Analysis of Efficient Public Transport Network Using Smart Card Data and Simulation Approach in Takamatsu, Japan

Masanobu KII a, Jun-ichi TERAO b, Kazuki NAKAMURA c

a, c Faculty of Engineering, Kagawa University, 2217-20 Hayashi-cho, Takamatsu, Kagawa 761-0396, Japan
a E-mail: kii@eng.kagawa-u.ac.jp
b Graduate School of Engineering, Kagawa University, 2217-20 Hayashi-cho, Takamatsu, Kagawa 761-0396, Japan
c E-mail: knaka@eng.kagawa-u.ac.jp

Abstract:
An efficient public transport network is indispensible for urban sustainability. This study examines the possibility of more efficient public transport network, using smart card data in the case of Takamatsu city, Japan. We developed a simulation system that estimates passenger flows on a public transport network and public transport fares iteratively under the condition of link-level fiscal neutrality of public transport operation. As a result, the public transport network can be more efficient by aggregating some bus routes. Sensitivity analysis indicates that improvement of public transport frequency reduces a total generalized user cost because it encourages route transfer that induces route aggregation. The reduction of transfer resistance at stations or bus stops is found not to affect the passenger flow solely but to be effective in combination with the frequency increase.

Keywords: Public Transport, Network Efficiency, Smart Card, Non-convex Network Equilibrium

1. INTRODUCTION
An efficient public transport system is indispensible for urban sustainability. In Japan, most of public transport operators in local cities are subsidized by governments due to the political request for providing services at low-demand areas. With cost-cutting efforts by transport operators, the financial balance of public transport is getting better in recent years, but it is still a deficit in the national average, and the total amount of subsidies by national and local governments to bus operators was 54.7 billion yen in 2012. This is mainly due to a decline of public transport demand reflecting the motorization and subsequent urban sprawl.

Meanwhile, it is often suggested that substantial bus routes are overlapping and some of the routes run alongside railway routes. This duplication is considered to be inefficient. Aggregating these overlapping routes and building a hub and spoke network (Lan and Chiou, 1999; Yajima et al., 2013) is sometimes suggested as a strategic direction of an efficient public transport network that is called zone bus system. However, it is not obvious how to design the network and how to evaluate the efficiency of the network.

Various studies have measured the efficiency by a total cost of an transport system including operator’s cost, passenger’s cost, and cost of unsatisfied transit users (Cipriani et al., 2012; Beltran et al., 2009; Fan and Machemehl, 2008). The network design is formulated as cost minimization problem in these studies. They are usually a complex non-convex problem and are solved using metaheuristic techniques such as generic algorithm and Tabu search. As
the nature of non-convex problem, it usually has plural local optimum solutions and sometimes faces a difficulty in computation for a real-sized network. Therefore, these studies mainly focused on algorithms and techniques for solving the problem and introducing various additional procedures and heuristics to solve a larger-network problem in faster time, but merely discussed how these solutions induce the strategic design of a public transport network. The public transport network design in practice sometimes requires not only cost minimization of the system but also elicitation of potential users and benefit of them. Therefore the demand reaction should be considered strategically in the network design.

Mizokami et al. (2005) proposed a method to classify bus routes by their production efficiency and elicitation potential demand. This classification is applied for the reorganization of a bus network and it is found that the revised network is estimated to increase the travel demand and improve the cost/income ratio in average. This approach is quite practical because the network is reorganized manually; through the manual process, they may reflect various issues which are usually omitted in the optimization studies. However, their classification is somewhat empirical and requires substantial cost and demand data for each route, which are usually not open to public.

As a tool for monitoring the passenger flow on a route level, smart cards are used to estimate passengers’ travel behaviors (Agard et al., 2006; Bagchi and White, 2005, Morency et al., 2007), demand matrix (Park and Kim, 2008; Munizaga and Palma, 2012) and the other various impacts (for literature review, Pelletier et al., 2011). Obviously in evaluating the efficiency of a bus route, Origin-Destination (OD) matrix at a bus-stop level is needed, but spatial resolution of ordinary travel surveys based on questionnaires is too rough to estimate it.

