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Multimodal Intercity Network Manageable on the Collected Fare --- Optimization Model Approach ---

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Abstract: Intercity transportation service requires huge amount of investment on network infrastructure as well as expensive rolling stocks or aircrafts. These investments, frequently done in FPI (Private Finance Initiative) scheme, such as BTO, BOT, BOO in developing economies, incur fixed cost corresponding to the configuration of network services. We have to decide the passengers fare attentively; it must exceed the return of liabilities and fixed cost, but not too expensive to make travel demand lurk. In order to search a best mix of network configuration and manageable fare level, we develop an optimization model based on the demand-endogenized network planning model of the present authors. We applied this model to a hypothetical network and analyzed the obtained optimal network shape and OD fare level.

Keywords: Intercity Transportation, Multimodal Network, Optimization, Endogenized Demand, Private Finance Initiative

1. INTRODUCTION

Parallel to the recent economic growth and development, intercity passenger travel demand is also growing fast in many countries. National government must make a network building/improvement plan corresponding to the growth of intercity travel market and empower the economical growth by providing efficient and convenient transportation service. Naturally, modern, convenient service requires huge investment on network infrastructure as well as expensive vehicles, rolling stocks, and aircrafts. In many developing countries in Asia and other, such investments are done in PFI (Private Finance Initiative), such as BTO (Build, Transfer, Operate), BOT (Build, Operate, Transfer), BOO (Build, Operate, Own), where variable operation cost, fixed cost of the project as well as the return of liabilities must be covered by the fare income collected from the users.

Setting appropriate fare will be, therefore, important issue for success of the project; the fare must be enough high to cover the variable cost and division of fixed cost, as well as the return of liabilities, but not too expensive to make travel demand lurk. We should understand the mutual relationships between the fare and the user volume; lower fare gathers more passengers, and larger number of passengers gives lower division of fixed cost and liabilities, then cheaper fare setting. Furthermore, long distance travels usually include the use of different links, sometime of different mode. In such cases, one passenger's route decision may

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affect to demand of other passengers who travel between different OD pair, but sharing at least one link service with the first one. In other words, mutual relationships are existent throughout the nationwide intercity network, then to find a best mix of network configuration and manageable fare level for each OD pair is not easy work.

This paper proposes an optimization model based on the demand-endogenized network planning model of the present authors. We applied this model to a hypothetical network and analyzed the optimal network shape obtained. The result revealed that two types of economy of scale appears in the optimal value of the total consumer surplus: a local quantitative effect from being able to divide fixed cost of link service by more users, and a qualitative effect from being able to support more expensive but more convenient service mode. It is necessary to consider the network as a whole, in order to capture the second effect. In this sense, the proposed model can function as a useful analytical tool.

2. RELATED STUDIES

2.1 Mixed Use of HSR and Air Service and Cooperation

Around year of 2000, LCC air service appeared in the countries possessing HSR, such as Western Europe Countries, fierce competition attracted researchers' interests; Park & Ha (2006), Clever & Hansen (2008), Wan *et al.* (2016) for Northeast Asian countries, and Dobruszkes (2011), Jimenez & Batancor (2012), Behrens & Pels (2012) and Albalate *et al.* (2015) for European countries analyzed the binomial modal choice of travelers between given city pairs under the exogenously given fares.

Contrast to these competition analyses, mixed use of railway and airline has been also studied by Stubbs & Jegede (1998), Givoni & Banister (2006), Vespermann & Wald (2011) , Luo (2015) and Orth & Weidmann (2015). Economic analyses with theoretical models were done by Socorro & Viecens (2013), Jiang & Zhang (2014), D'Alfonso *et al.* (2015), Takebayashi (2015), Takebayashi (2016), Jiang & Zhang (2016) and Xia & Zhang (2016). These studies give uss various important findings about cooperation strategies, but only in very simple geographical setting up to triangle cities.

