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Connectivity-based optimization of vehicle route and speed for improved fuel economy

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ABSTRACT

Traditionally, vehicle route planning problem focuses on route optimization based on traffic data and surrounding environment. This paper proposes a novel extended vehicle route planning problem, called vehicle macroscopic motion planning (VMMP) problem, to optimize vehicle route and speed simultaneously using both traffic data and vehicle characteristics to improve fuel economy for a given expected trip time. The required traffic data and neighbouring vehicle dynamic parameters can be collected through the vehicle connectivity (e.g. vehicle-to-vehicle, vehicle-to-infrastructure, vehicle-to-cloud, etc.) developed rapidly in recent years. A genetic algorithm based co-optimization method, along with an adaptive real-time optimization strategy, is proposed to solve the proposed VMMP problem. It is able to provide the fuel economic route and reference speed for drivers or automated vehicles to improve the vehicle fuel economy. A co-simulation model, combining a traffic model based on SUMO (Simulation of Urban MObility) with a Simulink powertrain model, is developed to validate the proposed VMMP method. Four simulation studies, based on a real traffic network, are conducted for validating the proposed VMMP: (1) ideal traffic environment without traffic light and jam for studying the fuel economy improvement, (2) traffic environment with traffic light for validating the proposed traffic light penalty model, (3) traffic environment with traffic light and jam for validating the proposed adaptive real-time optimization strategy, and (4) investigating the effect of different powertrain platforms to fuel economy using two different vehicle platforms. Simulation results show that the proposed VMMP method is able to improve vehicle fuel economy significantly. For instance, comparing with the fastest route, the fuel economy using the proposed VMMP method is improved by up to 15%.

1. Introduction

Vehicle route planning problem is very important in logistics and transportation. The shortest and fastest route navigations are classic vehicle route planning problems and have been widely used in our daily life through navigation tools. In recent years, due to the rapid development of connected and automated vehicles, more attention has been paid to the vehicle route planning problems (Davis, 2017; Lei et al., 2017). In addition, environmental and energy concerns encourage researchers to develop new energy efficient technologies. Vehicle route planning has the potential to further reduce vehicle fuel consumption and emissions by optimizing vehicle route and speed simultaneously (Lin et al., 2014; Zeng et al., 2016) based on the technological development of vehicle connectivity, a vehicular communication system sharing its real-time information with others through vehicle-to-vehicle, vehicle-to-infrastructure,

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vehicle-to-pedestrian, vehicle-to-cloud, and other communication methods (Amadeo et al., 2016; Lu et al., 2014). On the other hand, the improvement of vehicle fuel economy has the potential to reduce transportation cost, especially for heavy-duty trucks (Díaz-Ramirez et al., 2017).

Most of navigation tools provide the shortest and fastest routes for a given origin-destination (OD) pair regardless the trip time. Let $G = (\mathbf{N},\mathbf{W})$ be a directed graph of traffic network with a node set $\mathbf{N}$ and an edge weight set $\mathbf{W}$, where the edge is a road segment between two neighboring nodes (intersections or junctions) on an actual traffic network. The edge weight $w_{ij} \in \mathbf{W}$ is associated with road cost function (e.g. road length and travel time) from node n_i to n_j ($n_i,n_j \in \mathbf{N}$) (Bast et al., 2015; Prins et al., 2014). The shortest (or fastest) route is an ordered sequence of nodes from $\mathbf{N}$ with the route length (or travel time) minimized. The edge weights (route length and travel time) are independent and calculated based on traffic network data (e.g. road shape and node position) and traffic flow data (e.g. speed limit and traffic speed) over their edges. Note that the fastest route is the same for different vehicles with the same OD pair and departure time. There are many methods to solve this classic shortest/fastest route problem, such as Dijkstra's algorithm (Peyer et al., 2009), Bellman-Ford algorithm (Goldberg and Radzik, 1993), A^* search algorithm (Zeng and Church, 2009), Floyd-Warshall algorithm (Aini and Salehipour, 2012), and Johnson's algorithm (Johnson, 1977).

