

Transport Management and Land Value

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Abstract: The development of integrated transport supply and demand management (TS-DM) strategies is crucial for ensuring sustainable urban development. Any TS-DM strategy will not only affect the transport system performance, but also result in changes of the land use pattern. Moreover, implementing TS-DM strategies normally involves a progressively phased long-term schedule; one must take into account the total accruing costs and effects over time so as to optimize the system performance. This paper develops a mathematic optimization program with equilibrium constraints (MPEC) to study the impact of TS-DM strategies on transport system performance and activity location costs expressed as land value. Specifically, a bid-rent mechanism via the random utility approach is developed to model residential location choices. Finally, a numerical example is provided to compare among different strategies. Through this study, we hope to introduce promising planning perspectives to create win-win scenarios for both users and transport system managers.

Key Words: Bid-rent, Transport supply and demand management

1. INTRODUCTION

Highway construction is a common transportation supply strategy to relieve urban congestion. On the other hand, due to fiscal and environmental concerns, transportation demand management, e.g. road pricing, has also attracted much attention. Recently, researchers are interested in developing integrated transportation supply and demand management (TS-DM) strategies as a policy tool to address the problem. Any TS-DM strategy will not only change the performance of the transport system, but also indirectly affect the land use pattern. That is, there are interactions between TS-DM and land use. For developing mega-cities with large

growth potentials but insufficient infrastructure funding, it is crucial to formulate a sustainable land use and transport development plan with appropriate TS-DM strategies incorporated. To this end, it is important to internalize the interactions between transport and land use in a broader analysis framework, so that important questions on infrastructure provision, demand management, and activity location costs can be studied.

The transport and land use interaction has been studied for more than three decades. The theoretical foundation stems from micro-economic theories, e.g. bid-rent theory on housing location (Alonso, 1964), gravity model, entropy-maximization model on spatial interaction (Wilson, 1967), random utility theory (McFadden, 1978), etc. Anderstig and Mattsson (1991, 1998) developed a large-scale composite land use equilibrium model derived from random utility theory. The model attempted to represent the land market with endogenous shadow price and locational surplus. Eliasson and Mattsson (2001) and Mattsson (2007) studied the effects of road pricing on transport and location patterns. Ho and Wong (2007) developed a continuum model to study the interaction between land use and transport. At the same time, bid-rent models associated with the hedonic theory (Rosen, 1974; Cheshire and Sheppard, 1995) were introduced into land use models, providing useful insights into the relationship between locational characteristics and travel behavior (e.g. Mackett, 1991; Chang and Mackett, 2006). Martínez (1992) and Martínez and Henriquez (2007) proposed a bid-rent model within the static equilibrium framework to study the supply and demand of housing.

On the other hand, studying the costs and effects of TS-DM over time, e.g. gradual network expansion and pricing schemes, attracted much attention. Lo and Szeto (2004, 2009) and Szeto and Lo (2006) introduced time-dependent TS-DM strategies to the continuous network design problem via a bi-level program formulation (Yang and Bell, 1997). In this formulation, fiscal as well as equity concerns are incorporated, providing an analytical framework to study TS-DM strategies for improving the total system performance. Siu and Lo (2007, 2009) further extended the framework by capturing residents' location choices, shedding light on the possible impacts of time-dependent TS-DM on the activity location pattern.

In this paper, we intend to investigate the impact of time-dependent TS-DM strategies on land value. By formulating a mathematical program with equilibrium constraints (MPEC) and incorporating the bid-rent mechanism, the location rental or land value is internalized, which in turn influences residents' location choices. With this extended framework, TS-DM strategies over time are determined to optimize the system performance. Section 2 describes the overall modeling framework. Section 3 illustrates the framework with a small network example. Section 4 provides some concluding remark.

2. MODELING FRAMEWORK

To study the interaction between time-dependent TS-DM and activity location costs or land value, a general network equilibrium model is developed. Boyce (1980) formulated the combined trip distribution and traffic assignment modeling structure. Based on this approach, we further incorporate the interactions between transport and land use as captured via its activity location costs, with the model formulated as a MPEC. To model residents' location and travel choices, the population is separated into locators and non-locators (Lam and Huang, 1992). Locators have flexibility in choosing both their residential locations and workplaces. Non-locators are those with fixed residential locations but have flexibility in choosing their workplaces. In addition, both locators and non-locators can be further classified into different

income groups (Siu and Lo, 2009).

