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A framework for evaluating the role of electric vehicles in transportation network infrastructure under travel demand variability

Lauren M. Gardner [a,*], Melissa Duell [b], S. Travis Waller [c]

[a] CE 112, School of Civil and Environmental Engineering, The University of New South Wales and NICTA, Sydney, NSW 2052, Australia
[b] CE 113, School of Civil and Environmental Engineering, The University of New South Wales and NICTA, Sydney, NSW 2052, Australia
[c] CE 110, School of Civil and Environmental Engineering, The University of New South Wales and NICTA, Sydney, NSW 2052, Australia

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ABSTRACT

The introduction of plug-in electric vehicles (PEVs) represents an unprecedented interaction between the road network and electricity grid. By replacing the traditional fuel source, petrol, with electricity, PEVs will increase the demand for electric power in a region and change emission profiles. Overall, the impacts depend on the eventual penetration of PEV ownership, but the true market share of PEVs in the future is highly unclear and radically different scenarios are possible. This added forecasting volatility makes long-term transport models that explicitly consider travel demand uncertainty even more critical. This work utilizes transport modeling tools in order to quantify the relationship between the travel patterns of PEV drivers and PEV energy consumption rates, as well as the corresponding environmental impact (measured by emissions savings relative to traditional internal combustion engine vehicles). Furthermore, this research explicitly addresses the relationship between long term travel demand uncertainty and system level energy consumption variability, an essential issue for regional energy providers and planners. Results and implications are discussed on both a small demonstration network and the Sioux Falls network.

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1. Introduction and motivation

Plug-in electric vehicles (PEVs) are a rapidly evolving technology that represents a potential partial solution to global concerns related to petroleum dependence, energy security, and human contribution to climate change, particularly from the transport sector. PEVs are therefore of interest to researchers, policy-makers, consumers, and industry alike – a fact that is reflected by the vast efforts taking place to support the development of these vehicles. In addition, the ongoing PEV-related projects span a wide spectrum of fields. This research places particular emphasis on an aspect of PEVs that is often less recognized than the aforementioned issues: their potential to more closely link our transportation and electric power systems.

PEVs represent an unprecedented interaction between the road infrastructure and electricity grid, creating the opportunity to combine the two traditionally disconnected networks. This will aid in the design of a smarter, safer system to meet the needs of users in the most effective way possible. Thus, research that explicitly considers the addition of PEVs into the traditional transport system as well as the broader impact across multiple systems will be vital to the successful integration of this transformative technology, and furthermore to ensuring that PEVs are utilized to their fullest potential.

* Corresponding author.
E-mail addresses: l.gardner@unsw.edu.au (L.M. Gardner), m.duell@unsw.edu.au (M. Duell), s.waller@unsw.edu.au (S.T. Waller).

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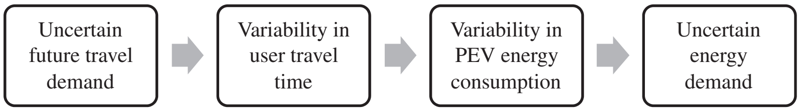

Fig. 1. Relationship between travel demand uncertainty and PEV energy consumption rates.

However, as of yet, relatively little work has been done in transportation modeling that explicitly accounts for the presence of PEVs. To address this growing domain, this work begins by providing a methodology for transport planners to quantifiably compare future transport network design scenarios with regards to both traditional transport goals and the impact on PEV drivers. In order to analyze different network designs, traffic assignment models were implemented to characterize vehicle travel patterns for a weekday peak period travel demand. The resulting travel patterns were used to quantify PEV energy consumption rates at the system level by aggregating consumption across all PEVs in the network during the period modeled. The amount of energy consumed by a single PEV during a trip is assumed to vary with travel speed, and is further detailed in Section 2.3. The availability of public charging infrastructure is not considered in this analysis.

As travel demand is inevitably stochastic in nature, this research explicitly addresses the relationship between long-term travel demand uncertainty (and correspondingly, uncertainty in varying PEV penetration levels) and variability in PEV energy consumption rates, an essential issue for regional energy providers. Additionally, the differences in PEV technology as compared with the energy consumption of traditional internal combustion engine vehicles (ICEVs) mean that energy consumption is a novel performance measure that needs to be considered by transport planners.

Provided travel demand is uncertain, traditional robust network designs are sought to maximize reliability of travel routes in terms of travel time. Analogously, travel routes that are reliable in terms of energy consumption are of importance to PEV drivers due to the limited range imposed by the electric battery capacity. However the impact of travel demand uncertainty on PEV energy consumption, and furthermore its potential role in both the transport and electric-power-grid system design process, is an issue that has not yet been addressed. In order to explore this point, this work quantifies the variability in PEV energy consumption resulting from uncertain travel demand. Under the same network conditions the environmental impact is also evaluated in terms of emissions.

Variability in PEV energy consumption has an impact at both the user level and the system level. Because PEV travel is constrained by the battery capacity and state of charge, range anxiety may result in PEV drivers preferring more reliable travel routes in terms of energy consumption to minimize the probability of getting stranded. At the system level the aggregation of highly variable individual PEV energy consumption patterns can result in significant variations in regional energy demand, making it difficult for electric-grid systems operators to allocate resources optimally. Therefore understanding the relationship between PEV energy consumption with regard to travel time variability (resulting from demand uncertainty) is a necessary first step in determining the spatiotemporal demand distribution. The basic relationship between travel demand variability and energy demand variability is summarized in Fig. 1.

In addition to the stated objectives this work seeks to answer the following questions:

1. How should traditional transport models accommodate the added presence of PEVs?
2. How should traditional power systems prepare for the added presence of PEVs?
3. What is the impact of travel demand uncertainty (in terms of total travel demand and PEV penetration levels) on PEV energy consumption?
4. How might transport network design differ when PEV energy consumption and energy variability are also accounted for?
5. How sub-optimal are the transport network designs when PEV energy consumption and energy variability are disregarded?
6. How can this sub-optimality be quantified?

The remainder of this work is organized as follows: Section 2 contains a literature review. Section 3 defines the problem properties and the modeling tools utilized in this work in detail. Section 4 presents the mathematical formulation of the problem and solution methodology. Section 5 further motivates the problem with a sample demonstration, and provides a case study of Sioux Falls to illustrate the behavior of system energy consumption under stochastic demand. Section 6 concludes the work with a brief review and discussion of future research.

2. Literature review

This research combines and applies previous transport modeling methodologies in a novel way that highlights several important aspects of PEVs. In particular, this work seeks to illustrate the impact of network-level travel patterns on PEV energy consumption levels. The research areas addressed in this work include static traffic assignment, demand uncertainty, travel time variability, electric vehicle technology, vehicle energy consumption and emissions rates, as well as electric power plant emissions rates. A complete literature review in just one of these fields is a daunting task of its own, and a comprehensive review is infeasible. Therefore the literature introduced in this section aims to provide the necessary background

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