INSTITUTE of TRANSPORT and LOGISTICS STUDIES
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Inland shipping network of LNG-fueled ships under emission control
- The case of China’s Belt and Road shipping corridor along the Yangtze river

Liquefied natural gas (LNG) is used as an environmentally friendly source of fuel for inland river shipping in selected markets. However, the investment costs for bunkering stations and the price volatility of LNG have prevented it from being used more widely. In this study, we investigate the operation of LNG-fueled shipping in an inland river network, taking into account the effects of emissions regulations, the bunkering station locations, the price competitiveness of LNG, and the heterogeneity of the navigational conditions in inland rivers. The model is used to study bulk-cargo transportation along the Yangtze River, a major inland waterway of growing importance due to the Chinese government’s Belt and Road initiative. The modeling results suggest that the optimal shipping operations and bunkering station locations are significantly affected by the emissions regulations and incentive policies. In the Yangtze River market studied, low-sulfur fuels are the preferred option for carriers at a wide range of emission control levels. However, LNG only becomes an attractive fuel option when the emissions cap is set significantly below the current emissions level. For the promotion of LNG-fueled shipping, unit fuel subsidies are more effective than lump-sum capital subsidies for bunkering stations when the LNG price is high. However, the availability of bunker stations is an important factor when the LNG price volatility is considered. Overall, our results suggest that although LNG-fueled shipping is a promising option in the long term, the optimal industry policy on fuel use is dependent on multiple factors including the fuel price, types of subsidy, and emissions targets.

LNG-fueled shipping, inland waterway, green shipping, bunkering station choice, Belt and Road initiative

Yu, Bell, Fu and Ge

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1. Introduction and industry background

The emissions from shipping and the maritime industry contribute significantly to air pollution. Corbett et al. (2007) used atmospheric modeling to assess the mortality from ship emissions and, as expected, found that regions with the greatest mortality effects were around busy ports. In consideration of the effects of shipping emissions, the IMO released stricter Tier III emission standards, which from 2016 onwards, all vessels must meet to travel through emission control areas (ECA). As a result of the stricter emissions requirements, shipping companies may not pass through the ECA by simply tuning the existing technology. Because most of the current engines would have to be equipped with costly post-treatment systems to comply with the government regulations, many carriers have sought to address this issue at the source by using clean fuels such as liquefied natural gas (LNG) or biomethane/compressed natural gas. LNG has been identified as a promising option due to its better environmental and economic performance. Anderson et al. (2015) have shown that there is great interest in using LNG as a marine fuel, particularly from an environmental perspective because of its considerably lower associated emissions of particles, NOX, SO2, and CO2. Moreover, Argyros et al. (2014) predict that in the long-term, the price of LNG will remain very competitive compared to most other fuels.

Many carriers have considered using LNG as a more economical and less polluting alternative fuel, especially on inland shipping routes where there are increasing environmental concerns. A number of studies have analyzed the feasibility of LNG fueled shipping under various emissions regulations, with a focus on the potential of using small size ships on coastal and inland shipping routes (see, for example, Schinas and Butler 2016, Wang and Notteboom 2014, Yallouros 2015, Xu et al. (2015), Hua et al. 2017, Seddiek 2015, Peksen et al. 2016, Elgohary et al. 2015, Brynolf et al. 2014a, Aroniets 2016, Brynolf et al. 2014b, Adachi et al. 2014, Yoo 2017, Ren and Lützen 2015, Soundararajan and Han 2014, Tichavska and Tovar 2015). Most of these studies predict good growth potential for LNG fueled ships, which is broadly consistent with the (emerging) market trends. In January 2018, DNL GL (2018) reported that 119 LNG-fueled ships were operating globally, with another 125 LNG-fueled ocean ships on order. Calderón et al. (2016) note that the LNG-fueled fleet is continuing to expand and the trend is to build smaller size ships for shorter routes. Smith et al. (2014) predict that pure LNG and dual fueled ships will be extensively used in the chemical tanker and product tanker markets for the less than 5k DWT segment. Many of these ships are used for inland river transport. The 2014 LNG Masterplan for Rhine-Main-Danube stated that 20 LNG-fueled vessels, which mainly included car/passenger ferries, Ro-Ro, LNG carriers, chemical tankers, and product tankers, were planned to be introduced in Europe (Pro Danube International, 2014). Fan et al. (2018) report that in China, more than 200,000 ships operate on inland waterways. The Interfax Information Services Group reports that there were 127 ships capable of running on LNG at the end of March 2017, comprising 90 newly built and 37 retrofitted vessels. Fan et al. (2018) also predict that by 2025, there will be about 2800 LNG-fueled vessels operating in the Yangtze River area, 700 vessels in the Pearl River area, and 3500 vessels in the Beijing-Hangzhou Canal.

