Optimization of Transport Infrastructure Upgrades Considering Air-Rail Interaction

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The object of this study is to analyze the interaction between HSR and airlines over Haneda Airport capacity distribution problem. Four levels of Haneda Airport capacity and four total lengths of HSR lines in Japan were analyzed. Distribution of Haneda Airport capacity to local airports and network shape of HSR lines were controlled by Genetic Algorithm to maximize consumer surplus, according to pre-defined constraints of total Haneda capacity and total HSR length. Results show that there is a complex interaction between rail and air transport. These modes are not always competitors and actually they may complement each other at some situations.

Key Words : *HSR, airlines, competition, cooperation, GA, network analysis*

1. INTRODUCTION

Traditionally, air and rail travel have been considered rivals for the direct intercity journeys because they provide similar travel times, frequency and comfort levels. This type of competition can be seen on the routes such as Paris-Lyon and Madrid-Seville which introduction of one mode lowered the share of the other[1)]. Besides, there is a growing tendency especially in Europe to regard the HSR and airlines as complementary modes rather than substitutive modes. This is largely due to the capacity constraints of airports, policy preference of EU Institutions toward railways and better environmental performance of railways. This type of cooperation was also realized on some routes such as Cologne-Frankfurt and Paris-Brussels and even alliances were formed between air and rail operators [2-3)]. On the other hand, there is not such example of air-rail cooperation in Japan despite having capacity problems, hub and spoke type air connections and highly developed high speed network similar to Europe. Possible reasons for this could be privatized rail and air companies, lack of direct HSR connections to airports and lack of detailed studies about air-rail cooperation.

In this study, we intend to analyze the possibility of HSR and air cooperation in Japan over the Haneda Airport capacity distribution problem. Because of the limitation of runways, total Haneda capacity apart from international flights needs to be distributed to airports across Japan in such a way that total domestic mobility is maximized. On the other hand, HSR network is being expanded by the new constructions which introduce new intermodal routes. This situation makes it a good example to find out how changes on one mode affect the other. However, complexity of the network and excessive number of links and nodes make it difficult to calculate the interactions by analytic methods. Instead, we implemented meta-heuristic approach to analyze the effects of Haneda Airport capacity change for different levels and change of HSR lines for different total lengths, based on the situation in the year 2000. Distribution of Haneda Airport capacity to domestic air routes and network shape of HSR lines were controlled by Genetic Algorithm to maximize consumer surplus, according to pre-defined constraints of Haneda capacity and total HSR length.

The paper is organized as follows. In section 2 network design, network analysis model and GA is explained. In section 3, HSR and air interaction is analyzed using several constraints on the model and results are discussed in Section 4.

2. METHODOLOGY

(1) Network Design

For the evaluation of alternative networks, we employed the total consumer surplus of the nation-wide intercity passengers over 300 km. 46 Prefectures besides Okinawa were used as zones, then 841 OD pairs over 300 km out of 1035 were considered. There were 275 rail links, 180 air links and 46 airport access links in the network. 26 out of 36 domestic airports that have flights to Haneda Airport were considered because 10 airports cannot be distinguished by the specified zoning system. Distance, fare, frequency and travel time data were taken from actual data for the year 2000. Existing rail network and Haneda Airport distribution for the year 2000 is shown in Figure-1. While fare and travel time information of air links and frequency of rail links were kept constant, frequency of Haneda flights and speed levels of rail links were selected as the design criteria to be controlled by the GA.

(2) Consumer Surplus Measurement and Model

For each alternative network, through the demand estimation of OD pairs, total consumer surplus is calculated by the following equation[4-5],

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

where, T_{OD}^{NW1}:the estimated number of travels for the alternative network, T_{OD}^{NW0}:the actual number of travels surveyed in 2000, ϕ,β_{GC} :parameters.

The population of the cities and the service level influences trips among the cities for the OD. The following gravity type model describes such causation. The parameters of the model were statistically estimated using the number of railway passengers, extracted from the Net Passenger Travel Survey in 2000.

