Dynamic wireless charging for CAEV taxi fleet in urban environment

Binod Vaidya | Hussein T. Mouftah

School of Electrical Engineering and Computer Science, University of Ottawa, Ottawa, Ontario, Canada

Correspondence
Binod Vaidya, School of Electrical Engineering and Computer Science, University of Ottawa, Ottawa, ON K1N6N5, Canada.
Email: bvaidya@uottawa.ca

Funding information
Smart Grid Fund, Ministry of Energy, The Ontario Government, Grant/Award Number: 129483; Ministry of Energy

Advent of emerging technologies in the transportation shall led to expansion of electric vehicles (EVs) to urban taxi fleets. In future, Connected and Autonomous Electric Vehicle (CAEV) could likely be the next transportation revolution, especially in taxi fleets. With adoption of CAEVs, it is expected to improve road safety, optimize traffic flow, reduce fuel consumption, and minimize carbon emission in urban environment. However, limited driving range and longer recharging time would be key limitations for widespread deployment of CAEVs. Even though range anxiety caused by limited driving range can be minimized by recharging CAEVs with Dynamic Wireless Charging (DWC) that uses inductive power transfer (IPT) technology. However, due to the sparsely deployed DWC infrastructure, charging CAEV taxi using roadway IPT might be challenging. In this paper, we propose a taxi dispatching solution with DWC plan for urban CAEV taxi fleet in the DWC system using roadway IPT charging technique. Objectives are to minimize waiting time for rider and curtail arrival delay due to detour. Compared to primal dispatching strategy, the proposed strategy can perform better.

KEYWORDS
connected and autonomous electric vehicle, dynamic wireless charging system, taxi fleet, urban transportation, wireless charging

1 INTRODUCTION

Urban transportation is going through a substantial evolution. The trend of urban mobility is towards achieving sustainable and energy efficient mobility, which is motivated due to the increasing concerns on greenhouse gas (GHG) emission. Deployment of electric vehicles (EVs) is one of the major directions taken to address those concerns.

Taxi service, which is an alternative urban transportation mode, is one of the most common personalized modes of transportation in many cities. The expansion of EVs to taxi fleets could be intriguing since EVs exhibit significant environmental benefits over ICE (internal combustion engine) based taxis. As the operation of taxi fleets are mainly preferred in highly dense urban areas, the deployment of EV taxi fleets could significantly reduce CO₂ emission and air pollution.

Furthermore, with the development of self-driving technology, Connected and Autonomous Electric Vehicles (CAEVs), which could provide energy efficient mobility and enhance driving comforts, captivate global attention for emerging innovations in the automotive domain. In future, CAEVs could likely be the next transportation revolution, especially in the taxi fleets. With the adoption of CAEVs, it is expected to improve road safety, optimize traffic flow, reduce fuel consumption, and minimize CO₂ emission in the urban environment. However, limited driving range and longer recharging time would be key limitations for the widespread deployment of CAEVs. So the employment of fast charging and/or wireless charging would be appropriate to tackle these issues.

Wireless power transfer (WPT) is getting increasing attention in the EV domain, since a plug-in or wired charging would be inconceivable while EVs are in the motion. Thus, the WPT would be the only solution for the in-motion charging. This would make wireless EV charging much more convenient as it could be recharged automatically without human intervention. With inductive power transfer (IPT) technology called Dynamic Wireless Charging (DWC), the CAEV can charge itself via charging pads embedded into the road surface. The vehicles drive over these pads and wirelessly get boost to their batteries, giving them extended range to travel. Hence, DWC being a captivating technology shall reduce the range anxiety issues associated with CAEVs.

This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

© 2020 The Authors. Internet Technology Letters published by John Wiley & Sons, Ltd.