This study aims to analyze the possibility of a more efficient public transport network, taking the case of Takamatsu city in Japan. The transport network to be analyzed consists of bus and railway services. In this study, the efficiency is measured as a total cost which is assumed to come down to a user cost in contrast to the efficiency definition in the past optimization studies. We assume that the network can be modified based on demand change and take a simulation approach to find the equilibrium state of passenger flows. This does not necessarily derive the optimum efficiency, but it analyzes the possibility of higher efficiency starting from the current network. For the estimation of station/bus stop level OD demand, we utilize smart-card data in target city.

This paper is organized as follows. Current situation of public transport in Takamatsu and smart-card data is presented in Section 2. Section 3 describes the method of a simulation and an algorithm deriving an equilibrium state. Section 4 presents the results of simulation and sensitivity analysis. The last section concludes them with a summary and further study needed.

2. CASE-STUDY AREA AND SMART-CARD DATA

Takamatsu city has 419 thousand people and 375 km² land area in 2010. 23% of population is aged people over 65. The population is expected to decline to 312 thousand in 2050 and the share of aged people will be 43% at the same period. There are 5 lines in total with 63km and 43 stations for railways, and 86 routes with 1176km and 456 stops for buses. Modal share of Takamatsu city and surrounding municipalities is 3.0% by rail, 1.1% by bus, 68% by car, 14.7% by bicycle, and 13.2% by walk in 2012.

Smart-card data covers 3 lines, 62km and 52 stations for railways in Takamatsu city including surrounding areas, and 71 routes of 849km, 333 bus stops for buses within
Takamatsu city. This smart-card data is obtained by a transit company and therefore routes are limited to that operated by the company. Therefore the area and routes of this data is not identical with all the transit within city of Takamatsu especially for railway. Another company operates different routes of railway. On the other hand, most of bus routes are operated by the company who provide this smart-card data. The data is obtained from the travel log of all smart-card users for every Tuesday between 1st week of October and 3rd week of November from 2008 to 2012, in total 36 days. The data includes user ID, date, route, ride-on time and bus stop/station ID, ride-off time and bus stop/station ID. The average number of recorded users per day is 15,658 and the average number of trips is 27,343 for rail and bus altogether. Connecting the trip data based on user ID and on/off-board time, trip chains can be constructed. We assume sequential trips within 20 minutes consists a trip chain.

The share of smart-card user is 27% of all passengers for buses and 64% for railways in travel length in daily average. The OD volume is estimated by multiplying the inverse of smart-card travel share for the whole city by the route-level OD volume obtained by smart-card data so as to be consistent with the total passenger volumes which are 88 thousand passenger-km/day for buses and 308 thousand passenger-km/day and for railways. The passenger volumes of railways are given by Annual Report on Railway Statistics, but the statistics for buses does not exist for the case study area. Instead, the prefectural level of passenger statistics is given by Shikoku District Transport Bureau, Ministry of Land, Infrastructure, Transport and Tourism (MLIT). Thus, the total volume of bus passengers in the case-study area is estimated based on the share of Takamatsu city and other municipalities given by person-trip survey data obtained in 2013. This reverse-deduction may possibly cause substantial loss of precision, but there is no information about the number of passengers by route and the attributes of no smart-card users. Of course, trips by passengers who do not have smart cards are also important, and their characteristics may be different from ones of smart-card users. However, our analysis may provide the first approximation of the whole spatial pattern of transit travel in the medium-sized city under the limited demand information.

The total operation distance of railways is 6,214km/day and that of bus is 9,110km/day. Estimated cost for bus operation is 291.67 yen/vehicle-km, and that for rail operation is 1141.2 yen/train-km. The speed is assumed to be 17.5km/h and 20km/h for buses and railways respectively. The estimated fares are 25.5 yen/km for buses and 23.7yen/km for railways. In total, the estimated current fiscal balance of railway operation is a profit of 77 million yen/year, but that of bus is a deficit of 145 million yen/year.