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

where, N_1,N_2:population of the two cities (N_1>N_2) (10.000 inhabitants), LOS_{OD}: service level between the two cities, Λ, α, β, γ:parameters to be estimated using the survey data. Based on the previous study, value of the parameters are estimated as follows; Λ=0.123, α=1.29, β=1.14, γ=1.52 [4-5]. The service level between the two cities is synthetically described by the following "log-sum" utility of the three available

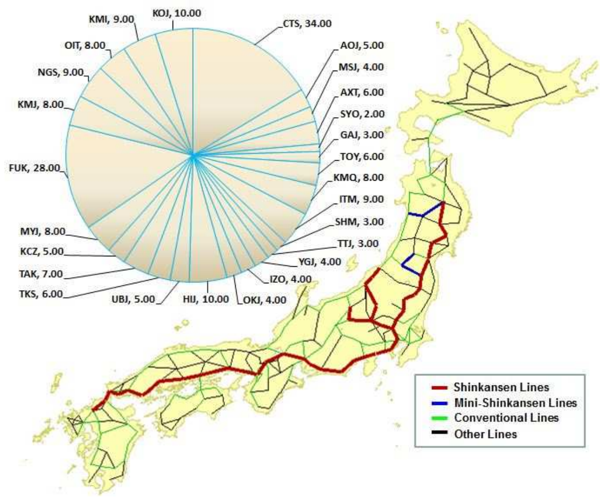

Fig.1 . Existing rail network and Haneda capacity distribution for the year 2000.

routes for the OD pair.

$$LOS_{OD} = \sum_m exp(V_{OD}^m) \qquad (3)$$

where, LOS_{OD} is systematic utility level of the altemate route m for the OD. Here, we build a route choice model of the inter-city passengers. For each OD pair, we consider the tri-nominal choice among a shortest time rail route and two inter-modal routes by a logit model. The systematic utility of routes is calculated by the following function of the generalized travel cost and the dummy variables for inter-modal routes.

$$V_m = \beta_{GC} GC_m + \beta_{m1} c_{m1} + \beta_{m2} c_{m2} \qquad (4)$$

where, GC_m: generalized travel cost of route m (10.000 yen), cm_1, cm_2: dummy constant for the first and second shortest inter-modal routes, β_{GC}, β_{m1}, β_{m2}: parameters to be estimated. These parameters were also statistically estimated using the 8622 samples of the survey data, as follows; β_{GC} =-0.16, β_{m1}=-0.12, β_{m2}=-1.62. In order to get the generalized travel cost GC_m from the fare C_m and travel time T_m, the time value is considered to be 3.000 yen/hour. Further, the rail-fare is considered to reflect the difference of the provided train speed.

$$GC_m = C_m + 0.3T_m \qquad (5)$$

where, C_m: fare of route m (10.000 yen), T_m: travel time of route m (hour). Travel time is given as the summation of link travel time, average waiting time and additional transfer time.

$$T_m = \sum_{i\in m} t_i + \sum_{j\in m}\frac{d_j}{s_j} + \sum_{k\in m} t_{ak} + w_m + s_m \tag{6}$$

where, t_i: exogenously given flight time of airline link i (hour), but 40 minutes is added for boarding and embarking time, d_j: length of rail link j (km), S_j: operation speed of railway link j, t_{ak}: exogenously given travel time of airport access link k from the nearest railway node (hour), w_m: average waiting time (hour) along route m, and s_m: additional transfer time between standard gauge and narrow gauge trains, 10 minutes is added if only one of conjunctive links is HSR and the other is conventional. The approximated waiting time w_m is calculated as expected waiting time for the representative frequency of route m.

$$W_m = \frac{1}{2}\frac{18}{F_m} \tag{7}$$

where, F_m : number of the trains or flights per day on the least frequent link along the route m. Once, control variables F_i and S_j are given, w_m and F_m are re-calculated through Eq.(7). Combined with other exogenous variables such as flight time, fares, frequency of railway links, time and fare for airport access links, we can calculate the OD demand and consumer surplus inversely through Eq.(l)-(6). Furthermore, number of air route passengers can be calculated as follows;

$$X_m^{OD} = T_{OD}^{NW}\frac{\exp(V_m)}{\sum_{m'\in OD}\exp(V_{m'})} \tag{8}$$

$$XX_i = \sum_{OD}\delta_{im}X_m^{OD} \tag{9}$$

where, X_m^{OD} : passenger flow of given OD through route m, δ_{im}, dummy variables indicating whether route m include link i or not, XX_i, :expected number of passengers at link i. In order to avoid excessive demand larger than available seats for airplanes, flight frequency FF_i is calculated as follows to replace it with initial frequency F_i.

$$FF_i = \sum_{i'} F_{i'}\frac{\max(F_{i'},(XX_i/xx))}{\sum_{i'}\max(F_{i'},(XX_{i'}/xx))} \tag{10}$$

where, xx : average number of seats in an aircraft, here, we set xx = 300 , reflecting that middle or large size aircrafts are used for Haneda line to secure maximum number of seats under the limited operation capacity.

