COMPARISON OF SUSTAINABILITY BETWEEN PRIVATE AND PUBLIC TRANSPORT CONSIDERING URBAN STRUCTURE

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It is said that the car is convenient but consumes high-energy per passenger, while public transport is an environmentally friendly mode but needs high cost of investment and management. However, this view does not take account of urban structure such as population size and density. For instance, higher population density would cause congestion and consequent inconvenience for car usage. This may shift demand to public transport use. On the other hand, in a lower density of urban area, public transport attracts only a small passenger demand and thereby accounts for a high-energy consumption per passenger than private cars. The urban structure therefore can be the dominant factor for determining the effectiveness of urban transport.

The urban structure is affected by the provision of transport infrastructure and its service level. In classical urban economic models, the location of agents and urban shape vary depending on the transport conditions. Therefore, the urban structure and transport effectiveness are inter-dependent. Even if the population size and density is the same, the efficiencies of private and public transport might be different due to the urban structure because of their historical pattern of land use and transport development.

In this paper, we present the interaction between urban structure and transport using a simple urban-transport model. We also examine the sustainability, measured by economic efficiency and environmental impact, of private and public transport in a hypothetical urban space. In this regard, it is specially focused on the path dependence of urban-transport interactions, and showed the possibility of multiple urban and transport situations. Several policy implications are proposed for utilizing the results of the models.

Key Words: Effectiveness of public/private transport, Urban structure, Compact city, Sustainability, Path dependence

1. INTRODUCTION

The effectiveness of private and public transport has been discussed for a long time in the context of sustainability. Previous studies[1,2] have shown that private car dependence is generally recognized as the largest factor of atmospheric pollutant emissions from the transport sector and use of public transport brings to a reduction in emissions. However, financial sustainability of public transport totally depends on population density[3]. New urban design concepts were also proposed as the name of compact city[4] and TOD[5], which is high population density, shorter trip length of transport and reduction of emissions of air pollutants from vehicles. The negative effects of these concepts are also argued. It is likely to oppose high density development against people to prefer living in lower density habitation and reduce the quality of life[6]. High density would cause traffic congestion and pollutant concentration, and so on. In this context, private car usage is better than public transport. Although these hypothetical propositions seem to be true, its validity might depend on the entire urban condition such as population size, geometric conditions, quality and quantity of infrastructures, cost structures of transport service, tax system/regulations, people's preferences and behavior, and so on. For instance, if there is a big enough population and adequate public transport services, relevant urban policy will realize the compact city that reduces environmental deterioration and improves the efficiency of people's activities. Contrarily, a strict zoning system for shrinking the urban area may not bring any environmental improvement due to congestion in the case of high-cost structure of public transport and dependence on private cars. In this case, sustainability of the urban activities would be severely aggravated. What conditions can determine the effectiveness of private/public transport? In order to answer this question, we need to identify the mechanism of interactions among transport and land use by considering their conditions and people's behavior. As these interactions have been accumulated by past studies[7,8] we can employ this knowledge and results.

The objective of this study is to examine the relationship between urban conditions and effectiveness of private / public transport by using a simple land use-transport model in hypothetical urban space. In chapter 2, we discuss what would be indices of effectiveness in transport policy analysis. Chapter 3 introduces the land use-transport model and discusses its proparties and interpretation in practical situation. In chapter 4, possible urban /transport situations are investigated by implementing this model to hypothetical urban space, and environmental and economic effectiveness of public /private transport are examined. Finally, policy measures for achieving both economic and environmental effectiveness improvement are discussed.

2. EFFECTIVENESS AS EVALUATION INDICES

What could be the appropriate index of effectiveness for transport from the standpoint of users? Policy makers generally use the cost-benefit ratio as one of the indices in feasibility studies. Fuel consumption rate of individual cars may also be the effectiveness index for car users. So, the indices of effectiveness would be different depending on the focus of an evaluation objective. The concern in this study is about comparison of sustainability, consisting of economical and environmental effectiveness, between car and rail and also their dependence on the urban structure. Therefore, static and absolute effectiveness indices can be appropriate rather than comparative or incremental change indices by policy impact.

On the other hand, our point of view for the comparison is on economic and environmental effectiveness because these two indices may characterize the impact of public/private transport modes on quality of life as mentioned in chapter 1. The simple static and absolute indices of cars or rail may be the generalized cost for users and volume of emissions. The former is the sum of the actual cost and time cost. In case of the private car, the actual cost would be determined by car price, maintenance costs and fuel consumption, and the time cost could be defined by the congestion rate on road links. In the case of rail, the actual cost is fare price and time cost which is defined by the time on board and waiting time. Regarding emissions, we consider green house gases such as CO_2 for comparison between public and private transport. The amount of CO_2 emission is almost in proportion to energy consumption. So, emission from a car depends on the number of vehicles and their total trip length, while emission from rail may depend on the product of trip length and frequency of train operation. This means that the larger number of passengers in each a coach reduces emissions per capita.

Therefore, congestion on roads, frequency of rail services and their trip length have to be considered in the proposed model. As to capture the property of each mode and the interaction between urban structure and transport, we will introduce a simple multi zonal land-use/transport model in next chapter.

