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Technical and Economic Feasibility of Electrified Highways for Heavy-Duty Electric Trucks

K. Qiu, H. Ribberink, E. Entchev
CanmetENERGY-Ottawa
Natural Resources Canada
1 Haanel Drive, Ottawa, Ontario
Canada K1A 1M1
kuanrong.qiu@canada.ca

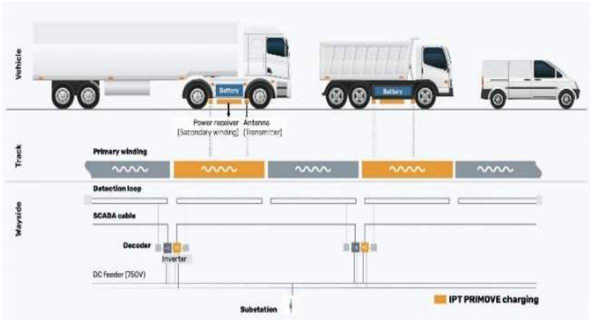
Abstract—New solutions to decarbonisation in the transport sector are prominently required to replace oil consumption. Full battery electric vehicles (BEVs) are usually limited to light-duty vehicles due to their energy density. The aim in this study is to evaluate the technical and economic feasibility of electric trucks that are supplemented by electrified highways (eHighways), instead of using conventional diesel, petrol, and full BEVs. The battery is the most expensive component of electric vehicles, especially for heavy-duty trucks. The principle of eHighway is that electricity is supplied to electric vehicles directly from the electric grid as they travel along the road. The eHighway concept is being developed with two primary methods to connect the roadway to the vehicle: conductive power transfer (CPT) where electric connection to the vehicle can be provided from above or below the vehicle and inductive power transfer that is in-motion wireless power transfer (WPT). If eHighways are installed on the major links that connect main cities, the eHighway technology can be suitable for long-distance journeys. This research evaluates the eHighway technologies of both CPT and in-motion WPT. A case study has been conducted. Various costs are calculated and analyzed. Results show that the driving cost (or selling price) of a heavy-duty electric truck on the eHighways using CPT technology ranges from $0.21 to 0.67 per km with varying daily traffic volume. The driving cost of a heavy-duty electric truck on the eHighways using in-motion WPT technology ranges from $0.22-1.03 depending on daily traffic volume. If fuel and vehicle prices evolve as predicted between now and 2050, eHighways could become an economically feasible form of road transport, especially for heavy-duty trucks, resulting in energy savings and thus reductions in CO_2 emission.

Keywords—eHighways, wireless power transfer, conductive power transfer, electric truck

I. Introduction (*Heading 1*)

Internal combustion engine (ICE) vehicles create environmental and economic issues. Electric vehicles (EVs) are leading clean technology with low emissions for road transportation and adoption of electric vehicles can be solutions to these issues. However, owing to high battery costs, inadequate energy density, insufficient charging infrastructure and long charging time, the technology has, to date, been limited mainly to small passenger vehicles. EVs can be charged through plug-in chargers but there are challenges such as heavy battery packs and high battery costs, especially for heavy-duty trucks. The battery pack comprises significant amount of the weight of proposed electrical trucks. Lithium iron phosphate (LFP) battery cost will account for a major cost of any heavy-duty electric trucks.

Electrified highways (eHighway) are one concept that could contribute to the decarbonisation of transport. The principal is that electric vehicles use electricity directly from the electric grid as they travel along the road, rather than relying on the storage medium of a battery. If eHighways are installed on the major links that connect main cities or highly populated urban centers together, then it will be possible to use eHighway technologies for long-distance journeys rather than using a long-range on-board battery. This could overcome the issues with plug-in charging, and heavy and costly battery packs. eHighway technologies include in-motion wireless power transfer (in-motion WPT) and conductive power transfer (CPT), as shown in Figure 1. Wireless charging technology has brought breakthroughs to electric vehicle technology. Wireless charging electric vehicles (WCEVs) have the potential to make road transportation more intelligent and promising. CPT could be trolley systems with efficient energy transfer from overhead wires (Figure 1 (b)).



