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Detailed Investigation of the Operation and Economics of Electric Taxis in Canada

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Summary

The operation and economics of 1-shift and 2-shift electric taxis in Ottawa, ON, Canada, were evaluated in a simulation study using real-world driving data from gasoline taxis and detailed battery life modelling. Electric taxis were able to operate like gasoline taxis on most days and showed favourable economics. Without any incentives, 1-shift taxis in Ottawa can provide significant net savings of almost $20,000 over a 6-year life, requiring only limited adjustments to driver behaviour. Similar or greater savings can potentially be created by 2-shift taxis, depending on battery longevity, availability of charging infrastructure and recharging frequency.

Keywords: case-study, BEV (battery electric vehicle), business model, charging, simulation

1 Introduction

Transportation is a large emitter of greenhouse gas (GHG) emissions, responsible for 28% of all GHG emissions in Canada [1]. The government of Canada recently announced a new target for GHG emissions: by 2050, Canada should have net-zero carbon emissions [2]. This new target will require an almost total emission reduction in all sectors, including transportation.

In Canada, over 80% of all electricity is generated from non-emitting sources [1]. Electrification of transportation could therefore result in drastic GHG emission reductions, and could be a pathway towards the goal of net-zero carbon emission in 2050.

Light-duty vehicles cause over 40% of transportation GHG emission. Within the group of light duty vehicles, taxis are among the vehicles with the highest emissions due to their high utilization. Because taxis typically drive within city limits, electrification of the taxi fleet has the potential to significantly reduce emissions and specifically improve inner-city air quality. Electric taxis could also play an important role in the general transition to electric driving. Experiencing an electric vehicle (EV) as taxi passenger may influence people to consider buying an EV themselves.

Several challenges still exist for electric vehicles to smoothly function as taxis, such as sufficient battery capacity to meet the daily driving distance, availability and location of charging stations, rate of charging, purchase price premium, and degradation and useful life of the EV battery. Published research on taxi electrification provides clues regarding how to overcome these challenges. Deyang et al. [3], for instance, concluded that 60 kWh batteries could satisfy the power required for electric taxis in Shanghai with achieving optimal economics and GHG emissions. Bischoff et al. [4] simulated taxis in a small city (Mielec, Poland) using MATSim simulation software with results indicating no negative impact on the level of service provided by electric taxis (versus conventional) for daily operations. They recommended that from the passengers' perspective it is useful to dispatch the electric taxis with the highest battery charge level first. Moniot et al. [5] studied the application of electric taxis with a 400 km range in the city of Columbus, OH, USA, using a large data set of actual taxi operation. They found that the availability of charging options had a major impact on the percentage of taxi driving days that could be completed without depleting the battery.

The potential to cost-effectively electrify taxi fleets strongly depends on local conditions like the taxi ownership model and mode of operation, city size, level of congestion, climate, and prices of electricity and gasoline. In Canada, most taxis are owned by their driver, who operates the vehicle for 8-12 hours per day (1-shift taxi). Some taxis are used 24 hours a day and are shared by two drivers each doing a shift (2-shift taxi). This study combined real-world driving data of 1-shift and 2-shift taxis and detailed battery life simulations to evaluate the practicality and lifetime economics of electric taxis in Ottawa, Ontario, Canada.

2 Methodology

Due to a lack of real-world performance data of electric taxis, modelling and simulation were used to evaluate the operation and economics of electric taxis assuming they would follow the identical drive patterns collected from conventional gasoline taxis. This required the combination of detailed simulation models and a number of different data sets. Realistic driving demands for the electric taxi were created [6] by combining 1-minute data of real-world taxi operation with high-resolution 1-second driving data from on-road testing of a long-range electric vehicle for various types of driving (highway, arterial, city, congested city) and under different ambient conditions (summer, winter). A detailed battery life model was employed to simulate EV batteries over the 6-year life of the taxi [6]. This model addressed the electro-chemical aspects of the EV batteries, as well as their thermal behaviour based upon correlations between ambient temperatures and internal battery temperatures [7].

