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The design of coastal shipping services subject to carbon emission reduction targets and state subsidy levels

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ABSTRACT

This paper presents a New Coastal Liner Route Design Model (NCLRDM) for coastal intermodal networks based on the user equilibrium assignment model (UE model). The NCLRDM can determine ports of call, call sequence, ship type and service frequency simultaneously with the objective of minimizing state subsidies for coastal shipping operators under a given carbon emission reduction target for the entire intermodal network. A network-topology method (Temporal–Spatial Expansion) captures differences in traffic assignment between waterway and highway networks. A genetic and Frank–Wolfe hybrid algorithm is used to solve the NCLRDM. The model is applied to the Bohai Bay in China.

1. Introduction

1.1. Background

Coastal liner shipping is a crucial component of the transport system in coastal regions. It is only since the late 1980s that coastal shipping has been recognized as a genuine sector with specific properties, specific problems and a specific task in regional freight mobility. In Europe, increased European integration, growing intra-European trade and a focus on an environment-friendly modal split led to a renewed interest in coastal shipping both in logistics and transport policy-making. In Asia, growing intra-regional trade and fast economic development have urged policy makers and market players to promote the use of coastal services. In the US, many impediments in American shipping regulations gravitating around the US Merchant Marine Act of 1920 (also known as the Jones Act) have led to only limited services between American ports. The Jones Act, which basically states that cargo may not be transported between two US ports unless it is transported by vessels owned by citizens of the US, built and registered in the US, and manned by a crew of US nationals, implies that the potential of domestic shipping in North America remains underutilized (Brooks and Trifts, 2008). During the last 50 years, the Jones Act has been revised many times, and the most recent version is the re-codified version of 2006. Invariably, the purpose is the same: to support the US coastal shipping industry.

Coastal shipping faces fierce competition from truck services in many regions around the world (García-Menéndez and Feo-Valero, 2009; Ng, 2009; Notteboom, 2011). Still, policy-makers and market players have also come to realize that the

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biggest potential for coastal shipping is not found in a direct confrontation with road transport through 'the modal shift' idea, but in its complementary function to road transportation and other modes (López-Navarro et al., 2011). This is where the relevance of the concepts of co-modality and synchro-modality come into play. It has also been recognized that coastal shipping can significantly contribute to a decrease in greenhouse gas emissions in coastal areas (Perakis and Denisis, 2008).

Coastal shipping operators are challenged to develop efficient services using larger ships, raising service frequency and increasing the number of ports of call. However, coastal shipping operators seldom do this voluntarily as such measures typically raise the operating cost. In many cases, the increased cost can hardly be offset by the benefits induced by the increased market scale (García-Menéndez and Feo-Valero, 2009). Facing this situation, some governments have introduced incentive policies. For example, the European Commission developed the Motorways of the Sea program with specific rules on State aid and Community funding (European Union, 2008; Douet and Cappuccilli, 2011). In the US, the "America's Marine Highway Program" is implemented to mitigate landside congestion and to reduce greenhouse gas emissions per ton-mile of freight moved in the Great Lakes/Saint Lawrence Seaway System, intra-coastal and coastal waterways (MARAD, 2011). In both cases, governments underline that the full range of public benefits of coastal services cannot be realized based solely on market-driven transportation choices. Hence, the development of a range of legislation and regulatory actions and financial support programs. These measures are aimed at helping operators to improve services, to introduce new coastal services, to raise the modal share of coastal shipping and to reduce the emissions generated by the entire regional transport system.

Therefore, the design of coastal liner services is not only a task for the operators, but may be influenced by governmental measures in the area of environmental policy and financial incentives. A competitive coastal liner service generates an operating profit and reduces carbon emissions with fewer or no subsidies.

1.2. Scope and aim of the paper

This paper analyzes two critical problems linked to the above discussion on the competitiveness and efficiency of coastal liner services: (a) how to design an efficient coastal liner service given a pre-determined carbon emission reduction goal; (b) how to determine the subsidy needed (if any) in order to minimize the operating loss of coastal service operations on a specific route. We introduce a Coastal Liner Route Design (CLRD) model whereby the objective function is aimed at minimizing the operators' loss and minimizing the need for state subsidies. The resulting complex CLRD problem is deeply affected by the ports of call, the call sequence, the ship type, the service frequency, and the traffic flow on the intermodal transport network (highway and maritime transport). Among them, the traffic flow is most crucial as it determines both the profit of the operators and the carbon emissions in the whole transport system. Thus, we propose to use traffic assignment on the intermodal transport network as the technical basis for the CLRD.

Several theories and application methods exist dealing with the traffic assignment problem. The User Equilibrium (UE) model is widely accepted. However, in order to utilize the UE model, one needs to know the "impedance function" of the links in the network. The function should be monotonous and differentiable. For highway links, the Bureau of Public Roads (BPR) function has been formulated (Sheffi, 1984). However, existing literature does not offer any insights on the impedance function for maritime or waterway links. If the differences between waterway and highway links are not considered, the results of the UE model might deviate significantly from the actual situation.

There are two key differences between highway and waterway links. First of all, a highway link is a facility corridor. Theoretically, it can be used by any user (cargo) at any time. A waterway link is a service channel, which consists of "ship" and "route". As liner ships sail on a fixed route between fixed ports of call on a regular pre-determined basis, the liner sailing schedule will determine the use of the waterway link. For example, if some cargos do not make it to the ship in time, they cannot be transported immediately and have to wait for the next ship. This feature is called "Periodic Connectivity (PC)". Secondly, all users of a highway link have the same or at least a very comparable travel speed. When congestion occurs, the speed of all users on the link will decrease by the same amount. However, congestion on a waterway link implies that the traffic volume is greater than the ship's capacity. When congestion occurs, the loaded cargos are still able to pass the link at normal speed, but for the cargos not loaded, the travel speed is zero. This feature of waterway links is referred to as the Asynchronous Change of Travel Speed (ACTS). PC and ACTS have to be taken into account when assigning traffic flows on an intermodal network.

Considering the two specific features of waterway/maritime links, this paper studies the CLRD from the perspective of state subsidy reduction, and develops a New Coastal Liner Route Design Model (NCLRDM) to optimize the selection of ports of call, the call sequence, the ship type and the service frequency simultaneously, with the objective of minimizing state subsidies.

First, we utilize a network-topology method (i.e. Temporal–Spatial Expansion) to deal with the PC and ACTS problems. This method can improve the reliability of the results of the UE model, and more importantly, it provides a simple, effective and realistic avenue for assigning traffic on liner-like networks, which are formed by large capacity transport units operating on fixed paths on a regular scheduled basis (e.g. railway transport networks or air transport networks). Next, we present the expression of the NCLRDM, and develop a Genetic and Frank–Wolfe Hybrid Algorithm (GFWHA) to solve the model.

The remainder of this paper is organized as follows: Section 2 reviews the relevant literature. Section 3 proposes the method of Temporal–Spatial Expansion and defines the impedance functions of the highway and waterway links. Section 4 develops the NCLRDM. Section 5 presents the GFWHA. Section 6 presents a numerical test to examine the model and the