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Investigation of Electric Highway Alternatives to MegaWatt Charging

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Summary

The economics of long haul trucking on both continuous and intermittent Electric Highways were evaluated from a technical perspective as alternatives to using conventional MegaWatt chargers. The study revealed complex and sensitive interplay between the various technical factors related to the vehicle, its battery pack and the configuration and construction of the electrified highway. For now, while there is no overwhelming case in favour of any particular technology, the study serves to highlight the relevant factors impacting anticipated design criteria for the electrification of highways.

Keywords: heavy-duty vehicles, batteries, wireless charging infrastructure, simulation, cost

1 Introduction

Different technologies are under development to electrify long haul transportation. Battery electric trucks (BETs) require large batteries and recharging at very high (megawatt) power level to approach the utility of diesel trucks. Electric Highways provide opportunities for electric trucks to receive electric power while they are driving. This concept allows for a significant reduction of the truck battery size, however the infrastructure costs for Electric Highways are high and could be a significant hurdle to their implementation.

In a simulation study, the National Research Council of Canada and Natural Resources Canada jointly investigated the operation and economics of electric trucks using MegaWatt charging and of Electric Highways with dynamic wireless power transfer (DWPT), specifically including the cost of battery degradation in the economic evaluation. Additionally, the potential of intermittent electrification of the 540 km highway between Toronto and Montreal in Canada was evaluated as a means to reduce investment costs.

2 Method

2.1 Route

The route between Toronto and Montreal in Canada is one of the busiest highways in North America. A total of about 8,000 trucks use it in either direction on a daily basis to transport goods between the two cities. Local depots of a shipping company in both cities were selected as the end points of the daily two-way duty cycle of 1,081 km, of which 99% is on highways. Speed limits and elevations at 500 m intervals for the route were obtained from Google Earth [1], and outdoor conditions along this route were given by hourly temperature data published by Environment Canada [2] for the year 2020. On the highway, the BET speed was set as 100 km/h.

2.2 Scenarios

Three Electric Highway (e-Hwy) scenarios were evaluated against a reference case of a truck using only battery power and being recharged with a MegaWatt charger:

1. A 100% electrified highway (providing 200 kW at 85% uptake efficiency [3] to the truck)
2. A 50% electrified highway with alternating sections of 20 km that are electrified (at 400 kW) or non-electrified
3. A 50% electrified highway with alternating sections of 2 km that are electrified (at 400 kW) or non-electrified

2.3 Electric Truck Battery Sizing

The reference basis for modeling an e-truck was the proposed Tesla Semi [4]. The Tesla Semi is specified to have a 947 kWh battery pack composed of yet to be commercialized 4860 format cylindrical cells with an anticipated 800 km driving range. For the intended Toronto to Montreal transit of 540 km, it was desired to have a BET with sufficient driving range to be able complete the trip over its lifetime (i.e. with decreasing battery capacity down to 60% of the original capacity) without requiring mid-trip recharging. For now, the battery pack that was used in the 2016 Tesla Model S [4] was used as a base unit for building a BET pack. In the simulated BET, cell banks of 3.07 Ah cells were configured in a 74-parallel and 84-series arrangement. For our simulations, packs were simulated in quantities ranging from 4 banks up to 16 banks (267 to 1,068 kWh) to power the BET. Battery capacities used in this study are summarized in Table 1 below. The 84-series specification was required for floor level 240 V operation.

2.4 Battery life model and economic model

BET power loads were determined by applying driving conditions to an expression from [3] given below.

$$P_{truck} = \frac{(\mu_f + \sin\alpha)Mg}{\eta_{\mathrm{eq}}} + \frac{C_d A v(t)^3 \rho}{2\eta_{\mathrm{eq}}} + \frac{\delta M a(t) v(t)}{\eta_{\mathrm{eq}}} = \eta_{\mathrm{eff}} \cdot IV \quad (1)$$

The terms in Eq. 1 account for rolling resistance, elevation change, form drag and acceleration effects. The current demand for the battery can then be determined by the equivalence of P_{truck} to $\eta_{\mathrm{eff}} \cdot IV$, where η_{eff} is the electric motor efficiency and I would be the current required from a battery at potential V. The simulation runs also employed some basic control logic, akin to the battery management system (BMS) found in an electric vehicle. In this case, the cell voltage range was restricted between 4.05 and 2.9 V. For the base reference case, the battery pack was fully charged to begin each driving trip. The power flow dynamics inside the BET are depicted in the schematic diagram below.

