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HINTERLAND ANALYSIS FOR INLAND PORTS IN CONTINUOUS-DISCRETE TRANSPORTATION NETWORK

TAN ZHIJIA[1] and MENG QIANG[2]

[1]*School of Maritime Economics and Management, Dalian Maritime University, Linghai Road 116026, Dalian, PR China*
E-mail: zjatan@dlmu.edu.cn
[2] *Department of Civil and Environmental Engineering, National University of Singapore, Singapore 117576, Singapore*
E-mail: ceemq@nus.edu.sg

This paper analyzed the hinterland of the inland river ports connected with the discrete highway network. Therefore, the dense hinterland transportation network and the sparse highway network, together with the inland waterway system, form a continuous-discrete multi-modal freight transportation system. We proposed an aggregate model to capture the shippers' joint route and port choice behavior with the mixed logit model. We compared the hinterland topologic structures with and without discrete highway network and investigate the utilization of the highway network in the continuous-discrete multi-modal freight transportation system. The proposed model is adopted to examine the hinterland topologic structure of the inland river ports located in the Yangtze River Economic Belt.

Keywords: hinterland, inland ports, continuous-discrete Network, multi-modal transportation.

1 Introduction

Port hinterland related to the freight market share is one of the most important concerns for the port managers and researchers. The traditional studies viewed the hinterland as an area adjacent to the trade center, in which, the economic and cultural activities are related to the center (Van Cleef, 1941). With the improvement of logistic market and the discontinuous nature of the logistic network, the distance-decay conceptualization of the port hinterland has been revisit to refer the continental area of origin and destination of freight traffic flows through a port (Van Klink and Van de Berg,1998). Notteboom and Rodrigue (2007) classified the port hinterland into three types: the macro-economic hinterland related transport demand, the physical hinterland related to the transport supply, and the logistical hinterland related to the freight flow.

Determinant of the port hinterland can trace back to the studies on the market boundaries among multiple geographically competing facilities or market for like good (Hyson and Hyson, 1950). Both deterministic and probabilistic models are used to capture the spatial choice behavior of customers. Zhuang and Yu (2014) used the gravity model embedded in ArcGIS to derive the hinterlands of two ports. The discrete choice model is most popular method to analyze the port hinterland. Meng and Wang (2010) developed a probit-based method to formulate a port's probabilistic hinterland area with Gaussian distributed route utilities. They further proposed a generalized model of probabilistic port hinterland with free distributions of route utilities to estimate the boundaries of a port (Wang et al., 2016). Many empirical studies investigated the port hinterland or competitiveness via questionnaire survey and case studies (Chang et al., 2008; Yeo et al., 2008; Lam and Gu, 2013; Wan et al., 2014). The mainly focus of those studies is to identify the factors affecting the shippers' choice behavior.

The previous studies are useful to the seaports, which are usually connected by the rail or inland water corridors. However, the inland waterway system has the significant difference from the deep-sea shipping system. First, the inland river ports are dense along the natural rivers with highly competitive shipping market. There are about 40 inland river ports along the Yangtze River with about 100 inland shipping lines provided by more than 28 carriers (http://www.sipgl-mt.com). Second, the rail system is not developed to connect each of those small-scaled river ports. Nevertheless, the highway system provides the high accessibility among those ports. Therefore, the dense local road system and the sparse highway system form a continuous and discrete transportation network in the region of the inland waterway.

2 The Continuous-discrete Multi-modal Transportation Network

Consider a region Ω consisting of $|N|$ separated economic zones, Ω_m, $m \in M = \{1,2,\cdots,|M|\}$ in the two-dimensional plane, namely, $\bigcup_{m=1}^{M} \Omega_m \subseteq \Omega$ and $\Omega_m \bigcap \Omega_{m'} = \varnothing$, $m, m' \in M$. The region and $|M|$ economic zones can be any polygons in plane expressed by a rectangular coordinate system or spherical coordinate system. An inland waterway system and the highway system jointly provide the cargo transshipment export service between the region and overseas market connected by a sea hub port. The inland waterway provides the transportation via the inland river ports and liner shipping companies. The former handles the cargo including containing, moving, charging and discharging cargos. The latter transport the containers to the sea hub port via their shipping lines. And the highway system provides the fast routes to and from the inland river ports via a set of highway ramps. The continuous-discrete road system and the waterway system form the multi-modal transportation network.

