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A TRAFFIC NETWORK DESIGN SCHEME BASED ON TRAVEL TIME RELIABILITY

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ABSTRACT

On the basis of travel time reliability, this paper puts forward the concepts of absolute reliability and relative reliability to better assess road network; simultaneously, regional traffic road network reliability formula is deducted according to series and parallel connection of link, OD pair and road network. Finally, a bi-level programming model is established to optimize road network. The upper model, integrating travel resistance and travel time reliability in the objective function, optimizes and chooses investable links and the lower model guarantees stochastic user equilibrium. Both Monte Carlo Stochastic Simulation based genetic algorithm and Frank-Wolfe algorithm are employed as solutions. And Nguyen-Dupuis net work calculation sample shows different investment has different effect on road network optimization. Even with the same investment the effect is more remarkable in transition intervals than that of peak and flat intervals.

Keywords: *Travel Time Reliability, Bi-Level Program, Road Network Design, Relative Reliability*

1. INTRODUCTION

Road network is the basis of urban traffic system, structure and distribution of which exerts decisive influence on urban traffic. Road network design refers to the process that a new road is constructed or an old is improved under given constraints to optimize traffic network function. Nowadays with travelers putting more demands on traffic quality, expanding the existing road networks in a scientific and reasonable way is of much significance. Particularly, with heavier traffic jams, travelers tend to focus on travel time reliability. It is one important indicator not only in weighing the probability of successful traveling within determined road networks and certain time but also in measuring travel time stability. And travel time reliability reflects road network performance in randomly fluctuating traffic conditions [1]. Both network reliability theory and travelers path choosing are considered in it from the perspective of road network users. Hence road network reliability is measurable in form of quantification [2, 3].

Numerous researches have been carried in traffic network optimization design. Chen [4] 、 SUBPRASOM [5] etc explored traffic network design strategies with uncertain demand and proposed the corresponding model and solution. CHOOTIAN [6] suggested reliability based network design model which aimed at maximizing road capacity reliability. In addition, a two-stage linear programming model with random demand was proposed on the basis of optimal dynamic distribution model in another research [7]. Xu Liang and Gao Ziyou [8], from supply fluctuation perspective, carried out reliability based network design according to probability user equilibrium, considering road capacity reliability. Road network design problem refers to continuous network design problem (CNDP) or discrete network design problem (DNDP). As road is improved mainly through adding lanes and the resulting capacity increase is jumping rather than continuous, discrete network design performs more effectively than continuous network design in reflecting real road network improvement. Some researches in the above focus on continuous network design which is not discussed in this paper. Researches in discrete network design mainly aim to shorten travel time or reduce cost to the largest degree, while travel time reliability is neglected to some degree and road network stability cannot be guaranteed.

Travel time reliability, assessing road network stability, should be depicted at both macroscopic and microcosmic levels. On the basis of road net work microcosmic characteristics, this paper puts forward the concepts of absolute reliability and relative reliability, by which road network situation in different intervals or same intervals is

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represented and the influence of road network on traffic flow is revealed. Meanwhile considering travel time reliability and traffic resistance, a discrete road network design scheme is established with practical demands of urban road network and investment constraint. This scheme is formulated as a bi-level program model and solved through an intelligent algorithm.

2. TRAVEL TIME RELIABILITY

2.1 Basic Assumptions

Assumptions are given as follows:

(1) Assume travelers are rational and know well the jam of their chosen roads and can choose the roads taking the least time.

(2) Assume prior to urban road network improvement, traffic planning and constructing department has proposed the initial scheme for improving numerous road networks according to city geography and distribution of property lines and purple lines.

2.2 Definition Of Travel Time Reliability

The concept of travel time reliability (TTR) was proposed by Asakura in 1991. It was defined as the probability of successful vehicle traveling from origin to destination within certain time. In term of mathematics, this definition can be expressed as

$$R = P(t \le T) \quad (1)$$

Where R is travel time reliability of chosen link，path or pair OD； t is travel time stochastic variable and T is time threshold set by urban traffic managers.

As no standard of travel time reliability has been set in our country, related rules in Holland state traffic policies 《Nota Mobility》 are adopted. Accordingly, for any travel within 50 Km, the time threshold standard is 1.2 times the average travel time. Travel time absolute reliability and relative reliability is introduced to fully display the influence of road network traffic on travel time.