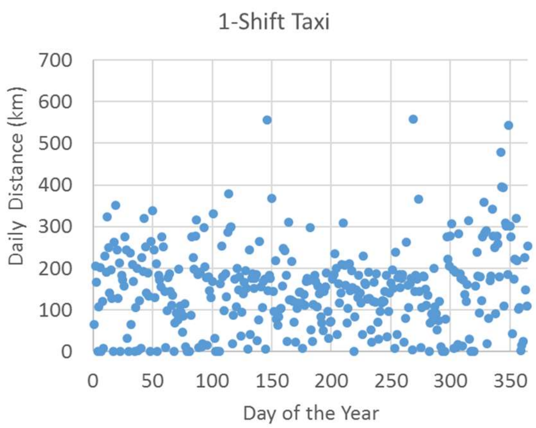
Simulations were conducted for an electric taxi having a range equivalent to the 383 km "window sticker" range of a Chevrolet Bolt. Weather data and economic parameters for Ottawa were used.

2.1 Real-world Taxi Driving Data

Data loggers were used to monitor the operation of 12 conventional gasoline fueled taxis in the cities of Halifax, NS (1-shift taxis) and Winnipeg, MB (2-shift taxis) from January 2017 to January 2018 [8]. The collected data consisted of trip-based information on the date and time of the start and end of each trip, the distance driven and the amount of fuel consumed. Additional GPS taxi location data was collected at a 1-minute resolution to identify when taxis were driving or waiting for their next fare with their engine on for cabin conditioning reasons. During longer breaks, taxis were parked with their engines off.

Using data collected from a 1-shift taxi over 8 months, an annual data set was created, resulting in a total driving distance of 55,280 km and an average distance of 151 km/day. One 2-shift taxi provided data for a full 12-month period, in which it drove 108,707 km in total (on average 298 km/day).

Figure 2 presents daily driving distances for the 1-shift and 2-shift taxis over the year. Both taxis showed a significant variation in the distance covered in one day, indicating the need to use detailed simulations to evaluate their electrification potential.



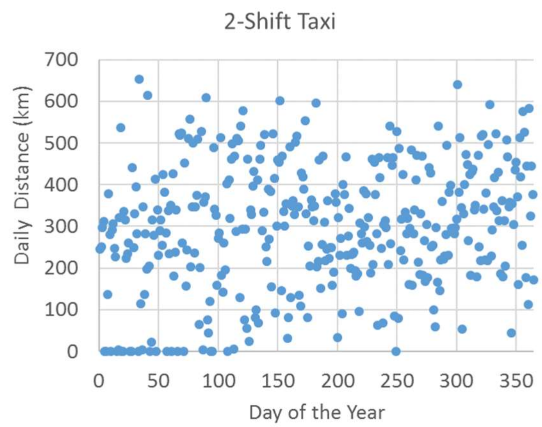


Figure 1: Daily driving distances (in km) for the 1-shift and 2-shift taxis used in the simulations

2.2 Economic Model

The total life-time costs for vehicle purchase and operation (electricity/fuel, maintenance) were calculated for electric taxis and gasoline taxis based upon a 6-year life. Table 1 presents the fuel and electricity prices used. Without incentives, electric taxis currently have a price premium over similar gasoline taxis of approximately $11,000 ($12,430 when including 13% VAT in the province of Ontario). Electric taxis save on maintenance costs: no oil changes ($50/5,000 km) and reduced other maintenance (for instance less brake work) was estimated at $500 per 50,000 km.

Table 1: Economic parameters

	Gasoline taxi	Electric taxi
Fuel costs ($/L)	1.100	
Fuel costs ($/km)	0.110	
Electricity costs (Level 2 – 6.6 kW, $/kWh)		0.120
Approx. electricity costs (Level 2, $/km)		0.024
Electricity costs (Level 3 – 50 kW, $/kWh)		0.300
Approx. electricity costs (Level 3/ $/km)		0.060

3 Taxi Operation, Battery Life and Economics

3.1 1-Shift Taxis

A number of different operating scenarios were evaluated for the electric 1-shift taxi. Two base scenarios were simulated, in which the taxi would only have access to Level 2 (L2) or Level 3 (L3) charging during overnight periods. In the context of this study, 'overnight' should be taken broadly as referring to a large break between shifts or driving periods. The actual timing of this break can be at any time of the day.

