The influence of transfer time on capacity reliability of transfer hubs

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Abstract: Transfer hubs are transport facilities to balance transit passengers with the coexistence of a variety of transportation models. It is a subsystem of urban passenger transport system. And transfer hub is a large integrated dynamic system with randomness, dynamic and complex nature. As we know, transfer time have a certain impact on the effectiveness of the overall control system. In order to study the influence of transfer time on hubs' capacity reliability and to convenient managers to control optimal transfer time, we will add traffic modes into a road network which is a three-dimensional virtual traffic network established in this work. The model divides transfer into zero distance transfer and non-zero distance transfer, and calculate and correct its reliability of transfer time. The results show that the influence of transfer time on road network capacity reliability of transfer hubs is obvious, and capacity reliability is inversely proportional to transfer time.

Keywords: Virtual network; Transfer time reliability; Road capacity.

1. INTRODUCTION

"Hub" is the key part of things and the central link between things. Urban passenger transfer hubs are transport facilities in order to balance transit passengers with the coexistence of a variety of transportation models. It is a subsystem of urban passenger transport system. Now formation process of transfer hubs can be divided into five stages in the following figure 1. (Wu, 2008; Cheng, 2005). However, transportation system is a complex system, which is reflected on the uncertainty between traffic demand and traffic supply. The occurrence of the traffic problems ultimately dues to the contradiction between supply and demand, which determines the necessity of reliability analysis (Xu et al., 2006; Liu et al., 2000).

Studies of road network reliability began in Japan in the 1980s (Mine & Kawai, 1982). Now the existing reliability studies are mainly focused on three aspects: connectivity, traveling time and capacity reliability. Among them, the capacity reliability is the most applicable for administrators to evaluate the capacity ability of the whole system (Xu & Gao, 2006).

The objective of this study is to research the influence of transfer time on capacity reliability of transfer hubs, then we can forecast passengers' demands of transferring and research the available transfer time and reliability. This paper will add traffic modes into a road network which is a three-dimensional virtual traffic network established in this work. Based on the study, a road network capacity reliability analysis model is proposed, in order to help managers to relieve the imbalance between supply and demand of public transport and also help to obtain the optimization transfer time arrangements.

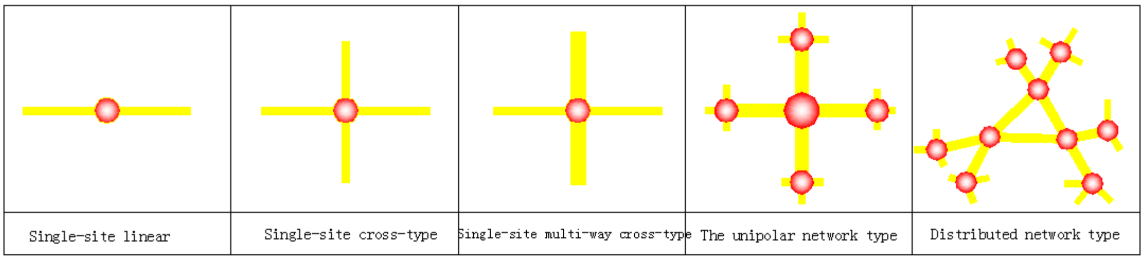

Figure 1.Process of transfer hub evolution

2. ANALYSIS OF TRANSFER DEMANDS BASED ON VIRTUAL TRAFFIC NETWORK

2.1. Transfer System Based trip Chain

Due to the complexity of urban passenger transport hubs, we still have not an effective computing model to predict the demand of passengers' transfer. In this paper, starting from the city multi-way traffic system, we'll analyze the prediction of transfer ring from the aspect of "users' trip chain"(Wen et al., 2005). According to the means of trip chain, traffic hub system can be divided into three cases: distribution, transferring and directly transiting. This paper mainly analyzes the second case of the trip chain: transferring problem within the passenger transport hubs.

2.2. Description of Virtual Traffic Network

As previously mentioned, from the perspective of users' trip chain, this paper attempts to establish a multi-dimensional virtual network to forecast transfer demands. Its establishment is based on the assumption that: travelers' traveling displacement is actually realized by selecting a certain way and then changing to another traffic mode by walking .Its overall goal is to make the "Generalized travel costs" of entire trip smallest.