3. LAND USE-TRANSPORT MODEL FOR CAPTURING EFFECTIVENESS

The objective in this chapter is to formulate the mechanism of land use-transport interaction and to identify its property using economic /environmental indices discussed in the previous chapter. The discrete type land use model[9] can be utilized to show the mechanism and capture the effectiveness indices. This model is originally described in a general equilibrium manner, but we focus on the interaction. Therefore, only location /travel behavior of household and transport /floor rent markets are considered for simplicity. Service conditions of public transport are added to compare with private transport effectiveness.

3.1 Formulation of the interaction mechanism

This model includes two types of agents: household and landowner, and transport conditions. We assume that; 1) all households make commuting trips to the CBD zone, choose a transport mode from private car or rail, select a residential location from discrete zones, and consume goods and floor for residence; 2) generalized cost of each transport mode and floor rent are determined in transport and floor market respectively; and 3) total number of households is given exogenously. In this section, firstly the behavior of household, landowner and transport service level due to demand are formulated. Secondly, market conditions of transport and floor rent are introduced. Finally, its equilibrium condition, which determines the transport demand and zonal population, is derived.

(1) Behaviors and transport service formulation

Household behavior

Households select zone i for residence and transport mode k for commuting, and determine the consumption of goods Z and floor area for residence A so as to maximize their utility U under the constraint of income I. This behavior is drawn as below:

$$\max_{Z,A}(U = \alpha_Z \ln Z + \alpha_A \ln A) \tag{1}$$

$$\text{s.t. } I = p_z \cdot Z + p_{a,i} \cdot A + p_{i,k} \tag{2}$$

where, p_z: price of goods, $p_{a,i}$:unit floor rent, $p_{i,k}$: generalized commuting cost from zone i by mode k, α_Z,

α_A : parameters ($\alpha_Z + \alpha_A = 1$).

Solving this problem and assuming error terms given by Gumbel distribution with variance θ in utility function, travel demand $Q_{i,k}$ and total floor area demand A_i are derived as follows:

$$Q_{i,k} = Q \cdot \Psi_{i,k}(\mathbf{p}_t, \mathbf{p}_a : \theta) \tag{3}$$

$$A_i = Q \cdot \sum_k \Psi_{i,k}(\mathbf{p}_t, \mathbf{p}_a : \theta) \cdot A_{i,k}(p_{ik}, p_{ai}) \tag{4}$$

where, Q is total number of households, $\Psi_{i,k}$ is choice probability of zone i and mode k as formulated below:

$$\Psi_{i,k}(\mathbf{p}_t, \mathbf{p}_a : \theta) = \frac{(I - p_{i,k})^{\theta} / (p_{ai})^{\alpha_A \cdot \theta}}{\sum_{i',k'} (I - p_{i',k'})^{\theta} / (p_{ai'})^{\alpha_A \cdot \theta}} \tag{5}$$

$A_{i,k}$ is floor area of each household in zone i, who choose mode k, which is denoted as:

$$A_{i,k} = \frac{\alpha_A}{p_{ai}}(I - p_{i,k}) \tag{6}$$

and $\mathbf{p}_t$, $\mathbf{p}_a$ are column vectors of generalized commuting cost by modes and zones and of floor rent by zones respectively.

Landowner behavior

Landowners maximize their profit Π by lending floor to household. They produce the floor A using land L and construction materials κ. This is defined as below:

$$\max\ (\Pi_i = p_{a,i} \cdot A_i - p_\kappa \cdot \kappa_i) \tag{7}$$

where,

$$A_i = \gamma_A L_i^{\gamma_L} \kappa_i^{\gamma_\kappa} \tag{8}$$

p_κ: price of materials, and γ_A, γ_L, γ_κ: parameters.

As a solution of equation (7), supplied floor area is derived as follows:

$$A_i = \left(\frac{p_{a,i}}{p_\kappa} \gamma_A^{\frac{1}{\gamma_\kappa}} \gamma_\kappa L_i^{\gamma_L/\gamma_\kappa} \right)^{\frac{\gamma_\kappa}{1-\gamma_\kappa}} \tag{9}$$

Road service condition

Road service can be measured by generalized cost $p_{i,c}$ that consists of fixed cost for car usage c_0, fuel cost c_f and time required for commuting $g_{j,c}$. It is defined as:

$$p_{i,c} = \Sigma_{j=1}^{i} (\omega \cdot g_{j,c} + c_f) + c_0 \tag{10}$$

where, ω is value of time, $g_{j,c}$ is required travel time between zone j and j-1, and c_f is fuel cost. The travel time is defined by following BPR type function.

$$g_{j,c} = \delta_0 \left[1 + (\Sigma_{j'=j}^{|\Omega|} Q_{j',c}/c_j)^{\delta_1} \right] \tag{11}$$

Ω is a set of zone numbers, $|\Omega|$ is the maximum number of zones, $Q_{j',c}$ is number of car users dwelling in zone j', C_j is road capacity index between zone j and j-1, and δ_0, δ_1 are parameters.

