The Road Network Reliability: a Method Based on Risk

Shoufeng Ma
Visiting Scholar
Group for Transportation Planning and Transport Telematics
Institute for Land and Sea Transport Systems
Department of Transport System and Mechanical Engineering
Technical University Berlin
Salzufer 17-19
D-10587 Berlin, Germany
Tel.: +49-30-314-79821
Fax.: +49-30-314-26269
Shoufeng.ma@vsp.tu-berlin.de
Professor
Institute of Systems Engineering
Tianjin University
Tianjin 300072, China
Tel.: +86-22-27404446
Fax.: +86-22-27401810
sfma@tju.edu.cn

Kai Nagel
Professor
Group for Transportation Planning and Transport Telematics
Institute for Land and Sea Transport Systems
Department of Transport System and Mechanical Engineering
Technical University Berlin
Salzufer 17-19
D-10587 Berlin, Germany
Tel.: +49-30-314-23308
Fax.: +49-30-314-26269
nagel@vsp.tu-berlin.de

4766 words and 6 figures

Submission Date: July 25,2005

Abstract.

Based on the former research, this paper studies the reliability on road network from a different perspective---risk, which is called RBR (Reliability Based on Risk). Firstly the definition and its explanation of RBR concept are stated in this paper. Then the relation and connection between RBR and other reliability definitions is analyzed. By applying the kernel estimation method, an estimation method for the distribution function of traveling cost on a link based on the historical data is proposed. With such a function, the RBR of a link can be calculated. The error analysis and back testing methods are also given in this paper. This process is illustrated and verified by an example using the detective dada on a link in one of Chinese highways. Further more, the concepts of other RBR forms, such as route RBR, O-D pair RBR and network RBR, are proposed and possible calculation methods based on link RBR are suggested. At last, a conclusion and the applications of RBR in the traffic planning and management are put forward.

INTRODUCTION

Reliability is widely used in the engineering fields, which means the probability to accomplish one job under certain conditions. In the recent years reliability was introduced into road network. Although the research in this field is still in the original stage, there are some theories that have been proposed and adopted.

Yasunori Iida (*1*) regarded that road network reliability contains connectivity reliability and travel time reliability. Connectivity reliability means the probability that there exists at least one feasible link between an OD-pair at certain time. The travel time reliability is the probability for a vehicle to arrive at its destination within a given time period under current environment. Then it was also suggested that road network reliability should contain capacity reliability (*2*), which means the probability of road network to keep itself on an certain service level with certain traffic demand, namely it is the probability that the traffic demand does not surpass the road capacity. Lam and Zhang (*3*) mentioned that road network reliability should take into account the potential traffic demand, such as the potential traffic demand caused by rush hour or the paroxysmal traffic events. They pointed out that if this kind of the potential traffic demand were not considered, the road network reliability would have been wrongly estimated. Also Bell and Schmocker (*4*) suggested another kind of reliability, the encounter reliability, which means the probability for a traveler not to encounter any link with declined capacity in his minimal cost path. Travelers always try to avoid such links with a high probability, so it may be helpful to route guidance information and the travelers' feedback to the guidance information. If travelers know the encounter probability and act according to it, the more travelers avoid the risk, the closer encounter reliability is to connectivity reliability. Bell (*5*) proposed another method, which applied the game theory to model the behaviors of the travelers and their hypothetic evil entity, while they are the two sides of a game. In this game, travelers try to choose the links with the minimal expected travel cost, while the evil entity try to maximize the expected travel cost by decline the capacity of key links in road network, the Nash equilibrium point for the game means the probability of the worst situation, which can be used to calculation road network reliability.

Although the researches mentioned above are widely received, there are still some problems and shortness in this filed of study.

