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DOI
10.1016/j.tre.2019.02.008

Publication date
2019

Document Version
Final published version

Published in
Transportation Research Part E: Logistics and Transportation Review

Citation (APA)
Duan, L., Tavasszy, L., & Rezaei, J. (2019). Freight service network design with heterogeneous preferences for transport time and reliability. *Transportation Research Part E: Logistics and Transportation Review*, *124*, 1-12. https://doi.org/10.1016/j.tre.2019.02.008

Transportation Research Part E 124 (2019) 1–12

Contents lists available at ScienceDirect

Transportation Research Part E

journal homepage: www.elsevier.com/locate/tre

Freight service network design with heterogeneous preferences for transport time and reliability

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ARTICLE INFO

Keywords:
Freight service network design
Value of time
Value of reliability
Heterogeneous preferences

ABSTRACT

Value of time and value of reliability are two important user attributes that reflect shippers' behavioral preferences, and as such influence the design of transport service networks. As shippers preferences will vary widely, it is important to consider these variations between users in the design of service networks. Up to now, network design research has ignored the combined use of time and reliability valuations for heterogeneous user populations. The objective of this paper is to address these attributes in a model for freight service network design targeting service performance improvement. We present a new frequency based service network design model with transshipments, capacity constraints and heterogeneous users. We apply the model to demonstrate that including heterogeneity explicitly in network design pays off in terms of an improved user performance of the network. A case study is conducted for a railway network in China. Values of time and reliability are estimated from a recent Stated Preference survey and used to determine distinct user classes. The proposed optimization problem is solved using an improved Simulated Annealing based heuristic method, for the case of the aggregate user group and the case of two distinct classes. Results show that by taking variations in shippers' VOT and VOR into account, users' total generalized cost is reduced while service levels improve. We conclude that incorporating heterogeneous VOT and VOR into the service network design problem is of interest for decisions on network investments.

1. Introduction

Service network design (SND) is a tactical problem in freight transportation, which is often used to help carriers to select and schedule the services to operate, specify the terminal operations and seek the best routes of freight (Crainic, 2000). The Frequency Service Network Design (FSND) problem addresses the type and frequency of services on freight routes. In the FSND problem, demand is usually described with a basic recognition of flows from different users, with different volumes on the various origin/destination pairs, termed as a multi-commodity perspective on flows. As a common case in FSND, multi-commodity flows exist in almost all transport modes, like road, rails and waterways. According to Kwon et al. (1998) and Crainic (2000), the identification of commodity types is mainly based on its appearance by weight, volume, origin, destination, departure time and delivery condition. It is more and more difficult to identify service preferences of shippers by the appearance of the goods or the commodity type (Zhang et al., 2015). The service preferences of shippers will also be determined by product logistics characteristics such as the supply chain

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https://doi.org/10.1016/j.tre.2019.02.008
Received 1 December 2018; Received in revised form 4 February 2019; Accepted 15 February 2019

design, product perishability and the inventory policy. Therefore, observing commodity type may not be enough to capture basic preferences of shippers for service attributes such as service frequency, reliability or delivery time window, like used in Crainic and Rousseau (1986), Smilowitz (2001) and Zhang et al. (2013). In addition, as the variation in products and the associated logistics services has increased, a detailed understanding of the heterogeneity of freight service demand has become important. Over time, with the increasingly fierce competition in product and service markets, shippers have diversified in terms of their preferences concerning service attributes such as service price, time, and reliability. Heterogeneity in freight service preferences across commodities has been already been observed by Arunotayanun and Polak (2011) and Duan et al. (2016a).

As transport time and reliability are two important service attributes affecting shippers' choice behavior, we will consider heterogeneity in their valuation of these attributes. Apart from being useful for differentiating between commodities, they also represent the shippers' willingness to pay for the improvement of service quality. In the literature, a number of studies discuss the relationship between heterogeneous value of time (VOT) and public transport network design. Yang et al. (2001) study how the distribution of VOT affects competition between bus services in terms of price and quality. Yang et al. (2002) investigate the impact of users' heterogeneity on the profitability and welfare gain of a private toll road in each network, also segmenting users according to their VOT. The authors suggest that incorporating user heterogeneity in VOT is important for stakeholder decisions about new investment projects. Yang and Huang (2004), Zhao and Kockelman (2006), Tan and Yang (2012) discuss the importance of VOT for travelers' route choice decisions and its impact on network design. With more and more theoretical and empirical studies of freight VOT and VOR (value of reliability) becoming available (see e.g. Zamparini and Reggiani, 2007; Fowkes, 2007; Feo Valero et al., 2011; De Jong et al., 2014; Shams et al., 2017) it has become necessary to rethink freight service network design problem by incorporating VOT and VOR. To the authors' knowledge, very limited research has been done in freight SND that includes VOT, no research that considers the VOR and no research that considers heterogeneity in valuations. The studies that allow some form of heterogeneity, using a multi-commodity formulation (e.g., Racunica and Wynter, 2005), do not address SND and do not consider variations between shippers in VOT and/or VOR. Andersen and Christiansen (2009) used VOT to define commodity groups, and designed a rail service network model which includes transport time cost and waiting time cost. The review of SteadieSeifi et al. (2014) confirms that these attributes, and preference heterogeneity in particular, has not yet been operationalized in freight FSND research. An additional literature search revealed that no study has emerged on this topic since then. Duan et al. (2016b) discuss possible use of VOT and its distribution for freight network design. The work presented here continues on that discussion.

The contributions of this study are the following. We present a new frequency based service network design model with transshipments, capacity constraints and heterogeneous users, from the perspective of service performance improvement. We apply the model to demonstrate that including heterogeneity explicitly in network design pays off in terms of an improved user performance of the network. A case study is conducted for a railway network in China. Values of time and reliability are estimated from a recent Stated Preference survey and used to determine distinct user classes. The proposed optimization problem is solved, using an improved Simulated Annealing based heuristic, for the case of the aggregate user group and the case of two distinct classes. Results show that by taking variations in shippers' VOT and VOR into account, users' total generalized cost is reduced while service levels improve.