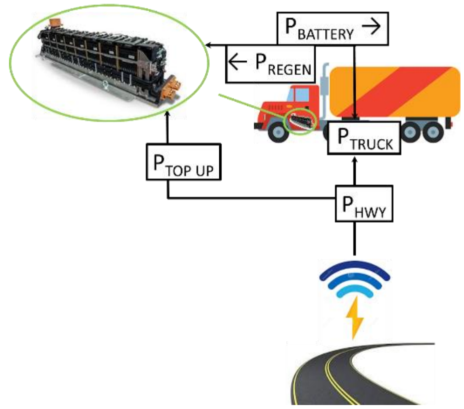

Figure 1: Power flow configuration for simulation BET.

The BET power demand P_{truck} is served by power provided by the e-Hwy P_{hwy} and supplemented by P_{battery} if required. If P_{hwy} was in excess of P_{truck}, the excess power available was provided to the battery pack if the DOD (Depth of Discharge) was greater than 0.50 and referred to as $P_{\mathrm{top\ up}}$. During some descents, regenerative braking power could be generated, and was supplied to the battery pack, referred to as P_{regen}.

The BET power model was then linked to an equivalent circuit model for battery operation [5]. Thermal states were tracked using an empirical transient model for the battery packs which accounted for ambient temperatures and battery function [6]. Battery electrochemical and thermal states then were applied to a capacity loss model to track cell State of Health (SOH) including intermittent effects [7]. Batteries were assumed to have reached their end of life when their SOH was reduced to 60%.

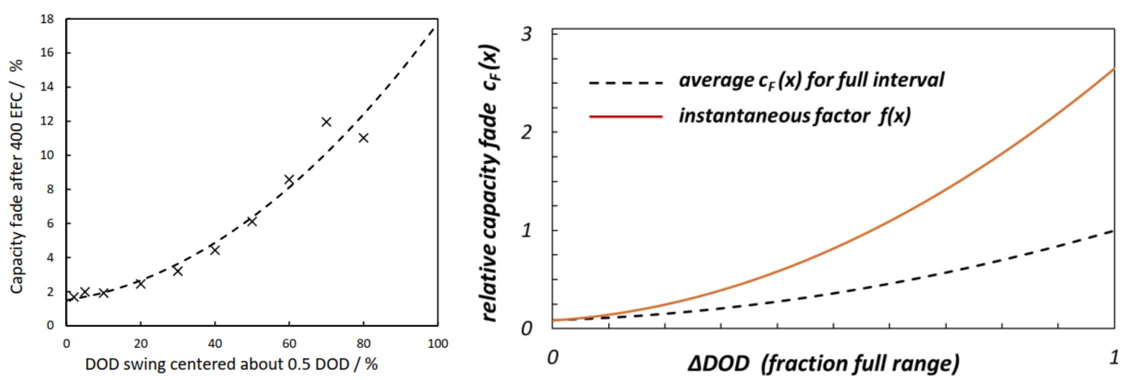

Figure 2: Left, experimental capacity fade rates in Li-ion cells plotted as a function of cycle amplitude. Right, the same curve in dashed black for ΔDOD (depth of discharge) intervals used as basis to determine relative instantaneous degradation factor for battery operation across any ΔDOD range.

This present study is the first to incorporate a model where operational duration effects and mode switching effects have been considered in capacity loss determinations [8]. Briefly, it was found that the capacity loss varied significantly as a function of cycle amplitude for tests conducted at the same current level and for the same length of time. Analysis in [9] was able to determine an instantaneous degradation driver for indeterminate operational lengths by finding values that applied over the interval produced the average value corresponding to the measured degradation from the variable amplitude experiments. Fig. 2 shows these experimental results and the analytical advance. The instantaneous degradation factor is relevant for situations such as driving on a highway with elevation changes or intermittent DWPT power provision which will produce abrupt changes in current direction in the battery or allow rest periods for the battery. During rests electrolyte phase lithium levels which drive degradation and are established during steady operation will relax and decrease the degradation rates. A partition function for the relative contributions of the discharge and recharge phases of current flow was also determined in [9] and is used in these e-Hwy scenarios for BETs.

