The Study of Traffic Impact Area Based on Travel Time Reliability

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Abstract: The determination of the traffic impact area is not only the basis of traffic impact analysis (TIA), but also one of its difficult issues. At present, the foreign subjective methods not suitable in China. Meanwhile, the domestic model methods have difficulties in calibrating parameters and are over-idealistic in road assumptions, so that they are too hard to be widely used. While, this paper propose method that based on travel time reliability. Firstly, it quantifies the factors of traffic impact area to get the travel time reliability function. Secondly, it demonstrates the overall process of this method to determine traffic impact area. Thirdly, it establishes traffic assignment model. Fourthly, it takes a practical developing project in Beijing as an example to verify its maneuverability and flexibility. Finally, it compares and analyses the benefits and drawbacks of the method and other methods. In conclusion, it is reasonable to say that this method is more suitable for the actual roads, easier to operate and has important practical significance.

1. Introduction

Traffic impact analysis has become an essential step in the approval of construction projects in large cities of China. It is also an important measure to judge the effects of development projects in urban traffic. TIA involves two areas: the research area of TIA and the traffic impact area of the project. Among them, the research area of TIA refers to the area where traffic conditions around project may be most affected by the proposed development project. The traffic impact area refers to the surrounding area where the planned project has obvious influence on. Generally, after the traffic impact area is determined, key sections and intersections within the area need to be fully analyzed. Therefore, with the gradual popularization of TIA, the determination of traffic impact area, as the accurate basis for TIA, becomes increasingly important.

2. Quantification Factors of Traffic Impact Area--Study of Travel Time Reliability Function

2.1. Expression of Travel Time Reliability Function

Currently, there are two main factors for quantifying traffic impact area: service level and isochron, while this paper regards travel time reliability as the quantifying factor. There are two types of travel time reliability: section and path. The path travel time reliability refers to the probability, no matter which effective path is selected from the development project to the attractive point, that the time it takes do not exceed the normal travel time (threshold) on the path. The main model used in this paper is proposed by Bell et al.(1997)[1].He thinks that travel time reliability is mainly affected by traffic fluctuation. The travel time of the whole path is decided by the travel time of each section, and its expectation and variance are equal to the sum of expectation and variance of each section's travel time. Meanwhile, the travel time of path obeys normal distribution, as shown in formula (1).

$$T \sim N\left(\sum_{a\in A}\mu_a, \sum_{a\in A}\sigma_a^2\right) \tag{1}$$

Where T is the travel time of path A (h), μ_a is the expectation of travel time of section a passing through path A (h), σ_a^2 is the variance of travel time of section a .Reference 1 indicates that the path travel time reliability is the probability that the path travel time is less than a fixed value. The model of path travel time reliability, as shown in formula (2):

$$R_A = P(T \le t) = \Phi\left(\frac{t - \sum_{a\in m}\mu_a}{\sqrt{\sum_{a\in m}\sigma_a^2}}\right) \tag{2}$$

Where m is a set of section which consists of the sections through path A.According to the definition of path reliability, if a threshold is given, the corresponding probability expression of path reliability can be obtained. However, it is difficult to determine the reliability according to the formula (1-2), because the path is composed of sections and each section's travel time distribution and other related distribution characteristics are different,. Therefore, it is considered to solve the travel time reliability of each section instead of solving the travel time reliability of the whole path, by using the equation that proposed by Lee et al.(2000)[2], as shown in formula (3):

$$R_A = \prod_i r_i \tag{3}$$

Where r_i is the travel time reliability of section i, R_A is the travel time reliability of path A.

Assuming that the distribution of section travel time is similar to the distribution of path travel time, which obeys the normal distribution, its reliability can be calculated according to the definition:

$$r_{ma}(t) = P_{ma}(t < t^*) = \Phi\left(\frac{t^* - \mu_{ma}}{\sigma_{ma}}\right) \quad (4)$$

Where $r_{ma}(t)$ is the reliability of travel time t^* of section a at time m, μ_{ma} and σ^2_{ma} are the expectation and variance of the travel time of section a at time m. Therefore, travel time reliability of the path can be solved by formula (3).