The remainder of the paper is organized as follows: Section 2 presents the FSND model considering heterogeneous VOT and VOR and its solution approach. Section 3 describes the application for a case study in China, including the demand model estimation, the network design solution approach and the results. The conclusions and recommendations of the paper are presented in Section 4.

2. New FSND model with VOT and VOR

2.1. Model formulation

Given a directed graph $\mathcal{G} = (\mathcal{N}, \mathcal{A})$, $\mathcal{N}$ is a set of nodes, $\mathcal{A} = \{(i, j), i \neq j, i, j \in \mathcal{N}\}$ is a set of links between node i and j. Define d_{ij} and c_{ij} as link distance and capacity, respectively. t_{ij} is the transshipment time required on node j of link (i, j).

For a network with limited link capacity, knowledge of the set of K-shortest paths is necessary, to find K paths from the origin to the destination that have the shortest lengths. $\mathcal{K}$ is defined as the set of K-shortest paths between one OD pair in this network. To differentiate the service quality offered by carriers, the set of available service levels is defined as $\mathcal{R}$, which is measured by transport price p, speed f, reliability e and capacity u. Thus, a service s_{ij}^{kr} in this network is described by its starting node $i \in \mathcal{N}$ and ending node $j \in \mathcal{N}$, the shortest path $k \in \mathcal{K}$ it passes by, and the service level $r \in \mathcal{R}$. The set of commodities is denoted by Q. For a given commodity $q \in Q$, its origin node $i = o(q)$, and destination node$j = d(q)$. Furthermore, w_{ij}^q is defined as the demand volume, VOT_{ij}^q and VOR_{ij}^q are the value of time and value of reliability, respectively.

All necessary sets, parameters and decision variables in our model are presented blow.

Sets

$\mathcal{N}$: The set of nodes.

$\mathcal{A}$: The set of links.

$\mathcal{K}$: The set of shortest paths between two nodes in a transport network.

$\mathcal{R}$: The set of available service levels offered by logistics service providers.

Q: The set of commodities.

Parameters

T: The length of a given period.

d_{ij}: The distance of link (i, j).

c_{ij}: The maximum number of trains that can be transported from node i to node j in given period.
t_{ij}: The transshipment time needed at node j over link (i, j).
w_{ij}^{q}: The demand volume of commodity $q \in Q$ between node i and node j.
VOT_{ij}^{q}: The value of time of commodity $q \in Q$ between node i and node j.
VOR_{ij}^{q}: The value of reliability of commodity $q \in Q$ between node i and node j.
s_{ij}^{kr}: Service provided by logistics service providers between node i and node j through the kth shortest path with service level $r \in \mathcal{R}$.
p_{ij}^{kr}: The unit transport cost for service s_{ij}^{kr}.
f_{ij}^{kr}: The transport speed for service s_{ij}^{kr}.
e_{ij}^{kr}: Transport reliability for service s_{ij}^{kr}, described as average percentage not be delayed.
u_{ij}^{kr}: Transport capacity for service s_{ij}^{kr}.
Variables
x_{ij}^{kr}: integer variable, service frequency of services_{ij}^{kr}

$$y_{ij}^{qkr} = \begin{cases} 1, & \text{if commodity } q \in Q \text{ chooses service } s_{ij}^{kr}, \\ 0, & \textit{otherwise}. \end{cases}$$

$$z_{ij}^{qkr} = \begin{cases} 1, & \text{if commodity } q \in Q \text{ served by } s_{ij}^{kr} \text{ will transfer in node } j, \\ 0, & \textit{otherwise}. \end{cases}$$

To ensure that a demand flow on one OD pair can be transported as a whole and is not split up, it is assumed that a new train must be offered once the limit of transport capacity is exceeded. The waiting time for each service is assumed to be $\frac{T}{2x_{ij}^{kr}}$. Despite its simplicity, this assumption allows to incorporates service frequency into the objective function. In the calculation of waiting time cost, it indicates that a higher service frequency reduces waiting time costs and thus the total user costs (Andersen and Christiansen, 2009). This assumption is important to accumulate demand flow, to achieve economies of scale.

Hereby, shippers' total generalized costs during transportation in one service network with transshipment constraints and capacity constraints is defined as the sum of transport cost h_1, transport time cost h_2, and delay time cost h_3.

$$h_1 = \sum_{q \in Q} \sum_{k \in \mathcal{K}} \sum_{r \in \mathcal{R}} \sum_{(i,j) \in \mathcal{A}} p_{ij}^{kr} d_{ij} w_{ij}^{q} y_{ij}^{qkr} \tag{1}$$

$$h_2 = \sum_{q \in Q} \sum_{k \in \mathcal{K}} \sum_{r \in \mathcal{R}} \sum_{(i,j) \in \mathcal{A}} w_{ij}^{q} y_{ij}^{qkr} VOT_{ij}^{q} \left[\frac{d_{ij}}{f_{ij}^{kr}} + t_{ij} z_{ij}^{qkr} + \frac{T}{2x_{ij}^{kr}} \right] \tag{2}$$

$$h_3 = \sum_{q \in Q} \sum_{k \in \mathcal{K}} \sum_{r \in \mathcal{R}} \sum_{(i,j) \in \mathcal{A}} w_{ij}^{q} y_{ij}^{qkr} VOR_{ij}^{q} \frac{d_{ij}}{f_{ij}^{kr}} (1 - e_{ij}^{kr}) \tag{3}$$

