COMMUTER DEMAND CONCENTRATION MODEL BASED ON A TIME-SPACE NETWORK SCHEME

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Abstract: To improve the serious congestion in Tokyo's railway network, expansion projects are on the way but it seems that the supply side approach holds just a part of the solution and that demand management schemes such as flexible working time systems are needed as a supplement. Thus a methodology to forecast railway commuter demand on a large-scale network under flexible working time systems is required to quantify the impacts of policies and planned projects. This paper presents a traffic assignment model that is sensitive to expansion projects and flexible working time systems. Moreover, a methodology to simplify the Tokyo railway network to a manageable level is introduced. Calibration and validation of the model indicates that it can estimate traffic demand over time with reasonable accuracy. The model is then applied to the Tokyo rail network to forecast future congestion rates.

1. INTRODUCTION

Rapid concentration of population in Tokyo in the last decades has taken its toll on its urban transportation system, particularly its railway network, which services most of its commuter trips. Despite capacity expansion projects on existing lines and the addition of new lines, the congestion rates[1] at the Tokyo railway network still reach levels greater than 200% at peak hours and at present ranks as one of the worst in the world (Fig. 1). In 1992, the Japanese Ministry of Transportation set goals to reduce average congestion rates at peak hour to 180% by 2002 and a long-term goal to reduce congestion rates to 150% to improve level of service at Japan's rail network. However, the recent trend of marginal and even negative growth in railway demand has made it difficult for planners to foster interest in railway companies to invest in more expansion projects. Thus, a hybrid strategy of capacity expansion and demand management, like flexible working time system, may hold the key to Tokyo's railway network congestion problems. In this context, a railway traffic assignment model that is sensitive to the effects of future expansion projects and demand dispersion measures like flexible working time system is required to estimate the impacts of future railway plans and policies.

In 1985, the Transportation Economics Research Center developed TRAM (Tokyo Metropolitan Railway Masterplan) to forecast the Tokyo railway traffic demand by the year 2000 using a four-stage demand model. Umezaki (1996) also developed a simulation model to forecast the effects of planned capacity expansion projects to peak railway demand at the Tokyo rail network using the static user equilibrium assignment method. However, the TRAM model and the Umezaki model do not consider commuter's departure time selection behavior thus could not model the effects of

[1] Congestion rate of 100% is defined as 3 standing person/1m^2

flexible working time policies. Takemura (1997) developed a model to determine commuters workplace arrival time base on socioeconomic factors and office working time system. However, the model requires congestion rates as input rather as output. Furthermore, its disaggregate nature would impose .extensive computational requirements when applied to a large city such as Tokyo. Horiguchi (1997) attempted to solve simultaneously the departure time choice and route choice problem by combining the works of Takemura and Umezaki and applying the UE assignment method on a time-space network. Application of the Horiguchi model to the Tokyo rail network was unsuccessful due to overwhelming computational requirements. Iida (1991) has also solved the combined departure time and route selection problem on an imaginary road network but with no consideration to demand dispersion measures. Moreover, since road travel and rail travel are affected by congestion differently, the model could not be readily applied to rail networks.

This study intends to introduce a traffic assignment model that considers railway commuter's choice of departure time, called the Commuter Demand Concentration Model (CDCM). Moreover, a methodology to minimize computational requirement problems associated to CDCM's application to a large scale network such as the Tokyo rail network is illustrated.

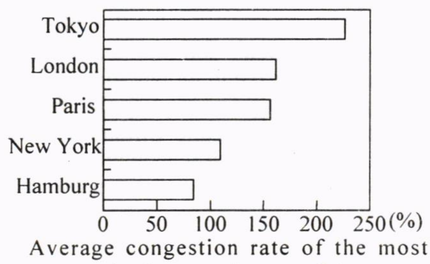


Figure 1. International Comparison of Subway Congestion Rate

1.1 Paper Outline

Chapter 2 of this paper introduces the CDCM and its components. Chapter 3 illustrates the application of the CDCM to the Tokyo rail network. And chapter 4 presents a summary and discussions on the results of the paper.

2. MODEL FORMULATION

2.1 Model Structure

The CDCM is composed of two sub-models; namely, the Workplace Arrival Time Sub-Model (WATS) and the Time-Space Network Sub-Model (TSNS). The structure of the DDCM is illustrated in Fig. 2.

2.2 Workplace Arrival Time Sub-Model (WATS)

The WATS is a set of six utility functions used to quantify the link costs in the TSNS. Descriptions of the utility functions are shown in Table 1. The WATS defines the preferences and behavior of commuters in departure time and route selection. Calibration of the WATS is achieved by assuming that commuters maximize the sum of the six utility items by controlling their workplace arrival time, t. Here, commuters are classified into two types: namely; commuters under the flexible working time system (FT commuter) and commuters under the fixed working time system (N-FT commuters).

