LAND-USE POLICY FOR TRANSIT STATION AREAS: PARK-AND-RIDE VERSUS TRANSIT-ORIENTED DEVELOPMENT

Wenbo Fan
School of Transportation and Logistics, Southwest Jiaotong University. National United Engineering Laboratory of Integrated and Intelligent Transportation. 111 Erhuan Road, Beiyiduan, Chengdu, 610031, China;
National Center for Smart Growth Research and Education, University of Maryland, College Park, USA;
wbfan@swjtu.edu.cn

Xinguo Jiang, Corresponding author
School of Transportation and Logistics, Southwest Jiaotong University; National United Engineering Laboratory of Integrated and Intelligent Transportation. 111 Erhuan Road, Beiyiduan, Chengdu, 610031, China
xjiang@swjtu.edu.cn

Sevgi Erdogan
National Center for Smart Growth Research and Education, 1112J Preinkert Field House, University of Maryland, College Park, MD, 20742, USA;
serdogan@umd.edu

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ABSTRACT

This paper examines the effectiveness of two transit station-area development policies, park-and-ride (PNR) and transit-oriented development (TOD), by integrating a households' residential relocation model with a conventional four-step travel demand model. Scenarios are designed on an experimental network with a single candidate metro station to assess the effectiveness of: i) building a new PNR lot; ii) replacing an existing PNR facility with TOD; and iii) developing new TOD communities. In addition, the analysis is extended to multiple stations where PNR versus TOD comparison is made considering multiple station sites with the goals of maximizing the transit patronage and minimizing the vehicle kilometers traveled (VKT) and vehicle hours of delay (VHD). The system performance in each scenario is evaluated with utilizing various measures including transit patronages, VKT, and VHD. Results show that: i) deployment of a new PNR facility or a new TOD can considerably increase the metro ridership and reduce the VKT/VHD; ii) replacing an existing PNR with a TOD appears to be unrealistic due to a considerable ridership loss; and iii) impromptu station-area land use plan may result in network performance significantly lower than that of the optimal solutions. The proposed analysis framework can readily be incorporated in the existing four-step transportation planning tools to guide transit agencies in their decision on system-wide station-area land use plans.

may mean construction

编入、合并

Single candidate metro station

Multiple candidate metro stations

Patronage在这里的意思应该类似于ridership表示客流量的意思本文中的上层规划目标为公交乘客量最大、机动车行驶里程最少、用户出行延误最小，可借鉴用于博士论文。另外，范老师博士论文：随机用户均衡下的P&R设施选址模型及案例，是在社会福利最大化的目标下开展的研究。至此，博士论文在TOD与P+R设施选址的双层规划模型中的四个目标：公交乘客量最大、机动车行驶里程最小、用户出行延误最小和社会总福利最大，基本都找到了理论依据。

Keywords: Transit; Station-area land use; Transit-oriented development; Park-and-ride

An impromptu action is one that you do without planning or organizing it in advance.

INTRODUCTION

Modern transit systems (e.g., metro, light rail transit, and bus rapid transit) have been playing an important role in public transportation systems, fundamentally changing the urban land use and travel patterns towards economic and environmental sustainability *(1,2)*. Successful examples of integrated transit and land use planning include Washington, D.C. (USA), Ottawa (Canada), Copenhagen (Denmark), Curitiba (Brazil), and Hong Kong (China) *(1)*. Regarding the station-area land use development, Park-and-Ride (PNR) facilities and Transit-Oriented Development (TOD) are two main strategies that integrate the transit system and potential travel demand. Both the PNR and TOD improve the accessibility of transit system and encourage travelers to take the public transport instead of driving, but they differ and even conflict in the practice of station-area land use planning *(3)*: the PNR builds massive parking spaces adjacent to the station, while the TOD requires high density, mixed land use development around the transit station to provide accessibility with non-motorized modes. Earlier studies considered either PNR or TOD for station area land use development. *(4)*. Recent studies have focused on the comparison of PNR and TOD strategies at the station areas, including the analysis of removing existing PNR facilities *(5)* and the replacement of PNR with TOD *(6,7)*. These studies, however, looked into performance measures reflecting transit agency's interests such as change in transit ridership, and neglected other measures that can reflect economic and environmental benefits e.g., reduction in vehicle kilometers traveled (VKT) and vehicle hours delayed (VHD).

