DESCRIPTIVE MODELS OF A TRANSFER SYSTEM FOR URBAN EXPRESSWAY NETWORKS

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abstract : A transfer system is proposed as a new technique to resolve traffic congestion by maintaining proper balance of traffic flows between urban expressways and urban streets. Firstly, an analytical model is proposed on the basis of the concept of user equilibrium (UE). The transfer system can be formulated with particular representation of the networks and consideration of link interaction. Secondly, the effects of introduction of the transfer system are discussed in terms of the system optimization. If the traffic flow would be controlled with certain techniques, the transfer system might give better performance in terms of total travel time for the urban networks. Thirdly, it is discussed that the improvement of the service for users induce new traffic demand. Therefore, the UE flow with variable demand is considered theoretically. Finally, the impact of multiple transfer systems is considered in a real scale network. This result shows that the transfer system may give the benefit to the public corporation as well as users.

1. INTRODUCTION

Inflow control such as closing entrances and restrictions of the number of booths is regraded as a main strategy of traffic control on urban expressways (Hanshin Expressway Public Corporation, 1990). This type of traffic control can be realized in Japanese urban expressways because the uniform fare system has been introduced as a regulated toll road network. The entrance for the expressways has a function to maintain the amount of inflow traffic. It is important to consider the relation between expressways and streets.
When a vehicle enters the expressway through the gate, an uniform fare should be charged in each time of entry. The uniform fare system can be implemented in urban expressway because the network is designed to cover the daily trip area of the drivers. On the other hand, the networks of the expressway have been extended according to the increasing traffic demand. The new routes are planned to be expanded to the original

networks. It usually takes several years to complete the new route to be open after starting construction. Therefore, it is often observed that some sections on a route begin to be in service even though the route is still isolated from the original network.

If a driver goes through this uncompleted route to reach the destination in the centre of the city, the driver on the route needs to enter the expressway twice. The double entering fares are charged according to the uniform toll system. It would be recommended that this situation is avoided in terms of fairness for user spending cost. In the real system such as Hanshin expressway, the exceptional treatment for this inevitable double charge has been regulated to be the same as a single charge. At present, the charging regulation for transfer traffic works in four areas involving particular on and off ramp pairs (Hanshin Expressway Public Corporation 1990, Akiyama and Sasaki 1993).

It was reported that the transfer system can be applied not only to realize the fair toll system and also to maintain the smooth traffic on the loop road located in the centre of the city (Ohtani 1993, Akiyama and Ohtani 1994) . If the detour routes can be provided for the users driving through the congested links, traffic condition can be improved.
In this study, an analytical model is given to analyze this charging system for transferring traffic. The charging system proposed here would be called as "Transfer System". Particularly, traffic assignment techniques based on the same theory are introduced to investigate the advantages of the transfer system with different conditions. The assessment of the transfer system would be reported. And the transfer system may be regarded as a soft measure to traffic congestion. The research results will give important ideas to progress the traffic management with information technologies.

2. THE ANALYTICAL MODEL OF TRANSFER SYSTEM

2.1 The Basic Formulation of The Transfer System

The elementary network in Figure 1 can be useful to understand the main idea of the transfer system (Akiyama and Ohtani 1994, Yasuda and Akiyama 1995). The network consists of expressway links and ordinary street links. The Figure is used to show a part of whole network related with particular origin and destination. The link numbers are shown on the respective links. The bold lines denotes expressway links. It is assumed that several routes connect to the loop roads at each radius directions. This causes heavy traffic congestion on the loop roads. In the Figure, link 2 is representing the congested link of the loop road. The narrow lines correspond to the urban streets. In particular, link 5 is regarded as an alternative street to the expressway.

There are two entrances for the expressway which are indicated as small booth boxes in the Figure. For the traffic from the origin to the destination, the users who are driving on the expressway from link 1 will be able to change routes to avoid congested road. However, the users would then have to pay fares at a second time for re-entering the expressway (at the second toll gate on the end of link 8) despite making only a single trip to the destination. Therefore, there are few traffic attracted to the detour routes and heavy congestion remains.
The transfer system proposed here would encourage the users on the expressway change routes, so as to reduce the traffic volume on the congested sections, by means of lifting

the toll charge when entering the expressway at a second time.