Internet Technology Letters. 2020;3:e153.
https://doi.org/10.1002/itl2.153
Issues related to CAEV taxis have acquired growing attention from researchers and automotive industries around the world. Though still the deployment of CAEV taxi fleets is in the early stage, several studies have been accomplished examining the feasibility of CAEV taxi fleets and their acceptability by the riders. For instance, Lu et al. have proposed a dispatching strategy with charging plans for electric taxi considering whether such an electric taxi can reach the destination location. Some works highlight dynamic wireless charging systems for EVs. Such as, the paper focuses on routing strategy for EVs that require recharging so that they can wirelessly charge using mobile energy disseminators. Nevertheless, due to the sparse DWC-enabled infrastructure, charging CAEV taxi using roadway IPT might be challenging. Some studies have investigated wireless charging for CAEVs. The paper elucidates on the charging strategies for wirelessly charging CAEVs in the static wireless charging system. However, such a system has longer recharging time. In our work, we present a dynamic wireless charging system for CAEV taxi fleets and propose an efficient taxi dispatching solution with DWC plan that can minimize a rider waiting time as well as reduce a detour time.

The remainder of this paper is organized as follows: Section 2 depicts backgrounds including CAEVs and wireless charging. Urban CAEV taxi fleet management including proposed solution is presented in Section 3. Finally, Section 4 summarizes conclusion and future works.

2 | BACKGROUNDS

2.1 Connected and autonomous electric vehicles

Connected and Autonomous Electric Vehicles (CAEVs) are essentially EVs that are capable of sensing their environment and navigating with little or no human intervention as well as can communicate with nearby vehicles, and infrastructure including road side units (RSUs). CAEVs definitely transform existing mobility paradigm. It can be observed that technological advancements in driving assistants and network connectivity yield further opportunities and services and meet the sustainable development for cleaner, safer, and smarter mobility.

CAEVs can sense their environment using various sensing devices including Radar, LiDAR (Light Detection and Ranging), image sensors, and 3D camera etc. They have communication modules that are capable of vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), or vehicle-to-anything (V2X). A storage battery system including an on-board charger and battery packs is encompassed in the CAEV that can be one of the crucial components for their widespread deployment. CAEVs have various levels of vehicle automation defined by Society of Automotive Engineers (SAE) as follows: Level 0 - no automation; Level 1 - driver assistance; Level 2 - partial automation; Level 3 - conditional automation; Level 4 - high automation; and Level 5 - full automation.

CAEVs offer many potential advantages in terms of sustainable development for environment-friendly urban mobility, which are as follows: improved safety; greater mobility; reduced parking lots; relaxed drivers; increased car-sharing; increased road capacity; fewer CO₂ emissions and pollutants; less fuel costs.

2.2 Wireless charging: static vs dynamic

Currently, wired charging of EVs are used, however, in future, wireless solution will be prevailing method of charging CAEVs. Wireless EV charging, which is based on IPT technology, has several desirable features, for instance, charging process is simple and automatic (ie, no human input), and no exposed electric connections. With the adoption of CAEVs, wireless charging will become an essential component of the electro-mobility (e-mobility) in the future.

Mainly, there are two types of IPT for the wireless charging. Static IPT is deployed when the vehicle is spotted in a parking lot; and dynamic IPT is deployed when the vehicle is on move. In the static wireless charging (SWC) system, CAEVs shall wirelessly communicate with the base controller of the wireless charging station for recharging process. While, in DWC system, charging pads (CPs) are placed under a portion of the roadbed and the CAEV’s battery is charged wirelessly while the CAEV is being driven over the CPs. As DWC systems enable the moving CAEVs to charge their batteries using magnetic IPT technology, such a technology can be referred as “Roadway IPT.” The investigations given in the paper demonstrate that the efficiency of the power transfer in DWC systems can be more than 80%. Figure 1 depicts the deployment of DWC system. In order to achieve such a system, the CAEVs need to communicate with various entities of the system such as a charging service provider (CSP), road side units (RSUs), and CPs. Each charging lane shall have a large number of CPs extended over a long distance (several miles) to allow the CAEVs to acquire enough amount of power while traveling within this distance.
3 | URBAN CAEV TAXI FLEET MANAGEMENT

A CAEV taxi fleet management system is presented in this section. The system consists of following key components: CAEV Back-end system, Charging facility operators (CFOs), CAEV taxi fleet and Rider mobile applications. Figure 2 depicts a high level diagram of CAEV taxi fleet management.

