AN EVALUATION METHOD OF LINK SIGNIFICANCE OF THE ROAD NETWORK CONSIDERING THE REGIONAL HIERARCHY

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Abstract

This paper aims at developing an evaluation method of road network based on several viewpoints including the regional hierarchy. The regional hierarchy describes non-quantity-based evaluation, considering that many conventional studies have discussed only quantity-based evaluation. Five link significance indices are proposed. They represent the significance related to route volume, route distance, link volume, link velocity, and OD-node hierarchy. An application in Fukuoka Metropolitan Area could draw the utilities of the indices and show the comprehensive significant links. Furthermore, comparison between network in 1990 and that in 2010 shows the effects and the problems of the road arrangement plan.

INTRODUCTION

The purpose of this study is to develop a method to evaluate the performance level of road network in city-region area, which is an important step in planning of road network development. Numerous studies have already discussed and developed the evaluation theories and methods. However, based on the review of those researches stated below, this paper proposes an alternative evaluating method.

Recently, the main focus of the evaluation of road network has been shifting. Reflecting the complexity of road network, there have been growing interests in the evaluation considering the whole network, in addition to the evaluations that mainly focused on the individual link properties (e.g. width of road, pavement ratio and congestion ratio).

The studies on the evaluation considering whole network can be characterized by four viewpoints. That is, the object (e.g. network itself, cut-phase of network, zone, node, node-pair, route and link), the situation (usual, disaster), the issue (e.g. demand, morphology and system), and the function (e.g. significance, connectivity, reliability and redundancy).

The above mentioned four viewpoints give the overview of the conventional studies when considering the following examples. Tinkler (1971) discussed the network morphologically by examining the eigen-functions of the dichotomous matrices of network. Kimura *et al* (1987) discussed the connectivity of network morphologically in usual situation. He also discussed the redundancy in disaster situation by cutting certain link in the network. Okada *et al* (1987) investigated the performance level of whole network morphologically by using the fractal theory. Some studies evaluated link significance considering the socioeconomic indices (e.g. Okada, *et al*, 1988). The studies have some relations with the traffic demand. As for the studies evaluating reliability of node–pair, Takayama (1989) employed systematic network approach. Du *et al* (1993) and Asakura *et al* (1989) developed a method considering the traffic demand. Recently, Asakura *et al* (1997) also proposed another method considering the travel distance with the concept of detour limit.

The review shows two important facts. Firstly, although there are so many indices and ways to evaluate the network, individual evaluation might a limited aspect. The comprehensive understanding of the evaluation should be discussed. Secondly, the evaluation is so often discussed in association with traffic demand. In case it is not directly discussed on the traffic demand, socioeconomic aspects such as population and land use have actually strong relation with the traffic demand. As these evaluations tend to show the significant links mainly in city area that have large traffic demand, they can not provide the validity of road development plan in rural area. More emphasis should be put on the non-demand/quantity-based evaluation.

The viewpoints of this paper will be discussed taking into consideration the above two facts and our purpose. The object of evaluation is link significance because the road network is developed by individual link development. Needless to say, the link significance means the relative significance among the links that constitute the whole network. This study assumes that the situation is usual, which provides the basic planning. As for the issues, this paper proposes the evaluation considering the regional hierarchy besides the traffic demand. The regional hierarchy takes a role of non-quantity-based evaluation. It is well known that the regional hierarchy is an important concept for understanding regional system.

FORMULATION OF LINK SIGNIFICANCE

Meaning of significance

The link significance has to represent the degree of performance of the link in the network. The problem is how the performance should be identified. Many studies have discussed ways of identifying the performance, but the review shows the necessity for the re-composition of the ways.

To simplify the representation of the network performance, this paper puts the key on the basic elements that compose the network transportation; link, route, and Origin-Destination (OD) nodes. The relative link significance should be measured to reflect what kinds of OD nodes and routes use the link, and how is the situation of the link when the network performs. The composition of these significance would give the comprehensive significance.

The properties of route and link would be given by the result of the network simulation (traffic demand assignment). The properties of OD nodes could be measured by various indices, e.g. population, land use, and so on. However, socioeconomic indices have certain correlation with the traffic demand. Non-demand based indices or some indices that have different tendency from the demand-related indices are desirable. This paper introduces the regional hierarchy of node for this kind of index.

