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A Transit Route Network Design Considering Equity

형평성을 고려한 대중교통 노선망 설계

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서울대학교 대학원

공과대학 건설환경공학부

김 명 현

Abstract

Due to the polarization of incomes, low birth rate and aging population in modern society, there is a significant emphasis on social equity as imbalances deepen and conflicts become more frequent. Public transportation also has temporal and spatial imbalances, which are becoming more serious as faster and more direct service is provided between high-demand regions. Therefore, there is a need for an adjustment process. A recently developed new towns in suburban areas can be called as representative areas being affected by the operation strategy of public transportation with the purpose of minimizing costs. In this study, the public transport network assessment methodology considering modal and spatial equities is proposed. Here, equities are considered by two indexes which can reflect mobility and accessibility simultaneously. Also, heuristic transit route network determination process with sequential procedures which consist of target line selection, target node selection, and alternative line determination is proposed, and frequency setting procedure is implemented.

The model is configured through the bi-level modeling based on an iterative process in order to calculate the modal split and traffic and transit assignment with transit route network changes. Based on the transit route network taking account of the level of modal and spatial equities, in the upper model, frequency of each line is determined by genetic algorithm. On the other hand, in the lower

model, modal split and traffic and transit assignment are implemented. This transit route network design model and algorithms are applied on a sample network. As a result, improved solution with equity and total cost was found based on the comparison with existing transit route network.

There are some expected contributions in this study. First, “equity” indexes are proposed to assess the mobility and accessibility. Second, iterative transit route network determination methodology to maximize equity is proposed. Last, genetic algorithm to determine the frequency of each line is improved with practical frequency constraint, modal split and assignment with variable demand are reflected.

Keywords: transit route network design problem, frequency setting, genetic algorithm, equity, bi-level modelling, transit assessment

Student Number: 2009-20935

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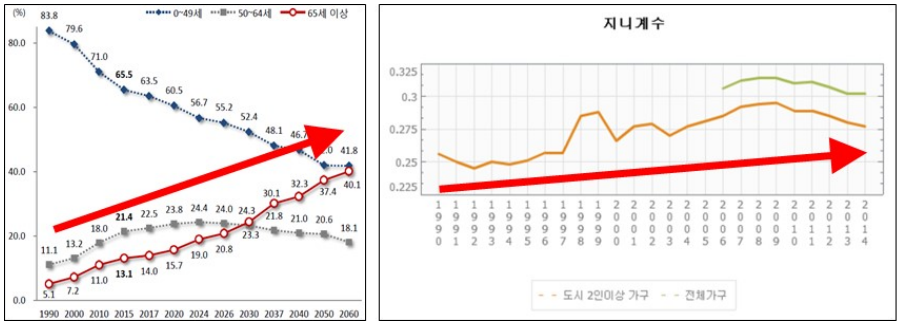
Chapter 1. Introduction

1.1 Purpose of this study

Aging population and income bipolarization are social problems that are continually raised in the modern society. Number of aging population of South Korea has been increased much faster than that of any other countries. The proportion of elderly population is 13.1% in 2015, which increases by 4.5 times since 1960 (2.9%). It is expected to increase to 24.3% in 2030 and to 40.1% in 2060. Gini Index of South Korea is 0.347 in 2013. Of 30 OECD countries, only four countries have higher Gini Index than South Korea. This means that problem of income inequality gets more serious among other developed countries.



Source: Statistics Korea (2015, and each year)

Figure 1.1 Aging population and income bipolarization of Korea

Aging population and income bipolarization problems can be accessed as supply imbalance in common. To solve these problems, fundamental approach

should be “equity”. Here, “equity” means that benefits are distributed equally based on certain criteria. It is composed of horizontal equity and vertical equity. Horizontal equity means that people are equally treated if they are socially equal. On the other hand, vertical equity indicates that people are treated differently if they are different. Elderly population and lower income group, relatively considered as vulnerable social groups, can be supported by the policies such as old age pension or basic pension for the improvement of their social equity. These policies are the product of efforts to solve imbalance problems.

Supply imbalance occurs in the network design problem. At most of the time, general Network Design Problem (NDP) focuses on minimizing total travel cost and operating cost for a single mode or several modes. As a result, it occurs inevitably at the regions with the lack of service. Due to the fact that public goods are served as infrastructure, public transportation should offer and maintain basic level of service. New towns of suburbs recently developed are classical regions which are relatively damaged by the transportation operating strategy for minimizing cost.

The role of public transportation was originally to help people who cannot use automobile to move, but is currently to relieve traffic congestion and enable faster movement as a result of increment of vehicle possession. Drivers including public transportation passengers experience the reduction in the travel cost and time by an improvement of level of service for public transportation. This public transportation service, however, causes a serious

spatial imbalance to travelers who are not provided with the service.

This study designs the public transportation network reflecting modal equity of travel time (automobile and public transportation) and spatial equity in urban network. Modal equity of travel time means the state where the travel time difference between automobiles and public transportation decreases. Spatial equity means that priority of adding routes to the regions with the lack of service sets based on the modal equity for public transportation of departure basis.

Because most public transportation routes in the metropolitan cities are determined by the high demand zonal trip, it may lead to infeasible solution if the route is designed to maximize equity index only. Therefore, this study uses the objective function for minimizing total costs of users and operators, with the consideration of equity index in order to determine route network.

1.2 Scope and Methodology

In this study, a range of equity analysis is a travel time between zones (origin and destination) of each mode. Modes are divided into passenger car and transit, and a travel time of each mode indicates the total travel time from origin to destination. Spatial range of this study comprises an urban network where a transit service is provided. Example network used is Mandl's network (1979) which is popularly used in the public transport network design problem.

Figure 1.2 shows the methodology and procedure of this study. First of all,

in chapter 2, previous studies for the equity and design of transportation networks are implemented. In the review of studies regarding equity, to clarify the concept of equity, in particular transport sector, the methodology of the analysis and the concept of equity in terms of public transport are to be discussed.

In the public transportation area, horizontal equity represents the extent that treats similarly in transportation service. However, vertical equity represents the extent treated differently by members of different classes in transportation service. In this study, equity is divided into modal equity and spatial equity with horizontal criteria. Definition and detailed explanations are to be discussed in the next chapter.

Relative studies have developed indexes related to equity, and applied them to compare and assess the given network. Next, we reviewed the literature reflecting the equity in transportation network design. Transportation network design is generally constructed for the purpose of maximizing the efficiency. Here, efficiency maximization has the meaning of maximization of social benefits, or minimization of the total time or cost. Since the 1990s, in the road network design problem related to road construction or expansion, and congestion toll imposition, equity among regions has been applied to objective function or constraints.

In chapter 3, based on the results of the literature review, the transit network design model considering equity is formulated. Equity between the modes and regions has been reflected in the transit network design, and this procedure can

be applied to the determination process of alternative line candidates. Modified DOCO (Degree of competitiveness) is applied to judge a mobility and accessibility synthetically and to assess the modal and spatial equity. After the procedure of determination of transit route network is completed, frequency setting determined by iterative game theory calculation process is carried out through the bi-level modeling. The objective function of the upper model is constructed in the form of minimizing the total cost of users and operators. However, in the lower model, modal split of passenger car / transit, and traffic and transit assignment are performed from variable frequency setting situation in the upper model. Binary logit model is applied to perform a modal split, and traffic and transit assignment is implemented by user equilibrium with convex combination and transit assignment model by H. Spiess and M. Florian (1989) respectively.

In chapter 4, methodologies of target line (line to alter) selection, target node (node to improve modal equity) selection, alternative line generation and line combination determination procedure, and frequency setting of each line are suggested. At this time, target line is selected by total DOCO of whole network ($TDOCO$), and target node is determined by DOCO of origin i ($DOCO_i$). Alternative line candidates are generated with minimum path via target node between every node. Of these, if circuity of route of candidate lines compared to the shortest route is higher than reference value or redundancy rate with the existing route is greater than reference value, relevant candidate line should be excluded from the list of alternative line candidates. In the frequency setting

procedure, with the bi-level modelling, genetic algorithm (GA) is applied to find an optimal solution.

In chapter 5, to confirm the orientation of the objective function, numerical example analysis was performed by Mandl's network. Comparison results for network improvement, improvement of equity and illustrations are shown from the example of network analysis. Also, model modification and application, policy suggestions are to be presented.

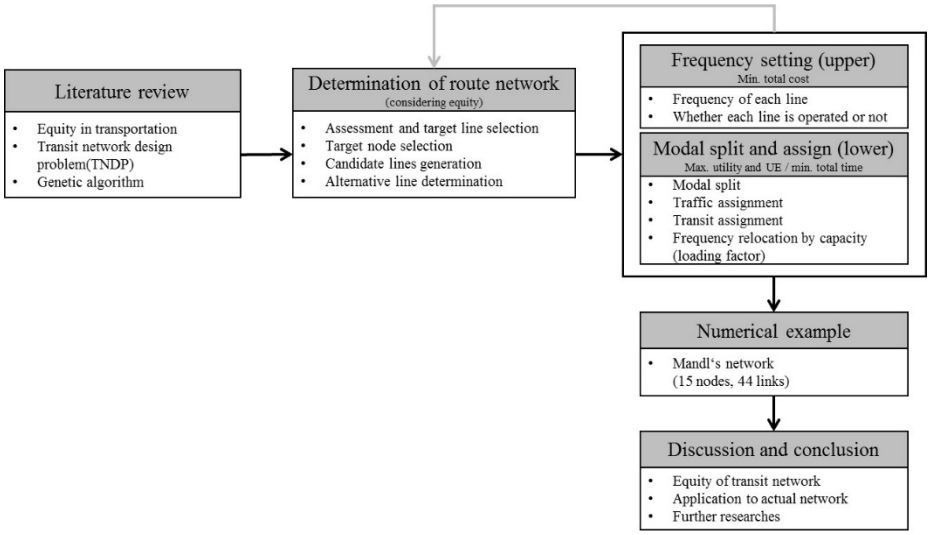


Figure 1.2 Process of this study

Chapter 2. Literature Review

2.1 Assessment of public transportation

2.1.1 Public transportation and equity

The concept of equity is following the two principles of justice by Rawls as follows. First, each person is to have an equal right to the most extensive basic liberty compatible with a similar liberty for others. Second, social and economic inequalities are to be arranged so that they are both (a) reasonably expected to be to everyone's advantage, and (b) attached to positions and offices open to all. All social values - liberty and opportunity, income and wealth, and the bases of self-respect - are to be distributed equally unless an unequal distribution of any, or all, of these values is to everyone's advantage. (Rawls, 2009)

Equity based on the definition of the principle by Rawls is divided in horizontal equity and vertical equity. The horizontal equity is the concept of equal opportunity which is meant to be open to everyone. Vertical equity means the principle of difference, which means the case that maximum benefit the least advantaged members of society of income, property, rights and responsibilities, and the like.

Equity in public transport is satisfied when policy makers establish and support the policies satisfying the horizontal and vertical equity, at the same

time, when people use the transportation facilities and modes rationally.

It was Kain's research (1970) that initiated the discussion of equity in transportation. The concept that inadequate transportation must be numbered among the disadvantages of the poor and that improved mobility, particularly as improves access to jobs, could increase their self-sufficiency was publicized widely in the mid-1960s. In the United States, with the suburbs relocation of the 1970s of industrial facilities, commuting distance is increased much. Therefore, transportation costs increased significantly, and equity in terms of transport service problem has been issue of.

Discussion of the equity of the initial public transport services has been approach the movement support to the passengers without holding the car who cannot travel for themselves. From now on, many researchers have been implemented with spatial and hierarchical distribution of public transport services. However, the purposes of the current public transport service have diversified like faster movement, road congestion relief. High speed rail service in metropolitan area and median bus lane are good examples. Paradoxically, high-speed public transportation services are further deepening the spatial imbalance of community.

In the transportation area, equity is further presented indicator of "spatial equity" based on the performed many studies on the spatial distribution of transportation facilities and services as described above. Spatial equity is associated with the right to mobility, and provision of identical conditions for citizens living in all parts of a certain region. Additionally, some researchers

consider the “longitudinal equity” associated with the comparison of conditions between present and past, for each citizen individually, and for social groups. Also, “modal equity” is described in some studies. Modal equity is associated with inter-modal differences or gaps between access by transit and automobile for the same TAZ or difference of access between different TAZ-s for the same mode. In this study, spatial equity and modal equity are considered, and studies about transportation equity assessment and indicator will be discussed in the next sections - indexes for public transportation service.

On the other hand, equity is divided into equity of opportunity and that of result. Equity of opportunity means to distribute the cost of constructing infrastructure, resource allocation or budget investment fairly and equally. Here, equity of result is that the result of distribution or investment derived become fair and equal.

At this moment, it is not possible to ensure the equity of the result when equity of opportunity is satisfied. For example, when it is assumed that central government supports the same amount of subsidy to the local government A and B to improve the public transport, if local government A bought bus fleets and local government B support subsidy to vulnerable user, equity of opportunity is equal but equity of result is different. In this study, equity will be analyzed by that of result with transit network improvement.

2.1.2 Index for public transportation service

In this section, we discuss the studies which evaluate the equity on public transportation. Duthie (2007) presented the considerations for equity on transportation planning. This study introduces the improvement of equity after the “Federal actions to address environmental justice in minority populations and low-income populations”. Based on this, this study indicates the transportation policy directions for equity. Taking into account the equity on transportation planning, analysis of the spatial distribution of traffic, precise prediction of current/future OD, analysis of the network level are necessary. In addition, this study suggests that there is a need to have a clear criteria for how to implement some of the transport policy for equity. For example, there is a policy with same benefit of 10 on two regions, and the other policy with benefit of 10 and 15 on each region. The former policy with similar benefit is better on the criteria of equity. However, this policy causes less total benefit than the latter policy. Meanwhile, even if the benefit is same in both regions, it is difficult to ensure equity if the regional scales are not equal. Therefore, we need to establish the clear criteria with equity on transportation planning process.

In order to assess the equity of public transport, there is a need for quantitative indicators to evaluate the public transport of given area or region. TCRP Report 88 (2003) shows the major evaluation criteria classified to public transportation stakeholders. It is classified to Customer, Community, Agency and Vehicle and driver. In the evaluation of public transport, the mobility and

accessibility, which are relatively easy to quantify, have been used as an important indicator.

Table 2.1 Transit performance measure points

Stakeholder	Performance points
Customer	· **Mobility (Travel time)** · **Availability (Service coverage, Frequency, Hours of service)** · Safety and Security
Community	· Tax and subsidy · Environment (Landscape, noise, Pollution, Crime) · Economic effect, Employment
Agency	· **V/C, R/C** · User satisfaction rate
Vehicle/Driver	· Empty vehicle time · Vehicle maintenance · Wage

Source: Kittelson et al. (2003), A guidebook for developing a transit performance-measurement system, TCRP Report 88.

Lee et al. (2008) suggested the indexes “DOCO (Degree of Competitiveness)” and “DOCI (Degree of Circuity) for indexing the mobility of public transportation. DOCO is the comparison index between auto and transit travel time and shows how transit service is competitive with auto for each origin-destination trip. DOCI measures how much the transit service or network configuration can be improved and indicates how circuitous a current transit network is compared to a hypothetical transit network with the possible shortest connections:

$$DOCO[\%] = 100 \times \frac{\Delta t_{ij}^{T_1} + t_{ij}^{t} + p_{ij}}{min\, t_{ij}^{a}}, \quad DOCI[\%] = 100 \times \frac{\Delta t_{ij}^{T_2} + t_{ij}^{t} + p_{ij}}{min\, t_{ij}^{i}}$$

where, Δt_{ij}^{T}= additional total travel time

t_{ij}^{t}= transfer time from i to j

p_{ij}= transfer penalty from i to j

min $t_{ij}^{a\ or\ i}$= auto/potential transit shortest path travel time.

This index can be used as an indicator of the overall public transport service level for a given network with aggregation to whole network. Lee's additional study (2015) conducted a comparison of five cities – Seoul, Busan, Suwon, Seong-nam, and Uijeongbu. The DOCO and DOCI derived for Average value and weighted average value to population are mutually different. Especially, since the public transportation service is provided on demand, weighted value is small in general. In this study, however, Busan and Uijeongbu have less difference compared to other cities. Therefore there is a need for more improved public transportation service in these cities.

Ferguson et al. (2012) research, through the minimization of bus transit time difference between the passenger car and public transport, was trying to improve the equity of the public bus transport service. "Accessibility" term in this study means comprehensive indicator of transit time between regions of passenger cars and public transport, number of transit line, and frequency.

The objective function, based on the average of accessibility difference

between passenger car and bus transportation, is minimizing the variation sum of squares of each value. Also, poverty rate and employment opportunities are subdivided to reflect the weight of each variable:

$$\min \frac{1}{W}\sum_{w=1}^{W}\left[\frac{1}{\overline{A^w}}\sqrt{\frac{1}{|I||J|}\sum_{i}\sum_{j}P_i^w\left(A_{ij}^w-\overline{A^w}\right)^2}\right]$$

where, w: uncertainty

$\overline{A^w}=\frac{1}{|I||J|}\sum_i\sum_j A_{ij}^w$

P_i^w: Weight of origin i $(\sum_i P_i^w=1)$

$A_{ij}^w=|A_{ij}^{wc}-A_{ij}^{wb}|$

$A_{ij}^{wb}=\frac{R_{ij}^b}{N_i}\cdot \mathrm{F_{ij}}\cdot\left(S_j^w\right)^\alpha\cdot e^{-\beta t_{ij}^b}$

$A_{ij}^{wc}=\frac{R_{ij}^c}{N_i}\cdot D_{ij}\cdot\left(S_j^w\right)^\alpha\cdot e^{-\beta t_{ij}^c}$

R_{ij}: Number of bus/car routes between $i-j$

F_{ij}: Total frequency (decision variable, per 1 hour)

D_{ij}: The number of potential departure times (60 in this study)

S_i: Number of employment opportunities

t_{ij}: Travel time of passenger bus/car.

In the study, sample network which replicate the US medium-sized city network was used. Genetic algorithm was conducted to find the optimal

frequency of each bus line. Change in A_{ij}^{w} is determined only by a change of frequency of each bus lane(F_{ij}), therefore change of travel time or waiting time cannot be reflected. Although this study does not include the process of the route configuration, there is a significance in terms that include the step of minimizing the objective function.

Currie et al. (2010) study presented the accessibility index of public transport, "Supply index" computed by the frequency of public transport and catchment (buffer) area ratio of each census collector district. The catchment of bus stop and tram station is 400m, and that of subway and rail station is 800m:

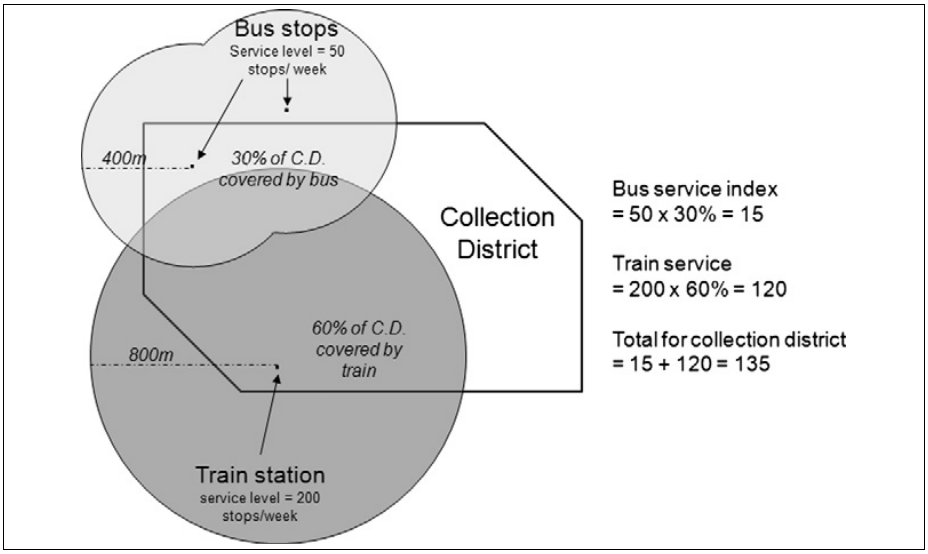
$$SI_{CCD} = \sum N \left(\frac{Area_{B_n}}{Area_{CCD}} \times SL_{B_n} \right)$$

where, CCD: Census Collector Districts

B_n: Buffer n for each stop/station in each CCD

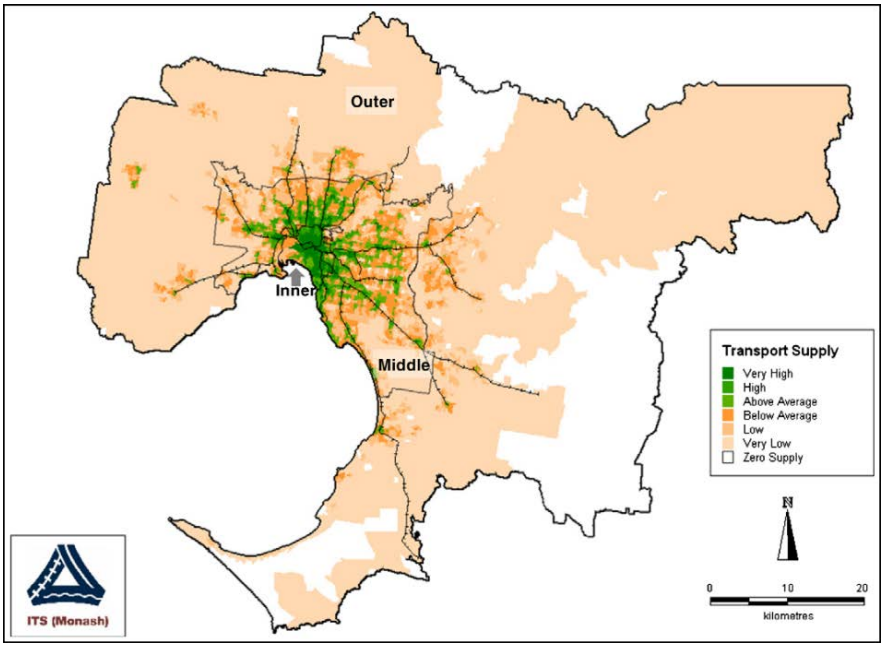
SL: Service level (number of vehicle arrivals per week).

