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Minimum cost path problem for Plug-in Hybrid Electric Vehicles

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A B S T R A C T

We introduce a practically important and theoretically challenging problem: finding the minimum cost path for PHEVs in a road network with refueling and charging stations. We show that this problem is NP-complete and present a mixed integer quadratically constrained formulation, a discrete approximation dynamic programming heuristic, and a shortest path heuristic as solution methodologies. Practical applications of the problem in transportation and logistics, considering specifically the long-distance trips, are discussed in detail. Through extensive computational experiments, significant insights are provided. In addition to the charging infrastructure availability, a driver's stopping tolerance arises as another critical factor affecting the transportation costs.

1. Introduction

Electric transportation technology is an emerging challenge for the transportation sector and an opportunity in logistics operations from the environmental and cost perspectives. The interest in electric vehicles (EVs) and their variants such as Plug-in Hybrid Electric Vehicles (PHEVs) is on the rise due to the economic, environmental and security concerns associated with gasoline. A PHEV has an electric motor and an internal combustion engine (ICE) as its power sources. It provides reduction in both transportation costs and greenhouse gas emissions with respect to a comparable conventional vehicle (CV) (Windecker and Ruder, 2013). It has the capabilities of an EV such as charging from a regular power outlet and the convenience of a gasoline powered CV such as long-distance trips. PHEVs operate in either charge depleting (CD) mode or charge sustaining (CS) mode. On CD mode, the electric motor generates the required power and the PHEV uses its batteries as the energy supply. Once a minimum state-of-charge is reached, the PHEV switches to CS mode, and the power that propels the vehicle is mainly generated by the ICE using gasoline as the energy source. Thus, the difference between an EV and a PHEV is the CS mode drive flexibility of the latter (Pistoia, 2010; Axsen and Kurani, 2010; Axsen et al., 2008; Markel and Wipke, 2001; Traut et al., 2011; He et al., 2013). PHEVs can be refueled at regular gasoline stations similar to CVs, or can be charged en-route in charging stations similar to EVs (U.S. Department of Energy, 2008). As such, with its unique capabilities, PHEV technology stands as a major milestone in the road to 'electrification of the automobile' (Tate et al., 2008).

1.1. Motivation

In this paper, we introduce the minimum cost path problem for PHEVs (MCPP-PHEV). This problem is fundamental for long-distance PHEV trips that possibly require several refueling/charging stops. As one of the initial steps of

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renewable energy revolution in transportation, benefits and shortcomings of PHEVs for the urban (short distance) trips are well appreciated and investigated. However, as we review in the related literature below, the long-distance use of PHEVs is not well studied. From the economic and environmental perspectives, long-distance travel is certainly an important subject when the potential benefits of these vehicles are considered, and focusing solely on the short range usage would fail to achieve a complete treatment of the topic. According to the National Household Travel Survey by the U.S. Department of Transportation (2010), the trips by personally owned vehicles that are longer than 50 miles added up to 575 billion miles in 2009 in US. The role of the long-distance trips is even more prominent in the logistics. This article is aimed to be a first attempt to study the long-distance PHEV trips that require several refueling/charging stops.

MCPP-PHEV is a practically important problem for a broad audience. The first and the foremost subjects of interest are the personal PHEV drivers. A recent study by Turrentine and Kurani (2007) reports that personal vehicle drivers lack the basic building blocks of knowledge related to transportation costs. When it comes to PHEVs, the cost components get much more complicated compared to single energy source vehicles, and decision-support models are needed both for the routing and refueling/charging decisions. In this respect, this study offers personal PHEV drivers the possibility of understanding the PHEV economics more clearly. Furthermore, navigation devices might implement the methodologies in this study to offer a valuable decision support tool for the PHEV drivers.

The second major interest group is the logistics firms with a green logistics perspective. Alternative fuel vehicles, and PHEVs in particular, are primarily used by individuals for personal transportation purposes. Nevertheless, a PHEV, with its comparatively long driving-range with respect to an EV, is a promising alternative to be used in logistics. There are different studies directed towards exploring the possible usage of EVs and PHEVs in the future transportation fleets (Juan et al., 2014; Sathaye, 2014; Parish and Pitkanen, 2012; Davis and Figliozzi, 2013). U.S. Department of Energy (2012) also prepared a handbook for fleet managers on the guidelines of incorporating EVs and PHEVs into their fleets. Navigant Research (2013) estimates that fleet purchases of EVs and PHEVs will be more than 291,000 in 2020 worldwide. Production of light, medium and heavy-duty PHEV trucks by several companies (Smith Electric Vehicles, 2015; Odyne Systems, 2015; Business Wire, 2014; Quantum Fuel Systems, 2012; Bloomberg, 2015; Volvo, 2015) is a strong indication of the expected proliferation of PHEVs in logistics fleets highlighting the practical significance of the problem investigated in this paper.

Finally, MCPP-PHEV is also an interesting problem for the governments and infrastructure investors. With economic, security and environmental motivations, governments take an active role in promoting EV and PHEV usage. They provide several incentives and subsidize investments in the infrastructure such as charging stations. Moreover, new incentives started to emerge targeting specifically the business use of PHEVs (United Kingdom Government, 2012; Clean Transport and Technology Limited, 2015; Mitsubishi Cars, 2015). Investigating the long-distance transportation costs of PHEVs, MCPP-PHEV is a significant tool for the governments to better direct their incentive programs and for businesses to assess the opportunities and risks regarding their investment decisions. In summary, MCPP-PHEV is an interesting problem for:

- Personal PHEV drivers who want to learn about the travel costs.
- Firms which want to offer navigation systems tailored for PHEV drivers.
- PHEV truck/van fleets that want to minimize the transportation costs.
- Policy makers from both the auto industries and the governments that decide on the infrastructure establishment incentives.
- Policy makers that decide on the subsidy offers for PHEVs.

1.2. Related literature

The use of electric vehicles in the logistics operations led to several new problems flourish in the literature such as pollution-routing problem (Bektaş and Laporte, 2011; Demir et al., 2012, 2014; Franceschetti et al., 2013; Kramer et al., 2015; Koç et al., 2014), green vehicle routing problem (Erdoğan and Miller-Hooks, 2012; Ćirović et al., 2014; Lin et al., 2014; Felipe et al., 2014), location optimization of alternative fuel stations (Kuby and Lim, 2005; Wang and Lin, 2009; Wang and Wang, 2010; Wang and Lin, 2013; Sathaye and Kelley, 2013; Xi et al., 2013; Li and Huang, 2014; Yıldız et al., 2015), and optimal routing problems (Goeke and Schneider, 2015; Schneider et al., 2014; Felipe et al., 2014). The common objective of these studies is to establish the environmental and cost impacts of electric vehicles from the logistics perspective. In this respect, Pelletier et al. (2014) cover possible research perspectives for the goods distribution with electric vehicles including PHEVs.

On the PHEV side, the literature mainly focuses on the energy management problem (Sioshansi, 2012; Flath et al., 2013; Cui et al., 2012) and demand analyses (Golob and Gould, 1998; Dagsvik et al., 2002; Mabit and Fosgerau, 2011; Lopes et al., 2014). In this research, we approach PHEVs from a routing perspective and analyze their travel costs. A driver of a vehicle may prefer to minimize total travel distance, total travel time or total travel cost of a trip, and these problems can basically be modeled as variants of the shortest path problem. In terms of cost, there are various studies that separately investigate the minimum cost path problem for CVs (MCPP-CV) and for EVs (MCPP-EV) as we review below, and polynomial time algorithms