An economic model was developed to calculate the aggregated costs per kilometer driven for battery use, electricity consumption and capital costs for the charging infrastructure. It takes a break-even perspective on the operation of the charging infrastructure, and a wide range of possible investment cost values were evaluated for both MegaWatt charging and Electric Highways, as accurate cost numbers are presently uncertain for these technologies that are still under development.

3 Results

3.1 Daily operation and battery life

Possible BET scenarios with DWPT are extensive and the cases considered here aim at first understanding the interplay among important input parameters with a view to identifying suitable pathways towards optimal operation. Continuous and intermittent highway electrification were compared to investigate whether a pulsed type of power provision could benefit battery performance and durability. The power flow logic employed here prioritized direct DWPT to the electric motor, and any additional available energy could recharge the battery when the state of charge was below 50%, while regenerative braking supplied recharge energy whenever it occurred. When BET power demands exceeded the 200 or 400 kW provision from the e-Hwy, the battery discharged the balance of the demand. With longer intermittency distances, the power flow occurred in longer and deeper cycling patterns. A reference case was simulated with a BET without DWPT and using post-trip 1 MW level recharging. For thermal control, the battery was not allowed to drop below -10°C when operating. The energy required for this was not tracked, but based on [7], an estimate for heating energy would represent an overall additional 0.08%, considered negligible for this preliminary study.

3.1.1 Reference and Base e-Hwy Cases

To illustrate the nature of the simulations more concretely, two example cases of driving are shown in Fig. 3, both simulated over 24 hours on January 1, reflected in the outdoor temperatures shown. Things to note from Fig. 3 are that for the no-DWPT base case, the battery SOC goes from a near fully charged state down to about 0.35 over the 540 km trip and then undergoes a complete recharge. These operations cause significant heating in the battery as well. For the case with e-Hwy power provision, the battery pack SOC varied only in a 3% range and ended the day at essentially the same level as it began. Thus, with e-Hwy power, no recharge operations were required, which absolved the battery pack of exposure to sustained high currents and significant temperature rises. For the electrified highway case, the significantly lower amount of power transfer to and from the battery also results in far smaller temperature swings.

It can be seen in Table 1 that the roughly 8.5 year lifetime determined for the reference case, moved to values greater than 15 years even for the 4 bank pack, and increased to over 20 years for the 8 bank pack This value is approaching the calendar life of the battery pack determined as 26.7 years under the same climatic conditions. In general, long-haul trucks known to typically last 7-8 years (specifically, 900,000 km or up to 17 years with light use) in Canada [10], so the results here show that the battery packs in the BETs simulated on the e-Hwy will normally not need replacement during the vehicle life. In terms of energy efficiency, a slight benefit can be seen for larger pack sizes in Table 1.