2.2 Intercity Network Design

In more complex network, one link is simultaneously used by passengers of several OD pairs, then fixed cost can be divided among them. This point had already well understood in "Hub Location Researches" developed from Operations Research studies. Alumur & Kara (2008) and Campbell & O'Kelly (2012) provided an insightful review and An *et al.* (2015) and Santos & Antunes (2015) showed an application example to nation-wide airline network design. The evaluation and optimization of networks share a common difficulty related to the change of a passenger's route, when there is variation in the service level. If the service is to be scaled down, it is possible to apply a K^{th} route search to the existing links and enumerate the available routes. Hazemoto *et al.* (2003), Murakami *et al.* (2006) and Hatoko & Nakagawa (2015) have used this pre-enumeration method. However, with this method, it is difficult to represent the passengers whose route changes drastically as the service level varies, especially in case of new route appearance. To avoid such problems Okumura *et al.* (2012) proposed a Multimodal Network Planning (MNP) model permitting multi-modal trips between OD cities and internalizing the enumeration of routes inside a mixed integer programming structure.

2.3 Endogenize Demand Response

Remarkable improvement of intercity transportation service stimulates travel demand via providing smaller generalized cost. Benefit of such link service improvement consists of four different parts: (a) reduction of travel cost for the previous service users, (b) benefit for induced traffic between the OD pairs same as the former, (c) travel cost reduction relative to the parallel competing service for the transferred travelers, and (d) benefit for the travelers of OD pairs who had not use the previous service but find a new economical route including the improved link service. Especially HSR (High Speed Rail) service can be used for many possible routes including partial segments of the relevant improved line, type (d) benefit can exist. In order to capture types (b) and (d) effects, demand response of users should be endogenized.

The present authors expanded the MNP model into a demand-endogenized model in Hoso & Okumura (2018), which made it possible to analyze how the improvement of a link service affects the convenience and number of passengers throughout the network, including the all types above. In order to avoid unnecessary complex calculation, we described OD based demand function as linear function and formulated the total consumer surplus used as the objective function as a quadratic function of the internal variables. Under the assumption that a national government prepare a budget to cover the total fixed cost for maintenance of all services without any burden of the travelers, the model was formulated as a mixed integer programming problem including a convex quadratic constraint, and calculated by commercial optimization tool. Hoso & Okumura (2018) utilized the proposed model and show how the improvement of the connection time between an airplane and another mode affected the optimal shape of the network.

Contrast to Hoso & Okumura (2018), focusing on the service improvement projects small enough to be funded by a public body without any additional payment of passengers, the present paper wants to analyze network building process in developing countries in the future. Large amount of investments is necessary and possibly to be enabled by application of PFI schemes. Variable operation cost, fixed cost of the project as well as the return of liabilities must be covered by the fare income collected from the users, then we have to decide the passengers fare attentively; it must exceed the return of liabilities and fixed cost, but not too expensive to make travel demand lurk. This study tackles to this issue by considering the fare for each OD not as exogenous parameter, but as variables in the problem. This change of formulation produces nonlinear constraints including a multiplication of fare variable and traffic volume variable appears. Kubo et al. (2012) shows that recent optimization packages can handle this kind of “rotated second-order cone constraint” in the family of second-order cone optimization.

3. MODEL FORMULATION

3.1 Basic Structure of the Model

In this model, the passengers between multiple ODs are distributed to a network composed of multiple modes in order to stipulate a network shape that increases the social net benefit, which will be defined later on. Since each link has fixed costs associated with the maintenance of the service and return of liabilities regardless of the number of passengers, it is necessary to think of an efficient network shape with a trade-off between the passengers’ convenience of mobility and the fixed costs of the link. Basically, this model will determine

