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Evaluation of Trunk Road Network in Fukuoka City Region using Inter-Nodes Distance Index

by

Satoshi TOI*, Tetsunobu YOSHITAKE** , Yoshitaka KAJITA***
and Hiroshi TATSUMI†

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Abstract

We have developed the 'Inter-Nodes Distance Index,' which consists of the average and standard deviation of the shortest distance between 2 nodes, in order to evaluate the balance in mobility among districts in a region. The purpose of this study is to show the effectiveness of applying this index to evaluate an actual road network. In this paper, the effectiveness of the trunk roads in the Fukuoka city region is evaluated from the viewpoint of the balance of mobility level over the whole region and each district. Further, the optimum order of road construction is investigated based on the amount of saved trip time during the period of construction.

Keywords: Road network, Evaluation, Mobility, Motorway, Travel time

1. Introduction

Measures toward increasing car traffic demand are extremely important in the city, and in this aspect there are a lot of existing methods for evaluating road networks. Road construction aimed solely to solve road congestion in a specific district runs the risk of concentrating the traffic demand and thus actually bringing further traffic congestion to the district. Therefore it is necessary to construct road networks that induce balanced development of the region and promote the decentralization of the traffic demand.

Thus far, the following researches have been conducted concerning the shape evaluation of road networks. The first group of studies includes research on the geometrical composition theory of road networks, such as the application of "Houghton's Law"[1)] and the fractal dimension[2)]. The second group is based on the standpoint of the cooperation and interchange between cities, such as the "Large Area Index"[3)] and the analysis of the hierarchy of road networks by graph theory[4)]. The

* Associate Professor, Department of Urban and Environmental Engineering
** Associate Professor, Department of Civil Engineering, Miyazaki University
*** Research Associate, Department of Urban and Environmental Engineering
† Associate Professor, Department of Civil Engineering, Kyushu Sangyo University

third group deals with the evaluation of city road network levels, such as the "Inter-Nodes Distance Index"[5] and the comparison of road networks in a city using mobility[6]. The fourth group deals with the degree of importance of links in an entire road network, such as the "Distance Position Index" proposal[7] and the evaluation of the layered structure in the region[8].

This study can be classified as research of the third group. We have developed the "Inter-Nodes Distance Index," consisting of the average and standard deviation of the shortest distance between 2 nodes, in order to evaluate the balance in mobility among districts in a region. From the above-mentioned consideration, the "Inter-Nodes Distance Index" is used as an index that evaluates the relation between the mobility in the various districts and the formation of the road network. This index enables us to evaluate the relative mobility from one district in the road network and to evaluate the average efficiency of the mobility and the differences among districts in the whole region.

This research aims to apply the "Inter-Nodes Distance Index" to the evaluation of the actual plan of a trunk road network and to show the effectiveness of road construction. The influence of the routes of the motorways currently under construction in the Fukuoka city region was evaluated, based on the efficiency of mobility in an individual district and in the full city range. In addition, the optimal order of the road construction was examined through Dynamic Programming (Hereafter written 'DP'), using as an evaluation function the amount of the total travel time until all routes would be completed.

2. Construction Plan of the Trunk Road Network in the Fukuoka City Region

The plan of trunk road network in the Fukuoka city region is shown in **Table 1** and **Fig. 1**. Line 1 of the Fukuoka City Expressway runs from east to west, Line 2 runs from north to south, and Line 3 runs from the center of the city to the airport. These three lines were already completely constructed as the motorway network.

To reinforce the ability to let traffic pass through the city in the future, Line 1 of the Fukuoka City Expressway was scheduled to be extended to Fukushige, Line 2 was to be extended to the Dazaifu Interchange of the Kyushu Expressway by 1998, and Line 4 was scheduled to be constructed from the Fukuoka Interchange to the Kaizuka Junction by 2000.

Moreover, in order to exclude the through traffic in the central district of the city, the Imajuku-Maebaru Road and the Fukuoka Outside Loop Road were scheduled to be constructed by 2003 and 2005, respectively, and the Fukuoka East Loop Road was scheduled to be constructed following their completion. Thus, the order of construction and extension is ②,③,①,⑥,⑤,④ noted as the case number column of **Table 1**.

Table 1 Outline of projects.