(3) Genetic Algorithm

For the GA procedure, 60 individuals were used to represent alternative networks. An individual was composed of two parts as one for 275 rail link genes and the other for 28 Haneda Airport capacity distribution genes. Each initial rail gene can take integer values between 1 and 4 randomly to represent four speed levels as 178 km/h, 118 km/h, 74 km/h and 48 km/h. This speed levels are intended for reflecting the type of rail link as Shinkansen, mini-Shinkansen, electrified conventional lines and non-electrified conventional lines, respectively. Each Haneda gene could take values between 1 and 30 randomly to represent frequency of related air link. There were two constraints on the formation of alternative networks. First is total length of HSR lines and the other is total number of Haneda flights.

GA is carried out at as follows. First, initial networks are generated randomly. After constraints check, passenger demand for each link on each network is estimated using the model explained above. Then, each network is evaluated using performance criteria and ranked according to performance score. Top five individual are selected as elite ones and transferred to next generation without cross-over operation. Other individuals are subject to two point cross-over, one for each half. Roulette wheel is used to select parents and crossover points are selected randomly. 2 bits mutation is also applied to 5 individuals in each generation. Thus, children networks are generated at the same number of parents and the process continues to next iteration. Finally, the process is terminated when maximum number of iterations (30.000) is reached and the best network is selected as the solution.

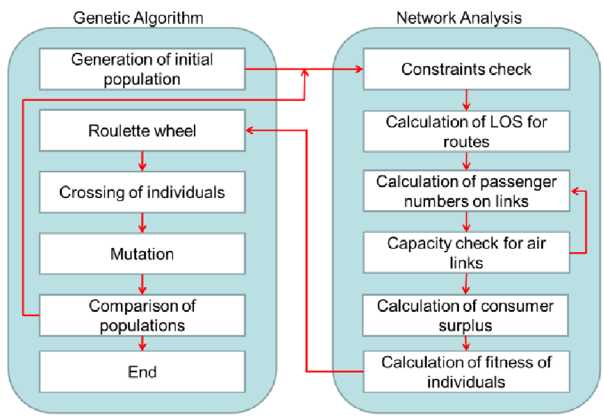

Fig.2 . Flow chart of the Genetic Algorithm

3. ANALYSIS

GA was run to find near-optimal network solutions for 4 different levels of Haneda Airport capacity as 200, 350, 450 and 550 and 4 different total HSR lengths as 1442 km, 1922 km, 2284 km and 3364 km. Situation for 250 Haneda capacity and 2403 km total HSR lines was used as the base case. Figure-3 shows the near-optimal solution reached by GA for the base case and it is quite similar to the existing network in year 2000.

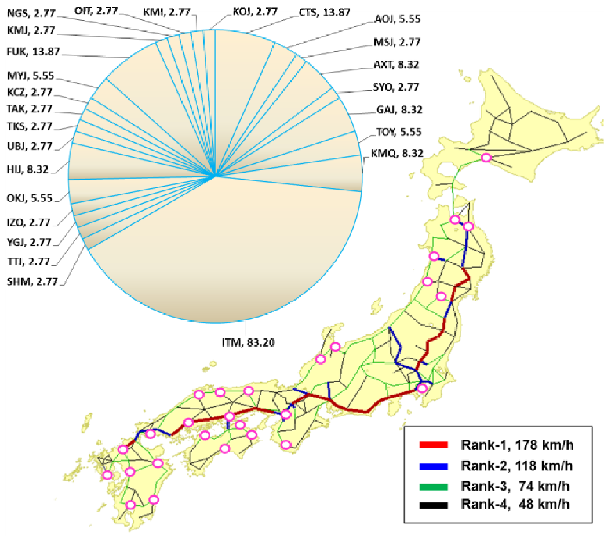

Fig.3. Near-optimal solution network and Haneda capacity distribution for the base case.

Figure-4 shows the effects of Haneda capacity change and total HSR lengths change on passenger numbers. It can be seen that Haneda capacity change causes steeper increase of passenger numbers than rail lengths change at the first steps. Then, effect of Haneda capacity change become lesser at higher levels but effect of rail lengths change continues by the same slope.

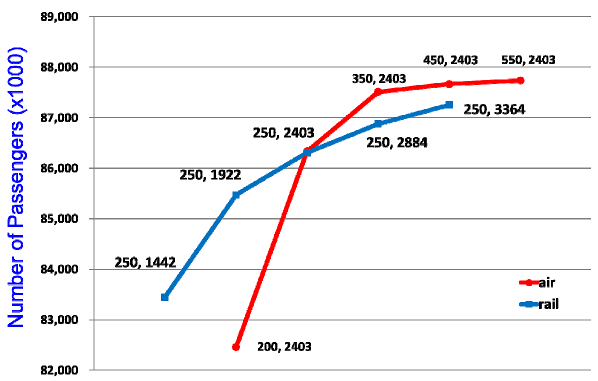

Fig.4 Effects of Haneda capacity change and total HSR length change on passenger numbers.