Basically, the WATS is referred from the work of Takemura (1997). The utility function forms used and its corresponding parameters are retained except for U_G, the utility function for getting up early. In the work of Takemura, it was assumed that all commuters wake up at the same time. This assumption is unrealistic; thus, it was replaced by a more realistic assumption that commuters wake up one hour before departure time. It is worth noting that estimated results notably improved when the revised U_G form is used.

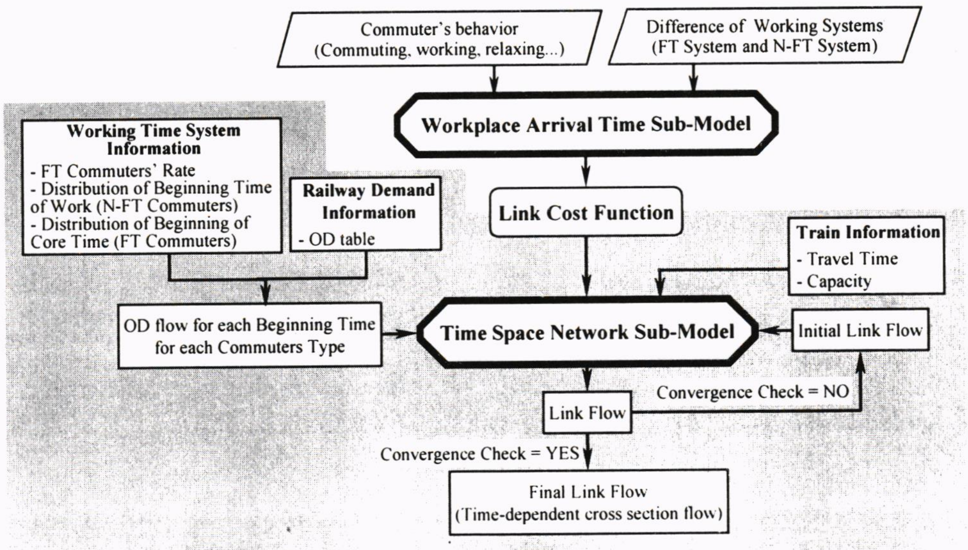


Figure 2. Structure of Commuter Demand Concentration Model

Table 1. Utility function of WATC sub-model

Utility Item(min.)	Flex Time Commuters	Non-Flex Time Commuters
U_G	$a\{\exp\{-\exp[-b(t_1-c)]\}-1\}$	
U_T	$\sum_{l=1}^{L}\left\{-t^R_{l,k} - 0.01 \times t^R_{l,k} \times \left[\exp\left(1.97 \times c_{l,k}\right)-1\right]\right\}$	
U_D	$-7.50 \times \ln(t_1+1)$	$-3.84 \times \ln(t_1+1)$
U_E		$-0.01 \times t_2$
U_B	$-3.92 \times t_3$	
U_L	$19.75 \times \ln(t_4+1)$	$21.48 \times \ln(t_4+1)$

where,

U_G: Disutility of getting up early--Calibration of parameters a, b, c are discussed in section 3.

U_T: Disutility or cost of travel -- It includes travel time cost and by congestion cost. (cf. Shida, 1989)

U_D: Disutility of arriving later than the designated work place starting time

U_B: Disutility of arriving later than the workplace average arrival time -- Usually Japanese employees come to work earlier than the designated starting time.

U_E: Disutility of arriving before the designated starting time (for N-FT commuters only)

U_L: Utility of leisure time

L: Number of links composing the commuting route
$t^R_{l,k}$ (min.): Travel time on link l, constant at each time period k^{th} (for example each time period is 10 minutes)
$c_{l,k}$(%): congestion rate of commuter train on link l, at time period k^{th}.
Below are the definitions of variables and constants (capital letters are used for constants, and small letter are used for variables).

Constants:

Different for FT and N-FT commuters:

T_S: Starting time for work (min.)
$\overline{T}_{SL}$: Average sleeping time (min.)
$\overline{T}_w$: Average working time (min.)
$\overline{T}_{AVG}$: Average workplace arrival time (min.)

Same for FT and N-FT commuters:

$\overline{T}_{ACC}$: Average access time, calculated as the average time for commuters to reach the nearest station and is determined for each station (min.)
$\overline{T}_{EGRESS}$: Average egress time, calculated as the average time for commuters to reach their offices and is determined for each station (min.)

Constants $\overline{T}_{AVG}$, $\overline{T}_{SL}$, and $\overline{T}_w$ are taken from the results of "The Questionnaire Survey on Commuter Behavior"(Takemura, 1997). T_S is taken from "Survey on Recent Labor Using"(1993). $\overline{T}_{ACC}$ and $\overline{T}_{EGRESS}$ are calculated using the 1995' Large City Transportation Census.