Example study was performed in network of Melbourne, Australia. The results were analyzed in consideration of the CCD's population. At this time, 74.8% of Melbourne's citizen were provided a supply of below-average public transportation. It means that the public transport services are concentrated in a CBD, therefore we need to diminish the imbalance of public transportation service.



Source: Delbosc and Currie (2011)

Figure 2.1 Simplified example of supply index calculation



Source: Currie (2010)

Figure 2.2 Simplified example of supply index calculation

Delbosc et al. (2011) extended Currie's study (2010) by suggesting the use of a "public transport index". Public transport index is made to assess a public transportation service macroscopically by evaluating an index with supply index and population ratio. This index is similar to Gini coefficient, a single simple mathematical metric to represent the overall degree of inequality. In the economics, Gini coefficient is used as an indicator to measure the degree of income inequality. If income of each person or household is exactly the same, the value should be equal to 0. If income is completely unfair, this value is 1. As you see from figure 2.3, dashed line represents a population of perfectly equitable income distribution; the solid curved line (Lorenz curve) represents an inequitable distribution of wealth. Here, the area A of area A+B is Gini coefficient.

Since a curved line is hard to formulate, Gini coefficient is generally calculated by using a simple following formula:

$$G = 1 - \sum_{k=1}^{n} (X_k - X_{k-1})(Y_k + Y_{k-1})$$

where, G: Gini index

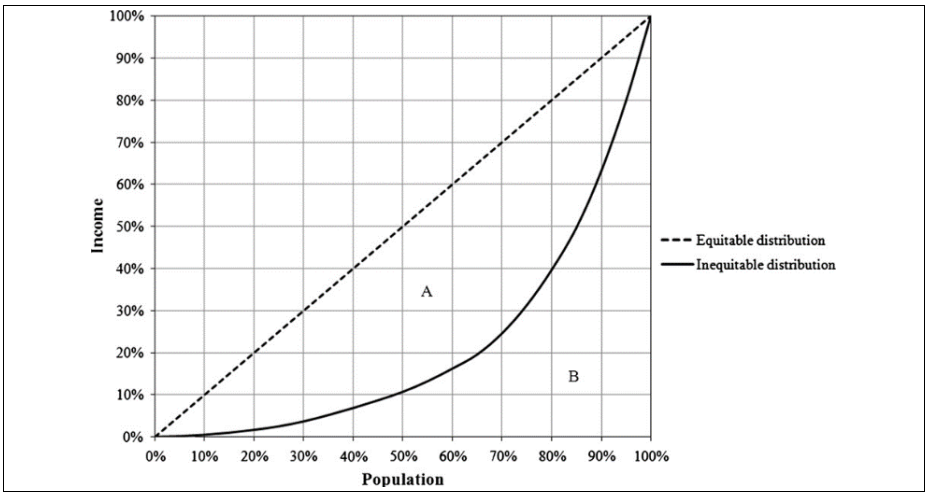
X_k: Cumulated proportion of the population

Y_k: Cumulated proportion of the income.

In the study, Lorenz curve by accumulating supply index of the CCD is calculated, and "public transport index" – same as Gini coefficient – is

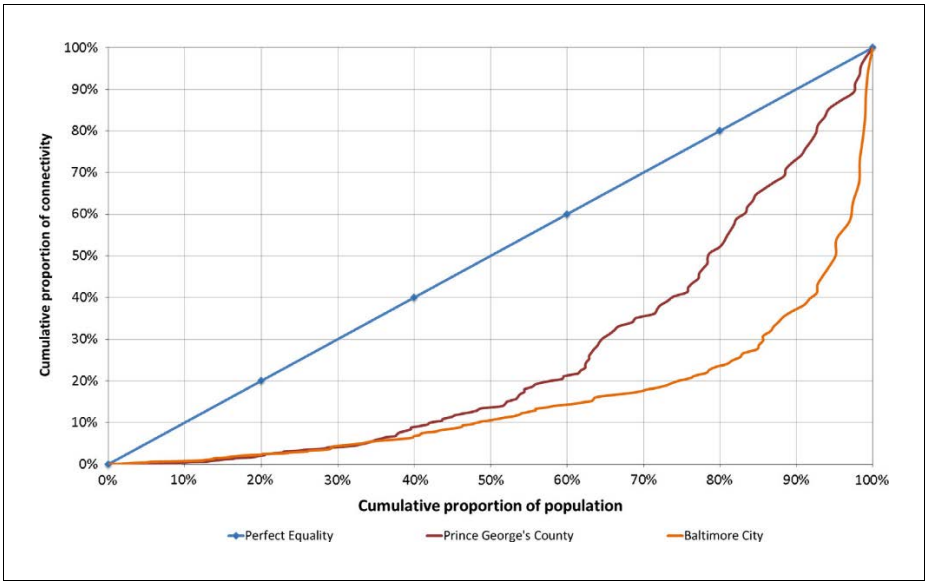
represented. This index of Melbourne, Australia was 0.68 based on population, and 0.62 based on population plus number of workers. Since this was the first time applied in the study, authors suggested that it was necessary to understand the validity of the calculated values by comparison with other cities.

Welch (2013) applied this index to some cities in Maryland, US. In the study, the name of index is “inequity index”, but concept and calculation process is same as former index. Inequity of the public transport service appeared higher in the big cities, this is because there is a tendency that the service is concentrated on the CBD in the metropolitan area. Figure 2.4 compares the result of the inequity index of Baltimore (city center) and Prince George County (suburban area).



Source: Delbosc et al. (2011)

Figure 2.3 Lorenz curve example



Source: Welch et al. (2013)

Figure 2.4 Transit equity Lorenz curves of two cities

Park and Kang (2011) defined the "connecting power" and "connectivity index". Connecting power of line l at node n is the index is calculated with frequency, daily hours of operation, capacity, speed and distance of line. This index is the average of the values for outbound and inbound on one node:

$$P_{l,n}^{t} = \frac{P_{l,n}^{o} + P_{l,n}^{i}}{2}$$

where, $P_{l,n}$: Connecting power of line l at node n.

Connecting power in each direction, outbound and inbound, follows the following formula:

$$P_{l,n}^{o} = \alpha\left(C_l \times \frac{60}{F_l} \times H_l\right) \times \beta V_l \times \gamma D_{l,n}^{o}$$

$$P_{l,n}^{i} = \alpha\left(C_l \times \frac{60}{F_l} \times H_l\right) \times \beta V_l \times \gamma D_{l,n}^{i}$$

where, C_l: Average vehicle capacity of line l

F_l: Frequency on line l (per hour)

H_l: Daily hours of operation of line l

V_l: Speed of line l

$D_{l,n}^{o\ or\ i}$: Distance of line l from/to node n.

Connecting power calculated for each stop of each line, each route refers to a representative value of the stop or route. In the study, connectivity index is a comprehensive public transport index separated by node, line, transfer, and regional connectivity. Mishra et al. (2012) applies the connectivity index to Washington DC and Baltimore, and assessed the transit network:

$$CI(v) = \sum_{l \in L} P_l^v \delta_l^v$$

$$CI(l) = \frac{1}{|S_l| - 1} \sum_{v \in S_l, v \neq v_o} CI(v)$$

$$CI(R) = \frac{1}{K_R} \sum_{v \in S_R} CI(v)$$

where, CI: Connectivity index of stop v / line l / area R

S_l: Set of stops that transit line l

K_R: Scaling factor (population of the area R).

An index showing the transfer convenience of transfer station "connectivity of transfer center" is a measure of negative exponential function relative to the transfer time in the transfer station. The higher the value means a good place to transfer, and it is expressed as follows:

$$\rho_{n_1,n} = a \times e^{-bt_{n_1,n}}$$

where, $\rho_{n_1,n}$: Passenger acceptance rate

$t_{n_1,n}$: Transfer time to travel from node n_1 to n

a, b: Parameters of passenger acceptance rate.

These public transport indexes are applied mainly in evaluation of given networks. Although the direction of macro improvement through such comparison between regions are presented, there are few studies that how to improve some of the routes or improvement of the index with the improvement of the improvement of public transport service.

Table 2.2 Literature review of public transportation assessment

Authors (year)	Index	Explanation	Applied Network
Lee (2008) Lee et al. (2015)	Degree of Competitiveness (DOCO) Degree of Circuity(DOCI)	DOCO: comparison index between auto and transit travel time DOCI: comparison index between actual transit travel time and possible transit travel time	Lee's network (2008) Five cities including Seoul (2015)
Ferguson et al. (2012)	Accessibility index	comprehensive indicator of transit time between the zone of passenger cars and public transport, number of transit line, and frequency	med-sized US metropolitan area
Currie (2010)	Supply index	frequency of public transport and catchment (buffer) area ratio of each census collector district	Melbourne, Australia
Delbosc et al. (2011)	Public transport index	Gini coefficient of Lorenz curve by accumulating supply index of the CCD	Melbourne, Australia
Park et al. (2011) Mishra et al. (2012) Welch (2013) Welch et al. (2013)	Connecting power of transit line	comprehensive indicator of frequency, daily hours of operation, capacity, speed and distance of line	toy network
	Connectivity of transfer center	measure of negative exponential function relative to the transfer time in the transfer station	
	Connectivity index	comprehensive accessibility index separated by node, line, transfer, and regional connectivity computed by connecting power	Washington DC, US Baltimore, US
	Transit catchment	station / stop with respect to the housing unit within a certain distance	Baltimore, US
	Inequality index	Gini coefficient of Lorenz curve by accumulating supply index of the CCD	

2.2 Network design problem

2.2.1 Transit network problem (TNP)

Transit network problem (TNP) Process is classified into five stages - network design, frequencies setting, timetable development, bus scheduling, and driver scheduling. Main independent input, decision variable and output are same as follows.

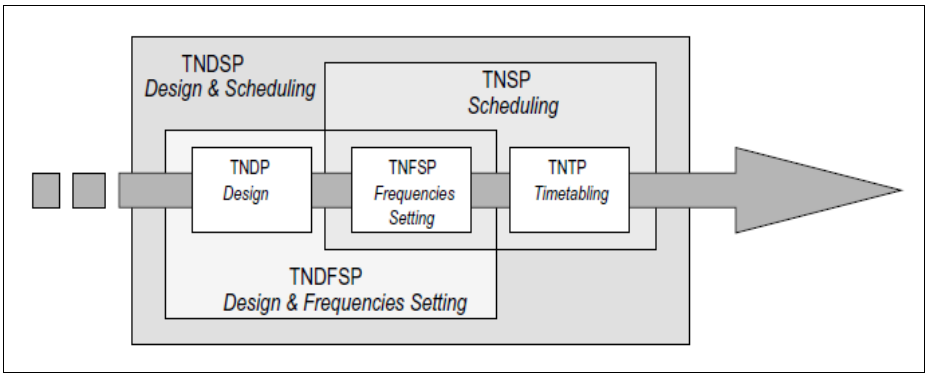
Table 2.3 Transit planning process

Independent inputs	Planning activity	Output
Demand data **Supply data** **Route performance indicators**	**Network design**	**Routh changes** **New routes** **Operating strategies**
Subsidy available **Buses available** **Service policies** **Current patronage**	**Frequencies setting**	**Service frequencies**
Demand by time of day Times for first and last trips Running times	Timetable development	Trip departure times Trip arrival times
Deadhead times Recovery times Schedule constraints Cost structure	Bus scheduling	Bus schedules
Driver work rules Run cost structure	Driver scheduling	Driver schedules

Source: Guihaire & Hao (2008), Transit network design and scheduling, Transportation Research Part A, pp. 1251-1273,
Original reference - Ceder and Wilson (1986)

There are many terminologies for transit network problem. For example, transit routes and frequencies setting problem is named as “transit route network design problem” (TRNDP), “bus network design problem” (BNDP), “line planning in public transport”, and “urban transportation network design problem” (UTNDP).

Guihaire and Hao (2008) proposed the terminology to organize denominations and relations among problems and sub-problems related to strategic and tactical transit planning. The study began with three basic transit network problems: design (TNDP), frequencies setting (TNFSP) and timetabling (TNTP), and introduced two combined problems: design and frequencies setting (TNDFSP=TNDP+TNFSP) and scheduling (TNSP= TNFSP+TNTP). Finally, whole design and scheduling problem (TNDSP) is defined as the composition of three basic problems. This study can be said TNDFSP determining route of transit lines and fleet number of each line.



Source: Guihaire & Hao (2008)

Figure 2.5 Transit network problems structure

The objective function most popularly used in the transit network program is to minimize the total travel time (TTT). Unlike passenger car travel time considered only in-vehicle time from origin to destination, public transport time is sum of access time from the departure point to the station, waiting time, in-vehicle time, and access time to the destination from get-off station by the flow of the movement in order. If there is no direct route to the destination, we also have to consider the transfer time.

Another objective functions in the transit network program are maximizing the number of direct passengers (minimizing transfers), minimizing overcrowding, maximizing network performance and accessibility, etc. Main constraints are frequency, fleet size, loading factor, capacity, and maximum number of transfer, and etc.

This study is transit network design and frequencies setting problem (TNDFSP) which determines the route of transit line combination and frequency of each line. In TNDFSP, transit network and frequency of each line are decision variables, and objective function of each situation is calculated with traffic and transit assignment. Because of the complexity of the design problem, many studies generally assume a fixed demand, rarely reflect the various demand.

Table 2.4 shows literature review result of TNDFSP. There are mainly five methodologies to solve a given problem - heuristic, mathematical, neighborhood search, evolutionary, and others.

Table 2.4 Literature review of TNDFSP

Author (year)	Objectives	Constraints	Me.
Lampkin (1967)	Number of direct passengers Total travel time	Fleet size	H
Silman (1974)	Fleet size Journey time Overcrowding	Budget	H
Bel (1979)	Passengers total travel time	Budget	H
Hasselstrom (1979/1981)	Number of transfers Number of passengers	Budget	M
Ceder (1986)	Excess travel time Transfer and waiting time Vehicle costs	Minimum frequency Fleet size Routh length	H
Van nes (1988)	Fulfil the demand Number of direct trips	Fleet size	M
Shih (1994/1998)	Travel time Satisfied demand Fleet size	-	O
Bussiek (1998)	Number of direct passengers Operator costs	Level of service Number of resources	M
Pattnaik (1998)	Operator costs Passengers travel time	Headway Load factor	E
Lee (2000)	Users travel time	Network Fixed total demand	H
Bielli (2002)	Average travel time Fleet size Network performance	Pre-defined possible lines only	E
Fusco (2002)	Overall system cost	Level of service Satisfied demand Lines configuration Frequency	O
Ceder (2003)	Operator and users costs Fleet size	Route length Deviation from shortest path	H

(Continued)

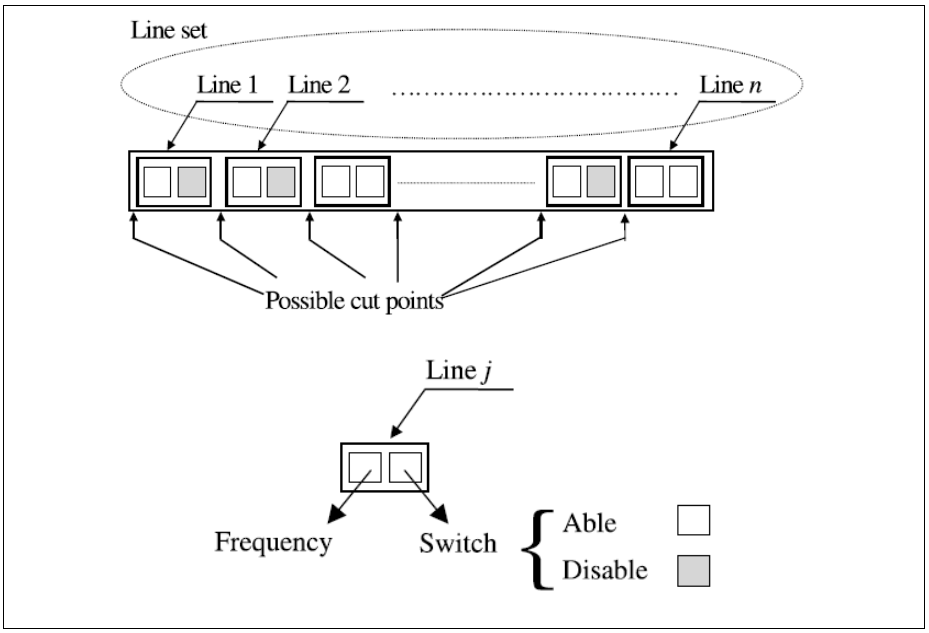
Author (year)	Objectives	Constraints	Me.
Ngamchai (2003)	Fleet size In-vehicle and waiting time	Service coverage	E
Tom (2003)	Operator costs Passengers total travel time	-	E
Wan (2003)	Operating costs	Frequency bounds Capacity requirements	M
Fan (2004/2006)	Waiting/walking/in-vehicle time Number of buses Unsatisfied demand costs	Route length	NS-E
Borndorfer (2005)	Passengers traveling time Operating costs	Demand satisfaction	M
Zhao (2006)	Number of transfers Service coverage	Route directness	NS
Park (2006)	Overall system cost	Bus capacity, Frequency Lines configuration	E
Borndorfer (2008)	Operation cost Total travel time	Demand satisfaction	H
Pacheco (2009)	Total waiting time Total travel time	Number of routes Fleet size Location of the bus stops	H
Szeto (2011)	Weighted sum of the number of transfers and network travel time	Fleet size Number of transit stops Frequency Route length	NS-E
Cipriani (2012)	Sum of operator and user costs	Bus capacity Frequency Route length	H
Kim (2012, 2016)	Overall system cost	Bus capacity Frequency Route configuration	NS
Arbex (2015)	Total travel time (User cost) Fleet size (Operator cost) Direct trips	Bus capacity Frequency Route configuration	E

Source: Guihaire et al. (2008), Farahano et al. (2013), Additional search in this study.
Remark: H-Heuristic, M-Mathematical, NS-Neighborhood Search, E-Evolutionary, O-Other

2.2.2 Evolutionary algorithm on TNDP

Because of the non-linearity and mathematical complexity of the objective function, determining the transit route network and frequencies of lines are said to be very difficult to solve. In this study, we examine cases in which genetic algorithms are applied in the design of public transport. It is known that genetic algorithms can be effectively used to solve complex objective function optimization problem.

Bielli et al. (2002) proposed a genetic algorithm that each gene (line) can be divided into two cells which determine whether the line operates or not, and number of vehicles to be operated.



Source: Bielli et al. (2002)

Figure 2.6 Genetic representation in Bielli et al. (2002)

Pattnaik et al. (1998) and Tom and Mohan (2003) also applied a genetic algorithm to determine whether to operate each line and frequencies. In study of Tom and Mohan (2003), they generated random numbers from 0 to 60 range by every candidate line. If the value between minimum vehicle allocation count and maximum count number is occurred, it operates the line depending on its value, unless not operate that line:

$$\text{If } f_{min} < f_k < f_{max} \; then \; select \; f_k$$
$$\text{otherwise } \mathrm{f_k} = 0$$

where, $f_k = [0,60]$.

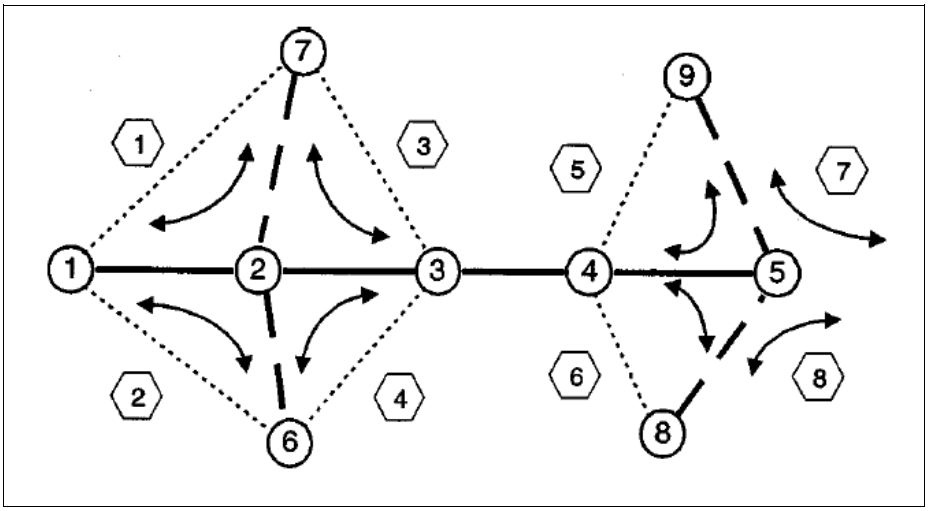
Park (2006) generated random numbers from $\mathrm{f_{min}}$ to $2\mathrm{f_{max}}$ range by every candidate line. This is because the probability of line operation can vary according to the minimum and maximum values with the former situation:

$$\text{If } f_{min} < f_k < f_{max} \; then \; select \; f_k$$
$$\text{otherwise } \mathrm{f_k} = 0$$

where, $f_k = [f_{min}, \; 2f_{max}]$.