In current years, population is declining and aging in Takamatsu city. This implies a decline of transport demand. The current fiscal balance of public transport is a deficit in total and probably it would be worse under the declining demand. This is unsustainable and requires efficiency improvement in their service provision.

3. METHOD AND ALGORITHM

A purpose of this study is to examine the possibility of a fiscally-efficient public transport network. Here, we assume all the costs for public transport operation is covered by fares paid by users, and the balance is cleared at a link level; i.e.
the fares can be different for each link. This means the total fiscal balance is also cleared to be neutral. This assumption is of course unrealistic but it will clarify where the inefficient links are, and that would lead discussion about the possibility to derive the efficient network.

We assume that the levels of service and cost of each link are fixed except on links where the demand comes to be zero. OD demand is also fixed to current pattern. Users choose cheapest route in terms of generalized cost which consists of fare, on-board time, waiting time and route transfer cost. The fare is determined as a quotient of operation cost divided by the number of daily passengers at a link level. Here, we assume that the link operation cost is fixed, and therefore the fare gets cheaper when link demand increases, and vice versa (Figure 1).

This is obviously a non-convex problem and represents “rich get richer” mechanism. This implies the existence of plural equilibrium solutions, and a meta-heuristic approach is needed to find the global optimum solution. However in this study, we have an accurate initial state of demand on a link level, and that would derive a plausible state premising the current public transport network and service.

It should be noted that we do not distinguish demand change in a day. In other words, differences of cost and congestion in peak and off-peak hours are averaged out. This assumption may possibly underestimate the cost for transit operation and the consequently estimated fare. This possible bias will be discussed later.

The route consists of links 1) from origin to station/bus stop (access link), 2) between stations or bus/stops on same route (PT link), 3) connecting different stations/bus stops for transfer (transfer link), and 4) from station/bus stops to destination (egress link) (see Figure 2). Here, the transfer links are set only when the distance between stations/bus stops is less than 50 meters.

![Figure 2. The structure of a public transport network](image)

### 3.1 Formulation of Cost Structure

To formulate the cost structure, the following notations are used:

**Suffixes**

- $a$ : Link (access, egress, railway and bus links)
- $i, j$ : Node (origin, destination, station, and bus stop)
- $k$ : Route of public transport

**Exogenous variables**

- $W_T$ : Value of time
- $N_k$ : Number of vehicles operated on route $k$
- $V_k$ : Average vehicle speed in route $k$
\[ V_w \] Speed for walking
\[ L_k \] Route length
\[ S_k \] Number of nodes on route \( k \)
\[ T_s \] Standing time at node
\[ T_t \] Standing time at terminal
\[ L_a \] Length of link \( a \)
\[ C_k \] Unit operation cost of route \( k \)
\[ Q_{ij} \] Travel demand between origin \( i \) and destination \( j \) (OD-\( ij \))
\[ R_X \] Value of transfer resistance
\[ H \] Dairy operating hours

Endogenous variables
\[ g_{Aa} \] Generalized cost for access link \( a \)
\[ g_{Pa} \] Generalized cost for PT link \( a \)
\[ g_{Xa} \] Generalized cost for transfer link \( a \)
\[ p_a \] Fare of link \( a \)
\[ d_a \] Number of daily passengers on link \( a \)
\[ t_j^w \] Time for waiting at node \( j \)

The minimum generalized cost for travel from origin \( i \) to destination \( j \) (OD-\( ij \)) is expressed by a following formula.

\[
g_{\Omega ij} = \sum_{a \in \Omega ij} (g_{Aa} + g_{Pa} + g_{Xa})
\]