Case no	Project Name	Extension	Design speed
①	Construction of City Expressway Line 4	6.9 km	40 km/h
②	Extension of City Expressway Line 2	9.3 km	30 km/h
③	Extension of City Expressway Line 1	5.1 km	50 km/h
④	Construction of Fukuoka East Loop Road	8.3 km	30 km/h
⑤	Construction of Fukuoka Outside Loop Road	16.2 km	55 km/h
⑥	Construction of Maebaru-Imajuku Road	18.0 km	60 km/h

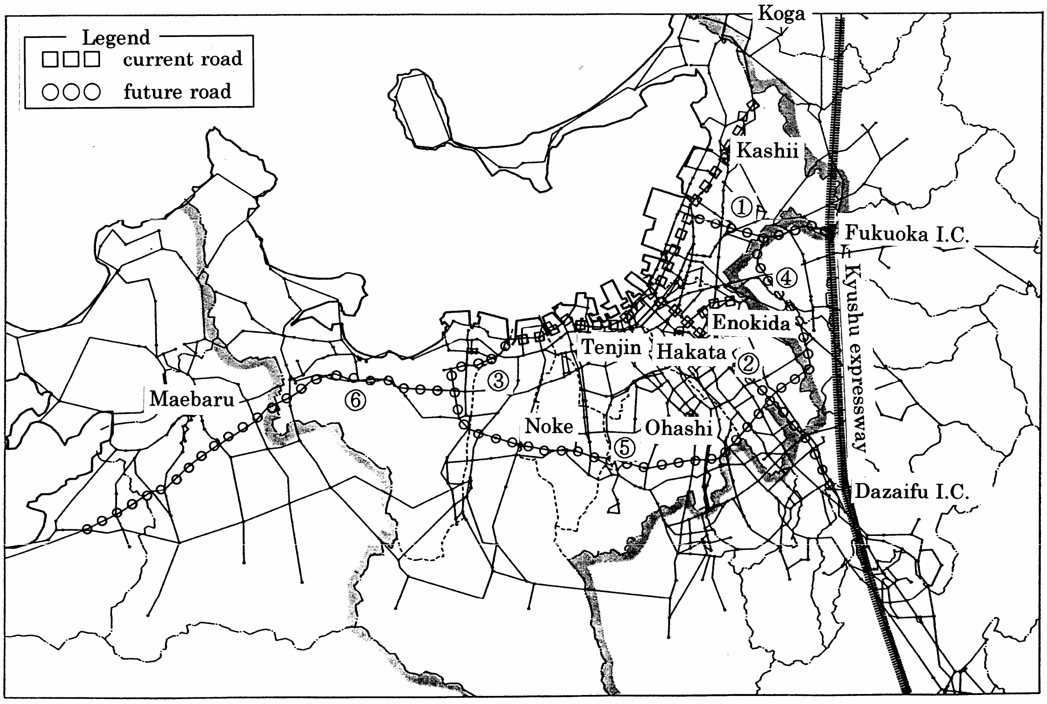

Fig. 1 Motorway road network plan of the Fukuoka city region.

3. Analysis of Construction Effects of Planned Routes

3.1 Analysis method

The analyzed road network is composed of the roads greater than main city roads and has a scale of 1511km of extensions, 1993 links, and 1233 nodes in total.

The time distance between nodes was used in this study to express the effect of road construction by the amount of time shortening. The travel time between nodes can be calculated based on the Origin and Destination (Hereafter written ‘OD’) volume at the completed year of each route. However, only the estimated OD volume of 2010 at the time of completion of the planned road network was used in this study because the period of time until completion of the road network is short. The travel times between nodes of seven cases were calculated, including the case of the current road network and six cases that were added by each planned route to the current network. The effects of these individual routes were analyzed.

There are two methods for averaging the travel times between nodes. One of them is the method of weighting all the travel times equally, and the other is the method of weighting the traffic volume between nodes for each travel time. The former proposes the potential given to each node based on the road network, and it may not be appropriate for a short-term evaluation. However, it is thought to be effective for road planning that aims at creating a decentralized regional structure because the possibilities for development of the region can be shown considering the mobility. On the other hand, the latter method enables a realistic evaluation in which economic efficiency can be evaluated. In this method, however, it is difficult to exceed the frame of demand following type planning. This method is not suited for analyzing the construction of a new regional structure. The effects of planned route construction from the above-mentioned two standpoints were analyzed because they each have their respective advantages.

3.2 Analysis of construction effects of planned route

3.2.1 Comparison between current and final road network

The calculation results of each case concerning the whole region are shown in **Table 2**. The evaluation values with weighting have been shortened by 15-20 minutes of the average value and 34.5-37.5 minutes of the standard deviation. The changes in the frequency distribution of the average travel time between nodes in the current and completed road network are shown in **Fig. 2** and **Fig. 3**.

The travel time between nodes in the final network and the width of distribution are greatly reduced for the current network, as shown in **Fig. 2**. **Figure 3** shows the frequency of the average travel time between nodes weighted by the OD traffic volume. In this case, the travel times are short compared to **Fig. 2**, and their distribution shifts to the left because the OD traffic volumes are larger between nodes with shorter travel times. Moreover, the difference between the current and the final network in **Fig. 3** is not as large as in **Fig. 2** because the effect of the surrounding district, where time shortening is large, decreased relatively by weighting with the OD traffic volume.