1. These studies are based on too much indices which are dependent each other. The connectivity reliability, capacity reliability and travel time reliability have very close relationship: the declination of capacity will cause certain links not feasible, and then it will cause the increase of travel time. So they could be regarded as the results observed from different views, rather than different definitions. Perhaps we need a unitive index to describe the reliability.
2. Few of the previous researches have constructed a whole system including the definition, computation and verification of the reliability. Firstly, most of these researches just give a probability value of without the confident interval of the reliability. In real, the reliability of network always change within a range, it's impossible for it to keep as a constant. Secondly, the previous research just point out how to calculate reliability but don't mention how to verify the value. Then, network state is time varying, the reliability also changes with time; the studies cannot analyze the relationship between reliability and time. So certain value of road network reliability is just corresponding with certain period. Lastly, the calculation methods given by such research are used under normal conditions, nothing has been suggested how to analyze reliability when the road network is abnormal such as rush hour, or special event.
3. Few feasible or practical methods have explicitly been mentioned to calculate the probability. Most of them are notional or general. For example, the calculation formula of travel time reliability is $\mathrm{P}\{T \leq T'\} = \alpha$. One must know the value of T' in order to calculate its reliability, T' is the key to the value, but it is hard to choose a proper T'; this is also the problem of capacity reliability, one must choose a maximum capacity to calculate.

Upon these, a different definition of network reliability based on risk evaluation is tried to propose in this paper and the methods to calculate and verify the network risk are also suggested. After this section where the analysis of the previous research and the existing problems are given, the next section will propose a new definition of link reliability-- the reliability based on risk (RBR). The calculation method for link RBR, and its error analysis and back testing methods will be given in the third section. In the following section, a computational example base on real data is given out to illustrate the process by the authors. Then the other concept forms of BRB and their estimation methods are stated. At last, the conclusion of the paper and some possible applications of RBR in traffic planning and management and its prospect are suggested.

THE RELIABILITY BASED ON RISK

For a given probability level $\alpha(\alpha < 1)$, the Reliability Based on Risk (RBR) is the possible maximum traveling cost *t* under such a probability, which is shown as the following Equation (1), where *f(t)* is the probability density function of the variable *t*, μ is its expectation and $P\{t \le RBR\}$ is the probability for $t \le RBR$.

$$P\{t \le RBR\} = 1 - \alpha \tag{1}$$

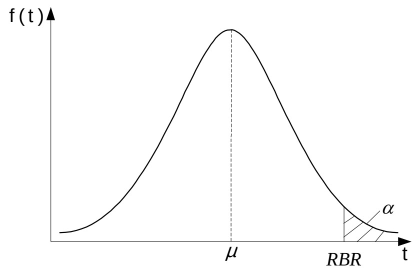

FIGURE 1 Illustration Of RBR

From this definition, it is clear that we use RBR, a value of the cost, instead of the probability, which depicts directly the maximum travel cost (simply, travel time) for a traveler to pass through a certain link (or route) under certain probability, which is just what the traveler needs mostly. When a traveler starts, the most he wants to know is that how much it will take him to pass through on the link or route, and which link or route he should choose. With such RBR, he can get valuable information for his decision-making.

Risk is a possibility that a bad situation will happen, which is always measured by a probability method. RBR is the fractile what makes the accumulative probability of a link or a route cost just equals to 1-*α*. In other word, the travelers still have to face and undertake the risk with probability level *α* that the cost perhaps exceeds the RBR. So it is called as the reliability based on risk. RBR contains the basic risk and the extra risk. The basic one means the travel cost under normal condition (namely without jam on the road network), this is the invariable risk. The extra risk means the other risk except the basic risk travelers take; this can be avoided by choosing right route. Also the extra risk is what we should pay more attention to. When people know how to control this risk, the road network reliability could greatly increase.

What is the connection between RBR and other definitions of the reliability? For travel time reliability, if one knows the probability distribution of the travel time on a link, the travel time reliability is the probability of travel time which does not surpass a certain given value (fractile), that is the probability corresponding to a fractile; while the RBR is the maximum travel cost under a certain given probability, that is the fractile corresponding to certain probability. So previous researches and RBR are the two sides of one object. But for network users, it's much more easy for them to assume and give out a probability than to estimate a traveling time. For connectivity reliability, if RBR surpasses normal value a lot under a fixed risk level, this means the connectivity between OD pair is bad, and the connectivity reliability is low. In all, RBR could be used to analyze road network reliability.