Travel time absolute reliability（TTAR）：

$$R_i = P(t_i \le 1.2T) \quad (2)$$

Travel time relative reliability（TTRR）：

$$R_i^{'} = P(t_i \le 1.2T_i^{'}) \quad (3)$$

Where t_i is travel time stochastic variable in interval i , T is average travel time in all intervals (one day or one year)， $T_i^{'}$ is average travel time in interval i ， $T = \sum_{i=1}^{t_n} z_i T_i^{'}$ ， t_n is number of intervals, z_i is weight in individual interval. R_i displays macroeconomic change in travel time, $R_i^{'}$ analyses microscopic stability of travel time in different intervals. R_i and $R_i^{'}$ will be represented by the same R in the following when distinction is unnecessary.

3. TTR OF ROAD NETWORKS

3.1 Defining Symbols

N is set of nodes in traffic network; A is set of links in the network; O_r is original traffic flow of node r ; D_s is attracted traffic flow of node s ; P_{rs} is set of links on OD pair connecting $r-s$; Q_{rs} is traffic demand of OD pair connecting $r-s$; x_a is traffic flow of link a ; $t_a(x)$ is resistance function of travel time on link a ; f_k^{rs} is traffic flow of path k within OD pair connecting $r-s$; c_k^{rs} is cost of link k within OD pair connecting $r-s$; δ_{ak}^{rs} is correlative coefficient of link a and OD pair connecting $r-s$ and if a is on k , the value is 1, otherwise 0; C_a is current traffic capacity of link a ; t_{a0} is free travel time of link a in BRP function.

3.2 Ttr Of Road Networks

Assume Q_{rs} is stochastic variable fitting logarithmic normal distribution with average being $q_{rs,av}$ ， and variance ε_{rs} . Apply user equilibrium allocation algorithm, distribute traffic demand to individual links with user optimization principle, then travel time T_a on individual link is derived and travel time reliability on all links R_a is computed.

Path k on OD pair connecting $r-s$ is formed through connecting correlated links a . Thus, travel time reliability of link k is expressed as

$$R_k = \prod_i R_i \quad \forall i, \delta_{ik}^{rs} = 1 \qquad (4)$$

As traffic flow on OD pair connecting $r-s$ takes place on a number of links, Q_{rs} and $f_k^{rs}(k \in P_{rs})$ are in parallel relation. According to parallel structure function formula [9]，travel time

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reliability of OD pair connecting $r-s$ is formulated as

$$R_{rs}=1-\prod_{k}(1-R_k)\quad k\in P_{rs} \tag{5}$$

Road networks aim at meeting travel demand of different OD pairs. And road network functions are actually accumulated functions of sub-systems of a number of OD pairs. With traffic flow variance in OD pairs, travel time reliability of road network can be formulated as：

$$R_A=\sum_{r\in O_r,s\in D_s}\frac{Q_{rs}R_{rs}}{\sum_{r\in O_r,s\in D_s}Q_{rs}} \tag{6}$$

4. NETWORK DESIGN MODEL BASED ON TTR

With traffic networks having been in shape in all cities nowadays, optimization design should be carried out through expanding or constructing roads on basis of present traffic networks. Restricted by construction expense and urban outline planning etc, road network optimization can only be conducted under certain constraints. While traffic networks provide service for travelers, the demand on the networks is different for different travelers and in different conditions. In one case, minimal traffic resistance is valued, while in another travel time reliability is stressed. And both cases will be considered in optimization designing in this paper; hence the network design model established is a bi-level program. The upper program guarantees the minimal generalized travel cost in overall traffic network system with limited budget and the lower realizes equilibrium distribution with user optimization principle. The model is formulated as：

$$(U)\quad MinZ_1=Min\{(1-u)\sum_{a\in A}x_a t_a(x)+uR_A^{-1}\} \tag{7}$$

$$S.T.:\quad \sum_{m\in M}ec(m)\le E \tag{8}$$

$$t_a(x)=\begin{cases} t_{a0}[1+\alpha(\frac{x_a}{C_a})^{\beta}] & a\notin M\\ t_{a0}[1+\alpha(\frac{x_a}{C_a+c_a})^{\beta}] & a\in M\end{cases} \tag{9}$$

$$(L)\quad MinZ_2=Min\sum_{a\in A}\int_0^{x(a)}t_a(w,C_a,c_a)dw \tag{10}$$

$$S.T.:\quad \sum_{k\in P_{rs}}f_k^{rs}=Q_{rs} \tag{11}$$

$$x_a=\sum_{r\in O_r}\sum_{s\in D_s}f_k^{rs}\delta_{ak}^{rs},\ f_k^{rs}\ge 0 \tag{12}$$

(7) shows upper model aims to optimize overall travel time and travel time reliability, where u is weight ratio of travel time reliability； (8) is investment constraint on road expansion and construction; E is the permitted maximal investment in the problem， $ec(m)$ is equivalent investment of link m , M is set of links needing improvement; c_a is increased road capacity of link a on which lanes are constructed or expanded; b is overall budgeted investment needed by per unit road capacity increase, which is available in empirical data； (9) is travel time formula when road is improved and not improved; (10) shows lower model aims to realize user equilibrium distribution and (11)、(12) display corresponding relations between all flow data.

