International Journal of Transportation Science and Technology xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

International Journal of Transportation Science and Technology

journal homepage: www.elsevier.com/locate/ijtst

A complementarity equilibrium model for electric vehicles with charging

Sina Bahrami [a,*], Hedayat Z. Aashtiani [b], Mehdi Nourinejad [a], Matthew J. Roorda [a]

[a] *Department of Civil Engineering, University of Toronto, 35 St. George Street, Toronto, ON M5S 1A4, Canada*
[b] *Department of Civil Engineering, Sharif University of Technology, Tehran, Iran*

A R T I C L E   I N F O

Article history:
Received 14 February 2017
Received in revised form 18 April 2017
Accepted 5 May 2017
Available online xxxx

Keywords:
Shortest path
Label correcting
Electric vehicles
Charging stations

A B S T R A C T

This paper presents a complementarity equilibrium model for electric vehicles (EVs). Under the equilibrium conditions, each EV takes the path that is shortest and does not violate the driving range. When the driving range has to be violated, the EVs are allowed to choose a path with a charging station to extend their driving range. To find the shortest such path, a constrained shortest path problem with replenishment (CSPP with replenishment) is formulated that considers the driving range limit of EVs. The CSPP is solved with a label-correcting algorithm with two additional steps that substantially reduce the computation time and the required memory. The first procedure is a pruning technique that eliminates exploring branches (of an enumeration tree) that can no longer become incumbent and the second procedure is an indexing technique that works as a pointer for navigating the generated (enumeration) tree when it becomes too large. Numerical experiments on a number of networks show a substantially lower computation time compared to existing algorithms and the results provide several insights into the driving patterns of EVs. When charging time is increased, the EVs shift to paths that have a longer travel time but a shorter distance. Hence, the total network distance decreases but the total network travel time increases. We also show that unregulated expansion of the charging infrastructure can actually increase the total network travel time due to the presence of Braess' paradox.

Introduction

Electric vehicles (EV) are now a popular form of transportation due to their energy efficiency (Romm, 2006), lower emissions (Samaras and Meisterling, 2008), and the provision of government support through incentive programs (Nie et al., 2016). Despite their many benefits, EVs have a limited driving range because of their finite battery capacity. To make EVs more convenient for long-distance inter-city trips and reduce the range-anxiety of drivers, many EV companies and governments (local and provincial) are overcoming the driving range by deploying charging stations at select locations. Among the different charging technologies, Type III DC chargers and battery swap stations are particularly desirable because they are fast. For instance, a Type III DC charger with a charging power of up to 90 kW can charge a vehicle to its full battery capacity

Peer review under responsibility of Tongji University and Tongji University Press.
* Corresponding author.
E-mail addresses: sina.bahrami@mail.utoronto.ca (S. Bahrami), ashtiani@sharif.edu (H.Z. Aashtiani), mehdi.nourinejad@mail.utoronto.ca (M. Nourinejad), roordam@ecf.utoronto.ca (M.J. Roorda).

http://dx.doi.org/10.1016/j.ijtst.2017.05.007
2046-0430/

in less than 30 min. Despite the popularity of EVs, the wide-scale deployment of these chargers is hindered because of their cost which can be as high as $100,000–$500,000 USD for each Type III DC charger. High costs and finite budgets limit the number of charging stations that can be deployed. Hence, it is critical to choose the optimal location of fast chargers in inter-city networks to both increase the coverage and decrease travel time of EVs.

Whereas substantial research is dedicated to finding the optimal location of charging infrastructure (Mak et al., 2013; He et al., 2013; Sathaye and Kelley, 2013; Ghamami et al., 2014; Gnann and Plötz, 2015; Jung et al., 2014; Nourinejad et al., 2016), fewer studies consider explicitly the role of charging infrastructure on how EVs choose their paths to avoid violating the driving range. According to Wardrop's principle, EVs choose their path such that no driver can deviate to another admissible path (that does not violate the driving range) with a lower cost. This eventually leads to an equilibrium for EVs that was first proposed by Jiang et al. (2012) and Jiang and Xie (2014) as a path-constrained traffic assignment model and later extended by He et al. (2014). The model of He et al. (2014) is a natural extension of user equilibrium for EVs and provides a meaningful level of detail in EV driving patterns by considering the charging time and the path choice of drivers. Nevertheless, the use of an integer linear program for solving the shortest path problem in the equilibrium model is overwhelmingly time-consuming for real-size networks and can limit the potential application of the model.