RBR is dependent on time and space. For time, RBR could be regarded as the evaluation of the road network reliability in past and also the prediction and the estimation of the future road network reliability. For space, a router between an OD pair is composed of many links, a road network is also comprised of links, RBR can have some different forms in space, link RBR, route RBR, OD RBR and network RBR. Space and time influence the value of reliability, so RBR is an estimation of road network reliability for a certain location in certain time period.

LINK RBR

The Estimation of Link RBR

Although there could be several different forms of RBR, such as link, path, OD and network, as mentioned before, the link RBR is the foundation of the others what can be derived from the link RBR or calculated by the similar method as that of the link RBR. To find the specific link RBR for the given risk level, the key is the distribution of the traveling cost of the link. From the definition of RBR, if the distribution density of travel cost *t*, $f(t)$, is known, the RBR can be obtained by finding a fractile *p** corresponding to a given risk level (confidence degree) *c* so that the following equation is satisfied:

$$c = \int_{\infty}^{P^*} f(p)dp \tag{2}$$

Here, *p** is the RBR we want.

For example, if t obeys the normal distribution, $t \sim N(\mu, \sigma^2)$, z_α is the fractile for the confidence degree $1-\alpha$, then $RBR = \mu + z_\alpha \cdot \sigma$

But mostly, the probability distribution of travel cost is not normal distribution or it's unknown at all, so other methods should be found to estimate RBR. Here the Gaussian Kernel Estimation, an estimation method based on historical data, can be applied to do this, which can give a smooth estimation of probability density (*6*). The kernel estimation is a kind of non-parameter fitting method, which uses a kernel function $K(x)$ (usually the Gaussian Normal Distribution Curve, as we do in next section of this paper) to give out the estimation of the probability density function of a random variable *x* with its sample series $X = [X_1, X_2 \ldots, X_n]$:

$$\hat{f}(x) = \frac{1}{n}\sum_{i=1}^{n} K\left(\frac{x - X_i}{h}\right) \tag{3}$$

Here, h is a smooth coefficient, the bigger the value of h, the more smooth the estimated curve.

When the method is applied to obtain a link RBR, the first step is to estimate the probability density function (pdf) and cumulated probability density function (cdf) of the traveling cost. Suppose we have historical sample data of travel cost $T_1, T_2, \ldots, T_n$, for every sample data point in the series, this method supposes it follows normal distribution. Use these data as the center of the probability density function and $0.9\sigma n^{-0.2}$ as the bandwidth (smooth coefficient) to smooth data to make a continuous curve, where σ is the standard deviation of the sample data, *n* is the sample size. As the sample size increases, the influence of each sample data becomes smaller, so the choice of the kernels has nothing to do with the result.

Let $f(t)$ be the probability density function of the cost, $F(t)$ is its accumulated probability density function, then the kernel estimation of $f(t)$ and $F(t)$ are:

$$\hat{f}(t) = \frac{1}{n(0.9\sigma n^{-0.2})}\sum_{i=1}^{n} \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{t-T_i}{0.9\sigma n^{-0.2}}\right)} \tag{4}$$

$$\hat{F}(t) = \int_{-\infty}^{t} \hat{f}(x)dx \tag{5}$$

Practically, the discrete form of Equation (5) is usually used by inserting equidistantly *n* data points $t_1, t_2, \ldots, t_n$ into available the cost interval to divide it into tiny intervals, so the probability that the traveling cost is less than t_m is:

$$\hat{F}(t_m) = \sum_{i=1}^{m} \hat{f}(t_i)\Delta t_i \tag{6}$$

$$\Delta t_i = t_i - t_{i-1} \tag{7}$$

The second step is the searching of the estimated value of the fractile. Supposed the fractile corresponding to the given risk level is the *j-th* sample in the ordered statistical sequence. For example, for a sample series with 200 sample data, the number of the sample data corresponding to 95% risk level is 10. Man must try to find the estimated probability density function for the 10th data in the series.

