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Joint optimization of logistics infrastructure investments and subsidies in a regional logistics network with CO_2 emission reduction targets

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A B S T R A C T

This study proposes an optimization model that simultaneously incorporates the selection of logistics infrastructure investments and subsidies for green transport modes to achieve specific CO_2 emission targets in a regional logistics network. The proposed model is formulated as a bi-level formulation, in which the upper level determines the optimal selection of logistics infrastructure investments and subsidies for green transport modes such that the benefit–cost ratio of the entire logistics system is maximized. The lower level describes the selected service routes of logistics users. A genetic and Frank–Wolfe hybrid algorithm is introduced to solve the proposed model. The proposed model is applied to the regional logistics network of Changsha City, China. Findings show that using the joint scheme of the selection of logistics infrastructure investments and green subsidies is more effective than using them solely. Carbon emission reduction targets can significantly affect logistics infrastructure investments and subsidy levels.

Introduction

Freight transportation is a major contributor to climate change, especially with global warming being attributed to various pollution emissions. Freight transportation is largely driven by the combustion of fossil fuels, mostly diesel fuel, which results in the emissions of greenhouse gases such as carbon dioxide (CO_2), nitrogen oxide, sulfur oxide, particulate matters, and air toxics (Qu et al., 2014). Freight transport is estimated to account for approximately 10% of energy-related carbon emissions (McKinnon et al., 2014). Therefore, implementing effective measures and policies to combat further environmental damage resulting from increased vehicular pollution emissions and developing sustainable, low-carbon regional transport and logistics systems are urgently needed.

Logistics network design and sustainable logistics management policies are two important aspects for developing a low-carbon regional logistics system. The former involves determining the optimal configuration of logistics infrastructure, whereas the latter mostly refers to subsidies for green transport modes or CO_2 emission taxes.

Determining optimal network configuration patterns and corresponding investment priorities for logistics infrastructure is an important objective in regional logistics network design (e.g., roads, railways, waterways, and logistics terminals)

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(Dablanc and Ross, 2012). Among all the configuration patterns of regional logistics network design, the configuration pattern based on a hub-and-spoke structure is the most widely applied (Wang, 2008). Alumur et al. (2012) investigated a hub location problem from the perspective of network design by jointly considering transportation cost and travel time and proposed a mixed integer programming formulation. Crainic et al. (2012) addressed a two-tiered freight distribution system in a large city to determine the optimal locations of logistics facilities.

The classic network design models based on a hub-and-spoke structure can efficiently describe the economies of scale by using transportation consolidation. However, such models cannot be used to characterize the interactive decision relationship among different shareholders. The freight network equilibrium models embedded with bi-level programming can capture the interactive decision relationships among different decision agents (logistics authorities, carriers, and shippers); these model involve seeking a transportation network supply configuration and a demand flow pattern that maximize a given objective function of a social type while satisfying the equilibrium constraint (Friesz et al., 1983; Harker and Friesz, 1986; Hurley and Petersen, 1994; Li et al., 2012b; Yang and Bell, 1998).

Harker and Friesz (1986) reviewed the major modeling techniques that had been applied in analyzing intercity freight network equilibrium and identified the shortcomings of spatial price equilibrium models. Guelat et al. (1990) investigated a multimode multiproduct network assignment model that had been used in Brazil to simulate flows, service levels, costs, and fuel consumption on the national multimodal freight network for multiple planning alternatives. Yamada et al. (2009) investigated the optimization problem of the multimodal freight transport network design and utilized a bi-level programming model for selecting a suitable set of actions from a set of alternatives (such as opening shipping lines, building ports, or adding new railways) with the objective of maximizing the benefit–cost ratio (BCR). Loureiro and Ralston (2001) developed a multi-commodity multimodal network optimization model designed to provide additional insights into the strategic stage of planning investments for intercity freight transportation networks; this model is solved with a heuristics algorithm combined with a column generation method. With the goal of minimizing total transportation costs, Meng and Wang (2011) developed an optimal programming model with equilibrium constraints for the intermodal hub-and-spoke network design problem to locate hubs and set highways, waterways, and railway corridors. Catalano and Migliore (2014) presented an optimal model for the design of logistics terminals based on the Stackelberg game, which aims to determine optimal location patterns and public shares in investments. This study revealed that transshipment and consolidation services should be concentrated at a few terminals to fully exploit economies of scale at the expense of the average travel time to reach logistics platforms. For a comprehensive review of multimodal freight network design, interested readers can refer to the references (Crainic, 2000; Crainic et al., 2009; SteadieSeifi et al., 2014).

The traditional logistics network design model mainly focuses on total costs or operator efficiency and only slightly considers external environmental costs. On the contrary, the green logistics network design problem focuses on improving logistics service efficiency, decreasing corresponding logistics costs, and reducing externalities while achieving a sustainable balance between economic, environmental, and social objectives (Dekker et al., 2012; Elhedhli and Merrick, 2012; McKinnon et al., 2012). Harris et al. (2011) assessed the effect of the traditional cost optimization approach to strategic modeling on overall logistics costs and CO_2 emissions by considering the supply chain structure and different freight vehicle utilization ratios. Their work indicated that the optimum design based on costs does not necessarily equate to an optimum solution for CO_2 emissions. Furthermore, a number of studies on logistics network design models integrate environment-related costs (e.g., GHGs) and the interactive decision relationship between logistics authorities and logistics users. The integrated logistics network optimization model is usually solved with bi-level programming; the upper level in this formulation searches for the optimal combinations of policy measures, whereas the lower level considers the behavior of network users when selecting logistics service routes (Nagurney and Toyasaki, 2003; Rudi et al., 2014; Zhang et al., 2015a,b).

Congestion pricing has been proposed as an efficient way to alleviate traffic congestion and to improve social welfare (Hammadou and Papaix, 2015; Wu et al., 2011). Yin et al. (2014) addressed the road toll pricing and capacity in a congested road network in a multi-criteria decision making framework by using a goal approach; this work provided an avenue for understanding the trade-offs among conflicting objectives and for designing a financially and environmentally sustainable transportation system. Dandotiya et al. (2011) addressed the joint optimization of freight rates and the terminal location problem to determine the optimal freight rate and the corresponding intermodal terminal location. King et al. (2014) examined the effect of road pricing on port freight activity in New York and New Jersey, USA. Their work showed that toll charges in the New York City metropolitan region may represent over 50% of the total costs for a short haul truck trip into or out of a maritime port depending on the location of the port facility and that road toll programs can impose non-trivial costs on truck trips to and from major regional freight centers.

Chen et al. (2014) investigated the coastal liner route design model for coastal intermodal networks subject to CO_2 emission reduction targets and state subsidy levels. The optimal model aims to determine ports of call, call sequences, ship types, and service frequencies and to minimize state subsidies for coastal shipping operators under a given carbon emission reduction target for the entire intermodal network. Bhadury and Eiselt (2012) developed a three-level location model to investigate the relationship among consumers, firms, and regional planners. The lowest level of the model describes the purchasing behavior of customers. At the second level, firms establish the optimal number of distribution centers to open with consideration of location costs, operation costs, and government subsidies. At the third and highest level, regional planners determine the optimal subsidies to maximize the total social welfare.

To the best of our knowledge, existing related studies integrating logistics infrastructure investments and subsidies for green transport modes are still scarce. The present work aims to fill this gap by focusing on the joint optimization of logis-