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Path-constrained traffic assignment: A trip chain analysis under range anxiety

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ABSTRACT

This paper proposes and analyzes a distance-constrained traffic assignment problem with trip chains embedded in equilibrium network flows. The purpose of studying this problem is to develop an appropriate modeling tool for characterizing traffic flow patterns in emerging transportation networks that serve a massive adoption of plug-in electric vehicles. This need arises from the facts that electric vehicles suffer from the "range anxiety" issue caused by the unavailability or insufficiency of public electricity-charging infrastructures and the far-below-expectation battery capacity. It is suggested that if range anxiety makes any impact on travel behaviors, it more likely occurs on the trip chain level rather than the trip level, where a trip chain here is defined as a series of trips between two possible charging opportunities (Tamor et al., 2013). The focus of this paper is thus given to the development of the modeling and solution methods for the proposed traffic assignment problem. In this modeling paradigm, given that trip chains are the basic modeling unit for individual decision making, any traveler's combined travel route and activity location choices under the distance limit results in a distance-constrained, node-sequenced shortest path problem. A cascading labeling algorithm is developed for this shortest path problem and embedded into a linear approximation framework for equilibrium network solutions. The numerical result derived from an illustrative example clearly shows the mechanism and magnitude of the distance limit and trip chain settings in reshaping network flows from the simple case characterized merely by user equilibrium.

1. Introduction

Electric vehicles offer an evidently promising approach to reducing greenhouse emissions and air pollution, mitigating risks associated with the shortage of fossil fuels, and utilizing excess energy from various renewable sources. The recent decade observes a fast penetration of electric vehicles of different technologies in many cities and regions worldwide. Despite the anticipated environmental and economic benefits to both individual drivers and the society, however, a massive adoption of electric vehicles is still an ambitious goal that may not be achieved in a short period. It is generally believed that the

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major barriers to wide acceptance and use of electric vehicles, especially battery electric vehicles, are the unavailability or insufficiency of public electricity-charging stations (Marrow et al., 2008; Dong et al., 2014) and limited driving ranges due to the current electricity charging and storage technologies (Pearre et al., 2011). As circulated in the general public, these factors poses the well-known *range anxiety* issue: The mental distress or fear of being stranded on roads because the battery runs out of charge.

How to incorporate range anxiety into the conventional travel demand modeling and transportation planning processes poses a series of interesting research questions. As an initial attempt, Jiang et al. (2012, 2014) and Jiang and Xie (2014) studied distance-constrained traffic assignment problems for predicting traffic network flows when a large number of plug-in electric vehicles prevail in congested networks while suffering from range anxiety. These researchers assumed that the distance constraint caused by range anxiety sets a restriction on trips and accordingly developed a set of trip-based models. However, most electric vehicles in the current market are of a driving range of 60 miles or higher if their onboard batteries are fully charged (Borden and Boske, 2013; NREL, 2015). Even if the batteries are not fully charged, the effective driving range is often well beyond the distance of a typical commuting trip or a trip of other purposes. Obviously, electric vehicle drivers typically consider the range anxiety concern (Tamor et al., 2013), if they do, more probably on the trip chain level than the trip level, since in most cases they have more charging opportunities at the destinations of their tours, such as home or workplace, rather than at some intermediate parking places. In other words, what these drivers are really concerned about is whether the electricity in the batteries is sufficient for completing an entire home-based or workplace-based tour.

Following such a behavioral speculation, we present in this paper a distance-constrained traffic assignment problem that incorporates trip chains, as a more realistic modeling tool to the ones proposed by Jiang et al. (2012, 2014). It is more reasonable to assume that the distance constraint caused by range anxiety enforces a restriction on the length of an entire trip chain than that of a single trip (Tamor et al., 2013). In the former case, individual travelers face a series of choices on activity sites and travel routes subject to the distance limit. Travelers visit one or more activity sites along a trip chain to satisfy a variety of predetermined socioeconomic purposes, such as shopping, dining, entertainment, education, religious activities, and so on.

For modeling convenience and solution tractability, we make the following modeling assumptions in this paper: (1) as similar to Jiang et al. (2012, 2014), a common distance limit is applied to the entire network or all electric vehicles in the population, which implies the battery capacity of all electric vehicles and the electricity consumption rate of these vehicles on roadways are constant; (2) the types of activity sites and the *order or sequence of activities* along a trip chain are exogenously given, although visiting which location in each type of activity sites is a decision making under equilibrium in the model; (3) activity disutility is simply modeled as a function of activity flow, while other explanatory factors are assumed to be exogenously determined and appear as fixed coefficients in our model; (4) activity and travel dynamics and time constraints on them are ignored. When needed, the first assumption can be readily relaxed, so as to take into account the heterogeneity of actual and perceived distance limits in the driving population. The second assumption can be eliminated as well, to accommodate a more general case, so that the types of activity sites and their orders along trip chains are endogenously determined. Either of the relaxations, however, will significantly increase the modeling and solution complexity. As for the last two assumptions, they are made here just for simplicity, which leads to a model as simple as what we introduce below. Moreover, in addition to the distance limit and trip chain settings, we also require network flow patterns to be still characterized by the classic Wardropian equilibrium principle (1952), under which all used trip chains connecting an origin–destination pair are of the same combined activity-travel disutility and no individual traveler can improve his or her combined disutility by unilaterally switching to any alternative activity site or alternative travel path. To this end, the major contribution of this paper is on the development and evaluation of modeling and solution methods for the proposed distance-constrained, trip chain-based traffic assignment problem.

The remaining part of this paper is organized as follows. The relevant literature is reviewed in the next section, including traffic assignment problems with trip chains, traffic assignment problems with combined choices, and traffic assignment problems with path constraints. Then we discuss the equilibrium conditions, problem formulation and equivalency and uniqueness of this formulation. A linear approximation algorithm is adopted for problem solutions, in which a newly developed cascading labeling algorithm is embedded for solving the linearized subproblem—a distance-constrained, node-sequenced shortest path problem. To our best knowledge, this algorithm has not appeared previously in the literature. We then present and analyze the numerical results from applying the solution algorithm for an illustrative problem. Finally, we conclude this paper with highlighting a few modeling and solution comments and some suggestions for future research, such as the relaxation of activity sequences and introduction of stochastic distance limits.

2. Relevant research

As we claimed earlier, this paper focuses on the development of a mathematical programming model and method for the proposed traffic assignment problem that encapsulates trip chains and distance limits. The combination of these extra modeling elements invites a greater deal of modeling complexity than the basic traffic assignment problem such as the one defined by Beckmann et al. (1956). Various forms of traffic assignment problems have been studied since the birth of the basic traffic assignment model. In many of these problems, extra constraints imposed on nodes, links, paths, or origin–destination pairs to restrict traffic flows were considered, which pose the so-called traffic assignment problems with