Ngamchi and Lovell (2003) set a problem of minimizing total time cost and vehicle operation cost. They used a genetic algorithm and select lines by combining lines based on transfer stations when performing a crossover procedure.

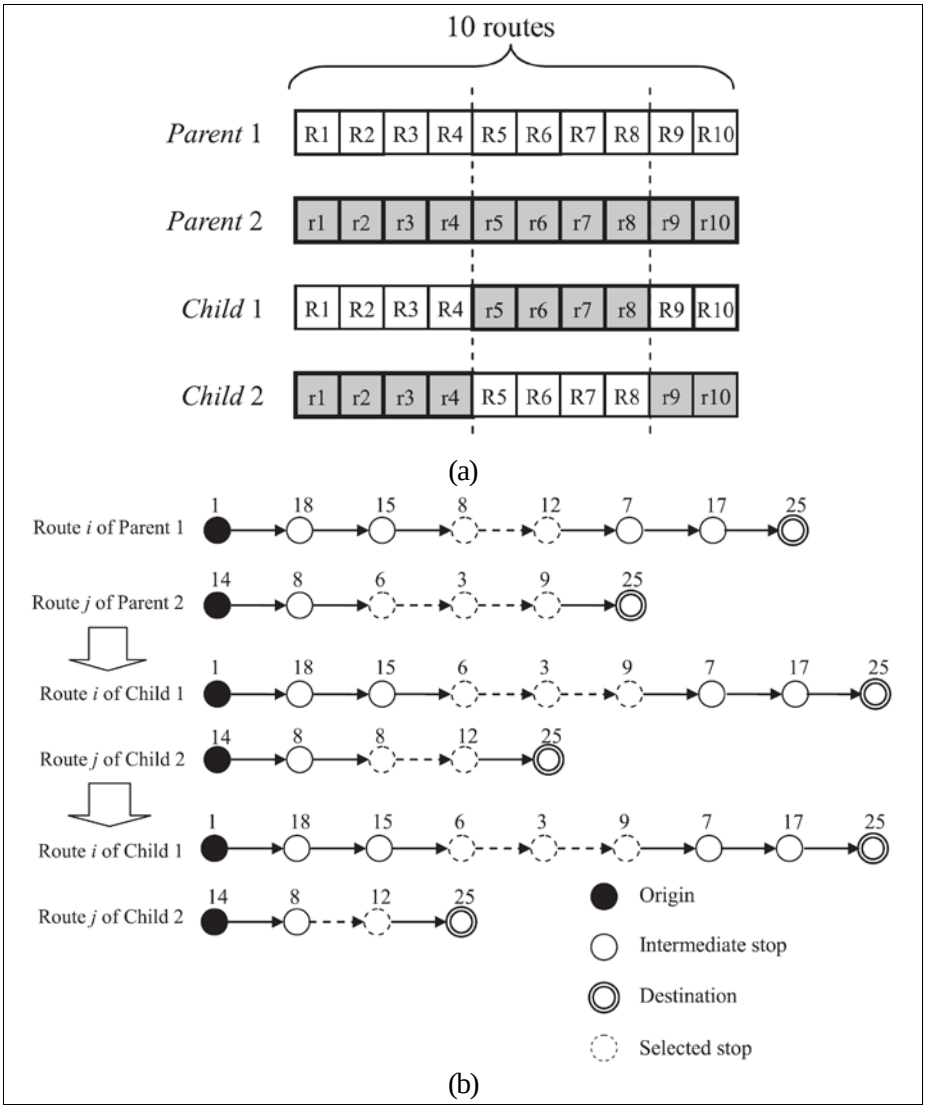
Depending on the combination of line, and direct / transfer trips of users time, operation cost changes. After the line configuration procedure, frequency of each line is determined by the demand through each route. The more demand, the vehicle increases.



Source: Ngamchi and Lovell(2003)

Figure 2.7 New route possibilities for crossover operators

Szeto and Wu (2011) set a problem of minimizing total time cost and number of transfers, and applied a genetic algorithm to determine a line configuration and frequency setting. They allocate the bus to each line with fixed total number, and calculated back frequency based on the round-trip time. Route was generated to constrain the origin and destination, candidates with respect to routes overlap links or stops are newly generated via the crossover process. Figure 2.8 shows the procedure of route crossover.



Source: Szeto and Wu(2011)

Figure 2.8(a) Illustration of route crossover, (b) stop crossover

Arbex and Cunha (2015) set a problem of minimizing total time and total number of bus fleet, and find Pareto frontiers of optimal solutions with maximizing direct trips (no transfer). Line candidates were the set of the

generated path by the shortest path algorithm and the k-shortest path algorithm. In the study, at least one line is operated at all the node in each combination of gene (line) and candidates with respect to routes overlap links or stops are also newly generated via the crossover process. Allocation number for each route, after transit assignment procedure of the alternative, was interpreted by calculating the required number based on the load factor. The transit assignment was performed through the calculation of the utility function associated with the transfer times of alternative, in accordance with a change in route, but total transit demand may not change with line configuration and operation alternative.

2.2.3 Considering equity on NDP

The objective function most popularly used in the transit network program is minimizing the total travel time (TTT) and maximizing the number of direct passengers (minimizing transfers). Also, minimizing overcrowding, maximizing network performance and accessibility are main objective functions of transit network problem.

To extend the range of the design of the whole transportation network, there are several researchers considering equity in fields of road network expansion and maintenance, and congestion charge, but few studies exist in transportation network field. There are many studies related to an equity assessment of a given public transport situation. However, effects by the equity improvement of the system and the optimal operation strategies considering equity are missing.

In this section, in order to reflect the equity in the design of public transport, it will be reviewed how the equity issues in the existing road transportation network expansion and maintenance field are reflected. The case of congestion toll is the most important problem, from the point of view of improving the interpersonal differences through the toll charges, and related studies have been conducted. But congestion toll issue is not a transportation network design problem, but operation strategy, therefore in this section, only a road network problem issue will be reviewed.

In the field of road network design, as well as the transit network design, the goal to minimize the cost of users and operator was common, but various

advanced research efforts have been conducted to measure the equity indexes related to travel time and the spatial distribution in the studies of road network construction and extension. If we continue the road construction or extension only on the basis of cost efficiency, spatial bias phenomenon of large areas of population and the bias of traffic demand are occur continuously.

Meng et al. (2002) set an objective function for the decrease of travel time due to road expansion projects. For the purpose of not occurring concentration to specific region, more than β of travel time difference between before / after expansion was not allowed. Chen et al. (2004) have same objective function as former study. In the study, equity ratio of each zone is not allowed to change the value more than a certain percentage.

Antunes et al. (2003) set an objective function for maximizing sum of accessibility index by centroids in proportion to the population size and inversely proportional to the travel time. The model was applied to example of Portuguese main road network expansion, and considered total budget to reflect a practicality. Reflecting the weight of the low-income, optimal solution was analyzed to expend the roads of eastern region and the Spanish border areas where falling behind.

There are several studies on the social equity but general consensus on the equity and efficiency is not clear yet, some studies have organized a multi-objective function. In the two studies of Feng and Wu (1999 & 2003), to set a highway investment business of Taiwan, two objective functions presented that takes into account the equity to minimize the travel time difference of inner-

region and inter-region, and the efficiency to minimize the total travel time. In the case of equity, it was classified horizontal equity to minimize the average traffic speed difference of inner-region, and vertical equity to minimize the difference between the regions. Optimal solutions of equity and efficiency objective functions were presented respectively, and it was presented that how change optimal solution depending on the respective purposes.

Duthie and Waller (2008) set a multi-objective function to minimize the total travel time of whole network and minimize the travel time of low-income population simultaneously, and presented solutions with Pareto frontier. Santos et al. (2008) set many objective functions to assess equity of road network improvement project. In the study, maximizing accessibility, maximization of accessibility to low-accessibility centers, maximizing accessibility and minimizing Gini coefficient simultaneously, and maximizing accessibility and minimizing Theil index simultaneously.

Studies before discussed which are taking into account the equity indexes in the objective function or constraints have a significance that strategies considering equity tries to be reflected together from the strategy that has been pursuing the efficiency unconditionally.

Table 2.5 Literature review of road network design considering equity

Author (year)	Obj. function	Constraints	Me.	Network
Meng (2002)	Minimizing travel time due to road expansion projects	Travel time difference between before / after expansion Budget allocation	NS	Sioux Falls network
Antunes (2003)	Max. accessibility (low-income weight)	Budget allocation	H-NS	Portuguese main road network
Feng (1999,2003)	Min. total travel time Max. inner region equity Max. inter region equity (1-2, 1-3 multi objective)	Budget allocation	M	Taiwan's highway network
Chen (2004)	Min. total travel time	Equity ratio of each zone	E	Sioux Falls network
Duthie (2008)	Min. total travel time Min total travel time of low-income population (Multi objective)	Budget allocation	E	Sioux Falls network
Santos (2008)	Max. accessibility Max accessibility to low-accessibility centers, Min. Gini coefficient Min. Theil index (1-2,1-3,1-4 multi-objective)	Budget allocation	M	Random networks (10 nodes)

Remark: H-Heuristic, M-Mathematical, NS-Neighborhood Search, E-Evolutionary

2.3 Review result and direction of this study

In section 1 of this chapter, we reviewed the equity issues in the transportation area and equity indexes of public transportation service, and in section 2, models and analysis methodologies of road and transit network design problem considering equity were reviewed. Equity in transportation is classified into horizontal and vertical equity, and spatial and longitudinal equity additionally. This is because spatial and longitudinal situation is very important element in the transportation area, especially in movement or trip.

From the review result of equity index of public transportation service in section 1, there are a large number of studies of indexing for the assessment of the current state of public transport in the field of urban planning and geography. However, depending on the focus on the current state indexing, there are few studies extended to the design issues for the network improvement. Even if the approach to the problem on the network design improvement, there is a limit that does not take into account the actual traffic situation or variable demand.

From the review result of transit network design problem in section 2, the objective function most popularly used in the transit network program is to minimize the total travel time or cost (maximizing efficiency), and other objective functions are maximizing the number of direct passengers (minimizing transfers), minimizing overcrowding, maximizing network performance and accessibility, and etc. Main constraints are frequency, fleet size, loading factor, capacity, and maximum number of transfer etc. In these

studies, there are many cases that demand is generally fixed. Accordingly, modal split and path choice behavior changes cannot be reflected. Also, route determination is very complicated process, heuristic methodologies – situation based method, simulated annealing, genetic algorithm, and etc. – are applied to find an optimal solution of problem. Especially in this study, studies that applied genetic algorithm to network design and frequency setting problem are reviewed.

By the way, the transit design problem to date generally has the purpose of minimizing such time and cost. There is a limit that does not reflect the trip characteristics or regional distribution of demographic and socio-economic factors. Since the 1990s, in the road network design problem related to road construction or expansion, and congestion toll imposition, equity among regions has been applied to objective function or constraints. However, the applications to transit network design problem are very few to the best of my knowledge.

Through the study of previous studies, we set the following direction of this study.

- Equity index to assess the mobility and accessibility
  (Modified DOCO)
- Iterative transit route determination methodology to maximize equity
- Improvement of genetic algorithm with practical frequency
- Reflecting the modal split and variable demand by bi-level modeling

In the route network determination process considering equity, we present the decision methodology of route determination with target line (line to alter) selection, target node (node to improve modal equity) selection, alternative line generation and line combination determination procedure. The more network size is increased, it becomes very difficult to calculate the solution because the number of line candidates are increasing geometrically. Therefore in this study, simplified heuristic algorithms based on the indicator of modal and spatial equity are applied. Target line is selected by total DOCO of whole network ($TDOCO$), and target node is selected by DOCO of origin i ($DOCO_i$). Alternative line candidates are generated with minimum path via target line between every nodes. Of these, if circuity of route of line candidates compared to the shortest route is higher than reference value or redundancy rate with the existing route is greater than reference value, relevant line candidate is excluded from the alternative line candidates.

Public transportation network have been operating in metropolitan areas are difficult to be changed easily because of various practical constraints. In particular, the railway transportation is not easy to change on the operation strategy, because large construction cost of the infrastructure was already invested. However, In the case of bus transportation, it is relatively possible to respond flexibly, such as the route change. In this study, we divided the lines into those can be changed and cannot be changed, such as railway or lines should not be changed by policy.

Transit route network determination procedure in this study has purpose of

maximizing modal and spatial equity and improving the transit network. Modal and spatial equity is defined as follows.

Modal equity

- The extent of difference between transit travel time and auto travel time is negligible through transit network improvement

Spatial equity

- The extent of difference of modal equity among regions is negligible by giving a priority of transit network improvement to the regions that have lower modal equity

The procedure of frequency setting is finding the optimal transit line configuration and frequency of each line to satisfy the efficiency of the user and operator's total cost. This procedure determined by iterative game theory calculation process is carried out through the bi-level modeling. In the frequency setting procedure, with the upper level of bi-level modelling, genetic algorithm (GA) is applied to find an optimal solution. From the result of previous studies about GA, range of each gene (fleet number per hour per line) is 1 to maximum possible fleet number in lines cannot be changed, and 1 to 1 to two times maximum number in altered lines.

Determination of transit route network and frequency setting procedure in this study are easily modified in response to changes in the practical problems.

For example, redundancy and circuity of alternative line, and lines that cannot be replaced can be vary depending on the situation. At the time of the actual network analysis and improvement, so many factors - population and trip distribution, budgetary constraints and development of new areas - change depending on the time diversely. Therefore it is very important that the modification of the model is easy in response to a change of realistic constraints. But, in this study, these factors are fixed with some assumptions.

In the modal split and car / transit assignment procedure, line configuration and frequency setting situation of upper level are decision variables of lower level problem. Lower level problem of bi-level model is modal split and car / transit assignment. Depending on the improvement or change of transit network, transit travel time between the zone changed, and mode choice changes between passenger car and transit occur. As a result, car travel time of the roads also changed with traffic volume change, transit travel time of the means for passing the road change together. This iterative calculation procedure reflect an actual mode and path choice of travelers into a model.

Chapter 3. Model Formulation

3.1 Model summary

A network design model of this study is to determine the route and frequency optimizing the objective function with constraints. Decision variables are combinations of routes and frequency by the routes. This problem is a kind of Transit Network Design and Frequency Setting Problem (TNDFSP).

The model of this study has two purposes: firstly, a process of route evaluation and choice considering modal and spatial equity is applied. Secondly, modal split and usage pattern for automobile and public transportation according to modification of the public transportation network.

The objective function of public transportation network design problem is generally to minimize the sum of users' cost and time and operator's cost, which are converted into the generalized cost. The cost is based on total travel cost by modes, total travel distance and service distance, and is calculated by modal split and trip assignment.

Since change of route varies the result of modal split and trip assignment, passengers' usage pattern must be included in constraints. These constraints, however, make the problem difficult. Bi-level model based on the game theory is applied to solve the problem.

Bi-level program, consists of upper level problem and lower level problem, is a mathematical problem applied to transportation substantially. It is used for

evaluating various transportation policies relieving traffic congestion, such as road expansion, signal design and congestion pricing. Upper level problem is generally constructed to optimize an objective function, and travelers' behaviors are reflected to the lower level problem.

When policy decision makers or transportation planners establish and implement policies, it is rational and realistic that they expect travelers' responses and behaviors. Therefore, structure of bi-level program is equal to the Stackelberg game which is one of the game theory. In this game, it is assumed that transportation planner or leader know how user of transportation network or follower reacts according to his or her strategy.

Upper level problem in this study includes a general objective function of public transportation network design, minimization of users' and operators' total cost. In addition, modal and spatial equity through equity assessment of line configuration and target line, target node and alternative line selection is reflected in the process of route choice. Modal equity is satisfied by decreasing ratio of travel time difference between automobile and public transportation. Also, spatial equity is met by decreasing the difference of modal equity among zones. Genetic algorithm, one of the heuristic models, is used for route frequency decision process and minimization of total cost by frequency according to population distribution and traffic is satisfied.

In the lower level problem, logit model is applied for the modal split according to change of public transportation route user equilibrium assignment is used for trip assignment of the road according to traffic change. Frank-Wolfe

Algorithm is applied for this process. For trip assignment of the public transportation, travel time and waiting time are minimized, Optimal Strategy that is generally used for trip assignment of public transportation is also applied for this study.

The following section (Section 2) describes the problem definition and variables. Section 3 and 4 provide a summary of the upper level problem and the lower level problem. The following section (Section 5) suggests the integrated model of public transportation network. Chapter 4 describes detailed process of the upper level problem.

3.2 Problem definition and variables

3.2.1 Precondition establishment

As I mentioned earlier, transit network design model of this study is to determine the line combination and frequency setting of each line to optimize the objective function of minimizing total cost in an equity constraint. This objective function is difficult to set a model and hard to find an optimal solution because feasible region is non-convex. Therefore bi-level form is built and find an optimal solution with iterative procedures.

Line configuration and frequency setting model of this study are early state of whole transit network design of network design, frequency setting, timetabling, fleet scheduling, and driver scheduling. With the model formulation, since it is not possible to take into account the reality of all the problems, using realistic assumptions to simplify the model to try to clarify the issue.

<u>General assumptions</u>

- Modes are divided into passenger car and transit.
  (subway, rail, and bus, etc.)
- Demand and network is with respect to the time of peak and symmetrical.
- All the nodes can be a terminal (start and end point), and possible to be a transfer point.
- The subway and rail lines are not affected by the road conditions, but the bus

lines may be in response to road conditions.

User side assumptions

- Total flow of network is identical, but modal split result change with transit network operation and road / transit assignment.
- Total time of transit includes access / egress time, waiting time, in-vehicle time, and transfer time.
- Distribution of users who arrive at the stop / station is random and uniform, therefore waiting time is half of headway.

Operator side assumptions

- Route of bus line is possible to change, but that of subway or railway is impossible to change.
- Operation cost includes that of rail and bus transportation.
- Load factor of each line do not exceed 1 finally.

3.2.2 Variable explanation

Notation of variables used in the model of this study is as follows.

<u>Upper level model</u>

$C_{time}^{c,t}$: Time cost of car and transit of link a

τ: Value of time

x_a: Volume of link a

$t_a(x_a)$: Link travel time of link a with volume x

l_k: Length of line k

n_s^k: Number of stops of line k

f_k: Frequency of line k

κ_k: Fleet capacity of line k

v_k: Maximum speed of line k

l_{fb}: Target line that has maximum increase of TDOCO per length among existing lines

$TDOCO$: Total Degree of Competitiveness (additional travel time that transit network requires when compared to auto travel time, aggregated to whole network)

n_{fb}: Target node (node where fall behind)

$DOCO_i$: Degree of Competitiveness of Origin i (additional travel time that transit network requires when compared to auto travel time, aggregated to origin i)

$\eta_{n_{fb}}^{k}$: 1 if alternative line k include a target line n_{fb}, otherwise 0

l_{min}: Minimum line length (km)

l_{max}: Maximum line length (km)

D_{ij}^{k}: Circuity of line k from i to j

$\mathrm{l}_{\mathrm{ij}}^{\mathrm{k}}$: Length of line k from i to j (km)

d_{ij}: Min. path length from i to j (km)

D_{max}: Maximum possible circuity

O_{n-e}^{k}: Redundancy rate between existing line and alternative line k

O_{exist}^{max}: Maximum possible redundancy

f_{min}: Minimum frequency (min)

f_{max}: Maximum frequency (min)

<u>Lower level model</u>

$\overline{q_{od}}$: Car volume between origin and destination

$\widehat{q_{od}}$: Transit volume between origin and destination

q_{od}: Total volume between origin and destination

$\overline{t_{od}}$: Minimum path time of car between origin and destination

$\widehat{t_{od}}$: Minimum path time of transit between origin and destination

$\overline{c_{od}}$: Minimum path cost of car between origin and destination

$\widehat{c_{od}}$: Minimum path cost of transit between origin and destination

α_1: Travel time parameter of utility function

α_2: Travel cost parameter of utility function

$\widehat{D}$: Dummy variable of transit

l_a: Length of link a

$\overline{v_a}$: Free flow speed of link a

α, β: Parameters of link travel time function

x_a: Volume of link a

c_a: Capacity of link a

f_r^{od}: Volume using path r from origin to destination

$\delta_{a,r}^{od}$: 1 if path r from origin to destination includes link a, otherwise 0

A: Link set

I: Node set

A_i^+: Link set outbound node i

A_i^-: Link set inbound node i

g_i: Transit volume from node i

x_a^t: Transit volume of line a

t_a^t: Transit time of link a

f_a: Frequency of link a

w_i: Waiting time of node i

3.2.3 Model formulation

The transit route network design model of this study is organized with bi-level modelling. The objective function of the upper model is constructed in the form of minimizing the total cost of users and operators with line candidate constraints, and in the lower model, modal split of passenger car / transit, and traffic and transit assignment are performed from variable frequency setting situation in the upper model. Binary logit model is applied to perform a modal split, and traffic and transit assignment is implemented by user equilibrium with convex combination and transit assignment model by H. Spiess and M. Florian (1989) respectively. Constraints excluding frequency constraints of the upper level problem are predetermined through route network determination process.

