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A freight transport optimization model for integrated network, service, and policy design

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A B S T R A C T

This paper presents a freight transport optimization model that simultaneously incorporates multimodal infrastructure, hub-based service network structures, and the various design objectives of multiple actors. The model has been calibrated and validated using real-life data from the case study of hinterland container transport of the Netherlands, where CO_2 pricing, terminal network configuration, and hub-service networks are chosen as the design measures. Policy packages combining multiple types of policies show better network performance as compared with the optimal performance resulting from a single policy type. This illustrates the value of incorporating multiple types of policies simultaneously in freight transport optimization.

1. Introduction

Shifting freight flows from road to more sustainable transport modes such as rail, inland waterway and sea transport, has been recognized by the European Commission (EC) as an important policy strategy "to establish a sustainable transport system that meets society's economic, social and environmental needs" (CEC, 2006, 2009; EC, 2001). For decades, there has been continuous effort to promote and implement such a modal shift (CEC, 2006). However, the available statistics indicate that the volumes shifted from road to the other above-mentioned transport modes have been limited with the expectation of the modal split stabilizing in the longer term (CEC, 2006). Under such circumstances, the EC Freight Transport and Logistics Action Plan (CEC, 2007) emphasizes that more efforts are needed to achieve a more substantial modal shift. The latest policy strategy of the White Paper on Transport of the European Commission (EC, 2011) includes infrastructure development, service quality enhancement, and regulatory measures.

In order to evaluate the combined effects of various policy strategies applied to different regions or different actors, design and evaluation approaches need to be developed that simultaneously incorporate infrastructure, services, and regulation at a large spatial scope.

Freight transport system has been studied extensively (Caris et al., 2013; Crainic, 2000). However, one of the main contributions of this paper has been lacking: inclusion of the governmental perspective by considering the social, economic, and environmental issues that inherently increase network design complexity, and bring new challenges for solutions from the following perspectives.

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Firstly, in strategic network design from a governmental perspective, the spatial scope of policy impacts is often enlarged to the national or international level. Consequently, multiple transport modes are available, thus requiring that the choice of mode and terminal be considered when solving routing problem(s). While evaluating different transport options, the potential cost efficiencies realized by better utilization of capacities of corridors, terminals, fleets, and vehicles need to be considered. Secondly, multiple types of commodities bring heterogeneous criteria in the choices of network use. Different commodities with different appearances and values could require transport networks of diverse modes, speed, costs, reliability, and security. Finally, the multiple actors participating in freight transport can introduce different design objectives into decision making, and introduce possibilities for cooperation or competition.

In addition to evaluating the impacts of different types of policies simultaneously, the model proposed in this paper contributes to dealing with the above-mentioned complexities and challenges of freight transport network design.

Substantial research has been carried out in developing appropriate methods for assessing the performance of freight transport policies. For example, Beuthe et al. (2002) simulated the impacts of internalizing the external costs on multimodal freight flows over a real-life network. Groothedde et al. (2005) developed a many-to-many hub-based service network design model for distributing fast-moving consumer goods. Yamada et al. (2009) introduced a multimodal freight transport network design model for minimizing the network costs from the governmental perspective, and the route costs from the network users' perspective. Limbourg and Jourquin (2009) developed a hub allocation model, which provided the optimal locations of the European intermodal terminals given a certain number of hubs and the candidate locations of these hubs. The necessity of integrating the service networks was also recognized through an extension of this model (Jourquin et al., 2009a,b). Yamada et al. (2011) presented a network design model by considering the transport network and the supply chain network simultaneously. A review of the multimodal freight transport models developed since 2005 has been compiled by SteadieSeifi et al. (2014). However, none of these models has been able to evaluate infrastructure, service network development, and regulatory policies simultaneously.

This paper aims to fill this gap by focusing on the interaction between the infrastructure network, service network, and regulatory policies. The model presented could be used for strategic network design in a medium- to long-term, mainly considered from a governmental perspective.

In support of this approach combining the three design dimensions, we have developed an extended bi-level optimization model that combines the demand and supply side of the freight transport system with two main innovative features. The novelty of the supply-side model is the interaction between infrastructure and the service network, while an important novelty on the demand side is the multimodal route choice model which enables terminal choice and has been calibrated using the transhipment data of intermodal terminals. We are not aware of any literature that reports on the empirical validity of a freight virtual network model for actual transhipment volumes. The application of the combined approach to a case study for the Dutch hinterland container network has resulted in original findings concerning the sensitivity of overall network performance to the three design dimensions.

In addition to this introductory section, the paper consists of three other sections. Section 2 presents the mathematical structure of the proposed model. Section 3 explains the case of hinterland container transport in the Netherlands, as well as the data preparation, model calibration and validation of this application. We presents six cases of application and a number of implications for the policy makers derived from the above-mentioned applications. Section 4 contains our conclusions and discussion of the results including potential directions for further research.

2. Model specification

2.1. Basic structure of the model

In terms of its basic structure, the proposed model can be considered as a multi-actor, multi-commodity, multimodality freight transport network optimization model. It captures the objectives of the particular actors/stakeholders involved such as the government authorities at different institutional levels, terminal, and transport operators. Government objectives are assumed to be reduction of the total network costs and the CO_2 (Carbon Dioxide) emissions through the terminal network configuration and CO_2 pricing. The terminal operators' aims are assumed to be attracting more freight flows, achieving economies of density and economies of scale, and thus providing services at lower costs. Transport operators are assumed to collaborate, and if possible, operate hub-based inland waterway transport services in order to save costs by improving the efficiency of capacity utilization. Shippers are assumed to choose the least expensive transport mode, terminal, and route in order to reduce their costs.

The model is formulated as a bi-level optimization model with two pre-processing procedures. The objective of government is reflected at the upper-level of the problem, which searches for the optimal alternatives leading to the optimal network performances represented by the minimum total network generalized costs and CO_2 emissions. The lower-level assigns the multi-commodity flow to the multimodal network, thus minimizing the users' costs based on the costs of each (possible) route.

The objectives of terminal and transport operators are taken into account through two pre-processing procedures that are linked to the flow assignment at the lower-level of the problem. One pre-processing procedure minimizes the service costs considering economic fleet size, and barge size, given the predicted demand for hub-based barge services, while the other