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Reducing CO_2 emissions in temperature-controlled road transportation using the LDVRP model

Helena M. Stellingwerf*, Argyris Kanellopoulos, Jack G.A.J. van der Vorst, Jacqueline M. Bloemhof

Operations Research and Logistics, Wageningen University, Hollandseweg 1, 6706 KN Wageningen, The Netherlands

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ABSTRACT

Temperature-controlled transport is needed to maintain the quality of products such as fresh and frozen foods and pharmaceuticals. Road transportation is responsible for a considerable part of global emissions. Temperature-controlled transportation exhausts even more emissions than ambient temperature transport because of the extra fuel requirements for cooling and because of leakage of refrigerant. The transportation sector is under pressure to improve both its environmental and economic performance. To explore opportunities to reach this goal, the Load-Dependent Vehicle Routing Problem (LDVRP) model has been developed to optimize routing decisions taking into account fuel consumption and emissions related to the load of the vehicle. However, this model does not take refrigeration related emissions into account. We therefore propose an extension of the LDVRP model to optimize routing decisions and to account for refrigeration emissions in temperature-controlled transportation systems. This extended LDVRP model is applied in a case study in the Dutch frozen food industry. We show that taking the emissions caused by refrigeration in road transportation can result in different optimal routes and speeds compared with the LDVRP model and the standard Vehicle Routing Problem model. Moreover, taking the emissions caused by refrigeration into account improves the estimation of emissions related to temperature-controlled transportation. This model can help to reduce emissions of temperature-controlled road transportation.

1. Introduction

Transportation of goods has substantial economic and environmental consequences (Palmer, 2007). The percentage of CO_2 emissions caused by truck transportation in the European Union has increased from 5.6% in 1990 to 9% in 2014; worldwide, transportation causes 14% of the global CO_2 emissions (Dekker et al., 2012). Greenhouse gas emissions from conventional diesel engine vapour compression refrigeration systems can be as high as 40% of the vehicle's emissions (Tassou et al., 2009). In general, current transportation systems are far from efficient and the problem is more severe in temperature-controlled transportation systems of, for example, frozen food and pharmaceuticals, for which additional energy is needed to regulate temperature and ensure quality, product safety and shelf-life (Adekomaya et al., 2016; Ketzenberg et al., 2015). It is therefore important to keep the temperature at the appropriate level. A survey showed that the thermal energy requirement is around 15–25% of the motive energy requirement of trucks (Tassou et al., 2009). Adekomaya et al. (2016) state that 15% of world's energy from fossil fuels is used in food transport

* Corresponding author.
E-mail addresses: heleen.stellingwerf@wur.nl (H.M. Stellingwerf), argyris.kanellopoulos@wur.nl (A. Kanellopoulos), jack.vandervorst@wur.nl (J.G.A.J. van der Vorst), jacqueline.bloemhof@wur.nl (J.M. Bloemhof).

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refrigeration, and that the environmental influence of emissions from food transport vehicles accounts for 40% of the global greenhouse effect (Adekomaya et al., 2016).

To improve the efficiency of current temperature-controlled transportation systems, we need appropriate decision support tools to compare different options to eliminate inefficiencies. Vehicle Routing Problem (VRP) models have been proposed to optimize operational routing decisions for transportation systems of various commodities (Toth and Vigo, 2014). The basic variants of these models minimize transportation costs or transportation distance and provide an optimal route to deliver or collect commodities (Toth and Vigo, 2014). Some variants of VRP models, known as Green Vehicle Routing Problem (GVRP) models (Lin et al., 2014), have also been used to minimize environmental impact, most often expressed as carbon dioxide (CO_2) emissions. Demir et al. (2014b) summarize different approaches to the GVRP. The Load-Dependent VRP (LDVRP) model can be considered as a special case of a GVRP model (Bektaş and Laporte, 2011; Zachariadis et al., 2015) that takes the load and the order of unloading into account when calculating fuel consumption. Existing green logistics VRP models do not account for the substantial emissions exhausted as a result of temperature control. Accurate quantification of the emissions of temperature controlled transportation requires not only to consider emissions caused by fuel use needed for driving, but also emissions caused by fuel use for refrigeration and refrigerant leakage. Consequently, existing green logistics VRP models need to be extended before they can be used to optimize operational decisions for temperature-controlled transportation systems.

