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Cost, carbon emissions and modal shift in intermodal network design decisions

Yann Bouchery [a,*], Jan Fransoo [b]

[a] Ecole de Management de Normandie, Axe Logistique Terre Mer Risque, 30 Rue de Richelieu, 76087 Le Havre, France
[b] Eindhoven University of Technology, School of Industrial Engineering, P.O. Box 513, 5600 MB Eindhoven, The Netherlands

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ABSTRACT

Intermodal transportation is often presented as an efficient solution for reducing carbon emissions without compromising economic growth. In this article, we present a new intermodal network design model in which both the terminal location and the allocation between direct truck transportation and intermodal transportation are optimized. This model allows for studying the dynamics of intermodal transportation solutions in the context of hinterland networks from a cost, carbon emissions and modal shift perspective. We show that maximizing the modal shift is harmful for both cost and carbon emissions and that there is a carbon optimal level of modal shift. We also show that even if transportation cost and carbon emissions share the same structure, these two objectives lead to different solutions and that the terminal is located closer to the port when optimizing cost and further away when optimizing carbon emissions. The model also allows for studying the tradeoff between distance and volume, the impact of using aggregated models for estimating train transportation cost and carbon emissions as well as the potential policy measures that enable aligning cost and carbon emissions.

1. Introduction

Transportation is crucial for economic growth and for citizens' quality of life. On the other hand, several downsides such as congestion, safety issues, oil dependence and pollution are often associated to transportation. For example, transportation is recognized as one of the main contributors of carbon emissions (IPCC, 2007). In a roadmap toward a competitive and resource efficient transport system (EC, 2011), the European Commission states that the main objective related to transportation is to reduce the downsides without compromising mobility and economic growth. Among the downsides targeted by the European Commission, carbon emissions play an important role as the European Union is committed to reduce carbon emissions (UNFCC, 1997). Thus the European targets its transportation sector to reduce carbon emissions by at least 60% by 2050 with respect to 1990 level (EC, 2011). When focusing on freight transportation, the main solution proposed by the European Commission is to promote intermodal transportation. Intermodal freight transportation is defined as the transportation of the load from origin to destination in the same transportation unit without handling of the goods themselves when changing modes (Crainic and Kim, 2007). Although the European Union is at the forefront in promoting intermodal freight transportation, other countries and regions are following the same objectives (GAO, 2006, 2007). This trend toward intermodal transportation is also supported by many leading companies (EDF, 2012). Thus, the logistics sector needs to take into account this new trend by proposing efficient intermodal transportation solutions.

The rationale behind promoting intermodal freight transportation as efficient in reducing carbon emissions without compromising economic growth can be explained as follows. Both trains and barges (the two most classical modes for the linehaul part of intermodal transportation) emit less carbon emissions than heavy duty trucks. Thus, if intermodal freight transportation networks can compete against road in terms of cost, then the economic growth would not be compromised and the carbon emissions would be reduced. The objective followed while promoting intermodal freight transportation is thus generally expressed in terms of modal shift, i.e., the number of ton kilometer (t.km) shifted from the road (or equivalently the percentage of the total amount of t.km shifted from the road). For example, the objective of the European Commission is that "30% of road freight over 300 km should shift to other modes such as rail or waterborne transport by 2030, and more than 50% by 2050" (EC, 2011). However, intermodal transportation induces an increase in the distance traveled due to origin and/or destination drayage compared with direct truck transportation. For example, assume that the distance traveled for drayage is greater or equal to the distance traveled for

* Corresponding author. Tel.: +33 2 32 92 59 60.
E-mail address: ybouchery@em-normandie.fr (Y. Bouchery).

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direct shipment by trucks (if intermodal terminals are located very far away from origin and destination). In this case, the carbon intensity of intermodal transportation would be higher than for direct truck transportation. Accordingly, Craig et al. (2013) have shown that the carbon intensity of intermodal transportation can be higher than direct truck transportation in practice. Thus, there is a tradeoff between the efficiency gain in the linehaul and the increase in the distance traveled. This article aims at studying such a tradeoff to better understand the dynamics of intermodal freight transportation with respect to cost, modal shift and carbon emissions.