Table 2 Travel times by construction case.

Case	Average travel time		S.D. of travel time	
	without weighting	with weighting	without weighting	with weighting
Current Network	53.00	33.27	60.92	26.46
+Route1	51.27	32.07	60.49	25.76
+Route2	52.12	32.89	60.48	26.12
+Route3	51.99	32.63	60.46	25.92
+Route4	52.93	33.23	60.84	26.44
+Route5	51.85	32.26	60.31	25.89
+Route6	45.37	29.48	57.04	20.25
Final Network	40.70	25.82	55.48	18.02

Note : S.D. is standard deviation

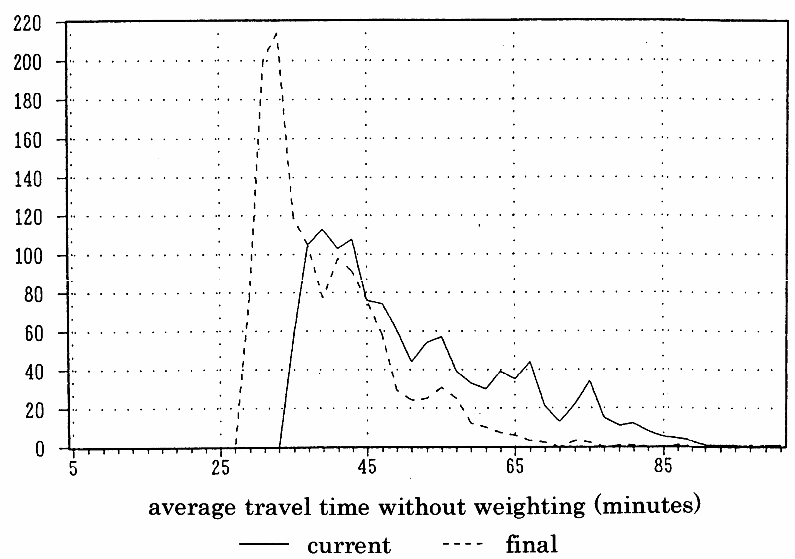

Fig. 2 Frequency of average travel time in cases without weighting.

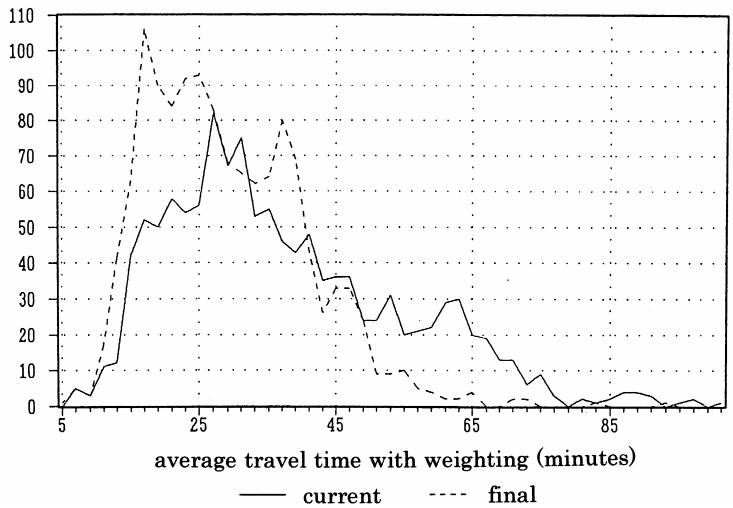

Fig. 3 Frequency of average travel time in cases with weighting.

3.2.2 Effect of shortening time by the construction of each route

Without weighting, the average travel time and the standard deviation between nodes were 53.0 minutes and 60.9 minutes respectively on the current network, while they were 40.7 minutes and 55.5 minutes respectively on the final network. Time shortening of about 12.3 minutes (14%) for average and about 5.4 minutes (9%) for standard deviation were obtained between the two cases. With weighting, on the other hand, time shortening of about 7.5 minutes (8%) for average and about 8.4 minutes (32%) for standard deviation were obtained. That is, in the case of the evaluation with weighting, the sensitivity to average mobility dulls while the sensitivity concerning the unbalance of the mobility sharpens.

The effect of time shortening for each route per unit extension is shown in **Fig. 4 (A)** and **(B).** The shortening of travel time is shown in **Fig. 4 (A)**, and the difference between routes is remarkably apparent. That is, the effect of route 6 excels in all the routes, and the effects of routes 1 and 3 are also high, but the effects of routes 2 and 5 are not high, and the effect of route 4 is very low. In the case of weighting, the effect of route 6 decreases by half, and the effect of route 2 disappears.