Where, \( \Omega_{ij}^R \) is a set of links on the shortest path between OD-\( ij \). \( g_{Aa} \), \( g_{Pa} \), and \( g_{Xa} \) are formulated as follows.

\[
g_{Aa} = W_T T_j^w
\]

\[
t_j^w \equiv t_k^w = \frac{1}{2N_k} \left( \frac{2L_a}{V_k} + S_k T_s + 2T_t \right)
\]

Where, \( j \) is a head node of access link \( a \), \( k \) is a PT route to where node \( j \) belongs.

\[
g_{Pa} = \frac{L_a}{V_k} W_T + P_a
\]

\[
p_a = \frac{C_k L_a}{d_a} \frac{H}{2T_k^w}
\]

Where \( a \) is a PT link belonging to PT route \( k \).

\[
g_{Xa} = W_T \left( T_j^w + \frac{L_a}{V_W} \right) + R_X
\]

Where, \( j \) is a head node of transfer link \( a \).

The number of passengers \( d_a \) is determined by a following formula.

\[
d_a = \sum_{ij \in \Omega_a^L} Q_{ij}
\]

Where \( \Omega_a^L \) is a set of OD pairs of which the shortest path contains link \( a \).

In this formula, generalized cost of each link affects route choice by users and the demand on each link determines the fare. Here, as the demand gets larger, the link cost gets cheaper by equations (4) and (5). When the cost gets lower, the possibility of the link to be chosen in the shortest path gets higher, which leads higher demand of the link, as equation (7) indicates. Therefore, the cost and demand interact, and it is expected to reach a better state.
reflecting the iterative cost update and the shortest path choice.

It should also be noted that two routes on the same path are distinguished by passenger in the model even though they share the bus stop. Passengers are assumed to choose a route which has the shortest path to the destination.

3.2 Algorithm to Derive an Equilibrium State

An equilibrium state can be estimated by iterative calculation of the shortest paths and the link costs. This algorithm (see Figure 3) first finds the shortest paths for all the OD pairs under the initial link costs, and puts all the OD demand on the shortest paths to calculate the link traffic flows. Obviously it is different from the initial link flows if the initial network is not efficient, otherwise users do not change the route. Then, it calculates the link fare only when the link is included in the shortest path of any OD pair. The fare is calculated as operation cost per user. If the updated fare of the link is cheaper than the previous one, this link may be selected in the next shortest path. Meanwhile, if the updated fare is higher than the previous one, this link may not be selected in the next shortest path. This iteration updates the fare so as to balance its cost and income at a link level, and expected to reach an equilibrium state where the shortest paths of all the OD pairs do not change any more.

The resulting state is expected to make the total cost better balanced and lower due to the assignment of demand flows by the iterative shortest-route selection. However, this may not be the optimal solution that minimizes the total cost. As mentioned above, the problem is non-convex, and this algorithm probably derives one of the local optimal states. Therefore another initial setting of passenger flows or link fares may derive a different solution, and possibly it may provide the lower total cost. Here, the current fares are cheaper than the costs because the total balance is a deficit in a public transport network. This means that the cost update is expected to make the link fares higher than the initial ones, which leads switching the links in the shortest paths until the fares of all the links are updated. This process is expected to alleviate the dependence on the initial state, i.e. we consider this feature reduces the possibility of path dependence of the simulation. In addition, the smart-card data provides the actual passenger flows at a node level. In other words, the initial state of passenger flows is given accurately, and therefore the consequential estimation is also expected to be more probable than other possible local solutions.

On the other hand, the existence of plural solutions does not necessarily mean that the algorithm does not converge to one solution. The algorithm introduced above reaches one solution which is expected to be a local optimum in terms of the overall travel cost. Link fare and route demand are interdependent, and if the shortest paths of all the OD pairs are same with the previous iteration then the fares of all links are also identical with the previous ones. This state will not change itself anymore, and we call it equilibrium.

