Modeling incentive strategies for landside integration in multimodal transport chains

Chenrui Qu a, Qingcheng Zeng a,⁎, Kevin X. Li b, Kun-Chin Lin c

a School of Maritime Economics and Management, Dalian Maritime University, No. 1 Linghai Road, Dalian 116026, China
b Ocean College, Zhejiang University, No. 1 Zheda Road, Zhoushan 316021, China
c Department of Politics and International Studies, University of Cambridge, Alison Richard Building, 7 West Road, Cambridge CB3 9DZ, United Kingdom

ARTICLE INFO

Keywords:
Port competition
Multimodal transport chain
Incentive strategy
Inland port

ABSTRACT

A significant bottleneck in port regionalization through multimodal transport chains is expensive and time-consuming inland transport. To be competitive, it is crucial for a port authority to build an effective transport system and develop collection-distribution abilities. Considering shipper preferences, this study proposes a pricing model to describe the markets of competing seaports and discusses several incentive strategies that may or may not bring mutual benefits for shippers and port authorities in the multimodal transport chain, such as the corridor investment strategy, subsidy strategy, and combinational strategy. Based on two adjacent ports in China, a comparative analysis is carried out for evaluating the effects of different strategies. The results show that the corridor investment strategy depends on unit investment capital for improving transport convenience. It is necessary to adopt a differentiated subsidy strategy based on transport distance when considering the subsidy strategy; however, there is a constraint on the subsidy level. In the combinational strategy, shippers’ preferences for transport convenience and low inland transport cost have a significant impact on a port authority’s total revenue.

1. Introduction

The inland port is a fundamental component of the port-oriented multimodal transport system and is closer to hinterland markets. Inland ports also become more active over time and support port development (Notteboom and Rodrigue, 2005). The geographical and functional expansion of inland ports is the outcome of the vertical integration of the intermodal chain (Monios and Wilmsmeier, 2012) to meet the increasing demands of shippers for door-to-door service. The concept of a captive market is gradually weakening, with the increasing use of contestable hinterland. For example, it is common to see a shipper choosing Los Angeles as the discharge port and delivering container cargos to the destination by truck, although there is a direct shipping route from the departure port to New York. To maintain competitive advantage in a contestable hinterland, it is vital for a port authority to make inland ports easily accessible to port terminals.

The inland port concept (dry port, inland terminal, inland container depot, etc.) is a logistics zone of seaports connected with roads and railways and plays a leading role in the regional system (Witte et al., 2019). The inland port transfers the distribution function of ports to inland areas and relieves port congestion (Ng and Gujar, 2009; Wang and Cheng, 2010; Rodrigue et al., 2010; Qiu et al., 2015; Crainic et al., 2015). However, serious inland congestion and limited capacity problems restrict the development of a...
high-performance multimodal transport chain. The bottleneck in intermodal transportation has shifted from the port/international shipping interface to the port/inland interface (Notteboom and Rodrigue, 2005; De Borger and De Bruyne, 2011; Ambrosino and Sciomachen, 2014; Nguyen and Notteboom 2019). Transport development is also gradually shifting to inland transportation, with a focus on developing port terminals and maritime shipping networks (Wiegmans et al., 2015; Rodrigue et al., 2016). In the long term, infrastructure investment, such as on-dock rails, bridges, tunnels, and viaducts, among others, will align with port function, synchronize with the growing demand, and establish hard port-hinterland connections to improve seaport accessibility (Monios et al., 2018). Although extremely effective, such development is time-consuming. Port authorities also attempt to reduce the costs of inland distribution through direct subsidies in the short term. If successful, the port-oriented transport system has the cost advantage of attracting shipping demand from distant hinterlands, which may belong to the captive hinterland of a competing port. Moreover, providing administrative conveniences, such as an integrated customs clearance mechanism and paperless documents, could simplify the document approval process significantly. The convenience and low cost of inland transport make it possible for shippers to select a better seaport for the export and import of cargos.

The integration of the inland distribution system and shipping networks is a critical phase in the development of a high-performance supply chain. However, several practical questions require answers. Is it profitable for a port authority to adopt a one-stop transport service strategy with extended services to inland hinterlands? How do the profits of the players change with the implementation of various strategies? Which strategy seems best: investment in corridors, direct subsidy, or the combinational strategy? This study proposes a pricing model based on game theory to describe the competition between seaports in a two-dimensional implementation of various strategies? Which strategy seems best: investment in corridors, direct subsidy, or the combinational strategy? This study proposes a pricing model based on game theory to describe the competition between seaports in a two-dimensional contestable hinterland and analyses the advantages of integration within the transport chain. Furthermore, it is possible to improve inland hinterland accessibility using several strategies; three scenarios are set for assessing the effectiveness of the different strategies adopted, considering the decisions of shippers on multimodal transport routes.

This paper is organized as follows. In Section 2, we review the related literature. In Section 3, we propose a pricing model to describe the equilibrium state of competition between port-oriented transport chains. In Section 4, we perform a comparative analysis to verify the effectiveness of incentive strategies. Section 5 concludes the results.

2. Literature review

Ports are crucial for urban development (Bottasso et al., 2014), and the massive infrastructural investments by governments have improved port competitiveness. There is extensive recent literature on the classical problem of port competition from various perspectives. Lee and Song (2017) thoroughly reviewed this subject; their primary methodology had two aspects: a conceptual framework based on empirical study to evaluate port performance and a game-theoretic model for demonstrating competitive relationships among ports. The port is a dominant element in the restructured and integrated transport system, and the development of port performance is crucial for achieving a more competitive transport system (Qu et al., 2017; Schøyen, 2018; Guo et al., 2018); therefore, port competition is based on competition between transport chains providing more valuable services to shippers, not just on operational efficiency and the location of a single port (Wang and Cullinane, 2006; Song et al., 2016; Chang and Talley, 2019). Port competition gradually transforms into competition between transport chains, promoted by the trend of multimodal transport. However, various players (truck companies, port authorities, shipping lines, etc.) would participate in the whole transport process on a complex multimodal transport network, and work together for the specific requirements of shippers or freight forwarders. Shippers constantly face problems of extra costs and undue delays related to poor coordination between different transport nodes. Thus, a port authority tends to focus on promoting mergers or cooperation between multiple participants for greater efficiency in the transport chain. For example, Lam (2013) analyzed the integration levels of the liner shipping industry. Wilmsmeier and Notteboom (2011) evaluated the effects of vertical integration on shipping network structure and operational efficiency. Álvarez-SanJaime et al. (2013) studied whether it was profitable for liner companies to integrate with container terminals. Saeed (2013) proved that vertical cooperation between inland carriers and shipping carriers was highly beneficial in multimodal transport services. Danese et al. (2013) found that supply chain integration enabled suppliers to respond to customers immediately.

With the increasing focus on the advantages of integrated transport, participants in transport chains gradually realized the importance of vertical cooperation. From the port’s perspective, the port authority concentrated on infrastructure development to attract liner companies owing to limited shipping capacities in the early stage. When increasingly fierce competition between liners led to the formation of a buyer’s market, weak links began to appear in logistics development, connecting shippers’ warehouse (close to inland terminals) with regional hub ports (Wilmsmeier et al., 2014). Inland distribution, such as by long-haul trucks and railway connection, is a vital factor in the performance of global maritime transportation. Veldman et al. (2011) also found that the return on investment in inland transport is much higher than the return associated with ocean shipping, from the perspective of potential investment targets. Ferrari et al. (2011) proposed a spatial interaction model for measuring hinterland accessibility. Port authorities have tried to establish a strong connection between ports and the hinterland and expand the market by adequate investment in hinterland infrastructure to collect diversified and decentralized cargoes from geographically distant areas at hub ports. Álvarez-SanJaime et al. (2015) assessed the effects of integrated inland port service on port competition and showed that there was a unilateral incentive to enhance the efficiency of integration between port and inland transport services. Wan et al. (2016) analyzed government investment incentives to improve landside accessibility in various scenarios with different coordination structures between inland terminals and sea ports. The port authority of Barcelona invested in a rail facility through equity participation for regular shuttle services from the hinterland to ports. Van den Berg and De Langen (2011) studied the effects of investment strategy on attracting containers from distant hinterlands. Distant hinterlands with obvious cost advantages and superior service quality gradually developed into inland ports due to investments in access corridors or cooperation between inland and shipping carriers.
Meanwhile, the rapid development of inland ports had a significant impact on trade flows, intermodal transport itineraries, traditional port functions, and so on (Notteboom and Rodrigue, 2005). Wilmsmeier et al. (2011) constructed a conceptual model to describe the developmental direction of intermodal corridors and stressed the importance of government policies in corridor development through a case study of different patterns; namely, Outside-In and Inside-Out development. Monios and Wilmsmeier (2012) focused on the relationship between ports and inland terminals and categorized spatial development patterns into six groups using a conceptual approach. Tan et al. (2018) illustrated that the optimal cooperation strategy between the inland carrier and the ocean carrier depended on the location of the inland port.