Variables:

t_U: wake up time (min.)
t_D: workplace departure time (min.)
t: workplace arrival time (min.)
t_N: time used in transport (min.)

$t = t_D + \overline{T}_{ACC} + t_N + \overline{T}_{EGRESS}$: arrive time (min.)
$t_U = t_D - 60$: assuming commuters wake up one hour before departure (min.)
$t_1 = t - T_S$: late time (min.)
$t_2 = T_S - t$: wasted time by arriving too early at the workplace (for N-FT commuter only) (min.)
$t_3 = t - \overline{T}_{AVG}$: arrival time deviation from the workplace average arrival time (min.)
$t_4 = \overline{T}_{SL} - (t + \overline{T}_w + t_N)$: leisure time (min.)

2.3 Time Space Network Sub-Model (TSNS)

The utility items from the WATS are then used in the TSNS to calculate link costs as summarized in Table 2. Base on the link costs, the TSNS solves for traffic flow at each station by assigning Origin and Destination (OD) flows on a Time-Space Network.

Table 2. Definition of Link Cost Function

Link Type	Starting Node	Finishing Node	Meaning of Link	Link Cost
Access Link	Origin Node	Train Stop Node	Express accession from house to station	$C1 = U_G$
Line-haul Link	Train Stop Node	Train Stop Node	Express travel process	$C2 = U_T$
Egress Link	Train Stop Node	Destination Node	Express egression from station to workplace	$C3 = U_D+U_E+U_B-U_L$

2.3.1 Time-Space Network Structure

To be able to account for commuter's departure-time selection, the traffic assignment is performed on a Time-Space Network. A Time-Space Network (Fig. 3) is a representation of the spatial and temporal dimension of a traffic assignment problem dealing with commuter departure time choice. The horizontal axis of the network represents the railway network and the vertical axis represents time. The starting point of commuters (i.e. houses) for a particular station is defined as the origin node (O node). The end points of commuter trips (i.e. workplace) are termed as destination nodes (D Node). Here, a representative origin point and destination point is approximated for each station. Both origin and destination points are independent of time. Intermediate nodes are defined as train stop nodes, which is set every time the train stops to disembark and embark at each station.

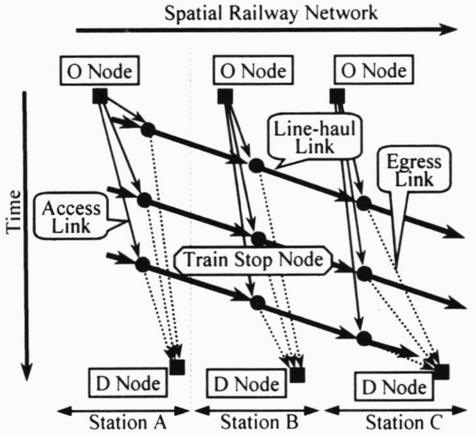


Figure 3. Structure of the Time-Space Network

2.3.2 Traffic Assignment Method

Since the path-related variable t_N is included in the cost function, the user equilibrium (UE) assignment rule and the Frank-Wolfe algorithm could not be applied to solve the assignment problem. Thus, the CDCM performs traffic assignment using the stochastic equilibrium assignment method. The CDCM's assignment procedure is as follows:

Step 1:Assuming that commuters with origin (O), i, and destination (D), j, select departure time following a logit model, calculate flow at a particular route at time k using Eq. 2.1 and by assuming, initial link flows = 0.

$$FLOW(k,ij) = \frac{\exp(\alpha U_{k,ij})}{\sum_{k=1}^{K} \exp(\alpha U_{k,ij})} \times ODFLOW(ij) \quad \text{......................} (2.1)$$

where,

$FLOW(k,ij)$: flow of route with k time choice between OD pair i-j.

$ODFLOW(ij)$: flow between OD pair i-j.
$U_{k,ij}$: utility of route under k time choice between OD pair i-j.
α : dispersion parameter (c.f. 3.3).
K: number of selectable time choice

Step 2 Calculate the average difference of boarding volume E, between iteration n and the iteration n-1, using Eq. 2.2. If E is greater than the set tolerance, ε =1.0%, then the whole process is repeated with the calculated $FLOW(k,ij)$ as the assumed link flow for the next iteration. Once the average error tolerance is satisfied the calculation is stopped and the final $FLOW(k,ij)$ is accepted.

$$E = \sum_{i=1}^{N} \frac{\sqrt{\sum_{k=1}^{K}(q^{n}{}_{ik} - q_{ik}^{n-1})^2}}{\sum_{k=1}^{K} q^{n-1}{}_{ik}} \quad \text{.......................................} (2.2)$$

q_{ik}^{n} : boarding volume at station i, time k calculated at iteration n.