Figure 3. The flowchart of algorithm
4. SIMULATION AND RESULTS

Using the above algorithm, we estimate the equilibrium state of passenger flows and the consequent public transport network. Here, the OD travel demand is fixed to the current level. In this section, we first explain about a setting of input data, and then show the results of simulation.

4.1 Input Data

The model for the cost estimation described in previous section has various input data. Some of them related to public transport provision are indicated in section 2. In this subsection, a setting of the other data is explained.

First, a value of time is assumed to be 40 yen/minute based on the cost-benefit analysis manual in Japan. Standing time at a bus stop/station is set based on observations and the time tables. Daily operating hours and frequency of each route is also set based on the time tables. Using the frequency, standing time, and route length, the number of vehicles of each routes is estimated, referencing to the equation (3).

The value of transfer resistance in the equation (6) is not observable because it includes reluctance of users for changing routes. We estimate the value so as to maximize the hit rate of the route choices of all the trips, and as a result, the value is estimated to be 276 yen/transfer. In total, the hit rate of the route choices is 98.2%. It sounds quite a high rate but it is reasonable because most trips do not transfer between the routes. Limiting the target trips for changing routes, which are 13,843 trips consisting only 1.5% of whole trips, the hit rate of the route choices is 73.3%. In the actual trip pattern, not all of the users choose the shortest path, and therefore this simulation does not necessarily reflect the real situation. However we assume all users have perfect information in time and fare and choose the cheapest routes for the trip rationally.

4.2 Equilibrium State

The results of simulation are summarized in Table 1. This table compares key indices under the current state and the simulated equilibrium state. First, the passenger kilometers of bus and railway increase in the equilibrium state, compared to the current state, and the number of route transfers increases slightly. On the other hand, the total fares decrease for both bus and railway. As assumed in this simulation, the fare is determined as cost per passenger, so the fiscal balance is cleared to be zero at an equilibrium for each link. The transport cost of railway is not changed but that of bus decreased about 8% due to the decline of vehicle-km. This means some of the bus routes are discontinued. Consequently, the travel lengths of some users get longer because of detours but the vehicle occupancy increased on average that leads to decline of the fare. As a result, the total fare decreases despite the increase of the travel length.

The total generalized user cost, which is the sum of fares, time and route transfer costs, decreases by 0.4%. In addition, the fiscal balance gets neutral, which means the cost of society is also decreased. The sum of the user cost and the deficit of public transport operation decreases by 0.7%.

Figure 2 shows the bus passenger flows at a link level for the current state and the equilibrium state as well as the discontinued bus routes at the equilibrium. The change is not significant but some of the routes are discontinued due to zero demand. The discontinued routes are not only in suburban areas but also in a city center where parallel routes exist.
Table 1. The simulation results

<table>
<thead>
<tr>
<th></th>
<th>Current</th>
<th>Equilibrium</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passenger-km/day</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bus</td>
<td>88,670</td>
<td>88,998</td>
</tr>
<tr>
<td>Railways</td>
<td>308,093</td>
<td>308,096</td>
</tr>
<tr>
<td>Sum</td>
<td>396,763</td>
<td>397,094</td>
</tr>
<tr>
<td>Vehicle-km/day</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bus</td>
<td>9,110</td>
<td>7,135</td>
</tr>
<tr>
<td>Railways</td>
<td>6,214</td>
<td>6,214</td>
</tr>
<tr>
<td>Sum</td>
<td>15,323</td>
<td>13,349</td>
</tr>
<tr>
<td>Total fare (thousand yen/day)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bus</td>
<td>2,261</td>
<td>2,081</td>
</tr>
<tr>
<td>Railways</td>
<td>7,302</td>
<td>7,091</td>
</tr>
<tr>
<td>Sum</td>
<td>9,563</td>
<td>9,172</td>
</tr>
<tr>
<td>Transport cost (thousand yen/day)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bus</td>
<td>2,657</td>
<td>2,081</td>
</tr>
<tr>
<td>Railways</td>
<td>7,091</td>
<td>7,091</td>
</tr>
<tr>
<td>Sum</td>
<td>9,748</td>
<td>9,172</td>
</tr>
<tr>
<td>Fiscal balance (thousand yen/day)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bus</td>
<td>-396</td>
<td>0</td>
</tr>
<tr>
<td>Railways</td>
<td>211</td>
<td>0</td>
</tr>
<tr>
<td>Sum</td>
<td>-185</td>
<td>0</td>
</tr>
<tr>
<td>Transfer passenger per day</td>
<td>3,769</td>
<td>3,786</td>
</tr>
<tr>
<td>Bus route length (km)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bus</td>
<td>849</td>
<td>795</td>
</tr>
<tr>
<td>Railways</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sum</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total ride-on time (hour)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bus</td>
<td>34,237</td>
<td>34,280</td>
</tr>
<tr>
<td>Railways</td>
<td>170,476</td>
<td>170,478</td>
</tr>
<tr>
<td>Sum</td>
<td>204,713</td>
<td>204,758</td>
</tr>
<tr>
<td>Total generalized cost of users</td>
<td>501,912</td>
<td>501,634</td>
</tr>
</tbody>
</table>

