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To save money or to save time: Intelligent routing design for plug-in hybrid electric vehicle ☆

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ABSTRACT

Electric vehicles (EVs) are promising alternative to conventional vehicles, due to their low fuel cost and low emissions. As a subset of EVs, plug-in hybrid electric vehicles (PHEVs) backup batteries with combustion engines, and thus have a longer traveling range than battery electric vehicles (BEVs). However, the energy cost of a PHEV is higher than a BEV because the gasoline price is higher than the electricity price. Hence, choosing a route with more charging opportunities may result in less fuel cost than the shortest route. Different with the traditional shortest-path and shortest-time routing methods, we propose a new routing choice with the lowest fuel cost for PHEV drivers. Existing algorithms for gasoline vehicles cannot be applied because they never considered the regenerative braking which may result in negative energy consumption on some road segments. Existing algorithms for BEVs are not competent too because PHEVs have two power sources. Thus, even if along the same route, different options of power source will lead to different energy consumption. This paper proposes a cost-optimal algorithm (COA) to deal with the challenges. The proposed algorithm is evaluated using real-world maps and data. The results show that there is a trade-off between traveling cost and time consumed when driving PHEVs. It is also observed that the average detour rate caused by COA is less than 14%. Significantly, the algorithm averagely saves more than 48% energy cost compared to the shortest-time routing.

Introduction

Our current transportation system contributes a lot to the climate change due to its heavy emission. For example, the U.S. transportation sector produces more than 1.8 billion tons of greenhouse gas in 2011 (EPA), which shares nearly 30% of the total emissions in U.S. (Car emissions and global warming). On the other hand, the household gasoline expenditures increases considerable in the recent 30 years. For example, in 2012, the gasoline expenditures for the average U.S. household reached $2912, or nearly 4% of income before taxes, according to U.S. Energy Information Administration estimates. This was the highest estimated percentage of household income spent on gasoline in nearly three decades (U.E.I. Administration, 2013) with the exception of 2008. Electric vehicles have been emerging as a promising technology to green our transportation system due to their low fuel cost and low emissions.

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Though with many advantages, drivers with battery electric vehicles (BEVs) usually suffer from the"range anxiety (Pearre et al., 2011)" in trips longer than 100 miles (Wu et al., 2015). Plug-in hybrid electric vehicles (PHEVs), another subset of EVs, which backup batteries with combustion engine, provide a comparable driving range to conventional vehicles. Various kinds of marketing models also forecast that there will be a high penetration of PHEVs in the coming decades (Al-Alawi and Bradley, 2013). A PHEV usually has two operation modes: charge depleting (CD) and charge sustaining (CS) (Zhang and Vahid, 2010). When driving in CD mode, the power mainly comes from the electric motor (EM) and the PHEV is operated like a BEV (Larminie and Lowry, 2003). After depleting batteries, the PHEV switches to CS mode and is driven by the internal combustion engine (ICE). By this hybridization, PHEVs have comparable driving range to conventional vehicles, while more cost-effective and energy-effective than BEVs. Existing PHEVs are usually equipped with batteries of 2–20 kW h and can be operated in CD mode for only tens of kilometers (Morrow et al., 2008). After depleting the battery, PHEVs have to be switched to CS mode.This paper studies the routing problem of the PHEV and reveals the trade-off between energy cost and time consumption.

