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Robustness of optimal inter-city railway network structure in Japan against alternative population distributions

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Abstract:

It takes long time and huge amount of money to construct inter-city railway network. Unexpected change of regional population or of the service level of competing transportation modes after the planning process, sometimes resulted in severe decrease of demand for the constructed railway lines. This paper discusses the robustness of optimal inter-city railway network structure in Japan against alternate population distributions. Genetic Algorithm is applied to find the best mixture of maximum operation speed category and number of daily train operation for each link, which maximize the total consumer surplus of nation-wide inter-city railway passengers. Besides the actual distribution of population in 197 Japanese local areas in year of 1995, we set four other hypothetic population distributions. We first obtain network structures optimized by the GA for each population setting. After that, we optimize train operation plans for different population settings. These results show that the actual spatial arrangement of high speed railway service in 1995 keeps optimality for wide range of population settings.

Keywords: Railway, Network Design, Genetic Algorithm, Robustness

JEL codes: R40,R42,C63

1. INTRODUCTION

It takes long time and huge amount of money to construct inter-city railway network. Careful demand forecasting and rational service planning are therefore required. However, long-range demand forecasting is always facing to unexpected changes of regional population or those of the service level of competing transportation modes such as airline. Those changes sometimes resulted in severe decrease of demand for the constructed railway lines and discussion of abolishment of train service occurs. In order to avoid such a tragedy, we want to build a robust network plan not vulnerable for the changes in the forecasting conditions.

This paper discusses the robustness of optimal inter-city railway network structure in Japan against alternate population distributions. Genetic Algorithm is applied to find the best mixture of operation speed category and number of daily train operations for each link, which maximize the total consumer surplus of inter-city railway passengers. Consumer surplus is assessed by a gravity demand model considering service level along several routes for each OD pair. Travel time calculated by the allocated link speed category, the allocated train frequency, and the estimated rail fare regressed by the travel speed, will be summarized as route service level via binary logit route choice model parameters. In the GA, we consider a chromosome consists of two parts; speed category of 275 links and relative operation distance of trains in those links.

Besides the actual distribution of population in 197 Japanese local areas in year of 1995, we set four other hypothetic population distributions; two of them concentrate in megalopolises like Tokyo and Osaka, the others disperse to geographically remote areas.

We first obtain network structures optimized by the GA for each population setting. Speed category allocations for the five network plans will be compared. Secondly, we calculate total consumer surplus of each network plan under the different population settings and discuss the vulnerability of those plans. Thirdly, we optimize train operation plans for different population settings under the given speed category arrangements.

The results show that actual spatial arrangement of high speed railway service in 1995 keeps optimality for wide range of population settings, if we adjust number of trains according to alternative population distribution.

This paper is organized as follows. **Section 2** reviews the preceding attempts of optimizing design of transportation network, and discuss the unique characteristics of railway network design problem. **Section 3** explains the GA procedure to find the best mixture of operation speed category and number of daily train service for each link. This part also shows how we calculate the consumer surplus as objective

function. **Section 4** shows the result of network design calculations under five different scenarios of the population distribution, and discuss the robustness of the calculated network design. **Section 5** summarizes the consideration, and further research issues.

2. TRANSPORTATION NETWORK DESIGN

2.1 Optimal network design attempts

There are many researches so far, which optimize transport network using the genetic algorithm, but many of them were done for the expressway and the air network.

In case of expressway network, increase of traffic in certain link causes increase of travel time and then the attractiveness of that link will be diminished. We can suppose a finite traffic increase when the travel time of link is reduced by the road improvement project. The increase of the traffic and benefit of road improvement are monotonous to the input used for the improvement project of the network. It takes long time to improve the road network, but in many developed countries, conventional highway network is already existent and the present traffic flows on it. So, we can assume that the bottle necks in the present network show the need of improvement or bypasses. As a result, network improvement planning become simple; based on the present congestion level, picking up bottle necks and compare the effect of improvement alternatives.

In the aerial network, the operation frequency strongly influences on the service level of the route, but the condition of the infrastructure such as airport gives weaker effect. In other words, they can change the service level to large extent in short-run, according to the change of the population and the demand. In such short-run situation, scheduling is strongly subjected by the availability of aircrafts, crews airport slots, and so on. Adding to the engineering aspects, competition among airline carries makes the problem more complex, if we consider the reaction of the passengers to the air fares. Short-run simulations and game theoretical analyses are insightful for such competitive situation.

2.2 Characteristics of railway network design

With contrast to these two modes, the railroad network design is complex. Both the travel time which depends on the railway track design standard and the frequency of the train operation influence on the service level. Therefore, the strategy of the long-range facility development and the short-range decision making of the operation must be considered in the same time.

There is a circular causation between the level of service and the number of the passengers; frequent operation on high demand route will gather the number of

passengers again.

Railway service level on one route is determined by the service level of many links along the route. Then the service level of routes for the different ODs become complement each other, if any common link is found along the two routes. Therefore, if they improve the common link in order to improve the service level of one route, the service level of other routes will be unintendedly improved. Such spatially complement relationship can not be seen in air network, where most flight links are corresponding to the major OD pairs.

Consequently, railway network design problem become very complex in nature, and to be analyzed both short and long range perspective.

3. RAILWAY NETWORK DESIGN PROBLEM

3.1 Problem Setting

In this research, the problem to optimize two elements, track standard deciding the operation speed and train frequency of each link, at the same time, in order to get efficient railway network design.