Additional scenarios were investigated, in which the taxi would also employ L3 charging at every stop between fares that lasted longer than 10 minutes ('mid-shift recharging'), or the taxi would apply 20 minute L3 recharging when the battery would be empty ('empty battery charging'), or both ('mid-shift and empty battery charging'). To simplify the simulations, it was assumed that the fast charging stations needed for these additional charging sessions were ubiquitously available and did not require the taxis to do any additional driving.

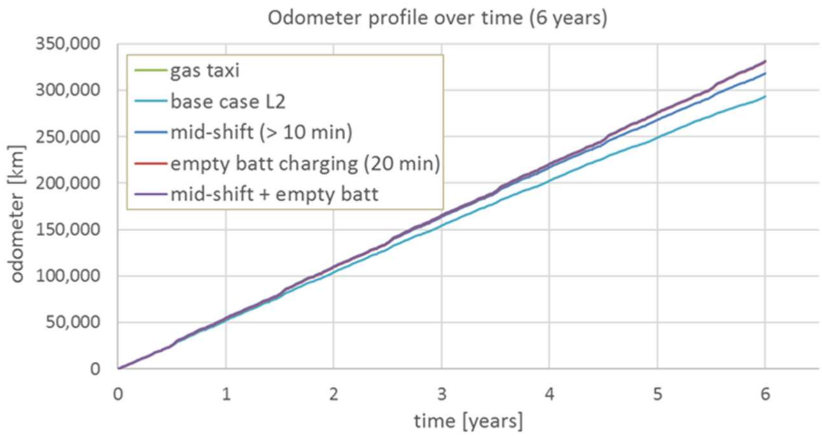


Figure 2: Odometer readings over time for the gasoline taxi and selected 1-shift electric taxi scenarios

Figure 2 displays the increase in odometer readings over time for the gasoline taxi and various electric taxi scenarios. Over time, the Level 2 base case 1-shift taxi is less capable of following the drive pattern of the gasoline taxi. The 1-shift taxi drives 95% of the distance of the gasoline taxi in the first year, but due to battery degradation this has dropped to 80% in the last year. On average over the life of the vehicle, the 1-shift taxi covers 89% of the distances driven by the gasoline taxi. Applying mid-shift charging on top of overnight charging increases the coverage of the drive pattern of the gasoline taxi to 96%, while the more hypothetical scenario of recharging when the battery is empty would result in an almost perfect following of the operation of the gasoline taxi by the electric taxi.

Table 2 presents details on the operational results of the five scenarios for the electric 1-shift taxi, while the associated economic results are given in Table 3. The simulation results show that an electric 1-shift taxi in Ottawa can operate in almost the same way as a conventional gasoline taxi when L3 charging is applied on an 'as needed' basis (empty battery) in addition to regular L2 overnight charging.

Table 2: Simulation results for 1-shift electric taxi scenarios (mid-shift recharging only for breaks greater than 10 minutes, 20 minute duration of empty battery recharging)

	Base case (L2)	Base case (L3)	Mid-shift recharging (L3)	Empty battery charging (L3)	Mid-shift and empty battery charging (L3)
Distance driven (km)	293,451	289,606	318,216	330,921	331,565
% of km gasoline taxi (%)	88.5 %	87.3 %	95.9 %	**99.8 %**	100.0 %
Overnight L2 charging (kWh)	57,763	-	24,280	53,221	22,014
Overnight L3 charging (kWh)	-	60,646	-	60,646	-
Mid-shift L3 charging (kWh)	-	-	41,309	-	43,282
Empty battery recharging (kWh)	-	-	-	14,998	4,054
Total charging (kWh)	57,763	60,646	65,589	68,219	69,350
Fraction of charging on L2	100 %	-	37%	78 %	32 %
Fraction of charging on L3	-	100 %	63%	22 %	68 %
Efficiency of el. taxi (km/kWh)	5.08	4.78	4.85	4.85	4.78
Remaining battery capacity (%)	75.2 %	72.6 %	69.0 %	**72.1 %**	68.1 %

