AN EFFICIENCY ANALYSIS OF TRANSPORTATION MANAGEMENT SCHEMES BY INTEGRATED MODELING APPROACH

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Abstract: In this paper, we present new approaches to evaluate transportation management schemes. Three traffic management schemes are evaluated for improving transportation network efficiency in different ways; 1) increasing road capacity, 2) levying congestion toll, 3) increasing running speed of transit system. To assess the schemes, we developed an integrated model considering the transfer behavior between auto and transit. From the preliminary results with an example network, Case 1) improves the network condition (or reduces congestion) slightly, but leads to change the mode choice pattern from transit to auto significantly. Case 2) also improves the system efficiency and the running speed of road network, but the generalized cost of users in network increases slightly. On the other hand, Case 3) reduces the generalized cost of users and improves the network condition. These results imply that Case 3) is the best scheme for improving transportation network and is beneficial to road users as well as system manager.

Key words: Transportation management schemes, Integrated model, Combined model, Transfer

1. INTRODUCTION

Recently many researchers have studied in transportation management schemes for Intelligent Transport Systems (ITS) environment. It is difficult to define what system management scheme is optimal. In transportation network management, two different objectives have always conflicted with each other. One is, in supply side, to maximize the existing network capacity and to minimize the travel time consumed in transportation network. Another is, in demand side, to reach the user equilibrium state proposed by Wardrop(1952). These two objectives represent totally different states and produce conflicting flow patterns in transportation network. But the optimal system management schemes controlled by traffic authorities should satisfy these two objectives simultaneously as possible.

As the complexity in traveler's behavior on road network has been increased, we have been confronted with the need for analysis method that is more flexible and robust than conventional approaches. One of the complexities, the transfer behavior of passengers on the way to their destinations is more complex and difficult to be modeled. The reason is stemmed from the fact that overall existing methods have been developed into two categories such as auto and transit separately. However, in order to simulate travelers' behaviors more precisely, it is necessary to integrate the transfer behavior within the model. In the junctions with transfer, some researchers have developed mathematical models for taking into account transfer behavior on the road networks. Sheffi(1985) has proposed a combined model in which the network includes both auto and transit mode. The solution includes the flow of transit patrons between each origin-destination pair in addition to the vehicle flow pattern over the network. At equilibrium, the transit and auto flows and the travel times between each origin-destination pair satisfy the equilibrium condition proposed by Wardrop (1952). The equilibrium condition is that for each origin-destination pair, the travel times on both the transit and road network should be equal if both are used. This model is referred to as the equivalent mathematical combined mode split/ traffic assignment model. To solve the combined model, we assume that some of the origin-destination pairs in the network are connected by transit, which are enable to accommodate the flows converting from auto to transit, or vice versa. In the model mode choice behavior should be also included. So as to take into account the mode choice between transit and auto, mode split functions have been adopted. One of the most widely used mode choice functions is the logit formula. Before loading the flow on the road network, the proportion of mode choice is determined by the choice model.

However, this kind of combined model has a critical limitation to describe the real world. It cannot consider the transfer behavior between transportation modes on the way of traveling. In real world, there are many transfer stations on the transportation network and passengers may need one or more transfers to complete their journey from auto to transit or vise versa. Therefore, to simulate the transportation network more precisely, a special attention should be given to the transfer behavior of passenger and should be also included in the model. Until now on, the transfer behavior has not been explicitly modeled, though some proxies might be occasionally used.

In this respect, we suggest a multiple mode transportation method, in which several transportation modes are integrated into a model. This model can consider explicitly the transfer behavior between auto and transit. In practice, multi-mode transportation networks should be regarded as a single integrated system, not in separate. For instance, when a system manager applies new management scheme to transportation system, he(or she) should do it in systematic environments for more exact evaluation. In some respects, the integrated model is significantly different from the combined model. Namely, the first is that the former describes the transfer behavior explicitly within the model; the second is that it can also depict mode choice behavior without standard formula such as logit mode choice function. According to travel cost, the split of each mode is determined endogenously within the model. Note that the model is based on person trip, not vehicle trip.

In this paper, we present new approaches to evaluate transportation management schemes with the integrated model. We define a new assessment measure; system efficiency (SE), which is defined the difference between total travel costs of user equilibrium state and of system optimal state. Thus, if user equilibrium traffic flow pattern is similar to system optimal traffic flow pattern, system is utilized efficiently and SE is high. With this definition, total travel cost of system optimal state is regarded as lower bound of system's total travel cost or ideal system states, but user equilibrium state represents realistic situation of transportation network. Three traffic management schemes are evaluated for improving transportation network efficiency in different ways; 1) increasing road capacity, 2) levying congestion toll, 3) increasing running speed of transit system.

This paper has been organized as follows. An integrated model developed in this paper is presented in the next section. And the formulation and its solution algorithm of this model are described in section 3. Some numerical experiences by this model are discussed in section 4 and finally conclusions are presented in section 5.

2. AN INTEGRATED MODEL CONSIDERING TRANSFER BEHAVIOR

In order to integrate auto with transit mode on the same network, this paper assumes that each link of the network describe the transportation mode respectively. This assumption implies that each transportation mode is classified by link type. Detailed explanations will be given later. Anyway, this assumption leads to calculate mode splits between auto and transit without explicit mode choice model. Next subsections discuss the travel cost functions of auto and transit mode. Shortest path algorithm of the multi-modal network is also provided.