Formulation of significance

The relative link significance should be measured to reflect properties and situation of the OD nodes, route and link.

The route that is used between certain OD nodes has three characteristics; traffic volume, distance and travel time. The travel time, however, is constant among alternative routes between certain OD nodes because of the Wardrop's first definition (1952). The significance of the route should be large when the route has larger traffic volume or when it has the shorter distance. Attaching the route significance to each link that composes the route, and summing it for all OD nodes, the link significance are given as the averages of them, as shown in eqns (1) and (2). The reason for averaging ($\Sigma\, \xi_{ijr}^{\,l}$) is that, in actual network, we found high correlation between $W_{ru}^{\,l}$,$W_{rd}^{\,l}$ and $W_{nh}^{\,l}$ (Yoshitake *et al*, 1996). The correlation might appear because the limited links are used in the assignment.

The properties of the link are shown by the traffic volume and the velocity. The larger volume and/or lower velocity means the significance. The significance related to the link properties are given by eqns (3) and (4).

The link significance concerning the OD nodes could be defined as an average of the weights for all routes and OD nodes, as shown in eqn (5). The weights ($w_{IJ}^{\,h}$) are proper to the regional hierarchy of OD nodes pair.

The problem is how the weights should be defined. It is natural to assume that the higher hierarchy has the larger weight. However, if the higher hierarchy nodes have larger weights, the significance concerning the OD nodes would possibly have certain correlation to the traffic demand/volume because the node of high hierarchy has the larger traffic volume. Taking into account this problem, it is also reasonable to consider the weight that has the reverse tendency. In this context, we suppose it exogenously. It is possible to give the weight on the viewpoint of political reason.

$$W_{ru}^{\,l} = \{ \sum_i \sum_j \sum_{r=1}^{R_{ij}} \xi_{ijr}^{\,l}\, q_{ijr} \,/\, Q_{ij} \} \,/\, \sum_{i,j,r} \xi_{ijr}^{\,l} \tag{1}$$

$$W_{rd}^{\,l} = \{ \sum_i \sum_j \sum_{r=1}^{R_{ij}} \xi_{ijr}^{\,l}\, d_{ij}^{\min} \,/\, d_{ijr} \} \,/\, \sum_{i,j,r} \xi_{ijr}^{\,l} \tag{2}$$

$$W_{lu}^{\,l} = u_l \,/\, \sum_{l=1}^{L} u_l \tag{3}$$

$$W_{lv}^{l} = v_l^* / v_l(u_l) \qquad (4)$$

$$W_{nh}^{l} = \{ \sum_{i,j,r} w_{IJ}^{h} \xi_{ijr}^{l} \} / \sum_{i,j,r} \xi_{ijr}^{l} \qquad (5)$$

where $W_{ru}^l, W_{rd}^l, W_{lu}^l, W_{lv}^l, W_{nh}^l$ denote the significance related to route traffic volume, route distance, link traffic volume, link velocity and regional hierarchy of OD node pair, respectively. *Rij* denotes the number of routes between OD nodes i and j ($i,j = 1,2,...N$: N is the number of OD nodes). ξ_{ijr}^l is 1 (0) when link l does (doesn't) constitute the r-th route between OD nodes i and j. q_{ijr} is the traffic volume of the r-th route between i and j. Q_{ij} denotes traffic volume between i and j. d_{ijr} and d_{ij}^{min} denote the distance of r-th and the shortest route between i and j, respectively. u_l denotes the traffic volume of link l. v_l^* and $v_l(u_l)$ denote free flow speed (velocity) and actual velocity of link l with traffic volume u_l, respectively. w_{IJ}^h denotes the weight that is proper to I-th and J-th regional hierarchy which include nodes i and j.

AN APPLICATION TO ACTUAL NETWORK

Network in Fukuoka Metropolitan Area

To investigate the nature and availability of proposed indices, an application for the actual network should be discussed. The study network is derived from Fukuoka Metropolitan Area. Fukuoka City, one of the regional hub cities of Japan, is located in the northern part of Kyushu Island and has over 1.2 million population. The Metropolitan area is consisted of 35 municipalities. The city-region is identified by Yoshitake *et al* (1988), using the commuting and attending to school OD-flow data.