5. MODEL SOLUTION ALGORITHM

Bi-level programming model is NP-Hard problem, whose solution is complicated and polynomial algorithm computation is not available. As bi-level program is a non-convex problem, local optimum tends to appear in general optimization algorithm. But if genetic algorithm is designed scientifically, global optimum can be obtained with local optimum being avoided. Thus this paper applies Monte Carlo Stochastic Simulation based genetic algorithm, proposed in reference [10], to upper-level program problem. And some research has put forward the successful Frank-Wolfe solution to user equilibrium distribution in lower model. Computation procedures are as follows：

Step 1：Initialization. Determine GA parameters including group scale P 、 iteration times N 、 crossover probability p_c 、 mutation probability p_i . Assume genetic algebra ng =1, temporary optimum

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Table Ⅰ: Related Parameters Of Links In Nguyen-Dupuis

Link a	t_{a0}（Min）	Number of lanes	C_a (vehicle/h)	c_a (vehicle/h)	Equivalent investment ec_a
1	5	3	3200	700	120
2	6	2	2400	1800	220
3	8	2	2500	1800	230
4	12	2	2200	2000	250
5	6	3	3100	800	110
6	7	3	3200	700	100
7	5	2	2400	1000	190
8	7	3	3300	700	110
9	9	2	2500	2000	220
10	7	2	2300	800	120
11	7	2	2200	900	130
12	6	2	2300	1600	210
13	9	3	3200	800	100
14	5	3	3500	700	110
15	9	3	3300	700	110
16	5	2	2500	1700	200
17	5	2	2300	1800	210
18	15	2	2400	1000	120
19	5	3	3300	700	120
20	7	0-2	0	2400	260
21	8	0-2	0	2500	240
22	8	0-3	0	3300	350
23	7	0-2	0	2500	230
24	5	0-3	0	3200	320
25	6	0-2	0	2400	250

Table Ⅰ: Logarithm Normal Distribution Parameters Of Od Pairs Traffic Demands

OD Pair	Flat interval		Transition interval		Peak interval	
	Average $q_{rs,av}$	variance ε_{rs}	average $q_{rs,av}$	variance ε_{rs}	average $q_{rs,av}$	variance ε_{rs}
1-2 4-3	6.4	0.1	7	0.13	7.35	0.12
1-3 4-2	6.2	0.1	6.8	0.13	7.2	0.12

$F_{\max}$ =0, global optimum F_{MAX} =0. Related parameters α , β , u are set. And traffic demand stochastic variable and current value of link traffic capacity are set. If historic statistics is available, calculate and set average travel time of all links T and average travel time of links $T_i^{'}$. Otherwise set initial value according to experience and adjust it in computing process.

Step 2：Choose P stochastic individuals as initial group Y in feasible region, $Y=\{y_i\}, i=1,2,3\cdots P$, $y_i=\{c_a \mid a\in M\}$;

Step 3：Apply Y to lower model and utilize Frank-Wolfe algorithm, then distribute traffic demand among road networks with user optimization principle. Traffic distribution on individual link a in interval i $x_{a,i}$ is obtained.

Step 4：Calculating travel time reliability：

(1) Calculate link travel time $t_{a,i}(x)$ in term of (9), then on this basis compute reliability $R_{a,i}$;

(2) Calculate travel time reliability of path, OD pair, and the whole road network. The terminal expression is

$$R_A=\sum_{r\in O_r,s\in D_s}\frac{Q_{rs}[1-\prod_k(1-\prod_a R_a,i)]}{\sum_{r\in O_r,s\in D_s}Q_{rs}} \quad (13)$$

Step 5：Upper model solution:

(1) Compute fitness function of each individual. The reciprocal of upper model optimization objective is used as fitness function. Besides, in order to display effectiveness of different c_m , punishment factor is introduced into fitness function, which is formulated as：

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$$F(c) = \frac{(1-v)}{\sum_{a\in A} x_a t_a(x)} + vR_A + \eta s(c) \qquad (14)$$

Where v is weight ratio of reliability, η is punishment factor， $s(c)$ is punishment function which can be represented as

$$s(c) = \begin{cases} E - ec(m) & E \geq ec(m) \\ 0 & E < ec(m) \end{cases} \qquad (15)$$