$q^{n-1}{}_{ik}$: boarding volume at station i, time k calculated at iteration n-1.

K: number of selectable time choice at each station.

N: number of station.

3. APPLICATION TO THE TOKYO RAIL NETWORK

This section presents the methodology and results in application of the model to the complex rail network of Tokyo to forecast its performance considering future projects and policies.

3.1 Simplification of the Railway Network

The Tokyo metropolitan rail network is extensive and complicated. It is a railway network web of about 3400 km of tracks carrying over five millions passenger from more than 1700 stations through more than 80 lines every morning. To directly apply the CDCM to the Tokyo rail network would result in computational requirements beyond practicality. Thus, to minimize computational requirements, the Tokyo railway network was simplified. Also, input data was modified to conform with the application of the CDCM to the simplified Tokyo railway network.

The Tokyo railway network consists of radial lines and a main loop line called the Yamanote line. The Yamanote line bounds most of the central area, where most offices are concentrated and a suburban area, where most residences are located. The simplification begins with the division of the network to a central part, nearly equal to the area inside Yamanote line, and a suburban part, which is the area outside the Yamanote line. Stations at the border of the central part and the suburban part are called terminal stations. Then, the suburban lines are divided into several sections of lengths equivalent to the distance traveled by the fastest train of that section in ten minutes (approximately 10km). Stations at each of section are then combined and represented by one station. All suburban lines are then combined to form one representative line. In the central area, four representative stations ten minutes apart are set up. The resulting network is illustrated in Fig. 4.

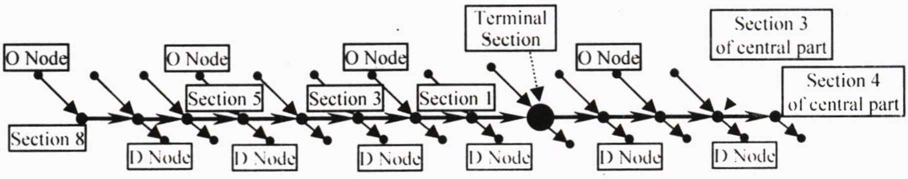


Figure 4. Simplification of Tokyo Railway Network

It is clear that the simplification of the network by combining lines would result in a flattened aggregate demand distribution if demand peaks at different time periods at each line. However, base data from the 1995 Large City Transportation Census indicates that railway demand at all lines in Tokyo characteristically peaks at the same time period with approximately the same distribution shape that aggregation would not result in any significant misestimation.

3.2 Simulation Data

1) Simulation time is set at six hours of starting from 6.a.m with 10 minutes periods.
2) Travel time between two adjacent representative stations was set to 10 minutes.
3) Railway capacity for every period for each representative is determined from train timetables.
4) Working Time System: the percentage of FT commuter was calculated to be 11.4% of total commuters. The distribution of starting time for work for N-FT commuters and the distribution of maximum starting time for work for FT commuters are illustrated in Fig. 5 and Fig. 6 respectively.

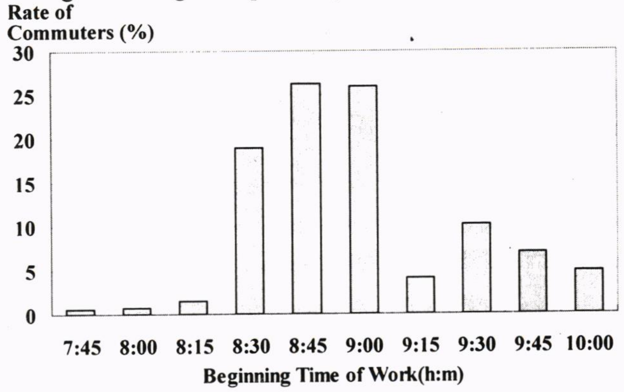


Figure 5. Distribution of Starting Time for Non-Flex-Time Commuters

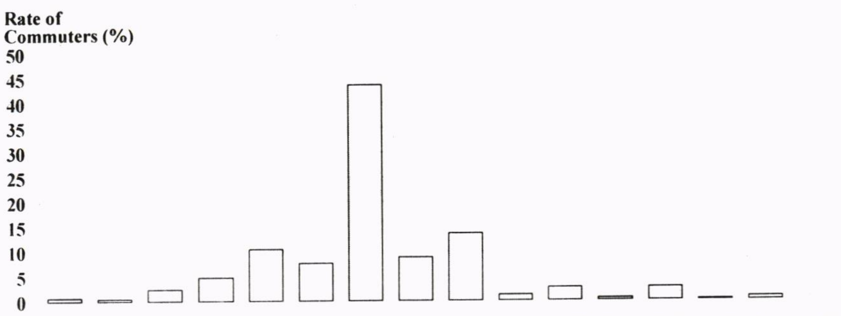


Figure 6. Distribution of Maximum Starting Time for Flex-Time Commuters

5) Average access time from commuter's houses to the boarding station and average egress time from alighting station to workplaces was calculated for each section based on the 1995' Large City Transportation Census.
6) OD flow: Station OD flows are converted to representative station OD flows using the procedure described in Appendix A.

