Crisis Management of Highway Network under Earthquake Environment

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Synopsis

This paper presents the comparative study for improving connectivity reliability between using probability importance (Birnbaum's structural importance) and criticality importance based on the reliability graph theory, *i.e*. connectivity reliability:

It is important to keep highway network highly reliable for both normal and abnormal period. Network reliability can be improved effectively by improving the most important key link on the network. When such important link is once discovered, it enables to improve and maintain network reliability efficiently. For the indicator for discovering the key link, Birnbaum's structural importance has been proposed so far. In series connected network, the least reliable link is chosen as the first priority link that should be improved and this result is rational as the practical and actual case. In parallel connected network, however, the most reliable link is chosen as the candidate link that should be improved, but this result is irrational, because under this decision making principle, the most reliable link would be improved more and more, and the less reliable link would never be improved. This paper presents these characteristics of Birnbaum's structural importance after discussion of the significances of crisis management of transportation systems after disaster. Then this article proposes the Criticality importance as the better indicator and compares the network performances improved by both importance indicators. In addition, this paper addresses the criticality importance can consider the fact that it is more difficult to improve the more reliable links than to improve the less reliable links. After these characteristics of two indicators are discussed using series and parallel network, a numerical examples are demonstrated. In this example, the link reliability is assumed to be a function of link flow. Stepwise improvement of link reliability based on the Birnbaum's structural importance or Criticality importance is executed using link cost method. The reliability between two nodes as the consequence of link reliability improvement is calculated. The network improvements based on Birnbaum's structural importance and Criticality importance are compared. The evaluation indices are node-to-node reliability and total travel time. The result is that the network improvement based on Criticality importance is better than that on Birnbaum's structural importance both in node-to-node reliability and total travel time.

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1. CRISIS MANAGEMENT OF TRANSPORTATION SYSTEMS

Under the earthquake environment, management of the transportation network is necessary to minimize the social confusion. This paper, firstly, addresses the management of transportation system which should be taken soon after a disaster, and then focuses on the importance assessment evaluation that find the important link maintaining or improving the connectivity reliability on the network.

In case of Japan, there is no permanent office of emergency with authority as FEMA (Federal Emergency Management Agency) in USA or OES (Office of Emergency Service) in the state of California. Thus, the temporary emergency office will be set up, and the disaster related organizations and agencies including authorities of transportation belong to the temporary emergency office. Then the temporary emergency office manages all authorities as headquarters.

In addition, many of Japanese transportation systems is operated under critical capacity condition. Stock of reasonable detour route is insufficient. Mass transit is also operated under congested condition, thus there is few room to accept trips as highway detour traffic. Therefore, as the authors had addressed (Wakabayashi and Kameda, 1992), unless a well-prepared transportation systems for disaster is constructed in advance, there would occur a great confusion after the earthquake in Japanese highly civilized cities. Unfortunately, this anxiety became true in the 1995 Kobe Earthquake. However, based on the lessons learned from this earthquake, the desirable transportation system is discussed here.

Basically, the fulfilment of hardware, that is, the earthquake-resistant facilities is important. Retrofit is also important. However, there will be a potential small damage suffered from an earthquake. Thus, the construction and the management operation strategy of the traffic system based on the network theory become important.

The following terms are important for highway network construction and its management in case of disaster.

a) The ex ante measures desirable are as follows:

1) Construction of and maintaining highly reliable highway network.
2) Leeway for cross section of highway and highway network.
3) Estimation of potential detour traffic in case of disaster and imaging and forecasting newly produced transport behaviour.
4) Estimation of where and what degree of potential congestion in the network (if possible, or approximately).
5) Transportation system management (TSM) for existing transportation facilities including traffic regulation, transportation demand management (TDM), and Information provision.
6) Preparation for quick emergency response on initial stage, and quick grasp of whole damage of overall area.
7) Multi / inter-agency coordination (both ex ante and ex post).
8) Co-operation or mutual aid between different authorities (both ex ante and ex post).
9) Continuity between normal period and emergency phase.
10) Flexible operation of the traffic system.
11) Implementation of the disaster training.
12) Implementation of the desk top simulation for consequences of earthquake, and release of lessons learned from the simulation.

b) The ex post measures desirable are as follows:

13) Quick emergency response on initial stage, and quick grasp of whole damage of overall area.
14) Quick implementation of TSM (especially, traffic regulation) and TDM, and information provision.
15) Monitoring of traffic and introduction of fare for traffic violation.
16) Provision of alternative transportation and its information.
17) Multi / inter-agency coordination (both ex ante and ex post).
18) Cooperation or mutual aid between different authorities (both ex ante and ex post).
19) Induction of time and spatial dispersion of person trip and logistics.
20) Utilization of ITS.
21) Utilization of GIS.