2.2. Solution of Travel Time Reliability Based on BPR Model

In general, the travel time of section and path is a random variable, which can be computed from BPR time function. If all of them obey normal distribution, travel time reliability can be described according to the definition after travel time mean and variance of section are obtained. Normally, section travel time will be calculated after traffic volume is obtained, because of its randomness.

Because traffic flow of the section changes randomly, so it is assumed that its changes independently and continuously, and the minimum value is zero. When the road network is in an abnormal state, the traffic flow of section is between the minimum and the maximum value, and the probability of each value is equal. Therefore, the traffic flow of section can be regarded as uniform distribution, which obeys the parameters of 0 and traffic flow c allocated in the section at peak hour. The probability density function is shown in formula(5).

$$f(x) = \begin{cases} \frac{1}{b-a} & a \le x \le b \\ 0 & \text{others} \end{cases} \quad (5)$$

Where a and b are the parameters of the uniformly distributed probability density function, and when a=0, b=c. The traffic flow at the peak time is solved based on the user equilibrium assignment model and allocated by TransCAD.

The section travel time depends on the section traffic volume. According to the research of Bell and Iida, it generally thinks that the path travel time obeys normal distribution, as shown in formula (1). According to this assumption, the travel time reliability of the path can be calculated.

The section travel time needs to be further considered after the section traffic flow is gained. Given that section capacity is constant, the BPR function[3], which developed by the BPR-Bureau of Public Road, can calculate the travel time.

$$t_a(q_a, C_a) = t_0\left[1 + \alpha\left(\frac{q_a}{C_a}\right)^\beta\right] \quad (6)$$

Then the mean and variance of section travel time can be expressed as:

$$E(t_a) = t_0\left[1 + \alpha E\left({}^{q_a}\!/\!_{C_a}\right)^\beta\right] = t_0 + \alpha t_0 C_a^{-\beta} E(q_a^\beta) \quad (7)$$

$$D(t_a)=(\alpha t_0)^2\cdot D\left(q_a/c_a\right)^{\beta}=\alpha^2 t_0^2 C_a^{-2\beta}D(q_a^{\beta})=\alpha^2 t_0^2 C_a^{-2\beta}\left[E(q_a^{2\beta})-E^2(q_a^{\beta})\right] \tag{8}$$

Where $t_a(q_a,C_a)$ is the travel time of section a (h), q_a is the traffic volume of section a (pcu/h), C_a is the section capacity (pcu/h), that is assumed to be constant, t_0 is the free flow travel time, α and β are model parameters, and usually α =0.15 and β =4.0.

Section travel time is affected by many factors. It is assumed that the capacity is constant and the section travel time only relates to the traffic flow section. Let:

$$t_a(q_a,C_a)=f(q) \tag{9}$$

Where q is a random variable, the mean value is m, and Taylor expansion is carried out at $q=m$. Then obtained:

$$t_a=f(q)=f(m)+(q-m)f'(m)+\frac{(q-m)^2}{2}f''(m)+\xi \tag{10}$$

Where ξ is remainder.

$$\begin{aligned}E(t_a)&=f(m)+E(q_a)f'(m)-mf'(m)+\frac{1}{2}E\left[(q-m)^2\right]f''(m)\\&=f(m)+\frac{1}{2}E\left[(q-m)^2\right]f''(m)=f(m)+\frac{1}{2}f''(m)D(q)\\&=t_0+t_0\alpha\left(\frac{m}{C_a}\right)^{\beta}+\frac{1}{2}t_0\alpha\beta(\beta-1)q^{\beta\text{-}2}m^{\beta-2}D(q)\end{aligned} \tag{11}$$

If $D(q)$ is very small, then $E(t_a)\approx f(m)$.

$$\begin{aligned}D(t_a)&=D[f(m)]+D[(q-m)f'(m)]+D(\xi)\\&=[f'(m)]^2D(q)=(t_0\alpha C_a^{-\beta}\beta m^{\beta-1})^2D(q)\end{aligned} \tag{12}$$

The section travel time approximately obeys the normal distribution with mean $E(t_a)$ and variance $D(t_a)$.When the traffic volume is zero, the travel time is free flow travel time. Meanwhile, the travel time increases as long as the traffic flow increases, which is consistent with the practical experience.