3.3 Parameter Estimation

Parameter α of the logit model in Eq. 2.1 and parameters a ,b and c of U_{Ci} in section 2.2 were calibrated using trial-and-error method. That is, change values of a, b, c and α in a certain range and choose the set of $(a,b,c,\ \alpha)$ which make the smallest error E', which is calculated by equation (3.3).

$$E' = \frac{\displaystyle\sum_{i=1}^{5} \frac{\sqrt{\sum_{k=1}^{K}(q_{FT,ik} - q^0_{FT,ik})^2}}{\sum_{k=1}^{K} q^0_{FT,ik}}}{5} + \frac{\displaystyle\sum_{i=1}^{5} \frac{\sqrt{\sum_{k=1}^{K}(q_{NFT,ik} - q^0_{NFT,ik})^2}}{\sum_{k=1}^{K} q^0_{NFT,ik}}}{5} \quad \text{................(3.1)}$$

$q_{FT,ik}$ (or $q_{NFT,ik}$): Calculated boarding volume of FT (or N-FT) commuters at station i, time k

$q^0_{FT,ik}$ (or $q^0_{NFT,ik}$): Observed boarding volume of FT (or FT) commuters at station i, time k

i: Representative stations (calibration was conducted base on the 5 stations nearest to the central area)

Calibrated parameter values are summarized in Table 3. Sensitivity analysis of parameters is presented in appendix B.

Table 3. Estimated Parameters

α=0.0053	A=384	B=0.0216	T_0=325

3.4 Model Validation

The model was validated on data from the 1995' Large City Transportation Census. Figures 7 to 10 compares the estimated and observed commuter demand over time at sections 1 to 6 for N-FT commuters and FT commuters respectively. Sections 7 and 8 were omitted from the analysis due to low boarding volumes at these sections. Figures 7 to 10 show that the model is able to replicate the observed data well.

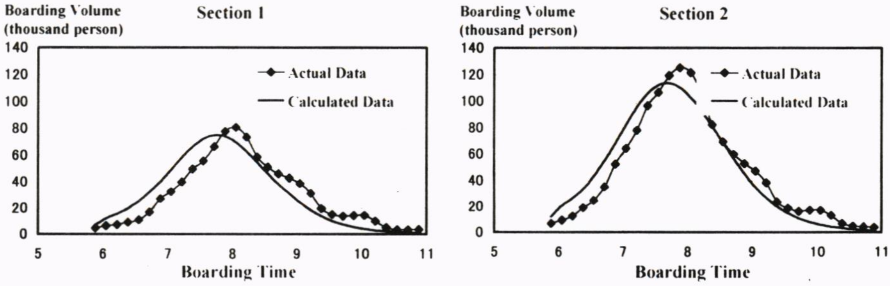


Figure 7. Comparison of Estimated and Observed Railway Demand with Respect to Time in Section 1 and 2 (N-FT commuters)

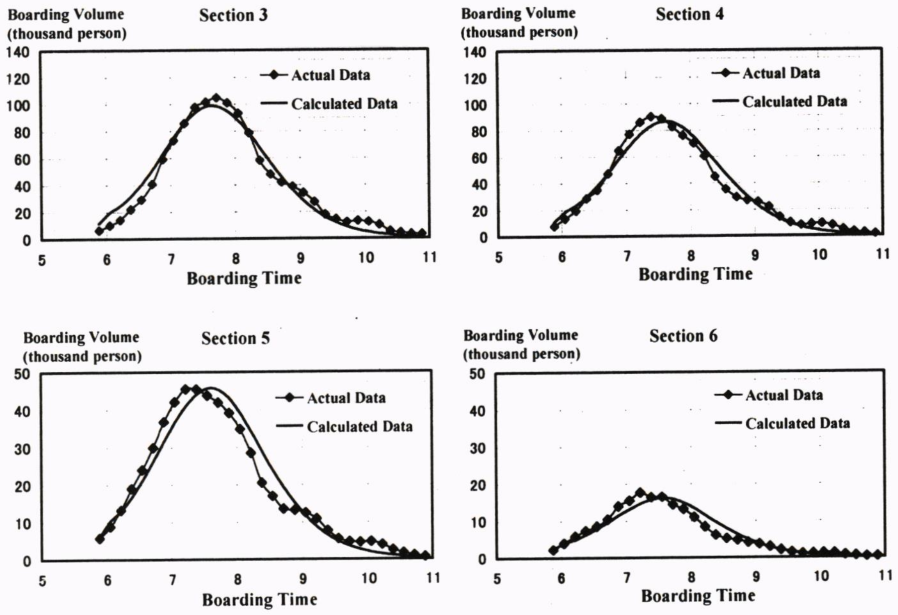


Figure 8. Comparison of Estimated and Observed Railway Demand with Respect to Time in Section 3 to Section 6 (N-FT commuters)