There exist $|I|$ inland container ports on the river with location Y_i, $i \in I = \{1,2,\cdots,|I|\}$. Each inland river port is associated with container cargo handling capacity, C_i, $i \in I$, which depends on the investment of the infrastructure and equipment of the port. The port capacity determines the efficiency of the container cargo, which can be measured by the container number per day handled by the port. Each port charges a port service fee of cargo handling, τ_i, $i \in I$, to all shipping companies who call the port. All the cargos are assumed to export to overseas, and thus, should be shipped to the sea hub port, denoted as number 0, $Y_0 \in \Omega$. The container shipping lines provided by many liner companies jointly cover all the inland river ports I. Let R denote the set of all the inland shipping lines, and each shipping line is denoted by r, $r \in R$. Since we only consider the export service, each shipping line can be represented by the subset of the inland river ports I and is associated with a service frequency, f_r, $r \in R$ (vessels per week). Suppose the freight rate charged by the liner shipping companies to the shippers at the same port is the same for all shipping lines calling the port and denoted by p_i, $i \in I$. That is to say, we will not distinguish the differentiated shipping services with different freight rate at the same port. In reality, the distinguished freight rates do exist at the same port which depends on the service types, such as, the normal service and fast-vessel service. The latter provides the direct transportation to the sea hub port.

The highway system can be viewed as separated system of the region with vertex in the plane. Let $G(V,E)$ denote the highway system with vertex set V and link set E. To incorporate the discrete highway system in the continuous region and can be used into the hinterland analysis, we assume that the vertex set only includes the highway ramps. From the practical consideration, we assume that $Y_i \in V$, $i \in \{0\} \cup I$, namely, the ports are directly connected with the highway system. Similar to Yang et al. (1994), we also assume that there exists a dense transportation system including natural roads and free roads on the surface of the plane represented by a continuum. Therefore, shippers transport their cargos to ports (inland river ports or sea hub port) having a choice between two routes: (a) using the surface roads to access highway system and then to the one of ports; (b) using the surface roads directly to the one of ports. When the inland river port is selected by the shippers as the target of the continuous-discrete transportation system, the transshipment service is selected by the shippers and the inland port and the shipping line should be simultaneously chosen by the shipper.

3 Determinant of the Port Hinterland

The cargo shipment demand is continuously distributed on each zone Ω_m with non-identical density. Let X be the location of shipper in the region, $X \in \Omega$. For the spherical coordinate system, X represents the longitude and latitude coordinates. Each economic zone is associated with a cargo shipment density $\overline{q}_m\left(X\right)$, $X \in \Omega_m$, $m \in M$, which depends on the socioeconomic factor. Each shipper must determine her/his own transportation chain including the port and transportation route: the entry point from her/his origin to the highway system, the exit point from the highway system to the inland port, the highway route from the entry point to the exit point, and the shipping line. The problem of the shippers is to select the path to transship their cargos facing the continuous-discrete multi-modal transportation network. For simplifying our calculation, we also assume that the shipper can choose any ramp in V to entry highway system. And thus, the natural road can provide an alternative route directly to each port. Each route from location X , $X \in \Omega_m$, to port i , $i \in \{0\} \cup I$, can be represented as $X \to O \to Y_i$, $O \in V_m$, $V_m \subseteq V$, $m \in M$, where V_m is the available highway ramp set for the shippers at location X in Ω_m. For location X beyond all local economic zones, the shipment demand is zero. The route $X \to O$ is the natural road segment, while route $O \to Y_i$ is the highway segment. Correspondingly, the route from the inland port Y_i to the sea hub port Y_0 is called waterway segment. Note that, if O and Y_i are identical, then the shipper transports the cargo directly to the port i via the natural road. If O and Y_i are different, then the shipper uses the highway system. The generalized transportation cost on each route is associated with the natural road segment, highway route segment, and/or waterway segment. The transportation cost (including the monetary cost and time cost) on the natural road and highway segments are proportional to the shortest distance on the plane or the discrete network, respectively. If the shipper chooses the inland waterway transportation, the transportation cost on the waterway segment includes the cargo handling cost at port and shipping cost.