Thus, the formulation of the FSND problem with VOT and VOR (Model FSND_VOT/VOR) is as follows:

$$\text{Min Total Costs} = h_1 + h_2 + h_3 \tag{4}$$

Subject to

$$\sum_{k \in \mathcal{K}} \sum_{r \in \mathcal{R}} w_{ij}^{q} y_{ij}^{qkr} - \sum_{k \in \mathcal{K}} \sum_{r \in \mathcal{R}} w_{li}^{q} y_{li}^{qkr} = \begin{cases} w_{ij}^{q}, & \forall\, i \in \mathcal{N}_{ij}^{q} \cap \{o(q)\} \\ -w_{ki}^{q}, & \forall\, i \in \mathcal{N}_{ij}^{q} \cap \{d(q)\} \\ 0, & \forall\, i \in \mathcal{N}_{ij}^{q} \backslash \{o(q), d(q)\} \end{cases} \tag{5}$$

$$\sum_{k \in \mathcal{K}} \sum_{r \in \mathcal{R}} y_{ij}^{qkr} = 1, \quad \forall\, q \in Q, \forall\, (i, j) \in \mathcal{A}_{ij}^{q} \tag{6}$$

$$z_{ij}^{qkr} - y_{ij}^{qkr} \le 0, \quad \forall\, k \in \mathcal{K}, \forall\, r \in \mathcal{R} \tag{7}$$

$$\sum_{q \in Q} w_{ij}^{q} y_{ij}^{qkr} \le u_{ij}^{kr} x_{ij}^{kr} \tag{8}$$

$$\sum_{k \in \mathcal{K}} \sum_{r \in \mathcal{R}} x_{ij}^{kr} \le c_{ij} \tag{9}$$

The model's objective (4) is to minimize the total generalized costs of railway shippers by taking VOT and VOR into account. Constraint (5)) is a flow conservation constraint, to guarantee the balance of demand flow entering and leaving a node. Constraint (6) is to ensure one single demand will not be divided into different parts. Constraint (7) restricts that for demand $q \in Q$ between node i and node j, transshipment can take place if and only if commodity q uses service s_{ij}^{kr}, and $j \in \mathcal{N}_{ij}^{q}$ is not the destination node. Constraints (8) and (9) are the service capacity constraint and the link capacity constraint, respectively.

2.2. Solution approach

Model FSND_VOT/VOR is a combinatorial optimization problem with a minimization cost function over a finite set of discrete variables. The difficulty to find the optimal solutions will increase with the size of variables in the network, which leads to it being unable to be solved within acceptable computation time. A heuristic algorithm will be helpful in looking for approximate solutions in a relatively short computation time. Simulated Annealing (SA) is a good candidate heuristic algorithm due to its simplicity, its stable performance and its wide application (Friesz et al., 1993; Michiels et al., 2008; Aarts et al., 2014; Abdinnourhelm, 2013; Lin et al., 2012). An improved SA algorithm is proposed which, next to the cooling variable, also allows heating of the system. The solution algorithm is described in the appendix of this paper.

3. Case study

To identify the impacts of incorporating users' heterogeneity into the FSND problem, the value of time and reliability are estimated with a Latent Class discrete choice model, in which several distinct classes with heterogeneous preferences can be identified. Then, the improved Simulated Annealing algorithm is applied to solve the frequency service network design model with transshipment, capacity constraints and heterogeneous users (Model FSND_VOT/VOR). To assess the impact of recognizing user classes, we compare the design for 2 classes with a baseline design, which is based on the preferences of the aggregated group of users.

3.1. VOT and VOR estimation

As an input to the FSND problem, we need information about the VOT and the VOR of users. These can be estimated using a behavioral model and data from a shippers' Stated Preference (SP) survey (Duan et al., 2016a). During the survey, shippers are asked to select one of several services differentiated by their transport attributes service price, time and reliability. Shippers' choice behavior is modelled by a Random Utility Maximization (RUM) model, which describes the decision rule of shippers as seeking the maximization of personal utility generated by each attribute.

For services with price, time and reliability as attributes, the utility of shipper i from the choice of service alternative n is modelled as below.

$$V_{ni} = \beta_{TP_n} X_{TP_{ni}} + \beta_{TT_n} X_{TT_{ni}} + \beta_{TR_n} X_{TR_{ni}} \tag{10}$$

$X_{TP_{ni}}, X_{TT_{ni}}, X_{TR_{ni}}$ are absolute values for service price, time and reliability. $\beta_{TP_n}, \beta_{TT_n}, \beta_{TR_n}$ are the coefficients for each service attribute, which are estimated based on a Multinomial Logit (MNL) structure with a maximum likelihood estimation technique.

The VOT and VOR are derived as follows:

$$VOT = \frac{\beta_{TT_n}}{\beta_{TP_n}}, \quad VOR = \frac{\beta_{TR_n}}{\beta_{TP_n}} \tag{11}$$

As pointed out by Significance (2012), when attributes are expressed as ratios relative to their base value, it will lead to a relative utility model,

$$V_{ni} = \beta_{TP_n} \frac{X_{TP_{ni}}}{X_{TP_o}} + \beta_{TT_n} \frac{X_{TT_{ni}}}{X_{TT_o}} + \beta_{TP_n} \frac{X_{TR_{ni}}}{X_{TR_o}} \tag{12}$$

$X_{TP_o}, X_{TT_o}, X_{TR_o}$ are base values for service price, time and reliability.

Here, the VOT and VOR are obtained by multiplying the ratios in formula (11) by the transport cost per hour for a mode (the so-called 'factor costs'). Thus,

$$VOT = \frac{\beta_{TT_n}}{\beta_{TP_n}} \times \text{factorcost}, \quad VOR = \frac{\beta_{TR_n}}{\beta_{TP_n}} \times \text{factorcost} \tag{13}$$

In our case, due to the fact that all the service attributes used in this survey are relative values, formula (12) and (13) will be applied later to calculate VOT and VOR.

To reveal the valuation of shippers we used the result of a Stated Preference (SP) survey used which conducted among Chinese railway shippers (for the survey description, see Duan et al. (2016a)). In this paper, 1120 choice observations from 70 respondents were used for the analysis. In the choice experiments, service reliability was treated as the average percentage of shipments not delayed with respect to the agreed total transport time. The average delay time is calculated by multiplying transport time by one minus reliability.

Based on these data, a Latent Class (LC) model (see e.g. Greene and Hensher (2003)), was estimated to identify clusters of respondents. The LC model, based on the multinomial logit (MNL) model, assumes that there are latent classes of respondents, each with its own distinct set of preferences. By assigning shippers to classes, a series of utility coefficients can be estimated for each class. Later we compare the performance of the networks designed on the basis of single nd multiple classes.