We consider the railway network with 275 links (actually operated by Japan Railway Companies) connecting the 194 local areas in Japanese four main islands. Design variables are the operation speed rank S_i and the number of express trains operated in one direction per day F_i on each link i . The distance of each link is exogenously given as d_i .

The designed network is evaluated from the passenger's view point; convenience. We measure it by the total consumer surplus for the nation-wide railway passengers, calculated through the demand simulation of the OD pairs of which we could observe the travels in the 1995 survey.

3.2 Consumer Surplus Measurement

For the evaluation of the alternative network design, we employ the total consumer surplus of the nation-wide railway passengers. For each alternative, through the demand estimation of all OD pairs where the passenger flow was observed in the 1995 survey, total consumer surplus is calculated by the following equation,

$$H = \sum_{OD} \frac{1}{\phi\beta_{GC}} (T_{OD}^{NW1} - T_{OD}^{NW0}) \quad (1)$$

where, T_{OD}^{NW1} :the estimated number of travels for the alternative network,

T_{OD}^{NW0} :the actual number of travels surveyed in 1995,

ϕ, β_{GC} : parameters(to be appeared afterwards).

The trips among the cities are influenced by the population of the cities, the distance between the departure and the destination cities, as well as the service level

for the OD. Such causation is described by the following gravity type model. The parameters of the model were statistically estimated using the number of railroad passenger, extracted from the Net Passenger Travel Survey in 1995 among the 194 Japanese local areas.

$$T_{OD}^{NW} = \Lambda(N_1)^\alpha(N_2)^\beta d_{OD}^\gamma (LOS_{OD})^\phi \quad (2)$$

where, N_1, N_2 : Population of the two cities ($N_1 > N_2$) (10,000 inhabitants),
 d_{OD} : distance of the shortest railway route (km), LOS_{OD} : service level between the two cities, $\Lambda, \alpha, \beta, \gamma, \phi$: parameters to be estimated.

The service level between the two cities is synthetically described by the following “log-sum” utility of the available routes,

$$LOS_{OD} = \prod_m \exp(V_m) \quad (3)$$

where, V_m : systematic utility level of the alternate route m for the OD.

The estimated value of the parameters are given as follows; $\Lambda = 6833.3, \alpha = 0.55, \beta = 0.48, \gamma = 0.88, \psi = 0.89$.

Here, we build a route choice model of the railroad passengers. For every OD, the binary choice between the first and the second shortest routes is expressed by the following logit type model.

$$P_{ODm} = \frac{\exp(V_m)}{\exp(V_1) + \exp(V_2)} \quad (4)$$

where, P_{ODm} : calculated share of the route m in the passengers for the OD,

The systematic utility of each route is calculated by the following function of the generalized travel cost and the expected waiting time.

$$V_m = \beta_{GC}GC_m + \beta_W W_m + \beta_c c_m \quad (5)$$

where, GC_m : generalized travel cost of route m (10,000 yen),

W_m : expected waiting time for route m (hour),

c_m : dummy constant for the shortest route,

$\beta_{GC}, \beta_W, \beta_c$: parameters to be estimated.

These parameters were also statistically estimated using the 1995 survey data, as follows; $\beta_{GC} = -0.15, \beta_W = -0.15, \beta_c = 1.46$.

In order to get the generalized travel cost from the rail-fare and travel time, the time value is considered to be 3,000 yen/hour. Further, the fare is considered to reflect the difference of the provided train speed.

$$GC_m = C_m + 0.3T_m \quad (6)$$

where, C_m : railway fare of route m (10,000 yen),

T_m : travel hour of route m (hour).

Travel hour is given as the summation of link travel time and changing time, if the conjunctive links have very different speed ranks.

$$T_m = \sum_{k \in m} \frac{d_k}{S_k} + s_m \quad (7)$$

where, S_k : operation speed of link k ,

s_m : required train changing time along route m .

The waiting time actually depends on the number of trains which go through the route from origin to the destination city. Passengers can also use two or more trains if their time table is well coordinated for changing. Because of data availability, we do not use train time tables, but the number of trains operated on each link are available. Therefore, in our analysis, we first find the least frequent link along the route in consideration, and use the number of trains on that link as the frequency of the route within 18 hours from 6 to 24 o'clock. Expected waiting time is then calculated by the following equation,

$$W_m = \frac{18}{F_m} \frac{1}{2} \quad (8)$$

where, F_m : number of the trains per day on the least frequent link along the route m .

The concrete evaluation process is as follows; For each alternate route for each OD pair, we find first the least frequent link and calculate the expected waiting time W_m by (8). From the given speed rank of link S_k and the exogenous distance d_k , we calculate the travel time through (7). Rail fare C_m is considered based on the average speed of route, and calculate the general cost GC_m by (6). Synthesizing those values by (5), we get utility level V_m for each route.

Based on (3), we get service level of each OD pair from those utilities. At last, the gravity model (2) teaches the number of passengers T_{OD} for the consumer surplus equation (1), based on the exogenously given population of the cities N_j .

3.3 Definition of the gene

The network design problem formulated above contains huge number of variables, and non-linear for them in the nature. Then, we rely on GA (genetic algorithm), one of the most popular heuristic optimization methods, to get quasi-optimal network design, which is composed by the track standard deciding the operation speed and train frequency of each link.

We consider the railway network with 275 links (actually operated by Japan Railway Companies) connecting the 194 local areas in Japanese four main islands. Design variables are the operation speed rank S_i and the number of express trains operated in one direction per day F_i on each link i . The distance of each link is exogenously given as d_i .