It is assumed that the urban transport network system contains three models: bus, car and rail transit. As is shown in the three-dimensional coordinates of the network system in the Figure 2:

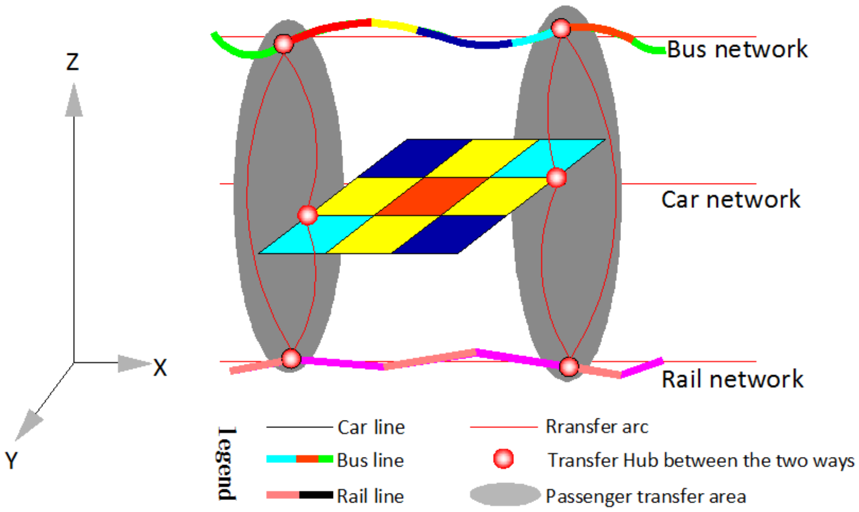

Figure 2.Three-dimensional virtual network of multi-mode traffic.

In the above network, the X, Y-axis plane stands for traditional flat road network, and Z-axis is the dimension for traffic modes. The same Z value represents a planar network of a particular way to travel; if two ways in a space point can be linked up, then we can use transfer arcs (values of Z continuously change) to connect the point between the two layers, and this transfer arc expresses another way-walking while transferring. Obviously, when a variety of ways are connected in space, they form passenger transfer hubs.

2.3. Hub Transfer Requirement Analysis Based On Virtual Traffic Network

Because rail transport, public transport, car and bicycle, etc. are often contained in major urban transportation, so there are a lot of transfer arcs in the virtual multi-mode network. Generally, a transfer point of two ways requires only one transfer arc; transfer points of three ways require three transfer arcs; however, transfer points of six ways require fifteen transfer arcs. So if we use ‘m’ to represent a number of types of optional traffic modes, this relationship between to the number of transfer arcs ‘M’ and types of optional traffic modes ‘m’ can be expressed as:

$$M = C_m^2 \tag{1}$$

First of all, we need to consider the ‘generalized travel cost’ on the road section. Assuming that the generalized travel cost Ca(xa) of section a is the sum of travel cost Ca(xa) and travel time ta(xa) .It can be expressed as:

$$C_a(x_a) = c_a(x_a) + t_a(x_a) \tag{2}$$

Secondly, consider the generalized cost on the transfer nodes. Set Tw to represent an actual waiting time when people transfer from one traffic mode to another. Due to the great perception differences between waiting time Tw and traveling time Tk , here we use waiting penalty factor Dw to calculate the weight Nw of transfer point V . The formula can be said:

$$N_w = T_w(1 + D_w) \tag{3}$$

Arguably, the shortest traveling path refers to a set of selected link points with minimum generalized travel costs for passengers from the beginning to the end.

In this network model, we assume that travelers' route choice conform with the principle of random balanced distribution (SUE) (Bell et al., 1997).This principle can be described that: In transportation network, each traveler can think that the chosen path by him/her is the path of least 'Impedance', and no travelers believe that they can just rely on changing the path to reduce its impedance. Where, the 'Impedance' is travelers' perception impedance, a random variable. However, the least impedance path perceived by passengers may not be the path with the actual least impedance. Here the 'Impedance' corresponds to the 'Travel cost' mentioned in previous text.

