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The Operating Efficiency Evaluation of the Highway Network under Accident Conditions

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Abstract

In order to improve the running safety of highway, to minimize traffic delay, and to avoid the secondary traffic accident, it is essential to evaluate the operating efficiency of the highway network under accident conditions. This article selects the time reliability as evaluation index and compares the index value of the highway network under normal, accident conditions and after emergency traffic organizations. Differences are used to perform an analysis on the impact on traffic of the accident, the result of the emergency traffic organization and the recovery degree of the transport. The paper provides some basis for the traffic organization plan optimization of the road network under the accident conditions.

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Keywords: Highway network management; Accident; traffic delay minimization

1. Introduction

Highway system has made a great contribution to ease the traffic pressure with the characteristics of high speed and large capacity. But with the continued growth in traffic, the highway system has become more sensitive. It will become very unstable when there is disturbance, especially when a traffic accident occurs. Therefore, it is necessary to assess the operating efficiency of the highway network under accident conditions.

The operating efficiency assessment of the road network under accident conditions is able to more fully reflect the running condition of the road network under accident conditions and the emergency organizational capacity to

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respond to emergencies, reduce the losses caused by the accident. It provides a theoretical basis for the optimization of management strategies and security facilities before accident, under accident and after accident. Travel time reliability can quantitatively evaluate the operation of the existing road network under traffic congestion, accidents and severe weather, and reflect the changes of traffic state. Therefore, it can be regarded as an effective indicator to measure the operational efficiency of the road network under accident conditions.

2. Travel Time Reliability

Travel time reliability refers to the probability that a vehicle can reach the destination within a predetermined time range from a starting point. Under normal circumstances, it's represented by the probability that the ratio of travel time between arbitrary OD in the recession and the normal state of the road network is less than or equal to a certain threshold. This representation uses the threshold to reflect the relationship between the travel time reliability and service levels. But the analytical relationship between the service level and threshold is not clear, which makes this representation has some limitations. In view of this, the travel time reliability can be delimited as " in certain road grade and conditions, the probability that the travel time in the recession state of the road network is less than or equal to the expected travel time at the requested service." The formula is as follows:

$$r_j(s,t)=\mathrm{P}(T_j \le T_{sg}) \tag{1}$$

In formula: $r_j\left(s,t\right)$ ----- Travel time reliability on the path j between OD pair s and t;

T_{j} ------- Travel time reliability on the path j;

T_{sg} ------- Maximum expected travel time.

In this definition, "a certain road grade and conditions" mainly include two aspects: one is involving sections (specifically referring to the grade of the highway and connected national and provincial roads etc.).Second is the external condition of the road including the normal state, traffic accidents, disasters, etc. The value of T_{sg} is need a large number of measured data to support. In order to preclude the interference of the road length to travel time, average expected travel time statistics of various roads $\overline{\mathrm{T}_{\mathrm{sg}}}$ can be collected as reference.

In the highway network, there are different travel paths between OD pair s and t. But $r_j\left(s,t\right)$ only represents the travel time reliability of one path j. in order to get the total reliability of OD, it can be seen as a parallel system to calculate. The model can be established as following:

$$R\left(s,t\right)=1-\prod_{j=1}^{m}(1-r_j(s,t)) \tag{2}$$

In formula: $\mathrm{R}(\mathrm{s},\mathrm{t})$ ------- The reliability between OD pair s and t;

m ------- The number of valid path between s and t.

The travel time reliability of OD (s, t) can be calculated by the Formula 2. In a certain extent, the model shows the possibility of arriving between a pair of nodes in the road network within a certain time range.

3. The travel time reliability analysis of road network

Under accident conditions, the road network capacity and path selection will change, causing changes of operating efficiency of the road network. In order to properly measure the impact of the accident to the running of road network and improve countermeasures management level responding to accidents, it is necessary to study the travel time reliability of road network under accident conditions (such as traffic accidents, geological disasters, fire and so on).