Hereafter, we call the arrangement of operation speed rank of each link as “network plan”, while we call the arrangement of train frequency of each link as “operation plan”. In our GA procedure, we use the chromosome consisted of two parts. The former half of it contains the arrangement of gene for speed rank of each link, while the latter half contains gene specifying the train frequency of each link.

For the speed rank S_i , we consider four categories of rail track standards; rank 1 is full standard of Shinkansen (High speed rail system with standard gage), rank 2 is “mini Shinkansen” (Standard gage but steep curvature or inclines, rank 3 is electrified conventional lines, and rank 4 means un-electrified conventional lines. According to the actual operation speed of links, categorized as those four types in year of 1995 as shown in **Figure 1**, we set the average operation speed as follows; rank 1: 178 km/hour; rank 2: 118 km/hour; rank 3: 74 km/hour; and rank 4: 48 km/hour.

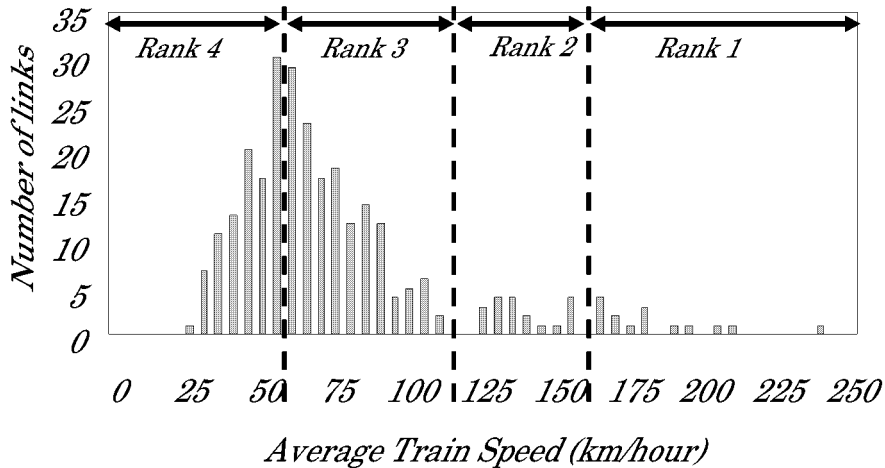


Figure 1. Operation speed of 275 links of JR in 1995

As for the construction cost, rank 1 track requires most, because it is elevated or tunneled to avoid the crossings with highway or other railways. rank 2 or 3 tracks require less than rank 1 but still more cost than rank 4, because of milder curvature and incline. Therefore, we consider the constraints of total distance of links for rank 1 through rank 4, in order to limit the required construction cost. We use the following distances; rank 1: 1,174 km; rank 2: 975 km; rank 3: 8,716 km; and rank 4: 6,321km. Two bits numbers, 1 through 4 are used for the gene meaning the speed rank of 275 links. If the total distance of each category exceeds the limit, the speed rank arrangement will be adjusted such that total length goes within the limits.

In order to determine the train frequency, we consider the total operation length

per day in each link. According to the actual operation in 1995, JR trains run 347,451 km per day. We describe the relative operation distance by the six bits numbers between 1 and 64. With proportion to those numbers, we distribute the train operation length into 275 links, then that length will be divided by the exogenously given length of the link d_k . Then we set the number of trains in one direction per day, F_k .

3.4 Performance of the GA

Standard genetic algorithm, composed by selection, crossover and mutant processes is applied for the set of randomly produced 50 individuals. Despite the dual structure of the chromosomes, we apply a single point crossover operator and top five elite individuals are left without crossover operation in the succeeding cycle. Those calculation cycle is repeated until the consumer surplus seems to be saturated.

The plot A in **Figure 2** shows the improvement trajectory of the consumer surplus value of the best individuals along the number of the iterations. The value seems to be saturated around 1,000 times iterations, but we repeated the calculation 5,000 times.

If we apply such genetic algorithm process only to the latter part of the chromosome, we can obtain the optimal train operation plan for the given network plan. The improvement trajectory shown as plot B in **Figure 2** illustrates the typical change of the value. Comparing to the full optimization using total chromosome, the operation optimization shows swift increase of the objective value, but it takes more iterations to reach the saturation. We also employ 5,000 times iterations for the operation optimizations.

4. ROBUSTNESS OF NETWORK DESIGN

4.1 Alternate distributions of population

Because the consumer surplus which is the evaluation measure for each individual in the GA process, strongly depends on the population distribution in each zone through the gravity model (2), the optimized network plan as well as operation plan can become very different ones, if we give the different distributions of population. We want to clarify the robustness of those plans against the changes in population distribution, which are sometimes unavoidable for the long range planning situation.

In order to analyze the robustness, we consider the actual distribution of population in 197 Japanese local areas in year of 1995 (case 0), and four other hypothetical population distributions; two of them concentrate in megalopolises like Tokyo, Nagoya and Fukuoka, the others disperse to geographically remote areas. The total population of all 197 areas is kept constant as the case 0.