The wide use of LNG in inland shipping calls for new infrastructures and operational practices. The Danish Maritime Authority (2012) and Adamo (2018) examined the value chain of LNG-fueled inland shipping, which can be illustrated as in Figure 1.
As shown in Figure 1, after extraction and liquefaction, the LNG is ready to transport to the downstream consumers. The suppliers of LNG usually have long-term contracts ranging from 20-25 years with their downstream customers. Once a contract is in effect, the supplier will deliver LNG following an annual delivery schedule (ADS). The ADS stipulates the LNG delivery plan from the LNG supplier to LNG terminals or directly to regasification terminals through LNG carriers or pipelines, which implies that long term planning is very important. Goel et al. (2012), Goel et al. (2015), and Halvorsen-Weare et al. (2013) studied the routing and scheduling of LNG deliveries in ADSs in relation to minimizing the transport costs. Recently, major LNG import countries such as China, Japan, and Korea began initiating new LNG receiving terminals along their coasts, which will serve as the junction points of their LNG transport networks. When imported LNG arrives at these junction terminals, barges and tankers transport the gas to bunkering stations or regasification terminals for inland shipping use.

As discussed, within the overall LNG supply chain of inland shipping networks, LNG terminals and bunkering stations are key facilities that can significantly influence the overall system operations. A few recent studies have examined the important decisions related to such infrastructures. Wang and Notteboom (2015) point out that the port authorities in Europe are playing a proactive role in facilitating the use of LNG-fueled shipping. They provide the details of the port practices in developing LNG bunkering infrastructure in Northern Europe and propose a set of port implementation policies to promote LNG fueled shipping. Calderón et al. (2016) outline the LNG import facilities in European terminals and show that the demand for LNG bunkering is gradually increasing, especially for inland and coastal shipping. Yun et al. (2015) propose a new conceptual design for an offshore LNG bunkering terminal in Korea, which can be used to receive and temporarily store imported LNG and then export to LNG bunkers or directly to LNG-fueled ships. These studies offer fresh insights into this emerging industry trend and identify the key challenges that need to be addressed. However, many of the existing studies do not use systematic analytical approaches to provide optimal designs of LNG-fueled ship networks with bunkering facilities.

Many studies have discussed shipping networks and the design of bunker stations (see, for example, Wang et al. 2013a, 2013b, Ishii et al. 2013, Zhen et al. 2016, Zheng and Yang
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2016, Teye et al. 2017, Tu et al. 2018, Tan et al. 2018). Moreover, Aymelek et al. (2014) examine the planning of bunkering management for ocean shipping. However, these studies mostly focus on marine shipping and need to be extended to the case of LNG shipping along inland waters. For example, ship size is an important factor in long distance LNG shipping, such as on the Yangtze River in China and the Mississippi River in the U.S., because there is significant heterogeneity in the navigational conditions along these rivers (e.g., in the depth and width of the shipping routes). The heterogeneity caused by seasonal and geographical variations also imposes tight constraints on the shipping size choices, which must be incorporated into the planning and operations (Tan et al. 2015). Another important issue is the interactive effects of the shipping demand, fuel price, bunker station choices, and government intervention. Building new LNG bunker stations involves substantial fixed costs and is only economical if there is sufficiently high shipping demand and the LNG price is competitive against alternative fuels. Alternatively, if only a small number of LNG bunker stations are available, the attractiveness of LNG will be reduced, thus leading to low traffic volumes and network coverage of LNG shipping, which will further reduce the incentives to adopt LNG shipping. A natural choice to address such a “chicken-and-egg” problem is government subsidies. However, few studies have quantitatively analyzed the optimal/economical types of subsidy (e.g., subsidies on LNG fuel vs. subsidies on bunker station construction).

To address these research gaps, this study investigates the operation of LNG-fueled shipping in an inland river network, simultaneously taking into account the effects of the emissions regulations, bunkering station locations, price competitiveness of LNG, and the heterogeneity of the navigational conditions along the inland rivers. A model is applied to study the bulk-cargo transportation along the Yangtze River, a major inland waterway of growing importance due to the Chinese government’s Belt and Road initiative. Our results suggest that the optimal shipping operations and bunkering station locations are significantly affected by the emissions regulations and incentive policies. To promote LNG-fueled shipping, unit fuel subsidies are more effective than lump-sum capital subsidies for bunkering stations when the LNG price is high. However, the availability of bunker stations is an important factor when the LNG price volatility is considered. Our results suggest that although LNG-fueled shipping is always attractive in the presence of strict emissions regulations, choosing the right industry policy is very important for the promotion of green shipping.

The rest of this study is organized as follows. Section 2 briefly introduces the development of the shipping industry in China, with a focus on inland shipping and the government policies on LNG fuel use. Section 3 presents the model formulation, which is used to study the inland shipping network along the Yangtze River in Section 4. The last section summarizes and concludes the study.

