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Freight network design with heterogeneous values of time

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Abstract

This paper aims to demonstrate the effect of recognizing heterogeneity in values of time on the design of a hub network for freight transportation. By taking the VOT distribution into account, we emphasize shippers' broader logistical, social and economic situation in the network design, and are not limited to commodity types. The paper employs the single allocation p-hub median problem which minimizes the total generalized transportation cost (time, distance, etc.) with given demands. VOT is assumed to be discretely distributed, and estimated by mean-dispersion model and Latent Class model, based on a Stated Preference survey conducted in China, investigating railway shippers' choice behavior of railway services. A local railway network with 14 nodes and 20 linkages is applied to discuss the effect of VOT distribution on multiple (i.e., 3) hub location strategy. Simulated Annealing (SA) is designed to solve the single allocation p-hub median problems. The numerical results shows that the VOT and its distribution should be taken into account for better simulating railway shippers' heterogeneous valuations of service time versus time.

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Keywords: freight transport; heterogeneity; VOT distribution; single allocation p-hub median probelm

1. Introduction

The hub network refers to a distribution system in which hubs are located for switching, transshipment and sorting, and non-hub nodes are allocated to one or more hubs, to pursuit the economies of scale for inter-hub transportation, rather than direct services between non-hub nodes. The main issues in hub network studies are, as noted by O'Kelly and Miller (1994), to find the optimal hub locations, to assign non-hub nodes to the hubs, to determine inter-hub

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linkages and to route demand flows through the network. Besides, a series of hub location and non-hub nodes allocation problems have been widely studied in transportation, logistics, and telecommunication, in last decades. And the main research focuses on hub network are: (1) p-hub median problem, (2) hub location problem with fixed costs, (3) p-hub center problem, and (4) hub covering problems. A comprehensive review on variants of hub network design problem involving with models and solution methods could be found in Alumur and Kara (2008), as well as Campbell and O'Kelly (2012). Since its advantages in multiple flows concentration and redistribution in freight transport, hub network has been adopted by major international logistics companies, like Federal Express and UPS, to organize air and ground transportation and delivery.

As the input of the hub network, demand in hub network design problem are normally assumed to be homogeneous, which can be represented by origin and destination nodes, as well as the hubs connected them. Demands sharing the same link by one transport mode are viewed as a single demand. However, there is considerable heterogeneity in network demand, especially for freight transport. As implied by De Jong (2000), demand heterogeneity in freight transport is more complicated than that in passenger transport, in terms of shipment diversity, like shape, size, value, etc.

As one critical component for measuring demand heterogeneity, the values of time (VOT) distribution and its effects on travelers' route/mode choice has been studied. Yang et al.（2001）studied how the distributions of values of time (VOT) would affect the competition among differentiated bus services in terms of price and quality. The VOT was assumed to distribute continuously across users, and was take as the critical component of generalized trip costs. Results showed that there was a highly significant relationship between VOT distribution and profitability of bus service providers. Then, Yang et al. (2002) investigated the impact of users' heterogeneity on the profitability and welfare gain of a private toll road in a given network, in which users was segmented into a number of distinct groups according to their VOT. Authors suggested that incorporating user heterogeneity in terms of VOT and its distribution were important for stakeholders' choice making on new investment projects. Yang and Huang (2004) examined the network equilibrium and system optimum problem in a network with a discrete distribution of VOT. Besides, Zhao and Kockelman (2006), Cantos-Sánchez et al. (2011) ,Tan and Yang (2012), Qian and Zhang (2013), Wang and Ehrgott (2013), Wang et al. (2014), and Wang et al. (2014) discussed the importance of VOT and its distribution for travelers' route choice decision.

On the other hand, there are a few articles about heterogeneity in freight transport, studies include Kwon, et al. (1998), which proposed a dynamic freight car routing and scheduling model based on railway time-space network, in which the traffic could be classified into several differentiated classes because of heterogeneous service requirement from railway shippers. And Francesco et al. (2006) focused on the empty container reallocation problem of logistic companies, which the empty containers were modeled as heterogeneous fleet with different sizes. However, heterogeneity captured by industrial activities, consignment commodity type or service requirement is often impracticable, as noted by Arunotayanun and Polak (2011), to study freight choice behavior.

Although there is abundant literature on freight network design, there is little work that explicitly takes into account heterogeneous preferences. Especially when it concerns the trade-off between transport time and tariffs, knowledge of this heterogeneity may play an important role in designing the network, increasing its overall performance.