2.1 Travel cost functions

Firstly, main notations in this paper are defined as follows.

$V_{start,p}$: Transit passenger on link p connected with origin node (person/hour)
$V_{thr,p}$: Transit passenger passing the upstream node of link p (person/hour)
$V_{tran,p}$: Transit passenger on link p, transferred from different transportation mode before link p (person/hour)
V_p : Transit passenger flow on link p (person/h)

$$(=V_{start,p}\delta_{start,p} + V_{thr,p}\delta_{thr,p} + V_{tran,p}\delta_{tran,p})$$

Where, $\delta_{start,p}, \delta_{thr,p}, \delta_{tran,p}$ are incidence matrix respectively; take a value of 1 if transit passengers belong to the cases otherwise 0

$V_{wait,p}$: Transit passenger waiting before link p for boarding

$$(=V_{start,p} + V_{tran,p})$$

t_p : Travel cost of link p (time unit)
$t_{p,0}$: Free flow link travel cost of link p
$t_{inveh,p}$: In-vehicle travel time of link p {=Length of link p / Transit average speed}
$t_{wait,p}$: Passenger waiting time at the upstream node of link p before boarding
$t_{tran,p}$: Transfer penalties, willing to pay for boarding a mode of link p
K_p : Capacity of link p
f_p : Frequencyof transit running on link p
h_p : Average headway of transit line running on link p (= $1/f_p$)

2.1.1 Link travel cost for road network

Several link travel times have been proposed for auto on the road. On of the most widely used formula is BPR (Bureau of Public Road, 1964) cost function. We also use this function. Since traffic flows are loaded based on person trip in this paper, it is required to convert person trip into vehicle trip. The value of 1.4 is used as a converting parameter from persons to a vehicle.

2.1.2 Capacity-constrained link travel cost for metro transit

One of the main limitations in transit model is that they do not consider congestion effects over the transit system. The assumption is made that all transit lines have unlimited capacity to accommodate any amount of demand. This assumption, however, is unrealistic when the model is used to study transit networks operating with high congestion levels due to insufficient capacity of the services. In this paper we assume that the transit system has a limited capacity and therefore, as passengers increase, travel times also increase. Then, as some routes become congested, passengers will consider using alternative routes. This is similar to the assumption for modeling congested road network. Usually congestion on transit networks is concentrated at transit stops. Therefore, passengers experience waiting times that depend on the total capacity of the lines considered and on the total number of passengers using those lines. In this respect, Cea and Fernandez (1993) proposed a cost function for transit mode as follows;

$$t_p = t_{inveh,p} + (\frac{\alpha}{f_p}) + \beta * \Phi(\frac{V_{wait,p} + V_{thr,p}}{K_p}) \tag{1}$$

Where t_p is the travel cost of link p and $t_{inveh,p}$ is the in-vehicle travel cost of link p. f_p is the headway on link p (sec/vehicle) and α and β are calibration parameters. $V_{wait,p}$ is the waiting passengers of link p before they board the train and $V_{thr,p}$ is the passengers on board of link p. K_p is the capacity of link p. The value of α depends on the distribution which is assumed for metros interval times (headway) and passenger arrival times. The normally used value is α =0.5, corresponds to a uniform random variable for passenger arrivals with fixed headways. The third term on the right of equation (1) takes explicitly into account the effect of congestion on waiting times and the form of function (Φ_p) should be such that t_p is strictly monotone in volumes (V). One of the possible forms is the power formula used in BPR functions;

$$\Phi_p(V) = (\frac{V_{wait,p} + V_{thr,p}}{K_p})^n \tag{2}$$

In practice, when congestion exists a fraction of the transit line will be full. In that case there is another delay as well as waiting time. The delay occurred from the fact that if a vehicle arriving is full, passengers cannot board and should wait following one. So as to represent this phenomena Cea et.al. (1993) introduced the concept of effective frequency. However, in this paper we simply use the ratio of occupancy of vehicle to represent this phenomena. The ratio of occupancy (Φ_p) depends on the capacity and the number of passengers passing the stop as follows.

$$\Phi_p = \frac{V_{thr,p}}{K_p} \tag{3}$$

As a consequence, the in-vehicle travel time and waiting time of link p will be used in this paper and are calculated respectively as follows;

$$t_{inveh,p} = \text{Length of link p / Transit average speed} \tag{4}$$

$$t_{wait,p} = (\frac{\alpha}{f_p}) \bullet [1 + (\frac{\Phi_p}{\gamma})] + \beta \bullet (\frac{V_{wait,p} + V_{thr,p}}{K_p})^n \tag{5}$$

Where α, β, γ and n are parameters, which should be calibrated through survey data. But in this paper we assume that α =0.5, β =0.05, γ =2 and n =2 respectively. Compared with the link travel cost, Equation (4) and equation (5) are similar to those of Cea et.al. (1993 and 1996). From the first term of right hand side in equation (5) we find that if congestion does not exit, Φ_p =0, then the waiting times depends only on the frequency, but as congestion increases passenger waiting times at stops will increase linearly.

2.1.3 Transfer cost

Transfer cost, $t_{tran,p}$ is incurred by transfer passenger from one mode to another. In this paper we take into account the cost explicitly, thus passengers who want to change their mode on the way of traveling have to pay extra cost. Parking fee around transit station, for instance, is a transfer cost. In practice transfer behaviors of passengers occur from auto to transit mode and vice versa, but most of transfer passengers are those who change their mode from auto to transit. Thus we assume that transfer only occurs from auto to transit and those transfer passengers are willing to pay a fixed additional cost.