2.1 Travel cost

In this model, travel cost refers to the travel time expressed into monetary value and the possible toll charge. The BPR link performance function is adopted:

$$t_a^{(\tau)} = t_a^{0(\tau)} \left(1 + \alpha_1^{(\tau)} \left(\frac{x_a^{(\tau)}}{C_a^{(\tau)}}\right)^{\alpha_2^{(\tau)}}\right), \quad (1)$$

$$C_a^{(\tau)} = C_a^{(\tau-1)} + y_a^{(\tau-1)}, \forall \tau \geq 1. \quad (2)$$

$t_a^{0(\tau)}$ is the free flow travel time on highway link a in period τ ; $x_a^{(\tau)}$ is the flow on highway link a in period τ ; $\alpha_1^{(\tau)}, \alpha_2^{(\tau)}$ are coefficients of the BPR function. The link capacity in period τ , $C_a^{(\tau)}$, is the sum of link capacity $C_a^{(\tau-1)}$ and the planned link expansion $y_a^{(\tau-1)}$ in the last period $\tau-1$.

2.2 Zonal attractiveness

Zonal attractiveness encompasses the amenities of the origin or destination zone, as a residential location or workplace, such as the environment, neighborhood, etc. In this formulation, it is measured by two terms: first, the zone's intrinsic attractiveness, which is a constant; second, a measure of the effect of land use intensity or congestion on zonal attractiveness (Yang and Meng, 1998; Siu and Lo, 2009). Mathematically, the zonal attractiveness for origin ($l^{rk(\tau)}$) and destination ($l^{sk(\tau)}$) zones, respectively, are formulated as:

$$l^{rk(\tau)} = l_0^{rk} - \theta^{rk(\tau)} \left(\frac{O^{r(\tau)}}{K^{r(\tau)}}\right)^2, \quad (3)$$

$$l^{sk(\tau)} = l_0^{sk} - \theta^{sk(\tau)} \left(\frac{D^{s(\tau)}}{K^{s(\tau)}}\right)^2, \quad (4)$$

where,

$$O^{r(\tau)} = \sum_k O^{rk(\tau)}, \quad (5)$$

$$D^{s(\tau)} = \sum_{i \in R} \sum_{p \in P^{is}} f_p^{is(\tau)}. \quad (6)$$

Let $r \in R$ denote an origin node belonging to the set of origins R ; likewise, $s \in S$ denote a destination node belonging to the set of destinations S . l_0^{rk}, l_0^{sk} , respectively, are the intrinsic attractiveness for r and s as valued by income group k , which are positive constants; similarly, $K^{r(\tau)}$ and $K^{s(\tau)}$, respectively, are the holding capacities within r and s in period τ arising from land use planning. $\theta^{rk(\tau)}, \theta^{sk(\tau)}$ are coefficients to be calibrated for each origin r , destination s of income group k . In Equation (5), $O^{rk(\tau)}$ is the total population of income group k residing in zone r in period τ , including both locators and non-locators, which can be obtained in the network equilibrium level formulated in the following section. In Equation (6), $f_p^{is(\tau)}$ is the path flow, including both locators and non-locators, between OD pair i and s through path p in period τ ; P^{is} refers to the path set between OD pair i and s . $O^{r(\tau)}(D^{s(\tau)})$ is the total productions (attractions) from origin r (to destination s) in period τ .

2.3 Locators' problem

The network equilibrium model involves an allocating process in which locators bid for their residential locations. Locators have the flexibility of choosing their residential locations, workplaces, and commute routes simultaneously. A bid-rent mechanism via the random utility framework is developed to solve the locators' problem. The bid-rent process, which produces the housing rent at each residential location (labeled as r_1, \dots, rr), is illustrated with the thickened arrows for residential zone r_1 in the left diagram in Figure 1. The bidding process is open to all income levels (labeled as High, Low) working in different workplaces (labeled as s_1, \dots, ss), after factoring in the relative location and transportation advantages of each residential location. The resultant bid-rent for each residential location then becomes the rental cost (a disutility measure) faced by locators in choosing their residential locations. One may consider this as a measure of affordability – locations with high intrinsic values and convenient accessibility will attract higher bid-rents, and hence become more expensive, as reflected by their rental costs. As shown in the right diagram in Figure 1, after considering the overall cost, including the resultant rents of all residential zones, as well as the perceived travel costs, locators of each income group (illustrated with the thickened arrows for the example of high income group working at s_1) choose their residences according to the random utility model. The combined bid-rent and residence choice model in this way considers both the bidding process in accordance of the relative location advantages as well as the affordability of locators in choosing their residential locations.