Table 1
Estimation results by MNL model and LC model.

Parameters	MNL		LC			
			Class 1		Class 2	
	Coef.	S.E.	Coef.	S.E.	Coef.	S.E.
β_{TP_n}	$-0.05826^{***\text{a}}$	0.00510	-0.09233^{***}	0.00873	-0.03758^{***}	0.00812
β_{TT_n}	-0.02538^{***}	0.00254	-0.05163^{***}	0.00629	-0.00853^{**}	0.00366
β_{TR_n}	0.05690^{***}	0.00407	0.13849^{***}	0.01607	0.01044^{*}	0.00569
Opt out	15.0752^{***}	0.76865	25.1730^{***}	2.44880	10.2717^{***}	1.19806
Membership Probability			0.60818^{***}	0.06701	0.39182^{***}	0.06701
AIC			2490.1			
Null LL	−1802.5705		−1802.5705			
Final LL	−1355.2094		−1232.0361			
R-squared	0.2482		0.3165			

[a]. ***, **, * : Significant at 1%, 5%, 10% level, respectively.

Table 1 lists the coefficient estimation results by the single class Multinomial Logit (MNL) model and the Latent Class (LC) model. For the application of the FSND model, shippers are classified into these two segments following to their attitudes towards service price, time and reliability. Table 1 shows the outcomes of the demand model estimations.

In the MNL model, all the attribute coefficients have the expected signs and are highly significant, indicating that shippers prefer lower cost, shorter time, and better service reliability. In the LC model as well, all the attributes are significant and have expected signs, for both classes. As expected, different valuations of the three attributes can be observed across the two classes. Class 1 consists of shippers who are highly sensitive to service reliability, while shippers in Class 2 show stronger preferences towards price than reliability and time.

As the service attributes used in this survey are relative values, a factor cost with a value of 3.55 ¥/ton*hour (Duan et al., 2016a) is used to estimate the VOT and VOR according to formulas (12) and (13). Finally, the VOT and VOR for the whole sample and for the shippers in two different classes is calculated following (13), by multiplying the ratio of the estimated time coefficient β_{TT} and reliability coefficient β_{TR} to the estimated cost coefficient β_{TP}, by the factor cost.

(1) Shippers as a whole: VOT=1.55 ¥/(ton and hour), VOR=3.47 ¥/(ton and hour)
(2) Shippers in two classes:
  Class 1 (60.82% of shippers): VOT_1= 1.99 ¥/(ton and hour), VOR_1= 5.32 ¥/(ton and hour)
  Class 2 (39.18% of shippers): VOT_2= 0.81 ¥/(ton and hour), VOR_2= 0.99 ¥/(ton and hour)

For comparison, the VOT values in our case are found to be consistent with international empirical results given by Feo Valero et al. (2011) and De Jong et al. (2014), ranging from 0.95 to 12.87 ¥/(ton and hour), after currency conversion. The values of VOR in our case are different with results from De Jong 2014 from 1.02 to 1.82 ¥/(ton and hour); no other results are available yet for further comparison.

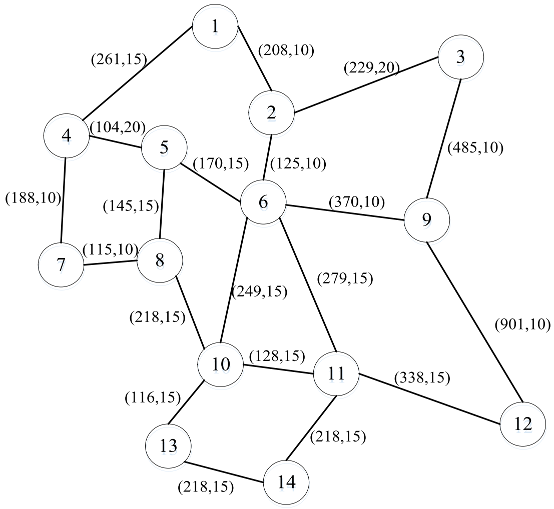

Fig. 1. The railway network (Ji et al., 2011).

Table 2
Service levels available in the network.

Service Level	Price (¥/tonkm)	Speed (km/hour)	Reliability	Capacity (ton)
S1	0.086	30	70%	2000
S2	0.098	35	85%	2000
S3	0.138	45	95%	2000

3.2. Application: Local railway network design

In this case, a local railway network in China as used in Ji et al. (2011), see Fig. 1. In this network, there are 14 nodes and 20 bidirectional links. Each link has a distance (km) and capacity (number of services), which are the numbers in brackets in Fig. 1. The transshipment time in each node is assumed to be 3 h.

Meanwhile, three different service levels are offered by carriers, which differ in price, speed and reliability (here, operationalized as average percentage not delayed). The details of these three service levels are presented in Table 2; values for price, speed, reliability and capacity were based on the data from the website of Customer Service Centre of China Railway, National Bureau of Statistics of the People's Republic of China.

Furthermore, to understand the impacts of incorporating shippers' heterogeneous preferences into the FSND problem, two problem scenarios are introduced based on the assumptions mentioned above, i.e., (a) shippers, as a whole, hold homogeneous VOT and VOR; (b) shippers in distinct classes hold heterogeneous VOT and VOR. In scenario (a), all flows in the network share the same VOT (1.55) and VOR (3.47). The demand volume per week is derived from Ji et al. (2011), where there are 12 demand OD pairs in this network. In scenario (b), each demand flow for one OD pair is divided into two classes according to the membership size given by Table 1, with different VOT and VOR. In total, there are 12 demand flows in scenario (a) and 24 demand flows in scenario (b), for 12 OD pairs. Table 3 shows the final demand flow specification.

3.3. Results

With Tables 2 and 3 as input data, Model FSND_VOT/VOR is applied with the improved Simulated Annealing algorithm. In addition, as the link capacity is limited in this case, a K-shortest path algorithm is applied to find more than one available path for demand flow along this link. Since the VOT and VOR attached to each demand flow is different, the priority is given to the demand flows with higher VOT/VOR and larger volume. More precisely, the priority of each demand to use the shortest path is decided by the value of (VOT*demand flow). In this way, key shippers can be served with the best resources.