From these equations, generalized cost for commuting by car is interpreted as function of car travel demand denoted as:

$$p_{i,c} = p_{i,c}(\mathbf{Q}_c) \tag{12}$$

where, $\mathbf{Q}_c$ is the column vector of zonal demand for a car.

Rail service condition

Service level of rail at zone i is also measured by its generalized cost $p_{i,r}$. It consists of fare $p_{f,i}$ and travel time cost. The travel time can be divided into "time on board" g_{bi} and "waiting time" g_{wi}. Time on board can be determined by travel distance and speed. Waiting time is defined by frequency H_i. It would be possible to consider that the frequency would be a function of demand under the capacity condition and minimum requirement for the service. We therefore assume the frequency is a function of rail demand as:

$$H_i = H_{\min,i} + \frac{H_{\max,i} - H_{\min,i}}{1 + \exp(\eta_1 \cdot Q_{ir} + \eta_2)} \tag{13}$$

where, $H_{min,i}$ and $H_{max,i}$ is minimum and maximum frequency of rail, $Q_{i,r}$ is rail demand in zone i, and η_1, η_2 are parameters.

We assume that the fare and minimum frequency are determined politically and maximum frequency is bounded by rail track capacity. Therefore, these factors are given exogenously. Frequency would increase in nature when demand $Q_{i,r}$ increases, therefore η_1 has to be negative. If we define the waiting time as,

$$g_{wi} = 1/(2H_i(Q_r)) \tag{14}$$

Generalized cost of rail is drawn as:

$$p_{i,r} = p_{fi} + \omega (g_{bi} + g_{wi}(Q_r)) \tag{15}$$

After all, the generalized cost of rail is also a function of demand $\mathbf{Q}_r$, and denoted as

$$p_{i,rail} = p_{i,rail}(\mathbf{Q}_r) \tag{16}$$

where, $\mathbf{Q}_r$ is the column vector of zonal demand for rail.

(2) Market equilibrium

Transport market

As equilibrium conditions of the transport market, the same cost and demand in equation (3), (12) and (16) is required. If 2 later equations are substituted into the former one, the equilibrium condition comes to:

$$Q_{i,k} = Q \cdot \Psi_{i,k}(\mathbf{p}_t, (\mathbf{Q}), \mathbf{p}_a{:}\theta) \tag{17}$$

for all i and k. Where, $\mathbf{p}_t(\mathbf{Q})$ means that all of the generalized travel costs are defined by the travel demands.

Floor market

At equilibrium point, rent and floor area have the same value in equation (4) and (9). Using equation (4), (6) and (9), the condition is derived as:

$$p_{ai}^{1-\gamma_1} = CL_i^{\gamma_2} \sum_k \Psi_{i,k}(\mathbf{p}_t, \mathbf{p}_a{:}\theta)(I - p_{i,k}) \tag{18}$$

for all i.

where, $\gamma_1 = \gamma_K/(\gamma_K - 1)$, $\gamma_2 = \gamma_L/(\gamma_K - 1)$, and

$C = \alpha_A Q(\gamma_A^{1/\gamma_K}\gamma_K/p_K)^{\frac{\gamma_K}{\gamma_K - 1}}$.

(see appendix A1 for derivation).

(3) Determination of demand

Both equations (17) and (18) will determine all the endogenous variables; travel demand, population, generalized travel cost and floor rent of each zone. In order to clarify the property of travel demand, integrate these 2 equations by eliminating rent variables.

For simplicity, we assume all the land input for floor production has the same constant value ($L_i \equiv L$ for $\forall_i$). Using equation (5) and (18), ratio of floor rent in zone i and s is:

$$\frac{p_{ai}}{p_{as}} = \left[\frac{\Sigma_k (I - p_{i,k})^{\theta+1}}{\Sigma_k (I - p_{s,k})^{\theta+1}}\right]^{\frac{1}{1-\gamma_1+\alpha_A\cdot\theta}} \tag{19}$$

In the same way, from equation (5) and (17), the ratio of demand for mode k in zone i and for mode τ in zone s is:

$$\frac{Q_{i,k}}{Q_{s,\tau}} = \left[\frac{(I - p_{i,k})}{(I - p_{s,\tau})}\right]^{\theta} \cdot \left[\frac{p_{ai}}{p_{as}}\right]^{\alpha_A\cdot\theta} \tag{20}$$

Substitution floor rent ratio in (20) with left side member of (19) derives:

$$Q_{i,k} = \left[\frac{(I - p_{i,k})}{(I - p_{s,\tau})}\right]^{\theta} \cdot \left[\frac{\Sigma_k (I - p_{i,k})^{\theta+1}}{\Sigma_k (I - p_{s,k})^{\theta+1}}\right]^{\Gamma} Q_{s,\tau} \tag{21}$$

where,

Here, Q is total population, the relation between Q and $Q_{s,\tau}$ is drawn as:

$$Q = \sum_{i,k} Q_{i,k} \tag{22}$$

From equation (21) and (22), the number of people who dwell in zone s and use transport mode τ is derived as:

$$Q_{s,\tau} = \frac{(I - p_{s,\tau})^{\theta} \cdot (\Sigma_k (I - p_{s,k})^{\theta+1})^{\Gamma}}{\sum_{i,k}\{(I - p_{i,k})^{\theta} \cdot (\Sigma_k (I - p_{i,k})^{\theta+1})^{\Gamma}\}} Q \tag{23}$$

Here, all the generalized costs for transport are function of demand vector $\mathbf{Q}$ as shown in equation (12) and (16). Therefore, equation (23) could be solved as a fixed-point problem. The property of this formula is examined by using the simplest numerical simulations in the next chapter.