Fig. 1 shows the principal road network in Fukuoka Metropolitan Area in 1990. The network is composed of national express way, urban express way, national highway, principal local road, and a few prefectural and municipal roads that are necessary for the connectivity of the network. In the area of Fukuoka City, the municipal (city) roads that take the trunk line function were added into the network. Finally, the network has 494 links and 321 nodes including 107 OD nodes.

The regional hierarchies of OD nodes (central, sub-central and peripheral) were set according to the method by Yoshitake *et al* (1988) that uses commuting and attending to school OD data. The numbers of the OD node of each hierarchy are 24 central nodes, 35 sub-central nodes, and 42 peripheral nodes. The remaining six nodes are dummy OD nodes. The central nodes are all in the area of Fukuoka City.

The OD traffic volumes are the ones estimated by Urban Research Center (URC), Fukuoka (1995). The incremental assignment (5 steps) was employed for calculating the above indices.

Natures of the proposed indices

It is necessary to prove the availability of the significant indices by investigating whether they show different natures and behaviors in the actual network. The reason for the investigation is that they possibly might have similar natures and behaviors, in spite of being defined by different ways.

At the beginning of the calculation, we have to discuss the determination of the weight w_{IJ}^h. As w_{IJ}^h is an exogenous variable previously mentioned, various points of view enable to give the flexibility to the weights. This paper, considering the flexibility, temporarily supposes two sets of weights (Table 1); Case-1 presents the lower hierarchy has the larger significance, Case-2 presents the reverse significance. Actual evaluation of link significance has to allow for only one set of weights. The supposition of two sets of weights is just for investigating the typical behaviors of W_{nh}^l.

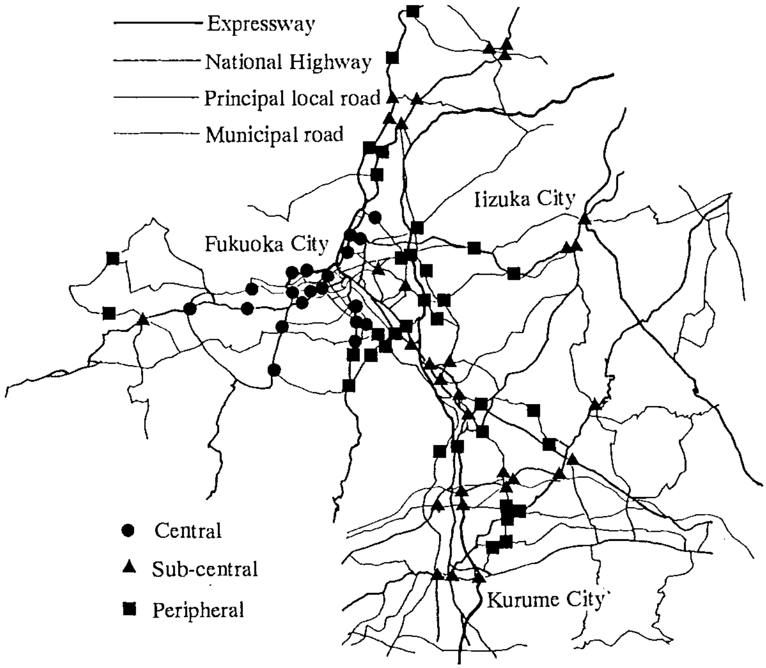

Figure 1 - Road network in Fukuoka Metropolitan Area

Table 1 - Two sets of w_{IJ}^h

Origin-Destination	Peripheral-Peripheral	Peripheral-Sub central	Peripheral - Central	Sub central - Sub central	Sub central - Central	Central - Central
Case -1	6.0	5.0	4.0	4.0	3.0	2.0
Case - 2	2.0	3.0	4.0	4.0	5.0	6.0