2.2 The User Equilibrium Approach for The Analysis

The transfer system can be formulated on the basis of traffic equilibrium analysis. The link performance function is defined for each link as follows:

$$t_a(x_a) = t_0\left\{1+\alpha\left(\frac{x_a}{Q}\right)^{\beta}\right\} \tag{1}$$

where x_a indicates traffic flow on link a and $t_a(x_a)$ refers to travel time for link a; This equation is the so-called modified BPR function (i.e. $\alpha = 2.62,\ \beta = 5$). The mathematical formulation of user equilibrium is well known as follows:

$$\min\ z_U(x) = \sum_a \int_0^{x_a} t_a(w)dw \tag{2}$$

subject to

$$\sum_k f_k^{rs} = q, \qquad \forall\ r,\ s \tag{3}$$

$$f_k^{rs} \geq 0, \qquad \forall\ k,\ r,\ s \tag{4}$$

Frank-Wolfe (F-W) algorithm is used to solve the standard user equilibrium problem. It is known as one of the most popular techniques to solve the equivalent mathematical programs of the UE problem (Sheffi 1985). The algorithm can be applied even to determine the user equilibrium condition with transfer system mentioned in the next section. Therefore it is shown as a standard procedure of calculation. The algorithm can be summarized as follows:

step.1 :*Direction finding.* Find y_n that solves

$$\min z^n(y) = \nabla z(x^n)\cdot y^T = \sum_i \left(\frac{\partial z(x^n)}{\partial x_i}\right) y_i$$

subject to

$$\sum_i h_{ij} y_i \geq b_j \quad \forall j \in \mathbf{J}$$

step.2 :*Step-size determination.* Find α_n that solves

$$\min_{0\leq\alpha\leq 1} z[x^n + \alpha(y^n - x^n)]$$

step.3 :*Move.* Set $x^{n+1} = x^n + \alpha(y^n - x^n)$.

step.4 :*Convergence test.* If $z(x^n) - z(x^{n+1}) \leq k$ stop. Otherwise, let n:=n+1 and go to step1.

where x^n and y^n indicate current solution and auxiliary feasible solution respectively.
The network in Figure 1 will be used as an example. The traffic flow for the O-D pair is assumed to be 100,000 vehicles. The traffic of 70,000 vehicles is always loaded on the loop road independently to the O-D traffic. It represents concentrated traffic from the other directions.
In the calculation, the uniform fare is assumed to be 600 yen corresponding to the real value of toll in Hanshin Expressway. This monetary cost is transformed to the equivalent travel time. Therefore, the uniform fare is equivalent to 7.5 minutes corresponding to the value of time as 80 yen/min/veh, which is used to consider the benefit of travel time reduction in Hanshin Expressway. The value of time is estimated by Hanshin Expressway (Hanshin Expressway Public Corporation 1995). It is calculated corresponding to the national average income in 1995. Two on-ramps are located in this network. The equivalent travel times are loaded on these points for the routes.

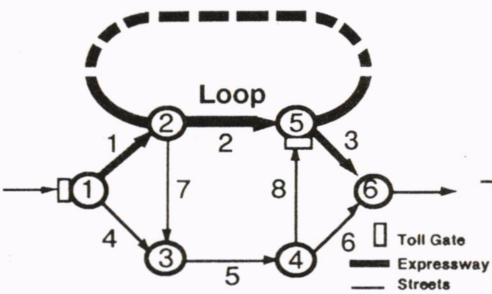

Fig.1 Networks Example

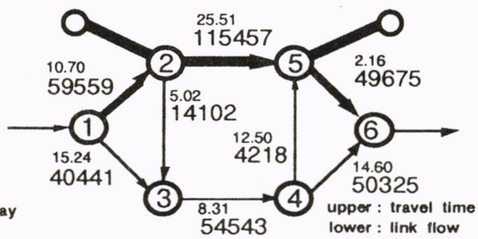

Fig.2 The User Equilibrium Flows (without Transfer System)

As the initial case, the ordinary traffic equilibrium without any conditions are considered. Therefore, the transfer system is not assumed to be introduced. Figure 2 illustrates the traffic volume for respective links as a result of calculation. The transferring traffic is quite small and is only 6 %. It shows that the cost for the detour which corresponds to the second charge has an influence to make users not to go off the expressway.