Figure 2. The passenger traffic flows of the current (left) and equilibrium (right) states, and the discontinued routes at the equilibrium state on the bus network

Figure 3. The estimated fare of each link at the equilibrium state
Figure 3 shows the estimated fare of each link. The blue lines indicate the links where the estimated fares are less than the current fare, 25.5 yen/km. These links can be interpreted as profitable links under the current fare. Many of the links in a city center as well as some of the suburban links are estimated to be profitable. On the other hand, red lines indicate that the cost per user at the equilibrium is more expensive than the current fare. Many of the links in the outskirt of the city indicates red lines. It seems natural due to the lower demand. However the fares of some of those outskirt links are not so expensive, less than 100 yen/km, because the frequency of outskirt routes are quite low and the costs are also repressed.

The fares of some routes running parallel with blue lines are estimated to be quite expensive; some of them exceed 400 yen/km that is more expensive than using a taxi. The iterative shortest-path search with the update of fares, passenger flows tend to converge into higher demand links and get away from lower demand links. Through this process, some links have no passenger flow and it comes to be discontinued routes. Some links remain to have non-zero passenger flows; probably passengers using those links have high costs in using alternative links by changing different routes or additional waiting time at transferring nodes. In this analysis, we assume a fixed generalized cost in changing routes and fixed frequencies of public transport at each link. As the frequencies get higher, the waiting time gets shorter but the operation cost increases, and vice versa.

The discontinuity of routes brings demand shift to the other transit routes. In this analysis, the demand is calculated with the daily-average capacity of transit vehicles. Here, the daily capacity of the route is calculated by multiplying vehicle capacity (50 people) and daily frequency. However, it should be noted that we do not consider the concentration of demand at peak hour. The consideration of peak-hour demand may increase the operation cost by providing more vehicles to meet the demand, which may increase the fare. Therefore, this assumption may cause a bias to overestimate the demand of high-demand routes and discontinue the parallel routes more. This means that our results possibly overestimate the effect of transit route restructuring. Time of day analysis will be needed for future study.

4.3 Sensitivity Analysis

We analyze the sensitivity of transfer costs and frequencies on the network efficiency. Regarding the transfer costs, we assume that various ways of upgrading convenience and amenity at transferring nodes, which may include installing weather protection and benches over bus stops or smart information-boards providing the expected waiting time, will suppress the psychological resistance in changing the routes. The frequency directly affects the waiting time and the selection of shortest paths in the analysis. Using more vehicles on the route increases the frequency and contrarily increases the operation cost.