The correlation analysis would show whether the proposed indices vary independently or not. Table 2 shows the correlation matrix between the indices, including W_{nh}^l of Case-1 and Case-2. The number of times that the assignment procedure uses the link l, shown as $\Sigma\ \xi_{ijr}^l$, is also added into the analysis for the reference. Looking at the column for $\Sigma\ \xi_{ijr}^l$, the results show it does not have high correlation with any indices. The proposed indices are independent from the number of times used. Examining the correlation among the indices, relatively high correlation is found between W_{ru}^l and W_{rd}^l, W_{ru}^l and $W_{nh}^l(1)$, W_{rd}^l and $W_{nh}^l(1),(2)$. For example, the relation between W_{ru}^l and W_{rd}^l, W_{ru}^l and $W_{nh}^l(1)$ are shown in Figs.2 and Fig.3, respectively. We can understand that the high correlation is caused by the zero-value of the indices, and that the indices do not have the functional relationships. These discussions can lead to the conclusion that the proposed indices are independent and have the proper meanings. Additionally, looking at the correlation between $W_{nh}^l(1)$ and $W_{nh}^l(2)$, it is -1.0 when calculating with the exclusion of the zero values. This means that W_{nh}^l is sensitive to the values of w_{IJ}^h, and therefore, it is much available for the evaluation.

As for the next step, for examples, Figs.4, 5 and 6 give the geographical distributions of the link significance of W_{rd}^l, W_{lu}^l and $W_{nh}^l(1)$, respectively (the values of W_{lu}^l are multiplied by 10^3). These indices show obviously different patterns. The significant links of W_{rd}^l (Fig.4), that tends to have larger values when the link takes a part of shorter route, exist in the fringe part as well as the central

Table 2 - Correlation matrix between significant indices

	W_{ru}^l	W_{rd}^l	W_{lu}^l	W_{lv}^l	W_{nh}^l (1)	W_{nh}^l (2)	$\Sigma_{ijr}\xi_{ijr}^l$
W_{ru}^l	-	0.768	0.205	0.139	0.645	0.661	0.077
W_{rd}^l		-	0.359	0.366	0.789	0.818	0.250
W_{lu}^l			-	0.454	0.269	0.377	0.681
W_{lv}^l				-	0.381	0.186	0.476
W_{nh}^l (1) (Case-1)					-	-1.000*	0.378
W_{nh}^l (2)*(Case-2)						-	0.162

note *: excluding the links with zero value

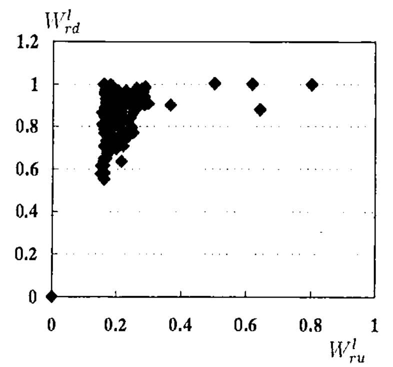

Figure - 2 Relation between W_{ru}^l and W_{rd}^l

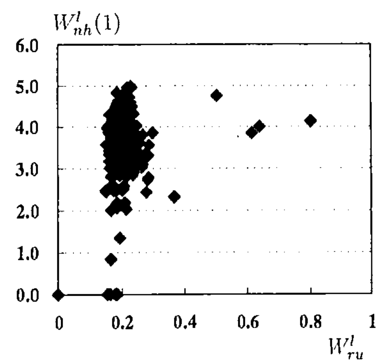

Figure - 3 Relation between W_{ru}^l and $W_{nh}^l(1)$

part of network. The significance in fringe might be caused by the large difference of distance between the shortest route and the other routes, which relates to low density of the links in the fringe. On the other hand, the large significance in central part would be due to the small difference of distance between alternative routes, which is caused by the high density of links.

Looking at Fig.5, the significant links of W_{lu}^l distribute along the "Y-shape" line, reflecting the regional structure. It may be natural because the larger cities are located along the line.

Fig.6 shows the distribution of $W_{nh}^l(1)$. Although the distribution pattern is somewhat similar to that of W_{rd}^l, some differences are found in the center and fringe part of the network. That is, in the center part, the links with low significance are evenly distributed while the links with large significance are found in the fringe part. It reflects the weight w_{IJ}^h and the location of node hierarchy. The nodes of lower hierarchy, that has the larger significance, tend to be located in fringe and the nodes of higher hierarchy, smaller significance, are located in center part.

Examining the significant link distribution of other indices, it should be concluded that the five indices have their own meanings and properties, and therefore, they are available.

