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Fuel emissions optimization in vehicle routing problems with time-varying speeds

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ABSTRACT

The problem considered in this paper is to produce routes and schedules for a fleet of delivery vehicles that minimize the fuel emissions in a road network where speeds depend on time. In the model, the route for each vehicle must be determined, and also the speeds of the vehicles along each road in their paths are treated as decision variables. The vehicle routes are limited by the capacities of the vehicles and time constraints on the total length of each route. The objective is to minimize the total emissions in terms of the amount of Greenhouse Gas (GHG) produced, measured by the equivalent weight of CO_2 (CO_2e).

A column generation based tabu search algorithm is adapted and presented to solve the problem. The method is tested with real traffic data from a London road network. The results are analysed to show the potential saving from the speed adjustment process. The analysis shows that most of the fuel emissions reduction is able to be attained in practice by ordering the customers to be visited on the route using a distance-based criterion, determining a suitable path between customers for each vehicle and travelling as fast as is allowed by the traffic conditions up to a preferred speed.

1. Introduction

Technical developments and the growth in road traffic pose new challenges for research in vehicle routing and scheduling for freight transport. Remote vehicle tracking techniques enable the road traffic data for different times of day and different days of the week to be collected, so as to provide detailed information on transit times for different roads by time of day and day of week. This provides an opportunity to plan vehicle routes and schedules taking time-varying speeds into account. In addition, the growth in road traffic and the use of road freight transport also bring problems of environmental pollution. Concerns about the environmental impact of transport activities have led to new vehicle routing models where the objective is to minimize the harmful effects of transportation on the environment.

An increasing number of papers are being published where fuel emissions are explicitly modelled. However many of these simplify the model by assuming that paths between customers are fixed or that the speeds of the vehicles are time-independent. In the model described in this paper, the speed of the traffic on the underlying road network is time dependent. In addition, the path used by a vehicle between a pair of customers and the speeds on the road segments are decision variables. This paper will describe a column generation based tabu search algorithm, which can work together with a solution method for single paths, in order to minimize fuel emissions for Vehicle Routing Problems (VRPs) with time-varying speeds.

The algorithm is then used for modelling a distribution operation using real traffic data from a road network located in London. The aim of these experiments is to discover how much reduction in CO_2e can be obtained by using the algorithm described in this paper, compared with other approaches that are faster to compute. Experiments are also carried out to determine the effect of allowing more waiting time at customers.

The paper is organized as follows. Section 2 contains a review of relevant literature. The problem is described in Section 3, which is followed by a set-partitioning model for the VRP. Section 4 introduces the framework of the column generation based tabu search algorithm, which is used to find a prospective sequence for a set of customers, and goes on to discuss details of the algorithm. The computational experiments and their results are then presented in Section 5. Finally, conclusions are drawn in Section 6, and the main findings are highlighted.

2. Literature review

In recent years, there has been increasing interest in estimating the environmental effects of vehicle routing policies. A survey of

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recent work in this area can be found in Eglese and Bektaş (2014). Various models have been proposed for estimating the fuel used by vehicles when travelling on roads. Examples include one published by the European Commission in the MEET report described by Hickman, Hassel, Joumard, Samaras, and Sorenson (1999) and the Comprehensive Modal Emissions Model (CMEM) described by Scora and Barth (2006). The CO_2 emissions are normally calculated as being proportional to the fuel used. The fuel consumption and hence the emissions may relate to factors such as the vehicle type, weight and speed. Demir, Bektaş, and Laporte (2011) provide a comparison of a number of such models.

Recent research on minimizing emissions in vehicle routing models can be divided into two main categories: the first is the set of models where time-independence is assumed and the second set includes models where the road conditions are subject to traffic congestion and so the time needed to travel along a road segment depends on the time of day.

Among the time-independent models, Palmer (2007) developed a model where vehicle speeds are inputs to the model and the approach is tested on a case study of home deliveries for grocery stores in the UK. He found an average saving of 4.8% in CO_2 emissions was possible compared to using routes that minimize time, but at the expense of a 3.8% increase in the time required. His model does not take vehicle loads explicitly into account, but Suzuki (2011) uses a model where load is taken into account and finds that delivering relatively heavy items early in a tour can be worthwhile in reducing the fuel consumption. Several case studies have been reported using time-independent approaches with the objective of minimizing fuel consumption and hence emissions. For example, Ubeda, Arcelus, and Faulin (2011) consider emission factors in planning routes for a food delivery operation. They show savings of around 25.5% in CO_2 emissions, but this is mainly due to reducing the number of routes needed compared to the original plan.