Based on the above research, when the section traffic volume is q_a and the section travel time is no more than t^*, the section travel time reliability can be expressed as

$$r_a(q_a) = P\{t_a \le t^*\} = P\{t_a \le \gamma t_0\} = \Phi\left\{\frac{\gamma t_0 - E(t_a)}{\sqrt{D(t_a)}}\right\} \tag{13}$$

Where $r_a(q_a)$ is the reliability of section a, γ is the parameter and $\gamma > 1$, t_0 is the free flow travel time(h) of section a, t_a is the maximum acceptable travel time(h) of section a.

γ represents an aspect of transport planning and management, which is an expectation of real road conditions. Therefore, it can be set in accordance with relevant management objectives (such as normal average speed range). According to the study of Bell[1] et al., generally γ =1.2, or can be chosen from a wide range, which is related to the depth of the study. In this paper, γ =1.2.

As a result, the section travel time reliability is a function of traffic volume. The steps of solving the optimal path based on the travel time reliability are shown below:

（1）OD matrices estimation is carried out basing on the peak hourly volume of road section. Traffic volume of each section can be obtained through the stochastic user equilibrium model (SUE) and TransCAD.

（2）Road design data decides free flow travel time and capacity of each section.

（3）Using formulas (7) and (8) to calculate the mean and variance of each section's travel time.

（4）Using the mean and variance of travel time into formula (13), the travel time reliability of each section can be computed.

（5）According to the formula (3), calculating the travel time reliability of each path between the origin and destination. Then, the path that has the highest reliability is the optimal path between the origin and destination.

2.3. Determination of Threshold of Traffic Impact Area

This paper focuses on method application, so the value of threshold will not be specifically discussed. According to the sensitivity of people daily travel reliability, the threshold is defined as shown in table 1. The threshold value can be adjusted by investigation in practical applications.

3. The Process of Determining Traffic Impact Area Based on Travel Time Reliability

In this paper, the specific processes of quantification method of traffic impact area based on travel time reliability is shown in Figure 1. From Figure 1, a cycle calculation process is required to determine the traffic impact area, and each adjustment of the impact area is an analysis of travel time reliability of road network around the project. First of all, comparing and analyzing the variation value of road network travel time reliability under two status: with or without construction projects. Then, comparing it with the threshold in table 1. It is possible to determine that whether the previously defined impact area was included in the research area and whether all traffic sensitive sections and intersections were included. Finally, making adjustments to quickly and accurately determine the project's traffic impact area. It is divided into the following steps: (1) Data preparation and input; (2) OD estimation and calculation of current travel time reliability; (3) Trip distribution forecast in feature years; (4) Calculation of travel time reliability in feature years and determination of traffic impact area.

Table 1: The affected indexes of section travel time reliability cost.

Section travel time reliability r_i	Section travel time reliability cost d_i	Reduction value of section travel time reliability after projects completion	Added value of section travel time reliability cost after projects completion
r_i >0.95	d_i <0.0513	0.15	0.17
0.60< r_i ≤0.95	0.0513≤ d_i < 0.5108	0.10	0.11～0.18（Take the median 0.145）
r_i ≤0.6	d_i ≥0.5108	0.05	0.09

The data preparation involves the establishment of road network in TransCAD and the input of corresponding properties, including length, traffic capacity, design speed, free flow travel time, etc. In the network, it is also necessary to set up corresponding actual road situations, such as traffic directions (for example, one-way traffic direction), traffic volume of critical sections, features of traffic intersections and junctions, etc.

It is impossible to investigate all sections traffic volume, so it is necessary to conduct traffic assignment after OD estimation in order to get the all sections traffic volume in the network. Their travel time reliability can be obtained by formula(13).

As shown in Figure 1, the traffic impact area needs to be determined by comparing the travel time reliability variation before and after projects completion. Therefore, it is necessary to conduct trip distribution forecast and traffic assignment to predict road network traffic volume in feature years. After obtaining the feature years traffic volume, the travel time reliability of feature years can be calculated from formula (13).The establishment of traffic assignment model is the key, which will introduce in Section 4.