Important point is not to implement these individual measures separately, but to implement these measures simultaneously as a package. In other words, establishment of the comprehensive crisis management of transportation system is very important. We learned a lot from the 1989 Loma Prieta Earthquake (San Francisco), the 1994 Northridge Earthquake (Los Angels) and the 1995 Kobe Earthquake (Japan). One of the most important lessons learned from the events in the Kobe Earthquake is the continuity between the normal state and the abnormal state (Wakabayashi, 1996). What were useful in the emergency period were those which had been familiar to, or had been used during normal state. What were prepared especially for an emergency period did not work very well. The crisis management in the traffic system has the same circumstances; the highway network should be constructed redundantly for the normal period, which contributes in the case of traffic accidents, closure for maintenance, snow fall, etc. as the usually anticipated events. Such system contributes for the abnormal period as well.

2. RELIABILITY

It is important to keep highway network highly reliable for both normal and abnormal period. Network reliability can be improved effectively by improving the most important key link on the network. When such important link is once discovered, it enables to improve and maintain network reliability efficiently. This paper presents the comparative study for improving connectivity reliability between using probability importance (Birnbaum's structural importance) and Criticality importance based on the reliability graph theory, *i.e.* connectivity reliability.

The concept of highway reliability began from connectivity reliability, then has been extending to various reliability concepts as stated below. The idea of reliability exists anywhere variations exist. Two types of variations affect reliability (Nicholson and Du, 1997, Nicholson, Schmoecker, Bell and Iida, 2003);
1) variation in the demand for transport services; and
2) variation in the supply of transport services.

Variation in the demand can be extended to variations in users' behaviour in transportation system. Thus further extension of reliability concepts is expected as long as these variations exist. Transportation users desire the stable transportation service, and network service supplier makes an effort that the system provides expected function. Under the stable transportation service, the travel time can be estimated accurately and these systems are well-received by travellers whose value of time is high.

Thus it is important to keep the system highly reliable. There are two ways to maintain system highly reliable.
1) More redundant system is introduced, *i.e.*, new route or new transportation is added to the existing transportation network.
2) To keep some links in network highly reliable. Traffic control and retrofit program are considered as its measure.

This paper focus on the assessment of importance in the connectivity reliability in the highway network. Before addressing the importance, reliability discussed because the importance is based on it.

According to the mathematical definition, reliability is the probability of a device performing its purpose adequately for the period of time intended under the operating conditions encountered (Barow and Proschan, 1965). This concept can be expanded to transport network reliability, and even in the transport network reliability, many concepts and definitions have been proposed. Firstly;
1) Connectivity Reliability (Terminal Reliabililty) was proposed by Iida and Wakabayashi (1989); and;
2) Travel Time Reliability by Asakura and Kashiwadani (1991), and Wakabayashi and Iida (1994),
3) Capacity Reliability by Chen *et al.* (1999),
are proposed. And,
4) Encountered Reliability
is also proposed by Bell and Schmoecker (2002). This idea is similar to the connected reliability (or terminal reliability). Encountered Reliability explains, however, less risk averse traveller with no information may encounter en-route degraded link. If traveller is more risk averse and sufficient information provided, they pointed out that the connected (terminal) reliability and encountered reliability is similar.
Capacity reliability can be extended to
5) Performance Reliability,
reflecting variations both of user demand / behaviour and service provided.
The travel time reliability of 2) can be generalised as
6) Travel Time and Cost Reliability (Schmoecker and Bell, 2002).
7) Flow Decrement Reliability
has been also proposed by Du and Nicholson(1997).
8) Parking Reliability
is proposed by Lam and Tam (2002) as the probability to secure parking space within the given time.
9) Reliability Mode Choice Model
is also proposed by Wakabayashi *et al.* (2001).

As stated above, the idea of transportation reliability has been expanding from connectivity reliability. The concept of importance addressed in this paper is also expected to expand.

3. IMPORTANCE

The concept of importance introduced in this paper, has been proposed long in the system engineering field, but has appeared in only some papers in the transportation field. Importance is defined as the degree of magnitude that improvement in reliability of a link contributes system reliability. Among various reliability as stated above, the importance focused on in this paper is based on the connectivity reliability.