Thus, this paper will study the relationship between VOT distribution and hub network design in freight transport. In detail, we employ the single allocation p-hub median network design model as theoretical basis, and VOT will be incorporated into the unit transport cost formulation, to calculate the generalized transport costs. What's more, VOT is assumed to be distributed discretely, based on a series of estimation by Latent Class (LC) model and the relative Mean-dispersion model.

The outline of this paper is as follows. Section 2 describes the single allocation p-hub median network design model. VOT distribution and formulation are discussed in Section 3. Section 4 presents a numerical analysis based on a local railway network in China. And Section 5 contains our discussions and conclusions.

2. SApHMP model

The single allocation p-hub median problem, referred to SApHMP in our paper, allocates non-hub nodes to one and only one hub node, and no direct services between non-hub nodes are allowed. SApHMP is first formulated by O'Kelly (1987) with a nonlinear programming model, which the total transport cost is minimized with given demand flows, demand nodes, and the number of hubs to locate (p).

SApHMP is modeled in our paper based on the work by O'Kelly (1987) which presented a nonlinear integer programming formulation. Given a graph $G=(N,A)$, N and A are the set of nodes and arcs, respectively. Denote d_{ij} as the distance from node i to node j, and W_{ij} is the given demand flow for node pair (i, j). And the number of hubs in the network is settled to be p, and n is the total number of nodes to be interconnected. In the hub network, the transport cost for one unit flow from node i to node j is C_{ij}, and the discount factor for inter-hub transportation is α, which in nonlinear with the amount of flow.

Define $X_{ik} \in \{0,1\}$ be 1 if node i is allocated to hub at k, and 0 otherwise. $X_{kk}=1$ when the node k is selected as a hub, 0 otherwise. Then the SApHMP is to select p hubs from the set of nodes N, and locate them in the network. Then find the best non-hub nodes allocation plans to minimize the generalized total transport costs.

The basic model (O'Kelly, 1987) for SApHMP is as follows:

$$\text{Minimize} \quad \sum_i \sum_j W_{ij} \left(\sum_k X_{ik} C_{ik} + \sum_m X_{jm} C_{jm} + \alpha \sum_k \sum_m X_{ik} X_{jm} C_{km} \right) \tag{1}$$

$$s.t. \quad (n-p+1) X_{kk} - \sum_i X_{ik} \geq 0 \tag{2}$$

$$\sum_k X_{ik} = 1 \tag{3}$$

$$\sum_k X_{kk} = p \tag{4}$$

$$X_{ik} \in \{0,1\} \tag{5}$$

The components in objective function (1) are transport cost for collection from non-hub nodes to hubs, distribution from hubs to non-hub nodes, and inter-hub transfer, respectively. The inter-hub transport cost is discounted by $\alpha (0 \leq \alpha < 1)$ due to economies of scale when the capacity on the link is unlimited. Constrain (2) ensures that allocation of non-hub nodes to hubs only happens when one node is selected as a hub. Constrain (3) - (5) ensure that there are p hubs are selected and non-hub nodes can only be allocated to one and only one hub node.

3. VOT distribution

To incorporate the value of time (VOT) into SApHMP model, we define the transport cost C_{ij} as:

$$C_{ij} = d_{ij} (\text{VOT} / s_{ij} + f_{ij}) \tag{6}$$

Where, VOT is the value of time for demand flow originating from node i and terminating to node j. s_{ij} and

f_{ij} are the average transport speed and tariff for node pair (i , j), respectively.

As discussed earlier, here we discuss the heterogeneous VOT which discretely distributed across demand flow with the same origin and destination, to compare the homogeneous VOT for demand flow with the same origin and destination. For the VOTs estimation, due to the difficulty of acquirement VOT from freight firms, Stated Preference (SP) is the main way to measure VOT by a survey experiment, like the work by De Jong, et al. (2014). Based on our earlier SP survey about railway shippers' choice behaviour conducted in one Railway Company in China, we collected 114 completed questionnaires out of 543 handed-out questionnaires. Among them, 31 questionnaires were excluded because of missing data. This resulted in 83 respondents and 1660 choice observations. More details about this survey could be found in Duan, et al. (2016).