4. Traffic Assignment Model Based on Travel Time Reliability

Drivers hope to shorten the travel time and try to choose the shortest path, so the travel time of the selected path is same and the shortest, leading to an equilibrium state. However, with the rapid development of social economy, travel time fluctuates constantly with the change of road conditions. Road users actually prefer to choose the path with the least fluctuation of travel time. That is to say, even if the travel time of a path is longer, but its travel time is more reliable, then the probability of arriving at destinations on time through this path is higher. Consequently, it is reasonable to use the highest reliability as the foundation for traveler’s to select paths.

Assuming that road users know the status of the road network and try to choose the path with the lowest cost. When the road network reaches equilibrium, the cost of each used path of OD is greater than or equal to the lowest cost. It is also reasonable, if the section travel time reliability is used to replace the section travel cost. The road network users know the condition of the road network and try to choose the path with the highest reliability. When the road network reaches equilibrium, all the used paths of OD have the same and the highest reliability, while the reliability of the unused paths is lower than or equal to the highest reliability.

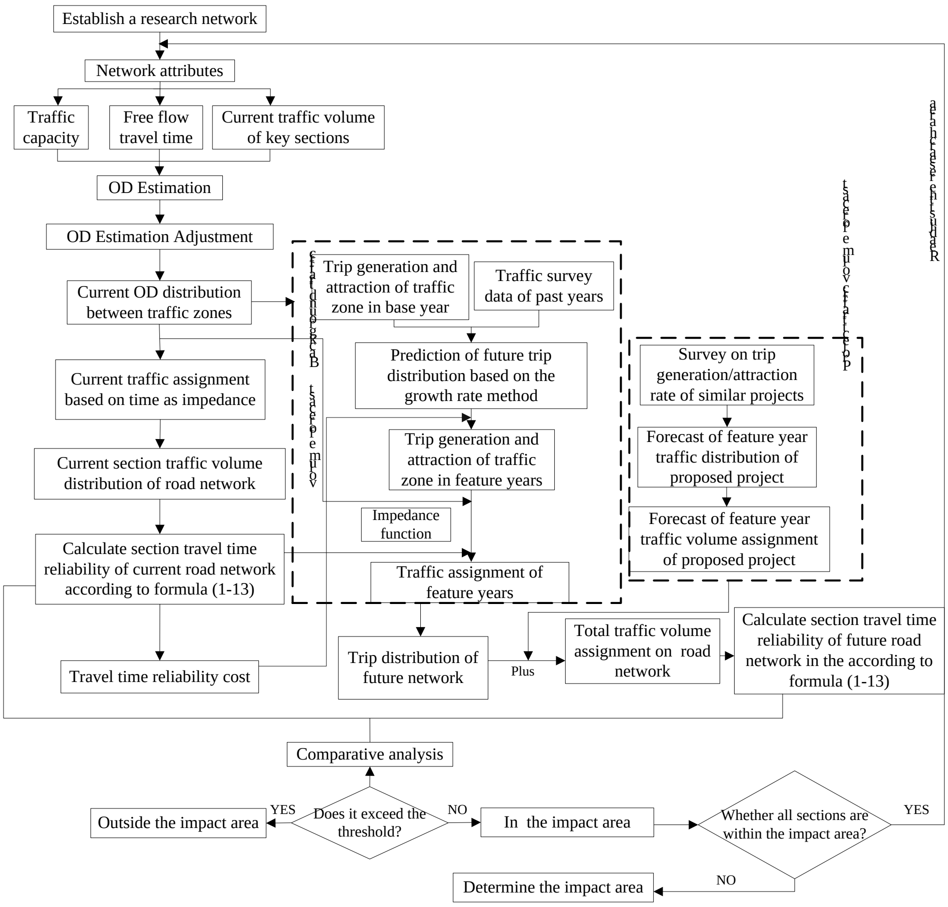

Figure 1: The process of traffic impact area analysis based on travel time reliability.

Conducting the optimization objective analysis first, then establishing the traffic assignment model.