(a)

(b)

Figure 1. eHighway for heavy-duty trucks. (a): in-motion wireless power transfer; (b); conductive power transfer using trolley systems with energy transfer from overhead wires (Siemens)

In the field of electric vehicles, the wireless charging mainly denotes medium-range WPT, through near-field (non-radiative) electromagnetic coupling [1, 2]. By the form of energy transfer, WCEVs technology is categorized into two types: capacitive wireless charging electric vehicles and inductive wireless charging electric vehicles. For the latter, the electric energy is transferred wirelessly through magnetic field between two coil plates, one loaded on the bottom of the vehicle and the other embedded in pavement. Capacitive WCEVs have development potential, especially in the field of dynamic WCEVs [3]. However, slow development of high-performance materials poses barriers for capacitive WCEVs [4-6]. Considering application scenarios of electric vehicles and the size of electromagnetic couplers, inductive wireless charging technology is considered the first choice for WCEVs. In 2009, Korea Advanced Institute of Science and Technology [7] developed the first commercially available in-motion wireless charging electric bus named on-line electric vehicle [8]. Oak Ridge National Laboratory [9], with the support of the US Department of Energy, has been implementing the WCEVs research and development of static passenger vehicles and dynamic charging since 2012.

The WCEVs technology can be grouped into stationary charging and dynamic charging [9]. Stationary wireless charging can be installed in garages and parking lots. For dynamic charging, the vehicle can be charged in motion through multiple sets of coils and accessories embedded along the road. The efficiency of more than 85% has been reported for wireless charging. WPT infrastructure brings additional costs of equipment procurement and installation. As for CPT such as trolley systems transferring power from overhead wires, infrastructural costs are involved as well. Therefore, the cost analysis associated with the application of eHighways is necessary.

Canada could be a country that is suitable for the implementation of eHighways, since the most population is distributed in a few large cities such as Toronto, Montreal and Ottawa that are located on a well-developed highway system. In-motion WPT offers a viable means of charging EVs, mitigating issues of vehicle range, the size of on-board energy storage and the network distribution of plug-in charging stations. The technology has the potential to increase user convenience, reduce EV costs and increase driving range indefinitely if the eHighway infrastructure becomes available. This paper aims to analyze the costs of eHighway infrastructure of in-motion WPT systems as well as CPT systems and compare energy consumption and driving costs of heavy-duty electric trucks for the two scenarios.

II. METHOD

A. *Description*

eHighway is a future transportation infrastructure that delivers charging of EVs in motion. The development of eHighways aims at the infrastructures that allow electrical power to be provided dynamically, with the EVs being capable to run longer distances with a small battery capacity. This function can be achieved by integrating charging equipment, either inductive or conductive, into existing roads. It is recognized that the gap is not technological; instead, it is an implementation issue. The goal of this study is to analyse the costs of eHighway infrastructure of in-motion WPT as well as CPT systems and compare energy consumption and costs of heavy-duty electric trucks on eHighway. An important and busy transportation route that connects Ottawa and Toronto and cities in between has been selected for a case study.

B. *Economic analysis*

It should be noted that the cost of eHighway infrastructure is extremely difficult to estimate at this time due to the fact that the concepts are still mostly at trial phase and market data are not available. In this section, investment costs have been calculated from the design point of view and data from literature survey. Investment costs of in-motion WPT system include:

1) Cost of copper Litz wire in the air cored primary winding based on the charging power level.
2) Power electronics involved in the WPT supply system.
3) Inverters. 4~6 inverters/km are needed with the frequency of 100 kHz.
4) Charge pads (Figure 2) that cover the highway section with in-motion WPT total road coverage, and the corresponding cost of air cored primary winding is included.
5) Design.
6) Road construction and installation.
7) Grid connection.
8) Operation and maintenance (O&M).