Table 3: Economic results ($ over six years) for 1-shift electric taxi (mid-shift recharging only for breaks greater than 10 minutes, 20 minute duration of empty battery recharging)

	Base case (L2)	Base case (L3)	Mid-shift recharging (L3)	Empty battery charging (L3)	Mid-shift and empty battery charging (L3)
Distance driven (km)	293,451	289,606	318,216	330,921	331,565
% of km gas taxi (%)	88.5 %	87.3 %	95.9 %	**99.8 %**	100.0 %
Gasoline costs	32,280	31,857	35,004	36,401	36,472
Electricity costs (L2)	6,932	-	2,914	6,387	2,642
Electricity costs (L3)	-	18,194	12,393	4,499	14,201
Electricity costs (Tot.)	6,932	18,194	15,306	10,886	16,842
Fuel cost savings	25,348	13,663	19,698	25,515	19,630
Maintenance savings	5,835	5,746	6,332	6,609	6,616
Total savings	31,183	19,409	26,030	32,125	26,245
El. taxi price premium	12,430	12,430	12,430	12,430	12,430
Overall savings	18,753	6,979	13,600	**19,695**	13,815
Annual savings	*3,125*	*1,163*	*2,267*	***3,282***	*2,303*

The electric taxi battery is expected to last the full 6-year life of the vehicle. Over those 6 years, the electric taxi fuel and maintenance savings could amount to $32,000. Taking into account the current price premium of the electric taxi, close to $20,000 can be saved in comparison to a gasoline taxi. The higher costs of L3 charging reduces the net savings to below $14,000 for taxis that recharge at every suitable stop between fares. Depending on driver behaviour, actual savings will likely be somewhere in between these amounts.

Operating the electric 1-shift taxi with overnight charging and regular top-ups when needed would require a network of fast charging stations in the service area of the taxi fleet, to ensure that the taxi can find a recharging spot close to the drop-off point of its last passenger. However, even if such a network would not be available and the taxi could only use L2 charging at a home base, it would still be able to obtain most of the savings from the optimal scenario. In this case, an adjustment would be needed in the way the taxi is operated (i.e. introducing a longer break to recharge the taxi) to prevent that the net income of the taxi driver would actually drop, because the reduction in revenue from missing a significant number of fares could totally eliminate the savings in fuel costs and maintenance.

3.2 2-Shift Taxis

The operation of the 2-shift taxi clearly differed from that of the 1-shift taxi, because it drove about double the distance of the 1-shift taxi. On many days, the 2-shift taxi operated almost continually without major break periods. The scenario with both mid-shift recharging and empty battery charging was therefore chosen as the base case for the 2-shift taxi. Again, a dense network of fast charging stations was assumed to be present.

Figure 3 displays the increase in odometer readings over time for the gasoline taxi and for scenarios for a 2-shift electric taxi applying mid-shift charging at each break greater than 10 minutes or for breaks greater than 5 minutes. The electric taxi is well capable of following the drive pattern of the gasoline taxi, achieving a 98% coverage over the 6-year period.

The data on the daily driving distances presented in Figure 1 shows that 2-shift taxis also experience a significant number of less busy days. During these days, much longer periods between shifts were recorded. Additional scenarios were evaluated, in which the electric taxi would use L2 recharging during these 'overnight' periods. Tables 4 and 5 present the operational and economic results for scenarios with a 10- or 5-minute minimum break for mid-shift charging and the use of either L3 or L2 charging during longer breaks between shifts ("overnight").