The probability density function of the traveling cost obtained in the last step is used to estimate the probability density function of the *j-th* sample, its mean and variance. Let *t* be the *j-th* random variable to be estimated, its probability density function is $g_j(t)$, cumulated probability function is $G_j(t)$. Then the probability of the value less than or equal to *t* is:

$$\frac{n!}{j!(n-j)!} F(t)^j (1 - F(t))^{n-j} \tag{8}$$

Then the cumulated probability function is:

$$G_j(t) = \sum_{k=j}^{n} \frac{n!}{k!(n-k)!} F(t)^k (1 - F(t))^{n-k} \tag{9}$$

Then the differential of $G_j(t)$ can be gotten, which is namely the probability density function of *t*:

$$g_j(t) = \frac{n!}{j!(n-j)!} f(t)F(t)^{j-1}(1-F(t))^{n-j} \tag{10}$$

The last step is to calculate the mean and standard variance of *t*, which is the estimation of RBR. Applying the square estimation of the probability density function we can get its integral (the estimation of RBR) and variance (or the estimation of standard error):

$$RBR = E(t) = \int_{-\infty}^{+\infty} t g_j(t)dt \tag{11}$$

$$Var(RBR) = Var(t) = \int_{-\infty}^{+\infty} t^2 g_j(t)dt - E^2(t) \tag{12}$$

The Error Analysis of Estimated RBR: Confidence Interval

RBR got in the last section is just an estimation of real value, which is influenced by sample data. When sample size $n \to \infty$ the estimation value will converge to its real value. But indeed the sample size cannot be too big, so there must exist error for the estimation. Therefore, rather than to know about the estimated value of a RBR, man must know the preciseness of the estimation, which is also a possible range that the RBR may vary.

To evaluation the preciseness of RBR estimation, a confidence interval could be build (*7*). The construction of the interval is quite easy if the traveling time distribution follows a normal distribution as discussed before, that is $RBR = \mu + z_\alpha \cdot \sigma$, z_α is the fractile corresponding to confidence degree α, σ is the standard error of travel cost. But the problem is that the factual σ is unknown, so man has to use the estimation of σ to analyze the estimation error of *RBR*.

Let *n* be the size of the sample, then variable $(n-1)\hat{\sigma}^2/\sigma^2$ submits to a x^2-distribution with a freedom degree of *n*-1. Here $\hat{\sigma}^2$ is the variance of the sample data, which can be seen as the estimation of σ^2, the variance of the traveling cost. So the confidence interval of σ^2 for 95% confident level is:

$$(n-1)\hat{\sigma}^2 / x_{0.975}^2 < \sigma^2 < (n-1)\hat{\sigma}^2 / x_{0.025}^2 \tag{13}$$

where, $\chi_{0.025}^2$ is the 2.5%-fractile of the χ^2-distribution, $\chi_{0.975}^2$ is the 97.5%-fractile of the χ^2-distribution. Then the confidence interval of the estimated *RBR* is:

$$\mu + z_\alpha \hat{\sigma}\sqrt{(n-1)/x_{0.975}^2} < RBR = \mu + z_\alpha \cdot \sigma < \mu + z_\alpha \hat{\sigma}\sqrt{(n-1)/x_{0.025}^2} \tag{14}$$

The Back Testing of RBR

In practice, due to the influence of many factors, the forecast reliability may be not feasible. To understand the RBR value and to improve RBR modal, the availability and the exactness of the RBR estimation should be verified and evaluated with the real data, which is the accuracy test of the *RBR*. The tests compare the estimation results of the RBR and the real values to appraise the availability of RBR modal. Because it is executed after the practical running, so it is called back testing.

Suppose the confidence degree for RBR is α, the sample size is *n*, the actual number of travel cost bigger than *RBR* is *m*, then the failure frequency for the estimation is $P\{m/n\}$. The assumption is $p = p^*$, here p^* is the desired failure probability, normally $p^* = 1-\alpha$. So if the failure frequency *p* is markedly different from p^*, the RBR modal is available.

