EVALUATION OF BUS NETWORK USING A TRANSIT NETWORK OPTIMISATION MODEL -CASE STUDY ON HIROSHIMA CITY BUS NETWORK-

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ABSTRACT

As the environmental concerns are recognised to be serious, the importance of public transportation systems has recently been increased because the energy efficiency of public transportation systems is better than that of private cars. However, the number of public transportation users decreasing year by year all over the world. Many of the measures, such as increasing the capacity and introducing off-peak fare, have been taken to increase the number of passengers, but very few of researches or cases paid attention to the network configuration. Therefore, this paper evaluates the existing bus network from the viewpoint of the passengers, operators and system efficiency using the output of the afore-constructed transportation network optimisation model. The transportation network optimisation model is formulated as bi-level optimisation problem whose lower problem is a transit assignment model. Also, since the upper problem is formulated as a bi-level optimisation problem with minimising passengers' and operators' cost, it is possible to evaluate the effects of reducing operators' cost against passengers with this evaluation framework. From a case study using the demand data in Hiroshima City, it was confirmed that the current bus network is close to the pareto front if the total cost of both passengers and operators are adopted as objective

functions. It was also confirmed that decreasing the operators cost too much causes not only increasing the passengers' cost but also increasing the inequity among passengers.

Keywords: Bus network evaluation, Transit assignment model, Bi-level optimisation

INTRODUCTION

As the environmental concerns are recognised to be serious, the importance of public transportation systems has recently been increased because the energy efficiency of public transportation systems is better than that of private cars. In order to make travellers shift from private car to public transportation, many public transport operators take such measures as reducing off-peak fares or increasing the capacity during the congested period. Also, Hiroshima City, where is a study area in this paper, establishes car-free day three times a month and appeals to refrain from using private cars. However, the number of bus riders decreasing year by year in the study area. There seems to be a room to make the network configuration more efficient at many of cities since one can find many inefficient bus networks, such as several overlapping lines in CBD areas, all over the world including a study area in this paper. Indeed, the number of passengers increased about 11% in Seoul metropolitan area as a result of the bus network reorganisation in 2004. An optimal public transportation route configuration can therefore help as a benchmark for route (re-)configuration which is commonly referred to as the transit route network design problem (TRNDP) (Kepaptsoglou et. al. (2009)).

Several researchers proposed TRNDP models. Yang et. al. (2007) also proposed a bus network optimisation model whose objective function is maximising the ratio of passengers travelling without transfer, and solved the model by a parallel ant colony algorithm and then applied to Dalian city bus network. The passengers' behaviour principle seems not to be described clearly in their model. Prabhat et. al (2006) proposed a model for optimising the feeder bus route, where the transfer point from the railway to the feeder bus is fixed and transferring between the feeder buses is not allowed. Guan et. al (2006) formulated a simultaneous optimisation problem of railway line configuration and passenger assignment as a linear binary integer problem. Since the line frequencies are not determined in their model, they charged a prior given transfer penalty as an additional waiting time. However, the additional waiting time for transfers should be depending on the service frequency; i.e. passengers' waiting time is small if the service frequency is high. Another feature of their model is that a branch and bound method is utilised as a solution algorithm to obtain an exact solution whereas all previous models are solved with heuristic algorithms. However, as they simplified the network to solve the model within a reasonable time, it would be difficult to apply a strict solution algorithm to a bus network optimisation problem in the real world, which is in general more complex than a railway network optimisation problem. Kepaptsoglou et. al. (2009) provide a structured review of TRNDP approaches distinguishing of objective variables, parameters and methodology.

The literature review so far reveals that many researches do not describe passengers' route choice behaviour accurately or otherwise, they imply that less transfer is desirable for passengers. Indeed, transfer behaviour can be troublesome for passengers in many cases, but passengers would not care about transfer so much if the frequency of alternative lines is high enough like in the CBD area of many major cities. Therefore, it is necessary to treat passengers' route and transfer choice behaviour more accurately. Nachtigall and Jerosch (2008) combine a line planning model and traffic assignment model and showed a solution algorithm based on the column generation method. However, their assignment model is very similar to the traditional assignment model and does not consider the "common lines problem", which is an essential for transit assignment in networks for which uniform passenger arrival can be assumed. Petrelli (2004) demonstrate a model framework of combining the TRNDP and a transit assignment model considering common lines (although some details of the transit assignment model are omitted). Beltran et. al. (2009) extended their model to decide the allocation of a limited number of environmental-friendly vehicles and applied the model to a real-size network. One of the authors also proposed TRNDP model (Shimamoto et. al. (2010)), which is applied only to a toy network. Similar to Shimamoto et. al. (2005), the proposed model is formulated as a bi-level optimisation problem whose lower problem is a transit assignment model considering the common lines (Kurauchi et. al. (2003)). Another feature is that the proposed model is defined as a multi-objective problem in the upper problem. Although the multi-objective problem in general takes much more computational cost than the single objective problem, it can explicitly consider the trade-off relationship among different stake holders. At most cases, there are more than two stake holders to be considered for some transportation policy. For example, after the virtual liberalisation of the bus operation service is introduced in Japan, many transit operators withdraw a service from unprofitable routes, which causes further inconvenience to passengers. Hence it is obviously important to consider the trade-off relationship among those stake holders for deciding a transportation policy.

In addition to the trade-off relationship among different stake holders, equity issues should also be taken into account for implementing some transportation policy (Victoria Transport Policy Institute (2010)). Viegas (2001) discussed problems laid on implementing the road pricing from the viewpoint of effectiveness and acceptability. He introduced the following four dimensions of equity in the paper;

- horizontal equity, associated with the equality of opportunities;
- territorial equity, associated with the right to mobility, and provision of identical conditions for citizens living in all parts of a certain country;
- vertical equity, associated with the protection of those in worst conditions;

- longitudinal equity, associated with the comparison of conditions between present and past (balance between gain and loose).

Furthermore, since several equity indexes, such as Gini coefficient, Theil index and Atkinson index, are proposed, it is possible to evaluate equity quantitatively. Therefore, some researchers implicated an objective function of a bi-level optimisation problem. Sumalee (2004) adopted minimisation of inequity among drivers as one of the objective functions of deciding optimal charging cordon design model. Shimamoto et. al. (2005) also adopted minimisation of inequity among passengers with the similar model framework. Although both models utilised only a Gini coefficient as an indicator of (in)equity, Feng et. al. (2009) compared different equity indicators as an objective function of road network design model. They showed that the different inequity indicator leads to different solution patterns. However, it seems not to reach any consensus as to which inequity indicators to be utilised for implementing the transportation policy.

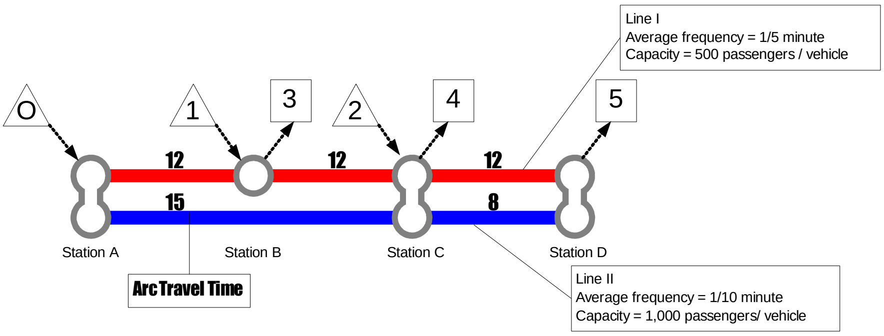
Based on these backgrounds, this paper evaluates the current bus network in Hiroshima city by comparing the output from the model. Not only the aggregated values (e.g. total passengers' cost) but also the equity among passengers are adopted as evaluation indicators. The remainder of the paper is organised as follows: Section 2 describes briefly the capacity constrained transit assignment model proposed by Kurauchi et. al. (2003) and Section 3 describes a mathematical formulation and a solution algorithm of the bus network optimisation model. Section 4 illustrates the current situation of the study area and then evaluates the existing bus network using the output from the model. Finally, Section 5 concludes and points out future research.