Regarding the parameters in SA algorithm, the initial and final temperature are set to be 1000 and 0.001, respectively. The temperature decrement ratio (TDR) in our case is 0.90. For each temperature point, it will need 100 iterative steps to update the solution. The heating up temperature is 100, which means that when the annealing process is cooling to below 100, a heating up parameter τ is applied to improve the acceptance possibility of worse solutions. ξ is set to 0.60.

For the variable x_{ij}^{kr}, since it appears as a nonlinear function in transport time cost formula (3), i.e., $\frac{T}{2x_{ij}^{kr}}$, to simplify the solving difficulty, x_{ij}^{kr} is set to be a random number within a range given by the analyst. The minimum service frequency is zero, and the maximum frequency is based on the link capacity.

To compare the performance of the basic Simulated Annealling algorithm (without heating up process) and improved Simulated Annealling algorithm (with heating up process), scenario (b) was first run since it is more complicated to be solved than scenario (a).

Table 3
Demand specification with VOT and VOR for 12 OD pairs.

O	D	Scenario (a) Homogeneous demand			Scenario (b) - Heterogeneous demand					
					Class 1 (60.82%)			Class 2 (39.18%)		
		W_{ij}	VOT	VOR	W_{ij}^1	VOT_1	VOR_1	W_{ij}^2	VOT_2	VOR_2
2	13	15,769	1.55	3.47	9591	1.99	5.32	6178	0.81	0.99
1	11	5000	1.55	3.47	3041	1.99	5.32	1959	0.81	0.99
1	12	5385	1.55	3.47	3275	1.99	5.32	2110	0.81	0.99
3	4	5385	1.55	3.47	3275	1.99	5.32	2110	0.81	0.99
4	9	5193	1.55	3.47	3158	1.99	5.32	2035	0.81	0.99
4	11	1923	1.55	3.47	1170	1.99	5.32	753	0.81	0.99
5	11	7308	1.55	3.47	4445	1.99	5.32	2863	0.81	0.99
4	10	3847	1.55	3.47	2340	1.99	5.32	1507	0.81	0.99
12	7	6539	1.55	3.47	3977	1.99	5.32	2562	0.81	0.99
12	5	4615	1.55	3.47	2807	1.99	5.32	1808	0.81	0.99
14	6	7308	1.55	3.47	4445	1.99	5.32	2863	0.81	0.99
8	14	4615	1.55	3.47	2807	1.99	5.32	1808	0.81	0.99

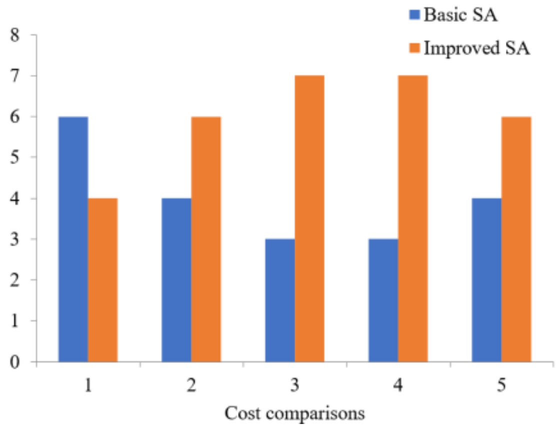

Fig. 2. Total generalized cost comparisons between the basic and improved SA algorithm.

Both algorithms were conducted 50 times with MATLAB R2014a on a 2.30 GHz Intel Core laptop, with a total memory of 8 GB. After running, the best total generalized cost in each running procedure is recorded. In total, there are 50 pairs of total generalized cost to be compared between the basic and improved SA algorithm. These comparisons are conducted in 5 rounds, each with 10 times comparisons, 1 point will be added up if one performs better than the other in terms of total generalized cost. Fig. 2 presents the cost comparison results for each round. The higher the column, the points are higher, which means the algorithm related can reach less cost than the other.

Clearly, the improved SA algorithm performs better than the basic SA algorithm with the capability to achieve a lower value of total generalized cost. Moreover, the lowest value is reached by the improved SA algorithm. Thus, the improved SA algorithm is applied to solve the FSND_VOT/VOR model in both scenarios.

We retained the best solutions of the 50 runs of the service network design model for further analysis. Table 4 lists all service schemes in both scenarios for 24 demand flows with different values of VOT/VOR. In the column "Service details", the entries S1, S2 and S3 correspond to the service levels in Table 2, indicating which service quality is offered. The distances of service links and service frequencies are provided in the adjacent columns.

In general, through the comparison of service details between scenarios (a) and (b) in Table 4, we can see that the service choice changes for more than half of the demand flows, and 9 demand flows (underlined) stay unchanged in both scenarios. Meanwhile,

Table 4
Service details for all demand flows in both scenarios (Dist. = distance, S.F. = service frequency).

