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Stochastic Eco-routing in a Signalized Traffic Network

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Abstract

In this paper, an eco-routing algorithm is developed for vehicles in a signalized traffic network. The proposed method incorporates a microscopic vehicle emission model into a Markov decision process (MDP). Instead of using GPS-based vehicle trajectory data, which are used by many existing eco-routing algorithm, high resolution traffic data including vehicle arrival and signal status information are used as primary inputs. The proposed method can work with any microscopic vehicle model that uses vehicle trajectories as inputs and gives related emission rates as outputs. Furthermore, a constrained eco-routing problem is proposed to deal with the situation where multiple costs present. This is done by transferring the original MDP based formulation to a linear programming formulation. Besides the primary cost, additional costs are considered as constraints. Two numerical examples are given using the field data obtained from City of Pasadena, California, USA. The eco-routing algorithm for single objective is compared against the traditional shortest path algorithm, Dijkstra's algorithm. Average reductions of CO emission around 20% are observed.

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Keywords: eco-routing; shortest path; traffic signal; vehicle emission

1. Introduction

In the U.S., approximately 30% of the nation's total petroleum consumption is made by vehicles on road (EPA, 2008b). Transportation sector is also a significant contributor of total greenhouse gas emission in U.S. (EPA, 2008a). Therefore, environmental problems related to transportation system have increasingly attracted people's attention. Recently, finding an optimal route that is most environmentally friendly is formulated as "eco-routing" problems and different solution methods have been proposed (Ericsson et al., 2006; Barth et al., 2007; Boriboonsomsin et al., 2012; Nie and Li, 2013).

By following the environmentally friendly paths, vehicles are expected to use less gas or make less emissions. Although there have been many methods to find the optimal paths in terms of travel distance or travel time, it has been shown that a time or distance minimizing route does not always minimize fuel consumption or emissions (Ahn and

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Rakha, 2008; Barth et al., 2007). The problem to consider environmentally related costs is much more complicated than those to use time or distance as costs, as vehicle fuel consumption and emissions depend on many factors. Because of this, various microscopic vehicle emission models have been developed to estimate vehicle fuel consumption and emissions (Barth et al., 2000; EPA, 2012; Frey et al., 2010; Oneyama et al., 2001; Rakha et al., 2004). These models usually use vehicle trajectories as one of the most important inputs to calculate vehicle fuel consumption rate and emissions rates. They also require other inputs such as road grades and vehicle characteristics. But such information is usually static and relatively easy to obtain.

The key to an eco-routing problem becomes how to estimate the vehicle trajectories. It is obvious that vehicle trajectories on a link depend on many factors. When dealing with eco-routing problem, people usually estimate a trajectory on a link based on historical vehicle trajectories collected by GPS devices or a set of explanatory variables for a link. Then, this information is used as the input to vehicle emission models to calculate the vehicles fuel consumption and emissions for that link. After calculating the environmental cost for each link, a standard shortest path algorithm is used to calculate the optimal path that minimizes the environmental impacts (Ericsson et al., 2006; Barth et al., 2007; Boriboonsomsin et al., 2012).

The above approaches usually involve the collection of a large amount of GPS-based vehicle trajectories, but they ignore detailed traffic signal and queue information that is obtainable from the traffic controller (Liu and Ma, 2009; Liu et al., 2009). Such information is essential in deciding vehicle trajectories in a signalized traffic network. The environmental consequences of vehicle activities in signalized traffic network can be significant due to frequent stops caused by traffic signals. Thus, it is crucial to incorporate such information into an eco-routing problem.

The presence of traffic signals brings much complexity into the problem. In the case of vehicle actuated traffic signals, the durations of red lights are not deterministic. This brings randomness into the problem. In addition, costs on adjacent links may be correlated because of traffic signal coordination on major corridors in urban areas. To deal with these issues, we employ a Markov decision process (MDP) based formulation of vehicle routing problem (Sun and Liu, 2014).

By using the MDP framework, we are able to estimate vehicle trajectories link by link given signal status at intersections. The estimation process assumes a vehicle only stops because of red lights or queued vehicles in front of it. The estimated trajectories are used as inputs to microscopic vehicle emission models, such as CMEM and VT-Micro (Barth et al., 2000; Rakha et al., 2004). Then, microscopic vehicle emission models provide vehicle fuel consumption and emission rates, which are used to calculate step costs needed in the MDP. Different from traditional shortest path algorithm, the MDP provides an optimal policy that gives a vehicle en-route guidance based on the newest available information, so that the expected total cost to the destination is minimized.

For an eco-routing problem, it might be insufficient to consider only one cost. Many microscopic vehicle emission models, such as CMEM and VT-Micro, can generate estimation of fuel consumption, HC, CO, NO_x and CO_2. Together with travel distance and time, there are multiple costs of interest for a single trip. As some of the objectives conflict with each other, it might be useful to consider several of them at the same time.

When there are multiple concerns in one problem, people usually formulate the problem as a multiple objective problem. One common approach to a multi-objective problem is to find an optimal solution to a problem with an objective of weighted average of different costs. Applying this approach to the problem described above is straightforward, once the weights are known.

But in some cases, the weighted average approach may not be most appropriate. For example, one may want to minimize the fuel consumption while keeping the travel time less than a given threshold. In this situation, it is more appropriate to use a constrained method, where there is a primary objective and some other objectives are considered as constraints of the problem. This is also consistent with the international agreement such as Kyoto Protocol that sets emission targets for given pollutants. Although minimization of some emissions, e.g. CO_2, may not be achievable, it is acceptable to maintain the emissions below a given level.

A constrained eco-routing problem can still be formulated as a MDP. It is known that an MDP problem can be transformed into a linear programm and solved using standard linear programming techniques (Altman, 1999). For a given constrained eco-routing problem, we first transformed the original MDP formulation into a linear programming formulation and set a primary objective such as travel time or fuel consumption. Then, other costs of interest are considered as constraints. For each addition cost, there is a corresponding constraint added to the transformed linear