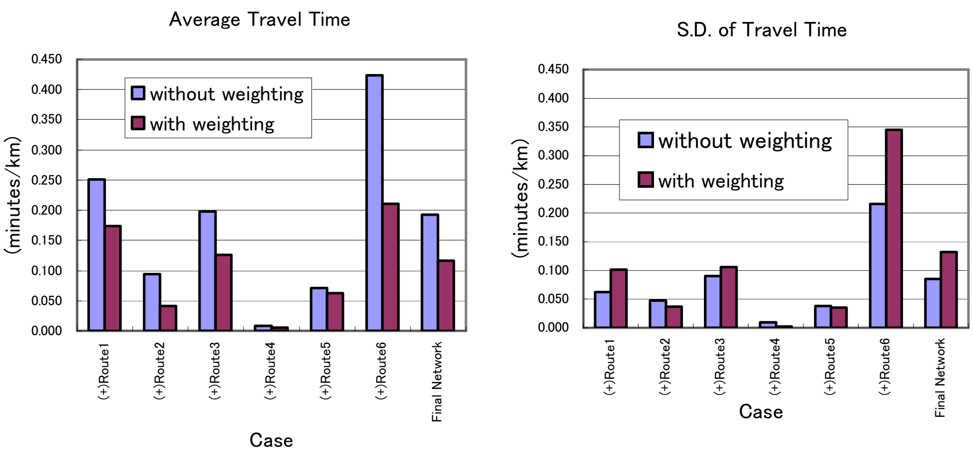

Fig. 4 Shortening effect of travel time between nodes.

Route 2 connects the Dazaifu Interchange to the city expressway network, and it was designed to allow long distance traffic between the inside and outside the city to pass through. However, the evaluation of route 2 is low even in the case of weighting by OD traffic volume. This is because the inside and outside traffic of the city region was not taken into consideration in this study.

Figure 4 (B) shows the change in standard deviation. It can be deduced from this information that the effect of route 6 is the maximum effect regarding standard deviation. This is because the vast Itoshima area extends along route 6, and the time distance from this region to the Fukuoka city region is shortened greatly by constructing route 6.

3.2.3 Analysis of influences on districts

The changes in the distribution of the travel times concerning nine typical districts are shown in **Fig. 5**. The distribution of each district changes considerably, the right range of distribution shifts to the left, and the peak rises. The changes in the distribution of the surrounding parts (Koga, Noke, Maebaru, and Dazaifu) are larger than the changes in the central district of the city (Hakata and Tenjin) and the sub-centers of the city (Kashii, Oohashi, and Nishijin), and the changes become more remarkable the farther the distance from the city center. In particular, the change in travel times is most remarkable in the Maebaru district because the extension of the current travel time is extremely large.

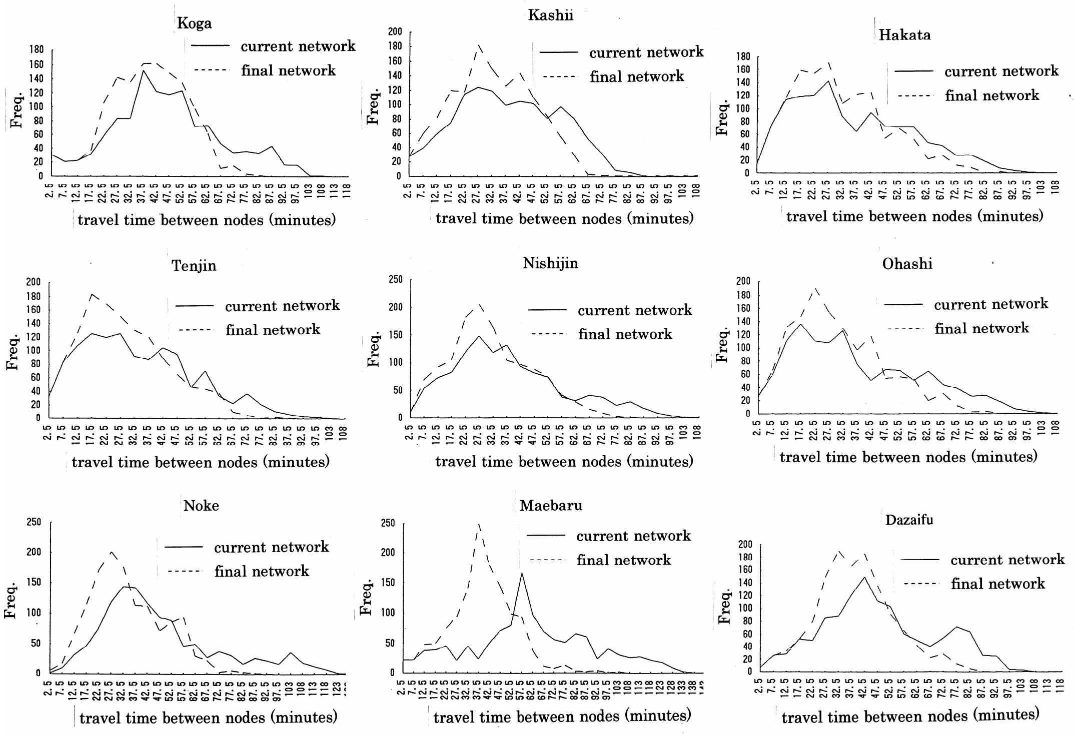

Fig. 5 Changes in the travel time distributions of nine typical districts.