3. HUB TRANSFER TIME RELIABULITY

In this paper, hub transfer time reliability is defined as the capability of a transfer system to complete specified transferring under the stated operating condition within specified time. Here the specified operating condition refers to the vehicle operation of different public transport modes (such as the rail transit to bus transit, bus transit to bus transit, etc.; while the specified time refers to the walking time and waiting time needed for transfer; and the specified transfer refers to ensuring that every passenger could accomplish transfer safely and comfortably. Hub transfer time reliability characterizes the service quality and comfortable degree of the transfer system and has prominent influences on travel mode selection.

Based on the hub transfer distance, the transfer time reliability analysis is carried out respectively on zero distance transfer situation and non-zero distance transfer situation (Dai et al., 2007).

3.1. Zero Distance Transfer Time Reliability

The zero distance transfer of hub means that transfer can be implemented in situ without walking. It can be abstract described with the following process. We assume that branch LF and trunk Lc form a transfer hub at O ; trip F on branch LF transfers to trunk Lc at hub O ;trip C on trunk Lc (access line) arrives at O at the closet time point with trip F ; trip N represents the trip on trunk Lc next to trip C. As is shown in Figure 3.

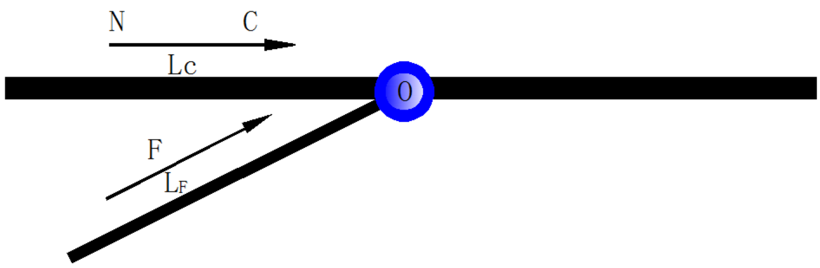

Figure 3. Sketch of zero distance transfer

The hub transfer model is based on the following four assumptions:

(1) The arrival time to hub O of trip F, trip C and trip N are separately represented by

independent random variable tF, tC and tN; and trip C and trip N leave at time dC and dN , respectively.

(2) The finite interval of trip F,trip C and trip N are respectively[αF , αF+δF] , [αC , αC+δC] and[αN , αN+δN] ;the lower limit α is the earliest possible time of arrival(usually earlier than the expected time of arrival),time δ is the limit of arrival time.

(3) To ensure that N cannot catch up C, we assume that δC⩽$\frac{1}{2}$hC and δF⩽$\frac{1}{2}$hC; hC=αN-αC is the time interval of access line LC .

(4) Passengers who need to transfer from trip F always get on at C or N;and transfer waiting time mainly depends on tF, tC and tN;

We define the waiting time function $\bar{\omega}$(tF, tC,tN) to represent the transfer waiting time with the arrival time being tF, tC and tN, and set up the waiting time model of the transfer hubs under the assumptions above.

$$\varpi(t_C,t_N,t_F)=\begin{cases} d_C-t_F & t_C\le d_C, t_F\le d_C \\ t_C-t_F & t_C>d_C, t_C>t_F \\ d_N-t_F & t_F>t_C, t_F\le d_N, t_N\le d_N \\ t_N\text{-}t_F & other; \end{cases} \tag{4}$$

The transfer time reliability defined in this paper is expressed by the expected transfer time divided by the average transfer time. If we use ω* to express the expected transfer time and the average transfer time can be calculated by formula (4), thus the transfer time reliability of transfer hub O can be expressed by the formula following.

$$R_O=\frac{\omega^*}{\varpi(t_C,t_N,t_F)} \tag{5}$$

Transfer time reliability is used to measure the comfort level for travelers under the condition that road transportation run stochastically. And the longer waiting time lasts, the worse the transfer time reliability is; conversely, the transfer time reliability is better.

3.2. Non-zero Distance Transfer Time Reliability

The non-zero distance transfer of hubs is that passengers need to walk for a short distance after get off from this line to the next line to realize the transfer. Due to various reasons, presently many transfer hubs cannot achieve zero distance transfer and the connections of lines are not ideal because of their long transfer distances, so the reliability of non-zero distance transfer should be took into consideration.