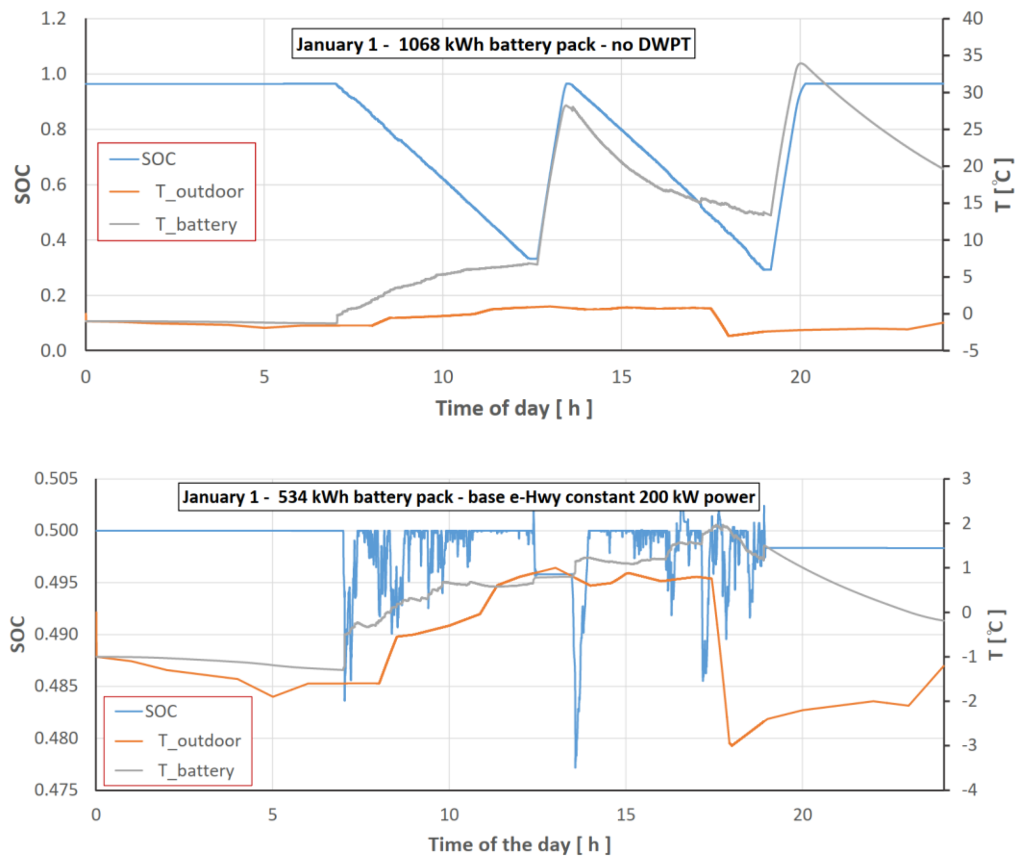

Figure 3: Plots tracking ambient temperature, battery pack temperature and battery SOC over a 24-hour period on January 1. The upper plot was simulated with a 16-bank pack and no DWPT. The lower plot show simulation output for a truck with an 8-bank pack, and full e-Hwy coverage with 200 kW DWPT power provision.

Table 1: Battery life for different scenarios and battery sizes

Battery size (kWh)	MegaWatt charging		100% electrified highway		50% electrified (20 km on/off)		50% electrified (2 km on/off)	
	# of eq cycles	End of life (yrs)	# of eq cycles	End of life (yrs)	# of eq cycles	End of life (yrs)	# of eq cycles	End of life (yrs)
267			3,872	15.89	6,059	6.24	6,888	6.98
401			3,089	18.86	7,232	10.87	7,667	11.22
534			2,481	20.12	7,022	13.97	7,194	14.08
1,068	4,235	8.41						

3.1.2 Intermittent e-Hwy Configurations

To make available the same amount of power over an equivalent distance, on/off intervals of equivalent segment length were simulated to assess the effects of intermittency in electrified highways. Initially, alternating powered and unpowered segments of 20 and 2 km were investigated.

The effect of the 200 kW and 400 kW e-Hwy power provision levels are shown in Fig. 4, with battery pack capacity and 2 km and 20 km intermittency intervals as additional parameters. It can be seen that increased e-

Hwy power benefits battery lifetime for large packs, and when comparing packs of equivalent capacity, smaller intermittent intervals provide slight lifetime gains. In general larger packs perform more efficiently, and the 2 km intervals showed slightly better energy efficiency compared to the 20 km intervals. At 200 kW e-Hwy power, significant energy from mid-trip recharging was required, notably with smaller battery packs, thus reducing BET lifetimes. While intermittent electrification has lower battery degradation on a per cycle basis, the truck battery was used much more than in the case of full electrification, leading to a shorter life (Table 1).

Much finer intervals of e-Hwy intermittency were investigated to see if such configurations could provide energy use benefits over the BET lifetime. Results in Table 1 already show slight benefits in battery lifetimes for 2 km on/off intervals compared to 20 km intervals, along with larger incremental gains as battery pack sizes increase. Regularly spaced on/off intervals shorter than 2 km were simulated; 1000 m, 500 m, 250 m and 100 m. A 100 km/h highway speed is 27.78 m/s, requiring less than four seconds to cover 100 m. In order to have proper spatial resolution for on/off e-Hwy switching over 100 m intervals, a simulation time step of 0.5 s was required. For these cases, an e-Hwy with 400 kW power provision was simulated with e-trucks with 4 and 8 bank battery packs, traveling the Toronto to Montreal route with intermittent DWPT.