Kupiec proposed a testing method (*8*), where a statistical variable is calculated as:

$$LR = -2\ln\left[(1-p^*)^{n-m} p^{*m}\right] + 2\ln\left[(1-m/n)^{n-m}(m/n)^m\right] \tag{15}$$

Here *LR* follows the x^2-distribution with a freedom degree of 1, which can be used to judge the validity of the estimation.

A COMPUTATON EXAMPLE FOR LINK RBR

Data and Method

Based on the observed volume data from a link of a highway in a Chinese City, Tianjin, an example to illustrate the computation process of link RBR is provided in this section.

Because of the lack of the actual traveling time data, the traveling cost formula based on the volume and capacity of a link (*9*), shown in Equation (16), is used to compute the cost.

$$V_Q = VOT \cdot T_0 \left[1 + \alpha \left(\frac{Q}{Q_{\max}} \right)^{\eta} \right] \tag{16}$$

Here, Q is the real volume of a link, $Q_{\max}$ is the link capacity, V_Q is the traveling cost when the volume on the link is Q, T_0 is the traveling time under zero-flow, *VOT* is the value of unit time, α and η are parameters.

The selected link is about 40.15km long, $Q_{\max}$ is 6000 Veh/h, T_0 is 0.5h, and we choose $\alpha = 0.15$, $\eta = 4$ as the suggestion of TRB, so the formula for this link is:

$$V_Q = 297 \times \left[1 + 0.15 * \left(\frac{Q}{6000} \right)^{4} \right] \tag{17}$$

The volume is computed every 5 minute based on the average data collected by detectors on the link. The volume series is consisted by 100 data, so that 100 traveling cost data in past 500 minute can be obtained through Equation (17), whose frequence distribution for the different traveling cost is shown in Figure 2. The mean value of the cost samples is 308.24 and their standard error is 13.89.

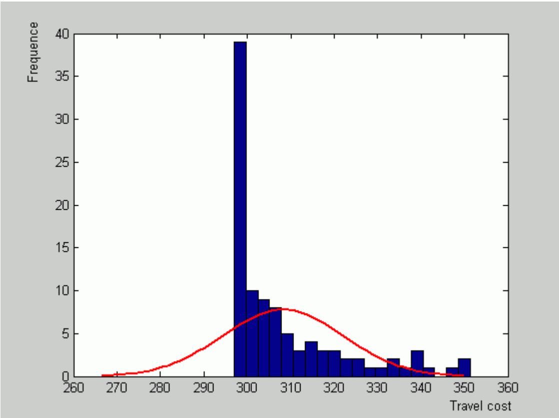

FIGURE 2 Frequence Distribution Of The Traveling Cost

The Estimation of the Probability Function of Traveling Cost

Applying the Gauss function as Equation(3), the estimation of the probability density function for *V* can be gotten, shown as Equation(18) and Figure 3, while the bandwidth is equal to $0.9 \times 13.89 \times 100^{-0.2}$ □4.98

$$f(v) = \frac{1}{100} \sum_{k=1}^{100} \frac{1}{4.98\sqrt{2\pi}} e^{-0.5\left(\frac{v-V_k}{4.98}\right)^2} \tag{18}$$

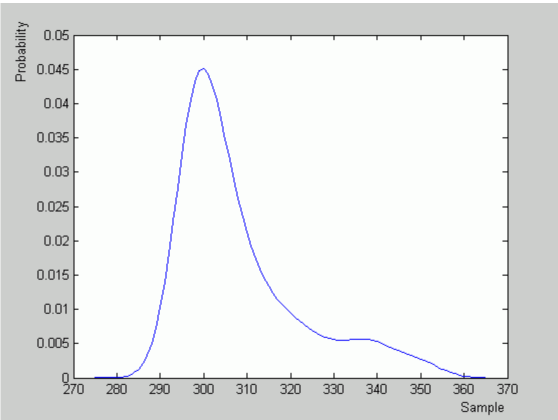

FIGURE 3 The Estimation Of The Probability Density Function

In order to get the accumulation probability function of the cost, the available cost interval [280,360] is divided into 500 tiny equal intervals by inserting equidistantly 499 points between 280 and 360, the *i-th* point in the 500-data series is expressed as v_i (i=1, 2,, 500), the length of every interval is 0.15, which is expressed by *step*. So the estimation of accumulation probability function for v_i is:

$$F(v_i) = \sum_{m=1}^{i} f(v_m) \cdot step \tag{19}$$

The Estimated RBR

For a 500-point series, the fractile for 95% risk level is 25. The probability density function of the 25th data point in the series, $g_{25}(v)$, can be obtained by Equation (10). Then the Gauss-Hermit integral method is used to calculate the expectation and variance of the 95%-fractile and the estimation results are

$$RBR = E(v) = \int_{-\infty}^{\infty} v g_{25}(v) dv = 332.14 \tag{20}$$

$$Var(RBR) = Var(v) = \int_{-\infty}^{\infty} v^2 g_{25}(v) dv - E(v)^2 = 5.44 \tag{21}$$

The results state that with 0.95-possibility the link cost is less than 332.14. In another words, the risk for a person who will take on the traveling cost higher than 332.14 is 5%.

The Confidence Interval of Estimated RBR

As we know, $\chi^2_{0.975}$ equals 128.42, $\chi^2_{0.025}$ equals 73.36 and $z_{0.95}$ is 1.65, the confidential interval under 95% confidential degree is calculated by Equation (14) as following:

$$308.24 + 1.65 * 13.89 * \sqrt{(100-1)/128.42} < RBR_R < 308.24 + 1.65 * 13.89 * \sqrt{(100-1)/73.36} \tag{22}$$

The confidential interval of the estimation is [328.36,334.24], which means it's normal when the RBR changes within this range.

OTHER RBR FORMS

Route RBR

There are still other possible forms of RBR for a space structure except the link RBR, which are also important for the network availability. A route is comprised of a link series, the route RBR can be defined as similar as the link RBR. The calculation or the estimation for a route RBR can be completed by two ways. One is to estimate the traveling cost of the whole route as the same as the process of link RBR by using the cost or traveling time data of the whole route; the other is to view the route as a serial combined structure and to use the method for such a structure given in the following section (for OD RBR) to estimate the value of route RBR.

O-D RBR

For a traveler, it's important to know the possible time to his destination from his original or current location. The RBR of an OD-pair can give the information about the risk he will undertake. Normally, there are several possible routes between an OD-pair, and perhaps some links are shared among these different routes. The O-D RBR is dependent on the traveling cost on all related routes. The calculation of O-D RBR should be started from the analysis of the structure of routes between the OD. From the view of graph theory, the basic components to connect an OD are the links, there exist two forms of the link combination: serial connection and parallel connection. For example as shown as figure 4, three routes exist between O and D: 1-2-5, 1-3-5 and 1-4-5. The combination between 2,3 and 4 is the parallel and the connection between these three links and link 1 or link 5 is serial. From such two kinds of connection, the O-D RBR can be derived.

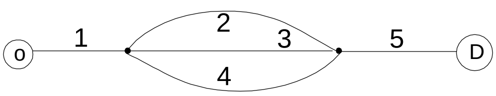

FIGURE 4 The Links Between An O-D Pair

The RBR for Serial Combination Structure

The simplest serial structure is comprised just like the following figure:

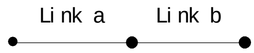

FIGURE 5 A Serial Structure

Suppose the travel costs of Link *a* and Link *b* can be gotten, then we could get their RBR of such structure. According to the definition of RBR:

$$\mathrm{P}\{t_a \le RBR_a\} = 1-\alpha \tag{23}$$

$$\mathrm{P}\{t_b \le RBR_b\} = 1-\alpha \tag{24}$$

Here, t_a and t_b are respectively the travel cost of link *a* and *b*, RBR_a and RBR_b are their *RBR*.
For the serial structure,

$$\mathrm{P}\{t \le RBR\} = \mathrm{P}\{t_1 + t_2 \le RBR\} = F(RBR) = 1-\alpha$$