<u>a) Upper level problem – transit network and frequency setting</u>

Objective function: Min $(\sum TC_{user} + \sum TC_{operator})$

Constraints: (a) Target line constraint by TDOCO, (b) Target node constraint by $\mathrm{DOCO_i}$, (c) Constraint of alternative lines via target node, (d) Minimum and maximum line length constraints, (e) Circuity constraint, (f) Redundancy with the existing line constraint, (g) Alternative line constraint by TDOCO, (h) Minimum and maximum frequency constraints of lines

<u>b) Lower level problem – modal split and car / transit assignment</u>

Car assignment (user equilibrium)

Objective function: $\min z(x) = \sum_a \int_0^{x_a^c} t_a^c(x_a^c)dx$

Constraints: traffic volume conservation, non-negative constraint

Transit assignment (optimal strategy)

Objective function: $\min \sum_a x_a^t t_a^t + \sum_i w_i^t$

Constraints: transit volume conservation, non-negative constraint

3.3 Upper level model

3.3.1 Objective function

The upper level problem is the procedure of frequency setting which is finding the optimal transit line configuration and frequency of each line to satisfy the efficiency of the user and operator's total cost. The transit route network is restricted by equity constraints. The objective function of upper level model is minimizing total cost consist of user cost and operation cost.

Objective function: Min $(\sum TC_{user} + \sum TC_{operator})$

First of all, user cost is the total time cost of people to use the passenger car and transit. Total time of transit includes access / egress time, waiting time, transfer time, dwell time, and in-vehicle time. The total time of each mode is calculated on the basis of each link by the volume and the link travel time. Total time cost is calculated by multiplying total time and value of time.

$$\sum \mathrm{TC}_{\mathrm{user}} = \sum_{a} C_{time}^{c} + \sum_{a} C_{time}^{t} = \sum_{\mathrm{a}} \tau \cdot t_a(x_a) \cdot x_a$$

Where, $C_{time}^{c,t}$: Time cost of car and transit of link a

τ: Value of time

x_a: Volume of link a

$t_a(x_a)$: Link travel time of link a with volume x

The operation cost with reference to the studies of Kim (2007) and Kim et al. (2012, 2016), is such as the following formula. The operation cost is determined by length of line, number of stops, frequency, fleet capacity, and maximum speed.

$$C_{\text{operation}}^{transit} = \sum_{k} l_k \left[a\sqrt{n_s^k} + \left(b_o \sqrt[3]{f_k} + b_1 \sqrt{f_k} \kappa_k + b_2 f_k \kappa_k v_k^2 \right) \right]$$

Where, l_k: Length of line k

n_s^k: Number of stops of line k

f_k: Frequency of line k

κ_k: Fleet capacity of line k

v_k: Maximum speed of line k

3.3.2 Constraints

Constraints of upper level model are divided into target line constraint by TDOCO, target node constraint by $DOCO_i$, constraint of alternative lines via target node, minimum and maximum line length constraints, circuity constraint, redundancy with the existing line constraint, alternative line constraint by TDOCO, and minimum and maximum frequency constraints of lines.

Assessment of existing network and alternative line decision procedure are predetermined before frequency setting procedure. This procedures include assessment of existing network and target line selection, target node selection, and alternative line decision. Table 3.1 shows the constraints corresponding to each procedure.

Table 3.1 Model procedure and constraints

Procedure	constraints
Assessment of existing network and target line selection	(a) Target line constraint by TDOCO
Target node selection	(b) Target node constraint by $DOCO_i$
Alternative line determination	(c) Constraint of alternative lines via target node (d) Min. and max. line length constraints (e) Circuity constraint (f) Redundancy with the existing line constraint (g) Alternative line constraint by TDOCO
Frequency setting	(h) Min. and max frequency constraints of lines

The constraints from (a) to (h) are represented by the formula are as follows.

(a) Target line constraint by $TDOCO$

$$l_{fb} = \min(\frac{\Delta TDOCO}{length\ of\ existing\ line})$$

Where, l_{fb}: Target line that has maximum increase of $TDOCO$ per length among existing lines

$TDOCO$: Total Degree of Competitiveness (additional travel time that transit network requires when compared to auto travel time, aggregated to whole network)

(b) Target node constraint by $DOCO_i$

$$\mathrm{n_{fb}} = \max(DOCO_i)$$

Where, n_{fb}: Target node (node where fall behind)

$DOCO_i$: Degree of Competitiveness of Origin i (additional travel time that transit network requires when compared to auto travel time, aggregated to origin i)

(c) Constraint of alternative lines via target node

$$\eta_{n_{fb}}^{k} = 1$$

Where, $\eta_{n_{fb}}^{k}$: 1 if alternative line *k* include a target line n_{fb}, otherwise 0

(d) Minimum and maximum line length constraints

$$l_{min} \leq l^k \leq l_{max}$$

Where, l_{min}: Minimum line length (km)

l_{max}: Maximum line length (km)

l_k: Length of line k

(e) Circuity constraint

$$D_{ij}^k = \frac{l_{ij}^k}{d_{ij}} \leq D_{max}$$

Where, D_{ij}^k: Circuity of line k from i to j

l_{ij}^k: Length of line k from i to j (km)

d_{ij}: Min. path length from i to j (km)

D_{max}: Maximum possible circuity

(f) Redundancy with the existing line constraint

$$O_{n-e}^k \leq O_{exist}^{max}$$

Where, O_{n-e}^k: Redundancy rate between existing line and alternative line k

O_{exist}^{max}: Maximum possible redundancy

(g) Alternative line constraint by TDOCO

$$l_{new} = \max(\frac{\Delta TDOCO}{length\ of\ candidate\ line})$$

Where, l_{new}: Line that has maximum improvement of $TDOCO$ per length among alternative line candidates

$TDOCO$: Total Degree of Competitiveness (additional travel time that transit network requires when compared to auto travel time, aggregated to whole network)

(h) Minimum and maximum frequency constraints of lines

$$f_{min} \leq f_k \leq f_{max}$$

Where, f_{min}: Minimum frequency (min)

f_{max}: Maximum frequency (min)

f_k: Frequency of line k (min)

For more information about the process and the algorithm of each stage, we explain more detail in Chapter 4.

3.4 Lower level model

Lower level problem of this study is multi-modal user equilibrium assignment model in car, and optimal strategy that minimize total travel time in transit. In this study, total flow between origin and destination is identical, but the flow of car and transit change by frequency setting of each line with modal split by logit model.

Lower level problem in this study is modal split and trip assignment procedure based on the result of trip generation and trip distribution of traditional 4 stage travel demand model. Modal split process is implemented with line configuration, frequency of each line. Next, car and transit flow are assigned on the given network respectively. Depending on the improvement or change of transit network, transit travel time between the zone changed, and mode choice changes between passenger car and transit occurs. As a result, car travel time of the roads also changed with traffic volume change, transit travel time of the means for passing the road change together. This iterative calculation procedure reflect an actual mode and path choice of travelers into a model. As a result, objective function value of upper level problem is calculation results of lower level model, and fitness function and line configuration of upper level model is calculated by these results.

3.4.1 Modal split

In this study, modal split is implemented by logit model based on the travel behavior of individuals. The probability of selecting mode K is calculated as follows.

$$P(K) = \frac{\exp(U_K)}{\sum_1^{\mathrm{n}} \exp(U_i)}$$

where, $P(K)$: Probability of selecting mode K

U_K: Utility of mode K

U_i: Utility of mode i

n: Number of modes

Utility is calculated based on the travel time, cost, and etc. General utility function is as follows.

$$U_{ijk} = \alpha_1 (T_{TIME})_{ijk} + \alpha_2 (T_{COST})_{ijk} + D_k + C_k$$

Where, U_{ijk}: Utility of mode k between origin i and destination j

$(T_{TIME})_{ijk}$: Total travel time of mode k between i and j

$(T_{COST})_{ijk}$: Total travel cost of mode k between i and j

D_k: Dummy variable with other factors

C_k: Coefficient of utility function

α_1, α_2: Parameters

Utility function consists of travel time, access time, total cost, and dummy variable which reflect the invisible characteristics of each mode. Parameter of each variable can be identical or not between the modes. In this study, same coefficient values are applied into parameters between the modes, different values are applied into dummy variable for each mode cited by feasibility manual of Korea. Here, α_1, and α_2 are negative value because utility decreases as time and cost increase. Total travel time of each mode means travel time through minimum path. Total travel cost of auto consist of fuel cost, and that of transit consist of fare of in-vehicle distance. Volume of each mode by logit model is as follows.

$$\overline{q_{od}} = \frac{q_{od}}{(1 + \exp\left(\alpha(\overline{t_{od}} - \widehat{t_{od}}) + \alpha_2(\overline{c_{od}} - \widehat{c_{od}}) + \widehat{D}\right)}$$

$$\widehat{q_{od}} = q_{od} - \overline{q_{od}}$$

where, $\overline{q_{od}}$: Car volume between origin and destination

$\widehat{q_{od}}$: Transit volume between origin and destination

q_{od}: Total volume between origin and destination

$\overline{t_{od}}$: Minimum path time of car between origin and destination

$\widehat{t_{od}}$: Minimum path time of transit between origin and destination

$\overline{c_{od}}$: Minimum path cost of car between origin and destination

$\widehat{c_{od}}$: Minimum path cost of transit between origin and destination

α_1: Travel time parameter of utility function

α_2: Travel cost parameter of utility function

$\widehat{D}$: Dummy variable of transit

3.4.2 Car assignment

User equilibrium state is assumed that all users select a route that has minimum generalized cost. A stable condition is reached only when no traveler can improve his travel time by unilaterally changing routes. This principle is presented in the study of Wardrop (1952). The travel times in all routes actually used are equal and less than those which would be experienced by a single vehicle on any unused route. Each user non-cooperatively seeks to minimize his cost of transportation.

Beckmann et al. (1956) formulated a model which estimate assigned traffic flow with equilibrium state, and this model can be expressed as follows.

$$\min C = \sum_{a} \int_{0}^{x_a} c_a(w)dw$$

$$\text{s.t. } \mathrm{x_a} = \sum_{i}\sum_{j}\sum_{r} T_{ijr} \cdot \delta_{ijr}^{a}$$

$$\sum_{\mathrm{r}} T_{ijr} = T_{ij}$$

$$T_{ijr} \geq 0$$

where, $c_a(w)$: Cost of link a with link volume w

x_a: Volume of link a

T_{ijr}: Volume using path r from node *i* to node j

T_{ij}: Volume from node *i* to node j

δ_{ijr}^{a}: 1 if path r includes link a, otherwise 0

Travel time of each link is calculated by BPR function as follows.

$$t_a(x_a) = \frac{l_a}{\overline{v_a}} \cdot \left[1 + \alpha \left(\frac{x_a}{c_a}\right)^{\beta}\right] \qquad \forall a \in A$$

where, l_a: Length of link a

$\overline{v_a}$: Free flow speed of link a

α, β: Parameters of link travel time function

x_a: Volume of link a

c_a: Capacity of link a

The objective function and constraints based on the user equilibrium state of car assignment is as follows.

$$\min C = \sum_a \int_0^{x_a} t_a(w)dw$$

$$\text{s.t. } x_a = \sum_o \sum_d \sum_r f_r^{od} \cdot \delta_{a,r}^{od} \qquad \forall a$$

$$\sum_{\mathrm{r}} f_r^{od} = \overline{q_{od}}$$

$$f_r^{od} \geq 0 \qquad \forall r, o, d$$

where, f_r^{od}: Volume using path r from origin to destination

$\overline{q_{od}}$: Car volume from origin to destination

$\delta_{\mathrm{a,r}}^{od}$: 1 if path r from origin to destination includes link a, otherwise 0

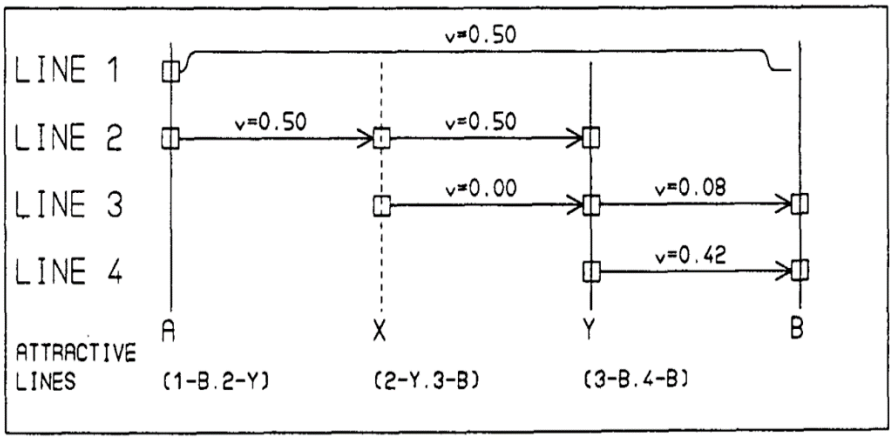
3.4.3 Transit assignment

Transit assignment of public transportation consists of single path assignment and multipath assignment. The single path assignment assigns an entire demand to the shortest path among traffic zones. This assignment gives basic information such as theoretical traffic demand according to desired route of trip and basic route plan. However, practicality of the model decreases as the number of routes and the number of public transportation trips increase.

This study uses the assignment model according to optimal strategy suggested by Spiess and Florian (1989), one of the multipath assignment model for transit assignment of public transportation. The optimal strategy is defined as a set of paths for passengers to reach destinations. The number and the type of strategies are determined by the information which a passenger get during the trip. Figure 3.1 shows a case of strategies a passenger moving from node A to B can choose.

- If no additional information is given to a passenger during the trip: Take line 2 to node Y and transfer to line 3.
- If a passenger knows which lines to be served next, while waiting at a node: Take the line arriving faster; if line 1 was taken, then get off at node B; if line 2 was taken, then get off at node Y and transfer to line 3 or 4.
- If more information, such as waiting time, vehicle arrival time, or other vehicles seen out of the vehicle window, can be given to a passenger: Wait for

a vehicle of line 1 up to five minutes; otherwise take line 2; if the passenger finds a vehicle of line 3 at node X, then transfer to the line 3 because it is faster than other lines, otherwise continue to node Y and transfer to line 3 or 4.



Source: Spiess, H., & Florian, M. (1989)

Figure 3.1 Illustration of optimal strategy

Spiess and Florian considered the second strategy of the previous case in order to model the strategy mathematically. They assumed that a passenger can get the only information during the trip while waiting a node that which line is served next. All trips are generated by the strategy minimizing passenger's travel time. This strategy is feasible if the route defined by the strategy does not include a cycle and the optimal strategy minimizes traveler's travel time. All trips are made according to the strategy.

A trip is carried out according to the following procedures once a strategy is

established as the previous case.

Step 0: Set origin node to NODE.

Step 1: Board vehicle which arrives first among the vehicles of the set of attractive lines at NODE.

Step 2: Alight at predetermined node according to the optimal strategy.

Step 3: If not yet at destination, set current node to NODE move to Step 1. Otherwise the trip is completed.

A transit trip in this model consists of access from origin to transit stop, waiting for a vehicle at transit stop, boarding the vehicle, alighting at the vehicle, walk between two transit stops, and access from transit stop to destination. Traveler's travel cost is defined as general concept including all these costs.

An objective function and constraints in the optimal strategy model are as follows. t means that traveler use transit.

$$\min \sum_{a} x_a^t t_a^t + \sum_{i} w_i$$

$$\text{s.t.} \quad \sum_{\mathrm{a} \in A_i^+} x_a^t - \sum_{\mathrm{a} \in A_i^-} x_a^t = g_i \quad i \in I$$

$$\mathrm{x}_{\mathrm{a}}^t \leq f_a w_i \quad \mathrm{a} \in A_i^+, i \in I$$

$$\mathrm{x}_{\mathrm{a}}^{\mathrm{t}} \geq 0 \quad a \in A$$

where, A: Link set

I: Node set

A_i^+: Link set outbound node i

A_i^-: Link set inbound node i

g_i: Transit volume from node i

x_a^t: Transit volume of link a

t_a^t: Transit time of link a

f_a: Frequency of link a

w_i: Waiting time of node i

Traffic assignment by the optimal strategy is assumed to be reasonable in terms of route search and for a passenger to board the first arriving vehicle among a set of the optimal strategy when the demand is assigned. User's behavior is represented clearly and simply by a method allocating demand in proportion to the frequency when traffic of node i, x_a^t are distributed to links. Because the optimal strategy does not consider a capacity constraint, the process of considering the number of vehicles needed by route after final traffic assignment or introducing a mode that has much capacity is needed.

3.5 Transit network design model considering equity

The transit network design model of this study is organized with bi-level modelling. The objective function of the upper model is constructed in the form of minimizing the total cost of users and operators with line candidate constraints, and in the lower model, modal split of passenger car / transit, and traffic and transit assignment are performed from variable frequency setting situation in the upper model. Binary logit model is applied to perform a modal split, and traffic and transit assignment is implemented by user equilibrium with convex combination and transit assignment model by H. Spiess and M. Florian (1989) respectively. Constraints excluding frequency constraints of the upper level problem are predetermined through line configuration determination process. Line configuration determination procedures includes target line (line to alter) selection, target node (node to improve modal equity) selection, alternative line generation and line combination determination. Model procedure of this study is illustrated in figure 3.2.

In target line selection procedure, Total Degree of Competitiveness ($TDOCO$), additional travel time the transit network requires when compared to auto travel time aggregated to whole network, is calculated to assess the existing line. Among total n-number of routes, when excluding one of the line except lines cannot be changed, the smallest route of the *TDOCO* change per unit length is selected to the "target line", and delete that line.

Next, with the line combination without target line, nodes are compared by

Degree of Competitiveness of Origin i ($DOCO_i$), additional travel time the transit network requires when compared to auto travel time aggregated to origin i. The highest node of $DOCO_i$ is set to "target node". Target node is where to improve modal equity by alternative line.

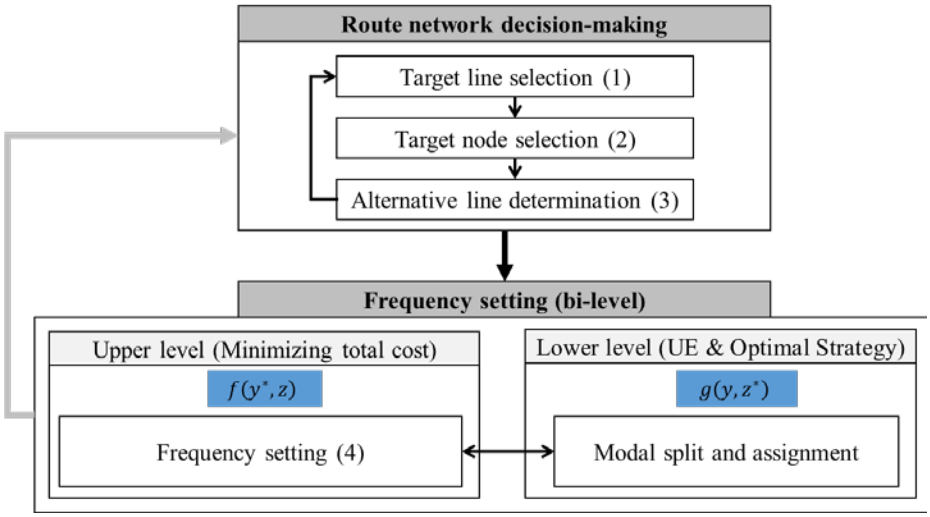


Figure 3.2 Model procedure of this study

Alternative line candidate is generated based on the many-to-many origin and destination. Route of alternative lines are minimum path via target node. Alternative lines are compared to minimum path of each origin and destination. If ratio of length of line to length of minimum path is higher than defined circuity, that line is deleted from alternative line. After that, if redundancy of alternative line with existing lines is higher than defined value, that line is deleted from alternative line. The reason of redundancy comparison is to reduce the operational inefficiencies.

Remained alternative lines are added to existing line configuration one by one repetitively. Alternative line that has maximum improvement of $TDOCO$ per unit length is new line of iteration j. The new alternative line enhances the directness and mobility of the vulnerable target node, and maximizes $TDOCO$ improvement per unit length.

From this new transit network, target line selection, target node selection, and new alternative line determination procedure are repeated. If target line of iteration j is same as new line of iteration j-1, infinite loop occur. In this case, target line is not deleted. Indeed, target node selection and alternative line determination procedures are implemented. This iterative process is repeated until candidate line is no longer generated in response to the redundancy constraint with existing lines.

This transit line network determination with iterative procedure satisfies the line and node-based equity criteria. In general, determination of the route is performed in a direction that minimizes the total time or operation cost with demand. Because many lines are operated on the high demand area, inevitably there is a problem that the regions where service of public transportation is insufficient are occurred. Line network determination methodology of this study can resolve this problem and can reduce the cost with following frequency setting procedure together.