Ports appealing to carriers are not equally attractive to shippers, the properties of a port attracting carriers could not be always extended to attract shippers (Castelein et al., 2019). From the shippers’ perspective, Tongzon (2009) and Yuen et al. (2012) verified key factors in port selection process, such as port efficiency, geographical location, charges, infrastructure, service quality etc., while hinterland connection and high efficiency were considered as the most crucial factors. Steven and Corsi (2012) found that the importance of each factor varied by shippers, and large shippers focused more on delivery speed. Cheon et al. (2017) pointed out processing time is an important factor for a port’s attractiveness to shippers, which supported that port authorities should give top priority to improve the overall transport efficiency. Goenaga and Cantillo (2018) proved the hypothesis that time value of the freight transport varied with vehicle type and cargo categories. Port selection is the byproduct of an intermodal transport itinerary; thus, port performance is a function of transport cost and operational efficiency in the intermodal transport network (Magala and Sammons, 2015). Kim (2014) categorized port users into four types, focusing on superior level of service and support, lower transportation cost, on-time transportation, and port infrastructure, respectively. However, the consensus among four types of users is intermodal links and land transport systems are considered as important factors for port selection. Infrastructure projects exert effects on port choice through the impacts on shippers’ perceived costs, and shippers are most sensitive to lower access cost of ports with convenient distribution infrastructure (Vega et al., 2019). Therefore, with the development of a corridor between seaports and inland ports, it would be possible to boost transport chain efficiency, significantly affecting the selection of intermodal transport itineraries. Tiwari et al. (2003) investigated both port congestion and distance from shipper’s location to the port had negative impact on shippers’ decisions. Wan et al. (2013) focused on port-related activities and empirically studied the effects of urban road congestion and capacity expansion on port competition. Their results showed that the port authority would effectively compete by mitigating road congestion delays, as there was significant improvement in the reliability of collecting container cargoes using trucks.

3. Pricing model in decentralized operation mechanism

Considering a rectangular hinterland with a total area \( S = (x_r - x_l) \cdot (y_u - y_d) \), the distribution of shippers is assumed to be uniform with a shipping demand density \( \rho \). There are two dominant ports, \( j \) and \( j' \), which are almost identical, except for their locations (Fig. 1). For analytical simplicity, we build a coordinate system with a line segment connecting the two ports on the \( x \)-axis and the perpendicular bisector for the \( y \)-axis. Now, the coordinates of the ports’ locations are \( P_j \left( x_j, y_j \right) \) and \( P_{j'} \left( x_{j'}, y_{j'} \right) \). Shippers would select an intermodal transport route for delivering their containerized cargoes according to generalized transport costs. Ports compete fiercely for the hinterland market, as all intermodal routes are alternatives for shippers.

A two-stage process would describe the pricing and route selection decisions of the port authority and shippers, respectively. In the first stage, competing ports make tactical decisions on port pricing individually. Each port maximizes the social welfare of the transport chain, accounting for several factors, namely, opponent’s reaction, inland infrastructure, and shippers’ behavior. An equilibrium state could occur after the alternate pricing decisions of two ports, while no port authority could improve revenue through unilateral price adjustment. In the second stage, shippers near inland terminals must choose between alternative intermodal transport routes. Evaluating the general transport cost of alternatives transshipped at different seaports, shippers would make a rational decision. The problem is solved by backward induction, as follows.

![Fig. 1. Inland hinterland area.](image-url)
3.1. Stage 2: Port choice decisions of shippers

Shipper \((x_i, y_i)\) is the only decision-maker among the market participants who makes a rational decision on intermodal transport routes with sufficient consideration of the general transportation cost of alternative routes. \(f(i, j)\) represents the general cost from a shipper's location to the hub port (Eq. (1)), which has three parts: inland costs for inland transportation service from the factory to a seaport, port dues for port or terminal operation, and ocean shipping cost. \(c'_i\) and \(c'_j\) denote the unit-distance inland transport cost for the two ports. Without loss of generality, the total cost of port operation and ocean shipping would be denoted by \(p_j\) and \(p_j^*\) for the two ports.

\[
f(i, j) = p_j + c'_j d_{ij}^2 \tag{1}
\]

The full cost of a shipper choosing an alternative route could be used to describe the attraction of a specific transshipment port, which would decrease with increasing inland transport distance. If only one port provides transshipment services to inland shippers, the market share is roughly circular because it has equal attraction for shippers in all directions. However, a boundary separates a competing hinterland area, and the market share of each regional hub port can be described clearly. Port \(j\) is taken as an example here to illustrate the port's market area. Only if the cost of arbitrary shipper \(i\) located in the inland hinterland area choosing its itinerary through \(p_j\) costs less than choosing \(p_j^*\), is the shipper in the market area of port \(p_j\). The area within the spatial constraint of Eq. (2) is defined as the market area of port \(j\), \(R_j\), which represents the attraction area of regional seaport \(j\).

\[
R_j = \{i \mid f(i, j) < f(i, j')\} \tag{2}
\]

The market size of the seaport hinges on the relative magnitudes of the general transport cost between two port-oriented intermodal transport systems. First, we focus on equal port dues and unit inland transport cost, \(p_j = p_j^*\), and \(c'_j = c'_j\), where the whole hinterland market area should be divided in the middle (Fig. 2a). Subsequently, if port \(j\)'s system could offer shippers a discount on inland transport cost when they select the system as their transport service supplier, where \(p_j = p_j^*\), but \(c'_j < c'_j\) (Fig. 2b), the whole port \(j\)-oriented intermodal transport system would become more attractive to shippers, and the market area would be larger.

To ensure the market size of each seaport, we must first identify the scope of the market area. If a shipper should incur the same general transport cost, regardless of the alternative itinerary, he could choose any viable alternative route. A fictitious boundary \(^1\) (Eq. (3)) dividing the entire market is formed by the location of shippers based on the condition \(f(i, j) = f(i, j')\). It is a circle with the center at \((M, 0)\) and a radius of \(\sqrt{K}\). Thus, the market area of port \(j\) enclosed by a circle of radius \(\sqrt{K}\) is \(S_j = \pi K\), while the remainder of the hinterland market is the market area of the competitor. Shippers would choose a port \(j\)-oriented multimodal system because they would be within the range of port \(j\)'s market area.

\[
\begin{align*}
(x_i - M)^2 + y_i^2 - K &= 0 \\
M &= \frac{y_j c'_j - y_i c'_i}{c'_j - c'_i} \\
K &= p_j^* - \frac{c'_j (y_j - y_i)^2}{c'_j - c'_i}
\end{align*} \tag{3}
\]

Notably, the boundary does exist under the condition \(K > 0\), which is equal to Eq. (4).

\[
p_j^* - p_j > -\frac{c'_j (x_i - y_i)^2}{c'_j - c'_i} \tag{4}
\]

This condition could provide decision support for the port authority to prevent one port from monopolizing the hinterland market, especially for port authorities in the transport system with higher inland costs. From the perspective of port \(j\) with higher inland cost, the port authority should set a price less than the upper bound, \(p_j^*\), to maintain a dominant market share. Otherwise, the other port authority is casual about a viable pricing strategy due to the inland cost advantage. The intermodal system could capture the whole market when port due is set under the lower bound \(p_j^*\).

\[
\begin{align*}
\bar{p}_j &= p_j + \frac{c'_j (y_j - y_i)^2}{c'_j - c'_i} \\
\bar{p}_j^* &= p_j^* - \frac{c'_j (y_j - y_i)^2}{c'_j - c'_i}
\end{align*} \tag{5}
\]

3.2. Stage 1: Pricing decision of port authority

Spatial competition always occurs in two ways. A port authority could gain a competitive edge over rivals through relocation or reconstruction in the long term, which would be freely applicable for state-owned ports (like South Africa and Spain). As for a municipality-owned ports, it would be a little complicated. For example, Shanghai Port located close to the hinterland, but suffered

\(^1\) We assume that \(c'_j > c'_i\) in the study because of the symmetry property.
from water depth constraints. And then, Yangshan Port, an offshore gateway hub, was constructed in the vicinity of Shanghai Port. Although the port construction is completed by Shanghai Province, the islands belong to Zhejiang Province. There would be problems and conflicts caused by governance between different municipal jurisdictions. Thus, Shanghai Province needs to align with Zhejiang Province for dealing with operation and management problems and the interest conflicts (Wang and Ducruet, 2012; Merk, 2018). However, it could reduce prices to attract more customers to avoid the considerable construction costs and time-consuming process of relocation. Eventually, a price war would break out. The price optimization problem is addressed in the first stage, and port authorities develop their pricing strategies independently. One port authority sets its port dues to maximize individual profit, assuming that the rival will follow suit. Meanwhile, the decision criteria of shippers are also significant factors in pricing strategy. Thus, port j maximizes

$$\Pi_j(p_j | \bar{p}_j) = p_j (S_j p).$$

(6)

where p is shipping demand density in the hinterland market.

Similarly, the objection function of port j’ is expressed as

$$\Pi_j(p_j | \bar{p}_j) = p_j [S_j - S_{j'}] p.$$

(7)

where the total hinterland area is $S_j = (x_j - x_{j'}) (y_j - y_{j'})$. Furthermore, a shipper’s port selection behavior in Stage 2 is involved in the pricing model of the port authority in Stage 1 through the variable $S_j$.