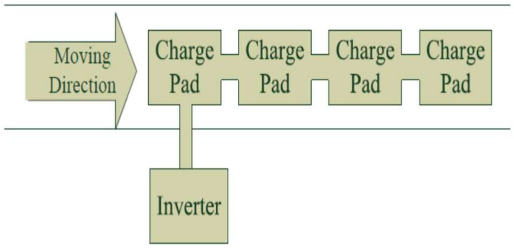


Figure 2.Schematic diagram of charge pads and inverter [10].

Similarly, investment costs of CPT from overhead wires include:

1) Cost of overhead wires based on the conductive power level.
2) Structures to support and mount overhead wires
3) Power electronics
4) Inverters.
5) Design
6) Road construction and installation
7) Grid connection
8) O&M

The equivalent annual cost is calculated as follows

$$EAC = \frac{C_t + d}{1-(1+d)^{-n}} + C_{O\&M} \quad (1)$$

where C_t is the total investment cost of the eHighway infrastructure, i.e. in-motion WPT or CPT, $C_{O\&M}$ 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 total investment cost of the in-motion WPT system is calculated as follows:

$$C_{tw} = \sum_{i=1}^{n} C_{wi} \quad (2)$$

where C_{wi} (i=1~7) is the cost of each system component involved as described above. Also, the total investment cost of the CPT system is calculated as follows:

$$C_{tc} = \sum_{i=1}^{n} C_{ci} \quad (3)$$

where C_{ci} (i=1~7) is the cost of each system component involved in the CPT system.

C. *Reduction of on-board energy storage*

The battery in electric trucks can be significantly downsized due to the eHighway availability. Thus the electric trucks can carry a smaller battery, resulting in the capacity reduction. C_a (kWh) is defined to be the battery capacity after capacity reduction. The battery downsizing for in-motion WPT scenario is calculated as follows [11].

$$C_a = \frac{C_{or} - E_{ot}}{S_{cr}} \quad (4)$$

$$E_{ot} = \eta P_e t \quad (5)$$

where C_{or} (kWh) is the minimum plug-in battery electricity amount requirement at the start of each day for an electric truck, E_{ot} is the total amount of electricity charged during operation time, S_{cr} is the state of charge range that is defined as the percentage of the C_{or} relative to the whole capacity of a new battery (kWh), η is the charging efficiency, P_e (kW) is the in-motion charging power and t is the in-motion charging time. Table 1 lists the values of these parameters. As per the conductive power transfer system, the required on-board energy storage or the battery capacity is minimal.

Table 1. THE PARAMETERS AND VALUES USED IN CALCULATION OF BATTERY DOWNSIZING FOR IN-MOTION WPT SCENARIO

Parameter	**Value**	**Unit**
C_{or}	525	kWh
S_{cr}	90	%
P_e	120	kW
η	85	%

D. *Vehicle cost analysis*

An economic analysis was conducted to compare the vehicle costs of different types. The price of an ICE heavy-duty truck was estimated at $120,000 [12]. For the fully electric heavy-duty truck, a purchase price of $200,000 was assumed with a battery range of 600 km. With a battery cost of $100/kWh projected, the battery cost of the long-range electric truck is estimated at $87000. Based on the calculation, the battery of the heavy-duty electric truck can be downsized by 65% when using in-motion WPT, resulting savings of $56550. It is expected the battery downsizing can be even more with the CPT eHighways. Maintenance costs of the ICE and electric trucks were considered as 4% and 2.5% of the purchase price per year, respectively [12, 13]. Also, it is assumed that the ICE and electric trucks run an average distance 300 km/day over a 12-year lifetime.

III. RESULTS.

In this study, a 360 km-long highway that connects Ottawa and Toronto and cities in between has been selected for a case study. It is assumed that that both in-motion WPT and CPT technologies will be applied in nonintermittent charging scenarios. The infrastructure cost to electrify the highway using in-motion WPT technology is calculated to be M$480 based on the design point of view and data from literature survey while the calculated cost is M$324 to electrify the highway using CPT technology [14]. Table 2 presents the investment costs needed and calculated results of eHighway usage fees and selling prices. The selling price (driving costs) is the eHighway usage fee plus electricity cost but does not include the cost of vehicles. The eHighway usage fees with in-motion WPT and CPT systems range from 0.084 $/km/electric truck to 0.836 $/km/electric truck and from 0.047 $/km/electric truck to 0.471 $/km/electric truck dependent upon the daily traffic volume. The selling prices for in-motion WPT and CPT range from 0.279 $/km/electric truck to 1.031 $/km/electric truck and from 0.242 $/km/electric truck to 0.666 $/km/electric truck depending on the daily traffic volume.