We introduce the route-section representation in the transit network proposed by de Cea and Fernanadez (1993) to consider the aggregative competition among all the shipping lines and the aggregative choice of the shippers. Denote A_i as the attractive shipping lines at inland river port i , $i \in I$, which is subset of the whole shipping lines, $A_i \subset R$. Suppose the shipment demand arrives at the port uniformly during any service period and thus, the average waiting time of shipping line r is completely determined by the service frequency of shipping line r, f_r, and can be expressed as $W_r^i = H/2f_r$, $r \in A_i$, $i \in I$, where H is the total working hours during a week, typically, $H = 7 \times 12$ by assuming 12 hours per day. The average cargo handling time cost or port time cost at the inland port is determined by the port capacity C_i and the aggregate cargo q_i demand at the port. We assume that the average cargo handling time cost is a non-decreasing of the ratio of q_i and C_i, which can be expressed as $S_i = S\left(q_i/C_i\right)$, $i \in I$ where the aggregate cargo demand at port i, q_i, is the sum of the cargo demand at all shipping lines in its attractive lines, namely, $q_i = \sum_{r \in A_i} q_r^i$.

To explicitly capture the total voyage time, we introduce the incidence parameter, δ_r^i, which equals 1 when shipping line *r* visits the inland river port *i*, and 0, otherwise. The sailing time is assumed to be fixed and determined by the sailing distance from the inland river port to the sea hub port with the given sailing speed. Denote t_i as the sailing time cost from inland river port *i* to the sea hub port 0. The shippers who choose shipping line *r* at port *i* also experience the port time at the downstream ports along the line. The total voyage time for the shippers selecting shipping line *r* at port *i* can be calculated as $T_r^i = \sum_{i' \in I, i' < i} S_{i'} \delta_r^{i'} + t_i$, $r \in A_i$, $i \in I$.

The generalized cost for the shippers at any point X in local economic zone Ω_m to choose highway ramps O_m in available ramp set V_m, to access the inland river port *i* and shipping line *r*, $r \in A_i$, $i \in \{1, 2, \cdots, N\}$, to transship their cargo to the sea hub port can be expressed as

$$U_r^i\left(X \middle| X \in \Omega_m\right) = D\left(X, V_m, Y_i \middle| X \in \Omega_m\right) + \alpha_1 W_r^i + \alpha_2 T_r^i + p_i\,, \tag{1}$$

where α_1 and α_2 are model parameters to convert the different measurements to monetary unit, $D\left(X, V_m, Y_i \middle| X \in \Omega_m\right)$ is minimal total generalized transportation cost of the road segments, including the natural road and highway segment, by selecting the highway ramp in the available ramp set V_m, namely, $D\left(X, V_m, Y_i \middle| X \in \Omega_m\right) = \min_{O \in V_m}\left\{\alpha_3 d_N\left(X, O\right) + \alpha_4 d_H\left(O, Y_i\right) : X \in \Omega_m\right\}$, where α_3 and α_4 are model parameters to convert the different measurements to monetary unit, functions $d_N\left(\cdot,\cdot\right)$ and $d_H\left(\cdot,\cdot\right)$ represent the shortest distance of the natural road and highway road segments, respectively, which can be calculated using the Euclidean distance or spherical distance. Specially, the road transportation mode is chosen by the shippers when they transport their cargo directly to the sea hub port 0. For simplifying our presentation, we also denote the attractive route of the sea hub port as A_0, which only includes the road transportation mode. The generalized cost of the road transportation mode is only the road transportation cost, namely,

$$U_r^0\left(X \middle| X \in \Omega_m\right) = D\left(X, V_m, Y_0 \middle| X \in \Omega_m\right) + p_0\,. \tag{2}$$