CAPACITY CONSTRAINED TRANSIT ASSIGNMENT MODEL WITH COMMON LINES

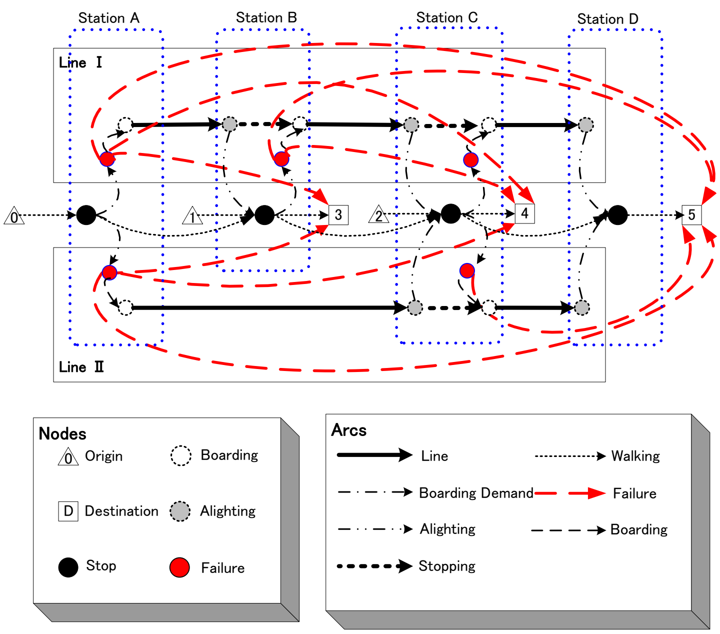
In this chapter, the capacity-constrained transit assignment model with common lines (named CapCon-CL) (Kurauchi et. al. (2003)), which is utilised in the lower problem of the proposed model, is briefly presented.

Network representation

In order to consider the capacities of the transit lines together with the common-lines problem, the transit network shown in Figure 1(a) is transformed into the graph model in Figure 1(b). An origin node represents a trip start node. A destination node represents a trip end node. A stop node represents a platform at a station. Any transit lines stopping at the same platform are connected via boarding demand arcs, failure nodes, and boarding arcs. At stop nodes, passengers can either take a bus or walk to a neighbouring bus stop. In case they take a bus, they are assigned to any of the attractive lines in proportion to the arc transition probabilities. A boarding node is a line-specific node at the platform where passengers board. An alighting node is a line-specific node at the platform where passengers alight. A failure node is a node that explains failure to board. When a transit line capacity is exceeded if all passengers board, some of them are forced to use the failure arc. One arc is connected to the corresponding boarding node and the others are connected to each destination node. Note that we assumed that those who failure to board at some stations do not have a priority to board in the next time step in order to deal with the model statically.



a) Example Transit Network



(b) Graph Network

Figure 1. Network Representation

A line arc represents a transit line connecting two stations. A boarding demand arc denotes an arc connecting the stop node to the failure node. The flow on this arc represents the boarding demand for the transit line from a specific platform. An alighting arc denotes an arc from an alighting node to a stop node. A stopping arc denotes a transit line stopping on a platform after the passengers alight and before the new passengers board. This arc is created to express the available capacity on the transit line explicitly. A walking arc connects an origin to a platform (access), a platform to a destination (egress) and between neighboring platforms (walk to neighbor platforms). A failure arc denotes the demand that failure to board. This excess demand is sent directly to its respective destination via this arc. A boarding arc, which represents the movement of passengers who can actually get on a vehicle, is an arc connecting a failure node to a boarding node.

Notations

We utilise following notations regarding to the transit assignment model. The other notations will be shown as appropriate.

A_p	:	Set of arcs on hyperpath *p*
L	:	Set of line arcs
L_l	:	Set of line arcs on line *l*
U_l	:	Set of platforms on transit line *l*
WA	:	Set of walking arcs
BD	:	Set of boarding demand arcs
S_p	:	Set of stop nodes on hyperpath *p*
E	:	Set of failure node
E_p	:	Set of failure node on hyperpath *p*
D_s	:	Set of failure arc destined to *s*
$OUT_p(i)$	:	Set of arcs that lead out of node *i* on hyperpath *p*
w_{kl}	:	Stopping arc of line *l* on platform *k*
b_{kl}	:	Boarding demand arc of line *l* on platform *k*
h_{kl}	:	Failure node of line *l* on platform *k*
$l(a)$	:	A transit line that is included in arc *a*
g_p	:	The cost of hyperpath *p*
c_a	:	Arc cost on arc $a \in A$
t_a	:	Travel time on arc $a \in A$
ξ	:	The on board value of time
ζ	:	The value of time for walking
η	:	The value of time for waiting
θ	:	Parameter for risk of failure to board
α_{ap}	:	Probability that traffic traverses arc *a*

β_{ip}	:	Probability that traffic traverses node *i*
q_k	:	Failure to board probability at platform *k*
f_l	:	Frequency of line *l* (1/minute)

THE COST OF HYPERPATHS

In this paper, the cost of a hyperpath is represented as a generalised cost, which consists of three elements; the monetary value of the travel time, the monetary value of the expected waiting time, and the implicit cost associated with the risk for failure to board. Note that we allow passengers to walk to other bus stops by creating walking arcs between every stop nodes. Therefore, the cost for each arc, ca, is defined as below;

$$c_a = \begin{cases} \xi t_a & (a \in L) \\ \varsigma t_a & (a \in WA) \\ \infty & (a \in D_s) \\ 0 & (\text{else}) \end{cases} \quad (1)$$

Using the cost of arc a, ca, the generalised cost of hyperpath p, gp, can be written as follows:

$$g_p = \sum_{a \in A_p} \alpha_{ap} c_a + \eta \sum_{k \in S_p} \frac{\beta_{kp}}{F_{kp}} - \theta \ln\left(\prod_{k \in E_p} (1 - q_k)^{\beta_{kp}} \right) \quad (2)$$

Where

$$F_{ip} = \sum_{a \in OUT_p(i)} f_{l(a)} \quad (3)$$

Note that □ap and □kp are obtained from the arc split probabilities in Figure 1 (b). The first term of Eq. (2) represents the “moving cost” which consists of the fare, any additional fare, and the monetary value of the in-vehicle time. The second and third terms represent the monetary value of the expected waiting time and the cost associated with the risk for failure to board, respectively. The parameter for the risk for failure to board, □ denotes risk averseness. If □ □□, then passengers are absolutely risk averse, and they are not interested in travel time or expected waiting time; when □ =0 passengers do not care about failing to board. As Eq. (2) can be separated by the subsequence node, Bellman’s principle can be applied to find the minimum-cost hyperpath. Finally, the CapCon-CL is formulated with a complementarily problem which finds hyperpath flows and failure-to-board probabilities satisfying both user equilibrium and capacity constraint conditions. The complementarily problem is solved by combining the method of successive averages and absorbing Markov chains (See, Kurauchi et. al. (2003)).