3.1 The Definition of Terminal Reliability and Birnbaum's Structural Importance

The terminal reliability of the highway network is defined as the probability that two given nodes over the network are connected with a certain service level of traffic for a given time period. Similarly, link reliability in the network is defined as the probability that the traffic is in a certain service level for a given time period.

Terminal reliability, R, is given by the minimal path sets expression;

$$R(\mathbf{r}) = \mathrm{E}\left[1-\prod_{s=1}^{p}\left(1-\prod_{a\in Ps} Xa\right)\right], \qquad \text{(Eq.1)}$$

where Ps is the s-th minimal path set, and p is the total number of minimal path set. This calculation method is called Boolean absorption method (Wakabayashi and Iida, 1992).
Xa is a binary indicator variable for link a, as follows:

$$X_a = \begin{cases} 1, & \text{if link } a \text{ provides the certain traffic service level,} \\ 0, & \text{otherwise.} \end{cases} \qquad \text{(Eq.2)}$$

Link reliability, r_a, is

$$r_a = \mathrm{E}[X_a]\,. \qquad \text{(Eq.3)}$$

In this paper, ra, is assumed to be a function of link flow and this function is monotonically decreasing function in terms of link flow.

Consider the problem to improve the terminal reliability given by Eq. (1) efficiently. This is the network improvement problem (NIP). For example, it is the problem to find the strategies to improve or maintain network reliability under a disaster environment. The strategy includes the traffic control on some links and re-construction of partial network.

To improve network reliability efficiently, it is essential to find out the key link whose reliability contributes to the terminal reliability a lot. For this purpose, The Birnbaum's structural importance has been proposed so far. The Birnbaum's structural importance, IPa in Wakabayashi and Iida (1992), is

$$IP_a = \frac{\partial R(\boldsymbol{r})}{\partial r_a}, \qquad \text{(Eq.4)}$$

and

$$0 \le IP_a \le 1\,. \qquad \text{(Eq.5)}$$

Birnbaum's structural importance indicates the impact of link that the increase or decrease in the link reliability affects the increase or decrease in the terminal reliability. When a link has high value of Birnbaum's structural importance, it is very important to maintain the reliability in such links. In addition, if the reliability in such links decreases, decrease in the terminal reliability is very large. Thus, construction of redundant link is also important for such links.

Although Birnbaum's structural importance has potentiality in improving network reliability, it has defects to be stated in the next section. In the next section, the comparative study of Birnbaum's structural importance and criticality importance for improving network reliability.

4. THE DEFECTS OF BIRNBAUM'S STRUCTURAL IMPORTANCE AND CRITICALITY IMPORTANCE

4.1 A Case of Simple Series Network (2 Links Network)

When the network has series construction, *i.e*. 2 links for convenience, the terminal reliability R_{AB} is

$$R_{AB} = r_1 \cdot r_2 , \qquad \text{(Eq.6)}$$

where r_1, r_2 are link reliability for link 1 and 2, respectively. The Birnbaum's structural importances for these two links are,

$$PI_1 = \partial R_{ab} / \partial r_1 \text{, for link 1; and,} \qquad \text{(Eq.7)}$$

$$PI_2 = \partial R_{ab} / \partial r_2 \text{, for link 2.} \qquad \text{(Eq.8)}$$

Thus

$$PI_1 = r_2 , \qquad \text{(Eq.9)}$$

$$PI_2 = r_1 . \qquad \text{(Eq.10)}$$

If $r_1 > r_2$,

$$PI_1 < PI_2 , \qquad \text{(Eq.11)}$$

is hold.

Equation (11) indicates that in case of series typed network, improving the link of the least reliable is most effective for improving terminal reliability. This fact is easily expanded for large series connected network. Thus in series network, the link with the highest value of the Birnbaum's structural importance is the link with the lowest value of link reliability. This result is actually rational for improving, managing and re-constructing network.

4.2 A Case of Simple Parallel Network (2 Links Network)

When the network has parallel construction shown in Fig.1, the terminal reliability R_{AB} is

$$R_{AB} = 1 - (1 - r_1)(1 - r_2) . \qquad \text{(Eq.12)}$$

Thus the Birnbaum's structural importances for link 1 and 2 are obtained as

$$PI_1 = 1 - r_2 , \text{ and;} \qquad \text{(Eq.13)}$$

$$PI_2 = 1 - r_1 . \qquad \text{(Eq.14)}$$

If $r_1 > r_2$,

$$PI_1 > PI_2 \qquad \text{(Eq.15)}$$

is hold. This suggests that the most reliable link is the target link for reliability improvement.