The procedure of frequency setting is to find the optimal transit line combination and frequency of each line in order to satisfy the efficiency of the user and operator's total cost. This procedure determined by iterative game

theory calculation process is carried out through the bi-level modeling. In the frequency setting procedure, with the upper level of bi-level modelling, genetic algorithm (GA) is applied to find an optimal solution. Range of each gene (fleet number per hour per line) varies from 1 to maximum possible fleet number in lines cannot be changed, and 1 to two times maximum number in altered lines. If value of gene exceeds maximum fleet number, that line would not be operated. Lower level problem of bi-level model is modal split and car / transit assignment. Depending on the improvement or change of transit network, transit travel time between the zone changed, and mode choice changes between passenger car and transit occurs. As a result, car travel time of the roads also changed with traffic volume change, transit travel time of the means for passing the road change together. This iterative calculation procedure reflect an actual mode and path choice of travelers into a model.

To solve this model, in this study, line configuration determination and genetic algorithm of frequency setting are analyzed by MATLAB 2015b, modal split and car / transit assignment are analyzed by EMME 3.3, commercial traffic analysis package. Figure 3.3 and 3.4 show the procedures of this study.

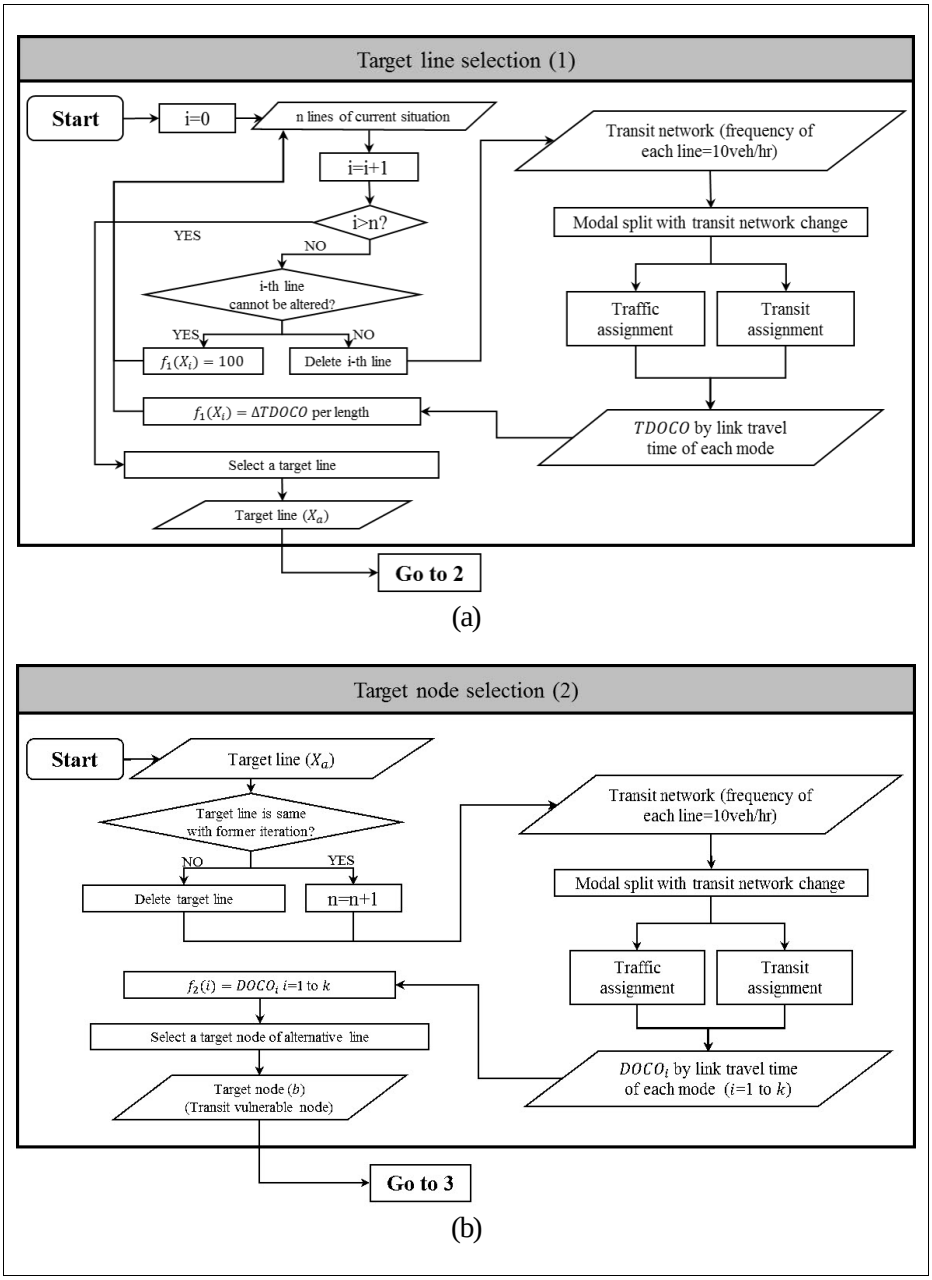


Figure 3.3 (a) Flowchart of target line selection procedure,

(b) Flowchart of target node selection procedure

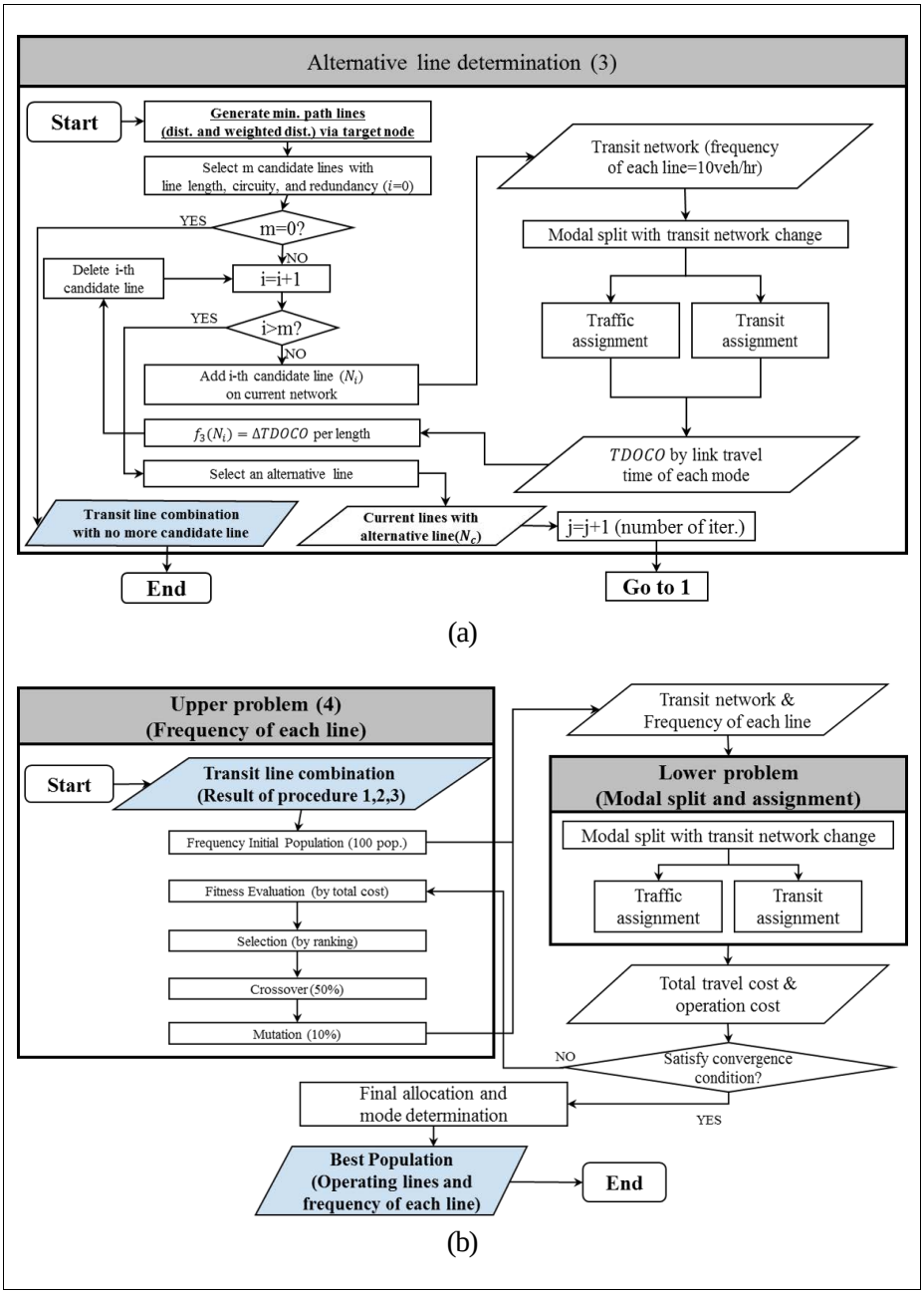


Figure 3.4 (a) Flowchart of alternative line addition procedure,

(b) Flowchart of frequency setting procedure

Chapter 4. Algorithm

4.1 Target line selection

4.1.1 Mobility reflection in transit assessment

From the literature review, there are many equity indexes for the public transport. These indexes indicate the service level of public transportation of each region or whole network. Most are based on the accessibility, because it is difficult to consider the actual traffic condition when planning or assessing the transit. However, the most influential factors that affect on the actual level of service is the total travel time. Therefore, we have to reflect the mobility on the indexes and assessment of transit service.

For the comparison between the index that reflect the mobility and that did not, *DOCO* (Degree of Competitiveness) and connecting power are compared. For the convenience of the analysis, it is assumed that transit service is equally operated by the other side.

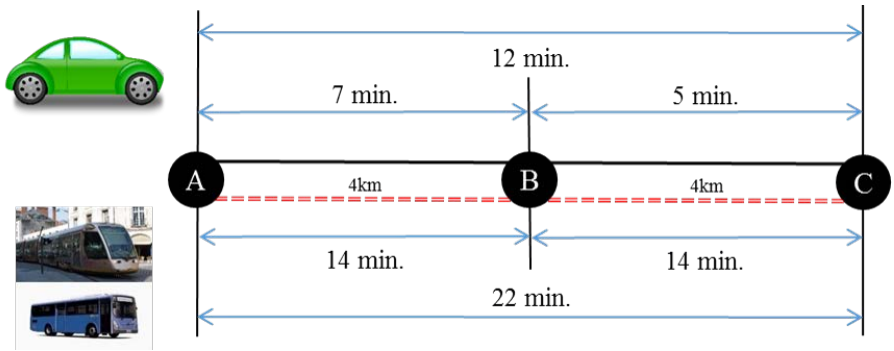


Figure 4.1 Sample network to compare Connecting power and DOCO

Figure 4.1 shows the sample network to compare the two indexes. If there is one transit line via A-B-C, connecting power of three nodes are identical as shown in Table 4.1. Capacity of each fleet is 100 person, frequency is 8 vehicles per hour, speed is 30km per hour, and length is 8km. Detailed formula of calculating the connecting power is described in chapter 2.

Table 4.1 Connecting power of sample network

NODE	Cumulative length +	Cumulative length −	$P^{o}_{l,n}$	$P^{i}_{l,n}$	CI(v)
A	0	8	0.000	1.000	0.500
B	4	4	0.500	0.500	0.500
C	8	0	1.000	0.000	0.500

Table 4.1 shows that connecting power of each node is same as in this sample network. This is because the connecting power has a limit that is not be able to reflect the mobility such as traffic situation of the link.

However, in the same network situation, *DOCO* is calculated differently between the nodes. Detailed formula of calculating the *DOCO* is also described in chapter 2. Table 4.2 shows the calculation result of *DOCO* of each node. Unlike the connecting power, it is confirmed that the different value for each node is calculated.

Table 4.2 $DOCO_i$ of sample network

Auto	A	B	C	Total
A	0	7	12	19
B	7	0	5	12
C	12	5	0	17
Transit	**A**	**B**	**C**	**Total**
A	0	14	22	36
B	14	0	14	28
C	22	14	0	36
DOCO	**A**	**B**	**C**	$\boldsymbol{DOCO_i}$
A	-	200%	183%	**189%**
B	200%	-	280%	**233%**
C	183%	280%	-	**212%**

Remark: speed is 30 km/hr, waiting time is 4 minute, and access/egress time 2 minute.

In this table, node B is analyzed that the largest difference in travel time between auto and transit. However, this node has shorter travel length compared to other nodes, therefore *DOCO* is relatively high compared to other nodes because of high percentage of access and waiting time. Here, *DOCO* is compared based on node A and C. Travel time between A to C and C to A are identical because it is symmetrical network situation, but travel time to B from A and C are different because of road condition. Therefore, in this sample network, *DOCO* of node C is higher than that of node A. Based on *DOCO*, transit network improvement is required to node C in this sample network. Connecting power and *DOCO* is compared on the expended sample network. This network is also applied to numerical example analysis in chapter 5.

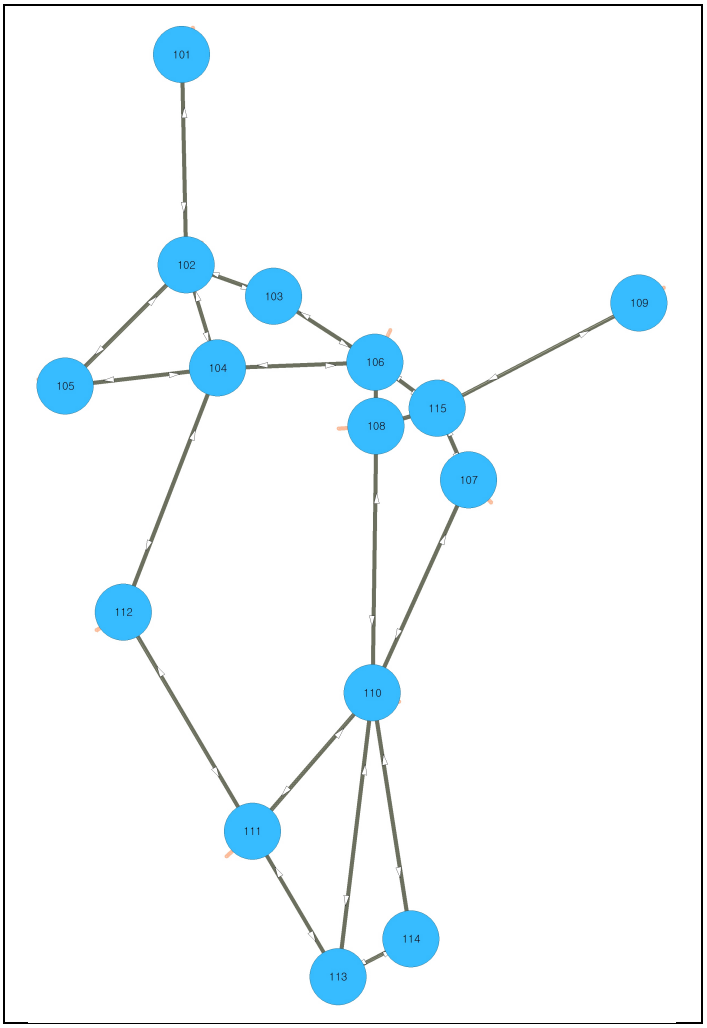


Figure 4.2 Mandl's network (sample network 2)

Table 4.3 Current lines of sample network 2

Line	Speed (km/hr)	Frequency (veh/hr)	Route
1	40	30	1-2-3-6-8-10-13
2	30	12	5-4-6-8-15-7
3	30	3	12-4-6-15-9
4	30	2	10-14-13

Table 4.4 Equity index from sample network 2

Node	Connecting Power	$DOCO_i$
101	1.353	1.600
102	1.353	2.386
103	1.353	2.258
104	0.387	2.538
105	0.257	2.531
106	1.740	2.217
107	0.257	2.627
108	1.610	2.219
109	0.130	2.557
110	1.385	2.060
111	0.000	4.170
112	0.130	2.220
113	1.385	2.255
114	0.032	2.635
115	0.387	2.486
Total	0.784 (average)	2.500 ($TDOCO$)

Connecting power and $DOCO_i$ are inversely related as shown in Table 4.4. Node 111 where no transit service is operated has the worst value both connecting power and $DOCO_i$. However, Node 101, 102, and 103 have same connecting power, but has different $DOCO_i$. It is because $DOCO_i$ can consider the mobility and accessibility simultaneously, while connecting power only

considers the accessibility. In this study, therefore, modified *DOCO*s are applied to assess the equity of transit network and to select target node, target line, and alternative line.

By the way, $DOCO_i$ of node 101 is lower than other nodes. It is because of the congestion of the surrounding roads, not a good transit service. Road expansion or rail transit service is required on this surrounding area.

In the extended study, new equity index may be developed by combining and considering the connecting power and $DOCO$ simultaneously. For example, target node may be selected by maximum $DOCO_i$ with connecting power that is lower than average value.

In this study, $TDOCO$ and $DOCO_i$ are formulated as follows. $TDOCO$ represents a modal equity of whole network, and $DOCO_i$ represents a modal equity of zone i. These values of each zone are compared between each zone to assess the modal and spatial equities of transit network.

$$TDOCO = \frac{\sum_{ij}\left(\min t_{ij}^{t} - \min t_{ij}^{a}\right)}{\sum_{ij}\left(\min t_{ij}^{a}\right)}$$

$$DOCO_i = \frac{\sum_{j}\left(\min t_{ij}^{t} - \min t_{ij}^{a}\right)}{\sum_{j}\left(\min t_{ij}^{a}\right)}$$

Where, t_{ij}^{t}: Travel time by transit from i to j

t_{ij}^{a}: Travel time by auto from i to j

4.1.2 Assessment of existing network and target line selection

In the target line selection procedure, $TDOCO$ per unit length is used to assess modal equity of existing lines. Among a total n-number of routes, when excluding the one of the line except lines cannot be changed, the smallest route of the *TDOCO* change per unit length is selected to the "target line", and delete that line.

Next, target line selection, target node selection, and new alternative line determination procedure are repeated. From this new transit network, target line selection procedure is also repeated. If target line of iteration *j* is same as new line of iteration *j*-1, infinite loop occur. In this case, target line is not deleted and target node selection and alternative line determination procedures are implemented. This iterative process is repeated until candidate line is no longer generated in response to the redundancy constraint with existing lines.

<u>(a) Target line constraint by $TDOCO$</u>

$$l_{fb} = \min\left(\frac{\Delta TDOCO}{length\ of\ existing\ line}\right)$$

Where, l_{fb}: Target line that has maximum increase of $TDOCO$ per length among existing lines

$TDOCO$: Total Degree of Competitiveness (additional travel time that transit network requires when compared to auto travel time, aggregated to whole network)

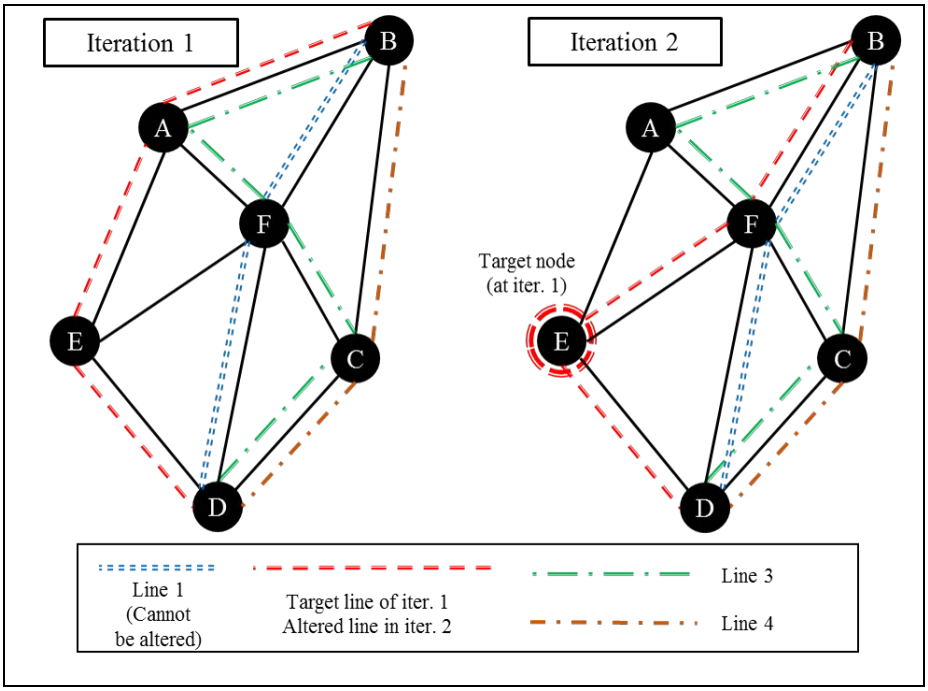


Figure 4.3 Illustration of target line to alternative line

Table 4.5 Target line selection by *TDOCO* calculation

iteration	$\Delta\ TDOCO$ per unit length				
	Line 1	Line 2	Line 3	Line 4	Line 5
1	Cannot be altered	0.32 (Target line)	0.54	0.45	-
2	Cannot be altered	0.57	0.42	0.25 (Target line)	-
3	Cannot be altered	0.48	0.37	0.25 (Target line, but not deleted)	-
4	Cannot be altered	0.34	0.16 (Target line)	0.20	0.35
5~	Cannot be altered	...	...	...	...