If the maximum travel time reliability path in the road network is the optimal path:

$$MaxR_{o} = Max\left(\prod_{i=1}^{n} r_i\right) \tag{14}$$

Take the logarithm of both sides of formula(14) to get:

$$\ln\left(MaxR_{o}\right) = \ln\left[Max\left(\prod_{i=1}^{n} r_i\right)\right] = Max\left[\ln\left(\prod_{i=1}^{n} r_i\right)\right] = Max\left(\sum_{i=1}^{n} \ln r_i\right) \tag{15}$$

Then, the maximum reliability of the optimal path is:

$$MaxR_{o} = e^{Max\left(\sum_{i=1}^{n} \ln r_i\right)} \tag{16}$$

Since $r_i \in [0,\ 1]$, according to the properties of $f(x) = \ln(x)$, gets $\ln r_i \leq 0$, and then gets $\sum_{i=1}^{n} \ln r_i \leq 0$, so formula (15) can be expressed as:

$$\ln(MaxR_{o}) = Max\left(\sum_{i=1}^{n} \ln r_i\right) = Min\left[\sum_{i=1}^{n} (-\ln r_i)\right] \tag{17}$$

Al last, from the static UE equilibrium assignment model, the assignment model based on the travel time reliability is established, as shown in formula (18).

$$\begin{aligned}
&\min Z(X) = \sum_{a} \int_{0}^{X_a} -\ln(r_i)dx \\
&S.T. \sum_{k} f_k^{rs} = q_{rs} \qquad \forall r,s \\
&X_a = \sum_{r,s} \sum_{k} f_k^{rs} \delta_{a,k}^{rs} \qquad \forall a \\
&f_k^{rs} \geq 0 \qquad \forall r,s
\end{aligned} \tag{18}$$

Where r_i is the travel time reliability of section i. The optimal solution of formula (18) is the optimal path in the road network, which is the maximum reliability path. The reliability of the maximum reliability path can be expressed as: $R_{max} = e^{MaxZ(X)}$.

5. Example Analysis

Taking a construction project in Beijing in 2007 as an example, the impact area of this project is analyzed by travel time reliability. Firstly, defining the preliminary research area of the project, and then the traffic impact area is determined based on the research area.

According to the road network and land use planning in the area where the project is located, as well as the main roads adjacent to the project, the traffic research area of the project is preliminarily determined as shown in Figure 2.The land within the research area is mainly planned to be education research and second-class housing area, and some commercial financial land. Considering the project construction plan, the feature year of this project impact is set as

2010.Based on the property of land use (Figure 3),trip purpose within the project research area are mainly to go to school and go to work, so the morning peak period (from 7:30 to 8:00) is selected as the research time.

Firstly, inputting the initial road network attributes as shown in Figure 4. In order to get the traffic volume of all sections of the current road network, OD estimation should be operated according to the key sections' traffic volume, the results as shown in Figure 5. Secondly, basing on the results, traffic volume of the current road network is obtained through traffic assignment. Thirdly, according to formula (13), the section travel time reliability of the current road network can be calculated, and the results as shown in Figure 6.

Fourthly, after the present OD matrix is obtained, the trip distribution and traffic assignment of feature year are performed according to the four-stage model. The shortest path matrix is established with -lnri as the impedance matrix of the traffic assignment in feature years, which making the section travel time reliability is considered in feature years.

Figure 2: Preliminary research area of the project.

Figure 3: Land use within the research area.

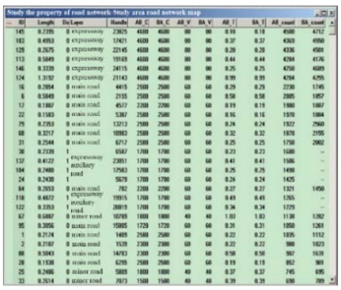

Figure 4: Attributes of initial road network.

Fifthly, the feature years traffic assignment model is established by formula (18), so the section traffic volume of the feature years is conducted and the section travel time reliability can be calculated by formula (13). Finally, comparing with the current travel time reliability according to the threshold value in Table 1 to determine the affected section, and the final traffic impact area is shown in Figure 7.