2.1.4 Relations between auto and transit cost

With the costs derived above, the total link travel cost of link p is calculated as follows;

$$t_p = t_{wait,p} + t_{inveh,p} + t_{tran,p} \tag{6}$$

Where if link p is auto
then,

waiting time is $t_{wait,p} = 0$

in-vehicle time is $t_{inveh,p} = t_{p,0} \cdot (1 + \alpha_{auto} \cdot (\frac{V_{inveh,p}}{K_p})^{\beta_{auto}})$

transfer time is $t_{tran,p} = 0$, link p is connected with origin
$= \infty$, previous link before link p is metro

where parameters are set $\alpha_{auto} = 0.15$ and $\beta_{auto} = 4$ respectively.

Otherwise, if link p is transit(metro)
waiting time is

$$t_{wait,p} = (\frac{\alpha_{transit}}{f_p}) \cdot [1 + (\frac{\Phi_p}{\gamma})] + \beta_{transit} \cdot (\frac{V_{wait,p} + V_{thr,p}}{K_p})^n$$

in-vehicle time is $t_{inveh,,p}$ = Length of link p / Transit average speed

transfer time is $t_{tran,p} = 0$, link p is connected with origin
$= C_a$, previous link before link p is auto
$= C_t$, previous link before link p is transit

Where, C_a, C_t are constant transfer cost from auto to transit, transit to transit respectively.

2.2 Shortest path searching method for multi-mode network

The multi-mode integrated network should consider the cost of transfer among travel modes, for instance, auto to public transit. In general, finding shortest path for public transit is more difficult than that of auto on the surface road network. The reason is that a link of public network has several transit lines and transfers between transportation modes. This property makes much hard to find the fastest path on the public network. In special, transfer behavior leads the conventional algorithms further difficult in finding optimal path because Bellman's ' Principle of Optimality' does not hold. Regarding this problem, more detailed descriptions are found in Kim and Lim (1999). Several approaches have been proposed for solving the problem. Among all methods currently available, the widely used method is network expansion, adding extra nodes and extra links to original network and modifies the network to easily implement conventional shortest path algorithm. Additional links represent the transfer between modes. Such kinds of techniques are found in Modesti et al. (1998) and Lam et al.(1999). The principal advantage of this method is that it can describe the mode change behavior perfectly. The method, however, has limitation of expanding network as the size of network increases. Recently Kim and Lim(1999) proposed a global searching method for finding shortest path with genetic algorithm. The method has a merit of no network expansion, but also has the disadvantage of computing time.

To overcome the limitations above-mentioned, in this paper we developed a Link-based Shortest Path Algorithm(LSPA) under integrated network. LSPA does not require the network expansion, thus enable to save the time of network modification and of computer running. The algorithm builds the shortest path based on the link-end cost instead of node cost and constructs path between origin and destination by link connection. The concept of link-based searching method was originated from Potts & Oliver(1972) in order to consider turn prohibitions. They, however, did not expand the idea into integrated network that has transfer between modes, which is principal issue in this paper.

Let a network consist of a set of nodes and a set of links connecting the nodes. The nodes are also referred to as vertices or points. The links are also called arcs, edges, and branch. A network can be represented by the notation G=(N,A) , where N is the set of nodes and A the set of links of the network G . Let LC(i,j) be the nonnegative link cost required to travel from node i to node j and LEC(o,i) be the link end cost, or minimum path cost from origin to node i through link(o,i) which refer to the directed link leading from node o to node i. MCC[link(o,i),link(i,j)] is the mode change cost which implies the transfer cost at node i between modes from link(o,i) to link(i,j) as shown in Figure 3. Let MT[link(i,j)] be mode type of the link(i,j). MCC[link(o,i),link(i,j)] is equal to zero if the mode of link(o,i), MT[link(o,i)] , and the mode of link(i,j). MT[link(i,j)] are the same, otherwise MCC[link(o,i),link(i,j)] has a positive transfer cost. With these notations we can define the link-based shortest path optimality condition for integrated transportation network which has a transfer between modes as follows.

$$LEC(o,i)+MCC[link(o,i),link(i,j)]+LC(i,j) \leq LEC(i,j), \qquad \text{FOR ALL } o,i,j \in N \tag{7}$$

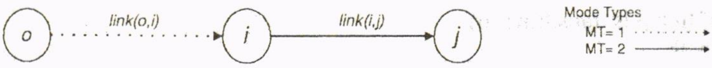

Figure 1. Basic concept of LSPA and Mode change(transfer)

The optimality condition in equation (7) has a unique solution, because we can easily take over the optimality theorem already proved for node-based cases by simply replacing link costs with the sum of link costs and transfer costs, MCC. The optimality theorem for node-based searching method is explained fully in Potts & Oliver(1972). In that paper, instead of preceding nodes in conventional shortest path algorithms, preceding links are used to memorize the track of shortest path. The preceding link from node i to node j , PL(i,j), of Figure 1 is defined as

$$PL(i,j)=link(o,i) \tag{8}$$

i.e. PL(i,j) is the link immediately before link(i,j) on the shortest path. Based on the equation (7) and (8), the steps of link-based shortest path algorithm are listed in Lim et al. (2001).