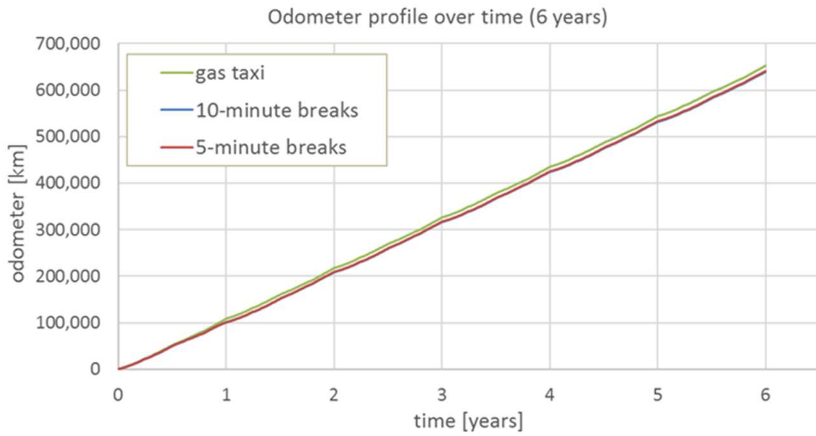


Figure 3: Odometer readings over time for the gasoline taxi and the 2-shift electric taxi using mid-shift recharging (with indicated minimum break times) and 20 minute empty battery charging

Table 4: Simulation results for 2-shift electric taxi scenarios (with mid-shift recharging only for breaks greater than 10 or 5 minutes and 20 minute duration of empty battery recharging)

	Overnight (L3) Mid-shift (≥ 10 min)	Overnight (L3) Mid-shift (≥ 5 min)	Overnight (L2) Mid-shift (≥ 10 min)	Overnight (L2) Mid-shift (≥ 5 min)
Distance driven (km)	639,767	640,495	637,776	639,387
% of km gasoline taxi (%)	98.1 %	98.2 %	**97.8 %**	98.0 %
Overnight L2 charging (kWh)	-	-	14,331	8,742
Overnight L3 charging (kWh)	16,900	9,924	-	
Mid-shift L3 charging (kWh)	94,840	115,094	96,303	115,634
Empty battery recharging (kWh)	24,738	11,752	24,155	11,286
Total charging (kWh)	136,477	136,769	134,790	135,662
Fraction of charging on L2	-	-	11 %	6 %
Fraction of charging on L3	100 %	100 %	89 %	94 %
Efficiency of el. taxi (km/kWh)	4.69	4.68	4.73	4.71
Remaining battery capacity (%)	47.6 %	44.3 %	**48.4 %**	44.9 %

Under all evaluated scenarios, the electric taxi can closely approximate a conventional gasoline taxi in 2-shift operation. There is hardly any difference in electric taxi operation for using a five or ten minute minimum duration of breaks between trips. However, scenarios with more frequent mid-shift charging show greater battery degradation. Battery degradation generally depends on the instantaneous state of charge of the battery [9]; for the scenarios with a 5-minute minimum break period, the electric taxi battery operates more under conditions with higher degradation factors.

Electric 2-shift taxis can create maximum savings in fuel and maintenance costs of $45,000 over its 6-year life, which results in net savings of over $32,000 when the purchase price premium for the electric taxi is deducted. Using L2 recharging instead of L3 recharging during longer breaks between shifts, has a small positive effect on the economic benefits and battery life.

Table 5: Economic results ($ over six years) for 2-shift taxi scenarios
with 20 minute duration of empty battery recharging