2. The Chinese shipping market
In recent decades, China has become one of the most important shipping markets in the world. Linking inland trade cities such as Wuhan and Chongqing to global hub ports in Shanghai and Ningbo, the Yangtze River is of critical importance to China’s national shipping network. In 2013, the Chinese government proposed the Belt and Road initiative to promote economic, trade, and political cooperation along the Asia–Middle East–Europe region. Inland cities such as Chongqing and Chengdu have become important nodes in the Eurasian land bridge,
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attracting high value-added and/or time sensitive cargoes. As a result, the inland waterway along the Yangtze River is expected to carry significantly higher traffic volumes in coming years to better serve the country’s major trade and transport gateway cities.

Emissions and environment related issues are of increasing public concern in China. The Ministry of Transport of China (MOT) released the Implementation Program for Ship Emission Control Areas in the Pearl River Delta, the Yangtze River Delta and around the Bohai Sea (IP2015), which defines the ECA along the eastern coast of China as depicted in Figure 2. All vessels must meet the requirement of less than 0.5% m/m SO2 emissions from 2019 to travel in the Chinese ECA. Because the major inland waterways pass through many metropolitan cities, emission controls are of even greater importance for the sector’s growth. Thus, the promotion of LNG-fueled shipping has been identified as a key industry policy. To promote the use of LNG-fueled shipping, in 2013 the MOT released the Guidelines for Promoting LNG-fueled Waterway Shipping (GD2013) to provide a step by step basis for developing LNG-fueled shipping. In 2017, the MOT released the Guidelines for Promoting Green-shipping Development along the Yangtze River (GD2017), which outline the infrastructure building plans related to LNG-fueled shipping, and proposed the Scheme of Locating LNG Bunkering Terminals along the Yangtze River, West River and Beijing-Hangzhou Canal (2017-2025) (S2017-2025) to improve the availability of LNG along these inland shipping networks. The planned bunkering stations are also depicted in the Figure 2. The development of LNG-fueled inland shipping in China is nearing a critical mass stage, at a time when gas consumption in China is expected to grow from 200 billion cubic meters (bcm) in 2016 to 340 bcm in 2022 (Chrisopoulou 2018).

Figure 2. Green shipping schemes along China’s coastal and inland waterways
As part of the government’s support for green shipping initiatives, China’s 13th Five-Year Plan provides strong policy support for clean energy use, including LNG-fueled inland shipping. This has led to substantially higher LNG imports (Chrisopoulou 2018). Since 2016, China has been pushing forward plans to build more LNG receiving terminals along the mainland coast. Jiaqing et al. (2016) reviewed the LNG terminals in operation and under construction along the mainland coast, which are summarized in Table 1. The construction of these additional LNG receiving terminals will greatly improve the supply of LNG fuel to the inland LNG-fueled shipping networks along the Yangtze River, Pearl River, and Beijing-Hangzhou Canal.

Table 1. Capacity of LNG terminals in operation and planning along the China coast (10,000 tonnes/year)

<table>
<thead>
<tr>
<th>Area</th>
<th>Province</th>
<th>City</th>
<th>In operation</th>
<th>Under Construction</th>
<th>Planning</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Guangdong</td>
<td></td>
<td>Shenzhen</td>
<td>370</td>
<td>400</td>
<td>300</td>
<td>1070</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Zhuhai</td>
<td>550</td>
<td></td>
<td>300</td>
<td>850</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dongguan</td>
<td>100</td>
<td></td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Pearl River Delta</td>
<td></td>
<td>Jieyang</td>
<td>200</td>
<td></td>
<td></td>
<td>200</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Maoming</td>
<td>300</td>
<td></td>
<td>300</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Shantou</td>
<td>150</td>
<td></td>
<td>150</td>
<td></td>
</tr>
<tr>
<td>Hainan</td>
<td></td>
<td>Yangpu</td>
<td>300</td>
<td></td>
<td>300</td>
<td></td>
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<tr>
<td>Guangxi</td>
<td></td>
<td>Beihai</td>
<td>300</td>
<td></td>
<td></td>
<td>300</td>
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<tr>
<td></td>
<td></td>
<td>Qinzhou</td>
<td>300</td>
<td></td>
<td></td>
<td>300</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Putian</td>
<td>260</td>
<td></td>
<td>300</td>
<td>560</td>
</tr>
<tr>
<td>Fujian</td>
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<td>Zhangzhou</td>
<td>300</td>
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<td>Wanan</td>
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<td></td>
<td></td>
<td>300</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Nantong</td>
<td>350</td>
<td>60</td>
<td></td>
<td>410</td>
</tr>
<tr>
<td>Jiangsu</td>
<td></td>
<td>Lianyungang</td>
<td>300</td>
<td></td>
<td></td>
<td>300</td>
</tr>
<tr>
<td>Yangtze River Delta</td>
<td></td>
<td>Yancheng</td>
<td>300</td>
<td></td>
<td>300</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ningbo</td>
<td>300</td>
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<tr>
<td>Zhejiang</td>
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<td>Zhoushan</td>
<td>300</td>
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<tr>
<td></td>
<td></td>
<td>Wenzhou</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shanghai</td>
<td></td>
<td>Shanghai</td>
<td>350</td>
<td></td>
<td></td>
<td>350</td>
</tr>
<tr>
<td>Anhui</td>
<td></td>
<td>Wuhu</td>
<td>100</td>
<td></td>
<td></td>
<td>100</td>
</tr>
<tr>
<td>Tianjin</td>
<td></td>
<td>Tianjin</td>
<td>220</td>
<td>300</td>
<td>520</td>
<td></td>
</tr>
<tr>
<td>Hebei</td>
<td></td>
<td>Tangshan</td>
<td>350</td>
<td></td>
<td></td>
<td>350</td>
</tr>
<tr>
<td>Bohai Gulf</td>
<td></td>
<td>Qinhuangdao</td>
<td>300</td>
<td></td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>Liaoning</td>
<td></td>
<td>Dalian</td>
<td>300</td>
<td></td>
<td></td>
<td>300</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Yingkou</td>
<td>300</td>
<td></td>
<td></td>
<td>300</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Qingdao</td>
<td>300</td>
<td></td>
<td></td>
<td>300</td>
</tr>
<tr>
<td>Shandong</td>
<td></td>
<td>Yantai</td>
<td>150</td>
<td></td>
<td>150</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Weihai</td>
<td>300</td>
<td></td>
<td>300</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>3750</td>
<td>1860</td>
<td>3900</td>
<td>9510</td>
</tr>
</tbody>
</table>
Despite the strong government will to promote LNG-fueled shipping in China, shipping firms will only invest in large scale LNG operations if it brings economic benefits. These firms also need better advice and planning tools to implement the transition from traditional fuel to LNG. These challenges likely explain the rather low percentage of LNG-fueled ships in the current global shipping fleet. In the following section, we develop a model with which LNG-fueled shipping networks can be designed for inland waterways. The model also allows us to evaluate alternative government policies.