F is union probability distribution of traveling cost for link *a* and link *b;* $f_a(x)$ and $f_b(x)$ are respectively the probability density function of traveling cost on link *a* and *b*, also the cost of *a* and *b* are independent, then:

$$F(z) = \mathrm{P}\{t \le z\} = \mathrm{P}\{t_1 + t_2 \le z\} = \iint_{t_1+t_2 \le z} \mathrm{f(x,y)dxdy}$$

$$= \int_{-\infty}^{z}[\int_{-\infty}^{\infty} f(x, v-x)dx]dv = \int_{-\infty}^{z}[\int_{-\infty}^{\infty} f_a(x) f_b(z-x)dx]dv \tag{25}$$

Then the RBR for level α is the *z*, which makes $F(z) = 1-\alpha$. The route *RBR* in last section can also be obtained by this kind of serial structure.

The RBR for Parallel Combination Structure

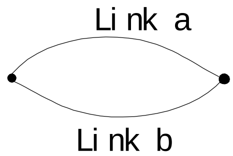

FIGURE 6 A Parallel Structure Of Two Links

What is shown in figure 6 is a typical parallel structure consisted of two links. Also suppose both the distribution of travel cost on link *a* and *b* are known, as formula (23) and (24). From the definition, the RBR of such a structure is:

$$\mathrm{P}\{t \le RBR\} = \mathrm{P}\{\max(t_a, t_b) \le RBR\} = \mathrm{F}(RBR) = 1-\alpha \tag{26}$$

F is the union probability distribution of a and b, if the cost of *a* and *b* are independent, then:

$$F(z) = \mathrm{P}\{t \le z\} = \mathrm{P}\{\max(t_1, t_2) \le \mathrm{z}\} = P\{t_1 \le z, t_2 \le z\}$$

$$= P\{t_1 \le z\}P\{t_2 \le z\} = F_a(z)F_b(z) \tag{27}$$

Then the RBR for the structure is the *z*, which can satisfy $\mathrm{F}(z) = 1-\alpha$.

For an O-D pair, it can be seen as a compound of many serial and parallel structures of links, and its RBR can be calculated by decomposing the O-D structure into some basic serial and parallel structures. But because the all previous is based on the assumption that the probability density function of the travel cost of the links are independent, which is not satisfied at most time in fact, so this method is just approximate.

Network RBR

If the previous method is till used to calculate network RBR, we will get the travel cost of the whole road network, but it is difficult to calculate and has little practical meaning for travelers and mangers. So here we will use the network RBR to express a whole risk state of a network by defining it as the average the traffic cost on every kilometer of the road network under the same risk level.

$$RBR_{net} = \frac{\sum_{i=1}^{n} RBR_i / l_i}{n} \tag{28}$$

Here, RBR_i is the *RBR* value of link *i*, l_i is the length of road link *i*, *n* is the number of links in the network.

To avoid the difference among the links, we could further define network *RBR* as the maximum lost travel cost to normal travel cost. Subtracting the normal travel cost or average cost from the actual cost will avoid the influence of different traffic condition (such as traffic capacity).

$$RBR_{net} = \frac{\sum_{i=1}^{n} (RBR_i - T_i) / l_i}{n} \qquad (29)$$

T_i is the normal travel cost of link *i*.

Now matter which of above definitions is to be used, it just illustrates an overall state of the network. From the practical point, network RBR has more concepts meaning and less the applying meaning than the other kinds of RBR. But its limit applications are to compare the efficiency of different network or states of the same network in different periods.

THE CHOICE OF SAMPLE DATA

Road network reliability could be applied to evaluate the past situations of a road network and also to forecast the future condition. No matter which kind of application, the methods are the same, and the difference is the choice of sample data.