4.2 Target node selection

4.2.1 Target node selection on transit service

With the line combination without target line, nodes are compared by Degree of Competitiveness of Origin i ($DOCO_i$), which is additional travel time of the transit network compared to auto travel time aggregated to origin i. This index indicates the modal equity of each origin, and if this index is higher than other node, that node has lower spatial equity than other nodes. The highest node of $DOCO_i$ is set to "target node". Target node is where to improve modal equity by alternative line. With transit network improvement of target node, maximum $DOCO_i$ decreases and spatial equity increases.

<u>(b) Target node constraint by $DOCO_i$</u>

$$\mathrm{n_{fb}} = \max(DOCO_i)$$

Where, n_{fb}: Target node (node where fall behind)

$DOCO_i$: Degree of Competitiveness of Origin i (additional travel time that transit network requires when compared to auto travel time, aggregated to origin i)

Strategies for reducing the $DOCO$ can be divided into two ways. First method is making cars go slow down, and second method is making transit go faster.

The former method is to be achieved through a reduced supply roads for passenger cars, such as the Transit mall (transit only zone) or road diet, however in this study, $DOCO$ improvement by these methods does not occur. In this study, by transit network improvement, transit go faster and *DOCO* index is improved. Since the new line altering the target line passes through the target node, $TDOCO$ and $DOCO_i$ are improved by transit network change with iteration.

Table 4.6 Target node selection by $DOCO_i$ calculation

iteration	$DOCO_i$					
	A	B	C	D	E	F
1	2.08	3.38	2.95	2.24	**4.22**	2.44
2	1.94	2.40	**2.94**	2.14	2.04	2.24
3	1.78	2.28	**2.82**	2.01	1.90	2.00
4	1.72	**2.19**	2.12	1.89	1.78	2.05
5	...	...	...	...	...	...

4.2.2 Significance of target node on transit route network design

Selecting the target line and target node in consideration of mobility and accessibility simultaneously have the following two meanings. Firstly, in the operational aspects of public transport in urban areas, transit route networks can be compared to quantify the service level of routes or regional transit service. Because public transportation operations do not have a clear quantitative criteria, these criteria of evaluating current state of the transit network can be applied to the prioritization of vulnerable area and generation and alternation of new routes. Also in this study, in consideration of mobility such as road congestion, it is possible for a comprehensive approach to service level of public transport. In previous studies, mobility is rarely applied, and almost all of the researchers only reflect an accessibility in the evaluation of the public transportation service.

Secondly, improvement of the overall network by transit time improvement of target node is reflected to the objective function in the upper model. As mentioned in the chapter 3, objective function of this study is minimizing total cost. If objective function is the total cost minimization, due to the improvement of regions that have many demand, there are transit routes concentration to that regions, and the service level of the other regions can be low. In this study, with the consideration of target link and target node by the equity criteria, improvement of total cost would be smaller than other alternatives but can have a better solution in terms of equity of transit services.

4.3 Alternative line determination

4.3.1 Candidate lines creation via target node

After selecting target node, generating candidate lines via target node has an advantage of reflecting the effects of improving the vulnerable node. In this study, minimum paths via target node, and minimum paths via target node by distance weighted to volume between all-to-all nodes are generated, and those are compared to minimum path between each nodes by circuity. Circuity in this study is ratio of length of minimum path via target node to minimum path between each nodes.

<u>(c) Constraint of alternative lines via target node</u>

$$\eta_{n_{fb}}^{k} = 1$$

Where, $\eta_{n_{fb}}^{k}$: 1 if alternative line k include a target line n_{fb}, otherwise 0

Figure 4.5 shows the examples of minimum path via target node. With an actual minimum path via target node, because of much volume on link from node A to node F, additional weighted minimum paths are generated in this figure. Consequentially, generated candidate lines pass through a target node and links has much volume simultaneously.

Calculation of minimum path is implemented by the shortest path algorithm of Dijkstra (1959) that is generally used in various area. Dijkstra algorithm is

an algorithm to compute the minimum path between origin and destination in the network where any link does not have a negative value, and applied to many studies related to network theory. In this study, this algorithm is applied equally to all minimum path finding problem – actual path and paths via target node.

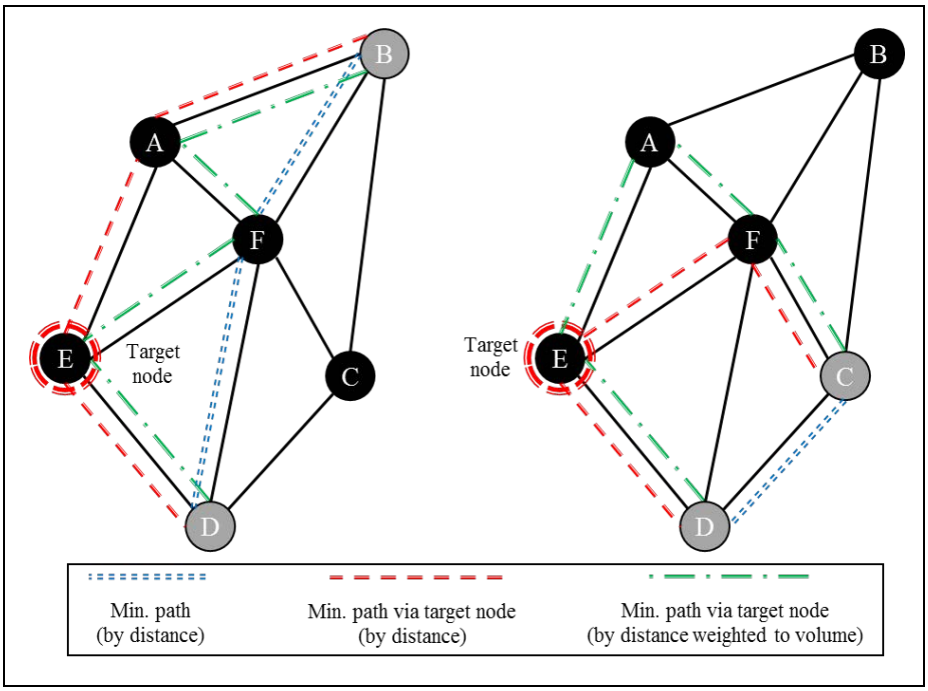


Figure 4.4 Illustration of min. path via target node

Table 4.7 Minimum paths via target node

O-D	Min. path	Min. path via target node	
		By distance	By distance weighted to volume
B-D	B-F-D	B-A-E-D	B-A-F-E-D
C-D	C-D	C-F-E-D	C-F-A-E-D

4.3.2 Circuity and Redundancy of candidate lines

Generated candidate lines are compared to minimum and maximum line length, minimum path, and existing lines. If candidate lines do not satisfy the constraint condition of length, then those lines are deleted. Remained lines are compared to minimum path between each nodes by circuity. Circuity in this study is ratio of length of minimum path via target node to minimum path between each nodes. If circuity is higher than defined value, that line is deleted from alternative line. After that, if redundancy of alternative line with existing lines is higher than defined value, that line is deleted from alternative line. Redundancy in this study is ratio of redundant length with existing lines of total line length. The reason of line length, circuity and redundancy comparison is to reduce the operational inefficiencies. Following procedures and terminologies are similar to framework of studies of Lee (1998) and Park (2006).

<u>(d) Minimum and maximum line length constraints</u>

$$l_{min} \leq l^k \leq l_{max}$$

Where, l_{min}: Minimum line length (km)

l_{max}: Maximum line length (km)

l_k: Length of line k

Public transportation has fixed cost regardless of the operation length, and higher fixed cost is entered compared to the private car. From this characteristic,

short length lines have greater operational inefficiencies due to higher fixed costs than economies of scale cases. Therefore, if a generated line length is shorter than given minimum length, that line is deleted from candidate line. On the contrary to this, if the line is too long, inefficiencies by fatigue level of the driver, break time problem, the difficulty of vehicle maintenance, and increasing of the round-trip time deviation by the road conditions increase. Therefore, if a generated line length is longer than given maximum length, that line is also deleted from candidate line.

Remained lines are compared to minimum path between each nodes by circuity. Based on the actual shortest path, candidate lines via target node are compared, lines whose redundancy exceeds $\mathrm{D_{max}}$ are deleted. Figure 4.6 shows that line via D-E-A-F-C is deleted from candidate line because of higher circuity than maximum value. The constraint represented by the formula is as follows.

<u>(e) Circuity constraint</u>

$$D_{ij}^{k} = \frac{l_{ij}^{k}}{d_{ij}} \leq D_{max}$$

Where, D_{ij}^{k}: Circuity of line k from i to j

l_{ij}^{k}: Length of line k from i to j (km)

d_{ij}: Min. path length from i to j (km)

D_{max}: Maximum possible circuity

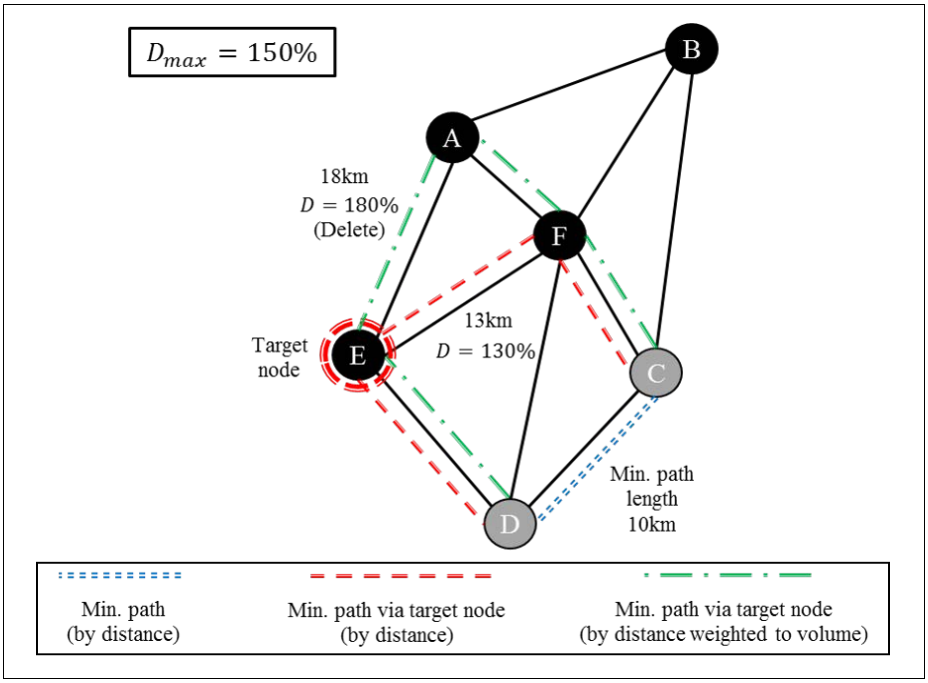
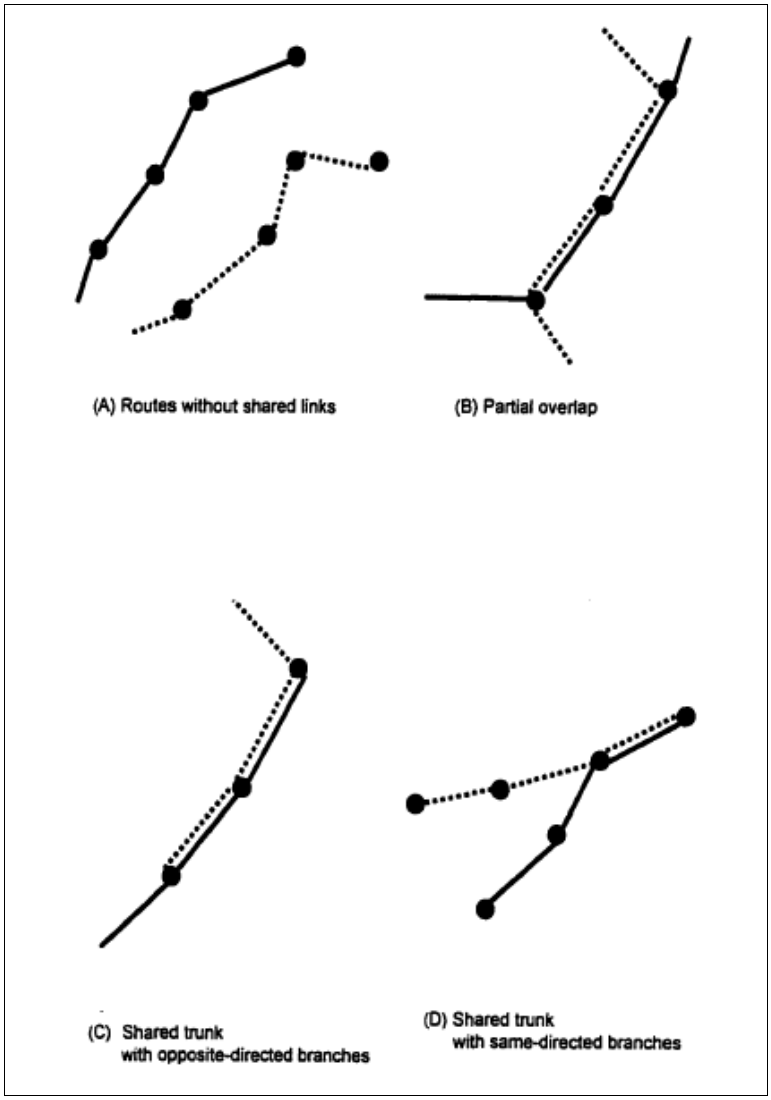


Figure 4.5 Illustration of checking circuity

Remained candidate lines until now are passing through a target node, and not detour routes compared to minimum paths. These remained candidate lines are compared to existing line to test a redundancy. Redundancy in this study is ratio of redundant length with existing lines of total line length. Figure 4.7 shows the redundancy type of transit line network, partial overlap, shared trunk with opposite-directed branches, and shared trunk with same-directed branches. All of the redundancy types are considered in this study. Redundant routes cause the inefficiency of the entire network by the waste of costs associated with duplicate investment and operation. If redundancy of candidate line with existing lines is higher than defined value, that line is deleted from alternative line. The lines not deleted are final alternative lines of this procedure.



Source: Lee, Y. J. (1998)

Figure 4.6 Illustration of redundancy type

Figure 4.8 shows the redundancy test procedure by illustration with a simple example. Candidate line 1 has 31% redundancy with existing line. Maximum redundancy in this illustration is 50%, because redundancy of this line does not

exceed the maximum value, it is not deleted and next procedure that alternative line determination is implemented. However, candidate line 2 have the redundancy of exceeding 50%, and are deleted in this procedure.

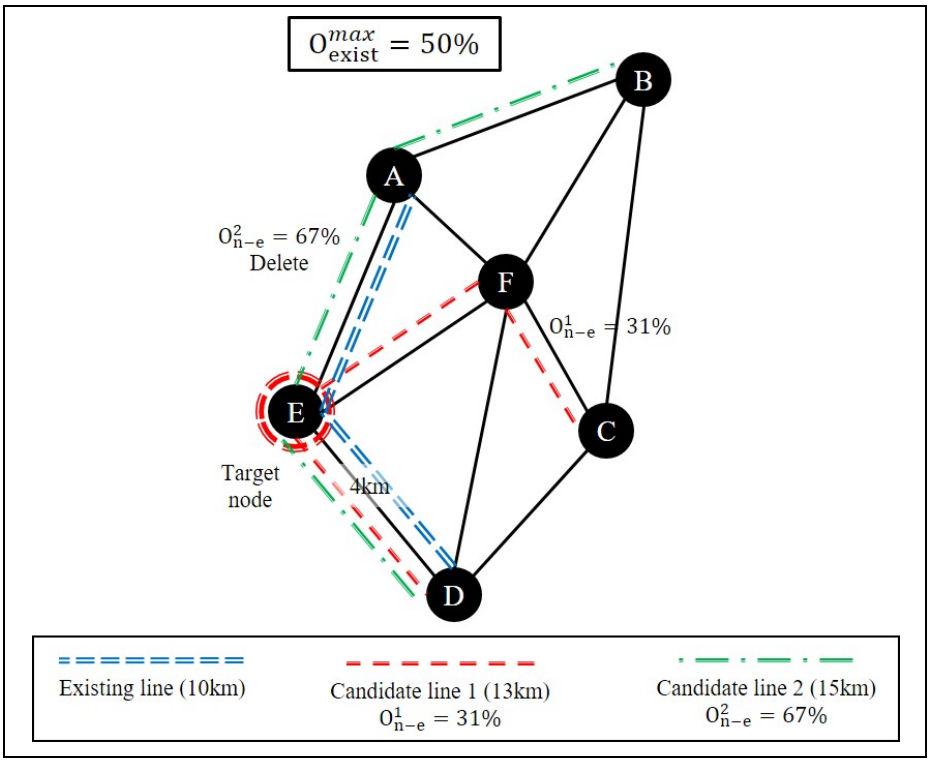


Figure 4.7 Illustration of checking redundancy

Table 4.8 Redundancy checking criteria

Line	Length	Redundant length	Redundancy	Result
Existing line	10km	-	-	-
Candidate line 1	13km	4km	31%	-
Candidate line 2	15km	10km	67%	Delete

Final alternative line if target line is selected in target line selecting procedure, or additional line if target line is net selected in that procedure, is determined in following procedure from remained candidate lines. The redundancy constraint are represented as a formula as follows.

(f) Redundancy with the existing line constraint

$$O_{n-e}^{k} \leq O_{exist}^{max}$$

Where, O_{n-e}^{k}: Redundancy rate between existing line and alternative line k

O_{exist}^{max}: Maximum possible redundancy

4.3.3 Determination of alternative line

Candidate lines via target node satisfying length, circuity, and redundancy are candidates of alternative line that alter the target line. These candidate lines are added to existing line configuration one by one repetitively. Candidate line that has maximum improvement of TDOCO per unit length is new alternative line of iteration j. The new line enhances the directness and mobility of the vulnerable target node and maximizes TDOCO improvement per unit length. Target line selection procedure of iteration j+1 is implemented with this line configuration. Altered line in right figure of figure 4.3 is the alternative line which maximize TDOCO improvement per unit length in iteration 1, and one of the existing lines in iteration 2.

<u>(g) Alternative line constraint by TDOCO</u>

$$l_{new} = \max\left(\frac{\Delta TDOCO}{length\ of\ candidate\ line}\right)$$

Where, l_{new}: Line that has maximum improvement of $TDOCO$ per length among alternative line candidates

$TDOCO$: Total Degree of Competitiveness (additional travel time that transit network requires when compared to auto travel time, aggregated to whole network)

Table 4.9 shows the whole procedure of determining line configuration in this study. In this table, the sample network include 6 nodes and 4 existing lines.

Table 4.9 Procedure of determining transit route network in this study

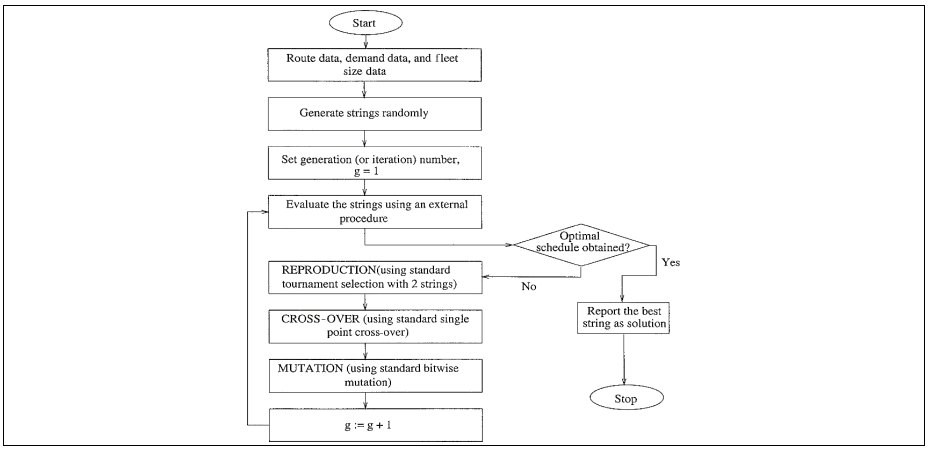
<table>
<tr><th>iteration</th><th colspan="6">Procedures</th></tr>
<tr><td rowspan="12">1</td><td colspan="6">(a) Target line selection by $\Delta\ TDOCO$ per unit length</td></tr>
<tr><td>Line 1</td><td colspan="2">Line 2</td><td colspan="2">Line 3</td><td>Line 4</td></tr>
<tr><td>Cannot be altered</td><td colspan="2">0.32 (Target line)</td><td colspan="2">0.54</td><td>0.45</td></tr>
<tr><td colspan="6">(b) Target node selection by $\mathrm{Max}(DOCO_i)$</td></tr>
<tr><td>A</td><td>B</td><td>C</td><td>D</td><td>E</td><td>F</td></tr>
<tr><td>2.08</td><td>3.38</td><td>2.95</td><td>2.24</td><td>4.22</td><td>2.44</td></tr>
<tr><td colspan="6">(c) ~ (f) Candidate lines generation – for example 3 lines.</td></tr>
<tr><td colspan="6">(g) Alternative line determination by $\Delta\ TDOCO$</td></tr>
<tr><td colspan="2">Candidate 1</td><td colspan="2">Candidate 2</td><td colspan="2">Candidate 3</td></tr>
<tr><td colspan="2">-0.37</td><td colspan="2">-0.21</td><td colspan="2">-0.55 (Alternative line)</td></tr>
<tr><td>2</td><td colspan="6">If target line of iteration j is same as new line of iteration j-1, target line is not deleted and target node selection and alternative line determination procedures are implemented. (n=n+1, n=number of existing lines)
This iterative process is repeated until candidate line is no longer generated in response to the redundancy constraint with existing lines.</td></tr>
</table>

4.4 Frequency setting of transit network

4.4.1 Outline

Genetic algorithm applications in transit network design and frequency setting problem are reviewed in chapter 2. Based on this review result, we suggest a genetic algorithm to determine frequency of each line.