With the objective of comparing the transit station-area land use plans (i.e., TOD versus PNR), the study applies a network equilibrium approach integrating a residential relocation demand model and a four-step travel demand model. The paper is organized as follows: next section presents a literature review. Section 3 describes all the models used in the study. A solution algorithm is proposed in Section 4. Section 5 conducts scenario analysis to validate the proposed methodologies and discuss the policy implications. Conclusions are drawn in the last section.

LITERATURE REVIEW

Early practices (during 1960s-1990s) regarding transit station area land use planning mainly focused on providing PNR lots in order to extend transit market coverage *(8)*. The effectiveness of PNR lots in extending transit accessibility has been demonstrated by successful practices in the US *(9)* and many other countries including UK, German, and Singapore *(10,11)*. Starting from 1990s, TOD has gained popularity in many countries as a way to promote smart urban growth, economic development, non-motorized transportation modes *(12-14)*. With the development of land-use-transport modeling techniques *(15,16)*, TOD has been incorporated in many metropolitan regional models for a regional station-area land use planning *(17,18)*. It was then realized that PNR lots with hundreds or thousands of spaces (e.g., parking lots of Bay Area Rapid Transit (BART) system) occupy scarce land adjacent to the station areas and become an obstacle for development of TOD *(4,9)*. Additional disadvantages of PNR against TOD include poor pedestrian environment, traffic noise, air pollution and auto-oriented city image *(6,19,20)*. Nevertheless, current metropolitan regional models typically focus on the macroscopic land-use-transport system and lack the capability of examining the neighborhood-scale land use variations (e.g., TOD or PNR) in the station areas *(21)*.

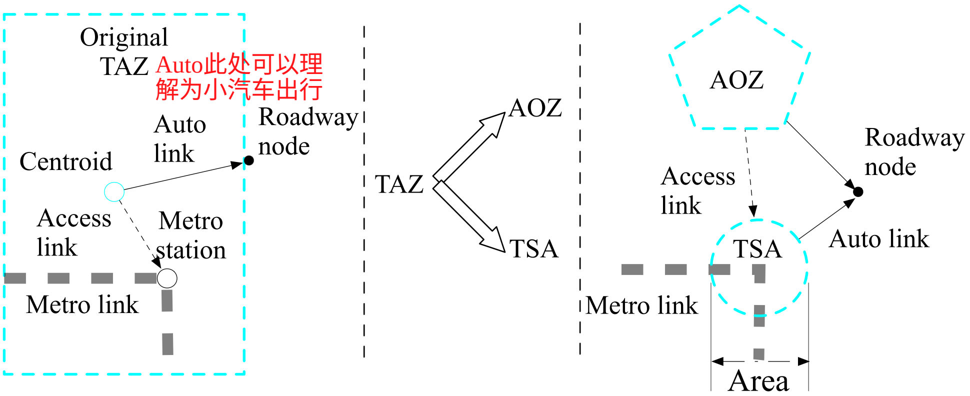
In recent years, as part of transit station-area land/access planning process *(22)*, a number of quantitive studies have been conducted to compare the outcomes of PNR and TOD *(4,6,7,23)*. Most of these studies focused on the BART system in California. For instance, Willson *(4)* and Willson and Menotti *(7)* reported a spreadsheet method using the aggregated transit demand to assess the ridership loss/gain of replacing parking with TOD. Martin and Hurrell *(23)* also applied the spreadsheet method to analyze the trade-offs between PNR and TOD in terms of transit ridership and investment costs. Duncan *(6)* developed a transit demand model based on the BART passenger survey data to examine the shift of transit ridership by replacing PNR with TOD. It is found that the level of development density of TOD required to offset the ridership loss due to replacing the PNR would be much higher than what is generally feasible *(6)*. Other PNR-TOD comparison studies include the work of Burgess *(24)* for the Massachusetts Bay Transportation Authority (MBTA) system in Boston, MA, and Ginn *(20)* for transit systems in several Australian cities. Burgess (2008) estimated the vehicle-miles traveled (VMT) changes of the PNR-TOD conversion, but the estimation was made based on an average auto trip length. Ginn (2009) utilized a preference survey method to identify the public's attitude towards incorporation of PNR and TOD at the station-area land.