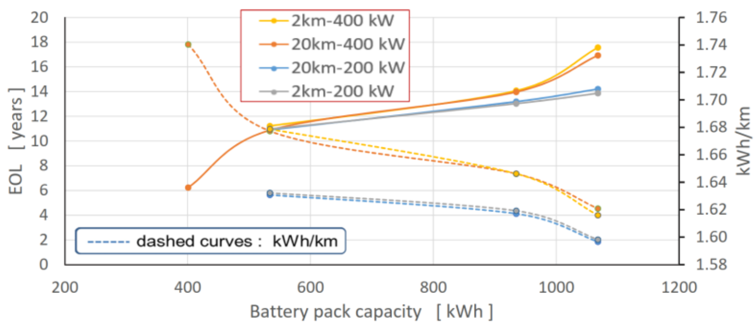

Figure 4: Battery lifetimes and energy use per km as a function of BET battery pack size on intermittent e-Hwys at 200 kW and 400 kW power provision levels.

In Fig. 5 a small lifetime benefit for 4-bank packs at shorter on/off electrified intervals can be observed. For an 8 bank pack, there is an essentially negligible benefit to very short intermittent intervals reflected by the near zero slope of the data. These output data confirm that larger battery packs have both longer life and more efficient performance. Based on the theoretical advances alluded to in Fig. 2, it is understood that fast mode switching, and/or continuous operations that experience rest intervals (akin to pulse charging) will expose the electrodes to smaller build-ups of excess lithium, known to be a significant degradation driver.

Also shown in Fig. 5 for the cases considered are curves with kWh/km values. The energy efficiency is very sensitive to many factors, and despite anticipated benefits of intermittency, the data show negligible benefits. The efficiency calculations show better performance with longer intervals which could possibly be a minor thermal effect given the lack of sophisticated thermal management modeled here. Over longer on/off intervals the battery will run slightly hotter, contributing to slight efficiency gains in generally cold operating environments.

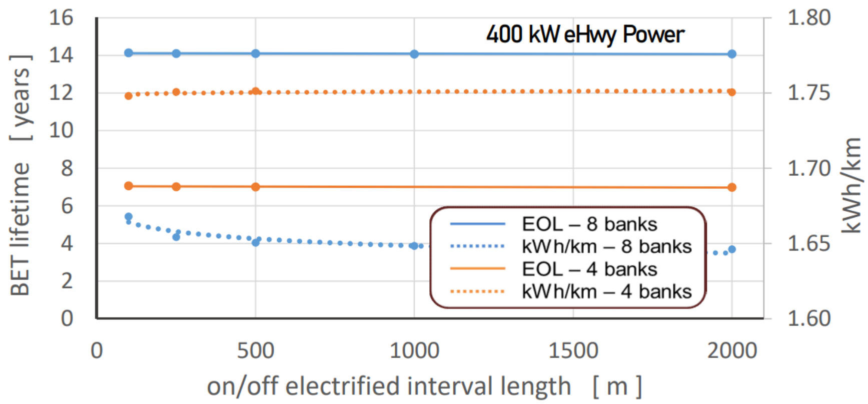

Figure 5: Battery lifetimes and energy use per km as a function of intermittency interval length for 4 and 8 bank BET batteries.

3.1.3 Discussion of the Operational Duration Effect

To better understand the limited benefits indicated in Fig. 5, the ΔDOD parameter used to determine the *f(x)* term as raw simulation output can be seen in Fig. 6. The raw ΔDOD parameter is erratic and made more so by intermittency. The data were fitted with a high order polynomial which produced a smooth curve over the trip distance suitable for comparing cases. The value can be thought of as a driver for battery degradation, since ΔDOD varies directly with it.

Fig. 6 shows the ΔDOD levels determined for 20 km, 2 km and 0.10 km e-Hwy intermittency over the Toronto to Montreal drive, as well as the main reference case of the BET with a 16 bank battery and no DWPT provision. The reference case shows about a 50% higher ΔDOD value for most of the trip, and it only becomes much higher for about the last 100 km of the trip where the route elevation features do not allow the ΔDOD value to relax like the intermittent cases. Thus the low duration driver values for degradation clearly contribute to intermittent cases with pack banks of 6 units or more having markedly longer lifetimes than the reference case.