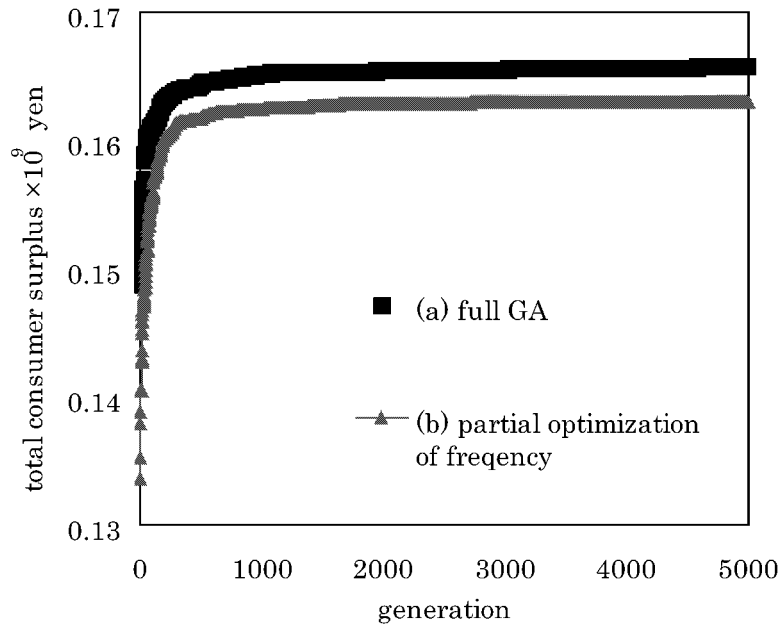


Figure 2. Trajectories of total consumer surplus in GA process

Since the late 1990s, population distribution are concentrating to Tokyo Metropolitan area, especially to the prefectures in outskirts of the metropolis. Shiga prefecture at the outskirts of the Osaka metropolis also gathers many Inhabitants. The Institute of Population and Social Security problems of Japan provides the estimation of the population in year of 2030, based on the recent trends of concentrating changes. Then, we use that estimation of prefecture population, in order to set the first hypothetical concentration pattern (case C1). We enlarge the actual population of each local areas in 1995 by the growth rate of the prefecture population (pop_{2030}/pop_{1995}).

Secondly, we set strongly concentrated distribution (case C2), by enlargement the difference between the actual case 0 and the above concentration case (case C1). In these concentrated distributions, Kanto region including Tokyo metropolitan area, Shiga and Fukuoka prefecture enjoy larger population, while the geographically remote areas such as Hokkaido, Tohoku, Hokuriku and South Kyushu areas lost the inhabitants.

Thirdly, we consider the hypothetical distribution dispersed to geographically remote areas (case D1), shifting the difference of case C1 from case 0 to the opposite direction. Then, geographically remote areas such as Hokkaido, Tohoku, Hokuriku and South Kyushu areas gain the inhabitants, than the actual distribution in year of 1995.

At last, we enlarged the shift of case D1 from case 0, and further add some

amount of population onto several local cities located in remote areas, then made the strongly dispersed distribution (case D2).

Table 1 shows the given population for nine sub-regions by the above five cases. While case C1 and D1 seems within the realistic shift of population in a few decades, case C2 and D2 seems too much exaggerated and unrealistic.

Table 1. The given population for nine sub-regions

sub-region	case D2	case D1	case 0	case C1	case C2
Hokkaido	13.12	6.21	5.69	5.10	0.94
Tohoku	22.24	10.37	9.83	9.22	4.46
Kanto	7.18	36.69	39.52	42.74	67.23
Hokuriku	0.29	6.94	6.50	6.00	1.60
Tokai	4.78	16.72	16.74	16.77	12.58
Kinki	5.36	20.73	20.63	20.51	25.14
Chugoku	23.19	8.36	7.77	7.10	1.85
Shikoku	8.34	4.56	4.18	3.76	0.72
Kyushu	39.80	13.71	13.42	13.10	9.78
Total	124.3	124.3	124.3	124.3	124.3

(million inhabitants)

4.2 Optimized network for the actual population pattern

For each population setting, our GA procedure was applied to find the best network plan and operation plan.

First, we see the result of the GA design for the actual population distribution case 0. We focus the layout of the links of speed ranks 1 and 2, because those ranks can be realized by the “Shinkansen ” of exceptional standard gage, where trains for conventional lines on the narrow gage track can not go through. This is why we consider the changing time at the node where rank 1 or 2 link and rank 3 or 4 link meet.

The best network plan for the actual population distribution (case 0) is shown in **Figure 4**, contains the Shinkansen links, similar at the place of the actual layout shown by **Figure 3**. Besides the actually existent Shinkansen from Tokyo to Fukuoka, through Nagoya, Osaka and Hiroshima, several short branches from Gifu and Kyoto to the northern side are added in the proposed design. Tohoku Shinkansen is expanded from Morioka to Hachinohe, but that part was actually opened in 2003 in reality. The Joetsu Shinkansen is operated from Tokyo to Niigata city, just as the actual situation in 1995, but Yamagata line was not designed as rank 2 in our GA calculation.

The operation plan optimized with the above network plan at once for case 0, is shown in **Figure 5**. This figure shows the frequent operations are set in Kanto

and Kinki regions around the Tokyo and Osaka metropolises. The frequency is also high on the rank 1 links shown in **Figure 4**, such as Tokaido Shinkansen, linking the two metropolises. Railway links between Kinki and Hokuriku areas are also frequently operated.