A CAEV Back-end system, which incorporates taxi dispatching module and charging management module, is the main component of the CAEV taxi fleet management. A rider shall send a CAEV taxi service request using a mobile application to the CAEV Back-end system that operates within a certain geographical region. The taxi service request shall include at least a pickup location, pickup time, and a drop-off location. Upon receiving rider requests, the CAEV Back-end system uses taxi dispatching mechanism along with DWC charging. It also uses relevant data from the IoT (Internet of Things) platform in order to assign a CAEV taxi to the given rider request. Then CAEV Back-end system provides appropriate information on pick-up/drop-off to the relevant CAEV taxi as well as CAEV taxi information to the rider.

Assuming that DWC-enabled infrastructure in the urban areas is deployed by public authorities (i.e., municipality, local government) in partnership with the Charging facility operators (CFOs), several dedicated roads, such as lanes in highways and multi-lane roads, have Roadway IPTs such that CFOs can provide Roadway IPT charging to the authorized CAEVs. CAEVs can be undoubtedly usher in a new era for transportation, especially urban taxi services but the automotive industry still needs to overcome some challenges before autonomous taxi fleet becomes practical.

Limited driving range, and longer recharge time are basic issues and challenges in the deployment of CAEV taxi fleets. This problem will yield to the range anxiety. Furthermore, due to the sparse DWC-enabled infrastructure in the urban areas, the charging for CAEV taxi using Roadway IPT charging plan will be challenging. Thus a comprehensive solution for proper CAEV taxi fleet management is required.

3.1 | Proposed solution

In this subsection, we explore two aspects - dispatching strategy for urban CAEV taxi fleet and DWC plan. Efficient taxi dispatching shall minimize a rider waiting time, whereas, effective DWC plan shall reduce a detour time, in turn, minimize an arrival delay. Thus, it is to find out effects on overall travel time while using CAEV taxi fleet. The system utilizes Google Map API that gives the travel time needed between two locations, for instance, source to destination with respect to the shortest path. Table 1 shows notations used in the proposed mechanism.

Mainly, two constraints are taken into consideration in the proposed mechanism, which are as follows.

- Detour constraint is the additional time taken for the detour in order to perform dynamic wireless EV charging in compared with the shortest trip route. That means, this constraint prevents the system from assigning unreasonable trip plan which takes longer detour and causes unacceptable arrival delay.
TABLE 1 Notations used in the proposed mechanism

| Symbol       | Description                                                                 |
|--------------|-----------------------------------------------------------------------------|
| $\text{SoC}_{\text{cur}}$, $\text{SoC}_{\text{lo}}$ | current SoC level & lower limit of SoC level respectively                   |
| $\text{SoC}_{\text{fin}}$   | estimated SoC level at the drop-off location                               |
| $t_{\text{wa}}, t_{\text{d}}, t_{\text{pu}}$ | waiting time for rider, detour time & estimated pickup time respectively   |
| $\tau_{\text{sp}}, \tau_{\text{dp}}$ | time taken for shortest path and for detoured path routes respectively      |
| $L_{\text{pu}}$ | pickup location                                                            |
| $\delta_{\text{pd}}, \delta_{\text{cp}}$ | travel distance from pickup to drop-off locations and from current to pickup locations respectively |

- Energy constraint describes the electricity consumption of CAEVs in the service process and enforces the battery capacity limits. This constraint determines whether the designated CAEV can reach the destination location with given SoC level.

Most commonly used taxi dispatching strategy is Nearest-idle-taxi, in which the nearest available taxi is dispatched to the first request in the queue. Thus, the system shall not only utilize Nearest-idle-taxi strategy but also check if a SoC level of a CAEV is sufficient to serve a designated trip. That means, the system shall check the reachability to the drop-off location from the current location. Due to the fact that CAEVs have relatively short driving range, the proposed solution shall allow routes with detour for DWC using Roadway IPT. Hence, the system shall not only check the SoC level for reachability analysis but also verify if the detour ratio is within the maximum allowed value and find the shortest route with detour for DWC plan. Figure 3 depicts a flow chart of the taxi dispatching mechanism along with DWC plan. In order to conduct the reachability analysis, the system requires to determine $\text{SoC}_{\text{fin}}$. For the sake of simplicity, $\text{SoC}_{\text{fin}}$ can be computed as follows:

$$\text{SoC}_{\text{fin}} = \text{SoC}_{\text{cur}} - \frac{(\delta_{\text{pd}} + \delta_{\text{cp}}) \times \zeta}{Q}$$

(1)

where $\zeta$ represents the power consumption per km (kWh/km); $Q$ represents the battery’s rated capacity (kWh).