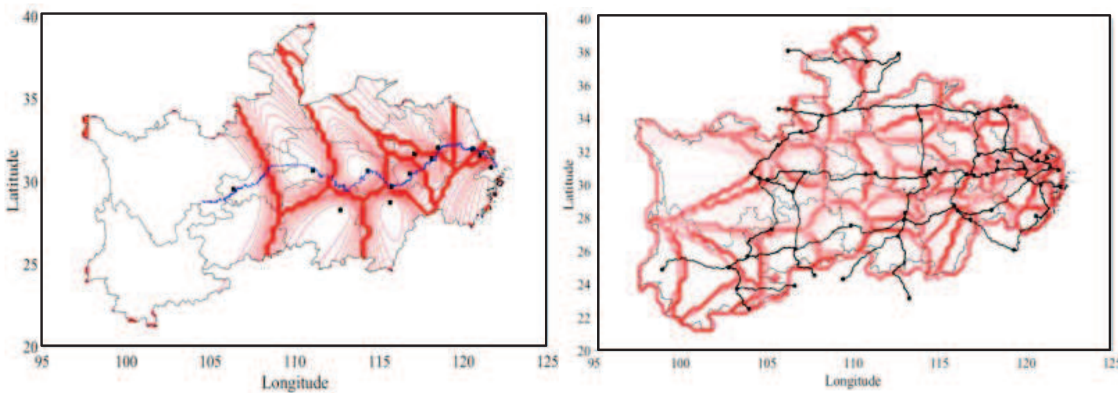
The multinomial logit model is adopted to express the joint choice of the shippers at any point X, $X \in \Omega_m$, on the port *i*, $i \in \{0\} \cup I$, and shipping line *r*, $r \in A_i$. The choice probability can be calculated as $\Pr\left(\left(i, r\right) \middle| X \in \Omega_m\right) = \frac{\exp\left(-\theta U_r^i\left(X \middle| X \in \Omega_m\right)\right)}{\sum_{i' \in \{0\} \cup I} \sum_{r' \in A_{i'}} \exp\left(-\theta U_{r'}^{i'}\left(X \middle| X \in \Omega_m\right)\right)}$. The choice probability of each port $i \in \{0\} \cup I$ by the shippers at X, $X \in \Omega_m$, is the summation of all corresponding shipping lines. Note that the choice probability $\Pr(i|X)$ is completely determined by the assignment of the shipment demand q_i at each port, while the shipment demand at each port has an effect on the port time, which affects the shippers' choice. At the choice equilibrium, no shipper can improve his/her expected utility by unilaterally adjusting his/her choice behavior. With the logit model, we define the hinterland of each port as the domain, on which any shipper has the highest probability to choose the port, $\Omega_i = \left\{ X \in \Omega \middle| \Pr(i|X) \geq \Pr(i'|X), i' \neq i, i, i' \in \{0\} \cup I \right\}$.

4 Numerical Example

In this section, the Yangtze River with the Yangtze River Economic Belt is adopted as an example. Consider 14 inland ports along the river and assume $\bar{q}_m(X) \equiv 1$ to investigate the probabilistic boundaries of each inland river port. The highway system in 1999 is adopted since the network is not dense and can highlight the hinterland structure. According to the posted price of JCTRANS, the average price on road system is about 0.8 yuan/km/ton. To distinguish the highway system and continuous road system, we assume that the time cost on road is 10 times of highway system because of the urban congestion and other costs. The speeds on both systems are 90km/hr and 30km/hr. The value-of-time is assumed to be 10 yuan/hr for one-ton freight. The waterway transportation cost per mile is 0.2 yuan and the sailing speed is 12 knots per hour. The transshipping cost on the inland port is assumed to 0.1 yuan/ton times the waiting time. The toll charge on the highway is 0.3 yuan per kilometer per ton. Furthermore, the port delay is neglected in this numerical example. With those assumptions, we have α_1=0.1 , $\alpha_2 = \frac{50}{12 \times 1.852} = 0.45$, $\alpha_3 = 0.8 + 10 \times \frac{10}{30} = 4.13$, $\alpha_4 = 0.8 + \frac{10}{100} + 0.3 = 1.2$, $p_i = p_0 = 0.2$. The distances on highway and river are taken the true values and the distances on the continuous road system are measured by the spherical distance on earth. The sensitivity parameter for the logit model is taken to be θ=0.005 .