When link reliability depends on the traffic volume, and is a monotonically decreasing function in terms of link flow, improvement in link reliability means restraining traffic flow under some control scheme. Consequently, congested link becomes more congested, and smooth link becomes smoother. As the result, flow pattern becomes by far apart from the equilibrium assignment. This result is actually irrational for improving, managing and re-constructing network and unacceptable by users.

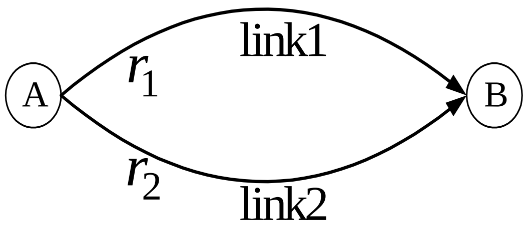

Fig.1 Parallel Network

In addition, it is difficult to improve highly reliable link whereas it is rather easy to improve lower reliable link. The Birnbaum's structural importance does not consider this fact.

Based on these discussions, the criticality importance is proposed. As stated below, Birnbaum's structural importance does not reflect the fact that it is easier to improve less reliable link than higher reliable link. Thus it is convenient to define the importance as the proportion of the marginal change in terminal reliability against the marginal change in link reliability. This is the Criticality Importance. Changing the definition of equation in the reliability engineering, the criticality importance CIa in the highway network is introduced as

$$\begin{aligned} CI_a &= \lim_{\Delta q_a \to 0}\left\{-\frac{\Delta R(\mathbf{r})/R(\mathbf{r})}{\Delta q_a / q_a}\right\} \\ &= -\frac{\partial R(\mathbf{r})}{\partial q_a}\times\frac{q_a}{R(\mathbf{r})} \end{aligned} \qquad \text{(Eq.16)}$$

using the unreliability of link,

$$q_a = 1 - r_a, \qquad \text{(Eq.17)}$$

From Eq.(17),

$$\begin{aligned} CI_a &= \lim_{\Delta q_a \to 0}\left\{-\frac{\Delta R(\mathbf{r})/R(\mathbf{r})}{\Delta q_a / q_a}\right\} \\ &= -\frac{\partial R(\mathbf{r})}{\partial q_a}\times\frac{q_a}{R(\mathbf{r})} \\ &= \frac{\partial R(\mathbf{r})}{\partial r_a}\times\frac{(1-r_a)}{R(\mathbf{r})} \\ &= PI_a \times \frac{(1-r_a)}{R(\mathbf{r})} \end{aligned} \qquad \text{(Eq.18)}$$

is obtained. Thus the relationship between CIa and PIa holds as

$$CI_a = \frac{(1-r_a)}{R} PI_a, \qquad \text{(Eq.19)}$$

Criticality importance considers the fact that it is more difficult to improve the more reliable links than to improve the less reliable links.

5. PROPERTIES OF CRITICALITY IMPORTANCE

5.1 A Case of Simple Series Network (2 Links Network)

Using the same notation as in **4.1**, consider series structure consisting of link 1 and link 2, and link reliability are r_1 and r_2 respectively. From Eqs. (6) and (19), the criticality importances for link 1 and 2 are obtained as ,

$$CI_1 = \frac{1-r_1}{r_1} = \frac{1}{r_1} - 1 \text{, and;} \quad \text{(Eq.20)}$$

$$CI_2 = \frac{1-r_2}{r_2} = \frac{1}{r_2} - 1. \quad \text{(Eq.21)}$$

If $r_1 > r_2$,

$$CI_1 < CI_2 , \quad \text{(Eq.22)}$$

is holds. Thus the criticality importance has the same property as Birnbaum's structural importance.

5.2 A Case of Simple Parallel Network (2 Links Network)

Similarly in **4.2**, from Eqs (12) and (19), the Criticality importances of link 1 and 2 are

$$CI_1 = \frac{1}{R_{AB}} \cdot (1-r_1)(1-r_2) \text{, and;} \quad \text{(Eq.23)}$$

$$CI_2 = \frac{1}{R_{AB}} \cdot (1-r_2)(1-r_1). \quad \text{(Eq.24)}$$

Unlike Birnbaum's structural importance, if $r_1 > r_2$, or $r_1 < r_2$,

$$CI_1 = CI_2 \quad \text{(Eq.25)}$$

is always holds. This suggests it requires other criteria for selecting the improving links.