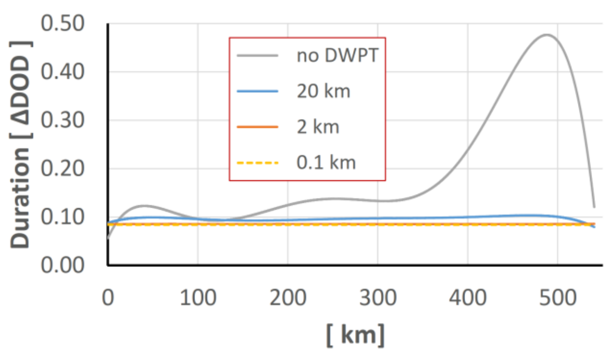

Figure 6: Smoothed ΔDOD curves for the reference no DWPT case and 20 km, 2 km and 0.10 km e-Hwy on/off intervals.

The irregularity of the power demand produces ΔDOD values that average around 0.10 for the 20 km intervals. The increased irregularity obtained from reducing the on/off interval to 2 km drops the average ΔDOD levels by about 15%. Given that this is a small decrease that manifests mainly during brief operational durations to begin with, the benefits in terms of extending battery life are small. When going from 2 km to 0.10 km intermittency, the ΔDOD levels decrease by only about 2 percent. The main takeaway here is that micro-intermittency below 2 km provides negligible battery durability benefit for the scenarios examined.

In hindsight, the results are consistent with the reference case depicted in the upper plot of Fig. 3. In that case, the entire 540 km trip was completed, depleting the SOC of an initially fully charged 16 bank battery by about 62%. Thus, even 20 km segments, proportionally would represent an SOC change (or ΔDOD) of around 2.3%, which would thus produce small ΔDOD-based degradation drivers. Relative to this, finer intermittency would simply be a slight incremental reduction of an already small quantity.

3.2 Economic evaluation

The economics of the electric highways variants and of the reference case of MegaWatt charging were evaluated by comparing their total cost per km for the infrastructure, the electricity consumed, and the cost of battery degradation. The per km costs for the reference case of MegaWatt charging are displayed in the left part of Figure 7. The costs strongly depend on the currently unknown costs to purchase and install 1 MW chargers and on their utilization rate. There is also a wide range in cost forecasts for electrifying highways. Additionally, the cost per km will depend on the number of trucks using the e-Hwy. The resulting costs per km for a fully electrified highway are given in the right part of Figure 7.

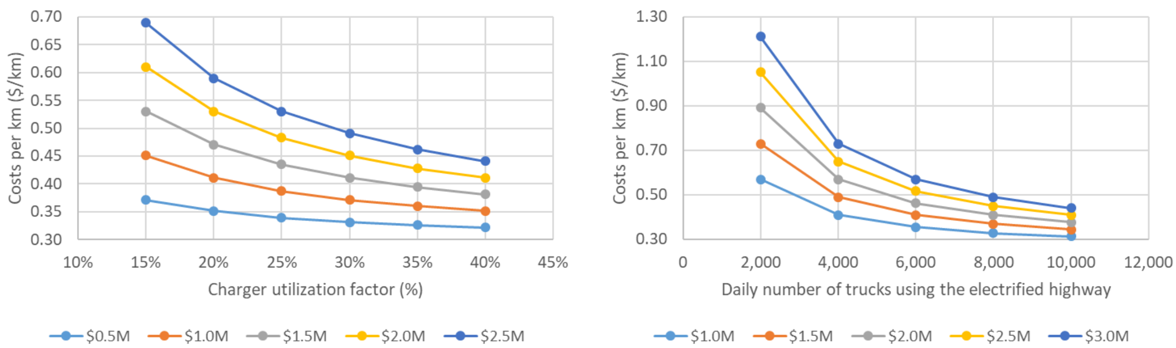

Figure 7: Costs per kilometer for the reference case of fast charging at a 1 MW power level for scenarios of different charger cost and charger utilization (left) and for the 100% electrified highway for different levels of investment costs per km and highway utilization (right).