Port profit is a concave function of port dues because second-order conditions hold (Eq. (8)).

$$\frac{\partial^2 \Pi_j}{\partial p_j^2} = \frac{\partial^2 \Pi_j}{\partial p_j^2} = - \frac{2 p}{c_j - c_{j'}} < 0$$

(8)

We next derive the optimal port prices (Eq. (9)) in equilibrium by solving the first-order conditions. The total revenues for the competing ports are shown as Eq. (10).

$$\begin{align*}
    p_j^* &= \frac{x_j c_j - \hat{c}_{j'}}{3 \hat{p}} + \frac{c_j x_j - \hat{c}_j y_j}{3 \hat{x}_j - \hat{c}_{j'}} \\
    p_{j'}^* &= \frac{2 x_j c_j - \hat{c}_{j'}}{3 \hat{p}} - \frac{c_j x_j - \hat{c}_j y_j}{3 \hat{x}_j - \hat{c}_{j'}} \\
    \Pi_j^* &= \frac{\hat{p} (c_j - \hat{c}_{j'})}{9} \left[ \frac{S_j}{\pi} + \frac{c_j x_j - \hat{c}_j y_j}{(c_j - \hat{c}_j)^2} \right]^2 \\
    \Pi_{j'}^* &= \frac{\hat{p} (c_j - \hat{c}_{j'})}{9} \left[ \frac{2 x_j c_j - \hat{c}_{j'}}{\hat{c}_j - \hat{c}_{j'}} \right]^2
\end{align*}$$

(9)

4. Effects of one-stop transport service strategy on port pricing

Low efficiency at any operational stage in the multimodal transportation process, including inland transport, handling operation, and ocean shipping, would have negative effects on the overall efficiency of containerized cargo movement, and shippers would pay higher costs (Steven and Corsi, 2012). Shippers would fully evaluate ports from three aspects, location, effectiveness, and connection, respectively, before they select transport modes or transport routes (Castelein et al., 2019). One-stop transport service, which results from the integration between port operations and inland transport, has considerable advantages in main attributes of multimodal transport, including transport cost, transport time, administrative convenience, service quality and reliability, etc. (Ugboma et al., 2006; Goenaga and Cantillo, 2018). Regarding the attributes of port-oriented multimodal transport considered by shippers, it relates to how much they would like to pay for transporting the goods. If they have high-value and time-sensitive goods, they are willing to pay for transport time savings. Otherwise, shippers are always less sensitive to the quality and time of delivery service if they have to transport low-value goods.
We can divide strategies aimed at improving the cooperation between seaports and inland ports into two categories. The first is to investigate corridors or operate a fleet of trucks for a highly efficient intermodal transport system. As an example, a corridor built in Zhejiang Province, linking the inland port and the seaport, is an important part of the collection and distribution system. Shippers in the inland hinterland are brought closer to the seaport through attractive multimodal transport, such as railway-marine multimodal transport and road-marine multimodal transport. Taking full advantage of multimodal transport can also support the mutual development of seaports and inland ports. Second, the preferential policies of governments for truck companies carrying containers between storage depots and container yards, for example, subsidy policy and intersectoral policy for administrative convenience, would also attract shippers due to cost advantages. In practice, the integrated customs clearance and inspection process in Caofeidian Port contributes significantly to a seamless connection between multiple transport modes. Shippers obtain first-rate services with lower time and administrative costs. Thus, should the port authority adopt a one-stop transport service strategy with extended service to inland hinterlands? How does the profit of the players change with strategy implementation? Which strategy seems more beneficial for the players?

In answering the above questions, we assume that port j sets out an integrated service strategy, while port j’ maintains its original independent operation strategy. There are two ways of implementing the one-stop transport service strategy: investment in transport corridors and cooperation with inland truck companies through subsidies.

4.1. Scenario 1: Invest in transport corridors for higher efficiency

The port authority could guarantee service convenience by developing connecting corridors to inland hinterlands; furthermore, the market share of the port seems significantly affected (Veldman and Bückmann, 2003). Efficient terminals, where containers are transferred from one transport mode to another, are crucial for the coordination of transport chain. Hams Hall Rail Terminal, as a multimodal terminal, is located on a rail route and connected with several motorways. There are terminals still being planned for improving the operational performance in the United Kingdom. Corridors from multimodal terminal to road/rail network give improved access for shippers. Corridors from the terminal direct to the port would also be developed when the freight terminal is located near the port. In 2017, 83 of the main European ports still needed to be fully connected with trans-European transport network by rail or road. The connecting corridors contribute to the competitiveness and connectivity of the port. Moreover, customized digital solutions and service packages are support for effective operations along the whole transport chain, which is also in accordance with efficiency interests of all participants. Convenient measures would also be designed to streamline the administrative process for timeliness of delivery. Although operational efficiency improves significantly with unchanged transport costs, shippers also have a stronger preference for improved services. We now examine the changes in shippers’ decisions. Eq. (11) is a changed generalized transport cost constraint for shippers on the boundary of the market area of the two ports.

\[ p^I_j + c_j d^I_j - \xi = p^I_j + c_j d^I_j, \]  

(11)

where superscript I denotes the scenario in which the port authority adopts an investment strategy within the multimodal transport system. \( \xi \) indicates the added value of shippers’ utility due to the extra convenience of the multimodal transport system, which is a computed value that shippers are willing to pay for the expected improvement in convenience.

The competition between multimodal transport systems generates a new equilibrium state, where the boundary between the market areas of competing ports is Eq. (12).

\[
\begin{cases}
(x^I - M^I)^2 + y^I - K^I = 0 \\
M^I = \frac{\gamma_j - \gamma_j}{\gamma_j - \gamma_j}
\end{cases}
\]  

(12)

Then, in the context of an integrated service strategy, port j sets a service price with profit maximization.

\[
1^I_j\left(p^I_j \mid p^I_j\right) = p^I_j \left(\pi K^I \varphi - h(\xi)\right),
\]

\[
1^I_j\left(p^I_j \mid p^I_j\right) = p^I_j \left(S - \pi K^I \varphi\right),
\]

(13)

where \( h(\xi) = a_\xi \), the total cost from the port authority’s investment strategy, is an increasing function of transportation convenience level. The more convenient the integrated shipping service is, the higher the capital investment necessary. Parameter \( a \) is the reciprocal of elastic coefficient of shippers’ utility to a change in unit investment, which measures the unit investment for the increase in shippers’ utility due to the improvement in transport convenience. It shows how easy it is for shippers to change their port selection behavior, when the port authority makes an effort to improve the convenience of multimodal transport.

Optimal pricing (Eq. (14)) could be obtained by solving the first-order conditions.
\[
\begin{align*}
\ell_{ij}^* &= \frac{1}{a} \xi + \frac{g_i^j(c_j - \eta_j)}{3\pi} + \frac{\xi g_i^j(c_j - \eta_j)^2}{3\eta_j^2 - \xi}, \\
\ell_{ij}^* &= -\frac{1}{a} \xi + \frac{2g_i^j(c_j - \eta_j)}{3\pi} - \frac{\xi g_i^j(c_j - \eta_j)^2}{3\eta_j^2 - \xi}.
\end{align*}
\]

At this time, the total profits of competing ports are shown in Eq. (15).

\[
\begin{align*}
\Pi_{ij}^* &= \frac{g_i^j(c_j - \eta_j)}{9} \left[ \frac{S_i}{\pi} + \frac{g_i^j(c_j - \eta_j)^2}{(\eta_j - \xi_j)^2} + \frac{\xi g_i^j(c_j - \eta_j)^2}{\eta_j - \xi_j} \right]^2 - a\xi, \\
\Pi_{ij}^* &= \frac{g_i^j(c_j - \eta_j)}{9} \left[ \frac{2S_i}{\pi} - \frac{\xi g_i^j(c_j - \eta_j)^2}{(\eta_j - \xi_j)^2} - \frac{\xi g_i^j(c_j - \eta_j)^2}{\eta_j - \xi_j} \right]^2.
\end{align*}
\]

Proposition 1.

1. When \( a \in \left(0, \frac{2g_i^j(c_j - \eta_j)}{9} \right) \), \( \Delta\Pi_{ij}^* \geq 0 \) always holds for any \( \xi \).

2. When \( a \in \left[ \frac{2g_i^j(c_j - \eta_j)}{9}, +\infty \right) \), \( \Delta\Pi_{ij}^* \geq 0 \) holds true within the domain \( \xi \geq \xi^* \), where
\[
\xi^* = \frac{9g_i^j(c_j - \eta_j)}{2(c_j - \eta_j)^2 + \left( \frac{2g_i^j(c_j - \eta_j)}{9} \right) - \frac{g_i^j(c_j - \eta_j)^2}{(c_j - \eta_j)^2}}.
\]

Proof. Compared with the initial equilibrium state, there is a change in the competitive state of the multimodal transport systems after the port authority adopts the investment strategy in the shoreside corridor. The variation in port revenue, Eq. (16), is a convex function of transport convenience.

\[
\begin{align*}
\Delta\Pi_{ij}^* = \Pi_{ij}^* - \Pi_{ij}^* = \frac{2g_i^j(c_j - \eta_j)}{9} \xi^2 + \left( \frac{2g_i^j(c_j - \eta_j)}{9} - \frac{g_i^j(c_j - \eta_j)^2}{(c_j - \eta_j)^2} \right) \cdot a \cdot \xi.
\end{align*}
\]

The increase in port revenue is a direct reflection of strategic effectiveness. That is, the investment strategy is proven to be effective if and only if \( \Pi_{ij}^* \geq 0 \).

\( \Delta\Pi_{ij}^* \) increases with \( \xi \) if parameter \( a \) meets the condition \( \frac{2g_i^j(c_j - \eta_j)}{9} - \frac{g_i^j(c_j - \eta_j)^2}{(c_j - \eta_j)^2} \cdot a \geq 0 \). Meanwhile, \( \Pi_{ij}^*_{\min} = 0 \) at \( \xi = 0 \). Therefore, Proposition 1(1) is proven.