We first set the toll charge of the highway system is much high such that the shippers are not willing to select the highway system. By doing so, the hinterland domains are reduced to the traditional analysis of the geographic boundary estimation. Figure 1 (a) shows that the hinterland boundary of each inland port without considering the effect of the highway system. The hinterland, as previous studies, surrounds the interested port, which is dependent on the cost saving via the waterway transportation in comparison with the mode of the pure road transportation. And thus, the hinterland domain is affected by the distance from the inland port to the sea hub port, the number of the shipping lines and corresponding frequencies, the marginal costs of the road and waterway transportation. It is clear that the area of the hinterland tends to smaller when the cost saving by the waterway transportation becomes less. Figure 1 (b) shows the domains of shippers of selecting the highway ramps to achieve the inland ports. Similar to port choice, we determine the domain of ramp choice by taking the maximal value of the choice probabilities of the shippers on each highway ramp. It is clear to see that, the domain surrounds each highway ramp. The natural phenomenon is that the traditional hinterland of each port would be changed with the effect of the road system. The hinterland is now divided into pieces and distributed around the highway ramps.

Figure 2 depicts the hinterland of the inland ports with the effect of the highway system. In comparison with the traditional hinterland analysis, the shippers who are far from a specified port but near some highway ramps would still have a higher probability to select the port. As shown in Figure 2, the cargos of Nanjing Port mainly come from the upper domain of the Yangtze River Economic Belt. Observing from Wuhan port in Figure 2, it is interesting that the many shippers surrounding the Yichang Port transport their cargos via the ramp near the port to Wuhan Port since the latter provides much more shipping lines than the former does.



(a) without highway system (b) with highway system

Figure 1. Hinterland of inland ports without highway system.