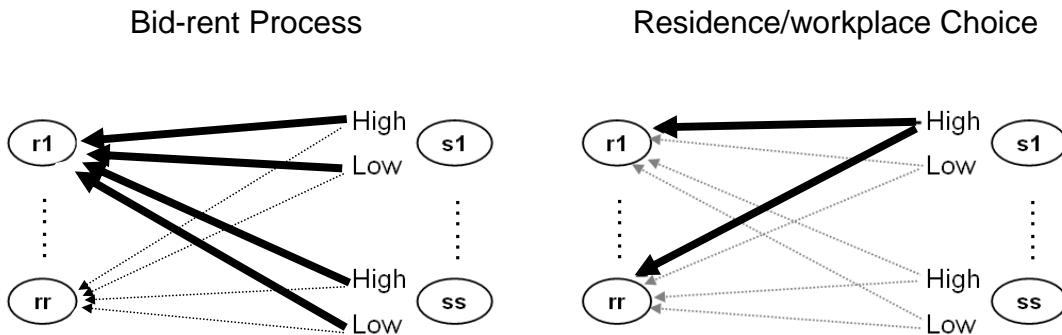


Figure 1 A schematic diagram for the bid-rent process and residence choice allocation

In this combined framework, the principle of utility maximization as represented by the logit model is adopted. Locators choose their residential locations according to the rental costs and travel costs. The overall utility function for locators in income group k choosing residential location r in period τ is expressed as:

$$\bar{V}^{rk(\tau)} = -\varphi^{rk(\tau)} - \kappa^{(\tau)} \cdot \pi^{rsk(\tau)}, \quad (7)$$

where $-\varphi^{rk(\tau)}$ is valuation of the rental cost at r by income group k as determined via the bid-rent process (which is to be further explained below); the second term is the valuation of the perceived travel cost, $\pi^{rsk(\tau)}$, by income group k in period τ , which can be regarded as an accessibility measure of residential locations.

Thereby, the probability of locators in income group k choosing to reside in location r in period τ is expressed as:

$$\bar{P}^{rk(\tau)} = \frac{\exp(\bar{\beta}^{k(\tau)} \cdot \bar{V}^{rk(\tau)})}{\sum_{i \in R} \exp(\bar{\beta}^{k(\tau)} \cdot \bar{V}^{ik(\tau)})}, \quad (8)$$

where the summation in the denominator works through each residential zone $i \in R$. The

number of locators in income group k choosing to reside in location r in period τ is then obtained by:

$$\bar{O}^{rk(\tau)} = \bar{H}^{k(\tau)} \cdot \bar{P}^{rk(\tau)}, \quad (9)$$

where $\bar{H}^{k(\tau)}$ is the total population of locators in income group k in period τ , which is exogenously given.

The rental cost at each residential zone r is determined via an allocating process in which locators bid for their residential locations. According to Equation (7), $\varphi^{rk(\tau)}$, the rental cost of residential location at r valued by locators in income group k , can be defined as:

$$\varphi^{rk(\tau)} = \frac{\bar{\varphi}^{r(\tau)}}{I^{k(\tau)}} \sigma. \quad (10)$$

$\bar{\varphi}^{r(\tau)}$ is the expected maximum willingness-to-pay for residential location r , which is obtained via bidding by all income groups. Since the land/residence owner is utility maximizing, it is expected that he/she will charge the rental cost at r to be exactly $\bar{\varphi}^{r(\tau)}$.

Note that the rental cost valued by income group k is adjusted by its income level, $I^{k(\tau)}$; i.e., the same monetary rent is perceived to be cheaper by the higher income groups as compared with the lower income groups. It implies that higher income groups intend to choose residential locations with higher rents (which also have better location and transportation advantages). σ is a parameter to be calibrated.

The valuation or expected maximum willingness-to-pay for residence at r , $\bar{\varphi}^{r(\tau)}$ is produced by a bid-rent process, which can be regarded as an approximation of an n-player non-cooperation oligopolistic Cournot game (Chang and Mackett, 2006). The process considers that all locators bid for residential locations after considering their incomes and other living expenses. The term “Willingness-to-Pay” (WP) is defined to measure the locator’s bid to pay for a particular residential location. The WP function for location r by a locator in income group k in period τ can be given by:

$$WP^{rk(\tau)} = I^{k(\tau)} + l^{rk(\tau)} - \pi^{rsk(\tau)} - U^{k(\tau)}, \quad (11)$$

where $I^{k(\tau)}$ is the income of group k in period τ ; $l^{rk(\tau)}$ is the zonal attractiveness of residential location r in period τ as defined by Equation (3); $\pi^{rsk(\tau)}$ is the minimum travel cost; $U^{k(\tau)}$ captures all other living expenses of income group k , including savings, reflecting a certain utility level or life style desired by different income groups (Rosen, 1974). According to Equation (11), the willingness-to-pay $WP^{rsk(\tau)}$ for location r , includes the travel cost $\pi^{rsk(\tau)}$. Therefore, any changes in the transport network and the resultant changes in travel cost will alter not only travelers’ route choices, but also their willingness-to-pay, or the housing rent or land value and their residence location choices. On the other hand, changes in the zonal attractiveness or changes in land use planning, such as increases in the supply of residential units, will have consequential effects on locators’ residence choices, which in turn will affect the transportation system performance. In this way, by capturing the location costs (i.e., housing rents) endogenously via the bid-rent process, the interaction between land use and transport can be established.