3. 2 Property of modal choice behavior

This model is applied to simple cases in order to examine the modal and location choice behavior and those equilibrium solutions. We examine 1-zone and 2-modes case. There is only one residential zone, and residents commute to CBD by private car or rail.

(1) Property of solution

In this case, using equation (23), (12) and (16), the rail demand is derived as follows (see appendix A2):

$$Q_r = \frac{(I - p_r)^{\theta}}{\sum_{k\in\{c,r\}} (I - p_k)^{\theta}} Q \tag{24}$$

$$p_c = a_{c0} + a_{c1} \cdot (Q - Q_r)^{\delta 1} \tag{25}$$

$$p_r = a_{r0} + \frac{a_{r1}}{a_{r2} + a_{r3}\exp(\eta_1 Q_r)} \tag{26}$$

where, $a_{c0} = \omega\delta_0 + c_{fuel} + c_{car} > 0$, $a_{c1} = (1/C)\delta_1 > 0$, $a_{r0} = p_f + \omega g_b + \omega/2H_{min} > 0$, $a_{r1} = 1 - H_{max}/H_{min} < 0$, $a_{r2} = 2H_{max} > 0$, $a_{r3} = 2H_{min} \cdot \exp(\eta_2) > 0$

Here, we assume the function f defined as left side member minus right side of equation (24). Its derivative by Q_r is drawn as follows:

$$\frac{\partial f}{\partial Q_r} = 1 + \theta\Psi_r\Psi_c\left\{\frac{\partial p_r}{\partial Q_r}\frac{1}{(I - p_r)} - \frac{\partial p_c}{\partial Q_r}\frac{1}{(I - p_c)}\right\} \tag{27}$$

where, $$\Psi_r = \frac{(I - p_r)^{\theta}}{\Sigma(I - p_k)^{\theta}} \tag{28}$$

$$\Psi_c = \frac{(I - p_c)^{\theta}}{\Sigma(I - p_k)^{\theta}} \tag{29}$$

$\partial p_r/\partial Q_r$ and $\partial p_c/\partial Q_r$ are negative by definition, but positive/negative of equation (27) could be changed depending on Q_r. This means there might be plural solution of Q_r for equation (24). Hereafter, the solution property of Q_r is shown by simple numerical simulations.

(2) Simulation

The solution patterns are examined under several cases of car fixed costs. Table 1 shows the settings of all other parameters. Figure 1 shows the value of the right side member of equation (24) with change of Q_r. Here, the horizontal axis is Q_r and vertical axis is the left side member of equation (24) denoted as Q_r'. The solution is an intersection of the diagonal line and the curve, because those points satisfy equation (24). There are three cases of fixed cost of car: $c_0 = 0.3$, 0.6 and 0.9, are shown in this figure. The case of $c_0 = 0.6$ has only plural solutions and the other cases have unique solutions. In the case of $c_0 = 0.9$, the solution $S9$ means most people choose rail for commuting. The solution $S3$ in $c_0 = 0.3$ were conversely means most people use a car. In case of $c_0 = 0.6$, there are three intersection points, but $S6$-2 is an unstable solution. In this case, if there are more rail passengers than at $S6$-2, frequency of rail and number of rail users increases synergistically until it reaches to $S6$-3. Conversely, if there are fewer passengers than that point, these values decrease until $S6$-1.

These results imply the possibility of path dependence of modal choice. For example, if sufficient rail services were provided before motorization like current cities of developed countries, they might keep a certain volume of rail demand even though the cost of car usage was decreased. On the other hand, if railways were developed after motorization, the number of rail passengers would start from 0 and reach to $S6$-1. In this case, when rail demand exceeded the point of $S6$-2 by tentative modal shift policies, such as subsidization on railway management or taxation on car usage, it would reach $S6$-3 even if those measures were canceled. But in case of $c_0 = 0.3$, those policy measures might not draw sustainable modal shift to rail and demand would return to $S3$ when they are canceled.