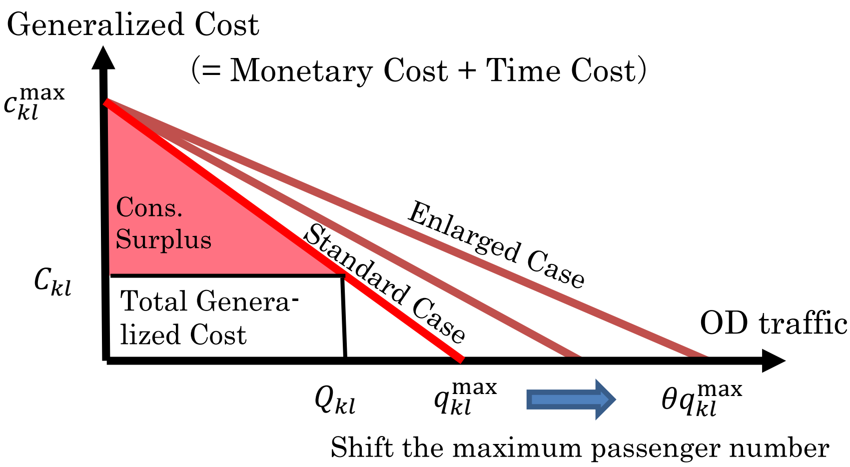

Figure 1 Linear function of each OD-demand

the shape of the network, as well as the OD based fare level to fully cover the incurred cost. Aggregated traffic flow of passengers in each mode and link are also calculated, but the individual route selection behaviors of the passengers and the profitability of the companies were not considered.

3.2 Operation Variables of the Model

For each city, a node $n \in N$ was set, and the links connecting these nodes in each direction were defined by mode $(m \in M)$ as $m \times (i,j) \in L$. Additionally, to express the connection between the modes, each node was divided into an arrival node or departure node for each mode, and the connection link $(m,m') \times n$ was set in between. Additionally, some of the nodes were defined as $k \in K \subset N$ (start and end point nodes), and the OD pairs between them were defined as $(k,l) \in K \times K$. There were eight operation variables. The 0/1 variable indicating the existence of service in each link was defined as Z_{mij}, and the traffic volume flowing through that link was defined as X_{mij}^{k} by the starting point. Division of fixed cost of the service in each link was defined as P_{mij}. The connecting traffic volume at the node was also defined by the starting point and set as Y_{nmm}^{k}. The generated traffic volume was defined by the mode and set as B_{m}^{k}, while the concentrated traffic volume was defined by the starting point and the mode and set as A_{lm}^{k}. Finally, the general costs between OD and the traffic volume between OD were defined as C_{kl} and Q_{kl}.

Some of the parameters were the fixed cost (d_{mij}), unit variable cost (e_{mij}), limit of capacity (g_{mij}) and required time (t_{mij}) at the link, and connection time $(g_{nmm'})$ at the node.

3.3 Demand Function and Consumer Surplus

The traffic volume between the OD of each start and end point (k,l) is given by the linear inverted demand function expressed by Eq. (1), as follows:

$$C_{kl} = c_{kl}^{max} - \beta_{kl} Q_{kl} \quad \forall\ (k,l) \in K \times K \tag{1}$$

In this OD section, c_{kl}^{max} is the maximum intended payment amount and αq_{kl}^{max} is the maximum traffic volume between the OD, where α is an enlargement factor for demand size. From the exogenously given parameters $c_{kl}^{max}, q_{kl}^{max}$ and α, the parameter β_{kl} in Eq.(1) is set as $\beta_{kl} = c_{kl}^{max}/(\alpha q_{kl}^{max})$. With this data, it was possible to evaluate the passengers' convenience of mobility between the OD (k, l) with consumer surplus CS_{kl}, as expressed by Eq. (2):

$$CS_{kl} = \frac{1}{2}(c_{kl}^{max} - C_{kl})Q_{kl} \quad \forall\, (k,l) \in K \times K \tag{2}$$

3.4 Traffic Volume Conservation Law and Service Technology

The two equations below are true in relation to the arriving traffic volume in the arrival node n:

$$\sum_{i \in N} X_{min}^{k} = A_{nm}^{k} + \sum_{m' \in M} Y_{nmm'}^{k} \quad \forall\, m \in M, k \in K, n \in N \tag{3}$$

$$\sum_{m \in M} A_{nm}^{k} = Q_{kn} \quad \forall\, k \in K, n \in N \tag{4}$$

Eq. (3) indicates that the passengers arriving at the arrival node n split into those whose destination is that node, and those who make a connection at that node and depart to the next node. Eq. (4) indicates that the sum of the traffic volume arriving at the destination from each starting point by each mode is equivalent to the traffic volume of OD.