2.3 The User Equilibrium with Transfer System

A modified model is considered by introducing the transfer system to the same network shown in Figure 1. The reduction of travel cost is observed for the detour route such as expressway - street - expressway links on the route. The traffic on this route can be given special discount according to the proposed system. In reality, this situation can be realized by providing the transfer tickets to the transferring users at the off-ramps.
The system is formulated similarly to the previous model. The representation of the network should be modified to illustrate the traffic flows with transfer system. The modified network is shown in Figure 3. The links 10 to 13 are dummies to specify the connection between links on each route. In this representation, links 5 and 9 indicate the same link as an alternative street. However, there are different types of users on the alternative street which is originally indicated as link 5 in Figure 1.

The ordinary street drivers are influenced by the users on the detour in this case. The traffic volumes of links are independent variables of the formulation of mathematical programming for UE problem. Since the problem considered here might be rather complicated, the standard F-W techniques cannot be applied.
Assume the traffic flow x_5 and x_9, the traffic volume as x_5+x_9 are loaded on the same link. In other words, it can be formulated that these links have traffic interaction in the modified networks. The travel time $t_5(x_5,x_9)$ and $t_9(x_9,x_5)$ are assumed be the same functions as equation (1). These are formulated as follows (Yasuda and Akiyama 1995a, 1995b):

$$t_5(x_5,x_9)=t_0\left\{1+\alpha\left(\frac{x_5+x_9}{Q}\right)^{\beta}\right\} \tag{5}$$

$$t_9(x_9,x_5)=t_0\left\{1+\alpha\left(\frac{x_5+x_9}{Q}\right)^{\beta}\right\} \tag{6}$$

The models of traffic assignment with link interaction are discussed by Sheffi (Sheffi 1985). Particularly, this problem corresponds to the traffic interaction with symmetric condition. Equations (5) and (6) imply that the Jacobian of $[t_5(x),\ t_9(x)]$ is non-negative definite. Therefore it is confirmed that the equilibrium flow pattern that solves this example is unique.
The solution can be found by the following minimization program. In the case of transfer system in Figure 3, the object function $z_U(x)$ describes the user equilibrium situation when the transfer system is introduced the detour traffic x_9 influences the traffic on the street as x_5 on the same link. This situation can be described as a sort of link interactions. Therefore, the first performance function $t_a(w,\ x_{a'})$ can be interpreted to represent travel time on link a with influence of the transfer traffic and the second function $t_a(w,\ 0)$ represents the travel time without transfer traffic:

$$\min\ z_U(x)=\frac{1}{2}\sum_a\{\int_0^{x_a}t_a(w,\ x_{a'})dw+\int_0^{x_a}t_a(w,\ 0)dw\} \tag{7}$$

subject to

$$\sum_k f_k^{rs}=q, \qquad \forall\ r,\ s \tag{8}$$

$$f_k^{rs}\geq 0, \qquad \forall\ k,\ r,\ s \tag{9}$$

where a' denotes the link opposite to link a. Therefore, the travel time for the trunk road section (link 5 or link 9) is considered to be a function of the flow, x_5+x_9. The objective function includes two terms for each link in the network. The first is the integral of the link's performance function, with respect to its own flow, when the flow in the opposite direction in held constant. On the other hand, the second term is the integral of the link's performance function when the flow on the opposite link is held at zero (Sheffi 1985).

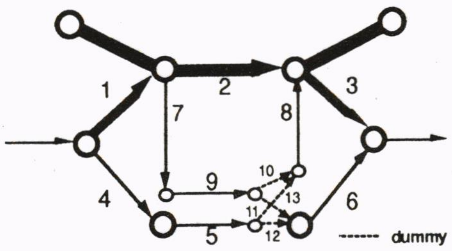

Fig.3 Network Reprensentation

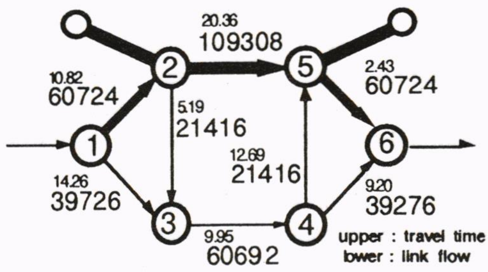

Fig.4 The User Equilibrium Flows (with Transfer System)