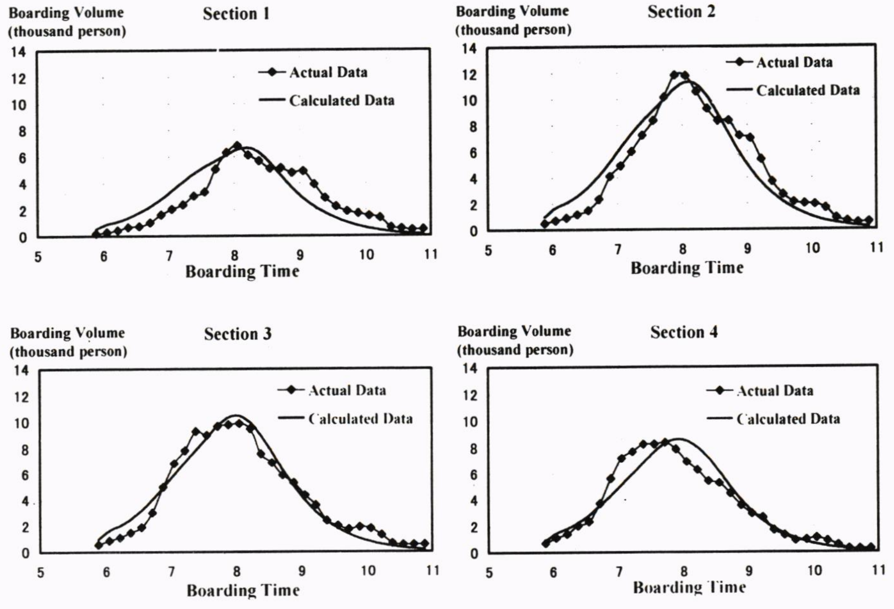
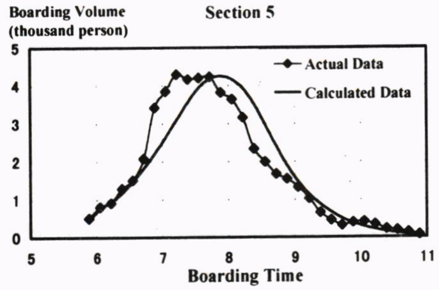


Figure 9. Comparison of Estimated and Observed Railway Demand with Respect to Time in Section 1 and 2 (FT commuters)



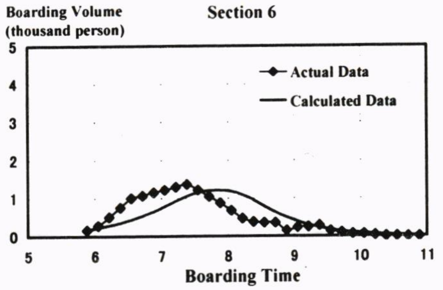


Figure 10. Comparison of Estimated and Observed Railway Demand with Respect to Time in Section 3 to Section 6 (FT commuters)

3.5 Forecast of Railway Demand Concentration in the Future

Here, estimates of future congestion rates in the Tokyo rail network are made considering growth trends in working population, capacity expansions and changes in flexible working time policies. Three scenarios are set up apart from the base scenario. The scenarios are described as follows,

Scenario 0: (1995) base case

Scenario 1: (2015) completion of presently planned railway capacity expansion projects and a decrease demand

$\Delta D_{0,1} = -10\%$

$\Delta C_{0,1} = +10\%$

where,

$\Delta D_{i,j}$: change in demand from scenario i to scenario j.

$\Delta C_{i,j}$: change in capacity from scenario i to scenario j.

