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The research of the road network capacity based on the unblocked reliability

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ABSTRACT

Under the background of the current urban traffic jams growing, how to keep the city road network unblocked has a important practical significance. in this paper, through using the concept of unblocked reliability, the method, and use back-up capacity model, established a back-up capacity of road network capacity analysis theory model and its calculation method, then gives a sample calculation. The results showed that, under the restriction of road connection relations, to ensure the smooth and reliable of road network, the actual network capacity is less than its structure capacity. This work provides a new perspective for urban road network planning.

KEYWORDS

Traffic engineering; Road network capacity; Unblocked reliability; Bi-level programming; Spare capacity.

INTRODUCTION

Road network capacity reliability is that the road network accepts the probability of quantitative traffic at an acceptable level of service. The concept of road network capacity reliability first proposed by Chen (1999,2002)[1,2] from American Utah State University with others on the basis of the concept of network reserve capacity from Wong and Yang (1997)[3], it evaluated the performance of road network from the perspective of the whole system and considers the traveler's behaviors about route choice, and it made up for that connective reliability had some shortcomings. Lo and others (2000)[4] thought road network capacity can also be defined as the maximum traffic of road network can be held, but it ought to satisfy road traffic capacity reliability and under the reliability constraint of road walking time. Domestic Liu Haixu and others (2002)[5] constructed reliability double-deck planning model was based on road network capacity of road traveling time capacity, this model adapted long-term reliability study of ability, it can be used to evaluate road network performance under random environment and provide the basis for the improvement of road network performance. Xu Liang and others (2006)[6] established double-deck planning model considering the urban traffic network design on the basis of introducing the basic idea and content of urban traffic network design, that this model combined reliability and condition of road capacity made that the urban traffic network reserve capacity became the largest one and introduced the reliability into urban traffic network design. However, in this realistic context, private cars and road congestion increase quickly in the current urban traffic. We discuss reliability of the urban road network capacity under the condition of the road is unblocked has certain research value.

TWO CONCEPTS ABOUT THE ROAD NETWORK CAPACITY

In order to facilitate on the later analysis, it is necessary to first explain the two concepts about road network capacity, namely structural capacity and reliable capacity.

Two concepts

(1) Structural capacity was defined as the network's largest capacity by traffic network own structure. The capacity has no direct contact with the actual distribution of traffic flow on the web. But this capacity merely decided because of the traffic network capacity of own point and edge and its connection relation. This capacity has nothing to do with the traffic flow, but merely as a metric of characteristics of network structure.

(2)Reliable capacity (i.e. capacity reliability) is a capacity; it ensures that traffic flow operations on the traffic network meeting specific service level under a certain probability. Reliable capacity is not only associated with the structure characteristics of traffic network, but at the same time it also limited by many factors without road network like traffic origin and route choice behavior.

Difference and relation

These two concepts have some difference also exists certain contact. On the whole, capacity reliability (i.e. reliable capacity) on the basis of structural capacity, but its connotation is higher than structural capacity. In order to clearly illustrate this problem, i will contrast two concepts in TABLE one.

TABLE 1 : The compare and analysis of the concept of structural capacity and capacity reliability

Comparison Project	Main Factors					Quantized Characteristics		
	Network Structure	Traffic Capacity	Path Selection Model	Traffic Origin Distribution	Traffic Operation Condition	Quantized Structure	Parameter Quantity	Relationship With Traffic Flow
Structure Capacity	concerned	concerned	irrelevant	irrelevant	irrelevant	certain quantity	1	invisibility
Capacity Reliability	concerned	concerned	concerned	concerned	concerned	random quantity	3	dominant

RELIABILITY ANALYSIS OF SERVICE LEVEL

The division standard of service level

Service level refers to the measure of feel represent the service quality of drivers and passengers during the process of vehicle operation in traffic flow, that road quality level of service provided when under some traffic conditions. Usually, there are many factors that can affect the service level of road, such as road conditions, traffic conditions, and control conditions and so on. The division of road service for drivers and passengers mainly based on the services quality which provided by road, the scope of its quality from the highest free flow level to the minimum saturated flow. Road service level in our country is divided into four levels, among them; Level 1 corresponds to the American standard. A, B; Level 2 corresponds to the American standard C; Level 3 corresponds to the United States American D; Level 4 corresponds to the American standard E, F. Large and medium-sized cities in our country generally adopted by the standard of service levels which showed in TABLE 2.