Non-zero distance transfer can be abstract described with the following process: we assume that passengers get off from station L on line a and transfer to line b at station L; the time variables are represent as the following:

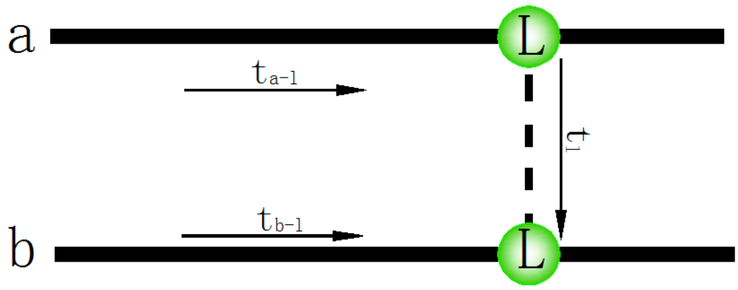

Figure 4.Sketch of non-zero distance transfer

Where,

ta-l=The travel time of link a from starting station to hub L;

tb-l = The travel time of link b from starting station to hub L;

a1+ta-l= The time of link a when the first vehicle reaches hub L at one time interval;

b1+tb-l = The time of link b when the first vehicle reaches hub L at one time interval;

an+ta-l =The time of link a when vehicle n reaches hub L at one time interval;

bm+tb-l = The time of link b when vehicle m reaches hub L at one time interval;

tl=The time of passengers between getting off link a and getting in link b;

Here,an=a1+(n-1)Ia, bn=b1+(m-1)Ib; Ia and Ib are the departure interval of link a and b, respectively. Thus the average transfer time ϖ between two links can be expressed as:

$$\varpi = \frac{1}{N}\sum_{n=1}^{N}\min_{m}\left\{(b_m + t_{b-l}) - (a_n + t_{a-l} + t_l) \middle| \left[(b_m + t_{b-l}) - (a_n + t_{a-l} + t_l)\right] \geq 0\right\} \quad (6)$$

Then, the reliability of non-zero distance transfer time in a junction terminal can be expressed as:

$$R_L = \frac{\omega^*}{\varpi} = \frac{\omega^* N}{\sum_{n=1}^{N}\min_{m}\left\{(b_m + t_{b-l}) - (a_n + t_{a-l} + t_l) \middle| \left[(b_m + t_{b-l}) - (a_n + t_{a-l} + t_l)\right] \geq 0\right\}} \quad (7)$$

It’s worth noting that, whether it’s Zero or Non-zero transfer, the calculation of the reliability of transfer time uses average waiting time. As the average waiting time ϖ is different from the actual waiting time in length, the reliability is not accurate enough. For example, it cannot tell the difference between the reliability of the one’s waiting time is 0 or 10min (the probabilities are 50%) and the reliability of the one’s waiting time is 5min. Therefore, it’s necessary to correct the model of transfer time reliability.

3.3. The Correction to The Model of Transfer Time Reliability

The model above is established upon the foundation of average waiting time and it cannot truly reflect the problem of transfer time reliability in the junction terminal. In fact, the average waiting time has defects that it cannot express the nonuniformity of the actual waiting time ω. When the waiting time ω exceeds the expecting waiting time ω, even the average one is small, the reliability may be reduced.

In order to avoid the defects mentioned above, Dai(2007) and some other people bring in penalty long function f(t) to guarantee 95% of waiting time can reach the time interval [0，ω*] (Dai et al., 2007; Zhao and Albert, 2003).

$$f(t) = \begin{cases} (k\lambda)\exp[-\lambda t], & t \in [0, \omega^*] \\ 0, & other; \end{cases} \tag{8}$$

Where, $\lambda = \frac{-\ln(1-0.95)}{\omega *} \approx \frac{3}{\omega *}$ represents that index random variable **t** between the 95% confidence interval of [0，ω *]; k=$\frac{1}{0.95}$ is the factor ensuring that $P_{(t \in [0, \omega *])}=1$;and **t** is the actual transfer waiting time.