Most of the current works aim to minimize fuel consumptions of PHEVs in powertrain level (Pisu and Rizzoni, 2007). This paper divides these works into three stages. The first is "non-explicit stage". At this stage, management strategies do not explicitly seek to optimize energy consumption. The most typical representative is the rule-based control strategies (Baumann et al., 2000; Schouten et al., 2002; Zhang et al., 2010; Lin et al., 2003). These strategies are easy to be implemented, while the resultant operation may be quite far from optimal due to the omission of detailed dynamic models. The second is "explicit-but-suboptimal stage". These kind of strategies (Paganelli et al., 2001, 2002) explicitly formulate a cost function for the fuel consumption to be optimized. An instantaneous minimization on the cost function is carried out. However, without priori information (future driving cycles, route information, future road conditions, etc.), the instantaneous optimum may be not equal to global optimum. The third is "optimal stage". At this stage, global optimal strategies (Gong et al., 2008; Zhang and Vahidi, 2012) integrated with priori information are developed. It is obviously that different input routes will lead to different fuel consumption. Thus, how to get a better route for the strategies at the third stage is exactly what will be discussed in this paper.

In addition to the classic shortest-path (SP) algorithms such as Dijkstra, Bellman-Ford (Cormen et al., 2001) and A* (Hart et al., 1968; Johnson, 1977) some new algorithms have been developed to the PHEV routing. Finding the shortest path for a vehicle is originally discussed by Ichimori et al. (1981), where a vehicle has a limited capacity and is allowed to stop and refuel at certain locations. On this basis, Adler et al. (2014) develop a Shortest-Walk algorithm for electric vehicle (EV) and add a limit to the number of times the EV can exchange battery. But Ichimori et al. (1981) and Adler et al. (2014) cannot be applied to PHEVs because they did not consider the option of power sources. Sanders et al. propose some hierarchy algorithms (Geisberger et al., 2008; Sanders and Schultes, 2005) which run faster in real road network, but they do not take the various constraints of vehicle into consideration. Moreover, the hierarchy algorithms cannot be applied to road networks where the weight a road segment can be negative. Artmeier et al. (2010) propose energy-optimal routing algorithm for EV with the constraints of battery capacity and negative weight road resulted from potential energy during deceleration phases. With the same constraints and association, Sachenbacher et al. (2011) develop a more efficient algorithm in the framework of A*. But Artmeier et al. (2010) and Sachenbacher et al. (2011) did not consider charging the vehicles on halfway. Laporte and Pascoal (2011) develop a labeling algorithm to find a minimum cost path from a source to a destination, along which relay nodes are located at a certain cost, subjected to a weight constraint. Brumbaugh-Smith and Shier (1989), Skriver and Andersen (2000), Martins (1984), and Guerriero and Musmanno (2001) also propose similarly labeling algorithms. But the different driving mode of PHEVs will makes the weight of arcs to be unfixed and these labeling algorithms cannot deals with graphs of unfixed weighted arcs. In this paper, to address these challenges, we propose a cost-optimal algorithm (COA) to find the optimal policies: where to go and where to recharge with an emphasis on saving energy cost.

COA introduces the concept of ***effective state*** and we prove the "principle of optimality" on this basis. Then the problem is solved by dynamic programming. To be specific, we make two major contributions. First, we model maps as multi-parameter directed graphs. Each arc in the map is assigned with three parameters: the electricity consumption in CD mode, the gasoline consumption in CD mode and the gasoline consumption in CS mode. Second, we find the "optimal substructure" of the problem on the base of ***effective state***. We design a global optimal COA algorithm and prove that the time complexity of COA is polynomial.

We evaluate COA using real-world maps and data. The results show that the COA on average saves more than 48% cost and reduce 10% energy consumption, compared to the shortest route. We also observe that the detours resulting from COA is less than 14%. In this sense, the delay of COA is tolerable once the fast charging stations are widespread.

The rest of this paper is organized as follows. Section 'Model and problem statement' presents the models and challenges. Section 'The cost-optimal algorithm' gives the detailed design of COA. Section 'Analysis of COA' proves the optimality of COA and analyzes its time complexity. Section 'Evaluation of COA' evaluates COA and gives some significant insights. Finally, we conclude this paper and give some future works.

Model and problem statement

In this section, we give the model of PHEV's energy consumption and energy cost first. Then we give a detailed model of the map we used. Finally, we summarize the challenges we have to deal with, to find an cost-optimal route of PHEV.