Similarly, the two equations expressing the departing traffic volume from the departure node n were established as follows:

$$B_{m}^{n} + \sum_{m' \in M} Y_{nm'm}^{k} = \sum_{j \in N} X_{mnj}^{k} \quad \forall\, m \in M, k \in K, n \in N \tag{5}$$

$$\sum_{l \in N} Q_{nl} = B_{m}^{n} \quad \forall\, n \in N \tag{6}$$

Eq. (5) indicates that the number of passengers taking mode m from the departure node n, and that of passengers connecting to mode m at that node, is equivalent to the traffic volume from that departure node. Eq. (6) indicates that the sum of the traffic volume of OD departs from that node by using any mode.

Additionally, the three equations below were considered as the conditions necessary to establish the link service:

$$\sum_{k \in K} X_{mij}^{k} \le g_{mij} Z_{mij} \quad \forall\, m \times (i,j) \in L \tag{7}$$

$$Z_{mij} = Z_{mji} \quad \forall\, m \times (i,j) \in L \tag{8}$$

$$P_{mij} \sum_{k \in K} X_{mij}^{k} \ge d_{mij} Z_{mij} \quad \forall\, m \times (i,j) \in L \tag{9}$$

Eq. (7) indicates that the link traffic volume stays within the exogenously given link capacity (g_{mij}). Eq. (8) indicates that the link service was set simultaneously in both directions. Eq. (9) indicates that passengers of the given link collectively cover the total required fixed cost (d_{mij}) through paying the link fare (P_{mij}).

3.5 Cost Balance by the Origin Node

The relationship between the general costs of OD trip (C_{kl}) and those of the links and nodes are formulated by the starting point expressed by Eq. (10), as follows:

$$\sum_{l\in K} C_{kl}Q_{kl} \geq \sum_{m\in M}\sum_{i\in N}\sum_{j\in N} P_{mij}X_{mij}^{k} + \sum_{m\in M}\sum_{i\in N}\sum_{j\in N} e_{mij}X_{mij}^{k} + v\sum_{m\in M}\sum_{i\in N}\sum_{j\in N} t_{mij}X_{mij}^{k} + v\sum_{n}\sum_{m}\sum_{m'} \tau_{nmm'}\, Y_{nmm'}^{k} \quad \forall\, k \in K \tag{10}$$

where, time value of all passengers is given exogenously with parameter v.

Finally, the domain of each operation variable is given by Eq. (11), as follows:

$$\begin{gathered} X_{mij}^{k} \geq 0, Y_{mm'n}^{k} \geq 0, A_{mn}^{k} \geq 0, B_{m}^{k} \geq 0 \\ P_{mij} \geq 0, C_{kl} \geq 0, Q_{kl} \geq 0, Z_{mij} \in \{0,1\} \end{gathered} \tag{11}$$

3.6 Solution

This model is a quadratic programming problem and includes the term of the product of different operation variables into the term of the consumer surplus of the objective function (Eq. (2)), and the limiting conditions (Eq. (9), (10)). With small modifications in the equation, each constraint becomes a convex constraint in a second-order cone optimization problem. This study uses Gurobi optimizer 8.1. with python on Windows 10 for numerical calculations.