Comprehensive evaluation of link significance

Five indices are proved to have five different significance. However, comprehensive understanding of significance would be sometimes required. It would be given for instance by the linear summation with some parameters. However, considering that the distribution of link significance of the indices depends on the network properties, e.g. size, shape and OD traffic patterns, the fixed parameters that

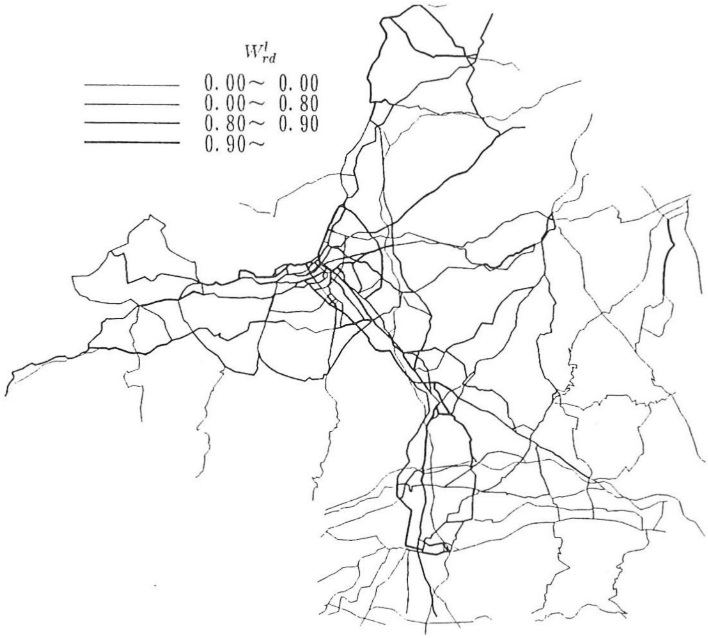

Figure 4 - Significant links of W_{rd}^l

Figure 5 - Significant links of W_{lu}^l

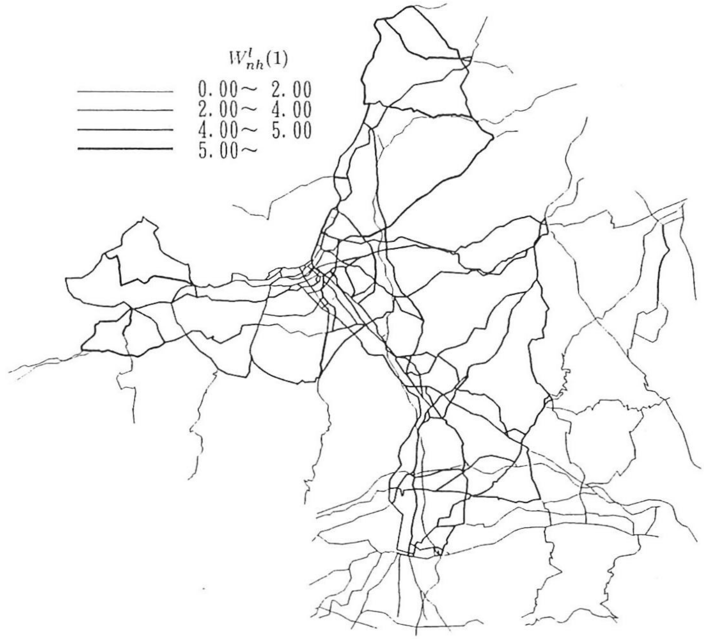

Figure 6 - Significant links of $W_{nh}'(1)$

are independent of the network are not suitable for the purpose. The comprehensive evaluation should also reflect the network properties.

The Principal Component Analysis (PCA) would provide a solution for this problem. The component score is defined with the parameters that depend on the values of five indices. Therefore, PCA can give the comprehensive significant links reflecting the network properties.

Table 4 summarizes the result of PCA for Case-1. Although the cumulative contribution rate up to the third component is 90.8%, the rate up to second component is large enough (79.2%) to make the comprehensive understanding. The larger score of the first component means the significance related to route and node properties. The second component has the relation with the link properties. The comprehensive significant links are considered to have the larger scores of both of the components. Examining the scores of the components, the two-third of standard deviations of each component score should be the criteria for picking up the significant links which was about 10% of all links.

Fig.7 shows the comprehensive significant links that have the larger scores than the criteria. The links drawn by thick line are significant. Although many significant links are found in the central part of the network, the distributing pattern of the significant links is much different from those shown in Figs.4, 5 and 6. The existence of two significant links in the eastern part of the network is interesting because those links do not have large traffic volume. Their significance is introduced by the indices related to e.g. the hierarchy and distance.