3. Model specifications

As mentioned, LNG bunkering is a key challenge when it comes to running ships on LNG. Although a few studies have considered the effects of bunkering demand management on LNG-fueled shipping, they mostly examine the maritime context instead of inland shipping. In this section, we develop a model to investigate the operation of LNG-fueled shipping in an inland river network, taking into account the effects of emissions regulations, the bunkering station locations, price competitiveness of LNG, and heterogeneity of the navigational conditions of inland rivers.

We consider a model in which the operator (e.g., a shipping company or transport planner) minimizes the total cost of transporting cargo over the origins and destinations by making the following decisions: (a) the types and locations of LNG bunkering stations to be newly built,¹ (b) the amount of cargo to be delivered by LNG ships and traditional ships, respectively, and (c) the operational plans, which include the ship type, types of bunkering station (if carried by an LNG ship) or type of fuel (if carried by a traditional ship). This problem is formulated as an MILP model in a similar style as the multi-modal terminal planning model of Teye et al. (2017).

The model specification is as follows.

Sets:

\(O\) : set of origin terminals indexed by \(i\).
\(D\) : set of destination terminals indexed by \(j\).
\(S_l\) : set of types of LNG-fueled ships indexed by \(s\). Because of the heterogeneity of the navigation conditions alone the inland river, the candidate ship set for a leg, denoted as \(S_{ij}\), is the set of candidate LNG-fueled ships available for the leg from terminal \(i\) to terminal \(j\),² where \(S_{ij} \in S_l\).
\(S_p\) : set of types of traditional ships indexed by \(s'\) and \(S_{ij}'\) is the set of candidate types of

¹ In practice, different bunkering methods can be applied, with three main options for inland bunkering terminals: (1) bunker from truck to ship (TTS); (2) bunker from bunkering pontoons to ship (PTS); and (3) bunker from a shore tanker with pipeline to ship (TPS). The storage of TTS tends to be quite small, whereas TPS is very expensive to implement. Fan et al. (2018) argue that rivers such as the Yangtze River and Pearl River have greatly varied channel widths and seasonal water levels, making TPS infeasible for most inland ports. As a result, bunkering pontoons are the first choice and are already in operation along the Yangtze River (Fan et al. 2018). This type of operation is considered in our study.