TABLE 2 : Road service level classification in large and medium-sized cities in our country

Road service level	Level 1	Level 2	Level 3	Level 4 Upper half	Level 4 Lower half
Saturation (V/C)	<0.6	0.6～0.75	0.75～0.9	0.9～1	>1.0

Reliability analysis of service level

The major factors that determine the level of service level are random variation of road capacity, random variation of traffic demand and traffic behavior changes. For the state of the road network capacity and traffic demand condition, we can obtain the only road section traffic by the specified traffic assignment models. Random changes of demand and supply lead to random changes of traffic flow. Service level as a function of the road traffic and road capacity is also random, it will changes along with the network and traffic demand. In supply or demand random changes of road network, road section and road network service level is no longer a fixed value, but also random change along with the change of road traffic conditions. Therefore, this article defines the service level of reliability is[7]:

The probability of road section capacity or (and) random changes of traffic demand keeping road section and road network service in a certain level. The reliability of service combine traffic demand which is change randomly and the road network, it can not only adapt to the traffic of time-varying, but also reflect the overall performance of network synthetically.

In general, the status of the main three parameters such as traffic flow, speed, density, reflect the characteristics of road traffic flow. In the urban road network, function of BPR usually is used to describe the relationship between the three parameters, as the model shown below.

$$t = t_f [1 + \alpha (\frac{V}{C})^{\beta}] \tag{1}$$

In the formula, t is for travel time of the road, H; tf is for travel time of the road under the condition of free flow the unit is h; V is for traffic flow of the road, the unit is pcu/h; C is for road capacity, unit is the pcu/h; α、β is the model parameters, usually are 0.15 and 4.5 respectively. V/C called saturation of road sections reflects the degree of traffic load.

In reality, for the state of the road people generally use the natural language to describe, usually expressed such as very smooth, standard smooth, basic smooth, not very smooth, not smooth. According to Chen (2006)[8] survey in Beijing, the division standard of urban road traffic flow running state are showed in TABLE 3 below.

TABLE 3 : The standard of road traffic flow

Classification of traffic flow running state	Megacities				Small and medium-sized cities
	Speed (km/h)				*V/C*
	Fast Road	Main road	Secondary road	Branch road	
Very smooth	>60	>50	>45	>30	<0.4
Standard smooth	40-60	35-50	30-45	20-30	0.4-0.6
Basic smooth	30-40	25-35	20-30	18-20	0.6-0.9
Not very smooth	20-30	18-25	15-20	14-18	0.9-1.0
Not smooth	<20	<18	<15	<14	>1.0

It can be seen from the formula (1) and TABLE 2, Sections of road smooth or not has close relationship between the saturation. Generally the degree of smooth and saturation have the relationship as follows[2].

$$PR_i = \alpha \left(\frac{V_i}{C_i}\right)^3 + \beta \left(\frac{V_i}{C_i}\right)^2 + \gamma \left(\frac{V_i}{C_i}\right) \quad + C \tag{2}$$

THE ANALYSIS AND ESTABLISHMENT OF THE MODEL ABOUT THE RELIABILITY DEGREE OF CAPACITY

The backup capacity model

Without considering the situation of signal setting, backup capacity model can be expressed as:

$$\max(\mu) \tag{3}$$

$$\text{s.t. } x_a(\mu) \le \rho_a c_a, \ a \in A \tag{4}$$

In which, the traffic flow model of a road section can be obtained by solving the following constrained user equilibrium model:

$$\min z(x) = \sum_{a\in A}\int_0^{x_a} t_a(\omega)d\omega \quad s.t. \tag{5}$$

$$\sum_{k\in R_w} f_k^w = \mu q_w, \forall w \in W \tag{6}$$

$$x_a = \sum_{w\in W}\sum_{k\in R_w} f_k^w \delta_{a,k}^w, \forall a \in A \tag{7}$$

$$f_k^w \geq 0, \forall k \in R_w, w \in W \tag{8}$$

In these formula, μ represents the multiplier of OD traffic capacity; ρ_a represents the maximum saturation degree the road section can withstand; Xa is the observed traffic flow of; f_k^w is the traffic flow through path k within OD points to W; $\delta_{a,k}^w$ is a {0,1} function, if the section a is in the path k within OD points to W, then take 1, otherwise, take 0. W is the collection of paired OD points; R_w is the collection of feasible paths within OD points to W.

The traffic flow pattern satisfies the conditions of user equilibrium, can be obtained by solving the underlying problems, yet the upper level problems are the multipliers to solve the OD traffic capacity satisfying the traffic capacity constraints. Assuming that μ^* is optimum obtained multiplier， if $\mu^* > 1$, it indicates that there is still a surplus in the road network capacity, it's reserved capacity is $\mu^* - 1$ of the current given OD traffic capacity, it's degree of the overload is $1 - \mu^*$ of the current given OD traffic capacity.