3. INTEGRATED MODEL AND ITS SOLUTION ALGORITHM

This paper analyzes the equilibrium problem over the multi-modes network. A feasible flow set will be called an equilibrium solution if it satisfies the conditions proposed by Wardrop(1952) over the network. However, since two transportation modes are dependent of each other in the paper, the link travel cost is asymmetric. Thus a mathematical equivalent program is not existed. Therefore we have formulated it as a variational inequality problem as follows. These kinds of formulations are proposed by several researchers(Cea et al.;1993 and 1996, Lee S. et al.;1996).

$$G(V) \equiv t(V_p^*)^T \bullet (V_p^* - V_p) \leq 0 \tag{9}$$

Where $t(V)$ is a vector, $\{ t_{inveh,p}, t_{wait,p}, t_{tran,p} \}$ and $V_p = \{ V_{start,p}, V_{thr,p}, V_{tran,p} \}$. V_p^* is link flow vector at equilibrium state. With the gap function G(V) of equation (9), Hearn(1982) has proved that if the value of G(V) be identical to zero, Wardrop's equilibrium is obtained. A solution algorithm is developed to solve the variation inequality problem as follows. The algorithm leads the gap value to zero as solution procedures execute.

[STEP 1] Initialization

Set initial feasible solution and $V_p^0 = \{ V_{start,p}^0, V_{thr,p}^0, V_{tran,p}^0 \}$.

n=1

[STEP 2]

2.1 Searching minimum path with LSPA based on $t_p^0 = t_p(V_p^0)$

2.2 Perform All-or-Nothing assignment along with minimum path and yields V_p^n

[STEP 3] Cost update

Updating link cost $t_p^n = t_p(V_p^n)$

Where, $t_p^n = \{t_{inveh,p}^n, t_{wait,p}^n, t_{tran,p}^n\}$

[STEP 4] Direction Finding

4.1 Minimum path searching based on t_p^n

4.2 Perform All-or-Nothing assignment and

yields a set of auxiliary flows $y_p^n = \{ y_{start,p}^n, y_{thr,p}^n, y_{tran,p}^n \}$.

[STEP 5] Determination of moving size

Calculating α_n that solves Gap function $\min_\alpha G(V_p^n + \alpha_n(y_p^n - V_p^n))$

[STEP 6] Updating link flow

Set $V_p^{n+1} = V_p^n + \alpha_n(y_p^n - V_p^n)$

[STEP 7] Convergence test

If $V_p^{n+1} \cong V_p^n$, stop and V_p^{n+1} is equilibrium solution.

otherwise set n=n+1 and go to [step 3]

4. NUMERICAL EXAMPLES

Three numerical examples are given to test the model developed in this paper. The first example shows the convergence and some properties of the model. The second and third examples explain the applications of this model to traffic management fields in real world.

4.1. Example 1

The first numerical example is presented to assess the developed integrated model and to compare it with the combined model. The example network is shown in Figure 2, including one origin-destination pair from node 1 to node 3 and four links. Each link represents for its transportation mode as shown in the figure. A combined model proposed by Sheffi(1985) is compared with the integrated model. The transportation modes in figure 2 and network data such as free flow speed, capacity and headway of transit are given in Table 1. Assume that origin-destination demand is 20,000 passengers per hour and the ratio of vehicle occupancy is 1.4 passengers per car, which represent the converting factor between the number of auto and the number of transit passengers. Transfer penalty is also assumed 30 seconds from auto to transit.

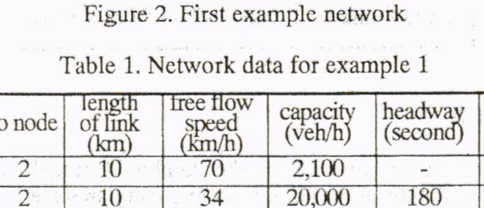

Figure 2. First example network

Table 1. Network data for example 1

links	from node	o node	length of link (km)	free flow speed (km/h)	capacity (veh/h)	headway (second)	mode type
1	1	2	10	70	2,100	-	auto
2	1	2	10	34	20,000	180	transit
3	2	3	10	50	1,000	-	auto
4	2	3	10	34	20,000	180	transit

Convergence of the model

The first example is presented to illustrate the convergence of Wardropean equilibrium and the quantitative properties of the difference between integrated model and combined model. It is proven that if the value of gap function in variational inequality gets to zero, the solution algorithm reaches equilibrium(Hearn, 1982). Figure 2 explains that the integrated model has been converged to equilibrium. After several fluctuations at earlier iteration numbers, the value of gap function is settled down to be zero, which represents equilibrium. Another explicit proof that the model converged to Wardrop equilibrium is shown in table 2. Table 2 shows the results of the three path costs considered in the paper from node 1 to node 3. Note that it is not possible to transfer from transit to auto in the paper. The three paths are as follows; the first path takes auto first and keeps the mode to given destination, the second takes metro and also keep its mode. On the other hand, the last one takes auto first, but transfers its mode at node 2 and arrives to destination by transit. As shown in the table, the cost of first path consists of in-vehicle travel time on link 1 and in-vehicle travel time on link 3. In the second path the cost is composed of waiting time before boarding, in-vehicle travel time on link 2 and in-vehicle travel time on link 4. The last path has additional cost, transfer penalty, as well as in-vehicle travel times of each mode. The last column of the table 2 shows the cost of three paths and hereby we find that the figures of the path costs are very similar for each other. The results imply that the model converges to Wardrop equilibrium state of which all paths between any O-D pair have equal and minimum costs. This results also explain that the model consider explicit transfer behavior of passengers. With the results in figure 2 and in table 2, it is shown that the integrated model and its solution algorithm converge to Wardrop equilibrium stably.