The calculation result is shown in Figure 4. The impact of implementation of the transfer system can be seen by comparing this figure with Figure 2. The flow on the loop road decreases to reduce the congestion because of providing the beneficial detour to the drivers by means of the transfer system. It is observed that the absolute travel time for user equilibrium have changed from 38.4 minutes to 33.4 minutes. It means that the equilibrium travel time for both of the expressway and the streets are reduced by 12 % in this study area. It is obvious that traffic condition for the whole network system might be better. About 35 percent of traffic transferred from the loop road to the detour.
The gross revenue of the toll is increased from 36,063 ($\times 10^3$) yen to 36,434 ($\times 10^3$) yen. The small positive influence to the monetary benefit as 371 ($\times 10^3$) yen for administration can be observed . In addition, the benefit of travel time reduction (817,580 veh·min) is counted as 6,541 $\times$ 10^4 yen as well.

3. THE SYSTEM OPTIMIZATION WITH TRANSFER SYSTEM

3.1 The System Optimization Flow

The efficiency of transfer system would be discussed in this chapter. The system optimization problem should be considered. Total travel time is a common measure of efficiency of the network concerned. The equivalent mathematical program can be expressed as follows :

$$z_S(x) = \sum_a x_a \cdot t_a(x_a) \tag{10}$$

subject to

$$\sum_k f_k^{rs} = q, \qquad \forall\ r,\ s \tag{11}$$

$$f_k^{rs} \geq 0, \qquad \forall\ k,\ r,\ s \tag{12}$$

In this formulation, the objective function in equation (2) is replaced by equation (10). Therefore, the same calculation algorithm in UE (i.e. Frank-Wolfe algorithm) is applicable to solve the problem as well.

The state of the system optimization is calculated to consider the efficiency improvement by the introduction of the transfer system. Generally, the system optimization on the networks corresponds to the direction of the traffic management. Figure 5 shows the system optimizing situation by standard technique. This condition does not include the transfer system implementation. Comparing the result of the UE flows without the transfer system in Figure 2, the expressway traffic (i.e. link 1) increases by about 9 %. The traffic on the detour (i.e. link 7) also is increased by 108 %. The result shows that the restriction of loop road traffic might produce a better condition on the network even if the transfer system is not implemented.

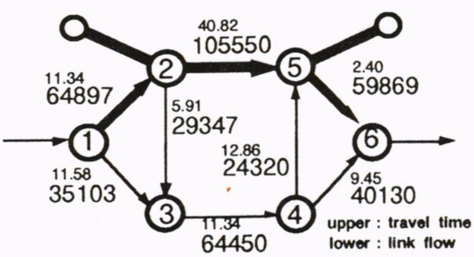

Fig.5 The System Optimization Flows (without Transfer System)

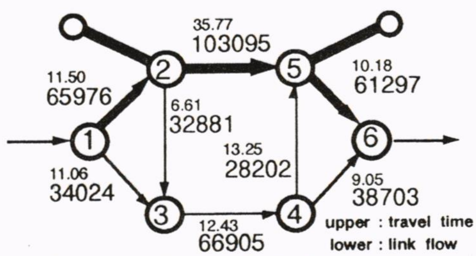

Fig.6 The System Optimization Flows (with Transfer System)

3.2 The System Optimization Flow with Transfer System

The transfer system can be introduced if the information about the available detour might be given to users. In this formulation, therefore, the objective function is the same as equation (7) and the network representation is shown in Figure 2. The system optimization with transfer system is calculated by the same algorithm. Comparing the result of the UE flows with the transfer system in Figure 4, the expressway traffic (i.e. link 1) increases by about 9 %. The traffic on the detour (i.e. link 7) also increases by 54 %.

The result shows that the information service and other devices related with traffic management can encourage the drivers to change routes to realize more efficient condition on the network. The transfer system seems to be successfully combined with traffic management as route guidance or navigation systems.