Table 2. THE COSTS USED IN THE CALCULATION AND CALCULATED RESULTS.

	Parameter	Value	Unit	Traffic volume
In-motion WPT system	Investment cost	1.35	M$/km	
	O&M	17500	$/km/year	
	Discount rate	6	%	
	Lifetime	20	year	
	Equivalent annual cost	152636	$/km	
	eHighway usage fee	0.836	$/km/electric truck	500 electric trucks/day
		0.279	$/km/electric truck	1500 electric trucks/day
		0.084	$/km/electric truck	5000 electric trucks/day
	Electricity price	0.15	$/kWh	
	Electricity consumption rate	1.3	kWh/km	
	Selling price	1.031	$/km/electric truck	500 electric trucks/day
		0.474	$/km/electric truck	1500 electric trucks/day
		0.279	$/km/electric truck	5000 electric trucks/day
CPT system	Investment cost	0.9	M$/km	
	O&M	7500	$/km/year	
	Discount rate	6	%	
	Lifetime	20	year	
	Equivalent annual cost	85966	$/km	
	eHighway usage fee	0.471	$/km/electric truck	500 electric trucks/day
		0.157	$/km/electric truck	1500 electric trucks/day
		0.047	$/km/electric truck	5000 electric trucks/day
	Electricity price	0.15	$/kWh	
	Electricity consumption rate	1.3	kWh/km	
	Selling price	0.666	$/km/electric truck	500 electric trucks/day
		0.352	$/km/electric truck	1500 electric trucks/day
		0.242	$/km/electric truck	5000 electric trucks/day

Figure 3 displays the variations of driving costs with daily traffic volume for in-motion WPT and CPT systems. Obviously, the driving cost or selling price decreases with the increase in the daily traffic volume. The battery downsizing results in a reduction in truck weight and thus improve the energy consumption. Moreover, a reduced truck weight consumes less energy, this gives rise to further downsizing of the battery and thus improve further energy consumption rate. The battery or truck weight reduction is calculated from battery specific energy (e.g. 0.15kWh per kg of Li-ion battery). The battery capacity would be 870 kWh for a driving range of 600 km. Specifications for fully electric trucks are not yet available. As an estimate, the gross weight of a long-range battery electric truck is assumed to be 38000 kg. With in-motion WPT or CPT technology used, the battery weight can be reduced by 3778 kg. That is about a 10% vehicle mass reduction. In principle, the energy consumption improvement resulting from the vehicle mass reduction can be calculated. However, due to insufficient data available at this time, literature data have been used. Based on the literature data [15], a 10% vehicle mass reduction leads to a 5.5% energy consumption reduction for electrical vehicles.

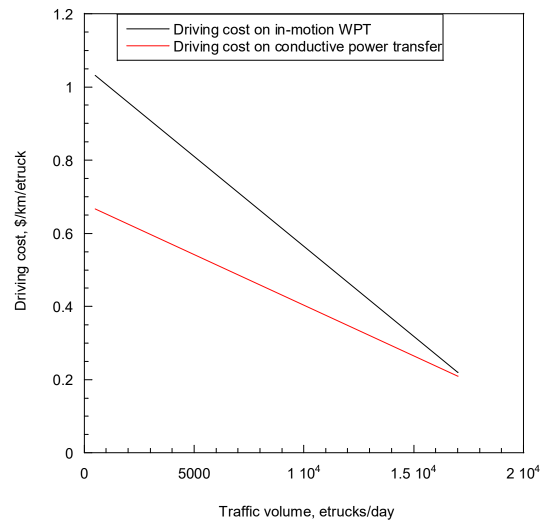


Figure 3. Variations of driving cost (selling price) with daily traffic volume for in-motion WPT and CPT systems