² The candidate LNG-fueled ships are chosen from those that can be used to navigate from terminal \(i\) to terminal \(j\) with full fuel.
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traditional ships for the leg from terminal $i$ to terminal $j$, where $S_i \in S_p$. $N$ : set of different kinds of bunkering stations, indexed by $n$. $M$ : set of different kinds of fuel that can be used, indexed by $m$. $f_{in}$ : fixed cost of building a type $n$ LNG bunkering station at terminal $i$. $F_{in}$ : the maximum LNG fuel storage of a type $n$ bunkering station at terminal $i$. $u_{ij}$ : the unit cargo LNG fuel demand of ship $s$ from terminal $i$ to destination terminal $j$. $q_{ij}$ : the quantity of cargo to be transported from origin terminal $i$ to destination terminal $j$. $\alpha_s^i(j)$ and $\alpha_s^{im}(j)$: fuel consumption for carrying a unit of cargo by ship $s$ and $s'$ from terminal $i$ to terminal $j$. For traditional ships, $m$ types of fuel may be used. $\beta_s^i(j)$ and $\beta_s^{im}(j)$: emissions caused by the consumption of one unit of fuel by ship $s$ and $s'$ from $i$ to $j$, where for the traditional ships the fuel consumption is also related to the $m$ types of the fuel applied. $E$: upper limit (cap) of emissions for the inland river. $Q_s$ and $Q_s'$ are the capacity for ship $s$ or $s'$ with full load, respectively. $\theta_{ij}$ and $\theta_{ij}'$ are the average transportation cost for ship $s$ or $s'$ with full load from terminal $i$ to $j$, respectively.

The general costs of transport for different types of ships are:

$c_{ij}^s$ : the cost of delivering one unit (ton or TEU) of cargo from origin terminal $i$ to destination terminal $j$, when the cargo is carried by LNG-fueled ship $s$ and is refueled by a type $n$ bunkering station.

$c_{ij}^m$ : the cost of delivering one unit (ton or TEU) of cargo from origin terminal $i$ to destination terminal $j$, when the cargo is carried by a traditional ship $s'$ and a type $m$ fuel is used.

These two costs are calculated as $c_{ij}^s = c_{in} + c_i^s + c_q^s$ and $c_{ij}^m = c_{in} + c_i^m + c_q^m$, where $c_i^s$ is the bunkering cost associated with carrying one unit of cargo using type $n$ bunkering station at terminal $i$ for ship $s$. $c_i^s$ and $c_i'$ are the terminal $i$ cost for handling one unit of cargo for ship $s$ or $s'$, respectively. $c_q^s$ is the transport cost for moving one unit of cargo from terminal $i$ to destination $j$ using LNG-fueled ship $s$. $c_q^m$ is the unit transport cost from terminal $i$ to destination $j$ using traditional ship $s'$ with fuel $m$.

The objective function can be specified as the MILP problem in Eq. (1), where the decision variables are:

$S_i$ equals 1 if a type $n$ bunkering station is built on terminal $i$.

$X_{ij}^s$ is the quantity of cargo to be transported by LNG-fueled ship $s$ and refueled by a type $n$ bunkering station from origin terminal $i$ to destination terminal $j$ (tons or TEU per day).

$X_{ij}^m$ is the quantity of cargo to be transported by ship $s'$ from origin terminal $i$ to destination terminal $j$ (tons or TEU per day) with fuel $m$. 


$Y_{ij}^s$ and $Y_{ij}^{s'}$ are the number of vessels $s$ or $s'$ for each day of transportation from terminal $i$ to $j$.

**Objective:**

$$\text{Min } f = \sum_{i=0}^{n} X_{ij}^w c_{ij} + \sum_{i=0}^{n} X_{ij}^w c_{ij} + \sum_{i=0}^{n} S_{ij} f_{ij} + \sum_{i=0}^{n} \theta_{ij} Y_{ij}^w + \sum_{i=0}^{n} \theta_{ij} Y_{ij}^{w'} - \sum_{i=0}^{n} \sum_{j=0}^{n} X_{ij}^w \frac{Q_i}{Q} - \sum_{i=0}^{n} \sum_{j=0}^{n} \sum_{s=0}^{n} X_{ij}^{w'} \frac{Q_i}{Q}$$

(1)

Here, the main objective (1) of our model is to minimize the total cost of the transport network, subject to:

$$\sum_{i=0}^{n} X_{ij}^* + \sum_{i=0}^{n} X_{ij}^{*'} = q_{ij}, \forall i, j \in D$$

(2)

$$\sum_{i=0}^{n} X_{ij}^* \alpha_i^*(j) \beta_i^*(j) + \sum_{i=0}^{n} X_{ij}^{*'} \alpha_i^{*'}(j) \beta_i^{*'}(j) \leq E$$

(3)

$$\sum_{i=0}^{n} X_{ij}^* u_{ij} \leq S_{in} F_{in}, \forall i \in D, n \in N$$

(4)

$$\sum_{i=0}^{n} \sum_{j=0}^{n} X_{ij}^* \leq Y_{ij}^w, \forall i \in O, j \in D, s \in S_i$$

(6)

$$\sum_{i=0}^{n} \sum_{j=0}^{n} X_{ij}^{*'} \leq Y_{ij}^{w'}, i \in O, j \in D, \forall s' \in S_p$$