BUS NETWORK CONFIGURATION AND FREQUENCY OPTIMISATION MODEL

Outline of the model

In this study, we consider two stakeholders; the operator and passengers. We assume the bus services are provided by only one operator, who wishes to minimise the total operational cost. Note that the bus service is operated by five bus companies in the study area, whose objective are not minimising the operational cost but maximising the total benefit. Therefore, we regard the operator not as bus companies but as a public agency whose aim is to realise a socially optimal bus network. Furthermore, the passengers are assumed to minimise their total cost shown in Eq. (2).

We further set following assumptions in the proposed model.

- The position of bus stops is given and fixed, but not all the bus stops have to be utilised,
- Express services are not considered, i.e., all the buses have to stop at all stops they pass en-route,
- Travel time between bus stops is constant, and
- The maximum number of lines and an origin/ destination of each line is fixed (due to depot constraints).
- The OD demand is fixed regardless of the bus network configuration.

Model Formulation

The decision variables in the model is the route and frequency of each line; denoted as r=(r1, r2, …, r|L|) and f=(f1, f2, …, f|L|) respectively. The model is formulated as below;

$$\min_{\mathbf{r},\mathbf{f}} \psi_m(\mathbf{y},\mathbf{q},\mathbf{r},\mathbf{f}),\, m=1,2,\cdots M \tag{4}$$

such that

$$(\mathbf{y}^*, \mathbf{q}^*) \text{ satisfies (User Equilibrium)} \tag{5}$$

$$C_l(\mathbf{r}_l) \le C_l^{\max} \tag{6}$$

$$\sum_{l=1}^{|L|} f_l C_l(\mathbf{r}_l) \le NV \tag{7}$$

Where,

M : The number of objective functions in the upper problem
$|L|$: The number of lines (fixed)
$C_l(\mathbf{r}_l)$: Travel time from theorigin to the destination of line l

$C_l^{\max}$: The upper value of travel time on line *l*
NV : The available number of vehicles

Eq. (4) represents the objective function of the upper problem defined in the following and Eq. (5) represents the passengers' equilibrium condition under a given network configuration and frequencies as introduced in the previous chapter. Eq. (6) represents the line length constraints to avoid too long lines and Eq. (7) the vehicle number constraints. Note that the number of required vehicles to operate a certain line is assumed to be proportional to the line length and frequency, which implicitly neglects the turning time or waiting time at the depots.

As mentioned before, the objective function of the operator is to minimise the total operational cost (ψ_1) and that of passengers is minimising total travel cost (ψ_2), which is formulated as below. Eq. (8) represents the total travel time for the operator since the left hand side of Eq. (7) represents the number of vehicles required to operate line l which is multiplied by the cost for each line.

$$\psi_1(\mathbf{r},\mathbf{f}) = \sum_{l=1}^{|L|} f_l C_l(\mathbf{r}_l)^2 \tag{8}$$

$$\psi_2(\mathbf{y},\mathbf{q},\mathbf{r},\mathbf{f}) = \sum_{rs \in W} \sum_{p \in H_{rs}^*} y_p \cdot g_p(\mathbf{y},\mathbf{q}) \tag{9}$$

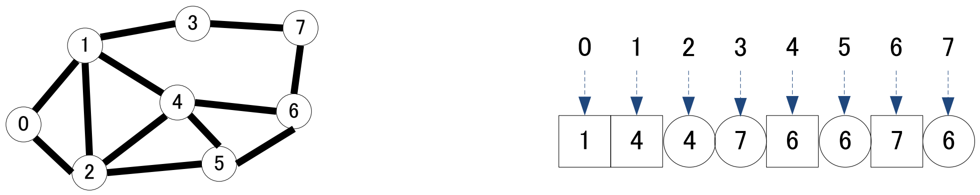
where,

$\boldsymbol{W}$: The set of OD pair
H_{rs}^* : The set of hyperpath between OD pair *rs*

Note that the result might be biased because of the possibility of multiple fixed points in the lower level problem. This bias is well known in MINLP (Mixed Integer Non-linear Programming) and is still a challenging problem.

SOLUTION ALGORITHM

As shown in Section 3, the proposed model is formulated as a multi-objective optimisation problem in the upper problem. To solve the upper problem, we utilise the elitist non-dominated sorting Genetic Algorithm (NSGA-II) proposed by Deb et al. (2000) to solve the multi-objective optimisation problem. An advantage of NSGA-II is that it requires fewer parameters than other methods. The candidate bus routes and frequencies are separately created with a GA procedure. Although it is possible to create not only the shortest route but also various alternative routes with a GA procedure, many fatal chromosomes which do not represent for the routes may be created with a typical GA procedure. Therefore, we utilise the improved GA procedure for route search proposed by Inagaki et. al. (1999). Hereafter, the modification of the GA procedure for route generation under the fixed origin and destination nodes is explained following Inagaki et al. (1999) using the example network shown in Figure 2 (a).



(a) Example network (b) Alignment of chromosomes
Figure 2 Alignment of genes in a chromosome

In the modified GA procedure, the number of genes in a chromosome is the same as the number of nodes in a network N. Each gene m can only take the values of the nodes to which direct links from the node m exist, in other words a link connecting nodes m and n is represented by assigning node ID n to the mth gene. Therefore the alignment of the genes in a chromosome can provide the ID of nodes that make up a route, if one keeps moving "jumping" from gene m to gene n, (in Fig. 3(b) this are the genes with a square). Therefore, the chromosome defined here consists of two types of genes, those contributing to the representation of the route and those not. Note that Proposition shows that from the genes that contribute to the route description, we can always obtain a valid route unless a cyclic route is obtained which occurs if the same node ID appears in at least two of these genes. Figure 2 (b) represents the route (0→1→4→6→7) if origin and destination node are defined as 0 and 7 respectively. For the genes that are not needed for the route description a random node ID among the available node IDs is selected. Creating new chromosomes then consists of the well known elements initialisation, crossover and mutation. Please refer to Shimamoto et. al. (2010) for the detail of these operations.

EVALUATION OF HIROSHIMA BUS NETOWORK

Outline of the Study Area

Hiroshima City is one of the core cities in the Chugoku are in Japan and the number of population is about 1,173,000 (November 2009). Recently, Hiroshima city synoecised suburb areas where many inhabitants commute to CBD area, and there are not few bus services between their residential area and CBD area. However, most of the suburb residential areas do not spread widely and hence there is little room to reconstruct bus lines connecting the suburb area and the CBD area. Therefore, the study area is limited to the CBD area shown in Figure 3 whose size is about 5 km square. The main public transportation modes in the study area are buses and trams, but we do not consider trams in this study due to the data limitation. Figure 4 shows the distribution of the boarding demand in the whole city, which is collected by Hiroshima city through the trip survey conducted in 2008. As seen the figure, the demand from 7:00 to 8:00 is highest and it occupies about 18% of the total demand. Therefore, we define as a morning peak hour from 7:00 to 8:00.

