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Just-in-time delivery for green fleets: A feedback control approach

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ABSTRACT

With increasing attention being paid to greenhouse gas (GHG) emissions, the transportation industry has become an important focus of approaches to reduce GHG emissions, especially carbon dioxide equivalent (CO_2e) emissions. In this competitive industry, of course, any new emissions reduction technique must be economically attractive and contribute to good operational performance. In this paper, a continuous-variable feedback control algorithm called GEET (Greening via Energy and Emissions in Transportation) is developed; customer deliveries are assigned to a fleet of vehicles with the objective function of Just-in-Time (JIT) delivery and fuel performance metrics akin to the vehicle routing problem with soft time windows (VRPSTW). GEET simultaneously determines vehicle routing and sets cruising speeds that can be either fixed for the entire trip or varied dynamically based on anticipated performance. Dynamic models for controlling vehicle cruising speed and departure times are proposed, and the impact of cruising speed on JIT performance and fuel performance are evaluated. Allowing GEET to vary cruising speed is found to produce an average of 12.0–16.0% better performance in fuel cost, and −36.0% to +16.0% discrepancy in the overall transportation cost as compared to the Adaptive Large Neighborhood Search (ALNS) heuristic for a set of benchmark problems. GEET offers the advantage of extremely fast computational times, which is a substantial strength, especially in a dynamic transportation environment.

Introduction

With ever-increasing attention being paid to greenhouse gas (GHG) emissions, the transportation industry has become the focus of attempts to reduce GHG emissions by economically attractive means while maintaining high performance standards. The U.S. transportation sector accounts for about 28% of GHG emissions and 28% of total U.S. energy consumption; about 5% of total energy consumption in the U.S. is in the operation of heavy trucks (U.S. Environmental Protection Agency [EPA], 2011). Therefore, the EPA and the U.S. Department of Transportation National Highway Traffic Safety Administration (NHTSA) recently announced a program to reduce GHG emissions and foster fuel efficiency in heavy-duty trucks by setting fuel consumption standards (U.S. Environmental Protection Agency [EPA], 2011). Also, the U.S. Department of Energy initiated the National Clean Fleets Partnership to help large companies reduce fuel consumption in their fleets by incorporating electric

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vehicles, alternative fuels, and fuel-saving measures into their daily operations. Many large companies have participated in developing energy- and eco-friendly business strategies, not only for environmental reasons but also because it is in their own best interests. For example, FedEx has continuously increased the number of hybrid-electric and electric vehicles in the FedEx fleet, resulting in a reduction of 3000 metric tons of CO_2 emissions and savings of 300,000 gallons of fuel in 2016 (Fedex company statistics, 2016).

Along with advancement of various "greening" vehicle propulsion and fuel technologies, growing attention has been recently paid to the planning aspect of transportation operations. "Greening" of transportation operations requires much less capital investment than changing propulsion and fuel technologies, because it involves changes in the "software" of transportation. We believe that there are significant opportunities to develop new planning techniques for transportation operations to include metrics for operations as well as energy performance.