Through the penalty function definition above, the transfer time reliability model is corrected as follows:

$$R = \int_0^{\infty} -\frac{\omega^*}{\varpi} \times f(t)\,dt \tag{9}$$

Synthesis of the formula (5) and (9), the modification model of zero distance transfer time reliability can be expressed as:

$$R_O = \begin{cases} \int_0^{\infty} -\frac{3.16\exp(-3t/\omega^*)}{\omega(t_C, t_N, t_F)} dt, & t \in [0, \omega^*] < 0 \\ 0, & other \end{cases} \tag{10}$$

Synthesis of the formula (7) and (9), the modification model of non-zero distance transfer time reliability can be expressed as:

$$R_L \begin{cases} N\int_0^{\infty} -3.16\exp\left(-\frac{3t}{\omega^*}\right)[\sum \min_m\{(b_m + t_{b-1}) - (a_n + t_{a-l} + t_l) \\ \parallel [(b_m + t_{b-l}) - (a_n + t_{a-l} + t_l) \geq 0\ \}] \qquad t \in [0, \omega^*] \\ \\ 0 \qquad\qquad other \end{cases} \tag{11}$$

Formula (10) and (11) is the hub transfer time reliability model we need.

4. CAPACITY RELIABILITY ANALYSIS BASED ON TRANSFER HUBS

4.1. The Programing of Capacity Reliability Model

Forecast of transfer demand, based on the virtual traffic network, adds transportation modes into the traffic network, and regards transfer arcs as one route of all sections, and we can consider the flow of transfer arcs equals to the demand flow between different means of transportation in transfer hubs.

Firstly, analyze travel cost function. Except the trip coat function on route, cast function of integrated route choice model of transfer hubs also needs take the transfer cost function spending on transfer hubs into consideration. Transfer cost function of transfer hubs **O** is defined as the sum of average transfer time and transfer time reliability.

$$c_o = \varphi_o \varpi + \vartheta_o R_o \tag{12}$$

Where ϖ can be obtained from formula (4) or (6), $\mathbf{R_o}$ can be obtained from formula (10) or (11), and $\varphi_0 > 0$ is the cost coefficient of the average travel time at **O**, which reflects the traveler's different attitudes towards the average travel time; $\theta_0 > 0$is the cost coefficient of the disutility associated with travel time reliability at **O**, which reflects the traveler's different trends towards the travel time reliability.

Supposed, O represents the set of hubs in the traffic network, and o is an element of set O. Then at the base of virtual network, the road capacity reliability model based on transfer hubs is established as follows:

$$R(D) = P(\mu \geq D) \tag{13a}$$

μ is calculated by the following bi-level programming model:

$$\max \quad \mu \tag{13b}$$

$$s.t. \qquad x_a(\mu q) \leq \left(\frac{\phi_a - 1}{\alpha}\right)^{\frac{1}{\beta}} F_{C_a}^{-1}(\gamma_a), \qquad a \in A \tag{13c}$$

where, $\{x_a(\mu q)\}$satisfies the following traveler equilibrium assignment problems :

$$\min Z(x,q) = \sum_{a \in A} \int_0^{x_a} c_a(\omega) d\omega + \sum_{o \in O} c_o - \sum_{w \in W} \int_0^{q_w} D_w^{-1}(\omega) d\omega \tag{13d}$$

$$s.t. \quad \sum_{r \in P_w} f_{wr} = \mu q_w \qquad w \in W \tag{13e}$$

$$\sum_{w \in W} \sum_{r \in P_w} f_{wr} \delta_{ar} = x_a, \qquad a \in A \tag{13f}$$

$$\sum_{o \in O} \sum_{r \in P_w} c_o \delta_{ar} = c_o, \qquad a \in A \tag{13g}$$

$$f_{wr} \geq 0, \qquad w \in W, r \in P_w \tag{13h}$$

$$q_w \leq q_w^m, \qquad w \in W \tag{13i}$$

Where $\mathbf{c_a}$ can be obtained from the formula (Fang & Pan,2011): $c_a = \eta_a \mu_a + \lambda_a \sigma_a + \theta_a \gamma_a$, $\mathbf{c_o}$ can be obtained from formula (12): $c_o = \varphi_o \omega + \theta_o R_o$. Through the different values of η_a、 λ_a、

θ_a、 $\varphi_o$and ϑ_o , the traveler's different preferences of routes and transfer hubs can be shown ,which can further reflected on the road capacity reliability. What's more, γ_a reflects the extent of travelers' recognition on the traffic congestion degree of road sections.