3.1. Assumptions

- (1) The road network is in the probability user equilibrium state (i.e., the relative equilibrium state of road network when the routes of travelers selected are unpredictable under abnormal events.), all run time possibly selected will distribute within a certain range, and equal to the minimum average of running time between OD pair s and t.
- (2) Travelers have the ability to select travel paths to reduce run-time changes.
- (3) Under accident conditions, the capacity of the road C_a is affected by many random factors. It is a randomly variable value, and its distribution is regarded as uniform distribution. Respectively the upper and lower limits are $\overline{C_a}, \zeta_a * \overline{C_a}$ $(0 \le \zeta_a < 1)$

3.2. Travel time of the section

To determine travel time of the path, we must first study travel time of the section. Here, the BRP function is used to calculate:

$$T_a = t_a \left[1 + \beta \left(\frac{x_a}{C_a} \right)^{\gamma} \right] \tag{3}$$

In formula: T_a --- The travel time on section a;

x_a ------Actual traffic flow on section a;

t_a ---- The average traveling time when there is free flow on section a;

β, γ ---- Model parameters.

Based on condition (3) in the assumption and Formula 3, we assume that the capacity of the section and traffic flow run on it is independent. In this case, the mean and variance of the travel time on the section can be got:

$$E(T_a) = t_a + \beta t_a x_a^{\gamma} \frac{1-\zeta_a^{1-\gamma}}{C_a^{-\gamma}(1-\zeta_a)(1-\gamma)} \tag{4}$$

$$D(T_a) = \beta^2 t_a^2 x_a^{2\gamma} \left\{ \frac{1-\zeta_a^{1-2\gamma}}{C_a^{1-2\gamma}(1-\zeta_a)(1-2\gamma)} - \left[\frac{1-\zeta_a^{1-\gamma}}{C_a^{-\gamma}(1-\zeta_a)(1-\gamma)} \right]^2 \right\} \tag{5}$$

3.3. Travel time of the path

Travel time of the path (T_p) is decided by each section:

$$T_p = \sum T_a \tag{6}$$

The distribution of T_p is regarded as normal distribution: $T_p \sim N\left[E(T_p), \sigma_{T_p}^2\right]$

$$E(T_p) = \sum_a \left[t_a + \beta t_a x_a^{\gamma} \cdot \frac{1-\zeta_a^{1-\gamma}}{C_a^{-\gamma}(1-\zeta_a)(1-\gamma)} \right] \tag{7}$$

$$\sigma_{T_p} = \sqrt{\sum_a \left\{ \beta^2 t_a^2 x_a^{2\gamma} \left\{ \frac{1\text{-}\zeta_a^{1-2\gamma}}{C_a^{-2\gamma}(1-\zeta_a)(1-2\gamma)} - \left[\frac{1-\zeta_a^{1-\gamma}}{C_a^{-\gamma}(1-\zeta_a)(1-\gamma)} \right]^2 \right\} \right\}} \tag{8}$$

The mean $E(T_p)$ and variance of the travel time of the path are used to measure the degree of deviation from the average running time. They are important data for analyzing the running time reliability of road network.

3.4. The travel time reliability of road network under accident conditions

Under accident conditions, the road network is in the probability user equilibrium state. The travel time of the path is always changing and meets the following conditions:

(1) The average travel time t^{rs} on the selected path P is equal to the minimum average running time of all paths between OD pair. The traffic flow on the path P is f_p. All these can be represented as the following formulas:

$$E(\mathrm{T}_p) \geq \mathrm{t}^{rs} \tag{9}$$

$$f_p\left[E(T_p) - t^{rs}\right] = 0, \forall p \in p^{rs} \tag{10}$$

In formula: t^{rs} ----- The average travel time between starting point r and endpoint s;

p^{rs} ---- A collection of all the paths between starting point r and endpoint s.

Assume (1) provides the required basic conditions of selected paths between OD pair s and t.