This paper presents a complementarity equilibrium model of EVs in large networks. Under equilibrium conditions, each EV takes the path that is shortest and does not violate the driving range. The EVs are allowed to choose a path with a charging station to extend their driving range. To find the shortest path, a constrained shortest path problem (CSPP) is formulated that considers the driving range limit of EVs. A solution algorithm is proposed for the CSPP and two procedures are proposed that significantly reduce the computation time and memory for solving the CSPP. The first procedure is to prune the generated shortest path tree to eliminate exploring branches that can no longer become incumbent and the second procedure is an indexing technique that works as a pointer for navigating the generated tree when it becomes too large. The computation time is further reduced by solving the CSPP in a one-to-many format by finding the shortest path from one origin to all other destinations.

The remainder of this paper is organized as follows. Section "Literature review" presents the relevant litersdature. Section "A one-to-many distance constrained shortest path model and algorithm" presents the CSPP algorithm. Section "A complementarity traffic assignment model with distance constrained shortest path" presents the complementarity equilibrium model and algorithm. Section "Numerical experiments" presents a set of numerical experiments. Section "Conclusion" presents the conclusions of this study.

Literature review

This section reviews the literature on the CSPP and the EV traffic equilibrium problem.

The constrained shortest path problem

The shortest path problem is to find the path between two nodes of a network such that the sum of the costs of its constituent links is minimized (Dreyfus, 1969; Ahuja et al., 1990). A variant of the shortest path problem is the constrained shortest path problem (CSPP) where each link of the network has a specified cost and distance[1]. The objective of the CSPP is to find the shortest (i.e. smallest cost) path such that the sum of the distances of the links of that path does not exceed a given limit (also known as budget). In the context of EVs, distance refers to the energy consumption of each link and budget refers to the battery capacity of the vehicle. An extension of the CSPP is the CSPP with replenishment where the vehicles can recharge and increase their remaining driving range.

The CSPP can be solved using the one-to-one or the one-to-many algorithms. The one-to-one algorithms find the shortest path from one origin to one destination whereas the one-to-many algorithms find the shortest path from one origin to all destinations. Although the CSPP has been solved using one-to-one solution algorithms (Handler and Zang, 1980; Beasley and Christofides, 1989; Mehlhorn and Ziegelmann, 2000), to the best of our knowledge, the CSPP with the one-to-many configuration is rarely addressed. Developing such a solution algorithm is particularly important in the traffic assignment problem with path constraints where the CSPP has to be solved many times. Consequently, using one-to-many CSPP, we can apply a decomposition by origin when solving the complementarity traffic assignment problem (Aashtiani and Magnanti, 1983). Given the very limited literature on the one-to-many configuration, we focus here on the one-to-one algorithms. Furthermore, given that we present an exact CSPP algorithm, we review only the studies on exact methods of solving the CSPP.

The CSPP is NP-complete due to the addition of the budget constraint (Carlyle et al., 2008). The exact one-to-one solution algorithms that solve the CSPP can be divided into the k-shortest path method (Handler and Zang, 1980; Santos et al., 2007), the Lagrangian relaxation method (Mehlhorn and Ziegelmann, 2000), and the node-labeling method derived from dynamic programming (Carlyle et al., 2008).

In the k-shortest path method for the CSPP, a set of k shortest paths between two nodes are found and the paths are sorted in descending order of cost. The paths are then consecutively checked from the top and the first path that justifies the budget

[1] The term "resource" has been used instead of the term "distance" in some studies.