The literature pertaining to vehicle routing algorithms for a variety of operational metrics is quite rich. Since the seminal work by Dantzig and Ramser (1959), numerous approaches to vehicle routing problems have been developed, ranging from exact algorithms to heuristic approaches; advances and issues have been well reviewed by Eksioglu et al. (2009) and Pillac et al. (2013). Most of the studies handled conventional performance measures, such as total travel distance and total travel time, but recently, customer need for JIT deliveries and government incentives for eco-friendly driving have become critical factors in developing transportation strategies. Recent research has begun to respond to these needs (Laporte, 2013). Specifically, Bektaş and Laporte (2011) present the pollution routing problem (PRP) an extension of the classical vehicle routing problem that takes into account not just travel distance but also carbon dioxide (CO_2) emissions, fuel use, travel times and cost. Suzuki (2011) developed the time-constrained, multiple-stop, truck-routing problem with objective functions of minimizing fuel consumption and pollutant emissions. He considered a way to minimize fuel consumption during truck idling at customer sites, as well as delivering on roads, considering average vehicle speed. Xiao et al. (2012) extended the classical capacitated vehicle routing problem by including the fuel consumption rate as the objective function and developed a simulated annealing algorithm with a hybrid exchange rule to solve the problem. Kuo (2010) proposed a time-dependent vehicle routing problem in which vehicle speed and travel times are assumed to depend on the time of travel and developed a simulated annealing algorithm to find routing schedules with the lowest total fuel consumption. Jemai et al. (2012) developed the non-dominating sorting genetic (NSGA) evolutionary algorithm, which is designed for solving non-convex and non-smooth multi-objective optimization problems, and applied it to the vehicle routing problem to minimize the total traveled distance and CO_2 emissions. These attempts to incorporate energy performance metrics into the classical vehicle routing problem represent significant progress, but there are still gaps between theoretical results and practical applications, resulting primarily from structural differences in control variables in vehicle routing models.

In this paper, a feedback control algorithm called Greening via Energy and Emissions in Transportation (GEET) is developed for the vehicle routing problem with soft time windows (VRPSTW). The JIT and fuel performance metrics are defined respectively in terms of (i) deviation of delivery completion time with respect to the customer requested time window and (ii) the level of fuel consumption and resulting carbon dioxide-equivalent (CO_2e) emissions, including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). It should be emphasized that these two measures can be obtained by dealing with heterogeneous types of control variables; control at the vehicle cruising level deals primarily with continuous variables, that is, cruising speed, while scheduling decisions at the vehicle routing planning level are concerned with a discrete sequence of customer orders. At the vehicle cruise speed control level, factors such as traffic congestion and speed limits require adaptive adjustment, which leads to changes in travel times among customer locations and therefore has a significant impact on JIT commitments. Furthermore, vehicle cruise speed is related to fuel consumption and CO_2e emissions, meaning that controlling vehicle cruise speed has an important role in not only improving JIT delivery but also controlling fuel consumption at the individual vehicle level.

In conventional vehicle routing problems (VRP), however, vehicle cruise speed and corresponding travel times are generally assumed to be static or have no limitations. Therefore, they employ static scheduling methods rather than dynamic scheduling methods. These assumptions may make vehicle routing schedules impractical and lead to significant variations in routing plans released in transportation management systems. Recent studies have shown that dynamically adjusting vehicle speed and resulting vehicle departure times in determining a routing schedule could give competitive results compared to an exact solution approach. The speed optimization algorithm (SOA) was proposed for the vessel fleet scheduling problem (Norstad et al., 2011) and adapted to PRP based on an evolutionary metaheuristic algorithm, Adaptive Large Neighborhood Search (ALNS) (Demir et al., 2012; Koç et al., 2014; Demir et al., 2014; Koç et al., 2015, 2016), in which optimal speed aiming to minimize fuel consumption on each route and vehicle departure times for each destination are dynamically adjusted while considering customer requested time windows. Another approach is that a discretized speed function was incorporated into an integer linear programming formulation in order to determine a vehicle routing schedule that minimizes total transportation cost, including fuel and emission costs (Bektaş and Laporte, 2011).

Although recent approaches have tried to consider vehicle speed as a decision variable, thereby reflecting an eco-friendly driving strategy into the conventional VRP structures, computational cost is a significant barrier to implementing those approaches in the dynamic transportation environment. To reflect dynamic vehicle routing operations as described above and minimize impracticality caused by non-interaction between vehicle routing schedules and vehicle speed, we use a continuous-variable control theoretic approach, in which the combinatorial scheduling problem dealing with discrete order sequences into a continuous-variable feedback control problem in vector space. The proposed approach treats discrete time variables (i.e., routing sequences) as continuous variables and combines them with vehicle speed variables, which are