#	OD	Class	Scenario (a)			Scenario (b)		
			Service details	Dist.	S.F.	Service details	Dist.	S.F.*
1	(2,13)	1	2–6-10–13(S1)	490	8	2–6-10–13(S3)↑	490	5↓
2	(2,13)	2	2–6-10–13(S1)	490	8	2–1-4–5-8–10-13(S1)	1052↑	4↓
3	(1,11)	1	1–4-5(S3), 5–6-11(S1)	814	3 + 3	1–4-5(S1), 5–6-11(S2)	814	4 + 7↑
4	(1,11)	2	1–4-5(S3), 5–6-11(S1)	814	3 + 3	1–4-5(S1), 5–6-11(S2)	814	4 + 7↑
5	(1,12)	1	1–4-5(S2), 5–6-11–12(S1)	1152	3 + 3	1–2-6–11-12(S3) ↑	950↓	2↓
6	(1,12)	2	1–4-5(S2), 5–6-11–12(S1)	1152	3 + 3	1–4-5(S1), 5–6-11–12(S2)	1152	4 + 2
7	(3,4)	1	3–2-1–4(S1)	698	3	3–2-6–5-4(S3) ↑	628↓	2↓
8	(3,4)	2	3–2-1–4(S1)	698	3	3–2-1–4(S1)	698	2↓
9	(4,9)	1	4–5-6–9(S1)	644	3	4–5-6–9(S1)	644	3
10	(4,9)	2	4–5-6–9(S1)	644	3	4–5-6–9(S1)	644	3
11	(4,11)	1	4–5-6–11(S1)	553	1	4–5-6–11(S2) ↑	553	1
12	(4,11)	2	4–5-6–11(S1)	553	1	4–5-8–10-11(S1)	595↑	1
13	(5,11)	1	5–6-11(S2)	449	4	5–6-11(S2)	449	7↑
14	(5,11)	2	5–6-11(S2)	449	4	5–6-11(S2)	449	7↑
15	(4,10)	1	4–5-8–10(S1)	467	2	4–5-8–10(S1)	467	2
16	(4,10)	2	4–5-8–10(S1)	467	2	4–5-8–10(S1)	467	2
17	(12,7)	1	12–11-10–8-7(S1)	799	4	12–11-10–8-7(S1)	799	4
18	(12,7)	2	12–11-10–8-7(S1)	799	4	12–11-10–8-7(S1)	799	4
19	(12,5)	1	12–11-6–5(S2)	787	3	12–11-6–5(S1) ↓	787	3
20	(12,5)	2	12–11-6–5(S2)	787	3	12–11-6–5(S1) ↓	787	3
21	(14,6)	1	14–11-6(S1)	497	4	14–11-6(S2) ↑	497	4
22	(14,6)	2	14–11-6(S1)	497	4	14–11-6(S2) ↑	497	4
23	(8,14)	1	8–10-13–14(S1)	552	3	8–10-13–14(S2) ↑	552	3
24	(8,14)	2	8–10-13–14(S1)	552	3	8–10-13–14(S2) ↑	552	3

* ↑ and↓ indicate the increase or decrease of frequencies, respectively.

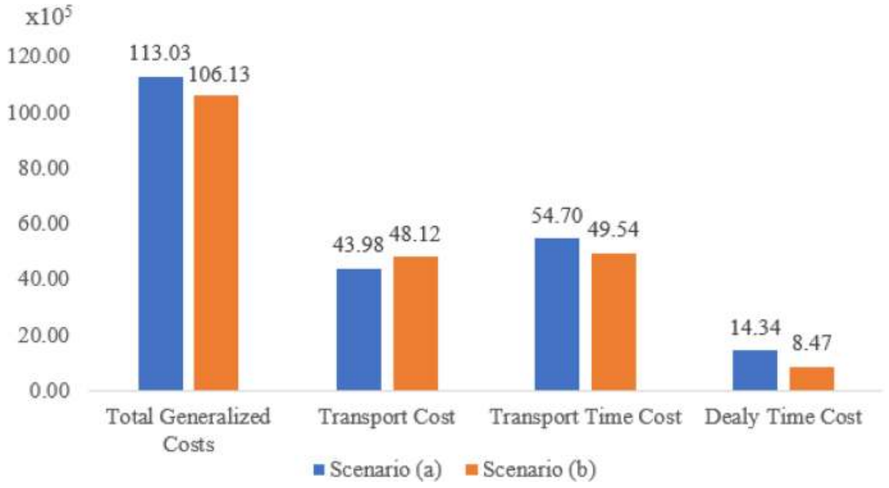

Fig. 3. Cost indicators in scenario (a) and (b).

there are 8 demands, with a total volume of 29,234 tons, of which the service level is clearly improved (indicated by up arrows), from S1 to S2 or S3. Only 2 demands with volume of 4615 tons are observed with decline of service levels (indicated by down arrows). Besides, demands with a higher VOT/VOR (Class 1), like demand #5 and #7, are assigned to shorter route. As a compensation, demand #2 and #12 are redirected to a longer route due to the capacity constraint.

For a fair comparison, in both scenarios, the calculation of shippers' generalized costs was based on the heterogeneous valuation of service time and reliability, since two user classes do exist in the sample. Fig. 3 presents all the cost indicators, including the total generalized costs, transport cost, transport time cost, and delay time cost. Meanwhile, the generalized cost and its components for each demand class in both scenarios are presented in Fig. 4.

In general, the total generalized cost for shippers in scenario (b) is less than that in scenario (a) by 6.10%. Given the fact that service quality has improved for 40% of the demand volumes, the performance of the network of the Model FSND_VOT/VOR is better than that of the traditional model without considering preference heterogeneity. At the same time, the improvement of service levels in scenario (b) has led to an increase in transport costs. According to formula (1), transport cost is affected by demand volume, transport distance and service price. Compared to scenario (a), the demand volumes stay unchanged in scenario (b). Even though there are changes on transport distances, the resulting effect on transport cost could be balanced to some extent. Therefore, the increase of transport cost in scenario (b) is mostly brought by the improvement of service levels, which means higher transport prices. Apart from that, both transport time cost and delay time cost benefit from better service quality and are decreased significantly, which compensates the increase of transport cost and leads to the decline of total generalized costs.

Further comparison between two classes, i.e., High VOT/VOR (Class 1) and Low VOT/VOR (Class 2), confirms that for demands with high VOT and VOR, the reduction in transport time costs and delay time costs associated with service quality improvement clearly exceeds the resulting increase in transport costs, which decreases the total generalized costs. Meanwhile, we should be aware of that the improvement of service quality is partly implemented by shortening the transport distance of demands with high VOT and

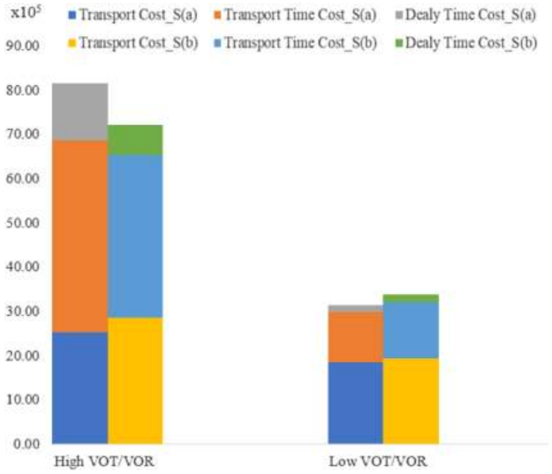

Fig. 4. Generalized cost for each demand class in scenario (a) and (b).