However, the shortest (or fastest) route does not always minimize the fuel consumption (Ahn and Rakha, 2008). As a result, the optimal fuel economic route cannot be solved by above mentioned methods due to the following reasons. First, different from the weighted shortest and fastest route problems, vehicle fuel consumption is not only related to the traffic data but also affected by factors such as vehicle speed, powertrain characteristics, road grade, and driver behavior (Zhou et al., 2016). Second, the edge weights (fuel consumption) are inter-dependent and affected by the information of neighboring edges. For example, the fuel consumption of a conventional ICE (internal combustion engine) powered vehicle over an edge is affected by the gear ratio over the previous edge via the gear-shifting schedule (Miao et al., 2018); and similarly, the fuel consumption of a hybrid electric vehicle (HEV) is affected by its terminal SOC over the previous edge and the information (such as road grade and traffic speed) over the current and neighboring edges used in the energy management control strategy (Kamal et al., 2013). Therefore, the route cost is not equal to the sum of weights whose corresponding edges compose the route. Last, the fuel consumption of an individual edge could be negative due to the brake regeneration for an HEV under downhill operations (Jurik et al., 2014), and it worth to note that most of optimization algorithms mentioned above can only deal with positive edge weights. In fact, the vehicle characteristics play an important role in vehicle route planning problems, even for the fastest route. For example, a small passenger car and a heavy-duty commercial truck could have different fastest routes due to the difference in vehicle acceleration/deceleration performance and related speed limit. The existing on-board powertrain controllers and navigation tools cannot optimize the route based on both traffic data and vehicle characteristics. Fortunately, the rapid development of vehicle connectivity makes it possible in near future to optimize vehicle fuel economic route using both traffic data and vehicle characteristics (Amadeo et al., 2016; Lu et al., 2014).

Fuel economy related vehicle route planning research got started in the past decades, such as eco-routing navigation (Boriboonsomsin et al., 2012; Lang et al., 2015; Zeng et al., 2016), green vehicle routing problem (Erdogan and Miller-Hooks, 2012; Tiwari and Chang, 2015; Turkensteen, 2017; Koç and Karaoglan, 2016; Leggieri and Haouari, 2017; Montoya et al., 2016; Bruglieri et al., 2016), and pollution vehicle routing problem (Ehmke et al., 2016; Tajik et al., 2014; Demir et al., 2012; Jabali et al., 2012; Bekta and Laporte, 2011). In these literature, authors try to minimize vehicle fuel consumption and/or emissions through the route optimization. In general, the proposed fuel economic route is generated in three steps. First, a cost function is established to evaluate fuel consumption and/or emissions. As mentioned above, the fuel consumption is affected by many factors and it is difficult to calculate it accurately in real-time. As a result, simplified fuel economy models are proposed to estimate fuel consumption based on vehicle dynamics, including instantaneous fuel consumption model, mean-value phenomenological model, engine-based model, vehicle-based model, comprehensive modal emission model (CMEM), and invariant models (Zhou et al., 2016; Turkensteen, 2017; Gołe¸biowski and Stoeck, 2014). The CMEM is the most widely used model based on fuel rate modules, vehicle speed, engine power and speed. Second, a mathematical model based on the directed graph and a mixed integer linear program (MILP) (Erdogan and Miller-Hooks, 2012; Mancini, 2017; Bruglieri et al., 2016) is formulated for the route planning problem. Third, the fuel economic route is solved using different methods, such as heuristic algorithm (Prins et al., 2014; Erdogan and Miller-Hooks, 2012; Montoya et al., 2016; Koç and Karaoglan, 2016; Demir et al., 2012), robust optimization (Tajik et al., 2014), genetic algorithm (Tiwari and Chang, 2015; Lau et al., 2010), particle swarm optimization approach (Gong et al., 2012), and ant colony system (Androutsopoulos and Zografos, 2017). The optimized results show that the fuel economic route has the potential to reduce fuel consumption and emissions with fixed traffic (vehicle) speed. In addition, some other related vehicle route planning problems based on HEVs (Mancini, 2017) and electric vehicles (Felipe et al., 2014; Schneider et al., 2014; Hiermann et al., 2015) were proposed for the environment improvement in recent years. Demir et al., 2012; Franceschetti et al., 2013; Barth and Boriboonsomsin, 2009; Huang et al., 2017; and Tas et al., 2014 studied the speed optimization problem with a given route and trip time constraint and showed that the speed optimization was able to decrease fuel consumption over a fixed route with a given trip time constraint. It indicates that vehicle fuel economy could be further improved by combining route planning and speed optimization into a co-optimization problem.

Therefore, a vehicle macroscopic motion planning (VMMP) problem is formulated to improve vehicle fuel economy by providing the economic route and speed for a given origin destination pair with an expected trip time. The VMMP problem is defined as a global co-optimization problem to find the economic vehicle route and speed profile simultaneously that minimize the cost function (e.g. fuel consumption) from origin to destination over a traffic network. This is motivated by the fact that vehicle route and speed are coupled in the fuel economy optimization problem. Considering the dependency of neighboring edges, a co-optimization method containing two coupled genetic algorithm (GA) optimization processes is proposed to optimize vehicle route and speed. In practice, vehicle route is not time-varying due to traffic rules and may remain unchanged before approaching an incoming intersection, therefore, an adaptive real-time optimization strategy is designed to update the route and speed under different rates for online