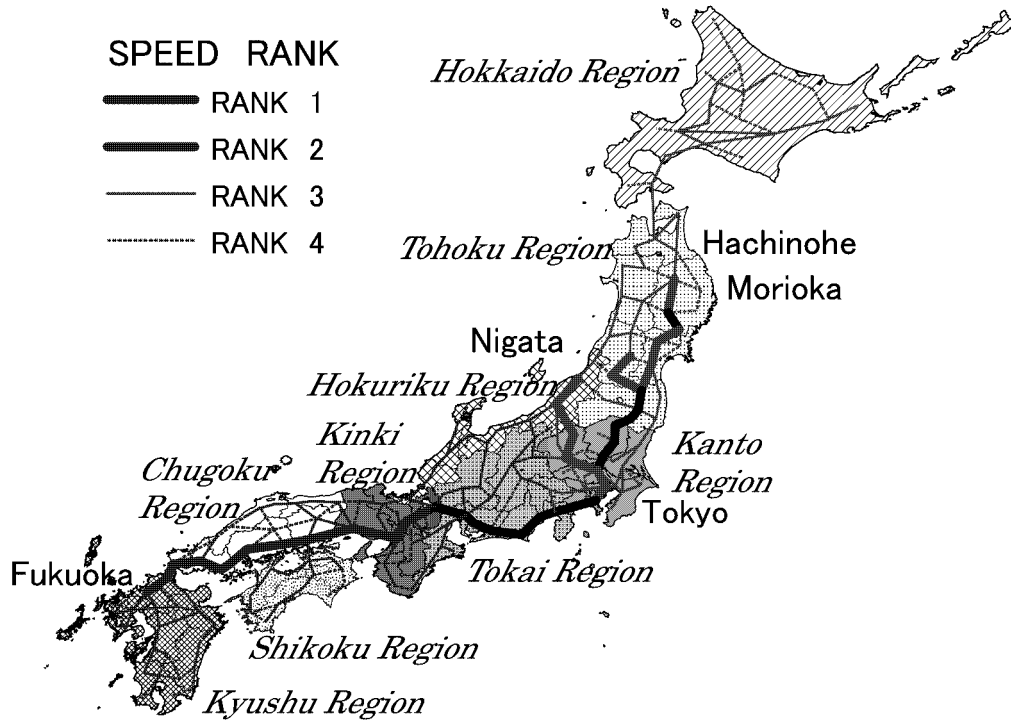


Figure 3. Speed rank, actually provided in 1995

4.3 Optimized network for the alternate population patterns

For the four alternate population settings, our GA procedure were applied to find the best network plan and operation plan. Speed category allocations for those four cases are shown in **Figures 6-9**. Two cases under the mild change in population distributions (case C1 and D1), there is no particular difference from the network design for case 0. actually existent Tohoku, Joetsu, Tokaido and Sanyo Shinkansen lines from Morioka/Niigata to Fukuoka via Tokyo, Nagoya and Osaka metropolises are appeared, and some short approach links to Hokuriku region are added.

Two other cases with exaggerated changes in population distribution case C2 and D2, Only the westward Tokaido and Sanyo Shinkansen appear, but the northward Tohoku and Joetsu lines diminished, except the parts in the Kanto Region. Besides the actual Shinkansen lines, those two cases support the short links in Shikoku, Kyushu and Hokkaido islands, where the railway demand is relatively high without middle distant air flight service.

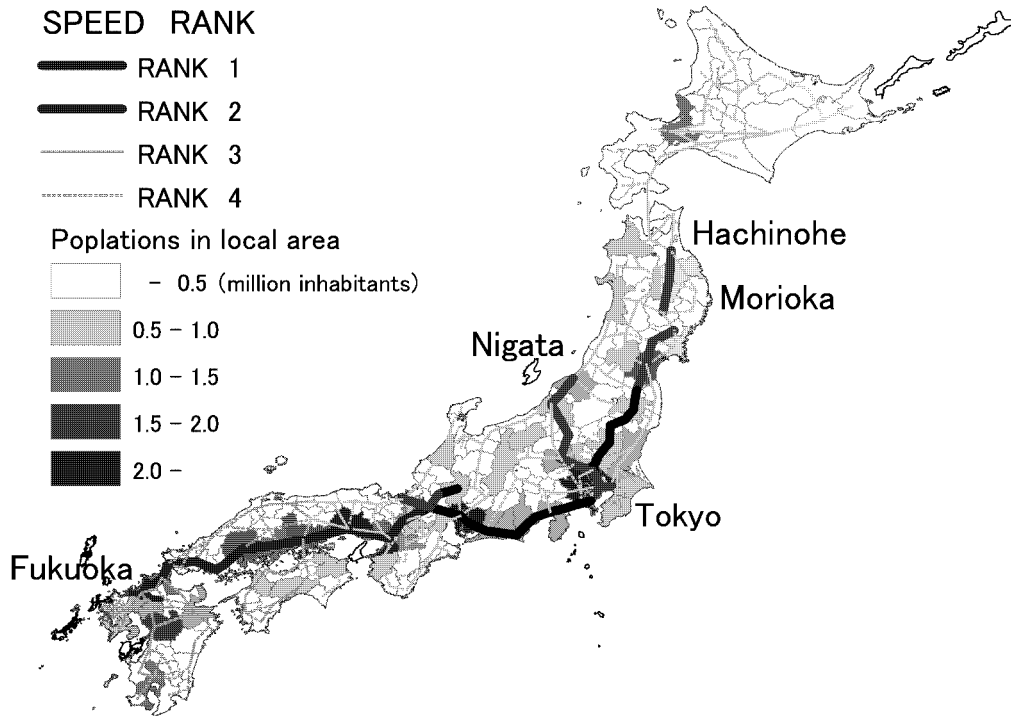


Figure 4. Speed rank optimized in Case 0

Because we had produced the C1 and D1 distributions based on the future estimation of population in 35 years, the population change expectable for 30 years is considered to be within the difference between these two cases. From the comparison of the designed networks in cases 0, C1 and D1, the actually opened Shinkansen lines of Tokaido, Sanyo, Tohoku and Joetsu are concluded to be very stable.