In addition, a vertex \( \xi^* \) minimizes the variation in port revenue if parameter \( a \) meets the condition \( \frac{2g_i^j(c_j - \eta_j)}{9} - \frac{g_i^j(c_j - \eta_j)^2}{(c_j - \eta_j)^2} \cdot a < 0 \). \( \Delta\Pi_{ij}^* \) decreases monotonically over the interval \( \xi \in (0, \xi^*] \), while \( \Delta\Pi_{ij}^* \) increases over the opening interval \( \xi \in (\xi^*, +\infty) \). At \( \xi = \xi^* \), \( \Delta\Pi_{ij}^* \) goes from negative to positive. Therefore, Proposition 1(2) is proven.

The port authority could attract shippers by improving transport convenience, which is closely related to unit investment. If shippers are sensitive to the extra convenience of a full transport service, the unit investment is lower. From Proposition 1(1), we see that it is more profitable for ports to adopt an investment strategy with lower unit investment costs for improving transport convenience for shippers. Proposition 1(2) reflects the case of higher investment cost when it is not the right choice for the port authority to adopt an investment strategy with small-scale investments. When the port authority makes such a massive investment that the transport convenience of the multimodal transport system reaches \( \xi^* \), the revenue returns are sufficiently large to offset the investment in the port. A balance is achieved between investment capital and profit. At this time, if the port authority continues to make additional investments, it will receive a good return on the investment. Moreover, the effectiveness of the investment strategy increases if the hinterland has further potential or if there is greater distance between competing ports.

4.2. Scenario 2: Subsidize inland truck companies for cost advantage

The port authority can cooperate with inland truck companies through a subsidy policy or preferential rate, which would reduce shippers’ expenses. In practice, the port authorities would adopt either an undifferentiated subsidy strategy by TEU, regardless of distance, or a differentiated subsidy strategy based on transport distance per TEU. Several port authorities tried to drive up cargo volumes through offering incentives for shippers and hauliers in the hinterland, including tax exemption of Port of Singaport and Port of Dunkerque, tariff discount of Qingdao Port, subsidy to multimodal transport by Dalian Port, etc. All of the financial incentives are used to attract more cargos in the hinterland.

Proposition 2. The port authority will not benefit from an undifferentiated subsidy strategy \((-SU)\), where it grants truck companies a direct subsidy per TEU.

Proof. In the undifferentiated subsidy strategy, truck companies will charge a lower commission for inland delivery services owing to the subsidy \( s \) from the port authority. The generalized transportation cost of shipper \( i \) choosing port \( j \) as the transshipment port
reduces to \( p_j' + c_j d_j^2 - s \). Then, the market area of port \( j \) is \( S_{SU} \) (Eq. (17)).

\[
\begin{align*}
S_{SU} &= \pi K_{SU}, \\
k_{SU} &= \frac{p_j^{SU} - p_j' + s}{\gamma_j} + \frac{c_j \gamma_j \sigma_j - \rho_j^2 (\gamma_j - \sigma_j)^2}{(\gamma_j - \sigma_j)^2},
\end{align*}
\]

(17)

where superscript ‘SU’ indicates that the port authority adopts an undifferentiated subsidy strategy within the multimodal transport system. The market area of port \( j \) changes accordingly, which is enclosed by a circle of radius \( \sqrt{K_{SU}} \). \( s \) denotes the unit subsidy provided by the port authorities in this case.

Competing port authorities make decisions on port service pricing considering individual profit maximization (Eq. (18)).

\[
\begin{align*}
\Pi_{j}^{SU} \left( p_{j}^{SU}, p_{j}^{SU} \right) &= p_{j}^{SU} \cdot (\pi K_{SU}, \rho) - h(s), \\
\Pi_{j}^{SU} \left( p_{j}^{SU}, p_{j}^{SU} \right) &= p_{j}^{SU} \cdot (S_{j} - \pi K_{SU}) \cdot \rho,
\end{align*}
\]

(18)

where \( h(s) = s \cdot S_{SU}^2 \rho \) is the overall investment capital in the undifferentiated subsidy strategy, which is positively correlated with shippers' total freight volume. The optimal pricing and total revenue of port authorities are shown in Eqs. (19)–(20).

\[
\begin{align*}
P_{j}^{SU*} &= s + \frac{S_{j}(\gamma_j - \sigma_j)}{3 \pi} + \frac{c_j \gamma_j \sigma_j - \rho_j^2}{3(\gamma_j - \sigma_j)^2}, \\
P_{j}^{SU*} &= \frac{2S_{j}(\gamma_j - \sigma_j)}{3 \pi} - \frac{c_j \gamma_j \sigma_j - \rho_j^2}{3(\gamma_j - \sigma_j)^2},
\end{align*}
\]

(19)

\[
\begin{align*}
P_{SU*} &= \frac{S_{j}(\gamma_j - \sigma_j)}{9} \left[ \frac{S_{j}}{\pi} + \frac{c_j \gamma_j \sigma_j - \rho_j^2}{3(\gamma_j - \sigma_j)^2} \right], \\
P_{SU*} &= \frac{2S_{j}(\gamma_j - \sigma_j)}{9} \left[ \frac{2S_{j}}{\pi} - \frac{c_j \gamma_j \sigma_j - \rho_j^2}{3(\gamma_j - \sigma_j)^2} \right].
\end{align*}
\]

(20)

From Proposition 2, we see that the port authority’s service pricing is higher than that in the initial state to make up for investment in the subsidy strategy. In comparison with the initial no strategy case, the port authority’s total profit in the nondifferentiated subsidy strategy remains unchanged. Therefore, it is difficult for the port authority to generate extra revenue through the nondifferentiated subsidy strategy.

**Proposition 3.** A differentiated subsidy strategy (SD) denotes that the port authority provides subsidies according to the distance between the inland terminal and seaport. The port authority will benefit from the differentiated subsidy strategy with massive investment only if \( s_{min} < 0 \), regardless of the subsidy amount, or if \( s_{min} > 0 \) with a relatively large-scale subsidy, where \( s_{min} \) is at the point of minimum changes in revenue.

**Proof.** In the differentiated subsidy strategy, inland companies could obtain subsidies estimated by distance and unit subsidy \( s \) per unit distance. The superscript ‘SD’ denotes the variables in the differentiated subsidy strategy adopted in a multimodal system. Then, the unit inland transport cost of shipper \( i \) choosing port \( j \) is changed to \( c_{ij}^{SD} = c_j - x \), and the general transportation cost reduces to \( p_j' + (c_j - s) d_j^2 \). After adoption of the differentiated subsidy strategy, the changed market area of port \( j \) is enclosed by a circle of radius \( \sqrt{K_{SD}} \), which is shown in Eq. (21).

\[
\begin{align*}
K_{SD} &= \pi K_{SD}, \\
k_{SD} &= \frac{p_j^{SD} - p_j' + s}{\gamma_j} + \frac{c_j \gamma_j \sigma_j - \rho_j^2 (\gamma_j - \sigma_j)^2}{(\gamma_j - \sigma_j)^2},
\end{align*}
\]

(21)

The overall investment is \( h(s) = h_0 + \frac{1}{2} \pi K_{SD} \cdot \rho \cdot s \), where \( h_0 \) is the basic investment in implementing the strategy, and the second part is the total subsidy offered to shippers.

Port authority \( j \) prices its port services focusing on individual profit maximization, and Eqs. (22)–(23) shows the optimal pricing and revenue in this case.

\[
\begin{align*}
P_{j}^{SD*} &= \frac{S_{j}(\gamma_j - \sigma_j)(\gamma_j^{SD} - \sigma_j) + s}{\pi \gamma_j} + \frac{c_j \gamma_j \sigma_j - \rho_j^2 (\gamma_j^{SD} - \sigma_j)^2}{(\gamma_j^{SD} - \sigma_j)^2}, \\
P_{j}^{SD*} &= \frac{2S_{j}(\gamma_j - \sigma_j)(\gamma_j^{SD} - \sigma_j) + s}{\pi \gamma_j} - \frac{c_j \gamma_j \sigma_j - \rho_j^2 (\gamma_j^{SD} - \sigma_j)^2}{(\gamma_j^{SD} - \sigma_j)^2}.
\end{align*}
\]

(22)
\[
\begin{aligned}
\begin{cases}
\Pi^{SD}_{j}\star = \frac{\tau C(2\delta C_j - \gamma_j)^{+}}{2(\delta C_j - \gamma_j)^{+}} \left[ \frac{\pi}{C_j - \gamma_j} \frac{\delta C_j (\gamma_j - \gamma_j')^2}{C_j - \gamma_j} \right] - \frac{\pi}{C_j - \gamma_j} \\
\Pi^{SD}_{j\star} = \frac{\tau C(\gamma_j - \gamma_j')}{(\delta C_j - \gamma_j)^{+}} \left[ \frac{\pi}{C_j - \gamma_j} \frac{\delta C_j (\gamma_j - \gamma_j')^2}{C_j - \gamma_j} \right]
\end{cases}
\end{aligned}
\]

Compared with the initial equilibrium state, the change in port revenue (Eq. (24)) is directly related to the adoption of the differentiated subsidy strategy. The higher the unit subsidy is, the narrower the gap in inland transport costs between competing multimodal systems.

\[
\Delta \Pi^{SD}_{j} = \Pi^{SD}_{j\star} - \frac{\tau C}{9} (\gamma_j - \gamma_j') \left[ \frac{\pi}{C_j - \gamma_j} \frac{c_j C_j \pi}{C_j - \gamma_j} \right]
\]

The change in port \(j\)'s revenue, \(\Delta \Pi^{SD}_{j}\), is a convex function of the cost difference in inland transport between systems because of the positive second derivative (Eq. (25)).

\[
\frac{d^2 \Delta \Pi^{SD}_{j}}{d \delta C_j^2} = \frac{\tau C}{9} \left[ \frac{12c_j - 12c_j - 4s}{(c_j - 3c_j - 2x_j)^2} A^2 + \frac{10c_j - 10c_j, s}{(c_j - 3c_j - 2x_j)^2} AB + \frac{2c_j - 2c_j, s}{(c_j - 3c_j - 2x_j)^2} (B^2 + A^2) \right]
\]

where \(A = \frac{S_j (\gamma_j - \gamma_j')}{C_j - \gamma_j}, (C - \gamma_j)^2, B = -\frac{S_j}{C_j - \gamma_j} + \frac{c_j C_j (\gamma_j - \gamma_j')^2}{(C_j - \gamma_j)^2}, \) and \(C = \frac{2c_j (\gamma_j - \gamma_j')}{(C_j - \gamma_j)^2}.