According to the discrete choice theory for the logit model (McFadden, 1978; Small and Rosen, 1981; Train, 2003), the expected maximum bid or willingness-to-pay, which constitutes the housing rent, can be defined by the well-known log-sum function, expressed as:

$$\bar{\varphi}^{r(\tau)} = E[\max_k \{WP^{rk(\tau)}\}] = \frac{1}{\mu} \ln \left(\sum_k \bar{H}^{k(\tau)} \exp(\mu \cdot WP^{rk(\tau)}) \right), \quad (12)$$

where μ is the coefficient associated with WP . The bid-rent process for each residential zone r is open to bidding by all locators with different income levels. In Equation (12), the summation on the RHS works through each income group k .

We note that the actual bid-rent process involves both locators and suppliers, e.g. real estate developers. In this formulation, we assume that the suppliers of each residential location know the expected bids placed by locators and that the suppliers charge the housing rent according to the expected maximum bid, which is then fixed and applied to all locators regardless of their subsequent choices. In practice, however, there exists a competitive housing market involving both suppliers and locators. The suppliers may or may not be able to charge rent at the same level as the expected maximum bid, depending on the competition by other suppliers in the same as well as other locations. To more completely model this housing market equilibrium, we need to pose the problem as a competitive equilibrium formulation involving both locators and supplier decisions, which is part of the ongoing research.

2.4 Non-locators' problem

In this formulation, non-locators have fixed residential locations but have the flexibility of choosing their workplaces and commute routes simultaneously. After allocating the residential locations for locators, both locators and non-locators make their workplace and route choices, based on the zonal attractiveness of the workplaces and the corresponding travel costs. The total number of population including both locators and non-locators in income group k in period τ defined in Equation (5) is summed by:

$$O^{rk(\tau)} = \bar{O}^{rk(\tau)} + \tilde{O}^{rk(\tau)}, \quad (13)$$

where $\bar{O}^{rk(\tau)}$ is the population of locators in income group k residing in zone r in period τ , which is determined by Equation (9); $\tilde{O}^{rk(\tau)}$ is the population of non-locators in income group k residing in zone r in period τ , which is exogenously given.

2.5 Network equilibrium

The residents' workplace and route choice process for both locators and non-locators is formulated as a combined trip distribution and traffic assignment problem. In this model, the problem is solved by reformulating it as an equivalent Nonlinear Complementarity Problem (NCP) (Lo and Chen, 2000). The equivalent NCP is to:

Find $\mathbf{Z}^* \geq 0$, such that

$$\mathbf{F}(\mathbf{Z}^*) \geq \mathbf{0}, \quad (14)$$

$$\mathbf{Z}^{*\top} \cdot \mathbf{F}(\mathbf{Z}^*) = \mathbf{0}, \quad (15)$$

where \mathbf{Z} is a column vector of the path flows including both locators and non-locators in income group k between each OD pair, with $\mathbf{Z} = (f_p^{rsk(\tau)}, \forall r, s, p, k, \tau)$. Correspondingly, $\mathbf{F}(\mathbf{Z})$ is a column vector, with $\mathbf{F}(\mathbf{Z}) = (f_p^{rsk(\tau)} - O^{rk(\tau)} \cdot \Pr_p^{rsk(\tau)}, \forall r, s, p, k, \tau)$. Under stochastic user equilibrium condition, $\Pr_p^{rsk(\tau)}$ is the probability of residents in income group k in location r , choosing to work in location s and travel through path p in period τ . It is defined by:

$$\Pr_p^{rsk(\tau)} = \frac{\exp(-\beta^{k(\tau)} c_p^{rsk(\tau)})}{\sum_{p' \in P^{rs}} \exp(-\beta^{k(\tau)} c_{p'}^{rsk(\tau)})}, \quad (16)$$

where $c_p^{rsk(\tau)}$ is the travel cost by income group k between OD pair r and s through path p in period τ . Note that the attractiveness of each workplace defined in Equation (4) can be regarded as the travel cost on a virtual link connecting each workplace to a virtual super destination. Thereby $c_p^{rsk(\tau)}$ is the summation of the path's link travel times $t_a^{(\tau)}$, toll charges, if any, $\rho_a^{(\tau)}$, and the attractiveness of workplace s in period τ :

$$c_p^{rsk(\tau)} = \sum_a \delta_{a,p}^{rs} (vot^{k(\tau)} \cdot t_a^{(\tau)} + \rho_a^{(\tau)}) + l^{sk(\tau)}, \quad (17)$$

where $vot^{k(\tau)}$ is the value of time of income group k in period τ ; $\delta_{a,p}^{rs}$ is the indicator for path-link incidence, equals 1 if link a is on the path p between OD pair r and s ; 0 otherwise.