4.4 Robustness of the optimized network for population change

In order to check how the calculated network plans are robust, we calculate the total consumer surplus of each plan when applied to the other population distributions. As shown in **Table 2**, the evaluation depends strongly on population distribution than the difference of the network plans.

It is natural that the optimized network always shows the best performance for the corresponding population distribution, than any other plans; it shows the credibility of the GA optimization. Three network plans optimized for cases 0, C1 and D1 give similar result when applied to the corresponding three population distributions, those values can not be reached by the network plans optimized for C2 or D2. In other words, these network plans seem robust for the population change expectable for a few decades.

Despite of lacking short-term flexibility of network plan, we can adjust the op-

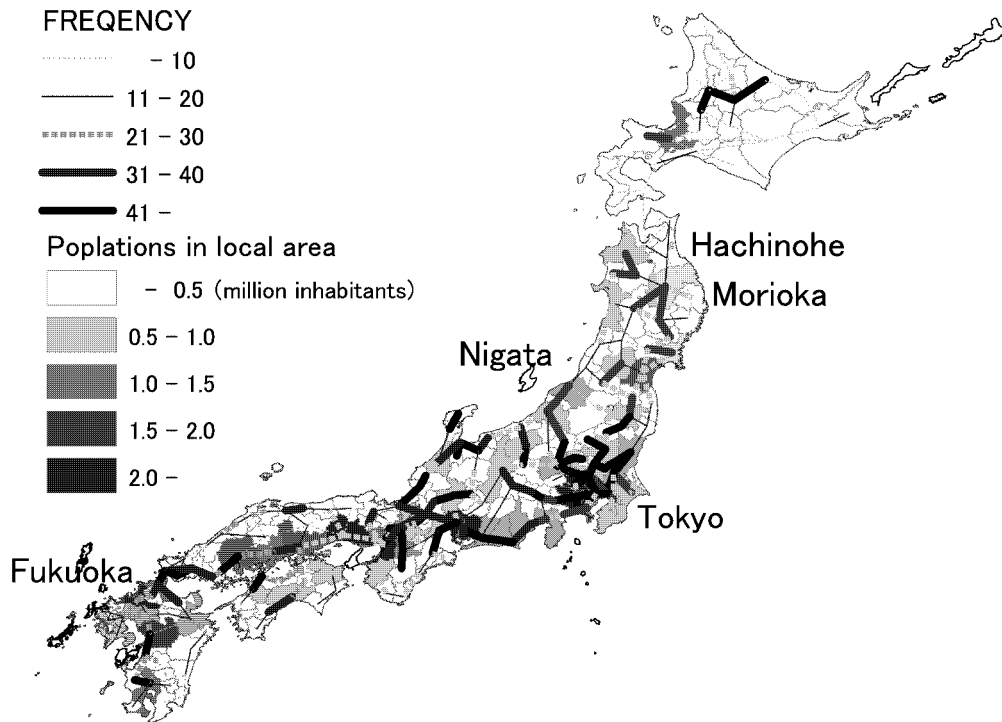


Figure 5. Frequencies optimized in Case 0

Table 2. Total consumer surplus for other population cases

Network \ Population	Case D2	Case D1	Case 0	Case C1	Case C2
NW optimized in D2	179.9	160.4	159.4	157.7	194.2
NW optimized in D1	175.5	166.3	164.2	162.6	199.1
NW optimised in 0	173.7	165.2	165.3	162.6	199.0
NW optimized in C1	174.3	165.3	164.4	163.6	199.3
NW optimized in C2	175.2	164.7	163.7	162.1	201.7

(in 10^6 yen/year)

eration plan, after the difference of population distribution will appear. Partly optimization of operation plan for the fixed network design can be done by the GA process explained in **Sec.3**. The result is shown in **Table 3**, where you cannot find any significant difference of the performances for the four network plans, initially optimized for cases 0, C1,C2 and D2. The network plan initially optimized for case D2 can not perform well for the other situations despite of operation plan adjustment, because the network structure is much different from the other plans.

We can conclude that, the network plans can perform almost as well for the possible population change in a few decades, if the operation plan is adequately adjusted.