We refer to Bontekoning et al. (2004) for a review on the early development of the research on intermodal freight transportation and to Caris et al. (2013) and SteadieSeifi et al. (2014) for recent reviews. Most of the literature on intermodal freight transportation states that intermodal transportation is an ecoefficient and sustainable alternative to truck transportation. However, the majority of these articles focus on a pure cost minimization model to assess if intermodal transportation can compete against road transportation. The literature on intermodal transportation taking carbon emissions into account is quite scarce. Janic (2007) proposes a model for calculating the full costs of an intermodal and road transport network. This cost includes the impact of the networks on society and the environment. Winebrake et al. (2008) present an energy and environmental analysis model to explore the tradeoffs among alternative routes in an intermodal transportation network. Cholette and Venkat (2009) present a case study in which several modes of transportation are available in a wine supply chain context. Their analysis accounts for cost, carbon emissions and energy consumption. Craig et al. (2013) calculate the carbon emissions intensity of intermodal transportation in the USA, based on a data set of more than 400,000 intermodal shipments. They show that some huge variations in carbon intensity exist and they apply the market area concept to explain these variations. Pan et al. (2013) investigate how freight consolidation and intermodal transportation can help in curbing carbon emissions. They formulate a carbon emissions minimization model in which both road and rail transportation are available. The model is applied to optimize the carbon emissions of two large retail chains.

The articles mentioned above take the perspective of a shipper who needs to decide among several transportation options including intermodal transportation. They assume that the intermodal network has already been designed and that the shippers aim at identifying the most efficient path in the network. Note that the comparison between direct shipment and terminal routing has also been extensively studied from a cost perspective (see e.g., Blumenfeld et al., 1985; Campbell, 1990; Daganzo, 1987; Hall, 1987a, 1987b). This stream of literature presents relevant and insightful results.

However, the increase in the distance traveled due to origin and destination drayage is determined at the design phase of the intermodal network when deciding on where to locate the intermodal terminals. Thus, considering network design decisions can be of great importance to better understand the tradeoff between efficiency gain in the linehaul and increase in distance traveled. To our knowledge, this problem has been considered in a single published article. Zhang et al. (2013) propose to include an environmental cost to the problem of optimally designing an intermodal network. They show in an example that the optimal layout of the network is sensitive to the carbon price. This demonstrates that taking carbon emissions into account at the design phase of an intermodal network may deserve attention. However, Zhang et al. (2013) primarily focus on solving a particular real life example. Their results provide limited insights into the dynamics of intermodal freight transportation with respect to cost, modal shift and carbon emissions.

Our work analyzes intermodal network design decisions from a cost, carbon emissions and modal shift perspective. We prove that maximizing the modal shift does not lead to the minimum level of carbon emissions and that there is a carbon optimal level of modal shift. Exceeding this optimal level of modal shift is harmful for both cost and carbon emissions. We also show that even if transportation cost and carbon emissions share the same structure, these two objectives lead to different solutions and that the terminal is located closer from the port when optimizing cost and further away when optimizing carbon emissions. The model also allows for studying the tradeoff between distance and volume. We show that intermodal transportation is feasible for short and medium distance if the volume is big and if the origin/destination drayage distances are low. We also prove that using an aggregated model for estimating train transportation emissions and cost negatively affects the performances of intermodal transportation and that this can lead to consider intermodal transportation as inefficient in situations in which such a solution could be implemented. We finally provide some insights on how to align cost and carbon emissions by using a tax scheme and/or subsidizing intermodal operations. We show that a well-chosen combination of a tax on truck transportation, a train usage fee and a subsidy via investment on the train network enables aligning cost and carbon emissions in an effective way.

The remainder of this article is organized as follows. Section 2 is devoted to the description of the model. Then, the model is solved and an example is presented in Section 3. The results are used in Section 4 to propose a series of insights. Finally, Section 5 is devoted to the conclusion.

2. Model description

2.1. Hypotheses

In this article, we study an intermodal hinterland network design problem. Hinterland networks are connected to at least one deepsea port and are primarily intended for the transportation of import and export flows, i.e., flows to and from the deepsea port. Hinterland networks play an important role in global supply chains due to the trend toward globalization. Moreover, the share of hinterland costs in the total transportation costs of a container shipping typically range from 40% to 80% (Notteboom and Rodrigue, 2005). Hinterland networks are also critical when focusing on intermodal transportation for several reasons. First, the container is the most common transportation unit used in intermodal hinterland networks (Crainic and Kim, 2007) and containerization has primarily been promoted by the maritime industry. Second, container transportation is expanding at an enormous pace. Indeed, world container traffic has been growing at almost three times world gross domestic product growth since the early 1990s (UN-ESCAP, 2005). We refer to Fransoo and Lee (2013) for a discussion on the critical role of container transportation in global supply chains. Third, hinterland networks imply an important concentration of the flows in the port area. This creates some favorable conditions for intermodal transportation as volume is often presented as a key issue for efficient train and barge transportation. Hinterland networks thus have a strong potential for intermodal transportation.

For the sake of clarity, we focus on import flows from a single port to various destinations. The problem could be reversed by considering export flows from various origins to a single port. Our results hold in that case. The flows under consideration are assumed to be containerized. As the dimension of containers have been standardized (Agarwal and Ergun, 2008), the proposed model takes only one type of container into account. Two options are available for delivering a container from origin to destination,