge National Laboratory, "Oak Ridge National Laboratory Wireless Charging of Electric Vehicles –CRADA Report", 2016. Web page consulted on 26.08.2019. https://info.ornl.gov/sites/publications/files/Pub68349.pdf

[7] Korea Advanced Institute of Science and Technology, "Wireless Online Electric Vehicle, OLEV, runs inner city roads", 2013. Web page consulted on 26.08.2019. https://phys.org/news/2013-08-wireless-online-electric-vehicleolev.html

[8] N.P. Suh, DH Cho and C.T. Rim, "Design of on-line electric vehicle (OLEV), in: Global Product Development". Springer, pp. 3–8, 2011.

[9] S. Li, and C.C. Mi, "Wireless power transfer for electric vehicle applications," IEEE journal of emerging and selected topics in power electronics, vol.3, pp.4-17, 2015

[10] D. Cho and J. Kim, "Magnetic field design for low emf and high efficiency wireless power transfer system in on-line electric vehicle," CIRP Design Conference 2011.

[11] S. Lee, J. Huh, C. Park, N.S. Choi, G.H. Cho and C.T. Rim, "On-Line Electric Vehicle using inductive power transfer system," 2010 IEEE Energy Conversion Congress and Exposition, IEEE, pp.1598–1601, 2010.

[12] G. Jung, B. Song, S. Shin, S. Lee, J. Shin, Y. Kim and S. Jeon, "High efficient inductive power supply and pickup system for on-line electric bus," Electric Vehicle Conference (IEVC), IEEE International, IEEE ,pp.1–5, 2012

[13] J. S. Gill, P. Bhavsar, M. Chowdhury, J. Johnson, J. Taiber and R. Fries, "Infrastructure cost issues related to inductively coupled power transfer for electric vehicles," Procedia Computer Science, vol.32, pp.545-552, 2014. doi:10.1016/j.procs.2014.05.459.

[14] F. He, Y. Yin and J. Zhou, "Integrated pricing of roads and electricity enabled by wireless power transfer," Transportation Research Part C: Emerging Technologies, vol.34, pp.1-15. 2013. doi: 10.1016/j.trc.2013.05.005.

[15] E. Sproul, D.A. Trinko, Z. D. Asher, B. Limb, T.H. Bradley and J.C. Quinn, "Electrification of Class 8 Trucking: Economic analysis of in-motion wireless power transfer compared to long-range batteries," IEEE Transportation Electrification Conference and Expo (ITEC), 2018. DOI:10.1109/ITEC.2018.8450203

[16] A. Foote, O.C. Onar, S. Debnath, M. Chinthavali, B. Ozpineci and D.E. Smith, "Optimal sizing of a dynamic wireless power transfer system for highway applications," IEEE Transportation Electrification Conference and Expo, pp. 1-6. 2018. IEEE, doi: 10.1109/ITEC.2018.8450095