4.2. Algorithm Model

The algorithm described by Fang et al. (2011) can be used to calculate the capacity reliability model based on transfer hubs, and the only difference is the confirmation of iterative step. The value of iterative step α^m of this algorithm is the solution of the one-dimensional minimum problem below:

$$\min_{0\le\alpha\le1} Z(\alpha)=\sum_a\int_0^{x_a+\alpha\left(y_a^m-x_a^m\right)} c_a(\omega)\,d\omega+\sum_{o\in O}c_o-\sum\int_0^{q_w} D_w^{-1}(\omega)\,d\omega \tag{14}$$

4.3. Numerical Example and Analysis

This case simulated and validated two traffic ways, which are ordinary traffic (this paper assumes that it contains conventional public traffic) and rail transit. In this paper we join rail transit into the network mentioned in 'Road Network Capacity Reliability Based on Traveler's Route Choice Behavior' (Fang et al., 2011), and assume that the network contains two hubs in zero distance transfer. We assume that sections 4,7,9,12,14,15,17,22 as transfer arcs. The section 4,7,14,15 are transfer arcs for ordinary traffic transfer to rail traffic, and the section 9,12,17,22 are transfer arcs for rail transit transfer to ordinary traffic, as is shown in Figure 5.

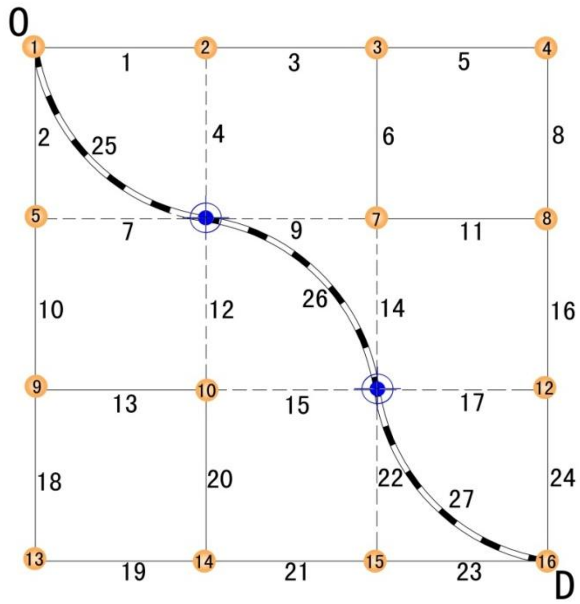

Figure 5. Example network

It still assumes that the existing traffic volume between OD couple is 100. The related data of ordinary traffic road, rail traffic sections and transfer arcs is shown as follows:

Table 1. Free-flow travel time and maximum capacity

Section	ordinary traffic													
Number of section	1	2	3	5	6	8	10	11	13	16	18	19	20	21
Free-flow travel time	10	12	12	15	8	12	5	17	12	10	6	7	15	8
Maximum capacity	50	48	52	60	56	51	47	61	57	42	62	38	43	51

Table 1. (continued) Free-flow travel time and maximum capacity

Section	ordinary traffic		Transfer arc								Rail traffic		
Number of section	23	24	4	7	9	12	14	15	17	22	25	26	27
Free-flow travel time	8	8	Transfer time								3	3	3
Maximum capacity	58	61	39	43	49	59	36	39	56	57	100	100	100

It is noted that:

(1) Transfer arc is a kind of virtual section, which means the travel section only in non-zero distance transfer;

(2) The hypothesis data in above example is only used to verify the adaptability of the model, without considering the characteristics of the transportation operation, thus the data has randomness.

Make the following hypothesis on hub transfer: the departure interval time of rail transit is 15 minutes, the terminal call time is 2 minutes and the transfer time that people can accept is 8 minutes. Vehicle arrival time follows uniform distribution. We can know from formula (4) that hub transfer time in [0, 17] subjects to uniform distribution. The other assumptions are as well as the paper written by Fang et al. (2011).