Scenario 2: (long term):

$\Delta C_{0,2} = 10\%$

$\Delta D_{1,2} = -5\%$ (or $\Delta D_{0,2} = -15\%$)

increase in the percentage of FT commuters from 11.4% to 30%

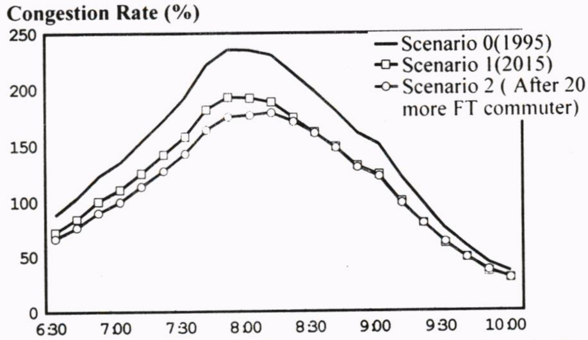


Figure 11. Concentration of Average Congestion Rate in Section 1

Even the demand in scenario 2 less than in scenario 1, but Fig. 11 shows that after peak time, the congestion level did not significantly change. This observation is attributed to the increase of FT commuter in scenario 2. That is, FT commuters can avoid peak congestion periods by leaving the residences at a later time. This result showed that the model can reflect well the alternative of flexible working time system policies on congestion situation.

In another view, the estimation results shown in Fig. 11, indicate that even with a substantial decrease in demand and an optimistic projection of the number employers applying flexible working time systems, the targeted congestion levels set by the Japanese Ministry of Transport would not be achieved. Estimated congestion levels at scenario 2 remain greater than 180% at peak hour at the most congested section and the average peak hour congestion levels remain greater than 160%. The results clearly state that even with decreased demand and an effective implementation of flexible working time systems, the Tokyo rail network could not achieve the desired level of service without additional capacity expansion projects.

Now assuming scenario 3 as follows,

Scenario 3: (long term), as in scenario 2, but with increased railway capacity.

$\Delta C_{2,3} = 15\%$ ($\Delta C_{0,3} = 25\%$)

- Railway capacity one hour before and after the peak hour is increased to 90% of that at peak hour

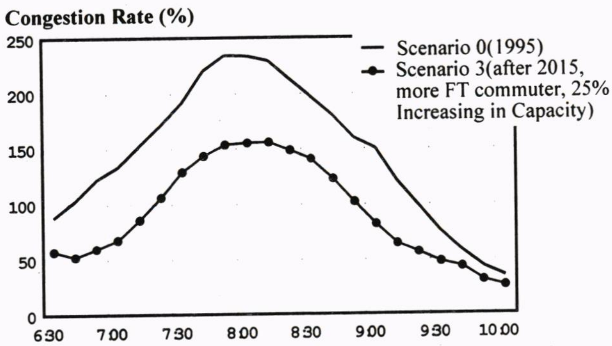


Figure 12. Congestion Rates over Time in the Section 1

The estimated congestion levels for scenario 3 are shown in Fig. 12. The results indicate that the long-term target set by the Ministry of Transportation can only be achieved under scenario 3 which projects a substantial decrease in demand, a considerable increase in railway capacity and an increase in the number of commuters under the flexible working time system. The results suggest that the solution to congestion problems in the Tokyo rail network is an effective implementation of transportation demand management and capacity expansion projects and that a one-sided solution would not achieve the desired targets in improving Tokyo railway network's level of service.

4. CONCLUSION

This study has introduced the CDCM to forecast the effects of capacity expansion projects and flexible working time policies on railway network congestion rates. The CDCM is composed two main sub-models; namely, the WATS and the TSNS. The WATS is an assembly of utility functions that can be used to reflect the preferences and behavior of commuters in selecting arrival times. Using the utility items in the WATS is then used by the TSNS to quantify link costs. Using a stochastic equilibrium assignment method on a time-space network, the TSNS is then able to estimate link flows and the effects of capacity expansion projects and flexible working time systems.

The CDCM is then applied to the Tokyo railway network to investigate likely scenarios intended to improve congestion rates. To minimize computational requirements, the complicated Tokyo railway network is simplified to a linear network with eight sub-urban representative stations and four central representative stations. The CDCM is then calibrated and validated. Validation results indicated that the model accurately estimates boarding volumes at all sections.

Assuming likely scenarios of rail commuter demand, rail network capacity and flexible working time policies in the future, the target set by the Japanese Ministry of Transportation to reduce congestion level to 180% by 2002 and to reduce it further to 150% in the long term is investigated. From the analysis it was concluded that it is optimistic that present capacity expansion projects, which would increase capacity by 15%, would be enough to achieve the set goals despite effective implementation of flexible working time system. It is estimated that a minimum of 25% increase in network capacity is required to achieve the long-term goals set by the Japanese Ministry of Transport. However, the impact of flexible working time policies should not be discounted, as without its effective implementation, capacity requirements would certainly increase.

This study reiterates the need for effective implementation of a double-edged approach in curbing congestion rates in Tokyo's rail network. It is demonstrated that capacity expansion alone could not practically achieve the immense task of improving level of service at Tokyo's rail network and that the supply side approach needs to be concerted with effective transportation demand management schemes.