Table 3 shows the effect of travel time shortening per unit of road length when each route is constructed alone and indicates the districts affected by the construction of each route.

Table 3 (A) and **(B)** show the effects of the shortening of average travel time. The influence of route 1 is large for the east parts of the city (Koga, Kashii) and the southern part (Dazaifu). The influence of route 3 is large for the west parts (Noke, Maebaru), and the influence of route 5 is large for the area of Noke. The influence of route 6 changes with weighting, but is generally large for the Maebaru district. Moreover, the influence on the Noke and Maebaru districts is large in a completed network. **Table 3 (C)** and **(D)** show the effects of the shortening of standard deviation. The effect of route 3 extends to the east districts of Koga, Umi, and Wajiro, and the effect of route 6 reaches all of the east districts, the center, and the west districts.

Table 3 Effect of route construction on local districts.

(A) Average (without weighting, minutes/Km)

	+Route1	+Route2	+Route3	+Route4	+Route5	+Route6	Final Network
Koga	0.599	0.172	0.149	0.005	0.006	0.206	0.128
Umi	0.122	0.027	0.155	0.011	0.025	0.092	0.095
Wajiro	0.301	0.061	0.165	0.004	0.009	0.043	0.079
Kashii	0.416	0.040	0.171	0.006	0.002	0.042	0.100
Hakata	0.133	0.022	0.163	0.007	0.012	0.086	0.075
Nishijin	0.151	0.010	0.035	0.004	0.015	0.219	0.109
Tenjin	0.154	0.013	0.182	0.005	0.010	0.107	0.086
Ohashi	0.174	0.033	0.137	0.007	0.120	0.185	0.111
Noke	0.093	0.086	0.298	0.002	0.248	0.377	0.219
Maebaru	0.135	0.001	0.457	0.000	0.136	1.018	0.360
Dazaifu	0.920	0.025	0.173	0.006	0.001	0.048	0.157

(B) Average (with weighting, minutes/Km)

	+Route1	+Route2	+Route3	+Route4	+Route5	+Route6	Final Network
Koga	0.599	0.103	0.063	0.002	0.017	0.050	0.086
Umi	0.129	0.018	0.059	0.014	0.013	0.136	0.095
Wajiro	0.184	0.031	0.065	0.001	0.014	0.013	0.037
Kashii	0.475	0.023	0.031	0.000	0.006	0.006	0.066
Hakata	0.026	0.001	0.031	0.004	0.004	0.031	0.019
Nishijin	0.019	0.008	0.022	0.002	0.002	0.033	0.022
Tenjin	0.033	0.002	0.063	0.000	0.006	0.041	0.025
Ohashi	0.010	0.011	0.043	0.000	0.056	0.054	0.032
Noke	0.003	0.008	0.180	0.002	0.280	0.062	0.132
Maebaru	0.086	0.008	0.433	0.001	0.166	0.889	0.334
Dazaifu	0.917	0.015	0.061	0.000	0.005	0.012	0.125

(C) S.D. (without weighting, minutes/Km)

	+Route1	+Route2	+Route3	+Route4	+Route5	+Route6	Final Network
Koga	0.138	0.035	0.145	0.008	0.023	0.188	0.069
Umi	0.001	0.017	0.112	0.005	0.022	0.077	0.055
Wajiro	0.041	0.043	0.120	0.008	0.021	0.057	0.048
Kashii	0.013	0.037	0.098	0.007	0.021	0.051	0.042
Hakata	0.075	0.020	0.076	0.007	0.020	0.078	0.050
Nishijin	0.070	0.023	0.006	0.007	0.019	0.130	0.054
Tenjin	0.058	0.023	0.057	0.007	0.020	0.085	0.050
Ohashi	0.088	0.018	0.082	0.007	0.058	0.136	0.067
Noke	0.099	0.078	0.120	0.008	0.023	0.237	0.085
Maebaru	0.103	0.026	0.118	0.008	0.031	0.327	0.114
Dazaifu	0.036	0.030	0.090	0.007	0.022	0.052	0.037

(D) S.D. (with weighting, minutes/Km)