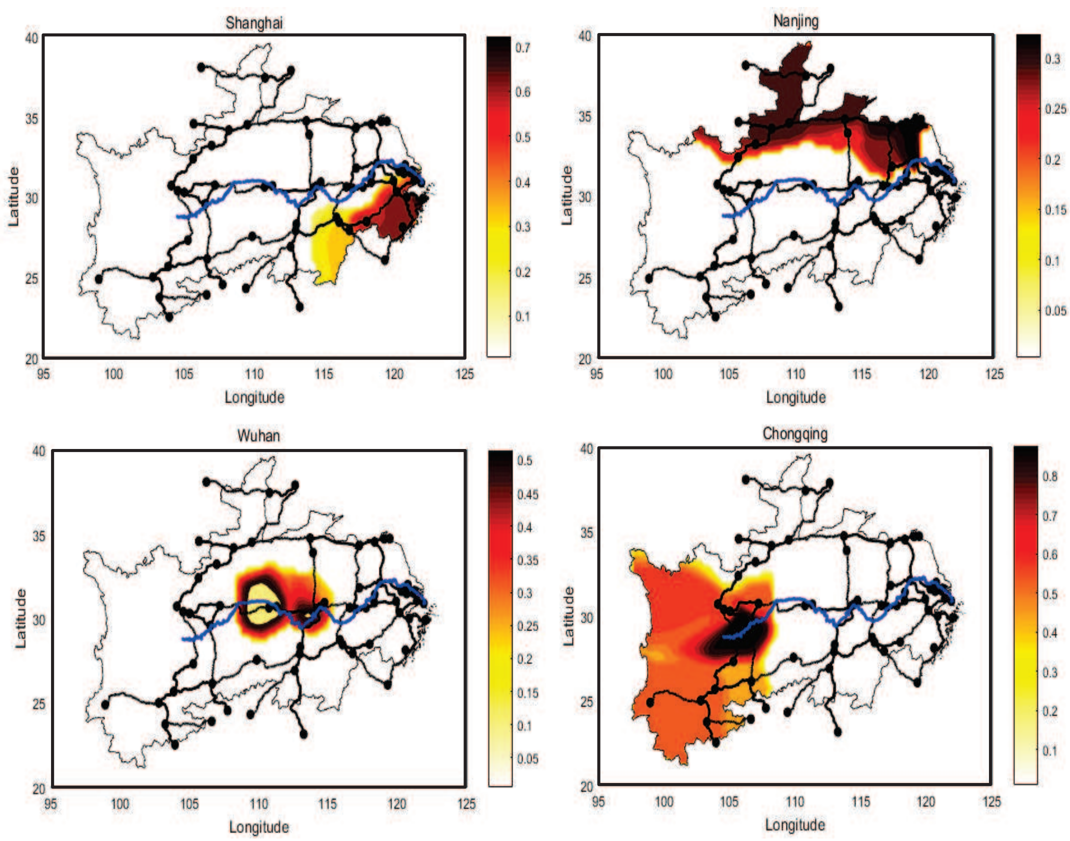


Figure 2. The hinterland of inland ports with the effect of the highway system.

5 Conclusions

It is challenging to estimate the hinterland for the inland river ports since those ports heavily compete to each other for the shipment demand with complicated road and highway system. This paper developed a continuous-discrete multi-modal transportation system to analyze the port hinterland. The shippers distribute a given two-dimensional region, who transport their cargos to the sea hub port via the dense road network, discrete highway network and the inland waterway system. The multinomial logit model was adopted to capture the shippers' road choice behavior. The Yangtze River Economic Belt with real highway system and 13 inland river ports are used to examine the validity of the proposed model and depicted that the model can explicitly obtain the port hinterlands by incorporating the effect of the highway system. The port hinterlands generally distribute among the highway ramps and not surround the ports as the traditional studies.

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References

Meng, Q., Wang, X., Utility-based estimation of probabilistic port hinterland for networks of intermodal freight transportation. J. Transport. Res. Board 20972618, 53-62, 2010.

Van Cleef, E.. Hinterland and umland. Geograph. Rev. 31 (2), 308 – 311, 1941.

Van Klink, H.A., Van de Berg, G., Gateways and intermodalism. J. Transport Geography 6 (1), 1-9, 1998.

Notteboom, T., Rodrigue, J.P., Re-assessing port-hinterland relationships in the context of global commodity chains. In: Wang, J.J. (Ed.), Ports, Cities, and Global Supply Chains, pp. 51-66 (Chapter 5) 2007.

Hyson, C.D., Hyson, W.P., The economic law of market areas. Quart. J. Econ. 64 (2), 319 – 327, 1950.

Zhuang, J., Yu, S., The hinterland spatial structure evolvement of competitive port based on ArcGIS. In: Wen, Z., Li, T. (Eds.), Practical Applications of Intelligent Systems, vol. 279. Springer, Berlin, Heidelberg, pp. 1143-1153, 2014.

Wang, X., Meng, Q., The impact of landbridge on the market shares of Asia ports. Transport. Res. Part E 47 (2), 190 – 203, 2011.

Wang, X., Meng, Q., Miao, L., Delimiting port hinterlands based on intermodal network flows: model and algorithm. Transport. Res. Part E, 88, 32-51, 2016.

Chang, Y.T., Lee, S.Y., Tongzon, J.L., Port selection factors by shipping lines: different perspectives between trunk liners and feeder service providers. Mar. Policy 32 (6), 877-885, 2008.

Yeo, G.T., Roe, M., Dinwoodie, J., Evaluating the competitiveness of container ports in Korea and China. Transport. Res. Part A 42 (6), 910-921, 2008.

Lam, J.S.L., Gu, Y., Port hinterland intermodal container flow optimisation with green concerns: a literature review and research agenda. Int. J. Ship. Transport Logist. 5 (3), 257-281, 2013.

Wan, Y., Yuen, A., Zhang, A., Effects of hinterland accessibility on U.S. container port efficiency. Int. J. Ship. Transport 6 (4), 422-440, 2014.

Erdödi F, Csortos C, Sparks L, Murányi A, Gergely P., Transit assignment for congested public transport system: an equilibrium model. Transport. Sci. 27(2), 133-147, 1993.