Thus, there exists an extreme point \(s_{\min} = \arg \min \Delta \Pi^{SD}_{j}\), the real root of the first-order condition (Eq. (26)), in which the revenue change of port \(j\) is minimized.

\[
\begin{aligned}
&\frac{d^2 \Delta \Pi^{SD}_{j}}{d \delta C_j^2} = \frac{\tau C}{9} \left[ \frac{12c_j - 12c_j - 4s}{(c_j - 3c_j - 2x_j)^2} A^2 + \frac{10c_j - 10c_j, s}{(c_j - 3c_j - 2x_j)^2} AB + \frac{2c_j - 2c_j, s}{(c_j - 3c_j - 2x_j)^2} (B^2 + A^2) \right] \\
&\text{where } A = \frac{S_j (\gamma_j - \gamma_j')}{C_j - \gamma_j}, (C - \gamma_j)^2, B = -\frac{S_j}{C_j - \gamma_j} + \frac{c_j C_j (\gamma_j - \gamma_j')^2}{(C_j - \gamma_j)^2}, \text{ and } C = \frac{2c_j (\gamma_j - \gamma_j')}{(C_j - \gamma_j)^2}.
\end{aligned}
\]

The solution (Eq. (27)) to Eq. (26) is solved by the Ferrari method and the Cardano formula.

\[
\Delta c^{SD}_{j(l,2)} = \frac{-D_1 - \sqrt{D_2}}{2} \left[ \begin{array}{r}
a^2 = \frac{D_2}{D_1} - c_j + 2\alpha
b^2 = \frac{\gamma}{\alpha}
\end{array} \right]
\]

\[
\Delta c^{SD}_{j(l,4)} = \frac{-D_1 - \sqrt{D_2}}{2} \left[ \begin{array}{r}
s f. \ y = \frac{\phi}{\psi} + \frac{g^2}{\psi} + \frac{g^2}{\psi} + \frac{1}{\psi} + \frac{h^2}{\psi} + \frac{h^2}{\psi} + \frac{1}{\psi} + \frac{h^2}{\psi}
\end{array} \right]
\]

Because of the positive second-derivative condition, \(s_{\min}\) is the only real root with minimum revenue increase. Moreover, \(\Delta \Pi^{SD}_{j} = 0\) holds if the subsidy strategy is not adopted, that is, \(s = 0\). Thus, the revenue increase is negative at the vertex \(s_{\min}\). □

From Proposition 3, it can be seen that the effects of a differentiated subsidy strategy to achieve higher revenue are related to the features of competing multimodal transport systems, including the inland transport cost of port-oriented transport systems, distance between competing ports, and inland market demand. Compared with the initial competitive state, the profit change from the adopted strategy, \(\Delta \Pi^{SD}_{j}\), is a function of the subsidy to shippers. There exists a vertex point, \(s_{\min}, s\), makes a minimum value of \(\Delta \Pi^{SD}_{j}\). The profit change of port authority is monotonically decreasing over an interval \((-\infty, s_{\min})\), while it turns to increase over the interval \((s_{\min}, +\infty)\). Only under the condition \(s > 0\), can the port authority to adopt a subsidy strategy. It is unreasonable to adopt a subsidy.
strategy with negative unit subsidy. Thus, the general trend of port revenue would be able to analyzed by comparing $s_{\text{min}}$ with zero. if $s_{\text{min}} < 0$, $\Delta \Pi_j^{SD}$ is a monotonically increasing function of $s$ over the rational interval $(0, +\infty)$. In this case, the minimum of $\Delta \Pi_j^{SD}$ is zero; thus, the differentiated subsidy strategy will benefit the port authority. The higher the subsidization is, the more the total revenue. In the case of $s_{\text{min}} > 0$, $\Delta \Pi_j^{SD}$ first decreases, then increases, with an increase in unit subsidy. And also, $\Delta \Pi_j^{SD}$ turns from negative to 0, when the unit subsidy achieves $2s_{\text{min}}$. Therefore, it also seems possible for the port authority to improve total revenue by adopting a large-scale investment. That is, the minimum unit investment in the differentiated subsidy strategy should achieve $2s_{\text{min}}$; otherwise, the port authority would not accept the consequence of such a subsidy strategy.

4.3. Effects of shippers’ preference on one-stop transport service strategy

The primary considerations of shippers when selecting multimodal transport chains are cost advantages and service convenience (Nir et al., 2003; Tongzon, 2009; Cheon et al., 2017; Vega et al., 2019). Such shippers’ preferences have also been proven by cargo owners and logistics service providers, who pursue cost-effective and efficient delivery. From the perspective of shippers, their preference for saving transport costs and improving transport convenience has a significant impact on the effectiveness of proposed strategies.

We now examine the changes in the selection decisions of shippers, which depend on the comparison between the generalized costs of two multimodal transport routes. Assume that port $j$ chooses to implement a one-stop service strategy (both Scenario 1 and Scenario 2 are included), while port $j$ maintains the original independent operation mechanism. Eq. (28) is a constraint condition of the generalized transport cost specific to the shippers located on the boundary of the market areas of competing seaports, where $c^j_S$, denotes a scenario that considers both strategies. $\xi$ indicates the added value of shippers’ utility due to the extra convenience of the multimodal transport system, and the inland cost after adopting the subsidy strategy is $c^j_S = c_j - s$.

$$p_j^c + c^j_S - d_j^c - \xi = p_j + c_j, d_j^c,$$

(28)

Considering the reactions of shippers, the two ports price their services for profit maximization. The optimal pricing in the equilibrium state is shown in Eq. (29).

$$p_j^{c^*} = \frac{1}{25} + \frac{8(s_c^j - s_d^j)}{3\epsilon} + \frac{\epsilon^j(s_d^j - s_s^j)^2}{3\epsilon(j - s_d^j)}$$

$$p_j^{s^*} = -\frac{1}{25} + \frac{2(s_c^j - s_d^j)}{3\epsilon} - \frac{\epsilon(s_d^j - s_s^j)^2}{3\epsilon(j - s_d^j)}$$

(29)

The overall revenue of port authorities is shown as Eq. (30).

$$\Pi_j^{c^*} = \frac{5(s_c^j - s_d^j)}{4} + \frac{8(s_c^j - s_d^j)}{3\epsilon} + \frac{\epsilon(s_d^j - s_s^j)^2}{3\epsilon(j - s_d^j)} - h(\xi, c^j_S)$$

$$\Pi_j^{s^*} = \frac{5(s_c^j - s_d^j)}{4} + \frac{8(s_c^j - s_d^j)}{3\epsilon} - \frac{\epsilon(s_d^j - s_s^j)^2}{3\epsilon(j - s_d^j)} - h(\xi, c^j_S)$$

(30)

$h(\xi, c^j_S)$, the total investment capital in the one-stop transport service strategy adopted by port authority $j$, is a function of both the inland transport cost and the convenience of integrated service. Theoretically, whether the port authority invests in inland channels depends mainly on the positive effects of the one-stop service strategy on overall revenue. However, it is crucial for the port authority to ensure that the investment capital is effective in attracting shippers to the integrated multimodal transport system.

Compared with the initial structure of a decentralized multimodal system, the joint effect of the one-stop transport service strategy on the port authority’s revenue (Eq. (31)) is directly related to the cost change in inland transport and the improvement in service convenience.

$$\Delta \Pi_j^{c^*} = \frac{\Delta p_j}{9} \left[ \frac{4}{\Delta c_j} + \frac{\Delta s}{\Delta c_j} + \frac{\Delta c_j}{\Delta s^j} \right] (s_d^j - s_j)^2 - h(\xi, c^j_S)$$

$$\Delta \Pi_j^{s^*} = \frac{\Delta p_j}{9} \left[ \frac{4}{\Delta c_j} + \frac{\Delta s}{\Delta c_j} + \frac{\Delta c_j}{\Delta s^j} \right] (s_d^j - s_j)^2 - h(\xi, c^j_S)$$

(31)

$\Delta c^j = c^j_S - c_j$; denotes the cost difference in inland transport between multimodal transport systems after port $j$ adopts the one-stop strategy. The more effective the strategy, the more significant will be the cost reduction in inland transport in the port $j$ oriented multimodal system. The gap in inland transport between the two systems narrows. The landside investment capital, $h(\Delta c_j, \Delta c^j)$ (Eq. (32)), is positively related to the convenience of the integrated service and negatively related to the difference in inland transport cost.

$$h(\Delta c_j, \Delta c^j) = a\Delta c_j - b\Delta c^j + h_0$$

(32)
Proposition 4.