Table 1 summarizes the calculating results in each case. In any case, the transfer system seems to work well to reduce the traffic congestion. Particularly, the percentage of the detour changes obviously after the transfer system is implemented. It is known that the system can produce a proper balance of the loaded traffic between the expressways and the streets as demonstrated by the results of simple numerical examples.

Table 1 Calculation Results in The Numerical Example

	User Equilibrium		System Optimization	
	original	transfer	original	transfer
Total Travel Time (veh · min)	5,139,870	4,322,290	4,084,440	4,022,520
Route Travel Time (min)	38.4	33.4		
Minimum Travel Time (min)			31.5	30.2
Maximum Travel Time (min)			43.8	39.6
Corporation Revenue (×1000yen)	36,063	36,434	38,938	39,586
Rate of Transfer	0.06	0.35	0.37	0.43

4. THE TRANSFER SYSTEM IN REALISTIC SITUATION

4.1 The Network Representation

In the previous analysis in Chapter 3, it was shown that the efficient use of the networks can be maintained by implementation of the transfer system. A realistic network representation is considered in this section. For example, the transport network in Osaka urban area consists of the expressways and the streets. Hanshin expressway network is located in the centre of Osaka as urban expressway system. This expressway is separated from the streets and consists of the loop roads and seven radius routes. And also, the uniform toll system is introduced.

Figure 7 represents the loop road and some other radius routes as a part of Hanshin Expressway networks. On the other hand, the trunk roads on the ordinary streets are represented in Figure 8. These networks might cover the OD traffic generated in central Osaka area. This example network consists of 26 nodes and 52 links for the streets as well as 23 nodes and 52 links for the expressways. The traffic flows in the central area in Osaka can be described even though the network might be rather small. Two sites are selected to consider plausibility of transfer system implementation. These detour routes are indicated by dashed lines. Site (A) involves the detour route from node 34 (off-ramp) to node 30 (on-ramp). On the other hand, Site (B) involves the detour route from node 37 (off-ramp) to node 42 (on-ramp).

4.2 The Performance of The Transfer System

Four different situations are considered to evaluate the scale of the impact of implementation of the transfer system in each site. The following cases are prepared to consider the influence of transfer system implementation:

Case 0 : The original UE flows without transfer system
Case 1 : The traffic flows with the transfer system at Site (A)
Case 2 : The traffic flows with the transfer system at Site (B)
Case 3 : The traffic flows with the transfer system at both site (A) and (B)