Table 1 Parameter setting

Population Q		200	Unit rail fare p_f		0.5
Income I		10	Unit travel time g_b		0.07
Time value ω		10	Minimum freq. H_{min}		5
Fuel cost C_f		0.1	Maximum freq. H_{max}		200
BPR parameters	δ_0	0.1	Freq. parameters	η_1	-0.06
	δ_1	4		η_2	10
Road capacity C_{ij}		300	Distribution parameters θ		30

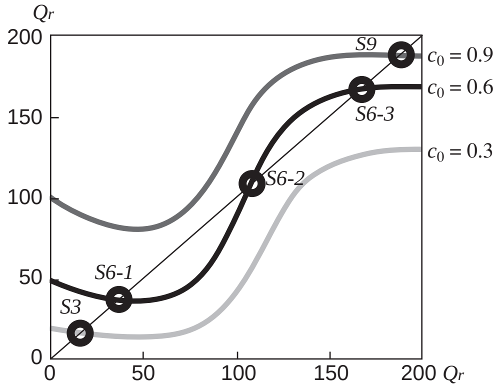

Fig. 1 Solution of equation (24)

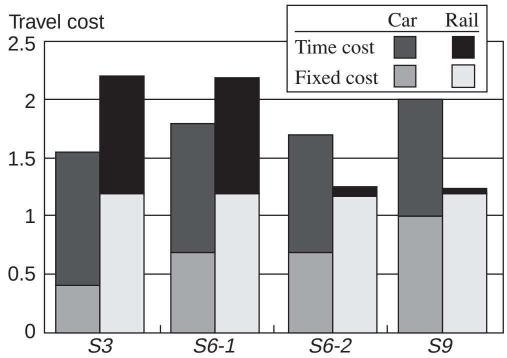

Fig. 2 Travel cost for each solution

Figure 2 shows the fixed cost and time cost for car and rail usage. It is defined that time cost will change by travel time for a car, and by waiting time for rail. Fixed cost of a car is becoming large due to the increase of c_0. At the point of $S3$ and $S6$-1, the time cost of rail is large because of a lower frequency. But at $S6$-2 and S9, it is so small that the total cost is lower than the car's one. At $S6$-2, in addition to the lower rail cost than $S6$-1, car cost is also slightly lower. This indicates modal shift to rail by increasing frequency of rail may reduce car travel demand and improve the congestion on roads.

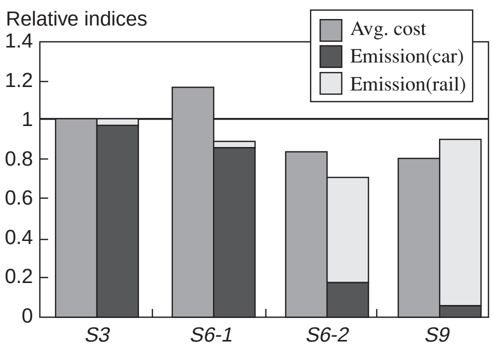

Fig. 3 Average cost and emissions

Figure 3 shows relative average travel cost and emission gas volume standardized by *S*3 case. Here, it is assumed that the emission from a car is 10-units / passenger-km and emission from rail is 10-units / train-km. This means that the more passengers on a train unit, the less emission per capita is exhausted from rail. On the other hand, emission from a car is assumed to increase linearly as the number of its users increases.

In this figure, only *S*6-1 is higher than *S*3 in average cost. This is due to doubled fixed cost of a car at *S*6-1. The demand of a car is slightly shifted and it affects reducing total emission. In the case of *S*6-2, both average cost and emission are lower than *S*3 and *S*6-1. In this case, frequency of rail is high enough to reduce generalized costs and attract more demand from the car. Consequently, car congestion is alleviated as shown in Figure 2, and the average cost be comes low. Total emissions from a car are surely lower due to an less demand, and emission from rail increases less than its demand increases. In case of *S*9, average cost is lower but emission is higher than *S*6-2. This is due to increase of more frequency than demand. Frequency of rail depends on its operation program in nature. If more passengers are accommodated in one train-unit and reduce frequency, the emission from rail will be reduced. But this may cut down the rail service level and encourage car usage, and consequently total emissions will increase.

In summary of this section, we examined the solution property of the model and the economic / environmental effectiveness of car and rail under a 1-zone 2-mode setting. It is cleared that: 1) modal shift from car to rail may be possible when the rail system has strong competitiveness with the car, 2) if modal shift from car to rail is realized, not only generalized cost of rail usage but also that of a car would be reduced, 3) in this case, both average cost and total emission could be reduced, 4) excessive rail service provision would reduce car usage but may bring a negative effect on the environment, and 5) in case of car costs are low enough or service provision cost of rail is high enough, modal shift would be impossible without essential renovation of the railway cost structure.

4. POSSIBLE URBAN-TRANSPORT SITUATIONS

As mentioned in chapter 1, the effectiveness of each transport mode may depend on the population and it's interaction with the urban structure. In this chapter, the impact of population change based on transport effectiveness is examined while considering the interaction with residential location choice behavior.

We assume a linear city consisting of seven residential zones and one CBD (central business district) zone. The zone number of CBD is 0 and a closer residential zone has a lower number. With this urban, the space, impact of total population change and road capacity improvement is examined here. Total population has been changed from 50 to 700 by intervals of 10, and 2 road capacity scenarios, $C_{ij} = 300$ and 350, are examined. All the solutions of equation (23) are calculated with the Monte-Carlo technique for each parameter set. Other parameters are fixed as shown in Table 2. Some parameters are determined referring to past studies[10,11], and the others are arbitrary. Relevance of these parameters is discussed in Appendix A3.