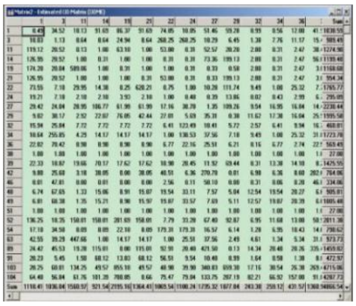

Figure 5: Result of OD estimation.

Figure 6: Reliability cost of travel time before completion.

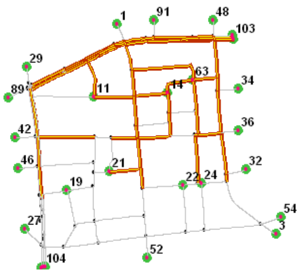

Figure 7: Determination of impact area

6. Analysis and Comparison

In this paper, quantification method of traffic impact area based on travel time reliability takes travel time reliability cost as the quantification factor to determine traffic impact are as after projects completion. According to the case that mentioned in Section 4, this section compares the advantages and disadvantages of this research method and other methods that commonly used in China and abroad in order to illustrate the scientific city and practicality of this method.

(1) Subjective Determination of Impact Area

The method of subjective determination of traffic impact area is simple and easy, which is widely used in China and abroad. It usually refers to development project as the center and sets a scope within the specified radius as the research area. Alternatively, sometimes it takes construction project as the center and regards the region that enclosed by urban main roads or rapid roads around the construction project as the research area, sometimes it is also determined by the experience of traffic engineers. For the case in Section 4, there is no consistent evaluation standard for transport planners, thus there will have significant different opinions in determining the traffic impact area. If subjective determination method is adopted, it will certainly affect the fairness of TIA.

(2) Circle Extrapolation Method

The premise of the circle extrapolation method is that there is no directional difference in the distribution of traffic volume attracted by construction projects on the road network. Besides, all sections of road network around development projects should be in the same grade and length. Obviously, this hypothesis is almost impossible in practical application. If the circle extrapolation method is applied, the actual road network need to be greatly simplified, as a result, the impact area calculated in this way might be greatly different from the actual.

In the case of Section 5, the project network consists of expressways, auxiliary roads of expressway, main roads, secondary roads and branch roads. If the circle extrapolation method is adopted, it is necessary to change the road grade, simplify the irregular shape of the road network to fit the circle extrapolation model, so that the accuracy of the impact area is difficult to be recognized. While, the method proposed in this paper can avoid the shortcomings of the circle extrapolation method. The hypothesis of the proposed method has no restrict on the level of road network and traffic volume, and is only for the convenience of calculation, so the actual difference is tiny. The contents that required investigation, such as road traffic, are easy to get. In the application, the traffic impact area can be defined by inputting the actual situation of the road network into the TransCAD software and analyzing according to the algorithm proposed in this paper.

(3) Cloud Model Method

The calculation formula of cloud model is complex and many parameters need to be determined. On one hand, it requires a lot of field survey to define a large number of parameters. On the other hand, some parameters cannot be investigated but rely on experience. As a result, to a large extent, this deters the popularization and application of this method. By contrast, most of the parameters of the proposed method do not need to be manually determined or investigated. The main data needed can be easily obtained, for instance traffic volume of key sections, sections capacity, design speed and free flow travel time, etc.

(4) Time-based Approach

Time-based approach almost overcomes the draw backs of subjective experience method, circle extrapolation method and cloud model method, which can be considered as the most practical and operational method at present. However, when considering the travel time impact of construction project, the time-based approach ignores the instability of the actual road network during its operation. That is to say, the method assumes the impact area of construction project under the normal operation of the road network.

In this paper, the travel time reliability model is established based on the time model. At the same time, the unstable factors effects of road network on travel path selection are considered, including the factors of time and travel fluctuation, which is more realistic. Therefore, the impact area that determined through this method can better reflect the actual situation.

7. Conclusions

At present, subjective method to determine the traffic impact area in foreign countries is not suitable for China. Besides, the existing model methods in China have some problems, such as parameter calibration and hypothesis are too idealistic, hence they cannot be widely used. In this paper, the proposed method considers not only the travel time, but also the travel time reliability that have a great impact on the traveler's path choice behavior. As a consequence, this method is more suitable for the actual roads, easier to operate and has important practical significance.

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