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APPENDIX A: Modification of Railway Data for Application To the Simplified Tokyo Railway Network

Base OD flow data for validation and calibration of the CDCM is at station to station

OD data format. Since, the network is simplified to a linear network of eight representative sub-urban stations and four central area representative stations, the station to station OD data needs to be converted to representative station to representative station OD data. The process of converting the station to station OD data is explained below.

Firstly, the Tokyo railway network is divided to sections and sectors as illustrated in Fig. 13. The network is divided into thirteen sectors. Each section is set up to be bounded by representative stations. Stations are then classified by the section and sector they occupy. Station to station OD data is then classified into five OD data types, as illustrated in Fig. 14.

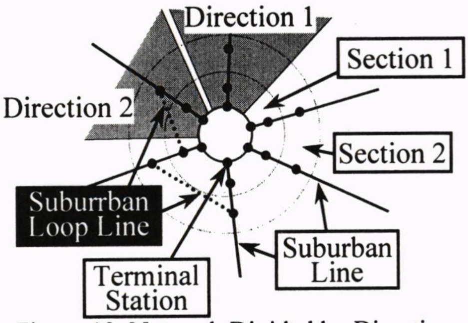

Figure 13. Network Divided by Direction

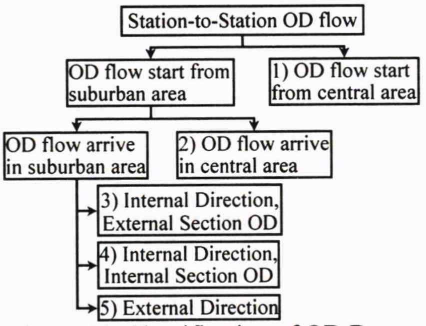

Figure 14. Classification of OD Data

The station to station OD data is then converted to representative station to representative station OD data as follows,

Type 1: OD flows starting from the central area:
Based on observed data the average ratio of users arriving at each destination station is determined. The OD data is then distributed among stations base on the determined percentage of riders arriving at each destination station. Trips from the central area with sub-urban destinations are omitted from the analysis.

Type 2: OD flows from suburban area to central area:
Type 2 OD flows are distributed to central stations by a predetermined ratio derived from observed data as in Type 1 OD data.

Type 3: Central area bound trips from suburban areas with sub-urban destinations in the same sector but to a section other than the origin section

Distribution of OD data is readily applicable.

Type 4: Central area bound trips from suburban areas with sub-urban destinations in the same sector and in the same section

OD flows from section N to section N are divided equally to OD flows from section (N-1) to section number N and OD flows from section N to section (N+1).

Type 5: Central area bound trips from suburban areas with sub-urban destinations in the sectors other than its origin sector

Type 5 OD data are further classified into trips passing a terminal station (i.e. using the Yamanote line) in changing sectors and trips that do not pass an terminal station and uses a sub-urban loop line to change sectors. OD data of trips passing a terminal station are assumed to end at a terminal station. Similarly, trips using a sub-urban loop line are assumed to end at the first transfer station. To maintain actual travel time for type 5 OD data commuters, its egress time is increased by an equivalent time required to travel from the assumed end station to the actual destination station.

APPENDIX B: Sensitivity Analysis of Parameters

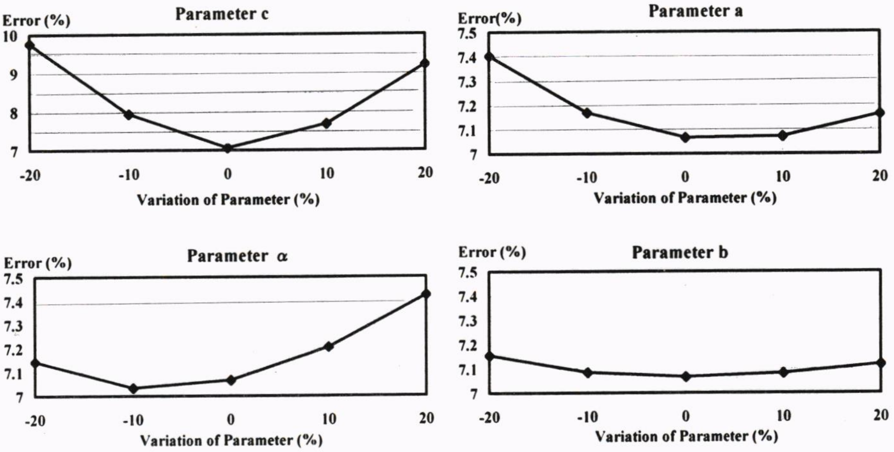

Figure 15. Sensitivity of Error Due to the Variation of Parameters