Figure 4 shows change of rail demand according to the population growth. The horizontal axis indicates total population and the vertical axis shows demand for rail. Rhombied and square shaped points indicate the case of $C_{ij} = 300$ and 350 respectively. Naturally, smaller road capacity case results in higher demand for rail. There are several gaps in demand increase in both cases. Around the discontinuity, two different rail demand are overlapped at the same population. This is the case of plural equilibrium solutions shown in the previous chapter. At this interval of population, appropriate policy measures may derive modal shift towards rail. But, the modal shift may not happen without those policies since high demand causes congested roads to loose precedence over rail system.

At lower population than these gap intervals, car usage has an advantage because of less congestion on roads and a lower frequency of rail. On the other hand, a larger population would break the limit of road congestion and drastic demand shift from car to rail would occur if the rail system potentially has a strong competitiveness against private cars. This modal shift would start to appear from the inner area. The gaps at a lower population in Figure 4 indicate the modal shift in closer number zones.

The effect of expanding road capacity is likely to move the rail demand curve towards the right-down direction in the Figure 3. This means that road investment would delay the modal shift. So, what kind of effects would be brought by modal shift from private car to rail?

Table 2 Parameter set for simulation

Parameters for HH behavior					
Population Q	50 to 700	Time value ω	10		
Income I	10	Goods price p_z	1		
α_A	0.5	Distribution parameter θ	15		
Parameters concerning car usage					
Car fixed cost c_0	1	Fuel cost c_{fuel}	0.1		
BPR parameter	δ_0	0.01	Road capacity C_{ij}	300 and 350	
	δ_1	2			
Concerning rail service					
Base rail fare p_{f0}	0.4	Increment fare d_{pf}	0.1	Time on board g_b	0.05
Freq. Parameters	η_1	-0.2	Minimum freq. H_{min}	5	
	η_2	20	Maximum freq. H_{max}	200	
Concerning floor production					
$\gamma_A = 1$	$\gamma_K = 0.5$	$\gamma_L = 0.5$			
Land input L	20	Price of materials p_κ	1		

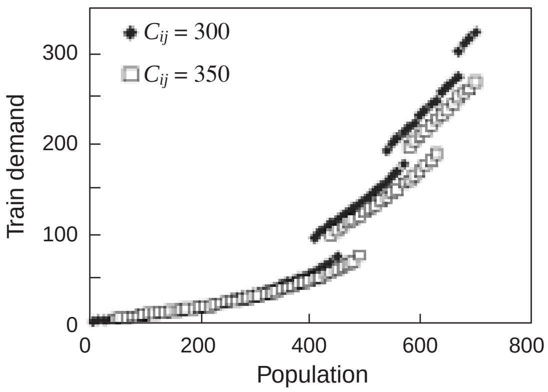

Fig. 4 Change of rail demand

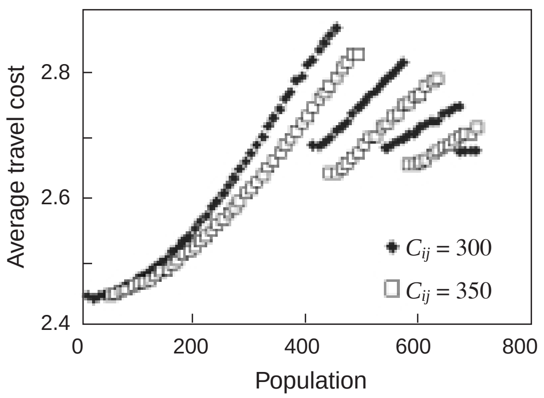

Fig. 5 Average travel cost

Figure 5 shows the average of generalized travel costs. It is clear that a larger population derives higher travel costs and expansion of road capacity reduces the average cost at the interval of a unique solution of modal share. But when modal shift once occurs, this cost drops down because rail frequency increases and road congestion decreases as shown in Figure 2. It is noteworthy that the cost in case of $C_{ij} = 300$ would be lower than that of $C_{ij} = 350$ when modal shift happened. This means road investment is not necessarily the best solution for economic efficiency improvement. This figure also shows that the cost in $C_{ij} = 300$ after modal shift is lower than that in $C_{ij} = 350$ before shift around a population of over 400. Of course, expansion of road capacity can reduce the travel cost of a car, but it shows that modal shift might have a more significant improvement of overall user cost. In this case, both road investment and modal shift would make travel cost sufficiently reduced.

Figure 6 shows the total emission from the transport in the two cases. The emission unit is assumed to be set in the same value as in chapter 3. In this figure, when the population is samll enough, both cases have almost the same total emission. But when the population becomes larger, the changing rate of emission against population is slower in the case of $C_{ij} = 300$ than in the case of $C_{ij} = 350$. That is due to the assumption of higher emission rate of car usage. Additionally, modal shift to rail brings a decline of emission.

However, the emission per user/passenger shows the different results especially at a small population. Figure 7 shows the emission per capita against population change in case of $C_{ij} = 300$. It is easily found that the rail exhausts produce much more emissions than cars when the population is very small because the rail emission rate is fixed to the train unit. Therefore, in the case of a small population, cars could be more environmentally friendly than rail.