	Overnight (L3) Mid-shift (≥ 10 min)	Overnight (L3) Mid-shift (≥ 5 min)	Overnight (L2) Mid-shift (≥ 10 min)	Overnight (L2) Mid-shift (≥ 5 min)
Distance driven (km)	639,767	640,495	637,776	639,387
% of km gasoline taxi (%)	98.1 %	98.2 %	**97.8 %**	98.0 %
Gasoline costs	70,374	70,454	70,155	70,333
Electricity costs (L2)	-	-	1,720	1,049
Electricity costs (L3)	40,943	41,031	36,138	38,076
Electricity costs (Total)	40,943	41,031	37,857	39,125
Fuel cost savings	29,431	29,424	32,298	31,208
Maintenance savings	12,748	12,805	12,728	12,744
Total savings	42,179	42,229	45,026	43,951
Electric taxi price premium	12,430	12,430	12,430	12,430
Overall savings	29,749	29,799	**32,596**	31,521
Annual savings	*4,958*	*4,966*	***5,433***	*5,254*

The electric 2-shift taxi is expected to have less than 50% of its original battery capacity after 6 years. Although the taxi can still follow most of the drive pattern of the gasoline taxi, it is to be investigated if an EV battery could be used in such a degraded state, and how the driver will experience the significantly increased need to plug the vehicle in. The large economic benefits for electric 2-shift taxis could likely allow a somewhat shorter operational life than the standard six years period, if demanded by battery life issues. This was, however, not part of the current study.

The 2-shift electric taxi heavily relies on fast chargers for its recharging. Additional research is needed to understand the specific requirements for a network of fast chargers for a fully electrified taxi fleet.

3.3 Sensitivity Analysis

The savings from operating an electric taxi instead of a gasoline taxi depend on many different parameters, like the price of gasoline and electricity, or the number of kilometers driven per year. Some of these parameters can vary considerably over time. Figure 4 present results of a sensitivity analysis into the impact of operational and economic parameters on the savings potential of 1-shift and 2-shift electric taxis.

For both taxis, changes in gasoline prices have the largest impact on overall savings, followed by the effect of driving more kilometers per year. Electricity price variations have a smaller impact, while an improvement in the efficiency of the electric taxi is shown to also increase savings.

The results for the variation in annual kilometers were calculated assuming ‘all other things equal’. These results are only valid for small changes in annual kilometers, because large differences will also cause changes in when the electric taxi will be recharged and at what power level.

A reduction of the purchase price premium for the electric taxi (e.g. through incentives or from economy of scale) will directly result in a similar increase in overall savings.

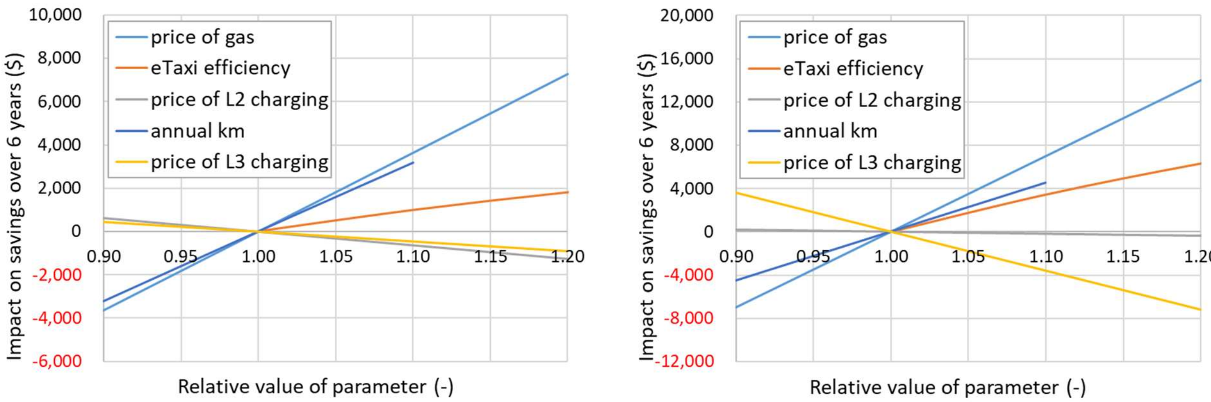


Figure 4: Impact of the relative value of input parameters on overall savings for the 1-shift taxi using L2 overnight charging and L3 empty battery charging (left), and for the 2-shift taxi using L2 overnight charging and L3 mid-shift and empty battery charging (right)

3.4 Reduced Battery Degradation through Advancements in Charging Technology

The results presented in Section 3.2 indicate that using electric taxis in a 2-shift operation over a 6-year period results in very significant battery degradation and in uncertainty on whether a 6-year operational life would be possible.

