Application of the support vector machine and heuristic k-shortest path algorithm to determine the most eco-friendly path with a travel time constraint

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ABSTRACT

This study aims to determine an eco-friendly path that results in minimum CO2 emissions while satisfying a specified budget for travel time. First, an aggregated CO2 emission model for light-duty cars is developed in a link-based level using a support vector machine. Second, a heuristic k-shortest path algorithm is proposed to solve the constrained shortest path problem. Finally, the CO2 emission model and the proposed eco-routing model are validated in a real-world network. Specifically, the benefit of the trade-off between CO2 emission reduction and the travel time budget is discussed by carrying out sensitivity analysis on a network-wide scale. A greater spare time budget may enable the eco-routing to search for the most eco-friendly path with higher probability. Compared to the original routes selected by travelers, the eco-friendly routes can save an average of 11% of CO2 emissions for the trip OD pairs with a straight distance between 6 km and 9 km when the travel time budget is set to 10% above the least travel time. The CO2 emission can also be reduced to some degree for other OD pairs by using eco-routing. Furthermore, the impact of market penetration of eco-routing users is quantified on the potential benefit for the environment and travel-time saving.

1. Introduction

With ever-increasing fossil fuel consumption, air pollution emissions are growing unceasingly. It has been noted that the transportation sector accounts for approximately 26% of the total global CO2 emissions, of which 73% is generated by road transport (JAMA, 2008). Various countermeasures, such as carbon tax policies (Hayashi et al., 2001), promotion of hybrid electric vehicle purchases (Xu et al., 2015), and improvement of engine efficiency (Sivak and Schoettle, 2012), are being studied for reducing air pollution emissions.

Recently, applications of intelligent transportation systems, especially in driving assistance systems (Hibberd et al., 2015; Mensing et al., 2014), have shown promising results in fuel saving. Among them, the eco-routing navigation system is one of the successful applications that enables a reduction in fuel consumption and CO2 emissions at the route choice level (Boriboonsomsin et al., 2012; Yao and Song, 2013; Guo et al., 2014). An investigation conducted in Sweden (Ericsson et al., 2006) found that 46% of the trips based on the spontaneous route choice of the traveler were not the most eco-friendly. Fuel consumption on these trips could
be reduced by 8.2% if the most eco-friendly routes were chosen. Similarly, Ahn and Rakha (2008) reported that a 4–20% reduction in vehicle emission can be achieved if an eco-routing strategy is adopted. Since the CO2 emission is highly related to instantaneous speed and acceleration, many studies have found that the eco-friendly path is not always consistent with the shortest path based on time or distance. For example, Andersen et al. (2013) gave a typical demo in Denmark showing that the eco-friendly path is not necessary similar to the shortest and fastest paths. A field study in Japan (Kono et al., 2008) found that the fuel consumption of the eco-friendly path is 9% lower than that of the least travel-time path, while the travel time is 9% longer. Ahn and Rakha (2013) also found that eco-routing did not necessary reduce the travel time. In such cases, an eco-routing navigation system might suggest the most eco-friendly path with lower vehicle emissions, but the travel time may exceed the travel time budget. However, this important issue in the eco-routing procedure has not yet received sufficient consideration.

The eco-routing problem addressed in this study is to find an eco-friendly path that produces minimum CO2 emissions while falling within a specified travel time budget. In particular, the contribution of this study is as follows:

(1) The support vector machine (SVM) model is applied to estimate the CO2 emission. Unlike multivariate regression models, the proposed SVM model can learn the nonlinear patterns that are hidden in the explanatory variables. A significant advantage is that it is not necessary to design the regression function repeatedly for different datasets. On the other hand, the link-based CO2 emission model can be easily applied to navigation systems compared to other models based on instantaneous variables.

(2) Differing from previous eco-routing literature, this study tries to develop a routing strategy that guarantees the path having the lowest CO2 emission within a specified travel time budget. Most of the eco-routing literature only took emission into account, but the travel time budget was not considered. In our study, we consider not only the CO2 emission but also the travel time budget, which can help avoid unexpected delays. The trade-off between CO2 emission reduction and spare-time budget can be analyzed in a large-scale transportation network.

The rest of this paper is structured as follows. Section 2, following this introduction, offers a brief literature review related to the vehicle emission model and eco-routing approach. Section 3 gives an overview of the routing framework. Section 4 describes the link-based CO2 emission model. Section 5 introduces the method for eco-routing based on the heuristic k-shortest path (KSP) algorithm. Section 6 validates the proposed CO2 emission model and conducts a sensitivity analysis for the trade-off between CO2 emission reduction and spare time budget. Finally, the achievements of this study and the direction for future research are outlined in Section 7.

2. Literature review

2.1. Vehicle emission model

An appropriate vehicle emission model is critical to the development of an eco-routing navigation system. Models in literature can be classified as macroscopic, mesoscopic, or microscopic models depending on the level of detail that the models incorporate in the calculation procedure. Macroscopic models usually estimate the average fuel consumption or vehicle emission rate from aggregated parameters, e.g., the MOBILE6 model (EPA, 2003). Such a model is intended to estimate the average emission for a large area, but it is not well suited for dynamic emission assessment (Barth et al., 2001). In contrast, microscopic models enable the continuous retrieval of microscopic parameters such as instantaneous speed and instantaneous engine condition. For example, the Comprehensive Modal Emissions Model (CMEM) estimates vehicle emissions based on the instantaneous engine output power that is determined by various vehicle-related parameters (Barth et al., 1996). Another model, known as the Virginia Tech Microscopic Energy and Emission Model (VT-Micro), was developed as a third-order regression model that estimates emission rates as a function of the instantaneous speed and acceleration (Rakha et al., 2004). Considering dynamic driving parameters, Jimenez-Palacios (1998) proposed a Vehicle Specific Power (VSP) based model, which had been incorporated into the Motor Vehicle Emission Simulator (MOVES) (Koupal et al., 2002). The real-time vehicle emission can be estimated by binning instantaneous VSP (Bandeira et al., 2013). Guo et al. (2012) conducted comparisons for 11 state-of-the-art methods and found that SIDRA-running (Bowyer et al., 1984) and VT-Micro had an acceptable accuracy in a real network. Since it is quite difficult to obtain instantaneous information, such as second-by-second speed profiles, except in an ideal laboratory, microscopic models may not be applicable to routing problems. To overcome this limitation, some studies proposed mesoscopic models. Unlike microscopic and macroscopic models, mesoscopic models usually estimate the fuel consumption or vehicle emissions on a link and it is not necessary to collect substantial amount of second-by-second speed profiles. For example, Minett et al. (2011) generated synthetic speed profiles based on historical link speed data and used them for calculating the fuel consumption per link. In recent years, machine learning (ML) has been introduced to establish the learning-based model for fuel consumption or vehicle emission (Masikos et al., 2013, 2015a, 2015b). It was found that the ML technique outperformed the multivariate regression technique (Boriboonsomsin et al., 2012) because it was capable of generating forecasts properly and adequately identifying the nonlinearities underlying the vehicle fuel consumption process.

2.2. Eco-routing concept

To mitigate CO2 emissions, recent years have seen the emergence of the eco-routing concept, in which fuel consumption or vehicle emissions are set as the objective of the routing problem. It should be noted that the concepts of eco-routing and eco-driving (Mensing et al., 2014; Lai, 2015) are different. Eco-routing is used to find the most eco-friendly path from the origin to the destination based on
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