With these survey data, we can estimate shippers VOTs with the relative Mean-dispersion models as mentioned by Significance, et al. (2012):

$$U_l = \beta'_C \frac{C_l}{C_0} + \beta'_T \frac{T_l}{T_0} + \beta'_F \frac{F_l}{F_0} + \beta'_R \frac{R_l}{R_0} + \beta'_E \frac{E_l}{E_0} \tag{7}$$

Where, C_l, T_l, F_l, R_l, E_l and C_0, T_0, F_0, R_0, E_0 are the simulated and base values for service attributes - transport cost, time, frequency, reliability and safety. Thus, the VOT could be estimated by:

$$VOT = \frac{\beta'_T}{\beta'_C} \times FactorCost \tag{8}$$

Besides, to allow VOT to be discretely distributed, we estimate a series of so-called Latent Class (LC) models, as discussed in Greene and Hensher (2003). The LC model assumes that there are latent classes (as opposed to observable segments) of respondents, each with its own distinct set of preferences. Each individual is assigned to a different class, up to a probability. In this way, a series of utility coefficients could be estimated for discrete shippers classes, thus, there would be discretely distributed VOTs.

With NLOGIT software (Greene, 2012), both one class assumption with MNL model and multiple classes assumption with LC model are estimated. And the Akaike information criterion (AIC) value shows that three classes segmentation gets the best model fit. Table 1 presents the estimation results by MNL and LC model, respectively.

Table 1. Estimation results by MNL and LC model.

Parameters	MNL		LC					
			Class 1		Class 2		Class 3	
	Coef.	S.E.	Coef.	S.E.	Coef.	S.E.	Coef.	S.E.
β'_C	-0.04874***[a]	0.00444	-0.08601***	0.00874	0.00320	0.01026	-0.09580***	0.01296
β'_T	-0.02071***	0.00221	-0.05147***	0.00791	-0.00195	0.00444	-0.00848*	0.00502
β'_F	0.01364***	0.00212	0.03957***	0.00529	-0.00165	0.00474	0.00669	0.00531
β'_R	0.04783***	0.00345	0.10836***	0.01243	-0.01639**	0.00653	0.07419***	0.00824
β'_E	0.09942***	0.00553	0.09083***	0.01134	0.02565**	0.01011	0.28325***	0.03891
Opt out[b]	13.0925***	0.65394	18.7972***	1.79295	-2.92205*	1.51806	32.7341***	4.04779
Membership Probability			0.44476***	0.07509	0.17592***	0.04428	0.37933***	0.07369
AIC			2861.7					
Null LL	-2137.3335		-2137.3335					
Final LL	-1680.3272		-1680.2781					
R-squared	0.2138		0.3399					

a. ***, **, * : Significant at 1%, 5%, 10% level, respectively.
b. Coefficients for None Choice option in the survey.

Besides, according to the website of Customer Service Centre of China Railway, the average tariff of both container and non-container cargoes is 0.1044 ¥/ton·km (http://hyfw.12306.cn/hyinfo/action/JgxxAction_index?type=1, Accessed February 29, 2016.). And the average travel speed of freight trains around 2009 is 34 km/h (An, 2009). So the factor cost for railway freight services is 3.5496 ¥/ton per hour. Thus, the VOT for all shippers (Homogeneous VOT) and for shippers in different classes (Heterogeneous VOT) could be roughly calculated by multiplying the ratio of the estimated time to the estimated cost coefficient, by the factor cost, which leads to 1.51 ¥/ton per hour for all shippers, 2.12 ¥/ton per hour for shippers in Class 1, 2.16 ¥/ton per hour for shippers in Class 2, and 0.31 ¥/ton per hour for shippers in Class 3.

4. Numerical analysis

Given the heterogeneous and homogeneous VOTs of Chinese shippers, we will test the SApHMP model with two scenarios: (a) traditional model with the same VOT for all shippers, and (b) discretely distributed VOTs for different classes of shippers. Since there is no available railway network and demand data in our SP survey, for both cases, we will test our model based on a small railway network in Northeast China, which was introduced by Ji et al. (2011),. In general, there are 14 nodes located in the network, and the number of hub nodes to be located is 3. Besides, to allow comparisons, the original demand flows in Ji et al. (2011) will be divided into three classes in scenario (b), then the VOT and proportion of each class is corresponding to the results in Section 4. Table 2 and Table 3 present the railway network linkages, distances, and demand flow.