(7)

$$S_{in} \in \{0, 1\}, \forall i \in O, n \in N$$

(8)

$$X_{ij}^* \geq 0, X_{ij}^{*'} \geq 0, Y_{ij}^w \geq 0, Y_{ij}^{w'} \geq 0, \forall i \in O, j \in D, n \in N, m \in M, s \in S_i, s' \in S_p$$

(9)

Eq. (2) guarantees that every shipment of cargo will be delivered, either by the LNG-fueled ships or traditional ships within the candidate ship sets from $i$ to $j$. Eq. (3) constrains the total emissions under the requirements of the emission regulations. Eq. (4) guarantees that the total LNG fuel demand is no more than the LNG storage of the type $n$ bunkering stations, and all of the LNG fuel demand should be fulfilled by the bunkering stations in the origin terminals of the shipping leg. Eq. (5) guarantees that no more than one type of bunkering station will be built at any location $i$. Eq. (6) and Eq. (7) describe the constraints of $Y_{ij}^w$ and $Y_{ij}^{w'}$. Constraints (8) and (9) describe the value range of each variable.

### 4. Inland shipping along the Yangtze River

The above model can be used to study the inland shipping operations along the Yangtze River. In this section, we first calibrate the model with the specifications of the key parameter values. Alternative scenarios are then analyzed so that relevant insights can be obtained for the Yangtze River inland shipping market in particular and LNG shipping in general.
4.1. Model calibration
According to the S2017-2025 plan, 45 bunkering stations are planned to be installed along the Yangtze River from Yibin port to Shanghai port. In our case, we simulate the origin-destinations of the cargo transportation between eight main ports based on the 2016 China Ports Yearbook and only consider the SO2 emissions. The details of the cargo flows are reported in Table 2. We consider three types of bunkering stations from small to big based on Fan et al. (2018), as summarized in Table 3. Following Tan et al. (2015), to consider the heterogeneity of the Yangtze River we consider four sizes of inland ships, as listed in Table 4. The prices of alternative fuels, based on the Rotterdam bunker prices, are summarized in Table 5.

Table 2. Cargo flows between inland ports (tonnes/day)

<table>
<thead>
<tr>
<th></th>
<th>Luzhou</th>
<th>Chongqing</th>
<th>Yichang</th>
<th>Wuhan</th>
<th>Anqing</th>
<th>Nanjing</th>
<th>Nantong</th>
<th>Shanghai</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luzhou</td>
<td>0</td>
<td>15000</td>
<td>10000</td>
<td>5000</td>
<td>5000</td>
<td>5000</td>
<td>5000</td>
<td>5000</td>
<td>50000</td>
</tr>
<tr>
<td>Chongqing</td>
<td>15000</td>
<td>0</td>
<td>10000</td>
<td>35000</td>
<td>20000</td>
<td>40000</td>
<td>10000</td>
<td>20000</td>
<td>150000</td>
</tr>
<tr>
<td>Yichang</td>
<td>10000</td>
<td>10000</td>
<td>0</td>
<td>15000</td>
<td>0</td>
<td>5000</td>
<td>0</td>
<td>10000</td>
<td>50000</td>
</tr>
<tr>
<td>Wuhan</td>
<td>5000</td>
<td>35000</td>
<td>15000</td>
<td>0</td>
<td>10000</td>
<td>75000</td>
<td>10000</td>
<td>100000</td>
<td>250000</td>
</tr>
<tr>
<td>Anqing</td>
<td>5000</td>
<td>20000</td>
<td>0</td>
<td>10000</td>
<td>0</td>
<td>5000</td>
<td>25000</td>
<td>75000</td>
<td>50000</td>
</tr>
<tr>
<td>Nanjing</td>
<td>5000</td>
<td>40000</td>
<td>5000</td>
<td>75000</td>
<td>5000</td>
<td>0</td>
<td>5000</td>
<td>40000</td>
<td>175000</td>
</tr>
<tr>
<td>Nantong</td>
<td>5000</td>
<td>10000</td>
<td>0</td>
<td>10000</td>
<td>25000</td>
<td>5000</td>
<td>0</td>
<td>17500</td>
<td>50000</td>
</tr>
<tr>
<td>Shanghai</td>
<td>5000</td>
<td>20000</td>
<td>10000</td>
<td>10000</td>
<td>7500</td>
<td>40000</td>
<td>17500</td>
<td>0</td>
<td>20000</td>
</tr>
<tr>
<td>Total</td>
<td>50000</td>
<td>150000</td>
<td>50000</td>
<td>250000</td>
<td>50000</td>
<td>175000</td>
<td>50000</td>
<td>200000</td>
<td>975000</td>
</tr>
</tbody>
</table>

Table 3. Options of LNG bunkering stations:

<table>
<thead>
<tr>
<th>No.</th>
<th>Fixed cost (yuan/day)</th>
<th>Bunkering ability (tonnes/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100000</td>
<td>280</td>
</tr>
<tr>
<td>2</td>
<td>120000</td>
<td>400</td>
</tr>
<tr>
<td>3</td>
<td>210000</td>
<td>700</td>
</tr>
</tbody>
</table>