(2) Derive fitness value of current optimal individual $F_{\max}$. If $F_{\max}$ > F_{MAX} ， we have $F_{MAX} = F_{\max}$;

(3) ng = ng +1. Decide whether it fits ending constraint $ng \geq N$. If it fits, end computation; otherwise switch to (4);

(4) Sort fitness value of individuals in the current group and choose new individual with roulette wheel method;

(5) According to p_c ， perform crossover on adjacent odd and double individuals;

(6) Perform mutation on all individuals according to p_i , then new group Y is produced;

Step 6： switch to step 3. Steps 3、4、5 are repeated in new group Y .

6. COMPUTATION SAMPLE ANALYSIS

Nguyen-Dupuis is studied as research road network which consists of 13 nodes、19 links and 4 OD pairs, as shown in Figure 1. Solid lines represent existing links that can be expanded and dotted lines refer to no-existing links that can be constructed. And TABLE Ⅰ displays lanes, free travel time, current capacity, capacity that can be increased, equivalent investment needed by increased capacity of all links in this road network. Traffic demand of all OD pairs follow logarithm normal distribution with average $q_{rs,av}$ and variance ε_{rs} . Set traffic demands in flat interval、 peak interval and transition interval as shown in TABLE Ⅱ. Each interval is divided into 30 moments and in each moment stochastic variable fitting distribution is produced once. In GA, set gene scale P =50、 iteration times N =1000 、 crossover probability p_c =0.6、mutation probability p_i =0.05 and z_i can be 0.7 then 0.1 then 0.2， α =0.15， β =4 in BPR function. Weight ratio u is 0.2、0.5、0.8 respectively and overall equivalent investment is 1000、1500、2000 respectively.

On the basis of the above assumptions, optimization design is conducted in this computation sample utilizing this algorithm. In order to calculate travel time reliability, set mean traffic demand $q_{rs,av}$ in every interval as demand at the beginning of algorithm. Distribute traffic equally, then derive average travel time of link k in interval i $T_{ki}^{'}$ and average travel time of link k in one whole day $T_k = \sum_{i=1}^{3} z_i T_{ki}^{'}$. Accordingly, travel time relative reliability, travel time absolute reliability can be obtained.

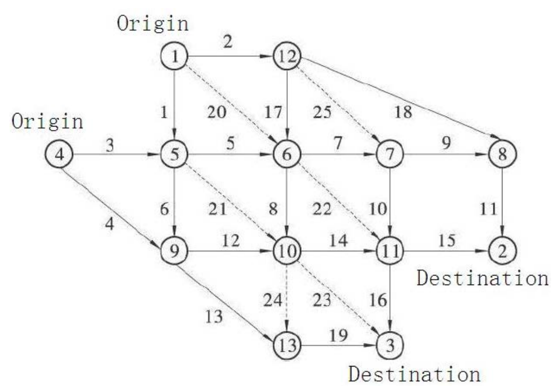

Figure 1: Nguyen-Dupuis Network

Figure 2 displays reliability change in links with overall investment 1500 and u =0.8. With flow increase, TTAR becomes lower. In flat intervals, reliability is usually above0.9, while in peak hours it is smaller than 0.1. Thus flow increase exerts remarkable influence on TTAR in each studied interval, but TTRR changes in a different way. Although its average is usually about 60%, the variance is small in flat intervals and larger in peak hours and largest in transition intervals. So in transition intervals, travel time is unstable.

TABLE Ⅲ lists final computation results in transition intervals with different values of u and overall investment 1500. Road network optimization design is carried out with different values of u . With u getting larger, road network reliability is on the rise and total vehicle travel time comes down. However, when u is large enough, no obvious change takes place in road network reliability and total road network travel time.

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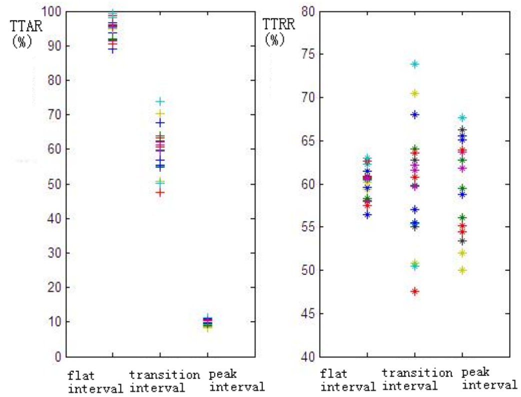