4. ANALYSIS OF A VIRTUAL NETWORK

4.1 Setting Numerical Values

This study considered a virtual network composed of airlines, railways, and buses, as shown in Fig. 2. The values in the figure represent the time required for the link of railway and bus. Airline link can be set between any two points. The time required for the airline links was shown in Table 1. For all nodes, the connection times between the modes were given the values of Table 2. A connection between airlines requires 0.5 hours, while a connection between an airline and other modes requires 1.0 hours. Additionally, for the two terrestrial modes, the connection requires 0 hours between the same mode, and 0.25 hours (15 minutes) between different modes. Table 3 shows the values given to the fixed and variable costs and capacity limit of the links, with consideration to the characteristics of each mode. These values are basically constant regardless of the location of the node or link. In this study, a fairly high value was given to the passenger capacity limits in order to disregard the congestion. Table 4 lists the values of the maximum traffic volume between each OD in the standard case. Moreover, the maximum intended payment with regard to general costs are listed in Table 5. The passengers' time value was set to 50 (yen/minutes), uniformly.

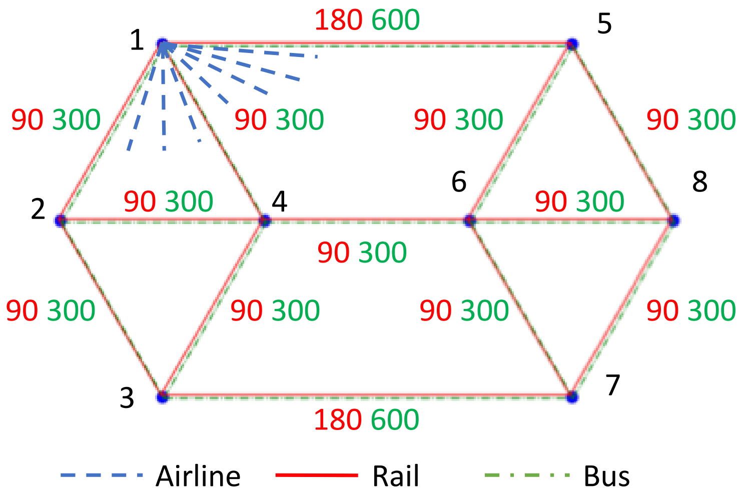

Figure 2. Possible Service in Hypothesized Network

Table 1. Airline Travel Time Required between Two nodes

	1	2	3	4	5	6	7	8
1	-	90	110	90	120	110	140	140
2	90	-	90	90	140	120	140	150
3	110	90	-	90	140	110	120	140
4	90	90	90	-	110	90	110	120
5	120	140	140	110	-	90	110	90
6	110	120	110	90	90	-	90	90
7	140	140	120	110	110	90	-	90
8	140	150	140	120	90	90	90	-

(unit: minutes)

Table 2. Transfer Time between Two modes

	Airline	Rail	Bus
Airline	30	60	60
Rail	60	0	15
Bus	60	15	0

(unit: minutes)

Table 3. Link Cost and Capacity Parameters by Mode

	Fixed Cost (JPY/day)	Variable Cost (JPY/PAX)	Seats Capacity (PAX/day)
Airline	1,500,000	10,000	30,000
Rail	12,000,000	3,000	30,000
Bus	100,000	2,000	30,000

Table 4. Values of the Maximum Traffic Volume between Each OD

	1	2	3	4	5	6	7	8	total
1	0	1008	504	1008	504	504	336	336	4200
2	1008	0	1008	1008	336	504	336	336	4536
3	504	1008	0	1008	336	504	504	336	4200
4	1008	1008	1008	0	504	1008	504	504	5544
5	504	336	336	504	0	1008	504	1008	4200
6	504	504	504	1008	1008	0	1008	1008	5544
7	336	336	504	504	504	1008	0	1008	4200
8	336	336	336	504	1008	1008	1008	0	4536
total	4200	4536	4200	5544	4200	5544	4200	4536	36960

Table 5. Maximum Intended Payment with Regard to Generalized Cost

	1	2	3	4	5	6	7	8
1	0	33,000	63,000	33,000	63,000	63,000	93,000	93,000
2	33,000	0	32,500	32,500	92,500	62,500	92,500	92,500
3	63,000	32,500	0	32,000	92,000	62,000	62,000	92,000
4	33,000	32,500	32,000	0	61,500	31,500	61,500	61,500
5	63,000	92,500	92,000	61,500	0	31,000	61,000	31,000
6	63,000	62,500	62,000	31,500	31,000	0	30,500	30,500
7	93,000	92,500	62,000	61,500	61,000	30,500	0	30,000
8	93,000	92,500	92,000	61,500	31,000	30,500	30,000	0

(unit: JPY/trip)

4.2 Network Development Calculation

Give the 25 different values $1.0, 1.125, 1.25, \cdots, 3.875, 4.0$ for enlargement factor α, change in optimal network shapes was calculated. We obtained six different optimal shape of the network, as shown in Figure 3.