	+Route1	+Route2	+Route3	+Route4	+Route5	+Route6	Final Network
Koga	0.254	0.069	0.110	0.002	0.006	0.104	0.068
Umi	0.009	0.006	0.065	0.001	0.019	0.266	0.132
Wajiro	0.135	0.051	0.102	0.004	0.001	0.043	0.051
Kashii	0.146	0.042	0.041	0.002	0.004	0.012	0.037
Hakata	0.065	0.013	0.067	0.002	0.008	0.119	0.059
Nishijin	0.045	0.002	0.000	0.000	0.009	0.082	0.039
Tenjin	0.059	0.003	0.061	0.001	0.007	0.107	0.052
Ohashi	0.030	0.009	0.098	0.005	0.085	0.143	0.063
Noke	0.035	0.030	0.102	0.001	0.019	0.131	0.064
Maebaru	0.128	0.012	0.192	0.005	0.035	0.553	0.198
Dazaifu	0.139	0.032	0.069	0.007	0.009	0.026	0.047

4. Analysis Concerning Construction Order

4.1 Analysis method

Three types of ordering were adopted regarding route construction: the order of the scheduled construction plan, the order of construction effect per unit extension, and the order of the optimum solution by DP. In this analysis, in order to reduce the amount of calculations, it is assumed that the construction of other routes does not start until the construction of one route is completed, though in actuality the roads are constructed and made available to drivers in each section as soon as they are completed. The construction period and cost for each route were assumed to be proportional to the scale of the route extension. The method of using DP is described as follows.

Regarding this problem, the average travel times between nodes take the same value at the final stage regardless of the order of route construction. Therefore it can be said that the type of construction order that reduces the average travel time at the earlier stages is most desirable. In such a case, the total travel time that will be saved by the time of completion of the road network will be maximized. The total travel time corresponds to the shadowed area in **Fig. 6**.

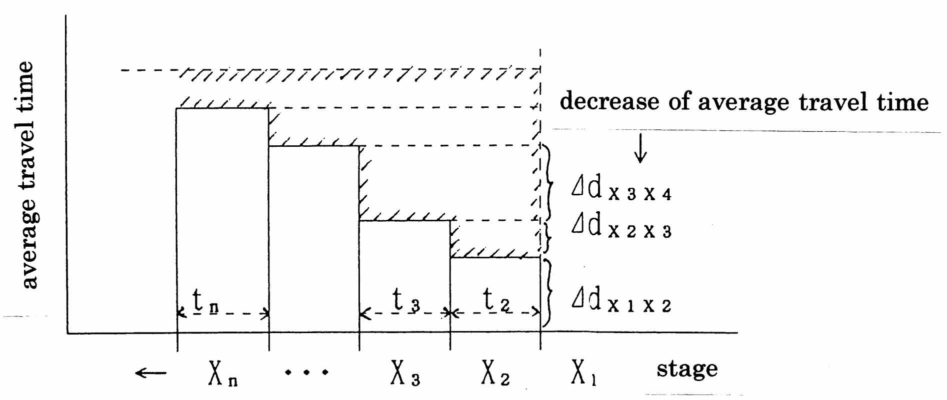

Fig. 6 Relation between construction stage and target function.

In this case, it cannot be assumed that the effect of route construction is linear and that the order of construction effect per unit extension is not necessarily the optimum order because the effects overlap between routes with respect to travel time shortening. This problem was next analyzed using DP. Expression (1) shows the reflexive expression between stages of the application of DP (retreat method) to this problem.

$$f_n^*(s) = \underset{x_n}{Max}\left\{ \Delta d_{xns}\left(\sum_{i=2}^{n} t_i \right) + f_{n-1}^*(x_n) \right\} \quad (1)$$

where,

x_n: the decision variable of n-th stage. It shows the situation of route construction. The final stage is x_1 and the current state is x_7 in this problem.

f_n*(s): the maximum value of target function at the final stage when the current state is (s) and x_n is chosen as a decision variable of the next n-th stage.

f_{n-1}*(x_n): the maximum value of target function of the final stage when x_n will be chosen as the decision variable of the next stage at (n-1) th stage.

$\triangle d_{xns}$: Amount of decrease of the average travel time between nodes when the state changes from s

into $x_{n.}$
t_i: the continuance period in stage i. That is, the construction time of the route that is constructed from stage i to stage i-1.

$\triangle d_{xns}$, the decrease of the average travel time from former stage (s) at each stage (x_n), should be obtained for this calculation. This problem decides the routes in the construction stage from the state of x_1 to x_7, as shown in **Fig. 7**.

The stages of x_2-x_6 have the combination of 5 routes and 1 route respectively. The numbers of the combinations are ${}_6C_5$, ${}_6C_4$, ${}_6C_3$, ${}_6C_2$ and ${}_6C_1$. It is then necessary to calculate the average travel time for all combinations (64 cases in total, including x_1 and x_7). The result of this calculation is shown in **Table 4**, which reflects the presence of weighting by the OD traffic volume.