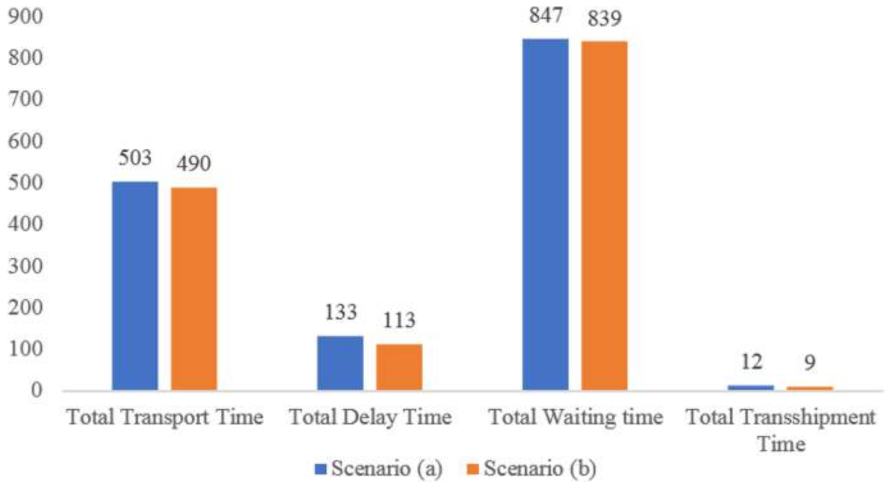

Fig. 5. Time indicators in scenario (a) and (b).

VOR, which causes the increase of transport distances of demands in Class 2. In addition, service improvements could also be observed in Class 2, i.e., demand #22 and #24, which contributes to the increase of transport cost in scenario (b). Hereby, the generalized costs of demands with low VOT/VOR in scenario (b) is slightly raised along with the transport cost, transport time cost and delay time cost.

To clarify the differences before and after segmentation on the basis of preference heterogeneity, all time-related indicators are identified and compared for both scenarios. Fig. 5 presents these time indicators, including total transport time (moving time), total delay time, total waiting time, and total transshipment time. It is clear that all indicators have decreased significantly along with the improvement of service quality (i.e. faster and more reliable services).

To further analyze the key performance of the services designed in both scenarios, three more indicators are introduced and calculated independently for each class of demand, including unit transport time, unit delay time, and unit waiting time. We define these as follows:

(i) unit transport time, i.e., UTT, is measured with the sum of demand flow multiplied by transport time for each demand OD, then divided by the total demand flow.
(ii) unit delay time, i.e., UDT, is measured with the sum of demand flow multiplied by the delay time for each demand OD, then divided by the total demand flow.
(iii) unit waiting time, i.e., UWT, is measured with the sum of demand flow multiplied by the waiting time for each demand OD, then divided by the total demand flow.

Thus, three indicators mentioned above are calculated respectively for each class of demand. Fig. 6 shows the differences between scenario (a) and (b) in terms of unit transport time, unit delay time and unit waiting time.

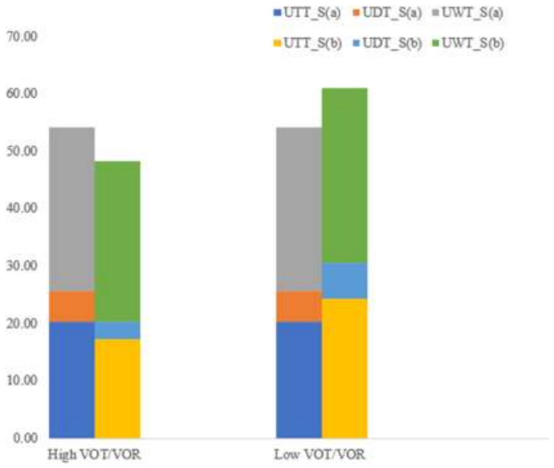

Fig. 6. Time indicators for distinct classes in scenario (a) and (b).

Clearly, the unit times in scenario (a) for two classes are the same, because the services designed in scenario (a) are based on preference homogeneity and thus demands are served with equivalent service level. However, due to the fact that demands in Class 1 are more sensitive to transport time and reliability, the unit transport time, unit delay time and unit waiting time are considerably shortened through offering faster and more reliable transport services to demands with high VOT/VOR in scenario (b). On the other hand, the unit times for Class 2 are all raised, in response to the lower VOT/VOR values of this class.

4. Conclusions

Service network design is an important tactical decision-making problem in freight transport. The designed network and its performance will be affected by the existence of demand segments in the market with different service preferences. Traditionally, in multi-commodity flow models, commodities are classified based on their appearance, origin/destination or ownership. However, this ignores shippers' heterogeneous preferences towards service quality. We incorporate preferences into frequency service network design (FSND) model by using a commodity abstract classification through value of time (VOT) and value of reliability (VOR) as part of generalized transport costs.

Based on discrete choice experiments conducted in China, shippers' VOT and VOR are estimated using a Random Utility Maximization (RUM) model. We incorporate the VOT and VOR into the frequency service network design model, considering capacity constraints and transshipment between service lines. As such the FSND_VOT/VOR model establishes a connection between service design and shippers needs. Demands with higher VOT/VOR will be treated with better service quality to avoid increase of time related costs. Meanwhile, due to this rearrangement, it becomes easier to assign heavy demand flows to links where capacity is available at low cost and low service level.