Other time-independent models allow the speeds of vehicles to be decision variables. The approach adopted by Bektaş and Laporte (2011) in their Pollution-Routing Problem (PRP) uses a CMEM-based model and considers both load and speed in estimating a cost function to be minimized. They propose a non-linear mixed integer mathematical programming formulation and show how it can be linearized. The formulation can only solve small PRP instances, but Demir, Bektaş, and Laporte (2012) provide an adaptive large neighbourhood search algorithm for much larger PRP instances. Van Woensel, Creten, and Vandaele (2001) develop a model showing how queuing theory can be used to describe traffic flows and calculate emissions using the model described in the MEET report.

In the set of time-dependent models, Eglese, Maden, and Slater (2006) make use of traffic speed information collected at different times on sections of a road network to create a Road Timetable showing the quickest times between origins and destinations starting at different times of the day. In Maden, Eglese, and Black (2010) the Road Timetable is used with a tabu-search called LANTIME to minimize the total time required for a distribution operation. Vehicles are assumed to travel at the speed which minimizes their emissions per unit distance unless the congestion indicates that this is not possible, when the vehicles travel at the average speed of the traffic recorded for that road segment at that time. Results from a case study based on the distribution plans for an electrical goods wholesaler in the UK show that CO_2 emissions can be reduced by around 7% with this approach. This is because routes with high congestion and hence, enforced low speeds and high emissions, are avoided. Figliozzi (2010) also takes into account congestion in minimizing emissions using a model based on the MEET report. An integer programming formulation is presented and a solution algorithm is described which is tested on modified Solomon benchmark problems. In contrast to Maden et al. (2010), the model allows vehicles to travel faster than their optimum speed that minimizes emissions if the traffic conditions and speed limits allow. Thus, there are examples where uncongested conditions can lead to increased emissions.

Vehicle speeds may also be used as decision variables in time-dependent models. Jabali, van Woensel, and de Kok (2012) use a similar model to Figliozzi (2011) but with speed as an additional decision variable, though without the use of time windows. Their model is based on a complete network where the nodes represent the depot and customers, while the maximum speeds on the arcs linking the nodes are subject to similar profiles. They describe a tabu search heuristic for solving the problem and test it on standard benchmark instances. The results suggest that a reduction of about 11.4% in CO_2 emissions can be achieved, but with a 17.1% increase in travel times. Franceschetti, Van Woensel, Honhon, Bektaş, and Laporte (2013) follow a similar approach which also takes costs into account in a similar way to Bektaş and Laporte (2011). A mathematical formulation is produced and provides insights on when it is profitable to wait at customers.

The model presented in this paper is in the last category of models which take into account time-dependent conditions and where vehicle speeds are decision variables. It is designed for use on a road network where information is available on the speed of traffic on individual road segments at different times of the day. The solution provides the path to follow between customers and the speeds to be applied on each road segment. It thus provides a more detailed model than the one used by Jabali et al. (2012); the path used between a pair of customers may change depending on the time of travel in our model. Also, it allows time window constraints for serving customers which are not included in Jabali et al. (2012).

If it is assumed that the path used between customers is fixed, then some other recent research on speed optimization is relevant. Fagerholt, Laporte, and Norstad (2010) present the Speed Optimization Problem (SOP) in the context of shipping, provide models to formulate the problem and a solution algorithm. Norstad, Fagerholt, and Laporte (2011) provide a recursive smoothing algorithm for the SOP that runs fast and has been shown to be optimal by Hvattum, Norstad, Fagerholt, and Laporte (2013).

It is often the case that reductions can be made in the emissions resulting from a distribution operation, but at the expense of more time or cost. There are methods explicitly aimed at modelling this issue through a multi-objective approach. One example is provided by Jemai, Zekri, and Mellouli (2012) where an evolutionary algorithm is used to solve a bi-objective VRP where one objective minimizes total distance, while the other minimizes CO_2 emissions. Demir, Bektaş, and Laporte (2014) consider the bi-objective PRP where fuel consumption and driving time are the two relevant objectives.

Finally, there is an emerging strand of research considering vehicle routing problems for alternatively powered vehicles that are designed to be more environmentally friendly. Such vehicles may have a more limited range before requiring refuelling and there may be a limited availability of refuelling points. An example is given by Erdoğan and Miller-Hooks (2012) in which they define a “Green Vehicle Routing Problem” where there are additional constraints on how far the vehicles may travel without refuelling and the refuelling stations are located at specific places. They formulate a mixed integer program to minimise the total distance and develop heuristics for its solution. Tests are carried out based on the location of stations supplying biodiesel fuel in a part of the USA.

3. Problem description and modelling

Let $G = (C, A)$ be a graph, where $C = \{c_0, c_1, \ldots, c_n\}$ contains a depot (c_0) and a set of customers to serve. We define $A = \{a(c_i, c_j) : c_i, c_j \in C,\ i \neq j\}$ as the set of arcs connecting customer nodes. For any pair c_i, c_j there may be more than one arc connecting them, representing different paths through the underlying road network. The time horizon for the delivery operation is divided into