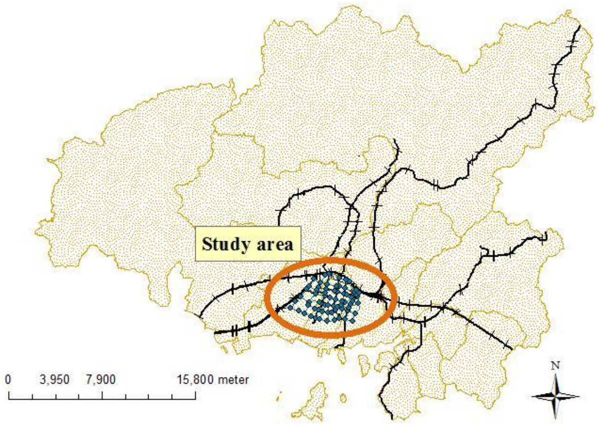


Figure 3 Map of Hiroshima city and location of the study area

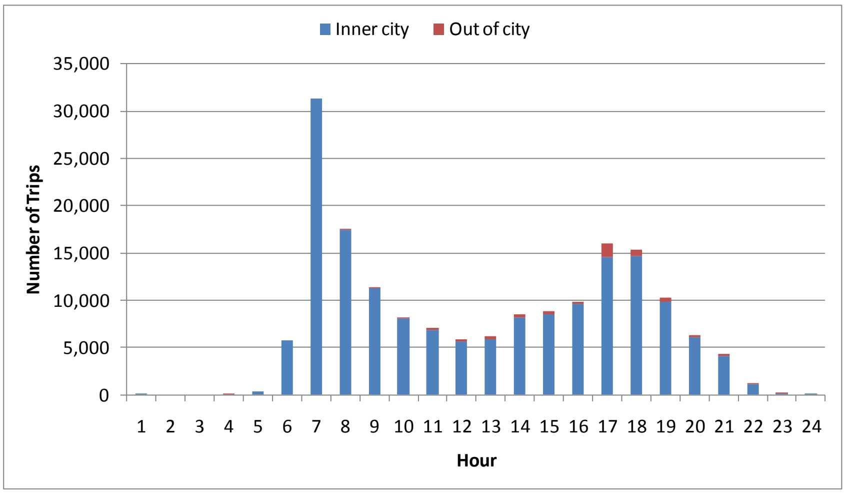


Figure 4 The distribution of the boarding demand in the whole city (weekday)

Figure 5 shows the distribution of the number of boarding and alighting passengers at the study network. and Figure 6 illustrates the sum of frequencies in each road section as a result of data aggregation described in the next section. The number of boarding and alighting passengers is larger at node 54, 37 and 44, where node 54 corresponds to the central station (Hiroshima station) and around the area between node 37 and 44 corresponds to the busiest downtown area of the study area. As a result, many buses run on the road connecting node 54 and node 37 or 44 as shown in Figure 6. This leads to inefficient bus operation such as “bunching effect” where more than two buses arrive at a stop at the same time, which often causes unreliable bus services.

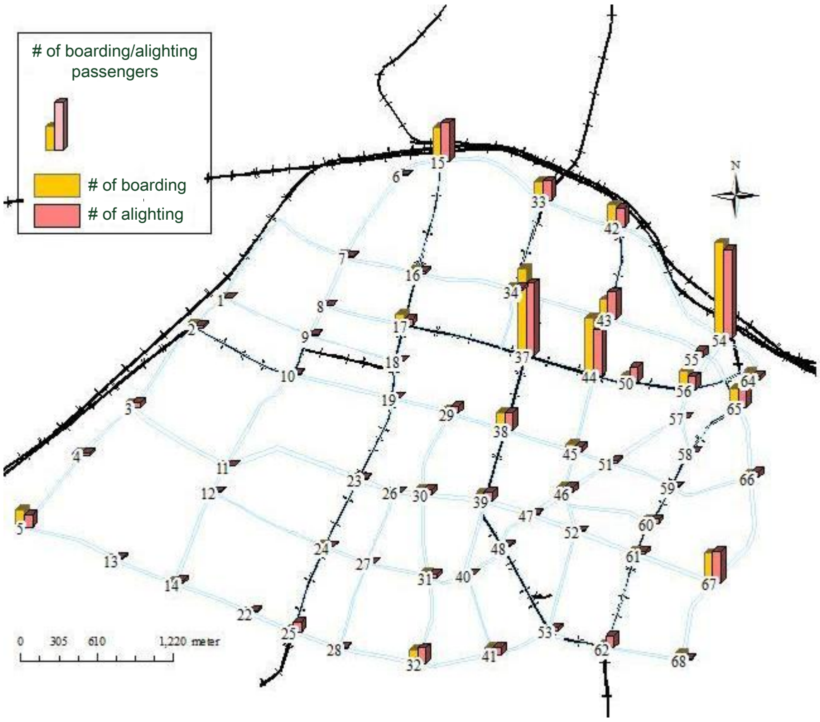


Figure 5 Distribution of the number of boarding/ alighting passengers from 7:00 to 8:00

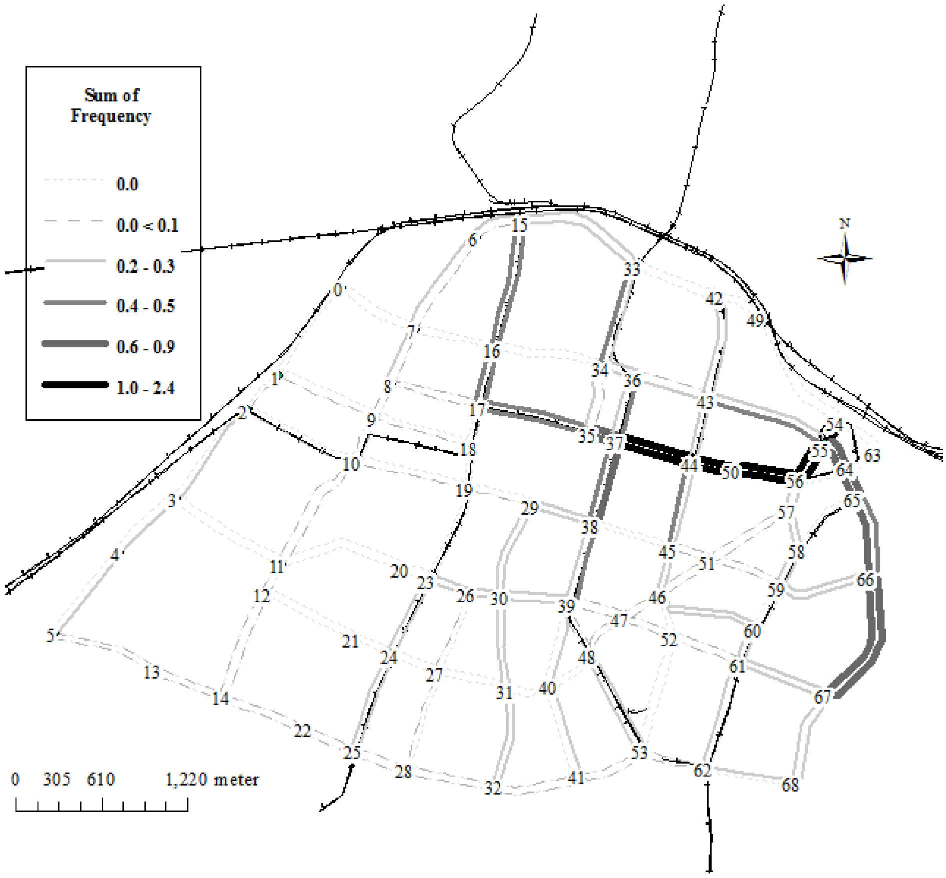


Figure 6 The sum of frequencies of each road section from 7:00 to 8:00 (Current network)

DATA COLLECTION AND PARAMETER SETTING

Data Collection

The passengers' demand data, which is counted from the numbered-tickets on October 2006, is obtained from the bus companies operated in the study area. Note that although there are five bus companies in the study area, we do not consider the competition between companies and treat as if there is one bus company in the study area. This means as previously mentioned that the network configuration obtained from the model is from the viewpoint of social rather than from that of each operator. Also, due to the data limitation, we conduct following two data arrangement. Firstly, since we only obtained the aggregated data by the month, it is impossible to figure out the demand fluctuation among days or among hours. Therefore, we firstly convert the original data to one-day data by dividing into 31 and then convert to on-peak (from 7:00 to 8:00) demand by multiplying by the ratio of the demand of that period obtained from Figure 4. Secondly, as the sectional fare structure starting from \150 (about €1.14) is adopted in the study area, the demand data is obtained only between the fare sections. Therefore, we firstly consolidate bus stops only at the major intersections. Since many of the fare zones have only one consolidated bus stop with this procedure, the origin or destination of these fare zones can be automatically converted to that consolidated bus stop. However, if more than two consolidated bus stops exist within one fare zone, passengers' boarding or alighting demand to this fare zone is distributed to the consolidated bus stops with proportional to the number of bus stops within this fare zone. Furthermore, since there exists several boarding demands whose origins or destinations is outside the study area, the origins or destinations of such boarding demands are hypothetically moved to their closest boundary bus stops. Finally, the fare is not included in the passengers' cost. Figure 7 illustrates the simplified network which has 69 bus stops and 228 links with both directions. As a result, there exists 36 lines with both directions at the study area, whose frequencies and the distances between bus stops are respectively obtained from the timetable and the GIS data.