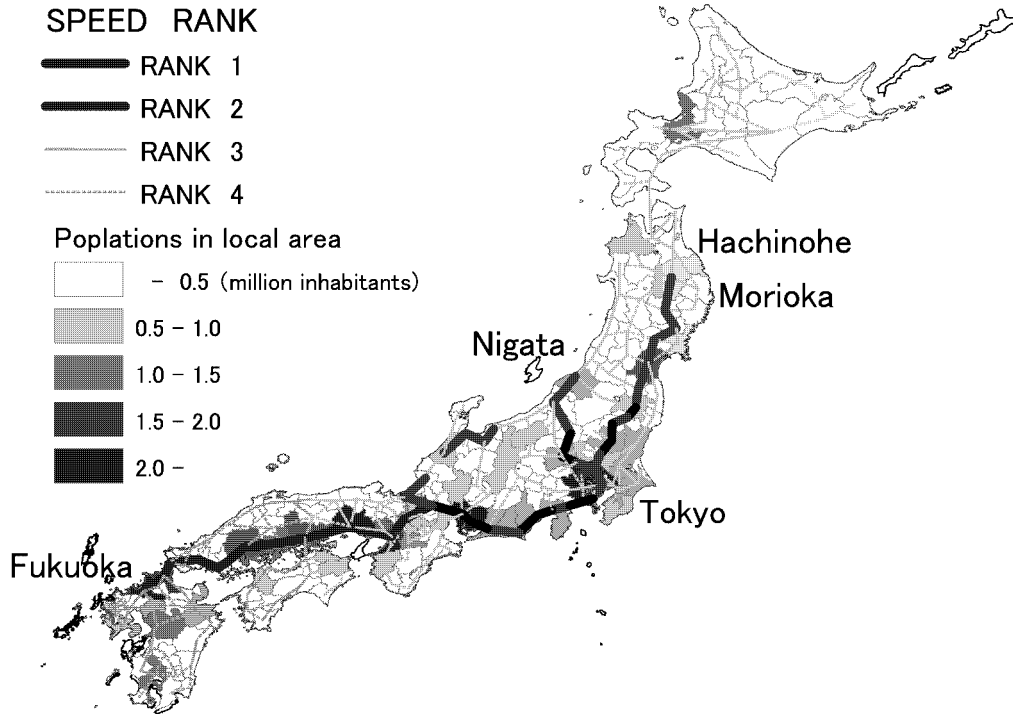


Figure 6. Speed rank optimized in Case C1

Table 3. Total consumer surplus after adjusting the operation plan

Network \ Population	Case D2	Case D1	Case 0	Case C1	Case C2
NW optimized in D2	179.9	164.5	163.4	161.8	198.4
NW optimized in D1	177.9	166.3	164.7	163.2	200.2
NW optimized in 0	177.1	165.8	165.3	163.3	199.9
NW optimized in C1	177.7	165.9	164.9	163.6	200.0
NW optimized in C2	178.3	165.6	164.8	162.9	201.7

(in 10^6 yen/year)

5. CONCLUSION

In this research, robustness of intercity network plan was assessed in term of the total consumer surplus. We proposed a genetic algorithm procedure manipulating the gene for speed of operation and those for frequency of trains of 275 JR links connecting the 197 Japanese local areas.

Based on the actual population distribution in 1995, four other hypothetical distributions were set, which have different concentration to the metropolises. The proposed GA process was applied to find the most efficient network for each of the five different population cases including the actual population distribution. Also, we assessed the total consumer surplus for the other distributions different from which the plan had been optimized for initially, and evaluated the robustness.

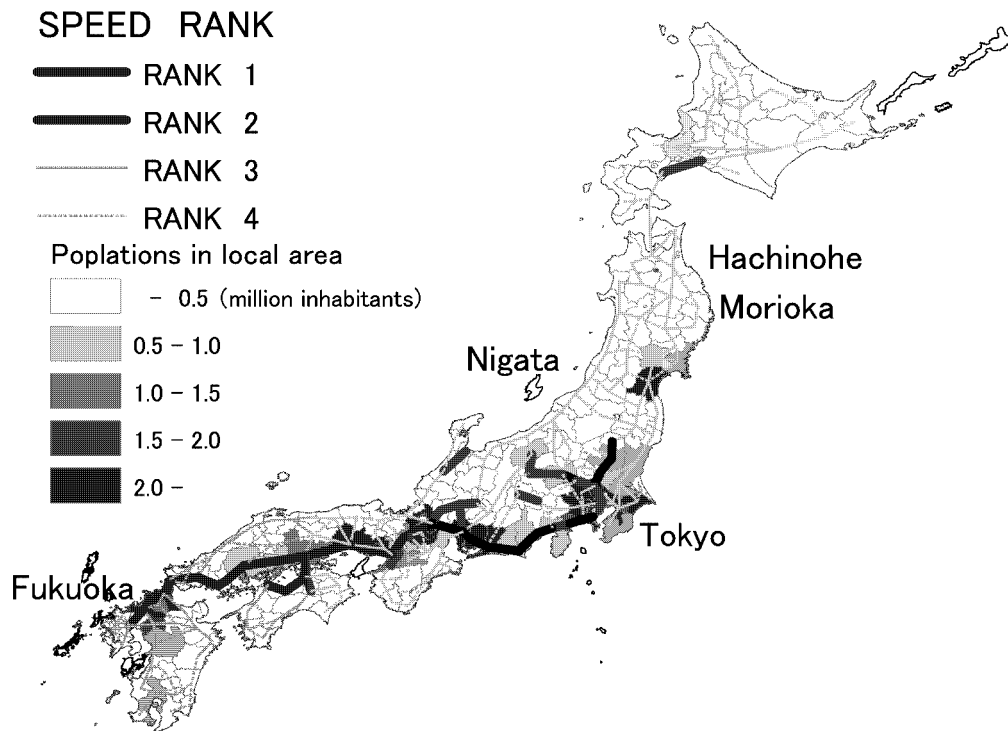


Figure 7. Speed rank optimized in Case C2

With the results of this study, they were found that actual railway network structure in 1995 robustly performs under the variation of population distribution possible in 30 years range. Tokaido, Sanyo, Tohoku and Joetsu Shinkansen lines from Morioka and Niigata to Fukuoka, via Tokyo robustly perform with the wider range change of the population distributions.

There are several directions for further research work. Our consumer surplus calculations are done not for all OD pairs between the 197 local areas, but for the OD pairs where we could observe the actual railway trips in the trip survey data in 1995. Route utility are also calculated only for the routes with report of use. These procedures may neglect new OD demands or new routes that become available by the improvements of links suggested in the GA process, consequently give affirmative evaluation to the networks similar to the actual network. We must think about the scope of calculation more carefully.