While demand size is small, point to point networks composed by airline or bus links appeared, because these services are rather inexpensive in terms of fixed cost. In Network (a), all shorter links are served by bus, while direct airline service cover all OD pairs requiring longer than 2 links. Owing to the long transfer time for airline, no passengers transfer the modes at intermediate node of the trip. If demand size becomes larger, faster but more expensive airline service can exist with replacing the inexpensive but slow bus service. After $\alpha \geq 1.375$, all OD pairs are covered by direct airline service as network (c), while network (b) seems transitional so that only links with larger size can be served by airlines.

Further increase of demand size, railway service appeared; links connecting to the two central hub nodes (node 4,6), in network (d). Short distance links of airline service disappear; they are replaced by connective trip of railway along two terrestrial links. Air service can exist only for the OD pair, where three and more railway links are required. In that way, larger amounts of passengers are guided to corrective use of railway, in order to suppress the burden of the fixed cost division. Some OD pairs ((1,2),(2,3),(5,8),(7,8)) must endure detour via one railway hub node. After $\alpha \geq 2.875$, all short OD pairs are covered by railway and direct airline service for longer distance, as network (f), while network (e) seems transitional so that only links with larger size can be served by direct railway service.

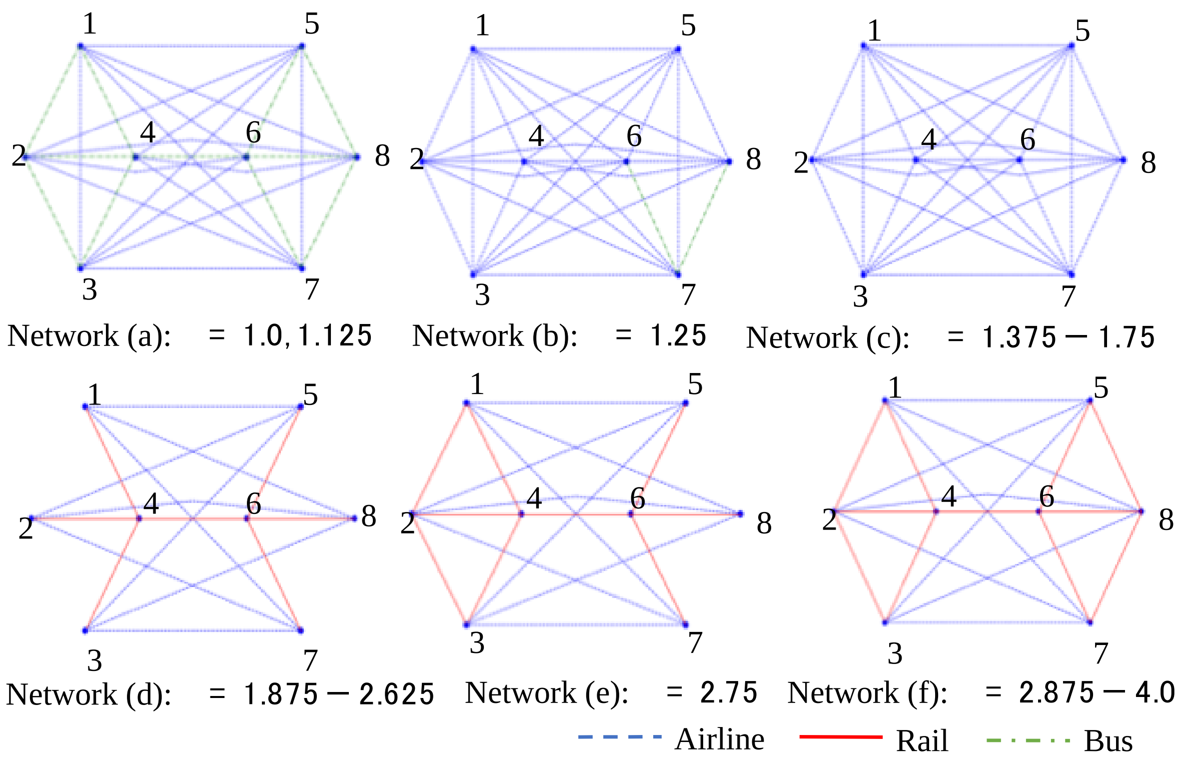

Figure 3. Optimal Network Shapes Appeared Under Different Demand Sizes

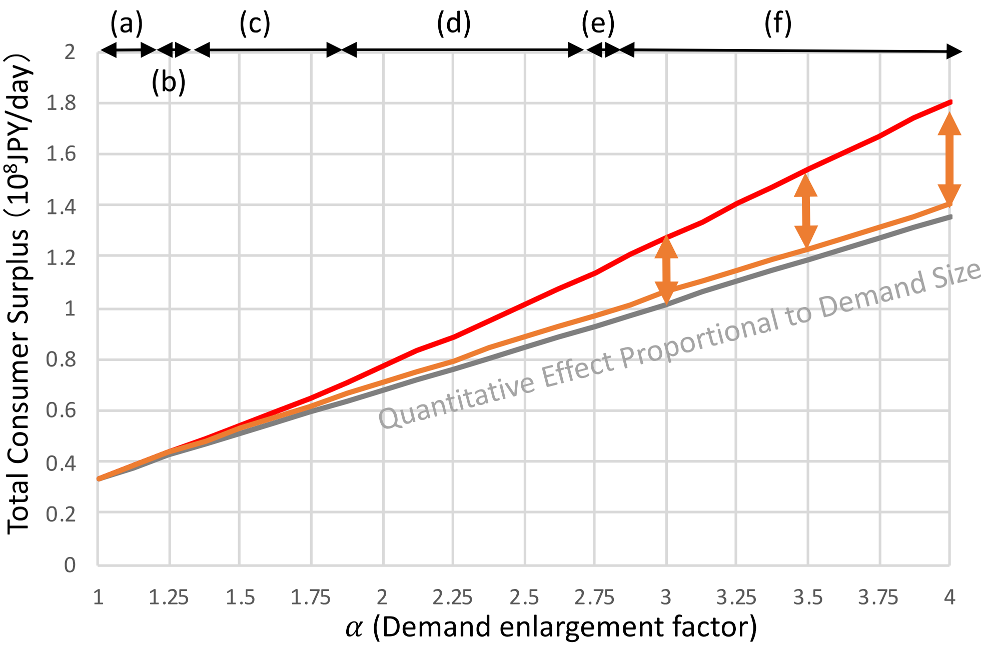

Figure 4. Total Consumer Surplus under Different Demand Sizes

Figure 4 shows the transition of the value of total consumer surplus, our objective function. If the cost for travels would be kept constant regardless the demand size, the consumer surplus might grow proportionally with the size factor, shown by grey line in Figure 4. In the middle, orange line shows the cases when network shape is kept as the initial (network a), when only the quantitative effects based on smaller division of fixed cost are there. Gaps between the upper red and middle orange lines can be understood as qualitative effect due to the change of network structure, which seems quite larger than the quantitative effect above.

4.3 Changes in a Link Service Fare

Link fare level of one typical link (1,4) is plotted in Figure 5. The graph is composed by four continuous sections with three gaps in between. Each of continuous section follows reciprocal curve, owing to the increase of passengers for the service. The first two gaps occurs at the point of mode change, while the third gap occurs at the point of appearance of direct service of OD (1,2), then they decide never to use the relevant link (1,4). The last gap causes negative effects to the users division of fixed cost, based on the growth of demands.