The nonlinear complementarity conditions in Equations (14)-(15) can be written as:

$$f_p^{rsk(\tau)} (f_p^{rsk(\tau)} - O^{rk(\tau)} \cdot \Pr_p^{rsk(\tau)}) = 0, \quad \forall r, s, p, k, \tau, \quad (18)$$

$$f_p^{rsk(\tau)} - O^{rk(\tau)} \cdot \Pr_p^{rsk(\tau)} \geq 0, \quad \forall r, s, p, k, \tau, \quad (19)$$

$$f_p^{rsk(\tau)} \geq 0, \quad \forall r, s, p, k, \tau. \quad (20)$$

According to Equation (18), if $f_p^{rsk(\tau)} > 0$, which is true under stochastic user equilibrium condition, then $f_p^{rsk(\tau)} = O^{rk(\tau)} \cdot \Pr_p^{rsk(\tau)}$.

The above NCP can be reformulated as a smooth and unconstrained optimization problem (Lo and Chen, 2000), by minimizing the following gap function to zero (Facchinei and Soares, 1995).

$$\min G(\mathbf{Z}) = \sum_{rsk} \sum_p \vartheta(f_p^{rsk(\tau)}, f_p^{rsk(\tau)} - O^{rk(\tau)} \cdot \Pr_p^{rsk(\tau)}), \quad (21)$$

where $\vartheta(\cdot)$ is defined as:

$$\vartheta(c, d) = \frac{1}{2} \phi^2(c, d), \quad (22)$$

$$\phi(c, d) = \sqrt{c^2 + d^2} - (c + d). \quad (23)$$

c and d in Equations (22)-(23) are any real numbers. By minimizing Equation (21), the path flows $f_p^{rsk(\tau)}$ can be obtained. And the link flow $x_a^{(\tau)}$ for each period, which is used to calculate the link congestion in Equation (1), is then calculated by:

$$x_a^{(\tau)} = \sum_r \sum_s \sum_p f_p^{rs(\tau)} \cdot \delta_{a,p}^{rs(\tau)}, \quad \forall a, \tau, \quad (24)$$

$$f_p^{rs(\tau)} = \sum_k f_p^{rsk(\tau)}, \quad \forall r, s, p, \tau. \quad (25)$$

The summation of the RHS in Equation (25) works through all the income groups.

Alternatively, to cast the network equilibrium problem in the form of a constraint set, equilibrium constraints to be specific, we express the gap function (21) as an equality constraint, i.e., $G(\mathbf{Z}) = 0$. When the gap function is zero, i.e., $G(\mathbf{Z}) = 0$, the NCP (18)-(20) is satisfied.

2.6 System optimization

The formulation in Equations (1)-(23) describes the combined equilibrium model. In this framework, the network capacity is given and fixed, as is the toll structure; therefore, solving this combined equilibrium model provides the resultant location and travel choices, and the location rental value, for a given TS-DM strategy. In this study, our objective is to devise time-dependent TS-DM strategies so as to optimize the desired objective of network management. A number of objectives can be defined for this purpose. For illustration purposes, we choose to minimize the discounted total system travel cost. This model follows a quasi-dynamic structure (Wegener, 1994, 1998), wherein the costs, tolls, and capacity improvements accrue over the planning horizon. The planning horizon is subdivided into discrete time periods (normally one or five years), with the decision and state variables sequentially linked across time periods. Moreover, to achieve financial viability of the long-term infrastructure investment, we add the overall cost recovery constraint – i.e. the total link construction and maintenance costs are fully covered by the toll revenue over the planning horizon. Hence, the total Net Present Value (NPV) over the planning horizon is set to be equal to 0:

$$NPV = \sum_{\tau} \sum_a \nu(j, \tau) x_a^{(\tau)} \rho_a^{(\tau)} - \sum_{\tau} \sum_a B_C t_a^{0(\tau)} y_a^{(\tau)} \left(\frac{1+ir}{1+dr} \right)^{n\tau} - \sum_a B_M t_a^{0(\tau)} \left[\sum_{t=0}^{nT+(n-1)} \left(\frac{1+ir}{1+dr} \right)^t C_a^{(0)} + \sum_{\tau=1}^{T-1} \sum_{t=n(\tau+1)}^{nT+(n-1)} \left(\frac{1+ir}{1+dr} \right)^t y_a^{(\tau)} \right], \quad (26)$$

where the first term of the RHS is the total discounted toll revenue. The second term is the discounted total construction cost. The third term is the total discounted maintenance cost. $\nu(dr, \tau)$ is a discount factor depending on the annual discount rate dr and the τ^{th} ($\tau \in [0, T]$) time period. It converts the total travel cost at time τ to the base year. B_C is the unit construction cost. B_M is the unit maintenance cost. ir is the annual inflation rate. dr is the annual discount rate. As a result, the MPEC program is:

$$\underset{y_a^{(\tau)}, \rho_a^{(\tau)}}{\text{Minimize}} \quad TSC = \sum_{\tau} \sum_{rs} \sum_k \sum_{p \in P^{rs}} \nu(d_r, \tau) \cdot c_p^{rsk(\tau)} \cdot f_p^{rsk(\tau)} \quad (27)$$

subject to

$$G(\mathbf{Z}) = 0 \quad (28)$$

Constraint (1)-(20)

$$0 \leq y_a^{(\tau)} \leq \bar{y}_a^{(\tau)} \quad \forall \tau \in [0, T] \quad (29)$$

$$0 \leq \rho_a^{(\tau)} \leq \bar{\rho}_a^{(\tau)} \quad \forall \tau \in [0, T] \quad (30)$$

$$NPV = 0 \quad (31)$$

The objective function represents the total discounted travel cost. $y_a^{(\tau)}$ and $\rho_a^{(\tau)}$ are the TS-DM strategy decisions on network expansion and toll charge, which are bounded by $\bar{y}_a^{(\tau)}$ and $\bar{\rho}_a^{(\tau)}$, respectively, arising from planning regulations. In Equation (28), the gap function $G(\mathbf{Z})$ is defined in Equation (21). For each solution set $(y_a^{(\tau)}, \rho_a^{(\tau)})$, there exists a unique set of link flows in the combined equilibrium model. Equations. (27)-(31) is a non-linear non-convex mathematical program, which can be solved by a commercial non-linear program solver. In this small example, we used Solver in Excel for solution. As is typical for MPEC, the global optimality of solution is not guaranteed.

3. NUMERICAL EXAMPLE

3.1 Modeling assumptions

To illustrate the modeling framework, a small network over the planning horizon of 30 years (in three 10-year periods) is used as the numerical example. The network (reported in Siu and Lo, 2009), shown in Figure 2, consists of two residential zones (Zone 1, 2), two CBDs, being workplaces (Zone 5, 6), and seven connected links.

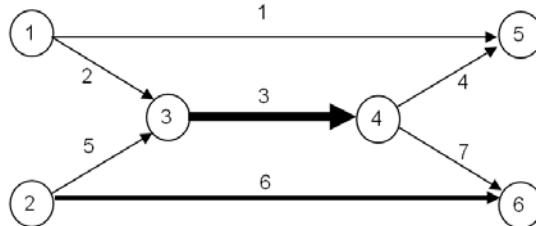


Figure 2 The example network

Zone 1 refers to a new residential area with a lower initial population but higher developing opportunities, while Zone 2 is an old residential area with a higher initial population but limited developing potentials, as shown in Table 1. Similarly, Zones 5 and 6 are the new and old central business districts (CBD), respectively. Zones 2 and 6 have a relatively higher intrinsic zonal attractiveness, such as more convenient amenities or facilities. At each period, the provision of both housing units and job opportunities is limited. As shown in Table 2, the links are classified into three types with different coefficients for the BPR function defined in Equation (1). Link 3 refers to a major arterial, while Link 6 is a minor arterial. The rest links are local streets.

Table 1 Zonal initial properties and planning limitation

Zone	Intrinsic attractiveness	Planning limitation $K^{r(\tau)} / K^{s(\tau)}$			Description
		$\tau = 0$	$\tau = 1$	$\tau = 2$	
1	5	200	250	300	New residential
2	10	200	220	240	Old residential
5	2	200	250	300	New CBD
6	5	200	220	240	Old CBD

Table 2 Link properties

Link	Initial Capacity (veh/hour)	Free flow time (min)	$\alpha_1^{(\tau)}$	$\alpha_2^{(\tau)}$	Link type
1	80	20	0.25	4	Local street
2	80	5	0.25	4	Local street
3	160	10	0.65	3.8	Major arterial
4	80	5	0.25	4	Local street
5	80	5	0.25	4	Local street
6	120	20	0.55	3	Minor arterial
7	80	5	0.25	4	Local street

The current demographic composition and the population growth rates are simplified to be as shown in Table 3. The population, consisting of locators and non-locators, are stratified into two income groups ($I^{high} = \$500/day$, $I^{low} = \$400/day$). It further assumes that each household contains one worker who uses car as the only transport mode. The annual inflation

rate and discount rate are 1% and 4%, respectively. The unit construction cost, B_C , is \$1000, and the unit maintenance cost, B_M , is \$6 per year.