When the number of vehicles on route $k$ is changed from $N_k$ to $(1+r)N_k$, the total incremental costs $\Delta C_k(r)$ consisting waiting-time cost and service-operation cost can be expressed as follows.

$$\Delta C_k(r) = \frac{Hc_k L_k N_k r}{2 L_k / V_k + S_k T_s + 2 T_i} - \frac{w Q_k}{2 N_k} \left( \frac{2L_k}{V_k} + S_k T_s + 2 T_i \right) r \left( 1 + r \right)$$

$$= \frac{Hc_k L_k r}{2 T_i} - \frac{w Q_k T_k w}{1 + r}$$

Where, $Q_k$ is the number of daily passengers using route $k$. The derivative of the above equation with regard to $r$ is expressed as follows.
\[
\frac{\partial \Delta C_k(r)}{\partial r} = \frac{HC_k L_k}{2T_k^w} \left(1 + \frac{wQ_k T_k^w}{(1 + r)^2}\right) \tag{9}
\]

to minimize incremental cost is derived by solving \(\frac{\partial \Delta C_k(r)}{\partial r} = 0\) as follows.

\[
r = \sqrt{\frac{2wQ_k T_k^w}{HC_k L_k} - 1} \tag{10}
\]

This solution is given under the fixed demand \(Q_k\). In this subsection, we analyze the following three cases; a) discount the cost of route transfer by 50%, b) change route frequencies using the equation (10) under the fixed demand to the equilibrium flows estimated in the previous subsection, and c) the combination between a) and b). In the case of b), the frequency update will change the demand, and that inversely affects the frequency minimizing the total cost as shown in the equation (10). Therefore, the iterative estimation of frequencies and demand possibly leads the better performance of the network, but we focus on the sensitivity analysis to only check the network efficiency under the fixed update of frequencies.

Table 2 shows the results of these three cases in Table 1 with the result of the equilibrium state for reference. First, the case of transfer cost discount, nothing but the total user cost is changed. The change of the total cost reflects only the change of transfer cost discount in this case, and no effect can be seen on the route choice and the demand flows. Here, the frequencies of most routes are low and the cost for waiting time to transfer is high, compare to the assumed transfer cost. As a result, the demand is insensitive to the discount.

| Table 2. The simulation results for sensitivity analysis |
|----------------------------------|----------|-----------|----------|----------|
|                                  | Equilibrium | 50% discount | Update frequency | Both      |
| Passenger-km/day                 |           |            |            |          |
| Bus                              | 88,998    | 88,998     | 86,547    | 86,254   |
| Railways                         | 308,096   | 308,096    | 308,192   | 308,299  |
| Sum                              | 397,094   | 397,094    | 394,739   | 394,553  |
| Vehicle-km/day                   |           |            |            |          |
| Bus                              | 7,135     | 7,135      | 21,958    | 21,958   |
| Railways                         | 6,214     | 6,214      | 9,456     | 9,456    |
| Sum                              | 13,349    | 13,349     | 31,414    | 31,414   |
| Total fare (thousand yen/day)    |           |            |            |          |
| Bus                              | 2,081     | 2,081      | 6,404     | 6,404    |
| Railways                         | 7,091     | 7,091      | 10,791    | 10,791   |
| Sum                              | 9,172     | 9,172      | 17,196    | 17,196   |
| Bus route length (km)            | 795       | 795        | 667       | 667      |
| Passenger transfer per day       | 3,786     | 3,786      | 4,446     | 4,515    |
| Total ride-on time(hour)         |           |            |            |          |
| Bus                              | 34,280    | 34,280     | 11,565    | 11,554   |
| Railways                         | 170,478   | 170,478    | 170,410   | 170,425  |
| Sum                              | 204,758   | 204,758    | 181,976   | 181,979  |
| Total generalized user cost      | 501,634   | 501,113    | 455,162   | 454,567  |

In the equation (10), when \(Q_k\) is zero, \(r=-1\). In this case, this route is set to be discontinued. All of the railway routes have non-zero demand, so no routes are discontinued. On the other hand, demands for some of the bus routes are zero at the equilibrium state. Originally, there are 71 routes and 849km for bus routes. At the equilibrium state, 8 routes have no demand and we assume these routes are discontinued. As a result, 63 routes and 795km are set to be continued in the analysis. Some routes increase the frequency and the
others decrease. In average, the frequencies for these survived routes increase by 52% for railways and by 224% for buses. Reflecting the postulate, the vehicle-km is largely increased as shown in Table 2. The increase of vehicle-km of railway is a same rate as the frequency increase, but that of bus is a little bit lower than it. This is due to the discontinuing routes where the demand comes to be zero with this update.