Table 2. Linkages and distances of the studied railway network.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	-	208	-	261	-	-	-	-	-	-	-	-	-	-
2	208	-	229	-	-	125	-	-	-	-	-	-	-	-
3	-	229	-	-	-	-	-	-	485	-	-	-	-	-
4	261	-	-	-	104	-	188	-	-	-	-	-	-	-
5	-	-	-	104	-	170	-	145	-	-	-	-	-	-
6	-	125	-	-	170	-	-	-	370	249	279	-	-	-
7	-	-	-	188	-	-	-	115	-	-	-	-	-	-
8	-	-	-	-	145	-	115	-	-	218	-	-	-	-
9	-	-	485	-	-	370	-	-	-	-	-	901	-	-
10	-	-	-	-	-	249	-	218	-	-	128	-	116	-
11	-	-	-	-	-	279	-	-	-	128	-	338	-	218
12	-	-	-	-	-	-	-	-	901	-	338	-	-	-
13	-	-	-	-	-	-	-	-	-	116	-	-	-	218
14	-	-	-	-	-	-	-	-	-	-	218	-	218	-

Table 3. Homogeneous and heterogeneous demand flow.

O	D	Homogeneous demand		Heterogeneous demand					
				Class 1 (0.44476)		Class 2 (0.17592)		Class 3 (0.37933)	
		W_{ij}	VOT_0	W_{ij}^1	VOT_1	W_{ij}^2	VOT_2	W_{ij}^3	VOT_3
2	13	820000	1.51	364703	2.12	144254	2.16	311051	0.31
1	11	260000	1.51	115638	2.12	45739	2.16	98626	0.31
1	12	280000	1.51	124533	2.12	49258	2.16	106212	0.31
3	4	280000	1.51	124533	2.12	49258	2.16	106212	0.31
4	9	270000	1.51	120085	2.12	47498	2.16	102419	0.31
4	11	100000	1.51	44476	2.12	17592	2.16	37933	0.31
5	11	380000	1.51	169009	2.12	66850	2.16	144145	0.31
4	10	200000	1.51	88952	2.12	35184	2.16	75866	0.31

12	7	340000	1.51	151218	2.12	59813	2.16	128972	0.31
12	5	240000	1.51	106742	2.12	42221	2.16	91039	0.31
14	6	380000	1.51	169009	2.12	66850	2.16	144145	0.31
8	14	240000	1.51	106742	2.12	42221	2.16	91039	0.31

Besides, to solve the SApHMP, a metaheuristic approach, i.e. Simulating Annealing (SA) algorithm is applied in our case with MATLAB 2014a platform. In detail, the initial and final temperature are 1000 and 0.001, respectively. And the temperature decrement ratio (TDR) in our case is tested by running a series of SApHMP models with homogeneous VOT by SA, with the discount factor ranging from 0.80 to 0.99, as discussed in Abdinnour-Helm (2001).

Table 4. Temperature decrement ratio test with single VOT.

Discount Factor	Solution Quality	TDR		
		0.85	0.90	0.95
0.80	Iterations	35	34	43
	Time (seconds)	49.32	46.82	59.05
0.90	Iterations	39	34	39
	Time (seconds)	53.47	47.11	53.83
0.99	Iterations	32	36	38
	Time (seconds)	44.21	49.63	52.85

In Table 4, it's clear that when the TDR=0.90, both the number of iterations and time are better than other cases (except when discount factor is 0.99). Thus, for both single VOT and multiple VOTs in our two scenarios, 0.90 will be used as the temperature decrement ratio. Further experiments with SA approach show that the optimal location for three hubs in both cases are node #2, #6 and #12, which lead to a coincident result by homogeneous VOT and heterogeneous VOTs.

5. Conclusions

This paper discussed the effects of VOT and its distribution on the single allocation p-hub median problem, by incorporating VOT into the transport cost formulation. RUM and LC models are applied to estimates railway shippers' differentiated valuations towards transport time versus cost. And railway shippers' segmentation is examined using Latent Class, and three classes of shippers are found to be existed in our respondents, thus leads to three different values of time in our case.

A local railway network configuration from Northeast of China is deployed with 14 nodes and 20 linkages. After running two scenarios with one single VOT and three distinct VOTs respectively, three hubs are located at node 2, 6 and 12. Results by Simulating Annealing approach show that both cases can get the optimal hub locations and allocations schemes. Besides, the discount factor and temperature decrement ratio are tested and compared with a series of SApHMP models.

Besides, there is only one mode in our numerical analysis. This can be further extended for intermodal transport network, which different transport mode can be differentiated in terms of transport speed, VOT, etc. Mode choice behavior can be studied more precisely associated service network design.

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