Table 3 Population growth over time (unit: person)

Zone	$\tau = 0$				$\tau = 1$	$\tau = 2$	
	Non-locators		Locators growth per time interval		Total population	Total population	Total population
	High income	Low income	High income	Low income			
1	10	10	50	50	200	300	400
2	40	40					

3.2 Comparison between Do-nothing and TS-DM

To evaluate the system performance under the optimized TS-DM strategy, two scenarios are developed. The “do-nothing” scenario refers to the base scenario where there is neither network expansion nor TS-DM strategy. Scenario I introduces both network expansion and toll charge over time under the overall cost recovery scheme as defined in Equations (27)-(31). The toll structure is determined so that the total toll revenue fully covers the total construction and maintenance costs over the planning horizon, i.e. NPV=0. Besides, to demonstrate that the modeling framework can encapsulate the interactions between transport and housing costs, the average income of the population is fixed at the current level, while the population and hence congestion are allowed to grow continuously over time for both the two scenarios. By solving the MPEC program defined in Section 2, the optimal TS-DM strategy is summarized in Table 4. Note that the total expansion over the planning horizon for each link is limited to 50% of its original capacity.

Table 5 shows the link V/C ratios of each scenario over time. According to the result of the “do-nothing” scenario, the congestion problem can be severe in the longer term, where the V/C ratios for all the links are higher than 1 in the time period $\tau = 2$. With the optimal TS-DM strategy, Scenario I reduces the congestion to a reasonable level, where all the V/C ratios are less than 1 throughout the planning horizon. As shown in Table 4, Links 1, 3, 6 (shown bolded) require more link expansions. In particular, the capacity of Link 1 will reach its ultimate limit and its corresponding V/C ratio in $\tau = 2$ is almost 1.

Table 4 Link expansion and toll charge of Scenario I over time

Link	Link expansion			Capacity limitation	Toll charge		
	$\tau = 0$	$\tau = 1$	Total		$\tau = 0$	$\tau = 1$	$\tau = 2$
1	37.2	2.8	40.00	40	0.01	0.01	0.05
2	3.4	7.0	10.32	40	0.02	0.01	0.00
3	19.1	11.2	30.27	80	0.01	0.03	0.01
4	0.9	0.6	1.53	40	0.00	0.01	0.02
5	0.2	0.5	0.62	40	0.00	8.08	0.02
6	30.6	0.2	30.76	60	0.13	7.84	0.02
7	18.2	1.4	19.56	40	2.02	0.55	0.00

Table 5 Comparison between congestion levels (V/C ratios)

Link	$\tau = 0$		$\tau = 1$		$\tau = 2$	
	Do-nothing	Scenario I	Do-nothing	Scenario I	Do-nothing	Scenario I

1	0.522	0.557	0.918	0.777	1.245	1.000
2	0.355	0.310	0.673	0.852	1.037	0.958
3	0.532	0.491	0.822	0.631	1.087	0.846
4	0.000	0.272	0.640	0.304	1.070	0.803
5	0.708	0.672	0.971	0.522	1.137	0.923
6	0.610	0.641	0.792	0.638	1.054	0.789
7	1.063	0.709	1.004	0.900	1.104	0.960

Not surprisingly, Scenario I has much better system performance than “do-nothing”, as shown in Table 6 and Figure 4. Although the consumers’ (or travelers’) costs are almost the same, the total travel time and total travel cost of Scenario I with optimal TS-DM are lowered by about 12% and 6%, respectively. Moreover, in Scenario I, all the infrastructure improvement and maintenance costs are fully recovered by the toll revenue; whereas in the case of no-thing, without toll revenue, the maintenance cost must be funded from another external source. Ultimately, Scenario I incurs a lower total social cost of 8% combining both travelers’ and government’s costs.

Table 6 Comparison of economic efficiency

	Do-nothing	Scenario I	% difference
Construction Cost	0	1822303	-
Maintenance Cost	849999	967050	14%
Toll Revenue	0	2789353	-
Increased Land value	0	0	-
Net Profit	-849999	0	-
Total Travel Time	47200875	41370168	-12%
Total Travel Cost	47200875	44159520	-6%
Total Social Cost*	48050874	44159520	-8%

* Total social cost is the total travel cost minus the net profit, i.e., the cost incurred by travelers and government combined.

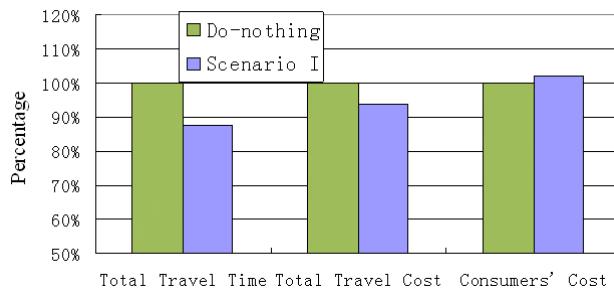


Figure 3 Comparison of system and travelers' costs

3.3 Studying the effect of TS-DM on land value and residents' location choices

To demonstrate that the modeling framework can encapsulate the interactions between TS-DM and rental value/cost, in this scenario, the incomes of the population are fixed at the current level, while the population and hence congestion are allowed to grow over time. This scenario may not happen but is set up to demonstrate the model characteristics. Generally, as the population grows over time, the housing rents for both Zone 1 and Zone 2 decrease (see in Figure 4). The reason is that as the income is kept constant and the population and hence congestion increase over time, the willingness-to-pay for housing and the associated expected maximum bid expressed in (11)-(12) decrease over time, leading to decreasing rental or land

value.

