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Path-constrained traffic assignment: Modeling and computing network impacts of stochastic range anxiety☆

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A B S T R A C T

It is notoriously known that range anxiety is one of the major barriers that hinder a wide adoption of plug-in electric vehicles, especially battery electric vehicles. Recent studies suggested that if the caused driving range limit makes any impact on travel behaviors, it more likely occurs on the tour or trip chain level than the trip level. To properly assess its impacts on travel choices and traffic congestion, this research is devoted to studying a new network equilibrium problem that implies activity location and travel path choices on the trip chain level subject to stochastic driving ranges. Convex optimization and variational inequality models are respectively constructed for characterizing the equilibrium conditions under both discretely and continuously distributed driving ranges. For deriving the equilibrium flow solutions for these problem cases, we suggested different adaptations of a well-known path-based algorithm—the projected gradient method.

While the problem instance with a discrete number of driving ranges can be simply treated as a multi-class version of its deterministic counterpart, the one with continuous driving ranges poses a much more complicated situation. To overcome this arising modeling and algorithmic complication, we introduce a couple of newly defined variables, namely, *path-indexed travel subdemand rate* and *traffic subflow rate*, by which the demand and flow rates as well as their corresponding feasible path sets can be *dynamically indexed* in the solution process with reference to path lengths. An illustrative example with various types and forms of driving range distributions demonstrates the applicability of the proposed modeling and solution methods and various impacts of the heterogeneity of range anxiety on network flows and computational costs. The numerical analysis results from this example show that stochastic driving ranges confine network flows in a different way from deterministic or no driving ranges and the projected gradient procedure relying on dynamically indexed subdemand and subflow rates is generally preferable to its counterpart on pre-indexed ones for both the discrete and continuous driving range cases.

1. Introduction

Range anxiety associated with those who drive plug-in electric vehicles, especially battery electric vehicles, is often referred to as their mental distress or fear of being stranded on roads because the battery runs out of charge (Marrow et al., 2008; Mock et al., 2010; Franke and Krems, 2013). This term first appeared in the press in 1997, in a San Diego Business Journal article authored by Acello (1997), who described his worry on the driving range of an example electric vehicle model

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produced by General Motors. Range anxiety has quickly become a popular topic in the public media in the first decade of the 21st century (Schott, 2009; Rahim, 2010; Malone, 2010; Eberle and von Helmolt, 2010),[1] with a climbing sales number of electric vehicles worldwide around that time. As a follow-up of this widespread concern, General Motors soon filed the term of range anxiety as a trademark, stating it was for the purpose of "promoting public awareness of electric vehicle capabilities" (Hyde, 2010).

Range anxiety is actually a common issue that harasses people's trip making and choice behaviors in driving any kind of vehicles when refueling opportunities are scarce (Xie and Jiang, 2016). For electric vehicles, the main technical reasons behind range anxiety are inadequate battery performance and capacity and insufficient public electricity-charging providers (Pearre et al., 2011; Neubauer and Wood, 2014). Even if the battery storage and charging technologies have experienced continuous, significant progress and the number of newly constructed public charging stations climbed at an increasing rate in the past decade, range anxiety is still one of the major concerns and barriers nowadays that impede the wide acceptance and adoption electric vehicles (Kassakian, 2013). Many automobile manufacturers and transportation economists predicted that the range anxiety phenomenon will last and concern the driving community for quite a long time, continuously affecting their travel behaviors, commuting customs and even daily schedules, unless a real breakthrough of relevant electricity storage and charging technologies occurs and the price, stability and durability of onboard batteries reaches a commercially satisfactory level.

Range anxiety imposes negligible impacts on the scope and flexibility of trip makings, spatially and temporarily restricting travel choices as well as productivity and life choices in different ways and levels. The aggregate U.S. driving distance distribution data provided by Tamor et al. (2013) on the trip chain level clearly shows that a significant amount of travel demand cannot be satisfied by any electric vehicle model in the current consumer-grade market, due to their insufficient driving ranges even under a full charge. The resulting range anxiety inevitably excludes the possibility of using electric vehicles for those long-distance trips or tours, or forces travelers to seek a multimodal travel solution and consider other travel choice alternatives. Beyond the travel distance supported by a single charge, range anxiety also impacts the total vehicles mile traveled by the entire driving population in a region or country, if a significant number of electric vehicles are injected into the market (Neuhauer and Wood, 2014).

To properly reflect these impacts in travel demand forecasting, Jiang et al. (2012, 2013) and Jiang and Xie (2014) first introduced range anxiety, as represented by the maximum driving distance or driving distance limit, into travel choice and network assignment problems. These authors presented a series of network equilibrium models involving spatially constrained travel choices by range anxiety, including destination choice, mode choice and route choice. This modeling concept was further extended by He et al. (2014) and Xie and Jiang (2016) to embrace the recharging requirement of electric vehicles for long-haul trips in congested networks. In all these mentioned studies, researchers hold a rather strict modeling assumption that all drivers in a traffic network are of the same driving distance limit.

This simple assumption seems to be largely deviated from the reality. What actually impacts individual travel behaviors is actually the estimated or perceived driving ranges by electric vehicle drivers. Given that this is the result of drivers' subjective perceptions and judgment on the actual driving range, it is much more reasonable to conjecture that the range anxiety within a driving population could be better represented by a stochastic distance limit, which consists of a diverse number of heterogeneous values instead of a single common value. The diversity is a reflection of multiple explanatory factors, including not only nominal battery capacity, initial state of charge, electricity consumption rate, driving environment and conditions and other physical factors, but also range gauge mechanisms and the drivers' cognitive, understanding, appraisal, coping, adapting, stress-buffering and risk-taking behaviors (e.g., the well-known "guess-o-meter" confusion on the dashboard reading). Psychological theory suggests that physically identical situations may constitute a fundamentally different psychological and decision making situation for different individuals (Bowers, 1973). A recent psychology experiment by Franke et al. (2012) revealed that the range anxiety with electric vehicle drivers is primarily quantified by their self-perceived *comfortable driving ranges*, for which personal stress-buffering competence and coping skills play a substantial role. As a result, the aggregate data of their experiment, collected from 40 participants driving electric vehicles for 6 months, showcased a large diversity in perceived driving ranges across the surveyed population.

Perceived driving ranges are often lower than what we expect or estimate. As an illustration, the distributional pattern of perceived driving ranges and its derivation process are given in Fig. 1. Note that in this figure the nominal, actual and perceived driving ranges are all represented by discrete distributions, which are the direct results sampled from a limited number of vehicles and drivers. This diagram shows that, for any rational electric vehicle driver, to make himself or herself feel "comfortable" or "not anxious", his or her perceived driving range is typically set lower than the actual driving range his or her vehicle can make, and in turn lower than the nominal driving range of his or her vehicle. Moreover, the distribution of perceived driving ranges tends to exhibit a more scattered or decentralized pattern, compared to actual and nominal driving ranges, since it is the interactive result from multiple stochastic physical and psychological factors.

To assess the impact of range anxiety on individual activity-travel choices and network equilibria, we consider for each driver a specific perceived driving range as the upper bound imposed on the driving distance he or she can drive farthest and assume that no driver would choose a path with its physical length greater than this bound. The aggregation of individual upper bounds over the driving population poses a probability distribution, as shown as the leftmost distribution

[1] For a comprehensive review on the range anxiety issue and its measure and mitigation strategies, interested readers may refer to Nilsson (2011).