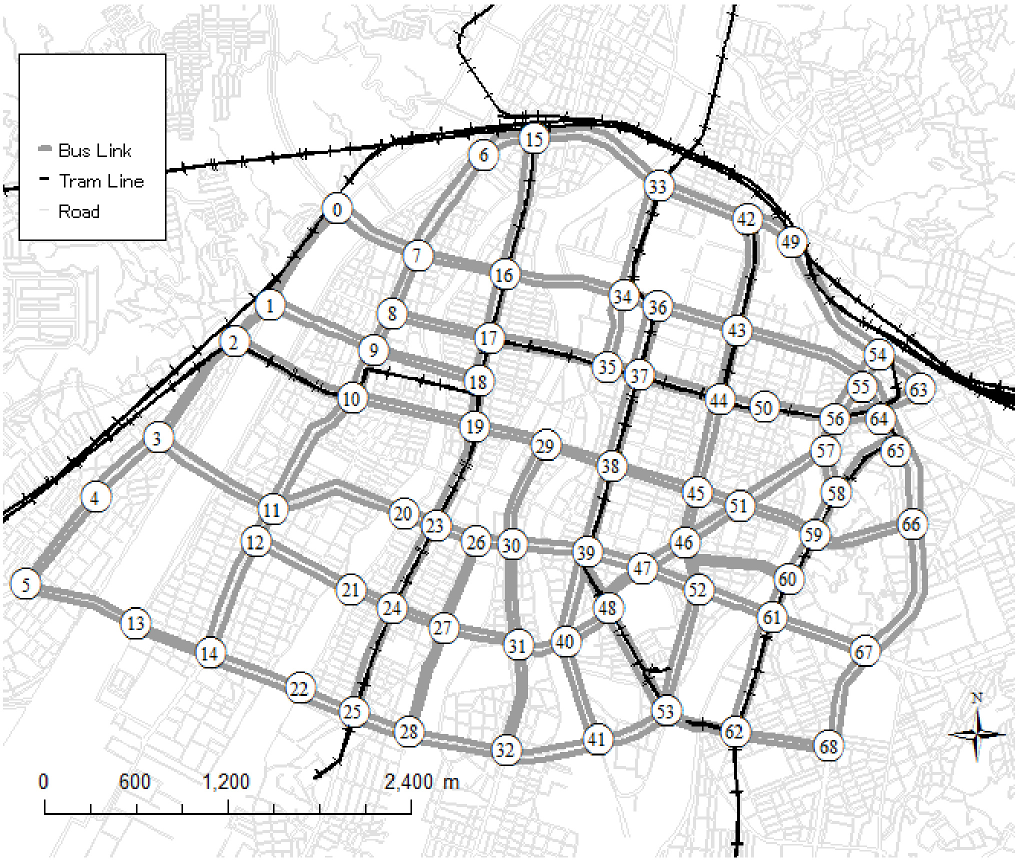


Figure 7 Study network

Parameter Setting

Although the observed bus travel speed data is not available, the census data in 2005 collected by Ministry of Land, Infrastructure, Transport and Tourism in Japan says that the average travel speed in the centre of Hiroshima City is approximately 18.8 km/hour (313.3 m/minute). Therefore, the travel speed of each mode is assumed as shown in Table 1 (a). The value of time is set as shown in Table 1 (b), which is estimated by Kurauchi et. al. (2004) from the SP-based mode choice survey data. The capacity of each vehicle is set as 45 (passengers / vehicle), which is based on the number of passengers in the overloaded bus counted by the authors. Furthermore, since a heuristic solution is applied to the proposed model, the frequency of each line should be decided discretely. If the frequency if each line is chosen from a wider range, the number of combination of frequencies and line configuration becomes exponentially larger and as a result, it becomes difficult to obtain an optimal result. Therefore, the frequency is chosen from following four options; i) twice ii) the same iii) half of the current frequency and iv) no service is operated. The parameters of NSGA-II are set as shown in Table 2.

Table 1 Parameters regarding to the transit assignment model

(a) Travel Speed

Bus	300	(m/minute)
Walk	50	(m/minute)

(b) Value of Time

On Board	13	(¥/minute)
Wait	26	(¥/minute)
Walk	50	(¥/minute)

Table 1 Parameters regarding to NSGA-II

Number of indivisuals	40
Number of generations	50
Crossover rate	0.9
Mutation rate	0.05

Since we cannot estimate the parameter for failure to board so far, we firstly compare the pareto front with different parameters using Figure 7. Note that $\theta = 0$ means that the passengers choose their route without considering the possibility failure to board. Although the passengers' cost with positive θ takes higher value than that with θ equal to 0 when the operational cost is around 300, the three pareto fronts are approximately the same. This implies that the overcapacity cannot be a serious problem even if the transit operator reduces the service level to some extend. One of the reasons for this might be that the on-peak demand is underestimated since we do not consider the difference of demand pattern between weekdays and weekends due to the data limitation. Only the results of not considering the capacity constraints are shown hereafter.