In particular, the housing rents under “do-nothing” reduce much faster due to the worsening traffic congestion as the population grows. In other words, the deterioration in accessibility over time gradually hurts the land value. The interaction between accessibility (or transportation) costs and rental value is clearly demonstrated in this example. An interesting observation, from Figure 4, is that for Scenario I, the TS-DM strategy is instrumental in helping to keep the rental or land value. But with the income kept unchanged for thirty years, while the population keeps growing, this hurts the affordability for housing. A TS-DM strategy, designed for transportation management, influences land value, but cannot be expected to hold land value especially under such a drastic, unfavorable condition.

According to Table 7 and Figure 4, under Scenario I, the housing rent of Zone 2 decreases substantially at $\tau = 1$. However, locators are more likely to choose Zone 1, although it has a relatively higher rental cost. The reason is that residents’ location choices depend on the tradeoff between rental cost and travel cost, and hence the travel time and toll. At $\tau = 1$, although the rental cost in Zone 2 is lower than that in Zone 1, the travel costs between Zone 2 and the two CBDs increase faster due to the higher tolls charged on Links 5 and 6. In other words, the higher tolls cannot be compensated by the corresponding reduction in traffic congestion. As a result, the accessibility of Zone 2 to both CBDs and the attractiveness to locators is impaired.

Table 7 Population allocation over time

Zone	Class	Do-nothing			Scenario I		
		$\tau = 0$	$\tau = 1$	$\tau = 2$	$\tau = 0$	$\tau = 1$	$\tau = 2$
1	Locators	High	25.2	27.1	26.5	24.9	43.2
		Low	25.0	30.0	28.7	24.4	49.6
	Non-locators	High	10.0	35.2	62.2	10.0	34.9
		Low	10.0	35.0	65.1	10.0	34.4
	Sum		70.2	127.3	182.5	69.3	162.1
							206.6
2	Locators	High	24.8	22.9	23.5	25.1	6.8
		Low	25.0	20.0	21.3	25.6	0.4
	Non-locators	High	40.0	64.8	87.8	40.0	65.1
		Low	40.0	65.0	84.9	40.0	65.6
	Sum		129.8	172.7	217.5	130.7	137.9
							193.4
Total		200.0	300.0	400.0	200.0	300.0	400.0

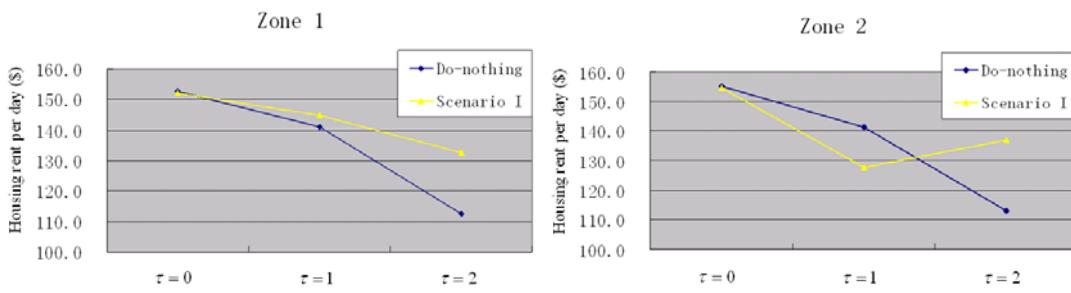


Figure 4 Unit housing rent over time

4. CONCLUDING REMARK

This paper developed a modeling framework to study the impact of time-dependent TS-DM strategies on land use and transport, including the effect of housing rents and corresponding residents' location choices. A combined bid-rent and random utility model is developed for residential land use allocation, with the combined trip distribution and traffic assignment problem formulated as an equivalent nonlinear complementarity problem. Using it as a modeling platform, the optimal time-dependent TS-DM strategy was determined so as to minimize the total system travel cost. Generally, the results demonstrated that travel cost or accessibility is instrumental in influencing the rental value of a location, and residents' location choices. And a well integrated TS-DM strategy can improve the system performance by addressing the concerns of both road users and transport system managers.

In this study, we caution that although we have attempted to ensure that the modeling assumptions approximate the real-world conditions, some of the modeling parameters need to be calibrated for the specific network scenario. Under different parametric conditions, some of the findings may vary. Therefore, we emphasize the results reported herein are for illustration purposes, mainly to reveal the characteristics of the modeling framework. Our ongoing studies focus on how this modeling platform can be extended to approximate the real-world situation even better.

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