The establishment of the model

Considering it must satisfy a certain service level when determining the backup capacity of the road network, that is, the traffic congestion degree may appear on the road should be in an acceptable range. Since the traffic capacity is a random variable, thus the corresponding constraints are probabilities. Use the expected travel time of the road sections to express this kind of service level, then, to any road sections, there is:

$$P\left\{T_a \geq \left(\frac{V_a}{C_a}\right) t_f^a\right\} \leq \gamma_a \tag{9}$$

In the formula, γ_a represents the exceeding probability of the acceptable congestion degree of road section a, reflects people's recognition degree to the traffic congestion degree of road section a. T_a represents the expected travel time of road section a, the unit is hour; t_f^a represents the travel time under the free flow conditions of road section a, the unit is hour; V_a/C_a represents the saturation degree of road section a.

According to the formula (1), we can transform the above formula (9) into:

$$P\left\{c_a \leq \frac{x_a}{\left(\frac{\frac{V_a}{C_a}-1}{\alpha}\right)^{\frac{1}{\beta}}}\right\} \leq \gamma_a \tag{10}$$

If we assume that the probability distribution of c_a is already known as $F(c_a)$, then the formula (10) can be transformed into:

$$x_a \leq \left(\frac{\frac{V_a}{C_a}-1}{\alpha}\right)^{\frac{1}{\beta}} F^{-1}(\gamma_a) \tag{10}$$

In the formula, $F^{-1}(\cdot)$ represents the inverse function of the probability distribution of c_a, the rest of the parameters have same meanings with the above model. Thus we can establish the reliability model (see formula (3) to formula (8)) of the road network capacity based on backup capacity, as follow:

$$\max(\mu) \tag{11}$$

$$\text{s.t. } x_a(\mu) \le \left(\frac{\frac{v_a}{c_a}-1}{\alpha}\right)^{\frac{1}{\beta}} F^{-1}(\gamma_a),\ a \in A \tag{12}$$

In the formulas, the traffic flow model of a road section can be obtained by solving the following user equilibrium model:

$$\min z(x) = \sum_{a\in A}\int_0^{x_a} t_a(\omega)d\omega \tag{13}$$

$$s.t. \sum_{k\in R_w} f_k^w = \mu q_w, \forall w \in W \tag{14}$$

$$x_a = \sum_{w\in W}\sum_{k\in R_w} f_k^w \delta_{a,k}^w, \forall a \in A \tag{15}$$

$$f_k^w \ge 0, \forall k \in R_w, w \in W \tag{16}$$

THE ALGORITHM AND EXAMPLES

The general algorithm

It uses the sensitivity analysis method; the specific steps are as follows:

Step 1: Set μ^1 as the initial value of the multiplier of OD traffic capacity, take n=1.

Step 2: For any given μ^n, we can obtain x^n, the equilibrium traffic flow, by solving the equilibrium problem of the underlying road network.

Step 3: Use the sensitivity analysis method of the equilibrium problem of the road network to calculate the derivative of x^n (the equilibrium traffic flow) to μ^n (the multiplier of the OD trip matrix). $d\mu/d\,x = (\mu^n - \mu^{n-1})/(x^n - x^{n-1})$

Step 4:

Step 5: If $|\mu^{n+1} - \mu^n| \le \varepsilon$ (the preinstalled error) is always tenable to $\forall a \in A$, then the iteration stop. Otherwise, take n=n+1, and return to step 2.

The approximate algorithm

For large-scale road network, the above algorithm is relatively complex. Considering the need of the model used to evaluate the road network planning scheme in practice, its convergence speed and calculation accuracy are more important. Thus, we propose an approximation algorithms of the finite exhaustion of fixed step, the specific steps are as follows:

Step 1: Determine an appropriate increment $\Delta\mu$, take $\mu^1 = \Delta\mu$, n=1。

Step 2: For a given μ^n, we can obtain $\{x_a^n\}$ by solving the equilibrium problem of the underlying users.

Step 3: For an arbitrary road section a ($a \in A$), if it is satisfied with the constraint formula (13), then takes $\mu^{n+1} = \mu^n + \Delta\mu$, n=n+1. Otherwise, takes $\mu^* = \mu^n$.

Compared with the general algorithm, approximation algorithm will sure converge after a certain number of iterations. But the accuracy of the calculation is subject to$\Delta\mu$, the preinstalled and fixed step size. Obviously, the smaller the step size is, the smaller the error is, but at the same time the amount of calculation increases greatly.

Assume that the road network is like the one shown in Figure 1, it consists of 5 nodes, 7 road sections and 2 OD pairs, (1, 5) and (2, 5), the traffic capacity between each OD pair respectively are $q_{15} = 22\text{pcu/h}$ and $q_{25} = 24\text{pcu/h}$. The free flow time and the traffic capacity of each road section are shown in TABLE 4.