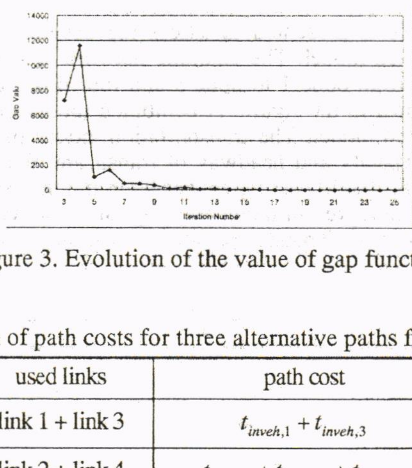

Figure 3. Evolution of the value of gap function

Table 2. Comparison of path costs for three alternative paths from node 1 to node 3

paths	used modes	used links	path cost	path cost(sec)
1	auto	link 1 + link 3	$t_{inveh,1} + t_{inveh,3}$	2210.0
2	transit	link 2 + link 4	$t_{wait,2} + t_{inveh,2} + t_{inveh,4}$	2210.7
3	auto + transit	link 1 + link 4	$t_{inveh,1} + t_{tran,4} + t_{wait,4} + t_{inveh,r}$	2210.2

Comparison of the models

From now we will compare the model with the combined model of Sheffi(1985). Table 3 shows the mode splits of the transportation modes and compares the integrated model with the combined model. In the integrated model auto takes 23.20% in total trips at departure, but after traveling it takes only 10.25% at arrival. The rest of the passengers arrived at destination were transferred into transit at transfer node, thus the mode split of transit increases from 76.80% at

departure to 89.75% at arrival.
On the other hand, in the combined model auto and transit have constant mode splits for each other and no transfer is occurred. The reason comes from the fact that the combined model computes the mode splits before starting trip, which is a basic assumption of the model. Hereby each mode keeps its fixed mode split through traveling from origin to destination, which is, however, unrealistic in real world.

Table 4 shows the changes of mode split for auto with varying demands from 5,000 passengers/hour to 30,000 passengers/hour incrementally. In the integrated model, as we expected, the mode split of auto at the time of departure is different from the one at arrival because of transfers on the way of traveling. While the combined model has the same values of mode split for each demand patterns. From the figures in the table, compared with the integrated model, we find that the combined model produces the same value between the split value of departure and of arrival, thus at departure the combined model is likely to underestimate the split of auto. This implies that the mode split values of auto from the combined model are close to the values from the integrated model at arrival. The phenomenon is getting stronger as the travel demands are increased. Table 4 also depicts that in the integrated model as the travel demand increases the mode split of auto decrease, since traffic congestion on the road network occurs. Decreasing the split of auto also decreases the proportion of transfer as shown in the table, but the split of transit increases instead. However, the auto split of combined model keeps a fixed value irrespective of increasing demands.
Comparing the performance of the model and algorithm proposed in this paper with the combined model, we may conclude that the integrated model enables to describe the behavior of passenger more preciously than the combined model.

Table 3. Comparison of modal splits between integrated model and combined model

		mode split at departure(%)	mode split at arrival(%)	proportion of transfer(%) from auto to transit
Integrated model	auto	23.20	10.25	12.95
	transit	76.80	89.75	
Combined model(Sheffi)	auto	12.03	12.03	0
	transit	87.97	87.97	

Table 4. Changes of the auto split with varying OD demands

			Travel Demands(passengers/h) from node 1 to node 3					
			5,000	10,000	15,000	20,000	25,000	30,000
auto split(%)	Integrated model	at departure (A)	94.5	46.9	31.1	23.2	18.5	15.3
		at arrival(B)	40.2	20.2	13.6	10.3	8.3	6.9
		proportion of transfer (A-B)	54.3	26.7	17.5	12.9	10.2	8.4
	Combined model	at departure(A)	48.1	24.0	16.1	12.0	9.6	9.0
		at arrival(B)	48.1	24.0	16.1	12.0	9.6	8.0
		proportion of transfer (A-B)	0.0	0.0	0.0	0.0	0.0	0.0

4.2. Example 2

The second example is presented to explain the applicability of the integrated model to real world. We expect that the model is also available to assess some traffic management schemes, which are widely used to alleviate traffic congestion on urban road network. So far it is not easy to assess the effects of such schemes precisely because adequate evaluation tools are not affordable. In this paper with the integrated model we assess three management schemes. The example network is the same in figure 2 of example 1. Here are four management scenarios as follows.