The procedures of former sections – target line and node selection, candidate line via target node generation, and alternative line determination – consider the modal and spatial equity by providing a basic transit service and improving the service, whereas frequency setting procedure consider the flow between the nodes and enhance the efficiency of network in terms of user and operator's total cost. Figure 4.9 shows the general process of genetic algorithm in the frequency setting procedure.



Source: Chakroborty(2003)

Figure 4.8 Flow chart of frequency setting by genetic algorithm

4.4.2 Improvement of genetic algorithm

The procedure of frequency setting is finding the optimal transit line combination and frequency of each line to satisfy the efficiency of the user and operator's total cost. This procedure determined by iterative game theory calculation process is carried out through the bi-level modeling. In the frequency setting procedure, with the upper level of bi-level modelling, genetic algorithm (GA) is applied to find an optimal solution. Range of each gene (fleet number per hour per line) varies from 1 to maximum possible fleet number in lines cannot be changed, and 1 to two times maximum number in altered lines. If value of gene exceeds maximum fleet number, that line is not operated. Here, fleet numbers per hour such as 11, 23 are excluded to calculate faster and effectively, and to enhance the efficiency of actual operation.

Table 4.10 Input variable candidates of frequency and fleet number

Random variable	fleet number (veh/hr)	frequency (min)
1	2	30
2	3	20
3	4	15
4	5	12
5	6	10
6	8	7.5
7	10	6
8	12	5
9	15	4
10	20	3
11	30	2
12~22	0	0

The minimum and maximum frequency constraint is represented as a formula as follows.

(h) Minimum and maximum frequency constraints of lines

$$f_{min} \leq f_k \leq f_{max}$$

Where, f_{min}: Minimum frequency (min)

f_{max}: Maximum frequency (min)

f_k: Frequency of line k (min)

Chapter 5. Numerical Example

5.1 Network explanation

5.1.1 Mandl's network

The example network of this study is Mandl's network (1979). Total traffic flow per 1 hour, road network and transit network are set and analyzed. This network consist of 15 nodes and 44 links, 1 line of railroad and 3 lines of bus are operated.

5.1.2 Basic unit input

The speed of lines are 40km/hr for railroad, 30km/hr for bus respectively. However, bus lines can be operated slower than 30km/hr because of traffic congestion. α, β of BPR function are 1.5 and 4 respectively. Coefficients of utility function of modal split are cited by feasibility study manual of Korea.

Access and egress length of transit user are 200m equally, and walking speed is 4km/hr, therefore access and egress time is total 6 minute. When candidate lines are generated, circuity and redundancy are 150% and 70% respectively. Minimum and maximum length are 10km and 30km respectively.

Figure 5.1 shows the illustration of existing network. One line of railroad cannot be altered, but the other lines can be altered to other alternative line. From this network, line configuration determination and frequency setting

procedures are implemented.

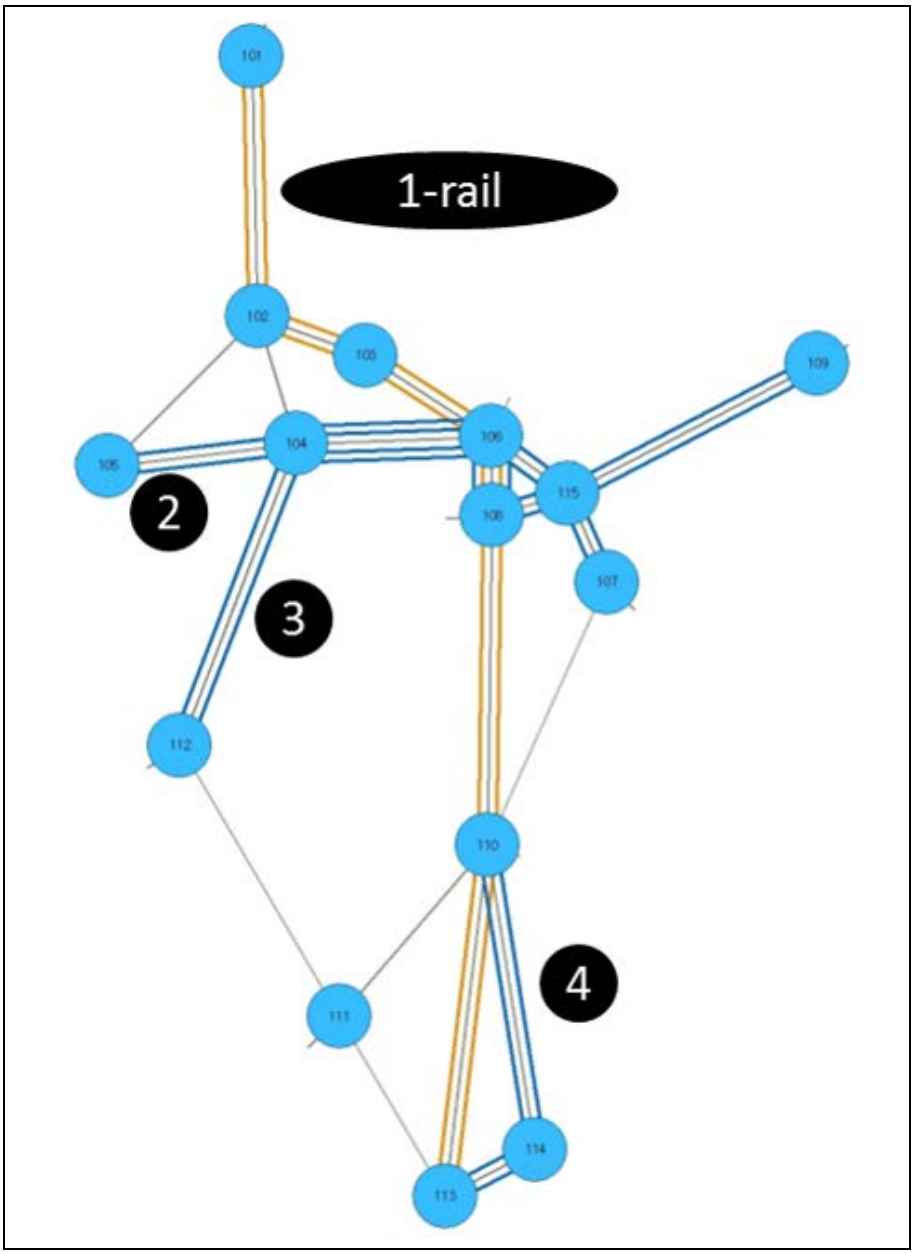


Figure 5.1 Illustration of existing network

5.2 Result

In this section, existing network input, iteration result of determining the line configuration and result of frequency setting of each line are presented.

5.2.1 Existing network

Existing network consists of one rail transit line and three bus lines. Speed of rail is 40 km per hour, and that of bus is 30 km per hour. Table 5.1 shows the frequency and route (stops) of each line.

Table 5.1 Line configuration of existing network

Line	Speed (km/hr)	Frequency (veh/hr)	Route
1 (Cannot be altered)	40	30	1-2-3-6-8-10-13
2	30	12	5-4-6-8-15-7
3	30	3	12-4-6-15-9
4	30	2	10-14-13

Total four transit lines are inputted in the EMME network at first. After that, modal split, and auto and transit trip assignment are implemented. Table 5.2 shows the result of modal split.

Table 5.2 Modal split result of existing network

Division	Auto	Transit	Total
Volume (trip/hr)	62,738	15,337	78,075
Modal split (%)	80.3	19.7	100.0

5.2.2 New transit network with equity consideration

Transit line determination procedure consists of assessment of existing network and target line selection, target node selection, and alternative line determination. In this numerical example, 26 line candidates are determined by 34 iterations. Table 5.3 shows the initial 3 iteration procedure and the result, and Table 5.4 shows the number of lines, target node, $TDOCO$ and $DOCO_i$ by the iterations. $TDOCO$ and $DOCO_i$ decrease simultaneously with iteration procedure.

In this line determination algorithm, nodes 5, 9, and 12 which are far from the central district of the network are selected to target node and alternative lines are passing through these nodes. At the same time, because of higher level of service of rail transit, lines redundant to rail line are not alternated. In the early stage of iterations, lines passing through the suburb area to maximize both modal and spatial equities are generated and altered. After that, in the last stage of iterations, lines not redundant to other lines are generated and altered.

Table 5.3 Iteration procedure of line determination

iteration	Procedure
1	Target line selection by $TDOCO$ (a)
	Line 1: Cannot be altered; Line 2: 0.031; Line 3: 0.054; **Line 4: 0.018**
	Target node selection by $DOCO_i$ (b)
	1: 1.603; 2: 2.407; 3: 2.273; 4: 2.481; 5: 2.455; 6: 2.185; 7: 2.632; 8: 2.194; 9: 2.383; 10: 2.080; **11: 4.222**; 12: 2.956; 13: 2.237; 14: 3.381; 15: 2.445
	Candidate line generation (c)~(f) – 32 candidate lines via node 111
	Alternative line determination by TDOCO (g)
	Candidate 1: -0.014; …; **Candidate 23: -0.039**; …; Candidate 32: -0.023
	Line 4 of existing network is altered to candidate line 32 of iteration 1
2	Target line selection by $TDOCO$ (a)
	Line 1: Cannot be altered; **Line 2: 0.033**; Line 3: 0.053; Line 4: 0.039
	Target node selection by $DOCO_i$ (b)
	1: 1.577; 2: 2.365; 3: 2.191; 4: 2.516; **5: 4.863**; 6: 2.116; 7: 3.969; 8: 2.293; 9: 2.367; 10: 2.068; 11: 2.229; 12: 2.996; 13: 2.270; 14: 2.553; 15: 2.507
	Candidate line generation (c)~(f) – 13 candidate lines via node 105
	Alternative line determination by $TDOCO$ (g)
	Candidate 1: -0.018; …; **Candidate 6: -0.033**; …; Candidate 13: -0.013
	Line 2 of existing network is altered to candidate line 6 of iteration 2
3	Target line selection by $TDOCO$ (a)
	Line 1: Cannot be altered; **Line 2: 0.032**; Line 3: 0.054; Line 4: 0.039
	Target line of iteration 3 is same as new line of iteration 2 (n=n+1)
	Target node selection by $DOCO_i$ (b)
	1: 1.480; 2: 2.110; 3: 1.942; 4: 2.207; 5: 2.286; 6: 1.830; 7: 2.406; 8: 2.014; 9: 2.211; 10: 1.873; 11: 2.027; **12: 2.818**; 13: 2.086; 14: 2.374; 15: 2.204
	Candidate line generation (c)~(f) – 22 candidate lines via node 112
	Alternative line determination by $TDOCO$ (g)
	Candidate 1: -0.022; …; Candidate 18: -0.032; …; Candidate 22: -0.023
	Candidate line 18 is 5th line of existing network
4~34	The end of the line configuration by 34th iteration

Table 5.4 Target node, $TDOCO$ and Max($DOCO_i$) by iterations

iteration	No. of lines	Target node	TDOCO	Max($DOCO_i$)
1	4	111	2.337	4.222
2	4	105	2.049	4.863
3	4	112	2.086	2.818
4	5	107	2.021	2.411
5	6	112	1.954	2.812
6	6	112	1.913	2.369
7	6	112	1.918	2.235
8	7	105	1.875	2.179
9	8	112	1.849	2.103
10	9	112	1.842	2.098
11	10	112	1.840	2.089
12	11	109	1.839	2.088
13	12	112	1.824	2.091
14	12	105	1.824	2.091
15	13	112	1.821	2.098
16	13	109	1.819	2.089
17	14	112	1.814	2.089
18	14	105	1.814	2.088
19	15	112	1.809	2.088
20	15	105	1.810	2.087
21	16	112	1.807	2.090
22	16	104	1.807	2.089
23	17	112	1.803	2.086
24	17	107	1.803	2.084
25	18	112	1.799	2.086
26	18	107	1.799	2.084
27	19	113	1.798	2.084
28	20	102	1.794	2.084
29	21	108	1.791	2.082
30	22	102	1.790	2.082
31	23	102	1.786	2.082
32	24	108	1.785	2.082
33	25	111	1.783	2.081
34	26	-	1.782	2.080

Remark: All the lines are operated with 10 min. headway

26 line candidates by 34 iterations are shown at Table 5.5 and illustrated in Figure 5.2.

Table 5.5 Line candidates of this model

Line	Length (km)	Mode	Route
1	33	Subway	1-2-3-6-8-10-13
2	13	Bus	5-4-6-15-7
3	27	Bus	12-4-6-15-9
4	15	Bus	12-4-2-3
5	23	Bus	12-11-10-14
6	11	Bus	8-15-7-10
7	17	Bus	12-11-13-14
8	28	Bus	5-4-6-8-10-14-13
9	22	Bus	7-10-11-12
10	27	Bus	11-12-4-6-3
11	23	Bus	8-10-11-12
12	16	Bus	2-3-6-15-9
13	14	Bus	1-2-5
14	29	Bus	9-15-6-8-10-14
15	29	Bus	2-5-4-6-8-10-11
16	21	Bus	1-2-3-6-4-5
17	20	Bus	1-2-4-6-15-7
18	17	Bus	7-10-14-13
19	17	Bus	7-10-13
20	23	Bus	4-2-3-6-8-10-11
21	13	Bus	4-2-3-6-15-7
22	11	Bus	2-3-6-8-15-7
23	29	Bus	2-3-6-8-10-14
24	14	Bus	5-2-3-6-15
25	20	Bus	5-4-6-8-15-9
26	12	Bus	10-11-13-14

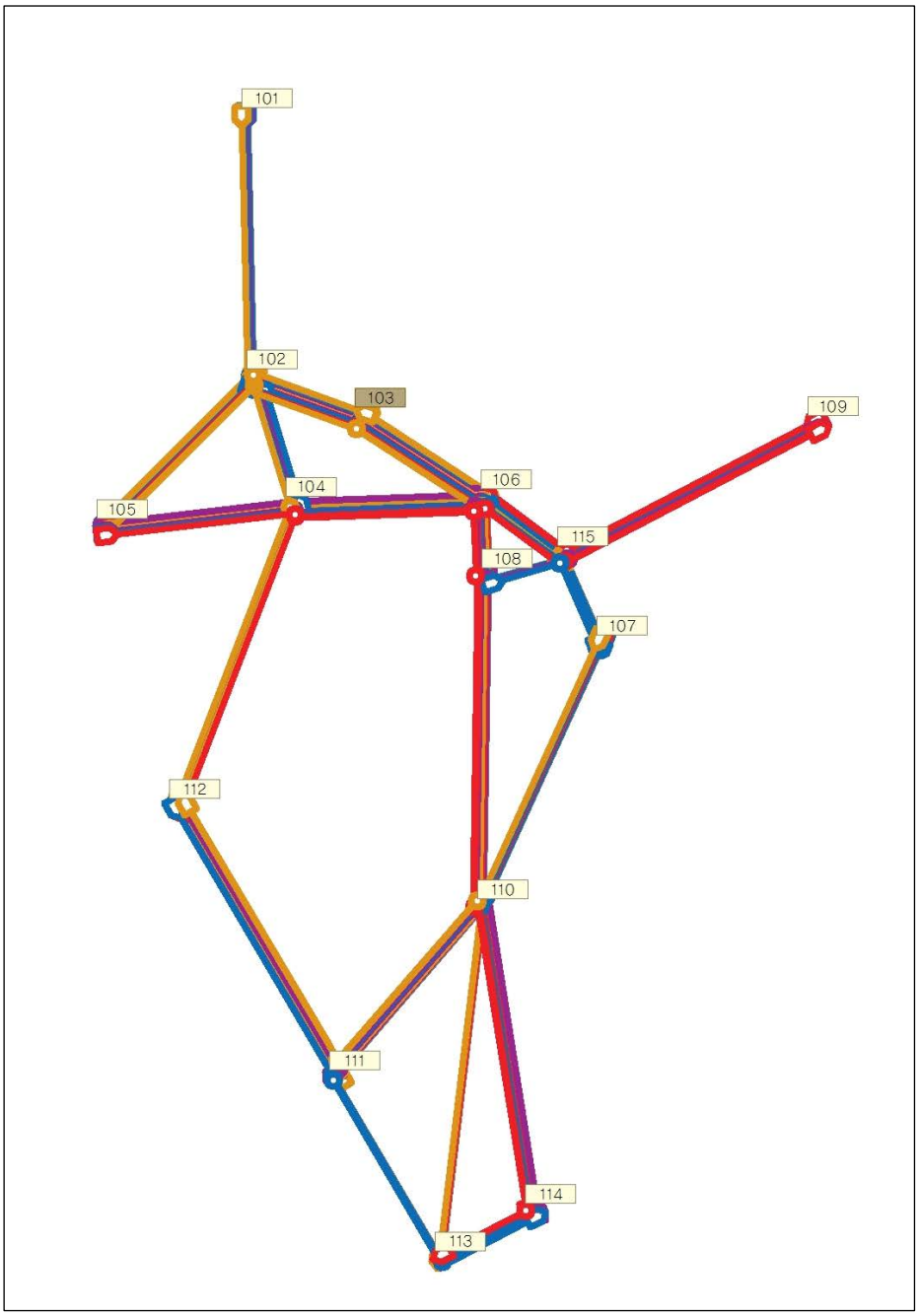


Figure 5.2 Illustration of candidate lines

5.2.3 Frequency setting

Line candidates which are determined in the former procedures are selected by horizontal equity criteria. Therefore, many lines are generated in the suburb area, and if all the lines are operated, it is not an efficient situation in travel demand and behavior. However, in this line configuration, there are many lines that have direct connection between suburb area and central area. This procedure consists of frequency setting with line configuration of former procedures. This procedure is based on the total cost of user and operator, and decision variable is frequency of each line candidate. Line candidate determination procedure is to maximize the equity, and this frequency setting procedure is to minimize the cost and maximize the efficiency.

In this frequency setting procedure, genetic algorithm (GA) is applied to find an optimal solution. Range of each gene (fleet number per hour per line) varies from 1 to maximum possible fleet number in the first line that cannot be changed, and 1 to two times maximum number in 25 altered lines. This means that operation probability of each line is 50%. If value of gene exceeds maximum fleet number, that line would not be operated. Here, fleet numbers per hour such as 11, 23 are excluded to calculate faster and effectively, and enhance the efficiency of actual operation. To reflect this, from 1 to 22 random integer variables are inputted to each line and converted to fleet number and frequency.

Table 5.6 Input variable candidates of frequency and fleet number

Random variable	fleet number (veh/hr)	frequency (min)
1	2	30
2	3	20
3	4	15
4	5	12
5	6	10
6	8	7.5
7	10	6
8	12	5
9	15	4
10	20	3
11	30	2
12~22	0	0

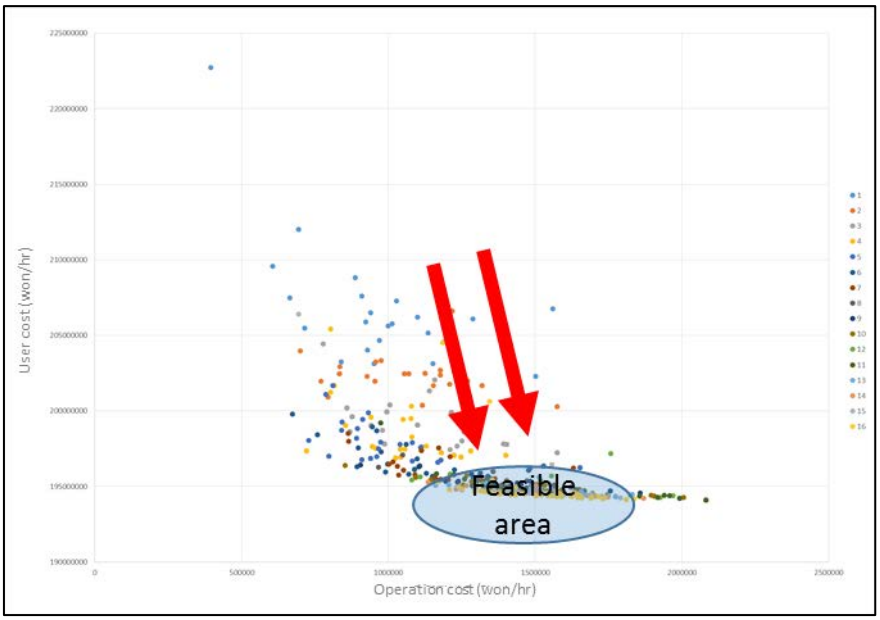
Additional constraint is added in this application that every node has at least one line passing through. Table 5.7 shows the fleet number (60 / frequency) of each line of the first population. As shown in the table, input variables of line 1 do not have the number 0, but other lines have the number 0. Number 0 means that those lines having number 0 is not operated. The probability that number of each gene is 0 is 50%.