Figure 2: Reliability Change In Links

TABLE Ⅲ: Computation Results With Different U And Overall Investment 1500

Value of u	TTR of Road network (%)	Total vehicle travel time（vehicle·h）	Invested links
0.2	65	58475	5、6、7、8、10、12、14
0.5	69	63761	6、7、8、10、14、19、21
0.8	72	65725	6、8、14、15、21、24
0.2	65	58475	5、6、7、8、10、12、14
0.5	69	63761	6、7、8、10、14、19、21
0.8	72	65725	6、8、14、15、21、24
0.2	65	58475	5、6、7、8、10、12、14

Figure 3 presents reliability change with different investment. With different investment, absolute reliability varies greatly which remains the lowest in flat intervals and the highest in peak hours. And relative reliability variance changes in the same way. However, in transition intervals, with investment increase, absolute reliability improves substantially and relative reliability variance decreases by almost 50%. So investment exerts remarkable influence on reliability.

Figure 4 displays computation results of travel time absolute reliability on link 13 in perk hours with overall investment 1500 and u=0.8. And these results are different with different iteration times. This fig shows that in the beginning of algorithm, optimal absolute reliability rises above 0.5 rapidly, but goes to maximum 0.67 after 600 steps, and no optimal solution is derived in subsequent computation. Thus quasi optimal solution can be obtained with determined iteration times although the optimal solution may not be derived through this algorithm.

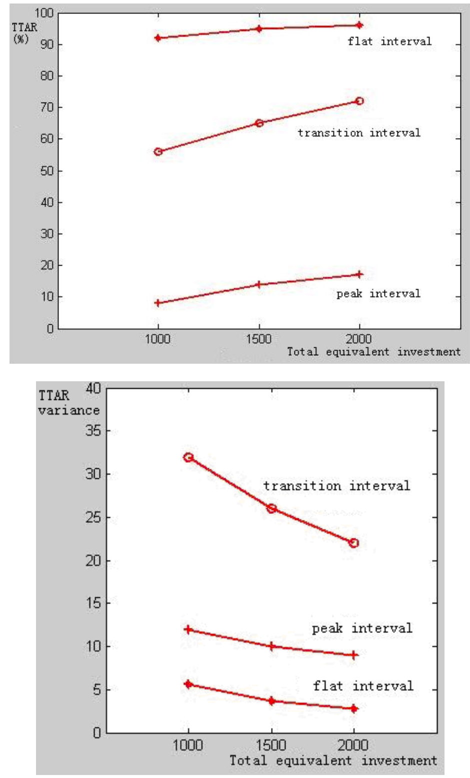

Figure 3: Change In Travel Time Reliability With Different Investment

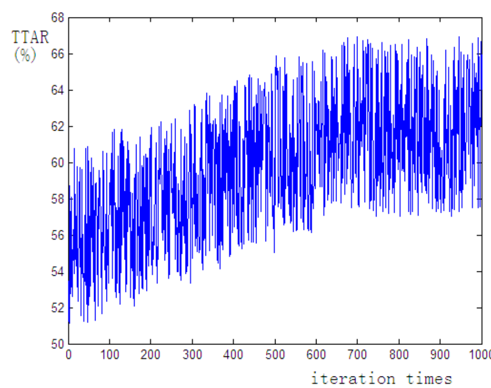

Figure 4: Changing Relation Between Reliability And Iteration Times

7. CONCLUSION

Firstly, this paper defines travel time absolute reliability (TTAR) and travel time relative reliability (TTRR) on the basis of analyzing the concept of travel time reliability. Then OD pair reliability and road network reliability is derived according to road network reliability. Finally, a

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road network design model integrating travel time reliability and travel resistance is established. In this model, the best road network improvement scheme is set up with newly constructed and expanded roads being regarded as optimizing objective. And the solution result is almost the optimal feasible scheme for real road network transform although it may not be the theoretically global optimum.

Computation sample in this paper shows that road network reliability can be improved substantially by applying this proposed model to practical road network design，optimizing traffic capacity scientifically and distributing investment reasonably. But the effect varies greatly in different intervals in that it is slightly improved in flat and peak intervals while remarkably improved by 10%-20% in transition intervals.

Road network absolute reliability generally rises with investment increase, while relative travel time reliability variance decreases greatly. In addition, with different values of u, road network optimization design scheme is different despite the same investment. The detailed regular change remains to be explored in the following researches.

It should be noted that hypothesis is made in establishing this model in order to depict complicated fluctuation in traffic supply and demand, which is different from real traffic. Thus functions in this model need further improvement by being applied into practical data to bridge the gap between the model and reality.

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