Do-nothing : no management schemes performs
Expanding road capacity : increasing capacities of link 1 and link 3 by 30% for auto
Levying congestion toll : congestion toll(additional 30% of link cost) is levied on link 3
Increasing transit speed : speed up transit velocity by 30%

Table 5 shows the results of each management scenarios. From the table we find that the figures are very reasonable. Compared with do-nothing scenario, road expansion increases the usage of auto while transit in decrease. This implies that highway capacity expansion may make a shift of transportation mode from transit to auto by some commuters. In this respect, highway capacity increases tend to result in unforeseen consequences of transportation system. One of them is known as the Downs-Thomson paradox that hypothesizes that highway capacity improvements may actually increase overall congestion and travel times in variable travel demand environment. But the paradox does not exist in this paper. On the other hand, levying congestion toll leads to decrease the split of auto at departure and also leads to further transfer to transit, as expected. Most of passengers shift their modes before congestion toll link and access their destinations by transit. Among the scenarios, increasing transit speed is most beneficial scheme for passengers as shown in the table. It encourages passengers to use transit and to save the travel time. Although the test network is very simple, from the results of the table we may conclude that the integrated model could be used for assessing the traffic management schemes.

Table 5. Numerical results for management schemes

anagement Scheme		mode split(%)		roportion of transfer(%)	total travel time (passenger-hour)
		at departure	at arrival		
Do-nothing	auto	23.20	10.25	12.95	17,191
	transit	76.80	89.75		
Expanding road capacity	auto	30.99	13.30	17.69	17,187
	transit	69.01	86.70		
Levying congestion toll	auto	22.89	8.84	14.05	17,198
	transit	77.11	91.16		
Increasing transit speed	auto	19.07	8.55	10.52	13,167
	transit	80.93	91.45		

4.3. Example 3

The third example is presented to test the efficiency of transportation management schemes as shown in figure 4. This network includes 10 nodes and 19 links, of which 15 links(dashed lines) represent for road network and 4 links (dotted lines) represent for transit network. Each node such as 1, 3, 5, 8, 10 is a transit station, where passengers are able to transfer from auto to transit through a given transfer cost. The input data for network is shown in table 6. In this table, it is postulated that the average headway of subway, h, is 180 seconds, the average speed of subway is 34km/h, as the parameters of cost function, $t_{wait,\ p}$, the value of $\alpha_{transit}$, $\beta_{transit}$, n is 2, 0.2, 1.5 and the value of α_{auto}, β_{auto} is 0.15, 4 respectively. And it is postulated that the transfer cost from auto to transit is 60 seconds and it is impossible to transfer from transit to auto. The network between origin and destination pairs is presented as shown in table 6.

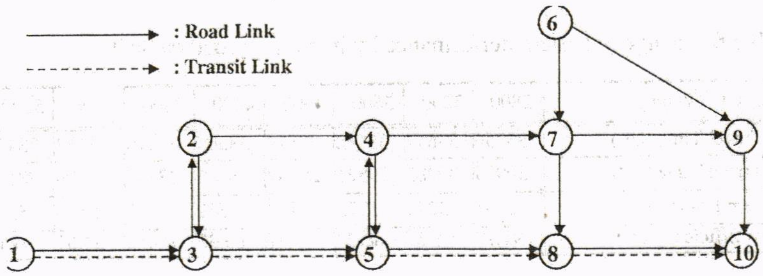

Figure 4. Representation of sample network

Table 6. Change of system performance by increasing road capacity

Link number	From node	To node	Link length (km)	Design speed (km/h)	Link capacity	Link type
1	1	3	10	80	2,800(veh/h)	Auto
2	2	3	5	80	2,800(veh/h)	Auto
3	2	4	10	70	2,100(veh/h)	Auto
4	3	2	5	80	2,800(veh/h)	Auto
5	3	5	10	80	2,800(veh/h)	Auto
6	4	5	5	60	1,400(veh/h)	Auto
7	4	7	10	70	2,100(veh/h)	Auto
8	5	4	5	60	1,400(veh/h)	Auto
9	5	8	10	80	2,800(veh/h)	Auto
10	6	7	5	60	1,400(veh/h)	Auto
11	6	9	12	60	1,400(veh/h)	Auto
12	7	8	5	60	1,400(veh/h)	Auto
13	7	9	10	70	2,100(veh/h)	Auto
14	8	10	10	80	2,800(veh/h)	Auto
15	9	10	5	70	2,100(veh/h)	Auto
16	1	3	10	34	20,000(per/h)	Transit
17	3	5	10	34	20,000(per/h)	Transit
18	5	8	10	34	20,000(per/h)	Transit
19	8	10	10	34	20,000(per/h)	Transit

Table 7. OD trip demands

O/D pairs	Origin	Destination	Demand(Person/h)
1	1	10	20,000
2	2	8	10,000
3	6	10	5,000

Case 1 (expanding road capacity)

In this case we will show how the system loss cost and the system efficiency would be changed by increasing the road capacity. The roads with expanding capacities are the set of link number {1, 2, 4, 5, 9, 14}, which is connected from origin node 1 or 2 to destination node 10 each other and overlapped with transit line. The capacity of this road is supposed to expand from 2,800 vehicles/h to 5,600 vehicles/h by increasing 400 vehicles/h respectively, as shown in table 8.

Table 8 shows that as the road capacity expands, the system loss cost and the system efficiency decrease. This result would be come from the fact that the decreasing rate of gross system optimum (SO) state override the decreasing rate of gross user equilibrium (UE) state. In UE state the capacity of this road increase twice, but the total travel time decrease at the rate of 0.96%. This means that the users' travel condition is not improved by the expanded capacity of roads.