Besides the population distribution, analyzed here, service level of the competing transportation modes such as airway and express bus service may cause the quantitative change of travel demand. We should consider the way to analyze the effect of the competing modes in the long run network planning.

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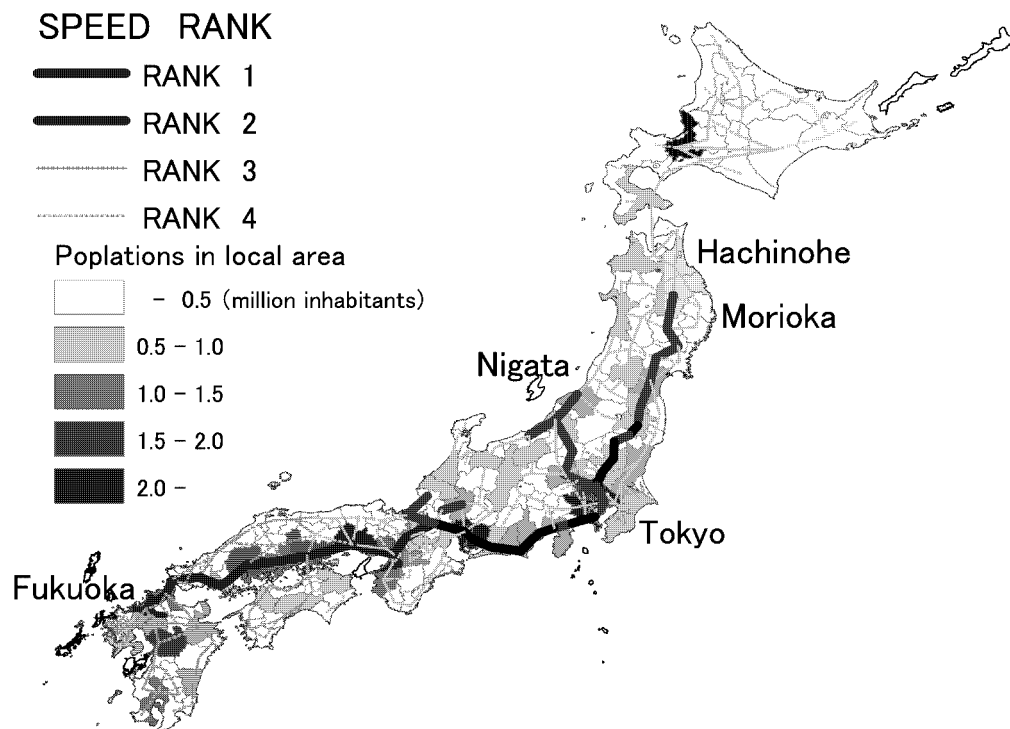


Figure 8. Speed rank optimized in Case D1

Hiroshima University.

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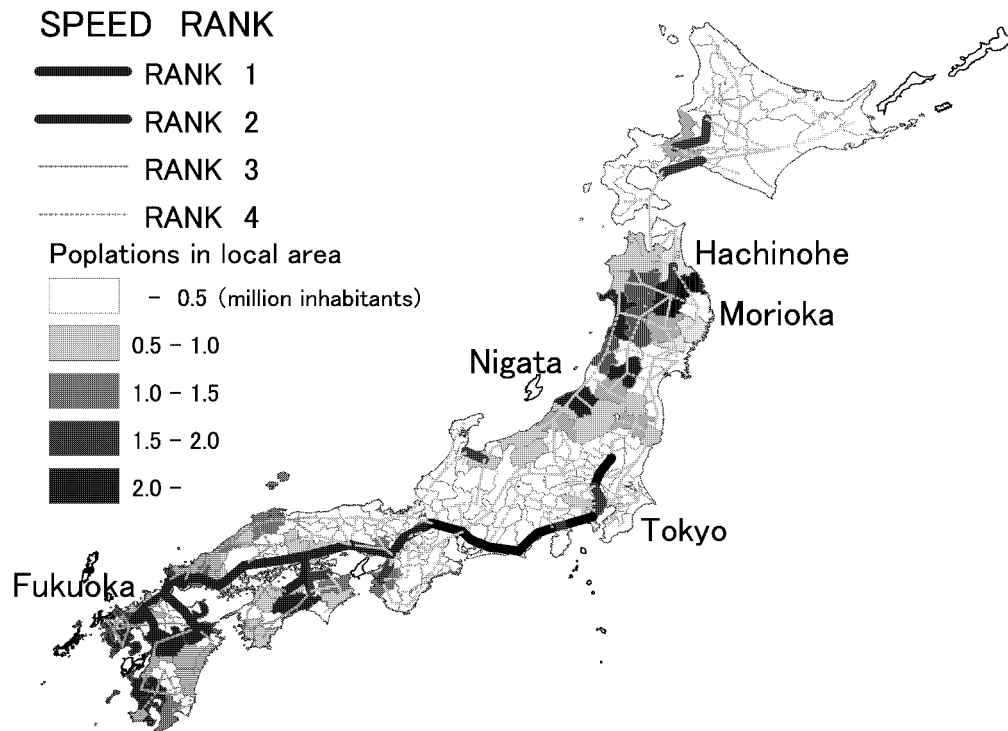


Figure 9. Speed rank optimized in Case D2

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