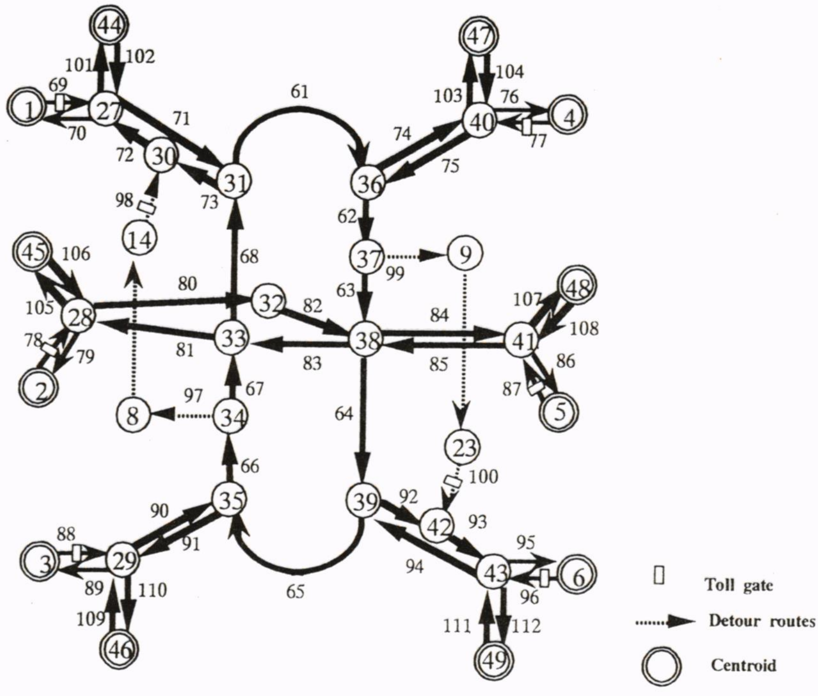

Fig. 7 The Expressway Network

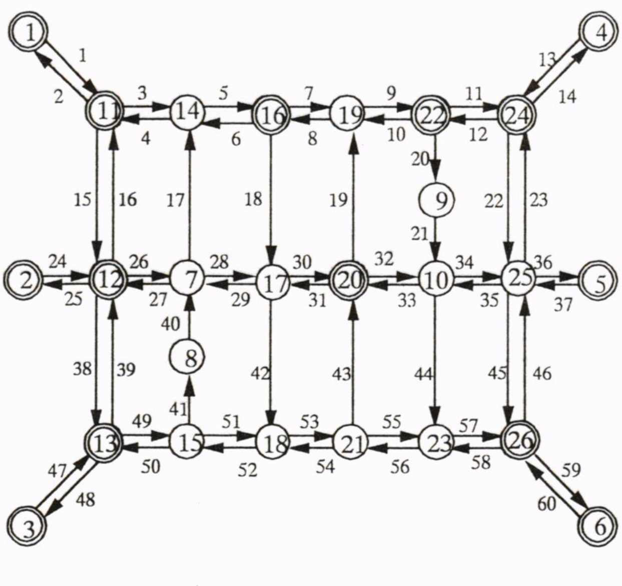

Fig. 8 The streets Network

Basically, the case 0 assumes to describe the original user equilibrium situation. It is also assumed that Case 1 to Case 3 may be regarded as available alternatives to the original situation. Therefore, the influence of the transfer system implementation is observed from the comparison of the situation in the other cases to that in the case 0.
In calculation, the same formulation and algorithm as shown in previous chapters can be applied to solve this problem. The formulation in equation (7) is applied to the two sites at the same time. As the objective function is replaced corresponding to the modified formulation, the same algorithm can be applied to the calculation.

Table 2 summarizes the calculating results in each case. The total travel time for the expressways as well as that for streets is reduced with transfer system in the site (A). On the other hand, the total travel time of the expressways increases in the case of transfer system in the site (B). The fact shows that the implementation of the transfer system cannot always produce the smooth traffic on the expressway. However, the total travel time for the whole network is reduced over 10% in each case. It may be true that the transfer system provides on efficient way to manage the traffic on the urban networks in the sense of social travel cost.
The revenue of the corporation is reduced corresponding to the efficient use of the network. However, the value of user benefit as the surplus is counted much greater than the value of benefit reduction in the corporation revenue. The transfer system may be recommendable in the sense of social benefit.

Table 2 Calculation Results for Transfer Systems

		Case 0 Original	Case 1 Transfer(A)	Case 2 Transfer(B)	Case 3 Transfer(A·B)
Corporation Revenue by Toll (yen)		90,875,000	90,428,000 (-447,000 -0.49)	90,846,000 (-29,000 -0.03)	90,574,000 (-301,000 -0.33)
Total Travel Time (veh·min)	Expressway	17,040,600	17,038,600 (-2,000 -0.01)	17,075,600 (35,000 0.21)	17,012,600 (-28,000 -0.16)
	Streets	21,583,000	21,545,000 (-38,000 -0.18)	21,428,200 (-154,800 -0.72)	21,448,900 (-134,100 -0.62)
	Total	38,623,600	38,583,600 (-40,000 -0.10)	38,503,800 (-119,800 -0.31)	38,461,500 (-162,100 -0.42)
User Benefit (yen)		—	3,200,000	9,584,000	12,968,000
Corporation Benefit (yen)		—	-447,000	-29,000	-301,000
Social Benefit (yen)		—	2,753,000	9,555,000	12,667,000

The last case illustrates the change of the traffic flow on the network with transfer system in the double sites. The detour traffic is counted as 2,688 in the case 1 as well as 3,300 in the case 2. The amount of the detour traffic with both transfer system (i.e. Case 3) is observed as 6,522. This amount is greater than the sum of the detour traffic in previous two cases. In terms of total travel time, the same result is given with the comparison. It is known from the observation that the synergistic effect should be considered in the case of transfer system application on the large scale network.