(2) The travel time of the selected paths should meet:

$$P(\text{-}\varepsilon \cdot t^{rs} \leq T_p - t^{rs} \leq \varepsilon \cdot t^{rs}) \geq \rho \quad \forall p \in p^{rs}, 0 \leq \varepsilon, \rho \leq 1 \tag{11}$$

In formula: ε ----A parameter used to describe the deviation of travel time from the minimum average time;

ρ ---- An indicator used to measure the distribution range of travel time between OD pair s and t under accident.

The assumption (2) limits the distribution range of the running time of the selected path.
In the case of satisfying the assumption (1), the form of Formula 11 is changed as follows:

$$P(\frac{-\varepsilon \cdot E(T_p)}{\sigma_{T_p}} \le \frac{T_p - E(T_p)}{\sigma_{T_p}} \le \frac{\varepsilon \cdot E(T_p)}{\sigma_{T_p}}) \ge \rho \tag{12}$$

If: $S_{T_p} = \frac{T_p - E(T_p)}{\sigma_{T_p}}$, $C_{T_p} = \frac{\sigma_{T_p}}{E(T_p)}$

Because $S_{T_p} \sim N(1,0)$, in the standard normal distribution, $\phi(-\eta) = 1 - \phi(\eta)$ is set up. Formula 12 is changed as follows：

$$1 - p(S_{T_p} \le \frac{-\varepsilon}{C_{T_p}}) - p(S_{T_p} \ge \frac{\varepsilon}{C_{T_p}}) \ge \rho \tag{13}$$

Scilicet: $$1\text{-}2\ (1\text{-}\phi\ (\frac{\varepsilon}{C_{T_p}})) \ge \rho \Rightarrow C_{T_p} \le \frac{\varepsilon}{\phi^{-1}(\frac{1+\rho}{2})} = \lambda$$

$$\Rightarrow C_{T_p} - \lambda \le 0 \tag{14}$$

Formula 7, 8 is brought into Formula 19,the following formula was got：

$$\frac{\sqrt{\sum_a \left\{ \beta^2 t_a^2 x_a^{2\gamma} \left\{ \frac{1-\zeta_a^{1-2\gamma}}{C_a^{-2\gamma}(1-\zeta_a)(1-2\gamma)} - \left[\frac{1-\zeta_a^{1-\gamma}}{C_a^{-\gamma}(1-\zeta_a)(1-\gamma)} \right]^2 \right\} \right\}}}{\sum_a \left[t_a + \beta t_a x_a^{\gamma} \cdot \frac{1-\zeta_a^{1-\gamma}}{C_a^{-\gamma}(1-\zeta_a)(1-\gamma)} \right]} \le \lambda \tag{15}$$

4. The assessment of operating efficiency of road network

In this paper, the travel time reliability is used to evaluate the operational efficiency of the road network under accident conditions. Because the state of road network is different, the travel time reliability is not the same. Therefore, the travel time reliability under different road network should be calculated quantitatively firstly. As Figure 1, the index value of three states--- R_1 、 R_2 、 R_3 are calculated, including normal state (before the accident, before t_1 , scilicet）, under accident（ $t_1 \sim t_2$ ）, after an accident (after the implementation of emergency traffic organization, ($t_2 \sim t_3$)).