Table 8. Change of system performance by increasing road capacity

Capacity (Veh/h)	2800	3200	3600	4000	4400	4800	5200	5600
Total Travel Time (UE)	33756	33657	33592	33544	33505	33476	33452	33431
Total Travel Time (SO)	30955	30382	29821	29442	28925	28761	28304	28114
System Loss Cost	2801	3275	3771	4102	4580	4715	5148	5317
System Efficiency (%)	91.70	90.27	88.77	87.77	86.33	85.91	84.61	84.10

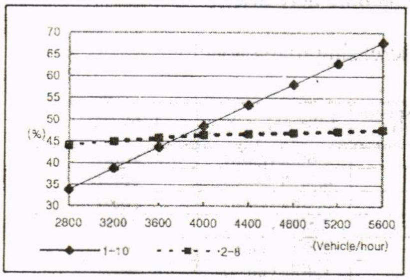

Figure 5. Change of mode split at arrival by O/D pair

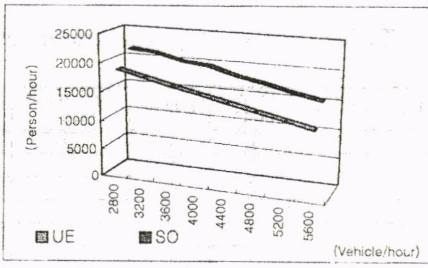

Figure 6. Change of transit passengers by system state

Expanding road capacity, however, influences very differently on mode split, especially on auto use. As shown in figure 5, when the origin-destination traffic volume is fixed, the mode split of auto increases twice from 33.88% to 68.80% on the path from node 1 to node 10 in user equilibrium state. On the other hand, in case of the path from node 2 to node 8 the mode split of auto increases slightly from 44.03% to 47.63%. This is because the decreasing rate of travel time in expanding road is relevantly low. Figure 6 shows that the number of transit passengers decreases as the road capacity increases. While the travel time from origin node 1 to destination node 10 decreases from 4,335 seconds to 4,328 seconds, the travel time from node 2 to node 8 decreases slightly from 3,057 seconds to 3,049 seconds and also the travel time from node 6 to node 10 decreases from 2,216 seconds to 2,165 seconds. The weighted average travel speed on road network increases from 48.49 km/h to 53.70 km/h.

As shown above, the policy to mitigate road congestion by means of expanding road capacity would not have significant effects on system efficiency. But expanding road capacity would be needed for future travel demand in the long run perspective. These results would be come from the fact that the transit passengers might transfer to autos owing to the increasing speed on road network. And this policy would bring about diminishing the revenue in public transport such as transit.

Case 2 (levying congestion toll)

In this case the main purpose is to test the impacts on the transportation system when the congestion toll is levied on a part of the links in road network. It is postulated that congestion toll is levied from 0 to 1400 Won on link 9, where has the heavy traffic in the tested network. To take into account the increasing cost by levying congestion toll, the value of travel time is postulated as 6,800 Won/h. The congestion toll increases with the total cost in the perspective of the generalized cost, but it is excluded in computing the results such as travel speed. As shown in table 9, the more congestion toll increases, the more system efficiency increases. This result was expected already in chapter 3. Table 9 shows that the total travel time increases a little in both cases of user equilibrium and system optimum condition.

Table 9. Change of system performance by levying congestion toll

Congestion Toll (won)	0	200	400	600	800	1000	1200	1400
Total Travel Time (UE)	33756	33756	33756	33763	33796	33828	33861	33861
Total Travel Time (SO)	30955	31071	31240	31435	31474	31615	31810	31901
System Loss Cost	2801	2686	2517	2329	2322	2214	2051	1960
System Efficiency (%)	91.70	92.04	92.54	93.10	93.13	93.46	93.94	94.21

Figure 7 shows the change in traffic volume of autos according to levying more congestion toll. On the path from node 1 to node 10, the traffic volumes at start decrease from 6,775 person/h, on both cases of those at start and at arrival in the case of levying no congestion toll, to 6,507 persons/h at start and to 6,275 persons/h at arrival in the case of levying congestion toll 1,200 Won. Especially the transfer from auto to transit occurs more significantly by levying congestion toll more than 1,000 Won. On the path from origin node 2 to destination node 8 the effect of decreasing travel demand occurs more sharply because the path from node 2 to node 8 is shorter than the path from node 1 to node 10 and the toll is levied on the link from node 5 to node 8 near to the destination node 10. The travel demand of auto decreases from 4,403 persons/h on node 2 to 3,575 persons/h on node 8 at the diminishing rate of 18.8%.
In the perspective of transit passengers, figure 8 shows that at station 1 the transit passengers increase slightly from 13,225 persons/h to 13,493 persons/h, but at station 3 the transit passengers decrease a little from 5,157 persons/h to 4,871 persons/h. On the other hand, at station 5 the transit passengers increase more than 4 times from 439 persons/h to 1,787 persons/h, owing to the more fast increase of transfer passengers from auto to transit. But at the station 3 the transit passengers decrease owing to the more fast decrease of transfer passengers, which is considered because the level of road congestion is reduced by levying congestion toll on the road path from node 5 to node 8, and the level of transit congestion is increased.