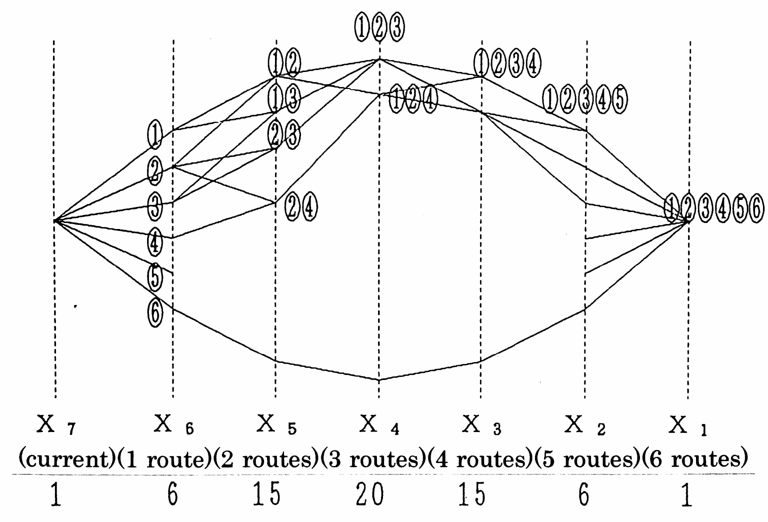

Fig. 7 Combinations at each stage.

4.2 Analysis results of construction order

Shown by the route numbers of **Table 1**, the routes are constructed following the scheduled plan in the order of ②③①⑥⑤④. The construction order starting with the effective routes per unit extension (the order of construction effect) was ⑥①③②⑤④ in the case of no weighting and ⑥①③⑤④②in the case of weighting. On the other hand, the optimum order calculated by DP without weighting was ⑥①③⑤④②.

Figure 8 is a display of the accumulation of time shortening based on the progress of route construction in the case of weighting. The order of the construction effect equals the order of the optimum calculation in the case of weighting. Three routes (⑥①③), which are common to both solutions and stretch from the east part to the west part of the city region, are chosen also in the case of no weighting. The other three routes in the two solutions are ②⑤④ and ⑤④②, respectively. Routes ⑤and ④, forming a loop road, were given priority in the optimum solution.

The shortening of travel time by one trip for the construction period changes depending on the order of road construction. In the case of no weighting, they are 5.4 minutes in the order of the construction plan, 7.0 minutes in the order of construction effect, and 7.1 minutes in the order of the optimum calculation. In the case of weighting, the values are 3.1 minutes, 4.0 minutes, and 4.0 minutes, respectively.

Table 4 Combinations of routes and average travel times (minutes) between nodes.

Route combination	with weighting	without weighting	Route combination	with weighting	without weighting
1 2 3 4 5 6 (Final)	40.70	25.82	1 5 6	43.21	27.58
2 3 4 5 6	41.87	26.72	1 4 6	44.12	29.40
1 3 4 5 6	41.29	26.16	1 4 5	49.77	30.54
1 2 4 5 6	41.82	26.74	1 3 6	43.45	28.03
1 2 3 5 6	41.27	26.22	1 3 5	49.02	30.28
1 2 3 4 6	42.83	27.65	1 3 4	43.45	28.03
1 2 3 4 5	47.82	29.26	1 2 6	43.57	28.20
3 4 5 6	42.42	27.02	1 2 5	49.29	30.71
2 4 5 6	42.99	27.66	1 2 4	50.31	31.59
2 3 5 6	42.48	27.14	1 2 3	49.40	31.04
2 3 4 6	44.10	28.66	5 6	42.49	27.12
2 3 4 5	49.47	30.40	4 6	45.33	29.45
1 4 5 6	42.49	27.12	4 5	51.46	31.67
1 3 5 6	41.79	26.52	3 6	44.65	28.96
1 3 4 6	43.40	27.99	3 5	50.71	31.41
1 3 4 5	48.64	29.71	3 4	51.91	32.54
1 2 5 6	42.63	27.25	2 6	44.85	29.21
1 2 4 6	43.51	28.14	2 5	50.93	31.86
1 2 4 5	48.90	30.05	2 4	52.03	32.83
1 2 3 6	42.88	27.70	2 3	51.13	32.27
1 2 3 5	48.20	29.90	1 6	44.16	28.54
1 2 3 4	49.31	30.98	1 5	50.17	31.12
4 5 6	43.60	28.00	1 4	51.19	32.05
3 5 6	42.96	27.38	1 3	50.26	31.45
3 4 6	44.61	28.93	1 2	50.39	31.68
3 4 5	50.32	30.83	6	45.37	29.48
2 5 6	43.85	28.19	5	51.85	32.26
2 4 6	44.79	29.16	4	52.93	33.23
2 4 5	50.53	31.20	3	51.99	32.63
2 3 6	44.15	28.70	2	52.12	32.89
2 3 5	49.86	31.05	1	51.27	32.07
2 3 4	51.04	32.21	Current	53.00	33.27