By the way, what is the importance of the significance in the network planning? The first answer is to make the links strong so as to maintain the functions even in unusual situation. The second answer is the development of new links to make the significance of existing links lower. It is undesirable that the specific and a few links have much larger significance compared with the rest links on the point of efficiency of the investment.

Table 4 - Result of PCA in 1990 network

Component	Cum. Contribution rate	Factor loadimg				
		W_{ru}^{l}	W_{rd}^{l}	W_{lu}^{l}	W_{lv}^{l}	$W_{nh}^{l}(1)$
1st	0.567	0.794	0.922	0.535	0.557	0.870
2nd	0.792	-0.449	-0.201	0.645	0.656	-0.194
3rd	0.908	0.908	0.013	0.540	-0.472	-0.192

Figure 7 - Comprehensive significant links in 1990

Evaluation of planning network

The proposed method is also applied to the planning network of Fukuoka Metropolitan area in 2010. The network is consisted of 619 links and 115 OD nodes. The network plan and the estimated traffic demand are also shown in the URC report (1995). The same regional hierarchy as that in 1990 is used. The set of the weight is for Case-1.

The comprehensive significant links are drawn by the result of PCA (Table 5). The comparison of Tables 4 and 5 tells that the differences of meanings and cumulative contribution rates of the components between two networks are very small. We could discuss the efficiency of the network plan by the direct comparison of the PCA results on the two networks.

Fig. 8 shows the significant links in 2010. They are identified by the same way in 1990. Although the distributing patterns of significant links in 1990 and 2010 do not show the drastic difference, some significant links linearly extend to eastern part and new significant links emerge in western part. As a whole, the significant links are found in the central part compared with the result in 1990. The linear linkage of significant links means that only one road, consisted of those links, has the significance. The linkage makes the effective investment to concentrate upon only one road.

On the other hand, however, it is somewhat dangerous that the network function depends on only one road, especially in unusual situation. To discuss the degree of the significance distribution, a new in-

Table 5 - Result of PCA in 2010 network

Component	Cum. Contribution rate	Factor loadimg				
		W_{ru}^{l}	W_{rd}^{l}	W_{lu}^{l}	W_{lv}^{l}	$W_{nh}^{l}(1)$
1st	0.552	0.824	0.918	0.487	0.499	0.870
2nd	0.496	-0.391	-0.236	0.696	0.703	-0.176
3rd	0.905	-0.132	-0.026	-0.522	0.476	0.170

Figure 8 - Comprehensive significant links in 2010

dex is introduced, as shown by eqn (6), where c_{**} denotes the coefficient of variation corresponding to the subscription $**$.

$$C = \sqrt{c_{ru}^{2} + c_{rd}^{2} + c_{lu}^{2} + c_{lv}^{2} + c_{nh}^{2}} \qquad (6)$$

The value of index C is large when the degree of the distribution of values of indices are large. The smaller value of C represents the de-concentration of the significance. As shown in Table 6, the values of C index of the network in 2010 is smaller (0.487) than that in 1990 (0.532). It reveals the effect, although it is small, of the development plan of the network.

Table 6 - *C* values in 1990 and 2010

	1990	2010
C	0.532	0.487

CONCLUDING REMARKS

This study aimed at developing an evaluation method of the road network performance level on the viewpoints including non-demand aspect as well as demand aspect. The method proposed that the network performance should be evaluated with the link significance reflecting the situation of whole network.

The conclusions duly arrived at through this study are summarized as follows:

(1) The link significance is defined by five indices. They represent the significance related to route traffic volume, route distance, link traffic volume, link velocity and the hierarchy of OD nodes. The index related to especially the regional hierarchy could have the non-demand nature that has not been discussed in conventional studies.
(2) The analysis of correlation and the geographical distribution of the significant links, on the application to actual road network of Fukuoka Metropolitan area in 1990, proved that the significant indices have their own meanings and characteristics. The comprehensive significant links are drawn by the use of principal component analysis. These resulted in the utilities of proposed method.
(3) The comparison of the significant links between the present network (in 1990) and planned network (in 2010) could prove the effects and the problems of the development plan. That is, the plan has certain effects because the deviation of the significance decreases. However, the linkage of significant links means the over depending on one road in the network function.

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