In the above mentioned assumptions, we adopt C++ Language to realize the solution. Because Fang (2011) has discussed the factors $\eta, \lambda, \theta, \gamma$, now in this paper we set η=0.5， λ=0.5， θ=0.5， γ=0.5 and make other conditions unchanged .Just pay attention to φ and ϑ. The effects on road capacity reliability by different values of φ and ϑ are as follows:

Table 2. The effects on road network capacity reliability by different values of φ and ϑ

η=0.5，λ=0.5 θ=0.5，γ=0.5	φ	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	ϑ	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2	0.1
	reliability	0.83	0.80	0.79	0.71	0.55	0.48	0.39	0.36	0.34

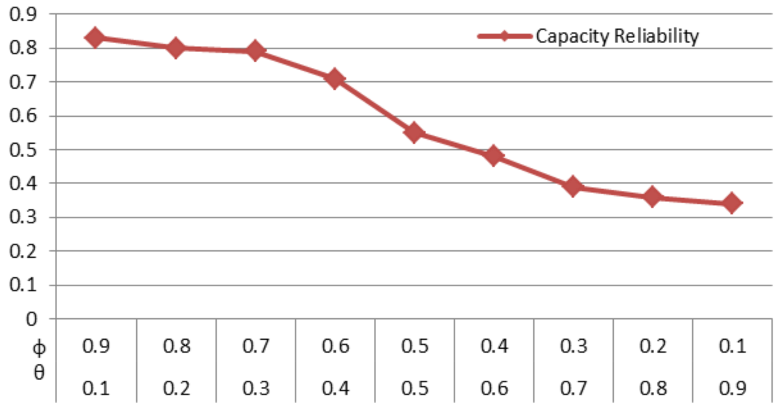

Figure 6. Road network capacity reliability by different values of φ and θ

As can be seen from the Figure 6, the value of road capacity reliability declines with the rising of φ and the decreasing of θ gradually. It shows that capacity reliability is directly proportional to the transfer time reliability and is inversely proportional to transfer time. In other words, in order to improve road capacity reliability, we must try to reduce the hub transfer time and to improve the transfer time reliability.

5. CONCOUSIONS

1 In order to study the influence of transfer time on transfer hubs of network capacity reliability, we propose a three-dimensional transportation network model containing a variety of transport modes. In the model, passenger transfer hub is formed when two or more ways are connected in space. Through this model, we can clearly understand the number and complexity of transfer arcs composed by many ways.

2 By numerical example and analysis, we can see that with the same travel route, the influence of transfer time on road network capacity reliability of transfer hubs is obvious. Capacity reliability is inversely proportional to transfer time and proportional to transfer time reliability.

3 Reducing transfer time has significant improvement trend on stability of hub capacity .However, only a small size road network is analyzed and many assumptions are made in this study, we still need do further in-depth study to support our conclusion. And use actual observed field data to extend to large-scale network.

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REFERENCES:

Bell,M.G.H.,Shield,C.M.,Busch,F.,Kruse,G.A.(1997).Stochastic user equilibrium path flow estimator. Transportation Research, 5C,197～210.

Cheng Jie.(2005)The Study of Planning City Passenger Traffic Hub[D], Xi'an University Of Architecture And Technology.

Dai Shuai,Jang Huaping,Chen Haiyong, etc..(2007).Study on Transfer Reliability of Integrated Public Transport[J]. Journal of Highway and Transportation Research and Development ,24(9):124-126.

Fang Zhao,ALBERT G.(2003).Optimization of transit network to minimize transfer [R]. Prepared for Research Center Florida Department of Trans2portation,5-140.

Liu Haixu,Bu Lei,Pu Yun,(2000).Review of Road Network Reliability[J]. World Sci-tech R & D, 4:68-71.

Mine H, Kawai H.(1982). Mathematics for reliability analysis. Tokyo: Asakura-shorten.

Qing Fang and Pan Xiaodong.(2011). Road Network Capacity Reliability Based on Traveler’s Route Choice Behavior[C]. COTA International Conference of Transportation Professionals (CICTP 2011), 471-484.

Xu Lang,Gao Ziyou.(2006).Urban Transport Network Design Based on Link Capacity Reliability[J]. China Journal of Highway and Transport,19(2):86-90.

Xu Lang,Gao Ziyou.(2006).Urban Road transportation network design problem based on reliability analysis[D].School of traffic and transportation Beijing jiaotong University,China.

Wu Xuegao.(2008).Study on Transfer Theory of Urban Comprehensive Passenger Terminal[D], Beijing jiaotong University.

Wen Ya,Yan Kefei,Cheng Feng.(2005).Trip chain based passenger transfer demand forecast model in city passenger transportation hubs[J].Traffic and Transportation.7:1-3