(1) When \( b \in \left( \frac{9a^2}{4\pi^2} - \frac{S_j a}{\pi}, \frac{4a^2}{4\pi^2} - \frac{S_j a}{\pi} \right) \), shippers are sensitive to both decreased inland transport cost and increased transport convenience. In this case, it is easier for the port authority to benefit from investment capital.

(2) When \( b \in \left( 0, \frac{9a^2}{4\pi^2} - \frac{S_j a}{\pi} \right) \), the port authority’s one-stop transport service strategy is effective only if the decrease in inland transport from the port authority’s investment capital satisfies \( \Delta c_j^C \in \left[ 0, -\frac{E_2 + \sqrt{E_2^2 - 4E_1E_3}}{2E_1} \right) \). The port authority could also derive benefits from the investment.

(3) When \( b \in \left( \frac{9a^2}{4\pi^2} - \frac{S_j a}{\pi}, \frac{4a^2}{4\pi^2} - \frac{S_j a}{\pi} \right) \), shippers are much more sensitive to direct cost decreases in inland transport. At this time, the port authority should focus on conveying this cost decrease to shippers directly, although it may be a slight decrease.

Proof. The first- and second-order derivatives of the revenue change of port authority \( j \), \( \Delta \Pi_j \), with respect to the improved service convenience, \( \Delta \xi_j^C \), are shown as Eqs. (33)–(34). Because of the positive second-order condition, there exists a local minimum, \( \xi_j^C \), minimizing the revenue change for the port authority.

\[
\frac{\partial \Delta \Pi_j}{\partial \xi_j^C} = \frac{2\pi}{9} \left[ \frac{\Delta \xi_j^C}{\Delta c_j^C} + \frac{S_j}{\pi} + \left( \frac{c_{j,2}}{\Delta c_j^C} \right) (x_j - x_{j,2})^2 \right] - a
\]

(33)

\[
\frac{\partial^2 \Delta \Pi_j}{\partial \xi_j^C^2} = \frac{2\pi}{9} c_{j,2} > 0
\]

(34)

Solve \( \frac{\partial \Delta \Pi_j}{\partial \xi_j^C} = 0 \) for \( \Delta \xi_j^C \) (Eq. (35)). At this time, the minimum revenue change for port authority \( j \) is Eq. (36).

\[
\Delta \xi_j^{C,\min} = \frac{\pi}{2\pi} \left[ \frac{9a}{2\pi c_j + \frac{S_j a}{\pi}} \right] - h(\Delta \xi_j^C, \Delta c_j^C)
\]

(35)

\[
\Delta \Pi_j^{C,\min} > 0
\]

(36)

The constraint, \( \Delta \Pi_j^{C,\min} > 0 \), could be simplified as follows.

\[
\begin{cases}
E_1 (\Delta c_j^C)^2 + E_2 \Delta c_j^C + E_3 < 0 \\
E_1 = \left( \frac{9a^2}{4\pi^2} - \frac{a S_j}{\pi} - b \right) \\
E_2 = E_{21} - ac_{j,2} (x_j - x_{j,2})^2 \\
E_3 = -ac_{j,2} (x_j - x_{j,2})^2
\end{cases}
\]

where \( E_{21} \) is a constant determined by the features of the port-oriented multimodal system.

\[
B_{21} = h_0 + \frac{\pi c_j (c_j - c_{j,2})^2}{9} \left[ \frac{S_j}{\pi} + \frac{c_j c_{j,2}}{(c_j - c_{j,2})^2} (x_j - x_{j,2})^2 \right]^2
\]

This case discusses the feasible region of the optimization problem that satisfies the constraints. Table 1 shows the results.

First, the criterion \( E_2^2 - 4E_1E_3 > 0 \), is always satisfied if \( E_1 > 0 \). The range of parameter \( b \) is \( b \in \left( 0, \frac{9a^2}{4\pi^2} - \frac{S_j a}{\pi} \right) \). \( \Delta \Pi_j^{C,\min} > 0 \) always

<table>
<thead>
<tr>
<th>Table 1</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Feasible region in various cases.</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Binomial Coefficient</th>
<th>Criterion</th>
<th>Roots</th>
<th>Parameter Range of b</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E_1 &gt; 0 )</td>
<td>( E_2^2 - 4E_1E_3 \leq 0 )</td>
<td>0</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>( E_2^2 - 4E_1E_3 &gt; 0 )</td>
<td>2</td>
<td>( \left( 0, \frac{9a^2}{4\pi^2} - \frac{S_j a}{\pi} \right) )</td>
</tr>
<tr>
<td>( E_1 &lt; 0 )</td>
<td>( E_2^2 - 4E_1E_3 \leq 0 )</td>
<td>0</td>
<td>( \left( \frac{9a^2}{4\pi^2} - \frac{a S_j}{\pi} - b \right), b \in \left( \left( \frac{9a^2}{4\pi^2} - \frac{a S_j}{\pi} - b \right), \frac{4a^2}{4\pi^2} - \frac{S_j a}{\pi} \right) )</td>
</tr>
<tr>
<td></td>
<td>( E_2^2 - 4E_1E_3 &gt; 0 )</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>
holds in the range of \( \Delta c_j^C \in \left(0, \frac{-b_2 + \sqrt{b_2^2 - 4b_1b_3}}{2b_1}\right) \); therefore, Proposition 4(2) is proved.

Second, if \( E_1 < 0 \) and \( E_2^2 - 4E_1E_3 > 0 \), \( \Delta \Pi_{j,\min}^C > 0 \) is satisfied in the range of \( \Delta c_j^C \in \left(\frac{-b_2 + \sqrt{b_2^2 - 4b_1b_3}}{2b_1}, c_j - c_j'\right) \). At this time, the range of parameter \( b \) is \( b \in \left(\frac{\alpha_1^2}{4\sigma^2} - \frac{S_a}{\sigma}, \frac{(b_2^2 - \phi_1\sigma_1^2\gamma_1^2)^2}{4\phi_1^2\sigma_1^2\gamma_1^2 + \frac{\alpha_1^2}{4\sigma^2} - \frac{S_a}{\sigma}}, \infty\right) \). Hence, Proposition 4(3) is proved.

Third, if \( E_1 < 0 \) while \( E_2^2 - 4E_1E_3 < 0 \), where \( b \in \left(\frac{(b_2^2 - \phi_1\sigma_1^2\gamma_1^2)^2}{4\phi_1^2\sigma_1^2\gamma_1^2 + \frac{\alpha_1^2}{4\sigma^2} - \frac{S_a}{\sigma}}, \infty\right) \). At this time, \( \Delta \Pi_{j,\min}^C > 0 \) holds for the feasible set of \( \Delta c_j^C \); therefore, Proposition 4(1) is proved. \( \square \)

5. Empirical study

We consider adjacent ports, the Port of Dalian and Yingkou, in port cluster of Liaoning Province, China. Dalian Port and Yingkou Port are the gateway to the northeast hinterland of China. Currently, despite its early development and good infrastructure, Dalian Port has to compete with neighboring ports with location advantages, such as Yingkou Port. The throughput proportion of Dalian Port to Yingkou Port decreased from 3.68 in 2004 to 1.51 in 2018 (Ministry of Transport of the People’s Republic of China), which could reflect the rapid development of Yingkou Port and intense regional competition. We use the model to analyze how Dalian Port maintains a better competitive position through obvious advantages in infrastructure and the service quality of its collection and distribution system.

Yingkou Port, which is approximately 200 km from Dalian Port, is closer to the inland hinterland. Consider a square hinterland area with a length of 1200 km and a width of 1200 km. Based on the collected data from the official websites of port authorities, the total throughput of Dalian Port and Yingkou Port in 2017 were 9.70 million TEU and 5.85 million TEU, respectively, and the demand density in the hinterland was 10.80 TEU/km². For the cost structure, the standard of inland transport cost is estimated at 0.7 USD/TEU/km (Konings, 2005), which is the Yingkou Port-oriented transport chain, while the distribution cost of delivering/collecting containers between Dalian Port and shippers’ warehouses is 1.5 times the standard. Furthermore, the shipping cost is estimated at 700 USD/TEU based on public information of the shipping route from Dalian Port to Rotterdam Port. Considering shippers’ port choice decisions, Table 2 is calculated based on Eqs. (9)–(10) and shows the optimal pricing strategy of port authorities, without any incentives.

Table 2 shows the results of the benchmark scenario, which does not consider the effects of distribution costs, integrated services, and time-consumings administrative procedures on shippers’ preferences in choosing transshipment ports. Theoretically, the price of cargo handling in Dalian Port is 25.24 USD higher than Yingkou Port, while the container volume is almost the same. Clearly, higher pricing for handling services in Dalian Port has become the norm because of the adequate terminal infrastructure and unique natural conditions. However, the total throughput of Yingkou Port is overestimated. We explain why the theoretical results are different from reality as follows. First, Yingkou Port, the only port of Shenyang economic zone, is closer to the hinterland. Although there is rapid growth in throughput, Yingkou Port is still confronted with main challenges, such as inefficiency logistics system, intensified competition (Notteboom, 2011). Yingkou Port signed an agreement with China Railway Corporation for lowering the distribution cost for shippers. The logistics enterprises offering storage and transportation services for Yingkou Port through their own transportation tools and storage apparatus can enjoy the preferential taxation policy. Other specially tailored tax exemption policies are provided for encouraging new investment and generating freight volume. By attracting more containers, its port authority has made a low pricing policy profitable. We fully consider the obvious cost advantage in the inland container distribution for Yingkou Port. Second, the quantification of superior service quality due to the distinctive characteristics of Dalian Port is not the focus of our basic model. Third, this study ignores supportive policies of national and local governments. We evaluate the last two important influencing factors in the following sections.