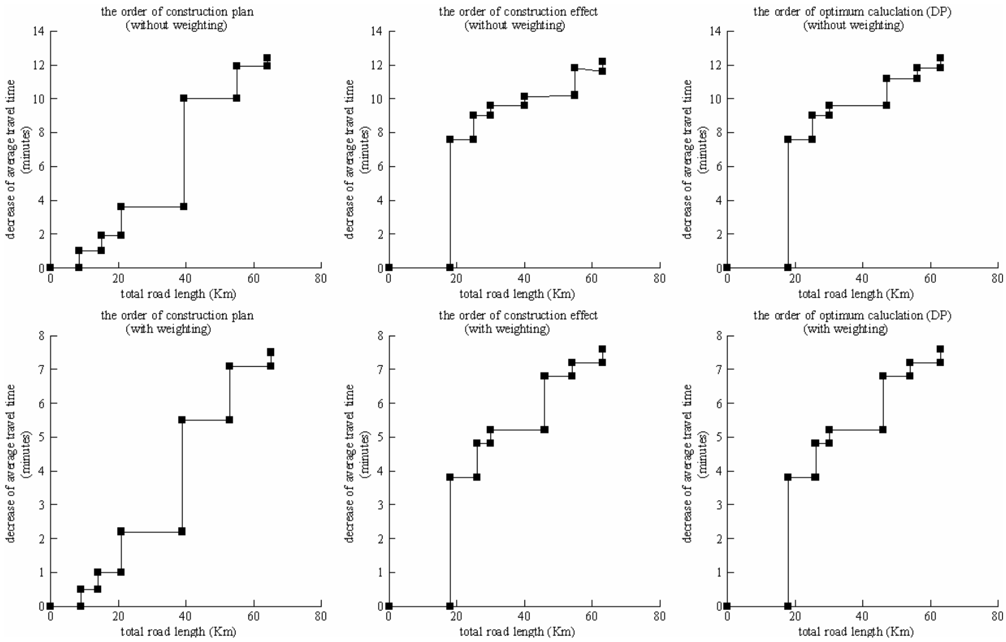

Fig. 8 Accumulation of time shortening by case.

5. Conclusion

This analysis, which uses the distance index between nodes, clarified that the construction of the planned road network would greatly impact the entire Fukuoka city region. At the end of the final stage of road construction, the average travel time and standard deviation in cases of no weighting are shortened by 12.3 minutes (14%) and 5.4 minutes (9%), respectively, for the whole region. This time shortening largely depends on large-scale shortening of the mobility between the surrounding districts and the city center as well as between surrounding districts. That is, it can be said that the construction of the motorway treated in this analysis will relatively improve the mobility of the surrounding districts of the Fukuoka city region, and it has the possibility to promote human and economic exchange in the surrounding districts.

The change of travel time was evaluated in both cases of with and without weighting by traffic volume. The advantage of an analysis without weighting is that the construction effects to the region can be evaluated as a possibility of development in the distant future when traffic demand can not be estimated. On the other hand, the advantage of an analysis with weighting by the OD traffic volume is that one can express the time shortening effect by one trip and can evaluate the real mobility. However, such an analysis leads to construction that overemphasizes traffic demand. The comparison of the results of the two analyses of the Fukuoka city region did not show a remarkable difference of contents regarding the effect of route construction.

In the examination of the order of route construction, the analysis of the accumulation of time shortening was analyzed with respect to three types of construction order until the completion of construction. As a result, it is understood that the evaluation value for the construction effect order is higher than for the construction plan order and that the former value is extremely close to the optimum order calculation by DP. The results show that priority is given to the routes extending from east to west and that the priority level of the routes in the center part is not high against the expectations.

With respect to this analysis, the introduction of DP was not as effective as expected, and consequentially the order of construction effect was sufficient. It will be necessary to examine the effectiveness of the optimum calculation again with a different road network.

This research aimed at measuring the mobility in city regions and revalued an actual road plan, but it did not ignore the existing plans. It is accepted that roads are generally constructed in the order considering the seriousness of problems of the area or the agreement of the residents. Such ideas and methods were found in the Fukuoka city region, and thus it is only natural that the order of construction based on the methods outlined in this research is different from the observed reality. However, it is important to create construction plans that take into consideration the influence of the road network on the development of the region as a whole, and therefore such ideas should be adopted into the evaluation procedures of road network planning in the future.

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