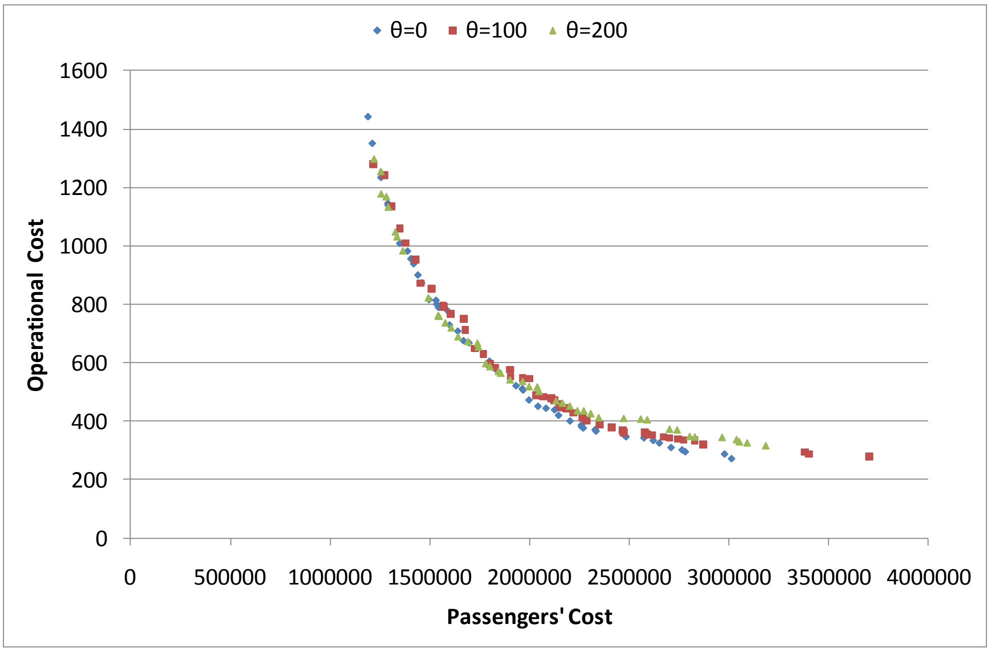


Figure 8 Pareto front with different parameters for failure to board

Discussion

Figure 9 shows the transition of chromosomes with regard to the number of generation. The chromosomes dispersing over the plains at younger generations. However, the chromosomes are accumulating to a curve with the passing of the generations, and finally the pareto front with 46 pareto solutions is obtained as illustrated in Figure 10. The two black dot lines shown in Figure 10 represent the objective values at current network. Since it is not realistic to investigate the network configuration of all the pareto solutions, the pareto solutions are labelled with the ascending order of the passengers' cost as shown in Figure 10 in order to see how the operational cost reduction along the pareto front affects the service level as whole of the network. Out of 46 solutions, two solutions (Solution 6 and 7) take better values than the current network regarding to both of passengers' cost and operational cost, but the current network (the vertex of two black dot lines) is very close to the pareto front.

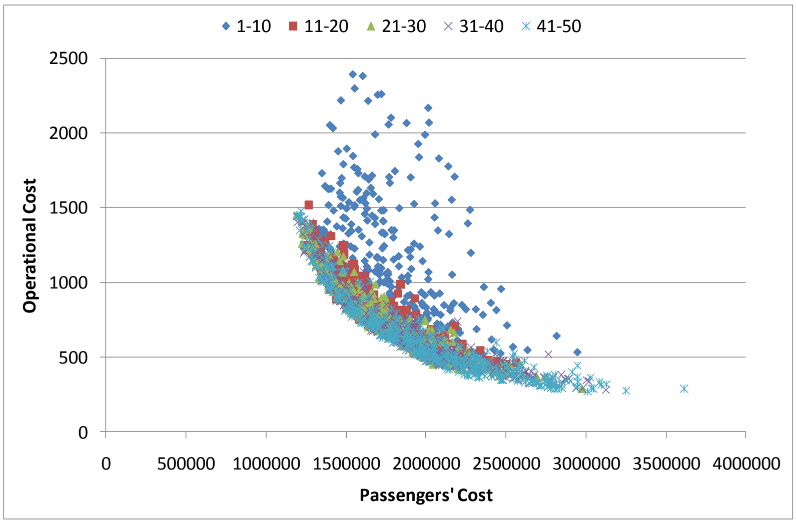


Figure 9 Transition of the chromosomes

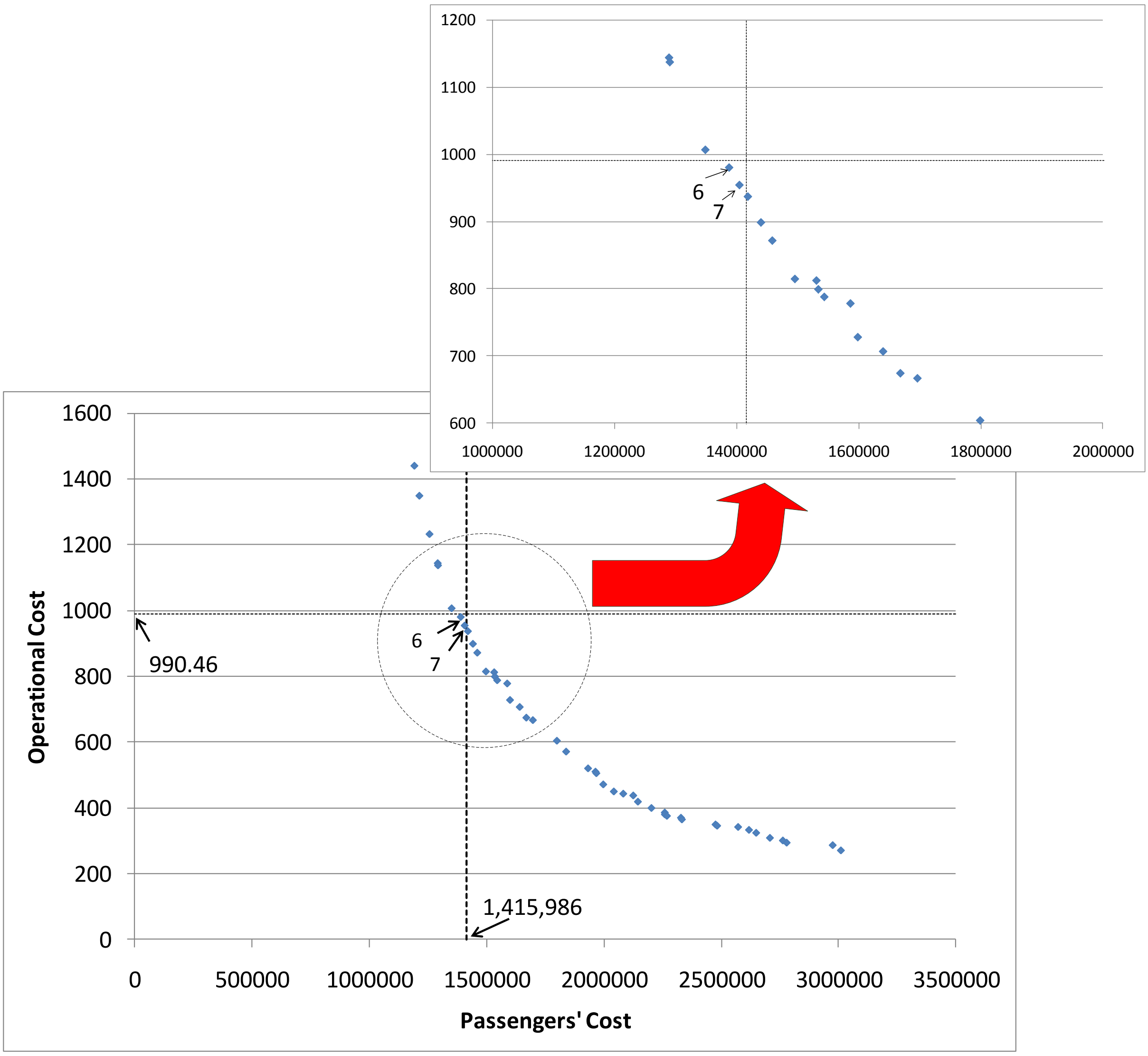


Figure 10 Pareto front with the cost of current network

As the frequencies of each line are selected from four options with this model, Figure 11 shows the suggested line frequencies in each solution. For example, if the model suggests that the frequencies of all the lines to be twice, the percentage of "twice" takes 100% and that of other options takes 0 %. Note that again that the solutions in the horizontal line are arranged with the ascending order of the passengers' cost. The percentage of lines increasing their frequency to twice reaches to 40 % at solution 0 (the solution with largest operational cost) and then, decreasing that percentage as the solution number increases. Alternatively, the percentage of lines with the same frequency increases and it takes largest values around solution 10. As the solution number increase further (which means reducing the operational cost), the percentage of lines with the same frequency increase and then, the percentage of lines halting their service increases. Finally, more than 40 % of lines halt the service and any lines do not increase the frequency at solution 45.