Intermittent electrification scenarios reduce investment costs through savings on the costs of the in-road part (for the 20 km and 2 km case) and on the costs for electricity distribution along the highway (only for the 20 km case). Savings for the 2 km case were therefore assumed to be half of those for the 20 km case. However, for most of the cases evaluated, the savings in investments were cancelled out by higher battery use costs and greater electricity losses (see the left part of Figure 8, Table 2). Despite the higher investment costs, simulation results indicated a benefit of installing a larger battery in the truck than strictly necessary for intermittently electrified highways (Figure 8 – right).

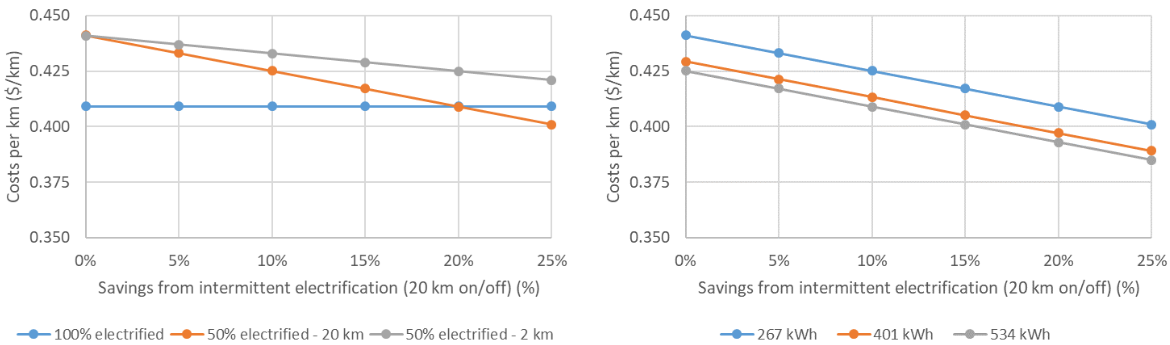

Figure 8: Costs per kilometer driven for different electrification scenarios using a 267 kWh battery (left) and for trucks with different battery sizes for intermittent electrification (20 km on/off) (right) - for different levels of cost reduction from intermittent electrification (for investment costs of $ 2.0 million/km and for 8,000 trucks per day)

Table 2 indicates that per km costs are similar for high usage scenarios for the middle of the current range of investment costs. More accurate investment cost data will be necessary to understand which technology will be more cost effective for the transportation sector.

Table 2: Per km costs for different cost components

	MegaWatt charging	100% electrified highway		50% electrified (20 km on/off)		50% electrified (2 km on/off)	
Battery size (kWh)	1,068	267	534	267	534	267	534
Battery use	$ 0.048	$ 0.006	$ 0.010	$ 0.016	$ 0.015	$ 0.015	$ 0.014
Capital costs	$ 0.102	$ 0.161	$ 0.161	$ 0.136	$ 0.136	$ 0.148	$ 0.148
Electricity	$ 0.243	$ 0.242	$ 0.241	$ 0.264	$ 0.250	$ 0.266	$ 0.250
Total	$ 0.394	$ 0.409	$ 0.412	$ 0.417	$ 0.401	$ 0.429	$ 0.413

4 Conclusions

On a purely technical level, this study has provided the rationale and context to incorporate temporal and current mode degradation drivers into BET usage simulations. General preliminary findings are that electrified highways significantly increase BET battery life, but total energy consumption is similar to 1 MW recharging of BETs driving on highways without DWPT. However, electrified highways allow battery packs less than 50% of the size required with BETs using 1 MW recharging. Important parameters for transport trucks on electrified highways were identified as battery size, e-Hwy power provision level and route elevation features.

This study also evaluated the operation and economics of continuous and intermittent Electric Highways as alternatives to using MegaWatt chargers. Because all of these technologies are still under development, there is a large uncertainty regarding their investment costs. For all technologies, a high utilization rate is necessary to obtain low costs per km, and mid-range investment costs currently lead to similar costs per km for all technologies.

Intermittent electrification was shown to increase the number of equivalent cycles within the life of the battery, but requires more intense battery usage, decreasing the actual battery life in number of calendar years. Equipping trucks with larger batteries than necessary reduced cost per km due to longer battery life.

Going forward from this present study, subjects that will require further investigation will be ways to better exploit intermittent electrification of highways including electrified interval lengths and their configurations. Such further studies will need to be closely tied to economic evaluations of the entire system including installed equipment and the operation of BETs in the e-Hwy environment.

Acknowledgments

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