To demonstrate the impact of considering preference heterogeneity on FSND, two scenarios are established in the case study, i.e., (a) shippers have the same VOT and VOR; and (b) VOT and VOR is different by group of shippers. Realistic, empirical values for VOT and VOR were estimated for both scenarios. With a Latent Class analysis, two distinct classes were found in our sample. A local railway network was used as case to test the service network design problem with the empirical demand data. The FSND_VOT/VOR model was solved with an improved Simulated Annealing algorithm, which also involves increasing the temperature in the last phase of the annealing process. The overall comparison between scenario (a) and (b) shows that, by taking shippers heterogeneous preference into account, the service levels for 40% of the demand volume in the service network improves. A further comparison of generalized costs, transport time, delay time and waiting time, reveals that service quality for shippers with higher VOT and VOR improves significantly, while maintaining lower generalized costs. The reduced level of user costs could not be obtained with the case of joint user classes. Clearly, it is useful to consider user classes to reduce total user costs.

Our paper continues on an earlier work Duan et al. (2016a, b), to find possible ways for China Railway to improve its service quality in both service design and service network design. By incorporating shippers differentiated VOT and VOR into service network design, railway companies can improve their service quality targeted to more valuable customers while maintaining its costs. This may support railway companies in China and other states in enhancing their marketing strategies and improving their competitive position in freight market.

For future research, it would be useful to extend the model with a dynamic time-space network structure. In this context, shipper demand and available transport resources will change dynamically. It will be more difficult to design services for differentiated shippers, due to the synchronization of different vehicles in terms of schedule and capacity. Here, the value of VOT and VOR will be much more important for carriers to design targeted services. In addition, the balance of service pricing strategy and service design may be better achieved when taking VOT and VOR into consideration. Although the model proposed here is not presented as multimodal, the approach lends itself very well for multimodal analysis, as the mode choice decision rests heavily on the trade-off between transport price and service level, in terms of speed and reliability. We expect that heterogeneity in the population of shippers will even play a larger role than when we only consider one mode of transport. Our current findings concerning the relevance of modelling preference heterogeneity in FSND will probably be articulated more strongly within a multimodal context. Furthermore, with more and more studies focusing on users' choice behavior under non-RUM assumptions (e.g. regret minimization, see Sun et al., 2016; Duan et al., 2016a), it may also be interesting to study the network design problem under conditions of non-RUM behavior.

Finally, an important assumption in the paper is that unit prices for the current service classes are such that they allow for a profitable provision of services, also within the redesigned network. Higher service levels come with significantly higher prices to allow for cost coverage and a profit markup. As a result, also design (b) will be profitable. As prices are already set for the Chinese case for different service classes, we believe this is a reasonable assumption. An alternative approach, however, that we can recommend for further research, is to derive prices from a production model that includes all costs and a profit mark-up. This can also help to answer the question how to optimize service levels and prices, beyond the current classes set by the Chinese railways.

Acknowledgements

The authors would like to thank three anonymous referees and editors for their valuable comments on this paper. This work was partially funded by the National Natural Science Foundation of China (Grant No. 61803057, Title: Collaborative Optimization of Intermodal Service Network Based on Choice Preference Heterogeneity), the Ministry of Education Humanities and Social Sciences Research Youth Fund Project (Grant No. 18XJCZH001, Title: Research on Resources Configuration Optimized Decision of Rail-road Intermodal Service Network Based on Choice Behavior Analysis), and the Basic Science and Frontier Technology Research (General) by Chongqing Science & Technology Commission(Grant No. cstc2017jcyjAX0218).

Appendix A

Simulated Annealing (SA) is an efficient procedure for solving combinatorial optimization problem. The strategy implemented by the conventional SA algorithm consists of exploring the solution space randomly from the neighborhood of an initial or existing solution s. Once a new solution s' is selected, its cost $f(s')$ is evaluated and compared with previous cost $f(s)$. If $f(s')$ is not worse than $f(s)$, the new solution, s' will be accepted immediately. If $f(s')$ is higher than $f(s)$, an acceptance rule will be used based on an exponential distribution. We use the decision rule based on Michiels et al. (2008): solution s' will be accepted if and only if $\exp\left(\frac{f(s)-f(s')}{c_T}\right) \geq random[0, 1)$, which c_T is the temperature.

However, when the temperature is cooling down, it will be much more difficult to find a new solution for the basic SA algorithm, as the exponential distribution controlled by temperature c_T is relatively low. To enhance local searching capability of basic SA in the last phase, a heating up parameter τ is necessary, especially when the solution is not updated for several rounds.

$$\tau = \frac{f(s) - f(s')}{c_T \log\xi}, \quad \xi \in [0.6, 0.9] \tag{A.1}$$

ξ is the acceptance possibility, normally ranging from 0.60 to 0.90, according to Zhu and Zhong (2009). The acceptance rule is then defined as follows:

s' will be accepted if and only if:

$$\exp\left(\frac{f(s) - f(s')}{\tau c_T}\right) \geq random[0, 1), \quad forf(s') > f(s), \quad \text{and} \quad c_T < T_h \tag{A.2}$$

T_h is defined as the temperature given by the analyst when heating up is needed.

The strategy of this improved Simulated Annealing algorithm follows the steps below:

Step 1. Given an initial solution s with objective function value or cost $f(s)$. Set an initial temperature with value T_0. T_h is the temperature when heating up is needed.

Step 2. For each temperature stage do the following:

Step 2.1. Generate a feasible candidate solution s' by a small random perturbation from the neighborhood of current solution s. Evaluate the difference in objective function value, i.e., $f(s) - f(s')$.

Step 2.2. If $f(s) - f(s') \geq 0$, the candidate solution s' has a better objective function value than the current solution s. Hence, solution s' is accepted with its cost $f(s')$ as new solution and objective function value, i.e., $s = s'$, and $f(s) = f(s')$.

If $f(s) - f(s') < 0$, the candidate solution s' has a worse objective function value than the current solution s. Then the acceptance probability of candidate solution s' will depend on the acceptance rule given by formula (A.1).

Step 2.3. If the 'thermal equilibrium' is not reached, go to step 2.1. Otherwise, go to step 3.

Step 3. If the annealing process is incomplete, reduce the temperature with a temperature decrement ratio (TDR) $\lambda \in [0.80, 0.99]$. Then go to step 2.

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