The objective of this article is to propose an extension of the LDVRP model to minimize emissions in temperature-controlled transportation systems. We propose a metric of CO_2 emissions that, next to emissions caused by fuel use for moving the truck, also considers emissions caused by fuel use for cooling the truck as well as emissions caused by leakage of refrigerant. To that aim, a Load-Dependent VRP is extended to account for emissions caused by fuel used for temperature control and for refrigerant leakage. This model is applied to a case study in frozen food transportation in the Netherlands. In Section 2, we present the methodology, in which we describe an LDVRP model and the extensions required to take emissions caused by refrigeration into account. The case study and the calculations are presented in Section 3 and the results in Section 4. We conclude with the discussion and conclusions in Section 5.

2. Methodology

This section first gives a review of relevant LDVRP literature (Section 2.1), then describes the LDVRP model (Section 2.2). In Section 2.3, characteristics of temperature controlled transportation are described and in Section 2.4 these characteristics are translated into a LDVRP extension. All nomenclature used is summarized in the Appendix.

2.1. The green vehicle routing Problem: Review of relevant literature

VRP models are used to find optimal routes for delivering or collecting products, mostly by minimizing total distance (Toth and Vigo, 2002). However, different objective functions have been used. For example, to minimize environmental impacts caused by the distance travelled, green VRPs have been developed (Demir et al. (2014a, 2014b); Jaehn, 2016; Lin et al., 2014). In ambient temperature transport, CO_2 emissions are linearly related to fuel consumption, which in turn is linearly related to the loaded distance (i.e. weight multiplied by distance) travelled. Because the fuel consumption and thus the emissions are directly related to the weighted distance, the order of unloading can have a significant impact on the pollution caused by a route (Kara et al., 2007; Molina et al., 2014; Xiao et al., 2012; Zachariadis et al., 2015). Recently, so-called Load-Dependent VRPs have been proposed. This type of VRP model takes the load and the order of unloading into account when comparing routes, for example, by minimizing total CO_2 emissions and transportation costs (Bektaş and Laporte, 2011; Bing et al., 2014; Kara et al., 2007; Xiao et al., 2012; Zachariadis et al., 2015).

Kara et al. (2007) use the LDVRP to minimize energy use on a route, and they provide two examples to show that the LDVRP model gives different results than a distance minimizing model. Xiao et al. (2012) take the load into account in a fuel consumption optimization model. Like Kara et al. (2007), they show that their model gives a different result than distance minimization. Also Ahn and Rakha (2008) describe show that taking the load into account can change the best route from an environmental and an energy perspective: the fastest route is no longer the best (Ahn and Rakha, 2008).

Zachariadis et al. (2015) use the LDVRP model proposed by Kara et al. (2007) and extend it to account for pickup and delivery time in order to analyse the influence of the maximum cargo to empty weight ratio. The authors state that the LDVRP model is suitable for optimizing transportation operations when the weight of the transported cargo has a significant contribution to the gross truck weight, such as logistics operations for supermarkets. In this case, the LDVRP model generates a more sensible transportation plan compared with basic VRP models (Zachariadis et al., 2015). For a sensitivity analysis, the authors compare the objective function values of two different routes with loads of varying weight.

Most LDVRP studies use one objective function. For example, Kara et al. (2007) and Xiao et al. (2012) both add the weighted distance (which they translate to energy and fuel consumption, respectively) into a cost function. Molina et al. (2014) combine three different objectives (i.e. to minimize internal costs, CO_2 emissions, and NO_x emissions) into one function. The Pollution Routing Problem is an example of an LDVRP that takes both the economic and environmental impact of different routes into account (Bektaş and Laporte, 2011). That study takes a broader view than the standard VRP by analysing routes based on four indicators: costs, emissions, distance, and time.