6. Numerical Example

In the previous chapters, properties of simple series and parallel network structure are clarified. Characteristics of more complex network are, however, unknown. Thus the actual behaviour of network reliability will be demonstrated using computational experiments.

The improvements of terminal reliability are compared between Birnbaum's structural importance and Criticality importance for small network shown in Fig.2. For expediential, assume two same networks.

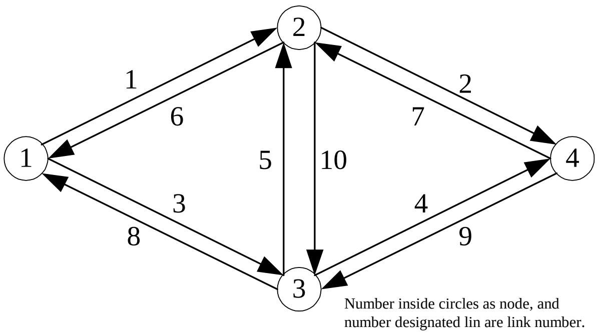

Fig. 2 Test Network(4-nodes, 10-links)

Table 1. Network Improvement by Birnbaum's Structural Importance (Total Flow: 3000Veh.)

		Initial Phase	Phase 1	Phase 2	Phase 3	Phase 4
Traffic Flow (Total 3000Vehicles) ( ): Travel Time (min.)	link 1	1860(6.86)	1560(5.28)	1380(4.58)	1200(4.04)	1080(3.76)
	link 2	1860(6.86)	1860(6.86)	1920(7.25)	1920(7.25)	1920(7.25)
	link 3	1140(6.74)	1440(11.56)	1620(15.60)	1800(20.66)	1920(24.65)
	link 4	1140(6.74)	1140(6.74)	1080(6.03)	1080(6.03)	1080(6.03)
	link 5	0(1.00)	300(1.00)	600(1.01)	780(1.03)	900(1.04)
	link 10	0(1.00)	0(1.00)	60(1.00)	60(1.00)	60(1.00)
Birnbaum's Structural Importance	link 1	0.481926	0.617914	0.656315	0.680140	0.690841
	link 2	0.481926	0.555051	0.554833	0.585226	0.592812
	link 3	0.296886	0.133832	0.055648	0.013198	0.003041
	link 4	0.296886	0.341934	0.416025	0.438814	0.444502
	link 5	0.054380	0.113670	0.002656	0.000438	0.000081
	link 10	0.054380	0.095643	0.14922	0.164307	0.169243
Criticality Importance	link 1	none	link 1	link 1	link 1	link 1
	link 2	0.359540	0.180432	0.072629	0.016956	0.003910
	link 3	0.359540	0.359542	0.361602	0.361602	0.361602
	link 4	0.359540	0.180432	0.072629	0.016923	0.003910
	link 5	0.359540	0.359542	0.361602	0.361602	0.361602
	link 10	0	0	0	0	0
	controled link	0	0	0	0	0
number of congested links	1.0 < DOC < 1.5	4	4	3	3	3
	1.5 < DOC	0	0	1	1	1
	Total	4	4	4	4	4
Terminal Reliability		0.541021	0.623112	0.684700	0.722207	0.731569
Total Travel Time (min.)		1620.232	1841.474	2109.479	2378.480	2652.143

DOC: Degree of congestion

Table 2. Network Improvement by Criticality Importance (Total Flow: 3000Veh., Larger Capacity Link Control)