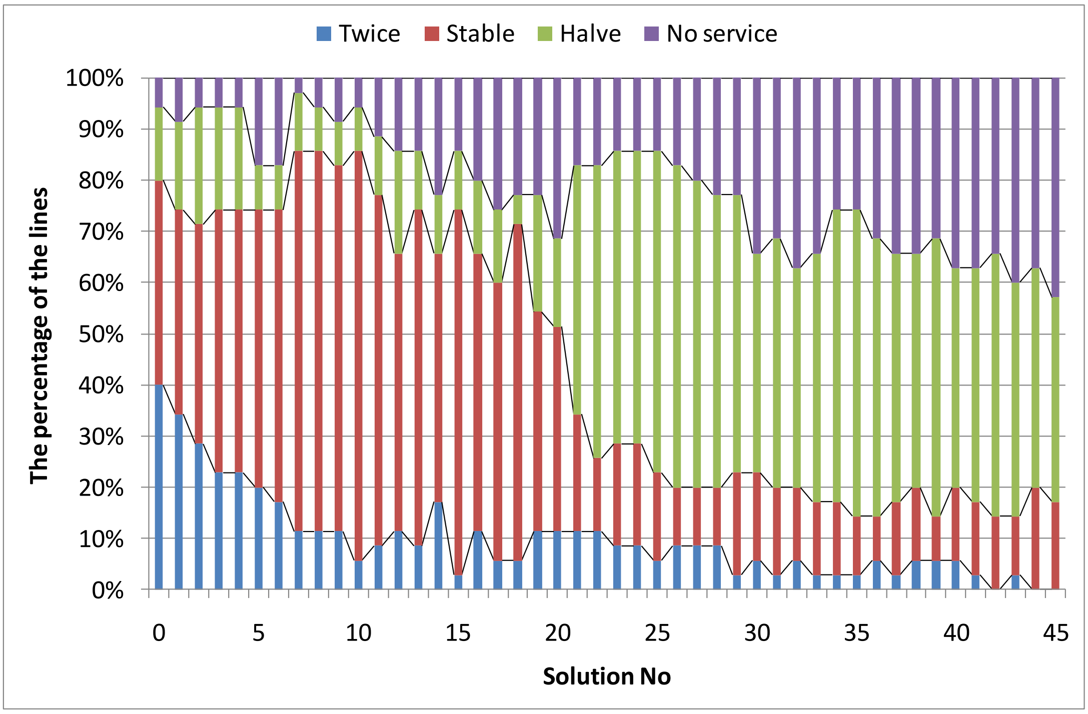
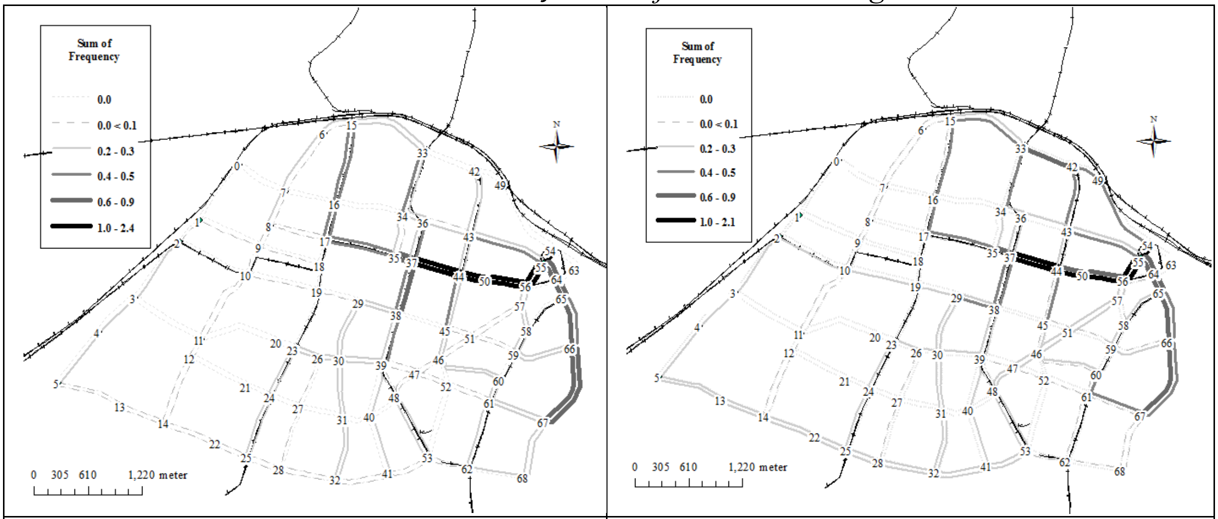


Figure 11 Suggested line frequencies in each solution

Figure 12 illustrates the sum of frequencies of current network and that of solution 6 (one of the solutions with both of objective values is better than the current network.) By comparing two figures, a new route connected a road section between node 54 and 42 is created. However, the number of road sections with dense frequency seems to decrease as a whole network. Indeed, the sum of the line frequencies of lines is 4.47 min-1 at solution 6 whereas that value is 5.28 min-1 at the current network. Also, the variance of frequencies among lines at solution 6 and at the current network respectively takes 0.0177 min-2 and 0.0168 min-2. These facts imply that the operators could provide better service than the current network from the viewpoint of whole of the passengers even if they reduce the total service frequency. One of the reasons for this is that the operational service is dispersed thorough the network at solution 6 since the variance of frequencies among lines is larger at solution 6 than that of at the current network. In addition, it is supposed that another reason for this is that many lines concentrate to a certain road section at the current network.



(a) Current network	(b) Solution 6

Figure 12 The sum of the frequencies of each road section

In order to confirm above supposition we now focus on the change of frequencies at local road sections where many buses are concentrated. Figure 13 illustrates the sum of the frequencies of each solution at Section A and Section B. Note that Section B, which is marked with red circle in the figure, connects between the central station and the busiest downtown area and many buses pass through this section as described previously. Section A, which is marked with blue circle in the figure, is chosen as an alternative section of Section B since both sections run parallel. The sum of the frequencies for west bound of both sections decrease with many solutions, but the decreasing ratio with regard to Section B seems to be larger than that of Section A. Furthermore, the sum of frequencies for east bound at Section B decreases with many solutions whereas the sum of frequencies for east bound at Section A increases with many solutions. Therefore, the concentration of busses to Section B is somewhat relieved at many of solutions, and one of the reasons for this is some lines' shifting from Section B to Section A.

To summarise above considerations, dispersing the service operation could bring a win-win relationship to both the passengers and the service operators at dense bus network. Furthermore, one of the solutions to realise this situation could be shifting some services from a section with dense service to another parallel section with less dense service.

Figure 13 The sum of the frequencies at section A and section B in each solution

As the pareto solutions are evaluated mainly from the viewpoint of the operators or whole of the systems so far, we now evaluate the pareto solutions from the viewpoint of passengers. Figure 14 illustrates the cost component in each solution. The boarding cost is stable through all the solutions, but the waiting time and the walking time increase as the solution number increase (which means as the operational cost decrease by reducing the level of service as shown in Figure 10 and Figure 11). Therefore, the passengers suffer from the inadequate service as the operational cost decreases, but the total boarding time is almost the same probably due to the assumption of fixed OD demand.

Finally, the equity level among OD pairs is compared using the equity indicator. Since there seems to reach no consensus as to which equity indicators are suitable for evaluating some transportation policies as described in Chapter 1, the Gini coefficient is utilised here as following the existing researches. Also, the longitudinal dimension, which is described in

Chapter 1, is adopted under the assumption that it is desirable to keep the differential of the level of service close to the current situation. The definition of the Gini coefficient and its' formulation with this case is shown in Appendix. Figure 15 shows the Gini coefficient in each pareto solution. The Gini coefficient increase as the solution number increase (which means as the operational cost decrease by reducing the level of service as well). To summarise above considerations, decreasing the operational cost affects not only increasing the passengers' cost but also increasing inequity among OD pairs.