Due to the sparse DWC capable infrastructure, Roadway IPT charging may increase detour distance. Since the delay caused by detour is one of major concerns of Roadway IPT charging, it is desired that the system ought to assign a reasonable trip plan which minimizes detour distance. In this regard, we have considered a detour ratio, which is defined as the ratio of the distance of the direct route and a detour distance (extra distance due to Roadway IPT charging plan). The detour ratio, $\rho_{\text{sd}}$, can be computed as

$$\rho_{\text{sd}} = \frac{\tau_{\text{sp}}}{\tau_{\text{dp}}}$$

(2)

As $\rho_{\text{sd}}$ measures the relative delay due to Roadway IPT charging plan, controlling $\rho_{\text{sd}}$ may prevent unacceptable arrival delays. Traveling for Roadway IPT charging plan shall be restricted such that $\rho_{\text{sd}}$ does not exceed its maximum allowed value $\Delta$. This means, $\rho_{\text{ad}}$ can be considered as the service quality parameter, which aims at preserving the comfort of the riders.
For the evaluation purpose, we have considered two strategies - a primal strategy and proposed one. In the primal strategy, the system shall use Nearest-idle-taxi as taxi dispatching strategy as well as check if a SoC level of a CAEV is sufficient to serve a designated trip. However, it does not consider the Roadway IPT charging plan. In case, if current SoC levels of CAEVs are insignificant, then they may fail to qualify reachability analysis, thus those CAEVs may be eliminated during taxi dispatching process. That means, the waiting time for the riders may drastically increase. We evaluate the proposed strategy compared to the primal strategy in terms of average waiting time $t_{wa}$ which can be stated as the time difference between the rider request time and the pick-up time.

For the preliminary evaluation, it is assumed that a number of available CAEV taxis, $N$, is 50 and a number of rider’s trip requests, $R$, varies from 25 to 200 such that a ratio $\Phi = \frac{N}{R}$ can be determined. We have considered two scenarios. In the first scenario, it is assumed that CAEV taxis have maintained SoC$_{cur}$ such that they can serve any trips requested by the riders. Whereas, in the second scenario, it is assumed that SoC$_{cur}$ of CAEV taxis are not uniform. Assuming about half of the CAEV taxis have SoC$_{cur}$ lower than 40%. Thus, they would not be able to serve all the rider trip requests with their SoC$_{cur}$.

Figure 4A shows average waiting time with respect to $\Phi$ in the first scenario. In both case, the trend is linear and decreases along with increase in $\Phi$. When the ratio $\Phi$ is high, the rider waiting time is low. In case there are more CAEV taxis than riders and then there are many offers, the probability to find a ride quickly becomes high. Figure 4B shows average waiting time with respect to $\Phi$ in the second scenario. In the primal strategy, waiting time drastically increases along with decrease in $\Phi$, whereas in the proposed one, it increases gradually. The difference in the waiting time is significant with $\Phi$ lower than 0.4.
4 | CONCLUSION AND FUTURE WORKS

It can be observed that DWC may help to alleviate range anxiety. However, due to the sparse DWC capable infrastructure, roadway IPT charging may increase arrival delay. In this paper, we have presented a DWC system for CAEV taxi fleets and proposed an efficient dispatching strategy with roadway IPT charging plan. The main objectives were to minimize a rider waiting time as well as to reduce a detour time and curtail an arrival delay. When the proposed strategy was compared with the primal strategy, the former outperformed the latter one. The preliminary results exhibited that even when remaining energy in CAEV taxis was low, the proposed strategy could use roadway IPT charging plan to boost the energy in those CAEV taxis. In future, we shall conduct more investigations on the impact of DWC-enabled infrastructure in urban settings including the impact of detour on the riders, and the user satisfaction on DWC-enabled dispatching mechanism.

ACKNOWLEDGMENTS

This research work is supported by Smart Grid Fund (SGF), Ministry of Energy, The Ontario Government and Canada Research Chair (CRC) Fund, Canada.