Figure 4 presents the breakdown of the overall costs per km for different heavy-duty trucks with in-motion WPT, CPT, long-range battery and diesel ICE truck systems. For the in-motion WPT and CPT eHighway systems, the traffic volumes are assumed to 1500 truck/day and 5000 truck/day. The costs per km for an ICE, long-range battery, in-motion WPT and CPT truck are $0.71, $0.47, $0.62 (1500 truck/day), $0.43(5000 truck/day) and $0.50 (1500 truck/day), $0.39 (5000 truck/day), respectively. Obviously electrifying heavy-duty trucks reduce fuel costs. Furthermore, the low purchase price of in-motion WPT and CPT vehicle makes savings compared to long-range battery trucks [16]. Maintenance for the long-range battery truck costs slightly more than for the in-motion WPT and CPT trucks due to the correlation between purchase price and maintenance costs within economic model assumptions. The economic results include the usage fees for the in-motion WPT and CPT infrastructure. The infrastructure usage fees decrease with rising traffic volume since more traffic volume generates more cash flow. As a result, in-motion WPT and CPT systems become competitive with long-range battery trucks when the traffic volume exceeds certain amount. Nevertheless, the in-motion WPT and CPT costs are competitive with that of ICE, and electrifying heavy-duty trucks will result in reducing greenhouse gas emissions.

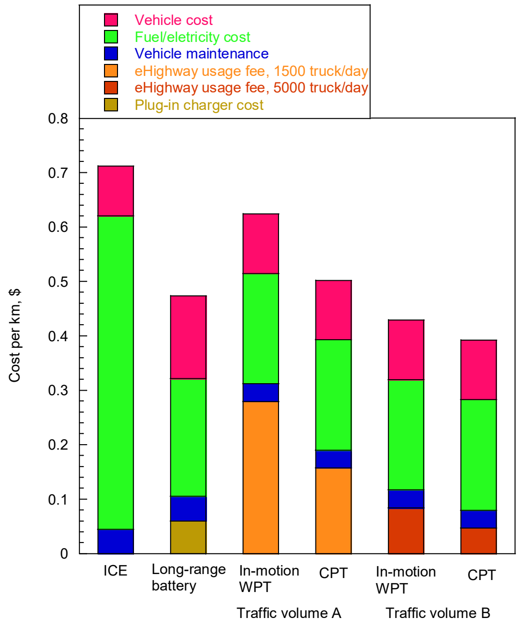


Figure 4. Costs per km of ICE diesel truck, long-range battery electric truck, in-motion WPT electric truck and CPT electric truck.

IV. CONCLUSION

The economic analysis of heavy-duty electric trucks supplemented by electrified highways or eHighways was conducted. On eHighways, electricity supplies the electric vehicles directly from the electric grid through in-motion WPT or CPT systems. If eHighways are installed between main cities, electric trucks can eliminate costly and heavy long-range batteries. From the present research, the infrastructure cost to electrify a 360 km-long highway that connects Ottawa and Toronto and cities in between using in-motion WPT technology is calculated to be M$480 while the cost is M$324 to electrify the highway using CPT technology. It has been shown that the electric vehicles can make meaningful cost savings, with the in-motion WPT and CPT turning out to be economically favorable systems compared to ICE and long-range battery trucks. The overall costs per km for an ICE, long-range battery, in-motion WPT and CPT truck are $0.71, $0.47, $0.62 (1500 truck/day), $0.43(5000 truck/day) and $0.50 (1500 truck/day), $0.39 (5000 truck/day), respectively. In addition, the degradation of long-range batteries and their disposal could increase further the maintenance costs of long-range battery trucks. If fuel and vehicle prices evolve as foreseen between now and 2050, eHighways could become an economically feasible form of road transport, especially for heavy-duty trucks, resulting in energy and cost savings and reduction in CO_2 emissions. Also, the implementation of eHighway allows for advanced controls such as driver-less control. This will optimize energy consumption profiles. In short, this research suggests that the development of eHighways offers an excellent opportunity for achieving transportation sustainability for the future.

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