Table 4. Options of inland shipping vessels

<table>
<thead>
<tr>
<th>No.</th>
<th>DWT</th>
<th>Navigable Ports</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>500</td>
<td>ALL</td>
</tr>
<tr>
<td>2</td>
<td>1000</td>
<td>Except Luzhou</td>
</tr>
<tr>
<td>3</td>
<td>3000</td>
<td>Except Luzhou and Chongqing</td>
</tr>
<tr>
<td>4</td>
<td>5000</td>
<td>Nanjing, Nantong, Shanghai</td>
</tr>
</tbody>
</table>

Table 5. Price of all fuel options:

<table>
<thead>
<tr>
<th>Fuel*</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>IFO380(SHANGHAI)</td>
<td>2.58yuan/L</td>
</tr>
<tr>
<td>LS0.5(SHANGHAI)</td>
<td>3.68yuan/L</td>
</tr>
<tr>
<td>LS0.1(SHANGHAI)</td>
<td>3.96yuan/L</td>
</tr>
<tr>
<td>LNG(SHANGHAI)</td>
<td>4yuan/m³</td>
</tr>
</tbody>
</table>

IFO380 are max 3.5% sulfur bunkers, LS0.5 is max 0.50% sulfur fuel oil, and LS0.1 is max 0.10% sulfur fuel oil for compliance with the 2015 ECA Regulations.
4.2. Location choice and costs of newly built bunkering stations

The relationship between the daily network cost and daily SO2 emissions of cargo transportation is depicted in Figure 3 for the Yangtze River network considered. The results show that the stricter emissions requirements increase the total cost of the overall network. If there is no limit to the SO2 emissions, the minimum cost to transport all of the cargo would be 19.4 million yuan per day, with 350,000 tonnes of SO2 being released per day. When the total SO2 emissions is set below 219,800 tonnes for the overall network, the cost quickly increases. Some carriers only start to use LNG when we limit the daily SO2 emissions to less than 6264 tonnes per day, leading to sharply increased costs including the costs associated with the bunkering stations that need to be newly built. As shown in Figure 3, it is not very cost effective to reduce SO2 emissions by introducing LNG fuel use, as it costs 10.58 million yuan each day to reduce the daily SO2 emissions to 3900 tonnes. Considering the limitations of the bunkering capacity of the overall system, the lowest daily SO2 emissions possible for all cargo transportation is 2440 tonnes with a cost of 40.47 million yuan per day.

![Figure 3. Balance between network costs and emission caps](image)

When the emission limit for SO2 is set as 6264 tonnes per day, LNG fuel is used and bunkering stations are needed to supply the LNG fuel. As shown in Figure 4, a small bunkering station in Nantong can help to control the daily emissions to under 6263 tonnes per day. In fact, for the Yangtze River corridor, the government had already established a plan to build the first LNG bunkering pontoon “seaport star 01” in Nanjing in 2013 (Wang et al. 2018). A similar plan is in place for the Rhine River, where Europe’s first shore-to-ship bunkering station for LNG is due to become operational in the Port of Cologne by the second quarter of 2019.

With the stricter emissions requirements, an LNG bunkering station is needed in Shanghai to serve the ships fueled with LNG in our network. Given Shanghai’s hub location and high shipping demand, bigger shore-based bunkering stations are needed rather than small bunkering pontoons. With the stricter emissions requirements, the important inland shipping gateways of Wuhan and Chongqing will also need to have their own bunkering stations. In fact, as depicted in Figure 2, the Chinese government’s S2017-2025 plan allows for more bunkering stations around the busy ports within the Yangtze corridor to prepare for the increasingly stricter
emissions controls. We can also see that when the requirements are set below 2440 tonnes per day, all inland ports need to have their own bunkering terminals. Overall, total emissions cannot be further reduced based on the total designed LNG storage capacity considered. Beyond this threshold, more LNG bunkering terminals and greater LNG storage capacity are needed to further reduce the SO2 emissions within the network.

![Figure 4. The choice of new-built LNG bunkering stations](image)

### 4.3. Effects of emissions requirements on fuel choice

We further examine the fuel choice for inland shipping under stricter emissions requirements. As expected, the carriers choose the cheapest fuel subject to the emissions control compliance requirements. As shown in Figure 5, no carriers use low-sulfur fuel when the emissions requirements are greater than 219,784 tonnes per day. With stricter SO2 emissions requirements, traditional fuels are gradually replaced. Low-sulfur fuels are fairly competitive under most of the emissions requirements considered in our case study. As shown in Figure 6, low-sulfur fuels are the best choice when the price of LNG is not competitive. The use of LS 0.5 already reduces the total SO2 emissions to a considerably low level. Most carriers still choose IF380 or LS 0.5 when the emissions requirements are not very strict. LS 0.1 is good/clean enough to attain reasonable emissions performances. In our case, LNG is not needed/used most of the time. When the emissions requirements are reduced to 6264 tonnes per day for the inland shipping network considered, the LNG becomes increasingly competitive against LS 0.1 fuel.