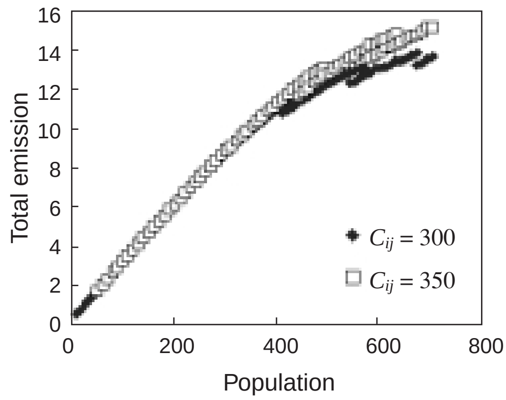

Fig. 6 Total emissions from transport

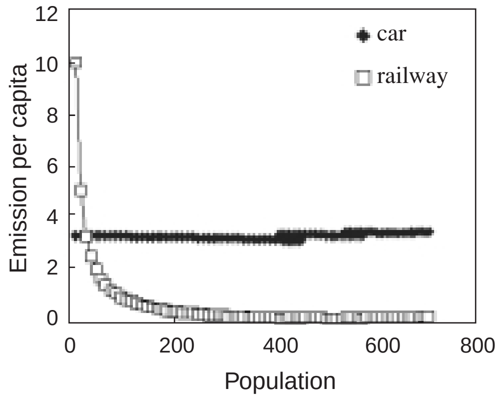

Fig. 7 Emission per car-user/passenger

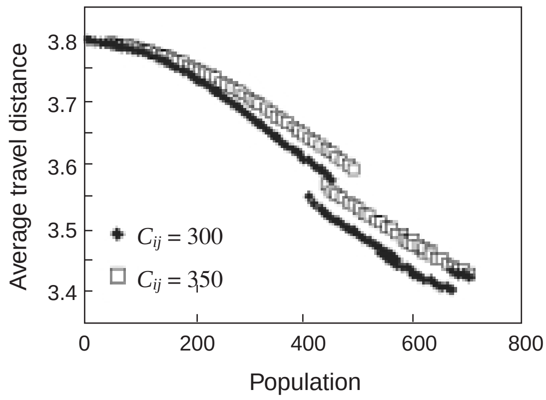

Fig. 8 Average travel distances

Finally, the interaction between transport and urban structure is discussed. Figure 8 shows the average travel distance against population. As population increases, the average trip distance becomes shorter for the most part. This means that increasing population tends to a locate inner urban areas at this population interval.

This result involves a complicated mechanism. All car traffic is generated in outer zone passes to inner zone roads. Therefore, roads of inner zones are always more congested than those of outer zones, and the travel time increases on zone roads is propagated to outer zones. As a result, inner zones always have any advantage against outer zones from the aspect of travel time by car. On the other hand, the service level of rail depends on fare, time on board and frequency. The former two factors are determined by distance from the center of the city. In other words, these costs are fixed by zone, so that the inner zone has a smaller cost. The latter factor depends on demand. As these cost structure, demand will increase from inner zones when the frequency is the same in all zones. This means that demand shift would occur from inner zones. This makes advantage of rail in inner zones and population may first concentrate there. Therefore, modal shift makes average trip length shorter.

Based on these mechanisms of car/rail demand increase, average trip length would get shorter as population increased in the first phase. But when it begins to increase population even in the outer zone, the average trip length will be increased. Figure 8 shows that the average length is being increased just before the population comes to 700 in the case of $C_{ij} = 300$. This phenomen is explained by urban structure and transport interaction.

In order to investigate the interaction more precisely, the zonal population distributions of each mode at several population levels are shown in Figures 9 and 10. The horizontal axis indicates zone number and vertical axis shows the population ratio of each zone against

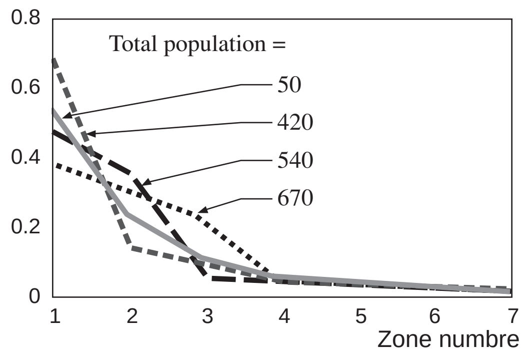

Fig. 9 Zonal population ratio of rail users

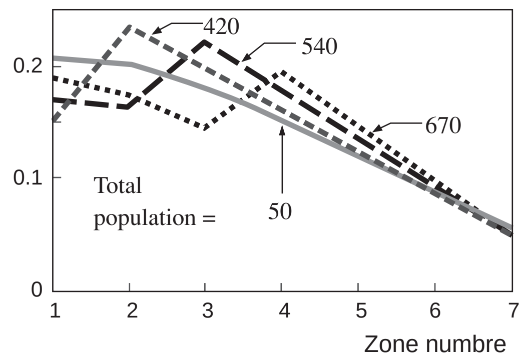

Fig. 10 Zonal population ratio of car users

total user numbers for each mode. Here, the referred total population is 50, 420, 540 and 670, and $C_{ij} = 300$ case is targeted. Firstly, the distribution of rail users is examined in Figure 9. It shows that rail users tend to dwell on the outer zone as population increases, except the interval of population change from 50 to 420. Rail users drastically increase and modal shift occurs in zone 1. This shift enhances population concentration to zone 1. Afterward, modal shift would occer in zone 2 and 3.