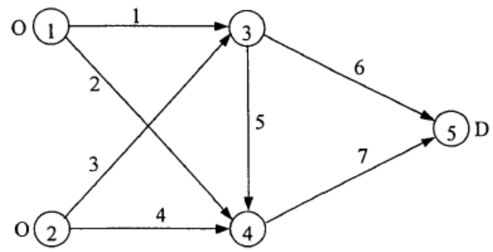

Figure 1 : The example network of calculation (The numbers in the figure represent the road sections and node numbers)

TABLE 4 : The free flow time and the traffic capacity of each road section

The road section number	1	2	3	4	5	6	7
The free flow time (h)	11	10	12	13	2	12	11
the traffic capacity (pcu/h)	18	18	18	18	18	30	30

Assume that $F(c_a)$ is subject to uniform distribution, the value of V_i/C_i is in the range of [0,1], for simplicity, we use the approximate algorithm to conduct a simulation calculation, preset the step size as 0.2, the results of the simulation calculation are shown in the following TABLE 5.

TABLE 5 : The results of the simulation calculation

road section	μ=0.2			μ=0.4			μ=0.6			μ=0.8			μ=1		
	FLOW	V/C	PR	FLOW	V/C	PR	FLOW	V/C	PR	FLOW	V/C	PR	FLOW	V/C	PR
1	4.40	0.24	0.59	8.80	0.49	0.42	13.20	0.73	0.31	17.60	0.98	0.08	22.00	1.22	-0.45
2	4.80	0.27	0.56	9.60	0.53	0.40	14.40	0.80	0.27	19.20	1.07	-0.07	24.00	1.33	-0.84
3	0.00	0.00	1.00	0.00	0.00	1.00	0.00	0.00	1.00	0.00	0.00	1.00	0.00	0.00	1.00
4	0.00	0.00	1.00	0.00	0.00	1.00	0.00	0.00	1.00	0.00	0.00	1.00	0.00	0.00	1.00
5	0.00	0.00	1.00	0.00	0.00	1.00	0.00	0.00	1.00	0.00	0.00	1.00	0.00	0.00	1.00
6	9.20	0.51	0.41	18.40	1.02	0.01	27.60	1.53	-1.86	36.80	2.04	-6.90	46.00	2.56	-16.79
7	0.00	0.00	1.00	0.00	0.00	1.00	0.00	0.00	1.00	0.00	0.00	1.00	0.00	0.00	1.00

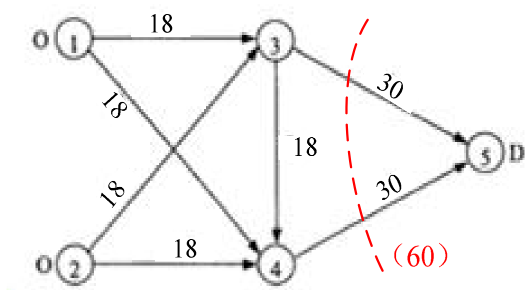

Figure 2 : The example network of calculation (The numbers in the figure represent the traffic capacity of the road sections and node numbers)

RESULT AND DISSCUSS

As can be seen from the data listed in TABLE 5, when μ=0.6, it comes that PR6=-1.8617<0, this indicates that the road section 6 has been overloaded at this time, it could not satisfy the determined service level. Therefore, in the analysis, we should take the status of the traffic flow distribution, when μ=0.4, as the standard of capacity calculation. Then the passable and reliable capacity of the road network is μq_w, that is, 0.4╳（22+24）=18pcu/h. This indicates that the total hours when traffic in [0, 18] or less, the road network is still likely to remain passable. Therefore, it can be considered that its reliable capacity is 18pcu/h.

In order to compare the concepts, we use the cut set method to calculate, and obtain the structure capacity of the road network is 60pcu/h, as is shown in Figure 2. This indicates that the capacity of the actual road network is less than its structure capacity.

CONCLUSIONS

Based on relevant research achievements from home and abroad, and, by using the concept of passable reliability and backup capacity model, the article put forward a model of network capacity to keep the road is passable and reliable. According to the research of this article, we get the following achievements:

(1) Urban road network capacity is an important index of urban transport planning; building a passable and reliable urban road network has an important significance either in theory or in practice.

(2)Using the passable and reliable concept of the road sections, the backup capacity of the road network can be expressed as a bi-level planning model restricted by the degree of passable reliability of the road section.

(3)The example calculation indicates that, under the restriction of connecting relations among road sections, in order to ensure the accessibility and reliability of road network, the actual received capacity of the road network is less than the capacity obtained by calculating in the cut set method.

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