5.1. Effects of investments in transport corridors

The financial crises have a lasting and devastating global impact, and the shipping market is no exception. Surplus capacity issues are arising from over-invested capital in ship building over the past decades, and the shipping market has since turned into a buyer’s market. This inevitably leads to multiple ports expanding their targeted hinterland markets to maximize port functionality and strengthen their market positions, resulting in a more competitive environment. Furthermore, greater geographical distance from shippers’ warehouse to the seaport makes it more necessary to implement a multimodal transport mode, which is a combination of

<table>
<thead>
<tr>
<th>Port</th>
<th>Pricing (USD/TEU)</th>
<th>Volume (million TEU)</th>
<th>Total Revenue (million USD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dalian Port</td>
<td>114.76</td>
<td>7.90</td>
<td>906.42</td>
</tr>
<tr>
<td>Yingkou Port</td>
<td>89.52</td>
<td>7.65</td>
<td>685.17</td>
</tr>
</tbody>
</table>
inland transport and shipping in a port-oriented transport system. The effects of traffic conditions are always considered in inter-modal transport planning (Li et al., 2015). Therefore, transport time and administrative convenience would affect the shippers' utility from the multimodal transport chain. Although there is no need to replace the container for the goods, the administrative procedure of transshipment between the truck and the ocean-going vessel is also a cumbersome and time-consuming process. Therefore, the port authority and shipping companies in a multimodal transport system without cost advantages would explore alternatives to attract shippers through reliable terminal operations, highly efficient transshipment processes, and convenient customs clearance. To achieve these goals, the port authority's investments in creating a transport corridor/on-dock rail or adopting customized digital solutions for fleet tracking and telematics would contribute to improvement in access to the hinterland and ensure higher efficiency of the local distribution of containers. A variable, $a$, is used for quantifying shippers' increased utility in an improved multimodal transport system. We also use the concept of elastic coefficient of shippers' utility to a change in unit investment for considering shippers' sensitivity to port authority's investment strategy. Whether it is a profitable investment depends on shippers' preferences for the extra convenience due to the port authority's strategy.

![Fig. 3. Changes in port authority's total revenue as shippers' utility increases.](image)

**Fig. 3.** Changes in port authority's total revenue as shippers' utility increases.

Fig. 3 shows the changes in the port authority's revenue after adoption of the investment strategy. These results are based on a scenario that does not ignore the value of time spent on inland delivery service. The profitability of the investment strategy mainly depends on the investment ratio $a$, which denotes the relationship between the investment amount of port authority and shippers' utility. It is usually an empirical value based on previous successful investment construction projects. The investment strategy of a port authority could not always effectively translate into shippers' utility. We define a concept of investment effect coefficient, calculated by reciprocal of parameter $a$. It is an elastic coefficient of shippers' utility to a change in port authority's investment, which could reflect the implementation effect of the proposed strategy. The bigger the parameter $a$ is, the less significant the effects are. The increased shippers' utility could be calculated by shippers' willingness-to-pay for saving an hour in inland transport and the time saved by improved transport efficiency. Shippers with different type and value of goods also show different willingness-to-pay for the improved convenience and efficiency (Beuthe and Bouffioux, 2008).

Fig. 3 shows that the increased revenue of the port authority is always positive if the investment ratio is less than 526.56. The critical value is calculated by Proposition 1. In this case, it is much easier for shippers to change their port selection behavior, when the port authority makes an effort to improve the convenience of multimodal transport. The port authority can always benefit from the investment strategy, regardless of the types of goods in the hinterland. The port authority should work out the investment budget based on shippers' utility to the projects. Usually, the port authority could invest in inland terminal, short-haul transport corridor, customized digital technology for efficient operations, and information channel for sharing information along the whole transport chain. In another case, the investment ratio exceeds 526.56, the returns of investment are not always acceptable for the port authority. The port authority should make a rational investment decision based on the analysis of the source of goods in the hinterland. Shippers' willingness-to-pay for different types of goods has been estimated by many researches. The value of time for high-value goods is estimated as 936 USD per day, while 60 USD per day for low-value goods (Pekin et al., 2013; Román et al., 2017; Vega et al.,
For example, when the investment ratio is pushed up to 600, the break-even point of shippers’ willingness-to-pay is 681.86 USD. If the goods in the hinterland market were mainly composed of time-sensitive and high-value goods and the total transport time is saved by at least 17.5 h, there would be an expected return on the investment project with total investment amount, 561.6 thousand USD. However, shippers are always less sensitive to the quality and time of delivery service if they have to transport low-value goods. There might be losses made on investment. Although the port authority will hope for an attractive return on its investment, it is still important to invest major infrastructure projects with huge cost. There would be long-term effects on hinterland accessibility, port reputation and competitiveness. As for the investment pattern, the port authority could lead the capital-intensive project on infrastructure and may take the form of co-investor with the private sector.

Currently, the difficulties in the development of multimodal transport are also bottlenecks to expanding into the hinterland. Establishing a direct corridor linking inland hinterlands with port terminals is the most straightforward way to reduce transport time. For instance, Sichuan Province developed a policy that would enable trucks to pass along dedicated lanes quickly. For improved access to container terminals, the Port of New York and New Jersey launched a rail program called the ExpressRail System, with an extensive roadway network for trucks. The customized digital solutions will help the port authority to standardize vehicles, collect real-time information, and achieve uniformity in the cargo-loading unit between various transport modes, which smooths the transport process. It also helps the port authority coordinate the deployment of trucks and avoid inefficiency in information transfer between different information systems.

5.2. Effects of direct subsidy policy for inland truck companies

The cost of inland transportation is one of the most important factors negatively affecting port choice decision (Wan et al., 2016; Vega et al., 2019). It may be effective for port authorities to provide subsidies to truck companies. In practice, the port authority/local government usually adopts an undifferentiated subsidy strategy. For example, the Fuzhou government provides 250 RMB/TEU for shippers who choose the rail/shipping multimodal transport mode. In hinterlands close to the seaport, the port authority still dominates the market without a subsidy strategy. The subsidy strategy should primarily attract shippers from the competitive hinterland, which is very far from the seaport. However, the undifferentiated subsidy strategy treats all shippers equally without a clear preference. It is widely used because it is easy to implement; however, it is necessary to study its actual effects.

In the undifferentiated subsidy strategy, the unit subsidy is set at $40 USD/TEU, according to the level of subsidy policy implemented in China, while the unit subsidy is set as $0.031 USD/TEU/km in the case of a differentiated subsidy strategy. For instance, the Fuzhou government provides 250 RMB/TEU for shippers who choose the rail/shipping multimodal transport mode. In hinterlands close to the seaport, the port authority still dominates the market without a subsidy strategy. The subsidy strategy should primarily attract shippers from the competitive hinterland, which is very far from the seaport. However, the undifferentiated subsidy strategy treats all shippers equally without a clear preference. It is widely used because it is easy to implement; however, it is necessary to study its actual effects.

The undifferentiated subsidy strategy is a prevailing trend, where the port authority offers subsidies to shippers indiscriminately. In this case, the optimal pricing for handling service at the port terminals is $154.76 USD/TEU. It is an attempt to cover the cost of subsidizing shippers by raising the price. The net profit remains unchanged after deducting the overall investment at 315.93 million USD. Intuitively, more money will be spent on shippers in exclusive hinterlands where the port authority does not need to invest. Therefore, attracting long-distance shippers seems difficult.

The proposed differentiated subsidy strategy in this study is a stepped subsidy system, according to the distance between the inland warehouse of the terminal/shipper and the seaport terminal. The total revenue of Dalian Port increases with the level of unit subsidy. From the results in Table 3, the total revenue reaches $1091.17 million USD when the unit subsidy is $ 0.031 USD/TEU/km; meanwhile, the overall investment is only 29.92 thousand USD. Here, if the unit subsidy continues to rise, Yingkou Port will turn from profit to loss. The toll on expressways in China varies between 0.81 and 2.4 RMB/TEU/km. Therefore, the differentiated subsidy strategy works well if the port authority of Dalian takes approximately 8–25% of the expressway toll as the level of unit subsidy, although it is impossible to attract all shippers. In addition, the pricing of handling services is considered particularly noteworthy, increasing from 114.76 to 134.83 USD/TEU. The hinterland could be divided into exclusive and competitive zones. For shippers in the exclusive hinterland, the seaport would still maintain its monopoly on handling services, although the shippers are charged a higher fee. The higher subsidies would attract shippers in the competitive hinterland.