Electric vehicle batteries are generally recharged using the so-called constant-power/constant-voltage charging method [10]. This means that the battery is charged with a constant power until its voltage reaches a predefined maximum value (to limit battery degradation), after which the charge voltage is kept constant and the battery charging is completed with a slowly decreasing current. An alternative to this method of continuous charging is intermittent charging or pulse charging. First results of recent experiments [11] indicate that pulse charging may cause much lower levels of battery degradation than the continuous charging method. Additional research will be needed to confirm the general validity of these results and the potential benefits for 2-shift electric taxis.

4 Conclusions

Despite today's price premium for electric vehicles, 1-shift taxis in Ottawa can already provide significant savings for their drivers (on average $3,300/year over a 6-year life), if they are willing to make small adjustments to the way they operate their taxi and accept missing some fares on busy days. Similar or greater savings could be created by 2-shift taxis, depending on battery longevity and the realization of larger changes to driver behaviour. Electric 2-shift taxis will require a network of fast charging stations for their operation.

Recent research findings seem to indicate that pulse charging of electric vehicle batteries may significantly reduce battery degradation in comparison to the conventional charging method, which would greatly enhance the viability of the electric 2-shift taxi concept.

Acknowledgments

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References

[1] Environment and Climate Change Canada, *National Inventory Report 1990-2017: Greenhouse Gas Sources and Sinks in Canada*, April 2019.

[2] Canada, Governor General, *Moving Forward Together: Speech from the Throne to Open the First Session of the Forty-third Parliamentof Canada*, December 5, 2019.

[3] Kong Deyang, Ma Dan, Wang Minmin, *A Simulation Study of Upgrading Urban Gasoline Taxis to Electric Taxis*, Energy Procedia, 2016 (104), pp. 390 – 395.

[4] Joschka Bischoff, Michal Maciejewski, *Agent-based simulation of electric taxicab fleets*, Transportation Research Procedia, 2014(4), pp. 191 – 198.

[5] Matthew Monoit, Clement Rames, Erin Burrell, *Feasibility Analysis of Taxi Fleet Electrification Using 4.9 Million Miles of Real-World Driving Data,* National Renewable Energy Laboratory (NREL/CP-5400-72944), Golden, CO, USA, May 2019.

[6] Ken Darcovich, et al., *The Feasibility of Electric Vehicles as Taxis in a Canadian Context*, EV2019 - Electric Vehicles International Conference, Bucharest, Romania, October 3-4, 2019.

[7] Hajo Ribberink, Kathleen Lombardi, Kieran Humphries, Aaron Loiselle-Lapointe, Nadia Stefopulos, Sharon Varghese, Natalie Pundsack, Impact of Ambient Temperature and Battery Activity on Internal Battery Temperatures of Electric Vehicles. 32nd International Electric Vehicle Symposium and Exhibition (EVS32), Lyon, France, May 19-22, 2019.

[8] Mohamed Ghorab, Hajo Ribberink, *Characterization of Taxi Operation in Canada,* Natural Resources Canada, December 2018.

[9] H. Ribberink, K. Darcovich, F. Pincet, *Battery Life Impact of Vehicle-to-Grid Application of Electric Vehicles*, 28th International Electric Vehicle Symposium and Exhibition, Goyang, Korea, May 3-6, 2015.

[10] Anna Tomaszewska, Chu Zhengyu, Feng Xuning, Simon O'Kane et al. *Lithium-ion battery fast charging: A review.* ETransportation 2019 (1) 100011, 28 pp.

[11] K. Darcovich, S. Recoskie, F. Fattal, *Fast Operational Mode Switching Effects on Battery Degradation*, Journal of Applied Electrochemistry, 2020 (50), pp. 111-124.

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