Meanwhile the total passenger-km is decreased; that of railway is slightly increased while that of bus is decreased by about 3%. This result indicates that the reduction of waiting time due to the frequency increase induces the route transfers as to using the route with shorter length. The number of route transfers increased by 17%. The higher frequency increases transport cost as well. The total fare increases almost two-fold. However, the total generalized user cost decreases by about 10% because of the reduction of waiting time. This indicates that upgrading level of service possibly reduces the total cost in using public transport and improves the efficiency of the network.

In the last case where both of the frequency update and 50% discount of transfer cost are applied, the total generalized user cost is reduced further from the case of upgrading frequency only. In contrast with the case of transfer cost discount, the combination with the frequency update makes the transfer cost discount effective on the route choice. This result suggests that the solely improvement of route transfer is not sufficiently effective to reform the public transport network; the combination with the improvement of transport service is essential in the study area.

Taking the third case, we examine the change of passenger flows at a link level, the discontinuity of routes and the fare of each link, as shown in figure 4. Passengers on some links increase in the bus network. This leads aggregation of bus routes; the number of discontinued routes increases from the original equilibrium state and the total bus route length decreases by 16%.

![Figure 4. The changes of passengers, discontinued routes, and fares under the case of both transfer cost discount and frequency increase](image-url)
Railways increase their passengers on most links, and there is no discontinued route in the railway network. The fares of bus links largely increase on many routes, compared to the original equilibrium state shown in Figure 3. It is due to the increase of the frequency and the cost is defrayed by the passengers. Despite these increases of fares, the increased frequency benefits the users by saving their waiting time and reduces the total generalized user cost, as shown above.

5. CONCLUSION

In this study, we examined the possibility of a more efficient public transport network in Takamatsu city, Japan, utilizing link-level passenger flow data obtained from smart cards. Instead of using an optimization approach, which sometimes leads a completely different network, we developed a simulation approach that estimates the passenger flow and the transport fares iteratively under the condition of link-level fiscal neutrality of a public transport network. This approach is applied to the analysis of the network efficiency of public transport in Takamatsu with the fixed origin-destination travel demand. As a result, we found it is possible to make public transport network more efficient by aggregating some bus routes.

Sensitivity analysis indicates that the further reduction of the total generalized user cost is possible by improving the public transport frequency even though it increases the direct cost. The waiting time decreases due to the frequency increase. That induces the route transfers and it works to aggregate the public transport routes. The reduction of transfer resistance was found not to affect the passenger flows solely. Reducing the transfer resistance is found to be effective in combination with the frequency increase.

For simplicity, we assumed the neutral fiscal balance of public transport at a link level. This assumption allows the aggregation of demands and routes and gives insights into the link-level network performance. In reality, the cost is not cleared by fare at a link level or even not at a network level. Other studies deal with user cost, operators cost and cost to quit using public transport separately. However, it requires further assumption in allocating the operating cost to users, operators and the society. Our study assumes a quite simple setting, but it would be intelligible to find the inefficiency of the public transport network.

Further consideration is needed for the value of waiting time. We assume that the values of waiting time and on-board time are same. However, if the waiting time is long, people are able to use that time for another activity. In addition, the origin destination demand is fixed in this study that raises a bias in passenger-flow estimation. More than 60% of trips are made by passenger car in Takamatsu, and therefore the competition among transport modes is inevitable. These issues should be addressed in future studies.

REFERENCES