**Table 3**

<table>
<thead>
<tr>
<th></th>
<th>Dalian Port</th>
<th>Yingkou Port</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Throughput (million TEU)</td>
<td>Total Revenue (million USD)</td>
</tr>
<tr>
<td>Benchmark</td>
<td>114.76</td>
<td>7.90</td>
</tr>
<tr>
<td>Undifferentiated subsidy strategy</td>
<td>154.76</td>
<td>7.90</td>
</tr>
<tr>
<td>Differentiated subsidy strategy</td>
<td>134.83</td>
<td>8.09</td>
</tr>
</tbody>
</table>

C. Qu, et al.  
Transportation Research Part A 137 (2020) 47–64
6. Discussion

Global containerized trade was increased by 6.4% in 2017, and total volumes were approximately 148 million TEUs. Such strong demand supports a better shipping market. The initiator of port-oriented transport chain is shippers in a highly competitive hinterland (Castelein et al., 2019). It is crucial for shippers to select a convenient and efficient multimodal transport route. Surrounding ports are in intense competition to attract more shippers from limited hinterland areas, and service providers in a multimodal transport system (inland carriers, port terminals, and shipping companies) need to interact with each other for competitive advantage in the context of collaborative transport chain. As the key node of a multimodal transport chain, the port authority needs to design effective measures to alleviate port congestion and remove severe constraints of hinterland connection, owing to the bottleneck has shifted from the maritime/port interface to the port/inland interface (Wan et al., 2014). Many adjacent port pairs have been widely studied in existing researches, such as Port of Los Angeles and Long Beach (Giuliano and O’Brien, 2008), Port of Shenzhen and Guangzhou, Port of Qingdao and Yantai (Wang et al., 2017), Port Antwerp and Rotterdam (Nazemzadeh and Vanselslander, 2015; Vermeiren and Macharis, 2016), Port of Barranquilla and Santa Marta (Vega et al., 2019), etc., the importance of hinterland connection has also been highlighted. Thus, port authorities should shift their focus to improving the efficiency of port-oriented transport chains, considering the fierce competition between neighboring ports.

With highly efficient multimodal transport system for cargo distribution, it is not uncommon to see the containers destined for a city near the east coast of the United States to be discharged in Port of Los Angeles and transhipped by truck/rail to the final destination (Wan et al., 2014). In 2017, Port of Los Angeles and Long Beach generated 16.84 million TEU, accounted for about 30% of total U.S. container traffic. The two ports are adjacent located in San Pedro Bay and aggressively competed with each other for the leading port position. The hinterland at regional level is in a range of about 800 km (De Oliveira and Cariou, 2015), thus the demand density in the hinterland was 26.31 TEU/km². In the scenario without incentive strategies adopted, the optimal wharves for Port of Los Angeles and Long Beach are 147.93 and 129.43 USD/TEU, and the volume for the two ports are 8.65 and 8.19 million TEU based on the proposed model. The increasing road traffic congestion and harmful emissions come along with the growing port throughput in Los Angeles-Long Beach Port Complex. The transport corridor linking the seaport with inland markets is a key conduit for the development of international trade. Improving the landside multimodal transport efficiency must be put on the agenda. The Alameda Corridor connects the port cluster with the national rail system in downtown Los Angeles, and serves for the freight distribution as a multimodal system. It significantly relieved traffic jams caused by limited road capacity, and carried 13,889 trains in 2018 (Alameda Corridor Transportation Authority). Both port authorities are willing to invest heavily in shoreside infrastructure to upgrade transport networks, strengthen multimodal connections among all transport forms, alleviate congestion at the gate, and foster the regional market. Long Beach approved an 870 million USD budget for on-dock rail terminals (Executive Director of Port of Long Beach, Mario Cordero). Coincidentally, Port of Los Angeles invested $127 million for on-dock rail yard and facilities in 2018 (Executive Director of Port of Los Angeles, Gene Seroka). 750 truck trips would be eliminated by a train. Although continued on-dock rail upgrades would be helpful for gaining competitive advantages, such a large-scale capital investment project usually has long-term returns. Based on the proposed model, the highest investment coefficient is 576.61. If the shippers with time-sensitive cargos in the hinterland are willing to pay 936 USD for saving another day, the total investment amount is 539.71 thousand USD by the port authority. If the transit efficiency is greatly improved through standardization among different transport modes and substantial time savings are achieved, the investment could also be increased accordingly. The port authority could launch a public and private partnership project and jointly engage in a massive investment for avoiding the financial risk. The on-dock rail projects would also create incalculable social benefits and regional economic impact, such as customs revenues, taxes, employment, environmental protection, etc.

Moreover, short-haul road transport accounts for a larger portion of the overall costs of multimodal transport than does long-distance shipping cost, including not only the road transport cost but also time-consuming administrative procedures. When a seaport has obvious advantages over competitors in infrastructure and the service quality of its collection and distribution system, there is not much difference between transshipment from various seaports. It is crucial for the port to coordinate multiple transport modes and improve the efficiency of the whole transport chain. The limited budget of the port authority could be invested in IT solutions, so that the limited resources could be effectively utilized. As a developing digital technology, blockchain applied in multimodal transport could streamline the administrative process, reduce operational cost, and tighten information security for data exchange within the transport chain. All participants (shippers, freight forwarders, carriers, customs, truck drivers, etc.) involved in the transport system share real-time data so they can track shipments and give quick responses to customer requirements. Even the whole productive process could be obtained for customer monitoring.

In the short term, if the port authority desires to offer a cost advantage to shippers to expand his customer base, he can promise that shippers or freight forwarders will receive a subsidy for choosing the port as their transshipment point. In practice, subsidy strategy is prevalent because it is easy to implement and coordinate the transport chain. Direct subsidy strategy to shippers/distributors is relatively costly; however, the expected effects usually fail to be achieved. The reasons are listed as follows. First, when the port authority holds a monopoly position in the shipping market, he leaves shippers with no other choice. Customers are subsidized by the government; meanwhile, they are charged higher port dues. In 2016, Hanjin shipping company and Hapag-Lloyd announced that they would no longer schedule regular shipping services through the Port of Portland, and shippers in the surrounding area lost the link to the global network. The Port of Portland almost came to a standstill, and shippers scrambled to send containers to the Port of Seattle by truck. At the moment, the port authority dominates the market, and the subsidy strategy is unnecessary. Second, a multimodal transport chain may sometimes not be cost effective for shippers, but the subsidy strategy/freight grant does help. The containers that were meant to be transferred at the competing port would shift to the port with shipping...
subsidies. However, once the local government stops or cuts the budget of transport subsidies for shippers, shipping demand might return to the original economic shipping route. Such an undifferentiated subsidy strategy by TEU is futile because the heterogeneity of shippers is not considered. Heung-A Shipping company started a regularly scheduled international shipping route in April 2006, and the port of Miike became involved in global distribution to China and Southeast Asia. From April 2007, financial subsidies (JPY 20,000 per container) were offered to shippers who considered the port of Miike as an export/import port. Until the present, the port of Miike has played a role in only the Asian network. The port authority could not identify the priority target customers in the traditional undifferentiated subsidy strategy. It is a matter of individual preference of selecting the multimodal transport route, which cannot be changed in a short period. However, if the government continues to prolong the subsidy strategy, tremendous capital loss might be generated. A differentiated subsidy strategy based on both shippers' factory location and shipping volume needs the attention of policy makers. Shippers whose factory is located near the port terminal are loyal customers; otherwise, they would have to truck containerized goods at extra expense to a geographically distant port. A differentiated subsidy offered to shippers who are located in the competitive hinterland may create greater consumer loyalty and preference.

7. Conclusions

Inland ports are vital for connecting inland hinterlands with distant seaports and provide convenience for both shippers and port authorities. The inland port has a dual function; it is an extended warehouse of port terminals and a distribution center for transiting containers by consolidating related logistical activities. A well-structured port-oriented transport chain with a low-cost inland transport system could guarantee a highly efficient transport service for inland shippers. This study builds a pricing model based on game theory to find the initial equilibrium state of the competition between seaports. Based on two adjacent ports in the northeast part of China, we perform a detailed comparative analysis to evaluate the effects of different incentive strategies on the multimodal transport system. The results show that a general cost advantage of inland transport or a service quality superior to that of other competing ports could attract shippers in distant hinterlands, regardless of long distances. There are significant differences in the effectiveness of various incentive strategies. First, the effects of investment in access corridors to inland ports depend on the unit investment capital for improving transport convenience. The larger the hinterland market or the greater the distance between competing seaports, the more effective the strategy will be. Second, in the direct subsidy strategy, it is not profitable for the port authority to adopt the undifferentiated subsidy strategy; however, the differentiated subsidy strategy that considers transport distance proves effective, with a tight restriction on minimum investment. Third, in the combinational strategy, port authorities should also consider shippers' preferences for transport convenience and inland transport cost. However, the related statements are concluded from the adjacent ports in China, which may not be universal owing to various business contexts, regulations, and management regimes applied in different countries. In future studies, the main insights of the paper may extend to general cases for analyzing the applicability of the proposed strategies, and many interesting questions arise if more factors are considered. First, because the management regimes of ports (state-owned port, municipality-owned port, etc.) differ significantly around the globe, which strategy is effective and applicable in different regions? Second, it is worthwhile to explore the cooperation between players in a port-oriented transport chain when the practical effects of various incentive strategies are discussed. Finally, what are the optimal strategies when we consider both intra-competition in a single transport chain and inter-competition between different transport chains?

Acknowledgements

The authors would like to thank the editors and anonymous referees for their careful reading and constructive suggestions. This work is supported by the National Natural Science Foundation of China [Grant No. 71671021].

CRediT authorship contribution statement

Chenrui Qu: Conceptualization, Methodology, Software, Data curation, Writing - original draft. Qingcheng Zeng: Investigation, Writing - original draft, Visualization, Supervision, Funding acquisition. Kevin X. Li: Writing - review & editing. Kun-Chin Lin: Investigation, Methodology, Software, Data curation, Writing - original draft.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.tra.2020.04.012.

References

C. Qu, et al.

Transportation Research Part A 137 (2020) 47–64