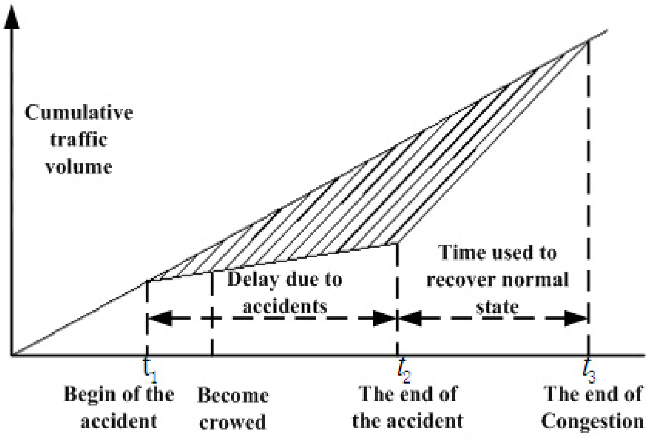

Fig.1. Diagram of different state of road network

Under normal conditions, the travel time reliability of road network can be obtained with Formula 1 and Formula 2. Under accident conditions, the various factors are always changing dynamically, so the reliability of road network changed with it. In this case, the travel time reliability of the road network running time is the same as that of the normal state in the calculation of the index value. Only the path selection has changed. Under Accident conditions, the path selection needs to meet Formula 9, Formula 10 and Formula 15, which makes the path in Formula 2 change in the process of the index value calculation and eventually causes R_2 to change. After the accident, by analyzing the impact and scope of the accident the relevant departments carry on emergency traffic organization, which makes the road network status gradually come back to another norm state from transient abnormal state. In this case, the index value (the travel time reliability (R_3) of the operating efficiency of the road network can also be obtained by the Formula 1 and Formula 2.

After the travel time reliability calculation of road network in the three states including before an accident (R_1), under an accident (R_2), after an accident (R_3), the index value is compared. The operating efficiency of road network is expressed with difference. The specific process is shown in Figure 2.

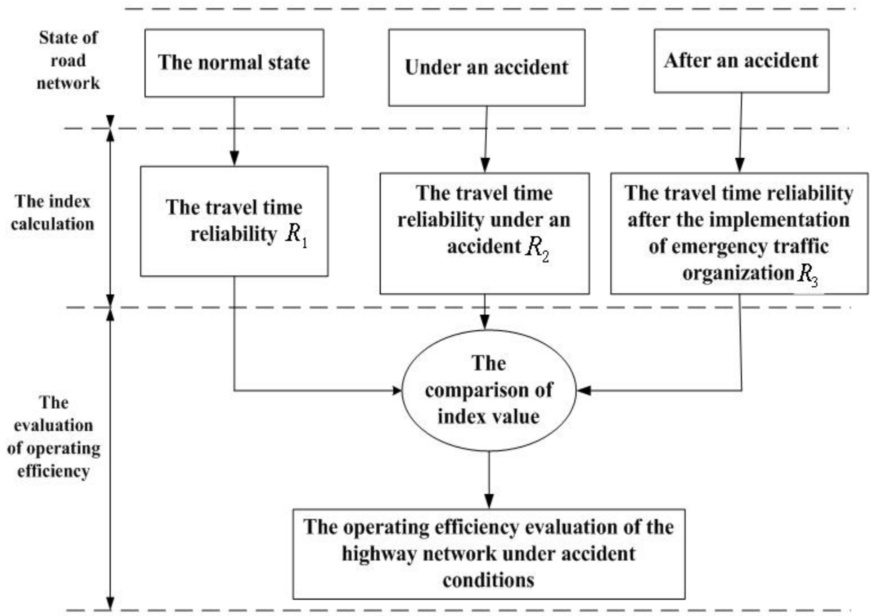

Fig.2. Assessment flowchart of operating efficiency of road network

The difference between the indexes value after the accident and under the accident—— $|R_3 - R_2|$ is regarded as quantitative index to measure the effect of the emergency traffic organization. $|R_3 - R_1|$—— the difference between the index value after the accident and before the accident is used to evaluate the recovery of after the implementation of the emergency traffic organization. The difference between the index value under the accident and before the accident $|R_2 - R_1|$ can reflect the degree of impact due to the accident. Provided by the definition of travel time reliability, some conclusion can be drawn as follows: the greater the value R_2, the higher the operation efficiency of the road network is. In addition, if the value $|R_2 - R_1|$ is substantially the same, the larger the value $|R_3 - R_2|$ is and the smaller the value $|R_3 - R_1|$ is, the better the effect of emergency traffic organization is and the higher the operation efficiency of the highway network is.

5. Summary

In this article, the change (mean, variance) of travel time of road network under accident conditions is studied. Based on this, the operational efficiency of the highway network is analyzed quantitatively. All these provide theory basis for studying traffic running state and the implementation of emergency traffic organization. However, the lack of considering in travelers psychological behavior and road network structure is the weak point of this article, which needs further study.

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