It means that demand growth gives positive effect on the consumer welfare in the whole network level, but it can also result to the service drop in some portion of the network. Because the growth effect does not evenly distribute throughout the network, careful analyses of possible network designs must be done in order to build a strategical network building process.

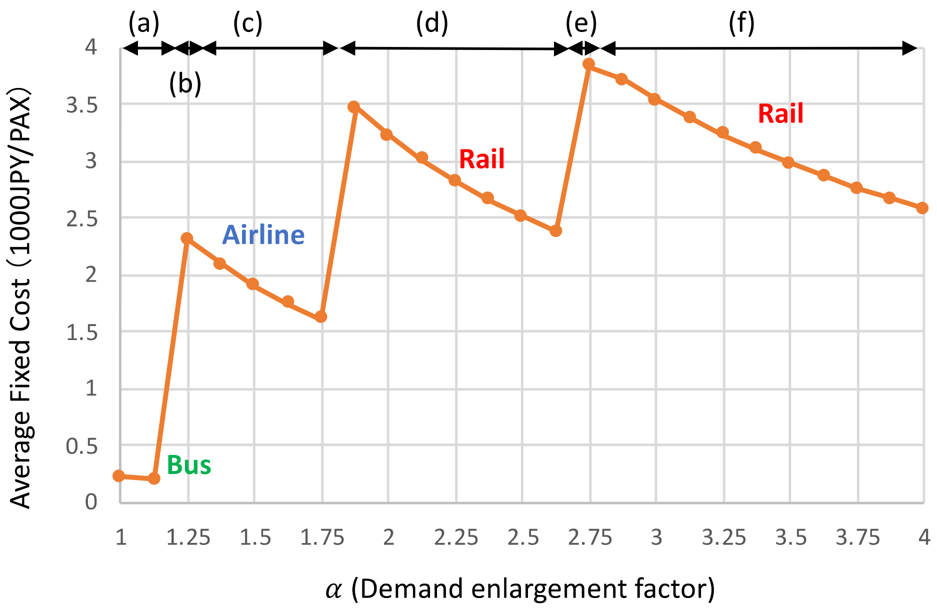

Figure 5. Fare for Average Link Cost of Link (1,4) under Different Demand Sizes

5. CONCLUSION

In order to search a best mix of network configuration and manageable fare level, this study developed an optimization model, where fixed cost for link service operation as well as the return of liabilities are covered by the link uses through fare. We applied this model to a hypothetical network and analyzed the optimal network shape obtained. As a result, different type of inter-city network appears for the different demand size; while demand size is not large, airline and bus service are provided for direct service between each OD pairs. Larger demand size enables the existence of convenient but more expensive railway service, concentrated in hub cities. At the end of demand growth, a network composed by the shorter railway links and the airline services in longer distance has appeared.

Moreover, the analysis showed the composition of total consumer surplus growth into three parts: quantitative effect proportional to the demand size, quantitative effect by smaller division of fixed cost by larger number of users, and the qualitative effect due to the introduction of more convenient, but expensive modes. This could be calculated only because the proposed model endogenized the enumeration of routes and demand expansion, as well as the changes in fare level. From the abovementioned results, it was concluded that the third qualitative effects might be larger than the second quantitative effect. Therefore, while discussing the long run transport network development plan, it is necessary to consider the strategic introduction of more convenient mode for the important links in entire network. Furthermore, the demand growth effect does not distribute evenly in the network; people in some part of the network can get negative effect by the demand growth. We need check the appearance of negative effects and further discuss the way to compensate them. The proposed model can be utilized as an effective tool to this end.

Although this paper had successfully shown the potential of the proposed model, several issues are left in the future. First, in the setting of the virtual network above, no multimodal trips including transfers in a middle appeared. We should try to apply the model to more realistic settings. Second, our calculation is totally dependent on the algorithm supplied in the commercial software. We are still facing to the size limit of the network. Third the applicability of the model should be checked through retrofit analyses of the real development history, such as Japan.

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