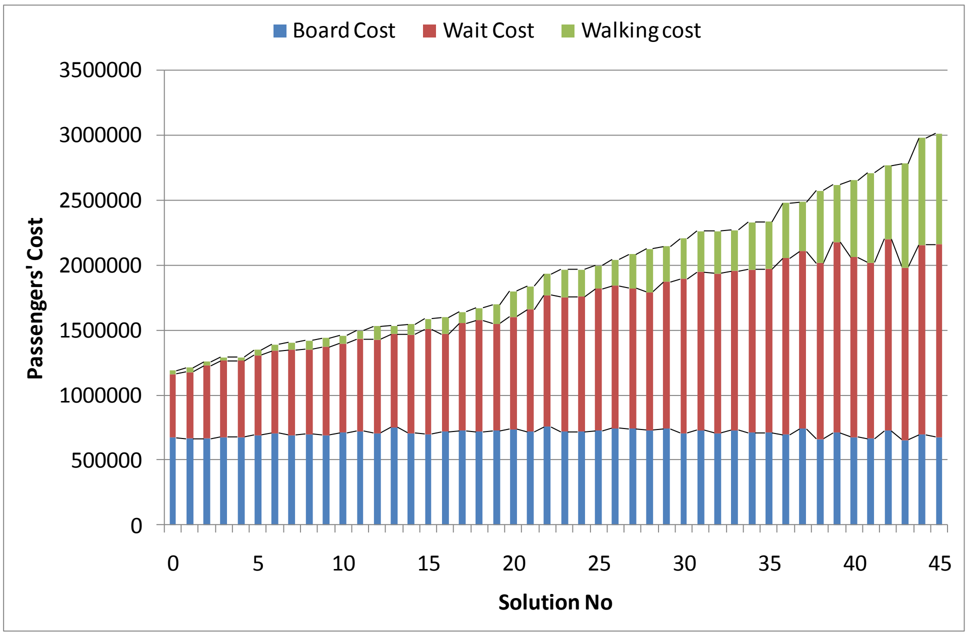


Figure 14 The cost component in each solution

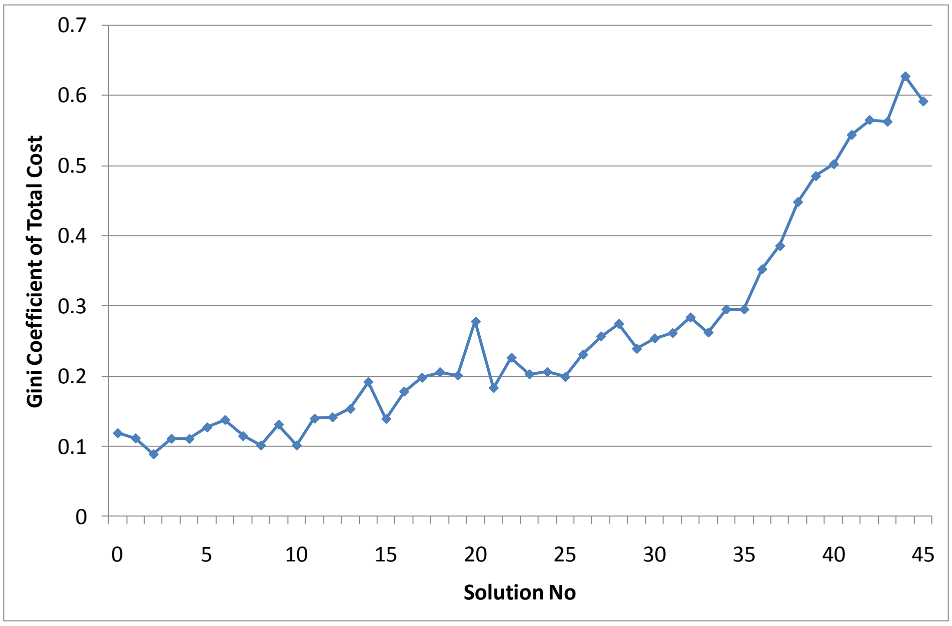


Figure 15 Gini coefficient with respect to the total cost in each solution

CONCLUSION

This paper evaluated the bus network configuration at the morning peak hour in the central area of Hiroshima city from the viewpoint of both operators and passengers. The previously constructed bus network optimisation model which can decide the line configurations and frequencies simultaneously was utilised for evaluation. Since the transit operators are regarded to be a public agency whose aim is not to maximise the benefit but to minimise the total operational cost in the model, the current bus network is compared with the socially optimal bus network.

From the comparison between the current bus network and the output of the model, it was confirmed that the current bus network is close to the pareto front if the total cost of both the passengers and operators are adopted as objective functions.. On the other hand, it was demonstrated that dispersing the service operation could bring a win-win relationship to both the passengers and the service operators and that one of the solutions to realise this situation is shifting some services from a section with dense service to another parallel section with less dense service. Therefore, there is still a room to realise more desirable network with less passengers' and operators' cost, but it was also demonstrated that decreasing the operators cost too much causes not only increasing the passengers' cost but also increasing the inequity among passengers.

As the future works, it is desirable to obtain more detailed OD data from IC card records in order to increase the accuracy of the analysed result. It is worth to further compare the result with different time period to confirm the robustness of the network configuration with variable demand if such rich data is available. Furthermore, it is required to expand the model to consider the elastic demand or interaction among other travel modes (such as private car and taxi). Finally, there is a room to add realistic constraints, such as drivers' scheduling, into the model in order to obtain more realistic result.
Note that above formulation is also an assumption which should be verified with observed bus operation data. δ^k_{ml} is introduced to consider the arrival correlation only for the same line, which implies that different bus lines run on different roads. The first term of Eq. (11) is defined as twice of the logistic function which takes values from 0 to 1, therefore, ρ^k_{ml} takes values from -1 to 1 and closer to 1 as the number of boarding and alighting passengers increases. Also, we introduce two positive scale parameters, κ^k_{ml} and ν^k_{ml}. κ^k_{ml} is a scale parameter related to the number of boarding and alighting passengers which takes a small value if the boarding and alighting time per passenger decreases due to, for example, introducing an IC card fare collection system. ν^k_{ml} is assumed to be related to other factors, such as the bus network configuration or the quality of the facilities, i.e., ν^k_{ml} takes a larger value if many lines gather in the same road section and a smaller value if the accelerating performance of the buses is good. Therefore with these two scale parameters, it is possible

to consider both factors of the bunching effects; i) increasing the boarding and alighting time due to the passengers' concentration to a certain vehicle, and ii) concentrating vehicles to a certain road segment.

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APENDIX

The Gini coefficient is a value which is often used to measure the income inequity and recently also finds applications in operations research (Shimamoto et. al. (2005)). The Gini coefficient is defined as twice the area between Lorentz curve and forty-five degree line in the population-share and income-share plain. From the definition, the Gini coefficient takes a value between 0 and 1, where 0 corresponds to perfect equity and 1 to perfect inequity. The Gini coefficient regarding to the total cost among OD pairs can be formulated as below;

$$Gini^m = \frac{1}{2 \cdot Q^2 \cdot \overline{CR}^m} \sum_{i=1}^{I} \sum_{j=1}^{I} Q_i Q_j \left| CR_i^m - CR_j^m \right| \quad \text{(A1)}$$

Where

$$CR_i^m = g_i^0 \Big/ g_i^m$$

$$\overline{CR}^m = \sum_{i=1}^{I} CR_i^m \Big/ I$$

Where

$Gini^m$: Gini coefficient at solution *m*

I : Set of OD pair

Q_i : Passengers' demand of OD pair *i*

g_i^0 : Generalise cost of OD pair *i* at current network

g_i^m : Generalise cost of OD pair *i* at solution *m*

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