		Initial Phase	Phase 1	Phase 2	Phase 3	Phase 4
Traffic Flow (Total 3000Vehicles) ( ): Travel Time (min.)	link 1	1860(6.86)	1560(5.28)	1620(5.55)	1380(4.58)	1380(4.5)
	link 2	1860(6.86)	1860(6.86)	1620(5.55)	1560(5.28)	1380(4.58)
	link 3	1140(6.74)	1440(11.56)	1380(10.41)	1620(15.60)	1620(15.60)
	link 4	1140(6.74)	1140(6.74)	1380(10.41)	1440(11.56)	1620(15.60)
	link 5	0(1.00)	300(1.00)	0(1.00)	180(1.00)	0(1.00)
	link 10	0(1.00)	0(1.00)	0(1.00)	0(1.00)	0(1.00)
Birnbaum's Structural Importance	link 1	0.481927	0.617914	0.665763	0.757045	0.833131
	link 2	0.481927	0.555051	0.665763	0.783197	0.833131
	link 3	0.296886	0.133832	0.183526	0.064188	0.070640
	link 4	0.296886	0.341934	0.183526	0.169630	0.070640
	link 5	0.054380	0.011370	0.026265	0.005538	0.006656
	link 10	0.054380	0.095643	0.026265	0.024032	0.006656
Criticality Importance	link 1	0.359542	0.180432	0.224130	0.072629	0.072629
	link 2	0.359542	0.359542	0.224130	0.180432	0.072629
	link 3	0.359542	0.180432	0.224130	0.072629	0.072629
	link 4	0.359542	0.359542	0.224130	0.180432	0.072629
	link 5	0	0	0	0	0
	link 10	0	0	0	0	0
	controled link	none	link 1	link 2	link 1	link 2
number of congested links	1.0 < DOC < 1.5	4	4	4	3	2
	1.5 < DOC	0	0	0	1	2
	Total	4	4	4	4	4
Terminal Reliability		0.541021	0.623112	0.667336	0.789786	0.869163
Total Travel Time (min.)		1620.232	1841.474	2060.500	2306.949	2565.588

DOC: Degree of congestion

1) First, set the same initial condition for both networks.
2) Traffic assignment is carried out under User Equilibrium principle.
3) Then compute link reliability r_a, assuming variation of link flow as

$$r_a = \int_0^1 f(g_a)\,dg_a , \qquad \text{(Eq.26)}$$

where g_a is the degree of congestion on link a such as

$$g_a = v_a / C_a \,, \qquad \text{(Eq.27)}$$

and $f(g_a)$ is the probability density function of g_a.
4) Then compute indices of Birnbaum's structural importance and criticality importance for every link of the networks.
5) The link with the largest value of index is chosen as the control link.
6) Using link cost method, traffic re-assignment is carried out to reduce the traffic volume on the controlled link.
7) After re-assignment, using Eq. (26) and (27), a set of link reliability is updated.
8) Then compute terminal reliability.
9) Iterate steps from 5) to 8).
This procedure is demonstrated for the test network. The evaluation indices are terminal reliability between node A and B, and total travel time. The results are shown in Table 1 and 2.

In both cases, although the congestion is inevitably deteriorates, the case of criticality importance gives lesser results, that is, total travel time increases from 1620 to 2565 by criticality importance whereas from 1620 to 2652 by Birnbaum's structural importance. In addition, using criticality importance leads better improvement in terminal reliability than Birnbaum's structural importance, *i.e*. 0.541 to 0.869 by criticality importance and 0.541 to 0.732 by Birnbaum's structural importance.

6. CONCLUSION

Birnbaum's structural importance has been said to be an effective index for improving reliability. This paper addressed two defects in Birnbaum's structural importance. Then the criticality importance is proposed as the alternative index. After the properties are designated, the comparative numerical investigation was demonstrated.

(1) This paper addresses the significance of crisis management under disaster, and summarized ex ante and ex post measures.
(2) Reliability studies on transportation network were briefly introduced. Then the significance of importance is addressed.
(3) Two defects in Birnbaum's structural importance were discussed for simple series and parallel networks. The two defects are as follows:
  a) Whereas Birnbaum's structural importance is a potential index for improving network reliability, it cannot consider the fact that it is more difficult to improve the more reliable components than to improve the less reliable components.
  b) For parallel network, the more reliable link is chosen as the candidate link to be improved, and consequently the imbalance of congestion expands. Thus, this control principle will not be acceptable.
(4) Criticality importance was proposed to overcome these defects of Birnbaum's structural importance.
(5) For series and parallel structured networks, the characteristics of the Birnbaum's structural importance and the Criticality importance are discussed. Criticality importance has the same characteristic as Birnbaum's structural importance for series connected network. But in parallel connected network, the parallel link is equally chosen unlike Birnbaum's structural importance.
(6) To clarify the characteristics of the two indices, a numerical example for a bridge type network was carried out. The network evaluation indicators are node-to-node reliability and total travel time. As the result, the effect of reliability improvement with the Criticality importance is larger than that with Birnbaum's structural importance for both indicators.

The behaviour of network improvement for more complex network and the application for actual network under earthquake environment are future subjects.

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