Table 5.7 Input variable of first iteration of genetic algorithm

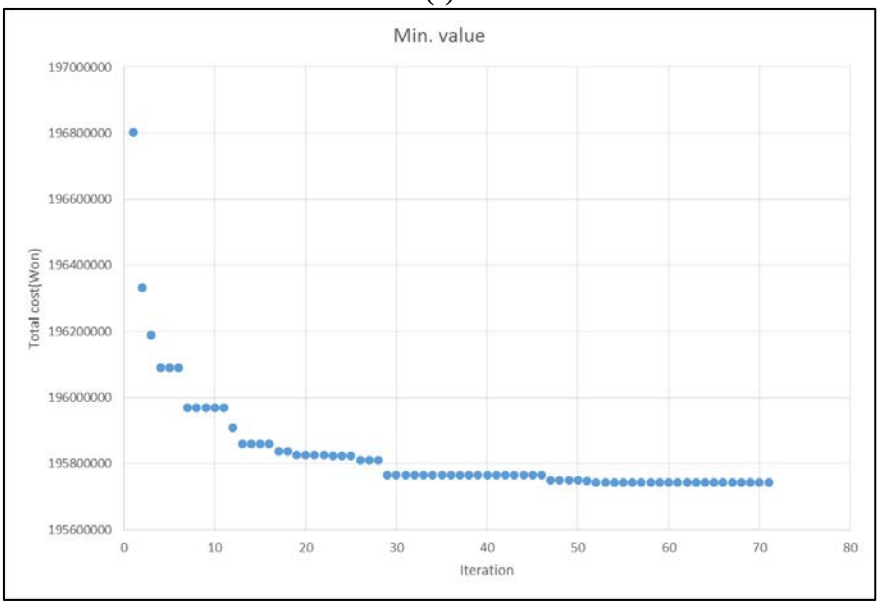
Population	Line 1 (1~11)	Line 2 (1~22)	Line 3 (1~22)	Line 4 (1~22)	…	Line 25 (1~22)	Line 26 (1~22)
1	3	30	5	12	...	6	0
2	6	0	0	0	...	10	3
3	12	0	10	12	...	3	20
4	6	6	0	20	...	0	6
5	10	4	4	6	...	5	0
6	30	15	0	5	...	0	30
7	6	6	10	4	...	12	6
8	3	0	30	6	...	0	0
9	10	30	0	6	...	0	12
10	6	10	0	0	...	0	12
11	6	0	0	0	...	0	0
12	15	3	0	20	...	20	0
...	...	...	...	...	...	...	...

Remark: If value of gene is 11 to 22, no operation (input 0)

In this sample network, 100 populations are generated. Crossover and mutation probability of each gene are 50% and 10% respectively. Figure 5.3 (a) shows the direction of optimal solution. As it can be seen in this figure, feasible area moves to lower right direction. This means that optimal solution is the situation that user cost reduction is no longer greater than operation cost increase, similar to the law of diminishing returns. Similarly, in the optimal situation, B/C ratio of additional transit operation may not exceed 1. Figure 5.3 (b) shows the convergence of the objective function (total cost). Stepwise convergence is occurred with iteration. Table 5.8 shows the final line configuration and frequency of each line. 11 lines are not operated because of low efficiency.



(a)



(b)

Figure 5.3 (a) Finding direction of genetic algorithm

(b) Convergence of objective function

Table 5.8 Final line configuration and frequency of each line

Line No.	Length (km)	Mode	Via node	Frequency (headway)
1	33	Subway	1-2-3-6-8-10-13	20(3)
2	13	Bus	5-4-6-15-7	20(3)
3	27	Bus	12-4-6-15-9	-
4	15	Bus	12-4-2-3	12(5)
5	23	Bus	12-11-10-14	5(12)
6	11	Bus	8-15-7-10	15(4)
7	17	Bus	12-11-13-14	-
8	28	Bus	5-4-6-8-10-14-13	-
9	22	Bus	7-10-11-12	5(12)
10	27	Bus	11-12-4-6-3	2(30)
11	23	Bus	8-10-11-12	5(12)
12	16	Bus	2-3-6-15-9	20(3)
13	14	Bus	1-2-5	12(5)
14	29	Bus	9-15-6-8-10-14	15(4)
15	29	Bus	2-5-4-6-8-10-11	6(10)
16	21	Bus	1-2-3-6-4-5	-
17	20	Bus	1-2-4-6-15-7	-
18	17	Bus	7-10-14-13	15(4)
19	17	Bus	7-10-13	12(5)
20	23	Bus	4-2-3-6-8-10-11	-
21	13	Bus	4-2-3-6-15-7	-
22	11	Bus	2-3-6-8-15-7	-
23	29	Bus	2-3-6-8-10-14	-
24	14	Bus	5-2-3-6-15	12(5)
25	20	Bus	5-4-6-8-15-9	-
26	12	Bus	10-11-13-14	-

User cost: 203.02 million won/hr, Operation cost: 1.80 million won/hr
Modal split: Auto 72.3%, Transit 27.7%

Remark: Frequency of each line is adjusted by loading factor

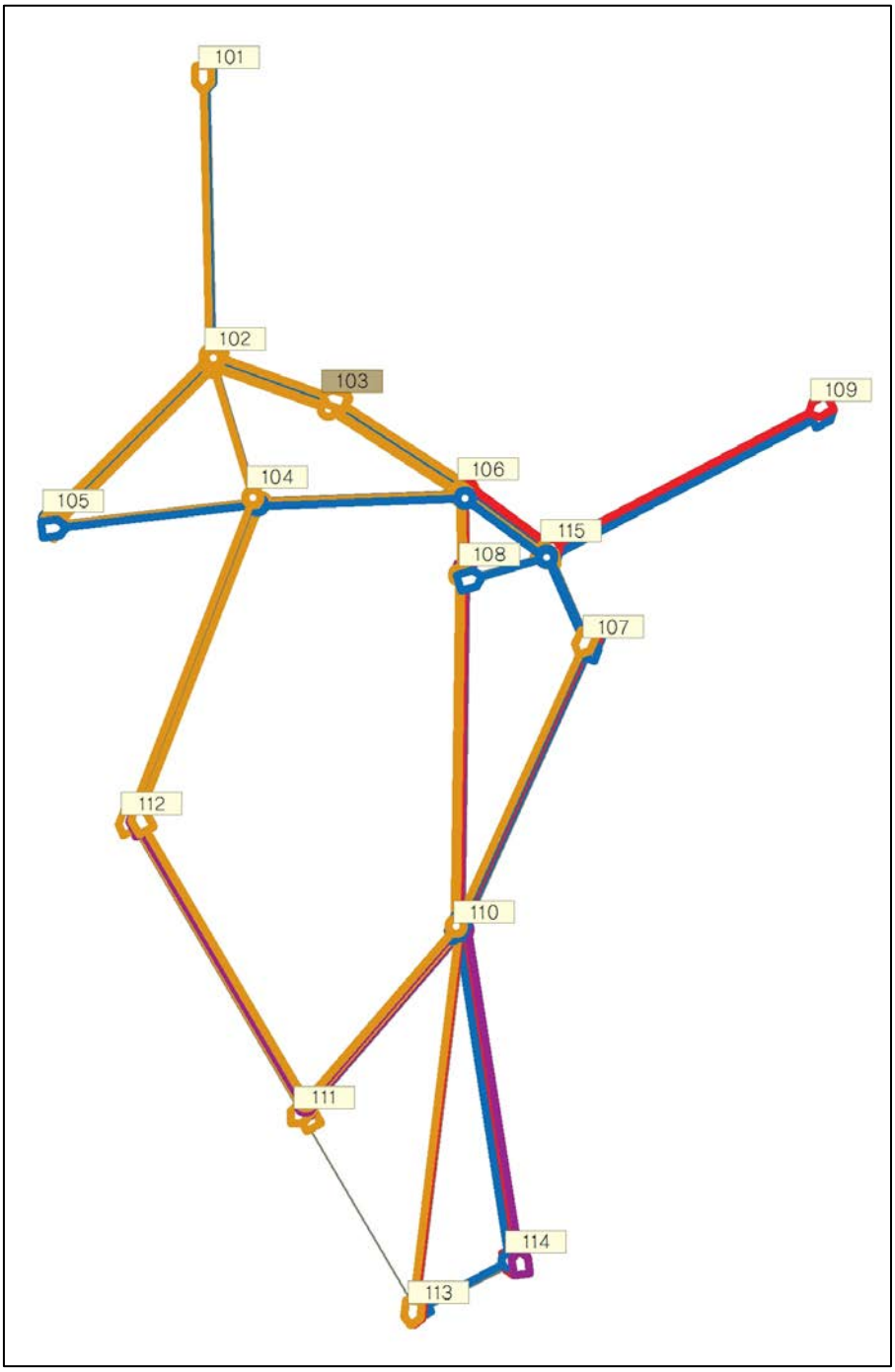


Figure 5.4 Illustration of final line configuration

5.3 Discussion

5.3.1 Transit route network improvement

In this study, line candidates are generated by iterative procedure of target line selection, target node selection and alternative line determination. There are many candidate lines passing through the regions where spatial equity is worse than other regions in the line candidates by the route network design procedure to improve the equity of corresponding regions. This situation occurs the inefficiency of operation because this route network design procedure consider only the equity criteria. Therefore, in the frequency setting procedure, total cost – user cost plus operator cost – is minimized by genetic algorithm. This final transit route network is equity considered network and cost effective network simultaneously.

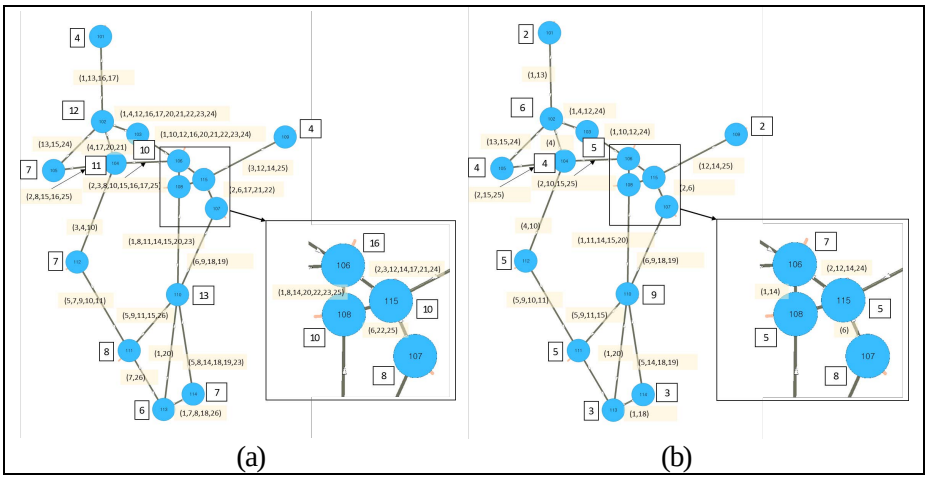


Figure 5.5 Number of lines passing through each node, (a) before frequency setting, (b) after frequency setting

Table 5.9 Number of lines passing through each node

Node	Number of lines	
	Before frequency setting	After frequency setting
1	4	2
2	12	6
3	10	5
4	11	4
5	7	4
6	16	7
7	8	5
8	10	5
9	4	2
10	13	9
11	8	5
12	7	5
13	6	3
14	7	3
15	10	5

Figure 5.5 and Table 5.9 show the number of lines passing through each node of before and after the frequency setting procedure. Transit route network of before frequency setting consider the modal and spatial equities with horizontal criteria, and that of after frequency setting additionally consider the total cost of user and operator. Many lines are passing through the node 6 and 10 after going through frequency setting procedure. This is because there are much demand in those nodes.

After route network design and frequency setting, improved network is better than existing network. Table 5.10 shows the comparison result between the

existing network and improved network. As mentioned earlier, more user cost decrease occurs compared to the increase of operation cost in the improved network. In this example, there are not many lines as compared with demand in existing network Therefore, much cost saving is realized with transit route network improvement. Also, modal split of transit increases with network improvement. Mode share of transit increased 19.7% to 27.7% in this sample network.

Table 5.10 Comparison of cost and modal split

Network	No. of lines	Total cost (million won/hr)	User cost (million won/hr)	Operation cost (million won/hr)	Modal split (Car / transit)
Existing	4	225.56	225.11	0.45	80.3% / 19.7%
Improved	16	204.82	203.02	1.80	72.3% / 27.7%

Table 5.11 shows the comparison of equity index between the existing network and improved network. Similar to the cost and modal split result, modal equity of whole network ($TDOCO$) and spatial equity ($Max.(DOCO_i)$) are improved with network improvement.

Table 5.11 Comparison of equity index

Network	$TDOCO$	$Max.(DOCO_i)$
Existing	2.306	4.221
Improved	1.797	2.075

5.3.2 Extension of this model

Transit route network in this study considers the modal and spatial equities by modified DOCO, and total cost is minimized with frequency setting procedure. This study proposed the equity assessment criteria considering the mobility and accessibility simultaneously, also reflect the variable demand with bi-level modelling.

This model can be easily modified in response to changes in the practical problems. For example, population and trip distribution, budgetary constraints and development of new areas and road network are the practical issue in reality. This route network design model divided into 3 procedures except the frequency setting. So each procedure of this model can move and can be skipped with practical constraints. If one network does not need to change the existing transit routes, first procedure of the route network design can be skipped. Also, constraints and assumptions can be relaxed with practical situation. For example, target nodes, target lines, circuity and redundancy rate can be changed.

In the transit route network design model, the result is transit route network considering modal and spatial equities by modified DOCO. Modal equity is considered by additional travel time of transit compared to auto travel time. TDOCO which is aggregated to whole network is applied to assess the modal equity of given network. Spatial equity is considered by $DOCO_i$ of each region. $DOCO_i$ indicates modal equity of each zone, and spatial equity is satisfied by

lower maximum value of modal equity of regions.

These equities in this study are based on the horizontal equity criteria which satisfies a basic level of transit service. The transit route combination in this study is also determined by this horizontal spatial and modal equities criteria. Here, we can consider the vertical equity criteria in the transit route network design procedures. For example, Distribution of population or that of vulnerable user such as elderly people or disabled persons can be considered. Here, Weighted Total DOCO ($TDOCO_w$) can be considered. This vertical equity index is TDOCO which is weighted to the each demand between the origin and destination. Meanwhile, in this study, $\mathrm{TDOCO_w}$ has a value of 89% of the TDOCO. The lower this ratio, the more degree of concentration on some particular origin and destination. These vertical equity indexes can be applied to the transit assessment and route network model in order to reflect demographic and socioeconomic characteristics.

Chapter 6. Conclusion

6.1 Summary and conclusion

Due to the polarization of incomes, low birth rate and aging population in modern society, there is a significant emphasis on social equity in accordance with the deepening of imbalances and conflicts. Public transportation also has the temporal and spatial imbalance and it is deepening with providing a faster and more direct service among high demand regions. Therefore, there is a need for an adjustment process. A recently developed new towns in suburban areas can be called as representative areas being affected by the operation strategy of public transportation with the purpose of minimizing costs.

In this study, the public transport network assessment methodology considering modal and spatial equities is proposed. Here, equities are considered by TDOCO and $DOCO_i$ which can reflect mobility and accessibility simultaneously. Also, heuristic transit route network determination process with sequential procedures which consist of target line selection, target node selection, and alternative line determination is proposed, and frequency setting procedure is implemented.

The model is configured through the bi-level modeling based on an iterative process in order to calculate the modal split and traffic / transit assignment with transit route network changes. Based on the transit route network taking account of the level of modal and spatial equities, in the upper model, frequency

of each line is determined by genetic algorithm. On the other hand, in the lower model, modal split and traffic and transit assignment are implemented. In the traffic assignment, road public transport such as buses is assigned with reflection of the congestion of the road, and it derives a more realistic result. In the transit route network decision process, route deletion of the adverse effect on the equity, region selection via alternative route with equity criteria, and generation and determination of alternative route procedure are sequentially implemented. This transit route network design model and algorithms are applied on a sample Mandl's network. As a result, improved solution with equity and total cost was found compared to existing transit route network.

There are some expected contributions in this study. First, “equity” indexes are proposed to assess the mobility and accessibility by modified DOCOs. Second, iterative transit route network determination methodology to maximize equity is proposed. Last, genetic algorithm to determine the frequency of each line is improved with practical frequency constraint, modal split and assignment with variable demand are reflected.

Transit route network design model considering the modal and spatial equities from this research proposed a heuristic algorithm to solve a problem which is commonly hard to apply the mathematical model. There is a great significance for the actual network. It is possible to evaluate the equity of the actual network and propose the operation improvement strategies.

6.2 Further research

First of all, in the course of the assessment and alteration, study of the standardization and indexation process of various indicators can be achieved. For example, high DOCO occurs with lower level of transit service and occurs by a lot of congestion of roads as well. Therefore, it is necessary to standardize the process of indexes of other criteria such as connecting power, transit catchment, and etc.

In the transit route network determination process, modified algorithms can be applied. More lines and nodes can be targets simultaneously, stochastic determination procedures of lines and nodes can be applied, and redundancy and circuity rates can be changed. For example, if one city want to create a new feeder bus routes with trunk subway line, by the very strong restraints of redundancy, circuity and line length, it can bring the results of short routes each region to nearby subway stations. Also, crossovers between two lines can bring about new line routes and additional solutions.

Objective function can be modified according to the purpose of studies or policies. Objective function of this study is to minimize total cost, but maximizing the equity can also be an objective function. Equity can be applied by horizontal criteria, vertical criteria or by both of them. Furthermore, multi-objective function of equity and efficiency (cost) can be applied with Pareto frontier.

In addition, it would be meaningful if transit route network model of this

study is applied to a large network, such as Seoul and Busan. Previous studies have provided solutions for the actual network, but unrealistic solutions exist like completely overturning the entire transit route network. In actual network, by targeting several routes that are required an improvement of equity, it is possible to reflect the methodology of this study and improve the entire transit network with equity considerations. Furthermore, maximum budget and fleets which are the practical constraints may be added to the actual situations.

Aggregation degree of zone or area in the actual network is also very good research topic. In the actual network, there are many nodes or stops in one zone or area. To apply a transit route network design methodology from this study, aggregation degree is critical in the accuracy of the solution and reflecting the actual behaviors of traveler in addition to and complexity of algorithm.

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초 록

형평성을 고려한 대중교통 노선망 설계

서울대학교 대학원
공과대학 건설환경공학부
김 명 현

소득양극화와 저출산, 고령화 등으로 인해 사회적 불균형 및 갈등이 더욱 심화됨에 따라 형평성에 대한 중요성도 매우 커지고 있다. 대중교통도 수요가 많은 지역에 더욱 빠르고 직결성이 높은 서비스를 제공함에 따라 시공간적 불균형이 심화되고 있으며, 이에 대한 조정 과정이 필요하다. 교외지역의 최근 개발된 신도시들은 비용 최소화를 목적으로 하는 대중교통 운영 전략에 의해 상대적으로 피해를 받고 있는 대표적인 지역이라고 할 수 있다.

본 연구에서는 수단 및 지역 간 형평성을 고려한 대중교통 노선망 평가방법론을 제시하였으며, 이 때 접근성 및 이동성 동시 반영이 가능한 TDOCO 및 $DOCO_i$를 이용하였다. 또한 개선 대상 노선 및 대중교통 취약지역 선정, 해당 지역 경유 노선 후보군 도출 및 노선별 배차횟수 결정 휴리스틱 알고리즘을 제시하였다.

모델 구성에서는 Bi-level 모델링을 통해 대중교통망 설계과정 및 대중교통망 변경에 따른 수단분담 및 승용차/대중교통 통행배정이 반복적으로 계산될 수 있도록 하였다. 대중교통 서비스수준의 수단

및 지역 간 형평성을 고려한 대중교통망 노선망을 기준으로, 상위모델에서는 배차횟수를 결정하였으며, 하위모델에서는 서비스수준 변화에 따른 승용차-대중교통 간 수단 전환 및 수단별 통행배정이 이루어지도록 하였다. 통행배정 시에는 버스와 같은 공로 대중교통수단은 도로 혼잡을 반영하여 더욱 현실성 있는 결과가 도출되도록 하였다.

본 연구에서 구성한 노선망 모델 및 알고리즘을 Mandl's network에 적용하여 예제네트워크 분석을 수행하였으며, 결과적으로 기존의 노선 운행에 비해 형평성 및 비용 측면에서 개선된 해를 찾을 수 있었다. 본 연구의 수단 및 지역 간 형평성을 고려한 대중교통망 설계 모형은 수학적 모델 적용이 어려운 노선망 디자인 문제 풀이의 휴리스틱 알고리즘을 제시하여 실제 대중교통이 운영되고 있는 여러 도시에 대해 데이터 구성을 토대로 대중교통 운영 현황의 형평성 평가 및 개선방향 제시가 가능하다는 점에서 큰 의의가 있다.

주요어: 노선망설계, 배차간격, 유전자알고리즘, 형평성, 바이레벨모델링, 대중교통평가

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