To evaluate the past condition, for example to analyze road network reliability at $[t, t+\Delta t]$ we should collect sample data of travel cost of the network during this period, use the kernel estimation method to calculate its *RBR*.

If we want to forecast the future reliability of road network, there is no future data so we have to use historical data. Generally, the traffic flow for the intervals Δt with $\Delta t <$15 min is very similar, namely the fluctuation of traffic flow in Δt min ago is very possible to happen again. So we can use historical data to predict future condition, which is called historical estimation. To calculate RBR of next Δt ($\Delta t <$15 min) , we could use historical data of Δt ($\Delta t <$15 min) ago.

But for Δt (Δt >15 min), we perhaps cannot use the historical data Δt ago because they have little resemblance. But according to conclusions from many research, the traffic conditions in the same period of everyday has much resemblance, for example the rush hour of every workday happens almost at the same time. So if we calculate RBR for Δt (Δt >15 min), we can first choose some days with similar traffic condition and use the historical data of those days.

CONCLUSIONS AND OUTLOOK

Different from the previous researches, this paper tried to analyze road network reliability from the point of risk, and to give a different kind of calculation methods. From above we can see *RBR* has the following characteristics. Firstly, it uses a unique index to measure road network reliability. Connectivity reliability, travel time reliability and capacity reliability are closely correlative; they can all be contained by RBR. *RBR* is the possible travel cost, including travel time, so it contains travel time reliability; if the *RBR* of one link is much greater than normal value then its capacity reliability is low; when the *RBR* of certain link converges to infinite its connectivity is low. Then, RBR focuses on solving some calculation the problems with network reliability. The previous researches need certain value to calculate, such as travel time reliability need T', while RBR doesn't have such problems; it only needs the confidential degree to be given. Also it has its calculation methods based on historical data and statistic estimation method to provide the value of RBR and its confidential interval.

BBR could be applied in Transportation planning and traffic management, such as the link RBR can be used into guidance system, to calculate the best route which is also the most reliable; The long-term RBR can be used into network planning and road design to evaluate the reliability of the designed road or network and make improvement; The network RBR can be used by traffic mangers to know about the whole network condition. RBR could also be used to compare the road network of different cities.

ACKNOWLEDGEMENTS

Chinese State Scholarship Fund supported one of the authors, Shoufeng Ma, to study and work in TU Berlin for one year and conduct part of this work there.

It's a pleasure for one of the authors (Shoufeng Ma) to thank the colleagues in the Group for Transportation Planning and Transport Telematics, TU Berlin for their friendly cooperation, help and the good working environment and condition they provided when Ma worked there.

REFERENCE

1. Yasunori Iida, Basic concepts and future directions of road network reliability analysis, Journal of advanced transportation. Vol.33, No.2□125-134,2000
2. Katja Berdica, An introduction to road vulnerability: what has been done, is done and should be done, Transport Policy. 2002.9□117-127
3. Lam, W.H.K., Zhang, N., 2000. A new concept of travel demand satisfaction reliability for assessing road network performance. Presented at the Matsuyama Workshop on Transport Network Analysis, August 2000
4. Bell, M.G.H., Schmocker, J.D., Estimating the terminal reliability of degradable transport networks, Triennial Symposium on Transportation Analysis (TRISTAN) IV, Azores Islands, Portugal, June, 2001.
5. Michael G H Bell, Measuring network reliability: a game theoretic approach. Journal of advanced transportation. Vol.33, No.2□135-146, 2000
6. Hendricks D. Evaluation value-at-risk using history data. Economy Policy Review, 1996,2: 39~70
7. Lopez J A. Regulatory evaluation of value-at-risk models:[working paper]. Wharton Financial Instituations Center. University of Pennsylvania, 1996.
8. Kupiec P. Techniques for verifying the accuracy of risk measurement models. Journal of derivatives, 1995,3: 73~84
9. Transportation Research Board, National Research Council, Highway Capacity Manual, Washington, D.C. 1995