5. CONCLUDING REMARKS

The transfer system on the uniform toll roads such as Hanshin Expressway was analyzed in terms of theoretical aspects. It was shown that the standard UE algorithm is applicable to solve the problem. The efficiency and the availability of the transfer system were considered with some different conditions. The main results of the research are summarized as follows:

Firstly, the theoretical analysis can be carried out by the theoretical formulation of the transfer system and the modification of the standard UE algorithm. It would be realized with the network representation for the transfer system and the consideration of link interaction. Particularly, the UE flows with transfer system might be shown as the basic situation to discuss about the impacts of the system introduction.
Secondly, the efficient situation with transfer system was discussed by the system optimization approach. The traffic management to produce the SO flow rather than the UE flow would be recommended to produce more efficient situation even in the implementation of the transfer system.
Thirdly, case studies are done to extend the model representation and to consider the applicability of the transfer system on the real scale expressway system (Yasuda, Daito and Akiyama 1995, Yasuda and Akiyama 1996). The implementation of transfer system is conceived to be a sort of improvement of the service for expressway users as well as social benefit.

In terms of the algorithm, the assignment techniques on the basis of path flows would be recommended to analyze the change of travel costs for particular paths related with transferring traffic (Yasuda, Daito and Akiyama 1995, 1996). The stochastic user equilibrium assignment seems to be useful to modify the model. In the practical aspects, the combinational optimization problem for the locations of off and on ramp pairs should be solved. Even though many possible routes can be found for implementation of the transfer system, the proper combination should be prepared. Otherwise, the transfer system does not work well because of the concentration of the traffic. The Genetic Algorithm (GA) is now planned to be applied to solve this problem.

ACKNOWLEDGMENTS

The authors record here warmest acknowledgment to Professor T. Sasaki, Kinki University, for his fundamental suggestion about the study, and to Mr. Daito, Institute of Urban Transport Planning for his advice. They also would like to thank to members of the investigation committee of traffic congestion in Hanshin Expressway for discussing the practical problems of the transfer system in the real networks and to Mr. T. Itoh for his drawing pictures and coding the program.

REFERENCES

Akiyama, T. and Sasaki, T. (1993) Formulations of Transfer System for Urban Expressway Networks, **Proc. of the 13th conference of Traffic Engineering,** 125-129, (in Japanese).

Akiyama, T. and Ohtani, S. (1994) User Equilibrium Analysis for Transfer System on Expressway, **Proc. of the 14th conference of Traffic Engineering,** 21-24, (in Japanese).

Akiyama, T., Yasuda, K. and Itoh, T. (1997) A Theoretical Model of Transfer System for Urban Expressway Networks, **Research Report of The Faculty of Engineering, Gifu University, 47**, 9-20.

Hanshin Expressway Public Corporation (1990) **Traffic Control System For Safe and Comfortable Driving**

Hanshin Expressway Public Corporation (1995) **Hanshin Expressway 1995**, (in Japanese).

Ohtani, S. (1993) Evaluation of Transfer System on Urban Expressways in terms of User Equilibrium, **The Master Thesis in Division of Global Environment Engineering Graduate School of Engineering Kyoto Univ** (in Japanese).

Sheffi, Y. (1985) **Urban Transportation Networks,** Practice-Hall.

Yasuda, K. and Akiyama, T. (1995a) Transfer System for Urban Express Networks, **Proc. of Annual Conference of Chubu Branch, JSCE,** 421-422, (in Japanese).

Yasuda, K. and Akiyama, T. (1995b) An Analysis of model for Transfer System on Expressway, **Proc. of the 15th conference of Traffic Engineering,** 105-108, (in Japanese).

Yasuda, K., Daito, T. and Akiyama, T. (1995) Some Practical Applications of Transfer System on Expressway, **Proc. of the Infrastructure Planning,** 18 (1), 105-108, (in Japanese).

Yasuda, K. and Akiyama, T. (1996) The Concept and Application of Transfer System on Expressway, **Proc. of Annual Conference of Chubu Branch, JSCE,** 465-466, (in Japanese).

Yasuda, K., Daito, T. and Akiyama, T. (1995) Practical Applications of Transfer System on Expressway, **Infrastructure Planning Review 13**, 893-900, (in Japanese).