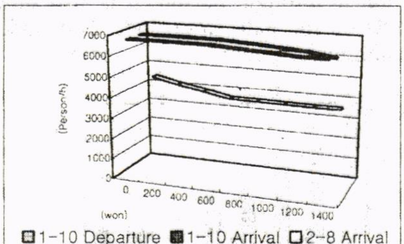

Figure 7. Change of auto traffic volumes by O/D pair

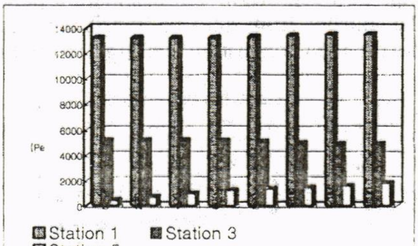

Figure 8. Change of transit passengers by station

In the perspective of the travel time from origin to destination, the total travel time from node 1 to node 10 is seldom changed and the total travel time from node 2 to node 8 increases from 3,057 seconds to 3,148 seconds, but the total travel time from node 6 to node 10 decreases from 2,216 seconds to 2,014 seconds. In case of the path from node 1 to node 10, the total travel time rarely increases, because the length of this path is relatively longer than any other path and there are other alternative paths between node 1 and node 10, which excludes the link with levying congestion toll. On the other hand, the generalized travel cost increases on the path from node 2 to node 8, because the length of this path is relatively shorter and there are few alternative paths between node 2 and node 8. On the path from node 6 to node 10 the travel time of auto decreases owing to the decrease of auto traffic volumes. The average travel speed on road network is improved from 37.64 km/h to 40.52 km/h.

Case 3 (increasing transit speed)
In this case the change of system performance is presented by increasing the travel speed from 34 km/h to 62 km/h at the rate of 4 km/h.

Table 10. Change of system performance by increasing transit speed

Operation Speed (km/h)	34	38	42	46	50	54	58	62
Total Travel Time (UE)	33756	30560	28109	26095	24404	22928	21696	20557
Total Travel Time (SO)	30955	28349	26462	24778	23392	22216	21147	20205
System Loss Cost	2801	2211	1647	1318	1012	712	549	351
System Efficiency (%)	91.70	92.77	94.14	94.95	95.85	96.89	97.47	98.29

Table 10 shows that both the total travel time and the system loss cost decrease at the diminishing rate. The total travel time decreases from 9.5% to 5.2%, and the system loss cost also decreases in the range from 21% to 36% by increasing the travel speed of transit at the rate of 4km/h. It is noticeable that the total travel time and the system loss cost in this case decrease by means of increasing transit speed, while the total travel time increases by means of levying congestion toll on a part of road network.
As shown in Figure 9, while the travel time from origin node 1 to destination node 10 decreases more sharply, the travel time between other origin-destination pairs decreases relatively lower. Figure 10 shows that the auto traffic volumes at arrival decrease more largely on the path from node 1 to node 10, but the auto traffic volumes on the path from node 2 to 8 seldom decrease. These results imply that the effect of decreasing travel time and that of increasing transfer from auto to transit between linkable origin-destination node pairs by means of improving subway system are large. But these also imply that the transfer rate between travel modes and the decreasing rate of travel time would be relatively low in case of the paths between origin and destination pairs using transit through transfer. It is also shown that the transfer from auto to transit has little impacts on the path from node 2 to node 8 because the road congestion is mitigated owing to the diminishing auto traffic volumes.

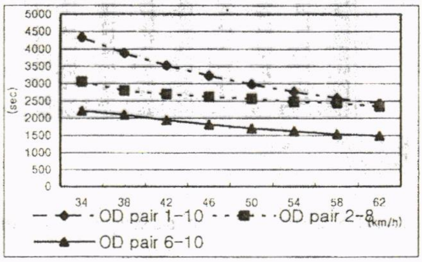

Figure 9. Change of travel time by O/D pair

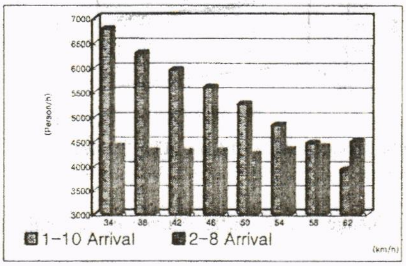

Figure 10. Change of auto traffic volumes at arrival

The average travel speed on the network increases from 37.64 km/h to 51.16 km/h, and the transit passengers also increase from 18,821 persons/h to 21,575 persons/h.

5. CONCLUSION

Even though passengers' travel behaviors are influenced by diverse factors, existing models have not fully considered such impacts. One of them is transfer to minimize disutility. In this paper an integrated network model considering explicit transfer behavior between transportation modes has been developed and also proposed a solution algorithm. Analytical approach is used to obtain a Wardrop's equilibrium between auto and transit mode. To test the efficiency of the solution algorithm, we compared it with the combined traffic assignment model proposed by Sheffi(1985). From the test results, the integrated model was brought out to be superior to others as we expected. Summaries of the results are followed.

Firstly, for each transportation mode it is possible to obtain the mode splits of origin and of destination respectively and able to consider the transfer behaviors of passengers.

Secondly, from the experimental test results with an example network, Case 3(Increasing transit speed) is the best scheme for improving transportation network. Case 1(Expanding road capacity) improves network condition (or reduces congestion) slightly, but leads to change the mode choice pattern from transit to auto significantly. Case 2(Levying congestion toll) also improves the system efficiency and the running speed of road network, but the generalized cost of users in network increases slightly. On the other hand, Case 3) reduces the generalized cost(the summation of travel cost and monetary cost) and improves the network condition. This result implies that case 3) is beneficial to road users and system manager as well.

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