![Figure 5. Choice of fuels under different emissions requirements](image)
Inland shipping network of LNG-fueled ships under emission control - The case of China’s Belt and Road shipping corridor along the Yangtze river

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4.4. Implications of incentive policies

Debates within the shipping industry and among regulators have focused on how to promote the use of LNG fuel in inland shipping. Our model can be used to examine this question by comparing the effects of two frequently studied incentive policies: the unit subsidy, with which the government provides a discount for every unit of LNG fuel used by carriers, and the lump-sum subsidy, in which the government pays for part of the investment costs associated with newly built bunkering stations. We compare the effects of these two incentive policies when the emissions cap is set at 6424 tonnes/day. We choose to examine this cap because at this level carriers will not use LNG absent a subsidy. The effects of these two incentives are shown as Figure 7. The left vertical axis depicts the volume of cargoes carried by LNG fueled ships under the unit subsidy policy, whereas the right hand side vertical axis depicts the case of the lump-sum subsidy. The horizontal axis depicts the total percentage of costs subsidized under the two policies. As shown in the figure, these two incentives are only effective when at least a 10% discount/subsidy is provided. When we increase the discount to 20%, under the lump-sum subsidy about 1000 tonnes of cargo are delivered using LNG fuel. However, the cargo volume does not increase further even if the discount on new bunkering station investment is increased. In comparison, with the increased unit subsidy, more cargo is delivered by LNG fuel powered shipping.
Inland shipping network of LNG-fueled ships under emission control
- The case of China’s Belt and Road shipping corridor along the Yangtze river

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Figure 7. Cargo volumes using LNG under alternative subsidy policies

Given the LNG bunkering capacity of the overall network, the maximum amount of cargo that can be delivered with LNG fueled shipping in the network considered is 616,360 tonnes/day, or 63% of the total cargo. The volumes of cargo transported with LNG fuel under the alternative subsidy policies are shown in Figures 8 and 9. The patterns are similar to those studied in Section 4.2. As the LNG fuel is progressively adopted, the first few bunkering stations are built around busy inland hub ports such as Wuhan, Nanjing, and Shanghai along the Yangtze River. The unit subsidy policy appears to promote the use of LNG fueled shipping around these busy ports, as illustrated in Figure 8. The case of the lump-sum subsidy is different because the investment decisions are not continuous due to the bunkering station location choices. As a result, the effects on the LNG shipping volumes are also not continuous, as illustrated in Figure 9, which restricts the total shipping volumes from increasing continuously.

Figure 8. Effect of the unit subsidy strategy
Inland shipping network of LNG-fueled ships under emission control
- The case of China’s Belt and Road shipping corridor along the Yangtze river
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5. Summary and conclusions
As stricter emission requirements are imposed on the shipping industry, LNG-fueled shipping is becoming an increasing priority for the industry and government regulators around the world. However, there are many changes that need to be addressed. In this study, we model the bunkering station location choice problem by taking the emission constraints into consideration. On the modeling side, to the best of our knowledge, this is the first study to investigate the operations of LNG-fueled shipping in an inland river network by simultaneously taking into account the effects of the emissions regulations, bunkering station locations, price competitiveness of LNG, and the heterogeneity of the navigational conditions along inland rivers. This model is applied to the inland shipping market along the Yangtze River, and the types and location choices of the bunkering stations are optimized under different emission control requirements. The fuel choices and alternative incentive policies are also studied so that recommendations for the promotion of LNG fuel can be obtained.

Our modeling results suggest that the optimal shipping operations and bunkering station locations are significantly affected by the emissions regulations and incentive policies. For the Yangtze River market studied, low-sulfur fuels are the preferred option for carriers at a wide range of emission control levels. LNG becomes an attractive fuel option only when the emissions cap is set significantly below the current emissions level. Rather than opposing the promising future of LNG, our modeling results highlight the cost considerations of shipping companies, and the timing choices for adopting LNG fuel subject to government emissions controls. To promote LNG-fueled shipping, our study further suggests that unit fuel subsidies are more effective than lump-sum capital subsidies for bunkering stations when the LNG price is high. However, the availability of bunker stations is an important factor when the LNG price volatility is considered.

Overall, our results suggest that although LNG-fueled shipping is a promising option in the long term, the optimal industry policy on fuel use is dependent on multiple factors including the fuel prices, types of subsidy, and emission targets. Therefore, dedicated analysis of specific
markets can provide important and useful insights. The model and application approach developed in our study contribute to such analysis and offers some general insights.

Although we have tried to incorporate many important factors simultaneously in our model, the bunkering safety and transport efficiency have not been fully considered. These areas could be useful extensions for future studies.

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