ORCID

Binod Vaidya https://orcid.org/0000-0002-7851-6897

REFERENCES

1. Zhu M, Liu XY, Tang F, et al. Public vehicles for future urban transportation. IEEE Trans Intell Transp Syst. 2016;17(2):3344-3353.
2. Lu JL, Yeh MY, Hsu YC, Yang SN, Gan CH, Chen MS. Operating electric taxi fleets: A new dispatching strategy with charging plans. Paper presented at: 2012 IEEE International Electric Vehicle Conference (IEVC); March 4-8, 2012; Greenville, SC.
3. Al Ridhawi I, Aloqaily M, Kantarci B, Jaraheh Y, Mouftah HT. A continuous diversified vehicular cloud service availability framework for smart cities. Comput Netw. 2018;145:207-218.
4. Alkheir AA, Aloqaily M, Mouftah HT. Connected and autonomous electric vehicles (CAEVs). IT Prof. 2018;20:54-61.
5. Bagloee SA, Tavana M, Asadi M, Oliver T. Autonomous vehicles: challenges, opportunities, and future implications for transportation policies. J Mod Transp. 2016;24(4):284-303.
6. Horl S. Agent-based simulation of autonomous taxi services with dynamic demand responses. Procedia Comput Sci. 2017;109:899-904.
7. Ahmad A, Alam MS, Chabaan R. A comprehensive review of wireless charging technologies for electric vehicles. IEEE T Transp Electr. 2018;4(1):38-63.
8. Manshadi SD, Khodayar ME, Abdelghany K, Uster H. Wireless charging of electric vehicles in electricity and transportation networks. IEEE T Smart Grid. 2018;9(5):4503-4512.
9. Garcia-Vazquez CA, Llorens-Iborra F, Fernandez-Ramirez LM, Sanchez-Sainz H, Jurado F. Comparative study of dynamic wireless charging of electric vehicles in motorway, highway and urban stretches. Energy. 2017;137:42-57.
10. Hyland M, Mahmassani HS. Dynamic autonomous vehicle fleet operations: optimization-based strategies to assign AVs to immediate traveler demand requests. Transp Res Part C Emerg Technol. 2018;92:278-297.
11. Lokhandwalaa M, Cai H. Dynamic ride sharing using traditional taxis and shared autonomous taxis: a case study of NYC. Transp Res Part C Emerg Technol. 2018;97:45-60.
12. Chen TD, Kockelman KM, Hanna JP. Operations of a shared, autonomous, electric vehicle fleet: implications of vehicle & charging infrastructure decisions. Transp Res A. 2016;94:243-254.
13. Foote A, Onar OC, Debnath S, Pries J, Galigekere VP, Ozpineci B. System design of dynamic wireless power transfer for automated highways. Paper presented at: IEEE Transportation Electrification Conference and Expo (ITEC 2019); June 19-21, 2019; Novi, MI.
14. Zaheer A, Neath M, Beh HZ, Covic GA. A dynamic EV charging system for slow moving traffic applications. IEEE T Transp Electr. 2017;3(2):354-369.
15. Hwang I, Jang YJ, Ko YD, Lee MS. System optimization for dynamic wireless charging electric vehicles operating in a multiple-route environment. IEEE T Intell Transp Syst. 2018;2(6):1709-1726.
16. Kosmanos D, Maglaras LA, Mavrovouniotis M, et al. Route optimization of electric vehicles based on dynamic wireless charging. IEEE Access. 2018;6:42551-42565.
17. Doan VD, Fujimoto H, Koseki T, Yasuda T, Kishi H, Fujita T. Allocation of wireless power transfer system from viewpoint of optimal control problem for autonomous driving electric vehicles. IEEE T Intell Transp Syst. 2018;19(10):3255-3270.
18. Vaidya B, Mouftah HT. IoT applications and services for connected and autonomous electric vehicles. Arab J Sci Eng. 2019. https://doi.org/10.1007/s13369-019-04216-8.

How to cite this article: Vaidya B, Mouftah HT. Dynamic wireless charging for CAEV taxi fleet in urban environment. Internet Technology Letters. 2020;3:e153. https://doi.org/10.1002/itl2.153