On the other hand, distribution of car users is a different property from that of rail users. Figure 10 shows that the peak shifts are outside population growth. Travel cost of inner zone is obviously cheaper than outer zones. But the land rent would increase because population increases at the zone where modal shift occurred. This makes car users choose outer zones for residence as population increases. As a result, Figure 8 is obtained as a superposition of these interactions.

5. POLICY IMPLICATIONS

It was shown that the mechanism of interaction between travel conditions and urban structure are a result of people's behavior. Which transport-urban policy measures could improve both economic and environmental efficiencies?

Transport policy effects, such as infrastructure provision or taxation on cars, would have two different consequences by stage of urban growth: incremental improvement and modal shift. When the population is stable and equation (23) has a unique solution, modal shift might not occur and policies of giving priority to rail might not be efficient and sustainable. On the other hand, in case of plural solutions, the priority policy of rail might improve economic efficiency for rail users as well as car users because modal shift may alleviate car congestion. In this case, emission from the total transport sector would also be reduced. Population growth stage may require a more prudent policy complex. Road investment for car use might delay the modal shift and encourage urban expansion that would induce an economic and environmentally inefficient urban structure. In this case, the policy should firstly give priority to public transport and secondly to car usage so as to maximize the effect and induce efficient transport and urban structure. Conversely, the reverse order of policy implementation might delay the modal shift and would be relatively inefficient. This is based on path dependence property of travel behavior discussed in this paper.

6. CONCLUSION

This study developed the simple land use-transport model, which can examine the effectiveness of public/private transport involved with urban structure. By using this model, some policy implications are obtained as follows:

1) There is the possibility of plural transport-land use situations under the same conditions of population and transport infrastructure/technology.
2) If there were plural situations, modal shift would occur by tentative public transport priority policies and may improve economic/environmental effectiveness.
3) In case that unique situation is expected, modal shift by tentative policy might not occur, and in the short term, policy measures for private car usage would improve overall effectiveness.
4) At the stage of population growth, the public and private transport policies might bring a different impact and consequences depending on the order of growth. The effectiveness of public/private transport varies depending on current and future urban-transport situations.

From the several numerical simulations, it is expected that this simple model has the potential of contribution to diagnosis of urban situations and evaluation of the policy measures. However, needless to say, these propositions are derived based on limited conditions and arbitrary settings. In future study, more various and actual situations have to be considered.

APPENDIX

A1. Derivation of equation (18)

Using equations (4) and (9), unit floor rent *p*a,i is determined as a solution of the following equation,

$$A_i = Q \cdot \sum_k \Psi_{i,k}(\mathbf{p}_t, \mathbf{p}_a : \theta) \cdot A_{i,k}(p_{ik}, p_{ai})$$
$$= \left(\frac{p_{a,i}}{p_\kappa} \gamma_A^{\frac{1}{\gamma_\kappa}} - \gamma_\kappa L_i^{\gamma L/\gamma_\kappa} \right)^{\frac{\gamma_\kappa}{1-\gamma_\kappa}} \quad \text{(A1)}$$

This is the equilibrium condition for total floor area in zone i. Here, substitute the right side of equation (6) for $A_{i,k}$ and transpose $p_{a},_{i}$ in the left side of eq. (A1) and the other constants in the right side to the opposite side, then equation (18) is derived.

A2. Derivation of equation (24)

In section 3.2, we assume a 1-zone and 2-mode case. Therefore, we can ignore the symbols i and s in eq. (23), and it is deformed as,

$$Q_\tau = \frac{(I-p_\tau)^\theta \cdot \left(\Sigma_k (I-p_k)^{\theta+1}\right)^\Gamma}{\sum_{i,k}(I-p_k)^\theta \cdot \left(\Sigma_k (I-p_k)^{\theta+1}\right)^\Gamma} Q \tag{A2}$$

When $(\Sigma_k (I-p_k)^{\theta+1})^\Gamma$ is canceled, equation (24) is derived.

A3. Relevance of parameters

The structure of the model was basically formulated to represent a typical case of transport-land use interaction in a urban setting. For the simulation results discussed in chapter 3 and 4, all the parameters are chosen arbitrarily, though attempts were made to ensure they fall in a realistic range. When attempted to apply to a practical city situation, relevance of these parameter numbers may, however, be changed. Needless to say, the preference of people or the cost structure of transport and land use might be different by countries or even by cities, therefore, we have to estimate those parameters based on appropriate data when this model is applied to actual cities. In this sense, the results of the analysis in this paper are just capturing one probable situation, and the other parameter settings should be examined for other situations. In spite of the arbitrariness in parameter settings, basic mechanisms of transport and land use interaction have been fairly represented by this model, and we can utilize it to explore and investigate the possible causes of differences among the actual cities.

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