Figure-5 shows the change of passenger numbers when both Haneda capacity and total HSR lengths changed together. At the first levels both improvements give quite good solutions for total passenger numbers than higher levels and this graph can be useful to determine minimum infrastructure level to achieve a certain level of network performance.

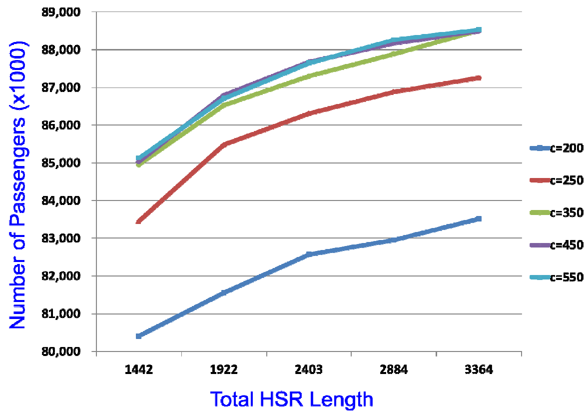

Fig.5 Effects of Haneda capacity change and total HSR lengths change on passenger numbers when changed together.

In order to analyze air-rail interaction, we first changed the Haneda capacity while keeping total HSR length constant (2403 km) and then changed the total HSR length while keeping Haneda distribution constant (250). Figure-6 shows the first situation. Here, increasing Haneda capacity also increases the benefit of rail operators, but eventually increase become lesser and even revenues start to decrease. On the other hand, increasing length of HST lines also increases the revenue of air operators, but similarly, after one point air revenue is affected negatively, as shown in Figure-7.

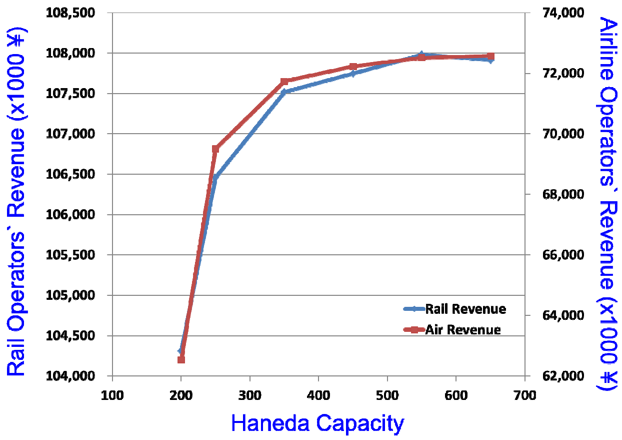

Fig.6. Effects of Haneda capacity change on revenues of rail and air operators.

What we can deduce from Figure-6 and Figure-7 is that until reaching "saturation" points, improvements on both modes affect each other positively, if the cooperation is established. Here, saturation means that service level of one mode is so much increased that alternative intermodal routes lose their attractiveness's and complimentary effect becomes insufficient to cover passenger numbers diverted to the rival mode. Considering the situation in the year 2000 which is the base case for this study, it is apparent that there is still room for improvements before reaching saturation points for both modes. Therefore, it can be beneficial for HSR and air operators to develop transport network mutually and focus on cooperation possibilities rather than detrimental competition.

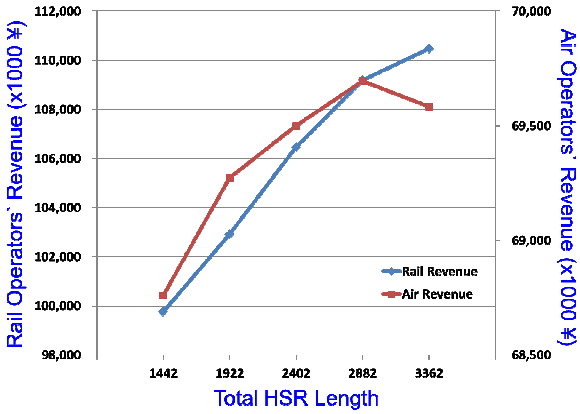

Fig.7. Effects of total HSR length change on revenues of rail and air operators.

4. CONCLUSION

HSR and air transport have different strengths and weaknesses. For example, airlines are the fastest but do not have enough capacity to carry whole traffic while trains are convenient but comparatively slow for long distances. They are indispensable for an efficient transportation system and they do not need to compete over every route. There is a complex interaction between these modes and actually they may complement each other at some situations. This interaction is affected not only by railway network shape but also by flight frequencies. Therefore, it can be said that good network solutions in favor of both passengers and operators are possible by the cooperation of rail and air modes.

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