The above-mentioned studies have provided transit agencies with insights into the effects of PNR and TOD on transit ridership and trade-offs between them. A single simplistic performance index (i.e. ridership or toll revenue), however, cannot fully justify the selection of PNR or TOD for the station-area land use development *(6)*. Other system performances such as VKT, VHD, and modal splits, should also be considered to reflect the sustainability effects of the selected plan in integrated transportation and land use system. In addition, existing studies neglected the interaction between land use and travel demand in PNR-TOD comparisons: the development of station-area land attracts/drives household relocation, which derives various travel demand; and then the varying travel demand is assigned on transit network as well as on roadway network, determining the system performance and affecting in turn the station-area land use decisions. Therefore, this study applies a network equilibrium analysis approach to shed some light onto the effectiveness of the alternative station-area land use policies in the future.

METHODOLOGIES

Analysis framework

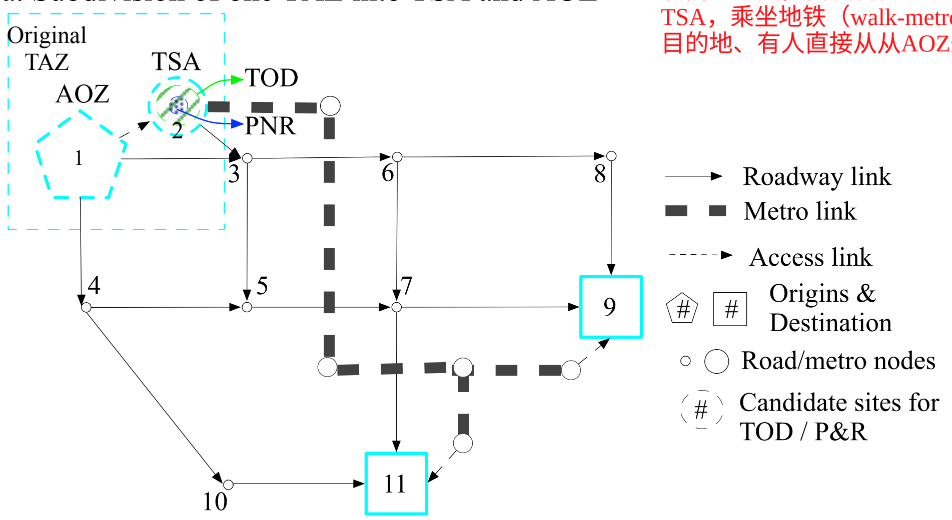
To incorporate station-area analysis capability, transportation analysis zones (TAZs) that contain the transit stations (e.g., metro stations) are subdivided into transit station areas (TSA) and auto-oriented zones (AOZ) (shown in Figure 1a), which are within walking distance and outside of walking shed (e.g., 800 m) of transit station, respectively. Note that one TAZ may cover several metro stations and one of the metro stations may be closer to the neighboring TAZ, and thus the subdivision of TAZs generate a set of spatial connections between AOZs and TSAs, which can be represented by a combination of unit TSA-AOZ connection in Figure 1a.



access此处可以理解为步行，即walking

a. Subdivision of one TAZ into TSA and AOZ

右侧这张图，我没看懂。是否可以理解为，有人愿意从AOZ走到TSA，乘坐地铁（walk-metro）、有人不坐地铁直接从TSA开车去目的地、有人直接从从AOZ开车去目的地这三种情况？



b. An example multimodal network

FIGURE 1 Layout of an integrated land use and transportation network.

Figure 1b shows a multimodal network (adopted and modified from the network proposed by Nguyen and Dupuis *(26)*) connecting TSA and AOZ as origins (assumed to be suburban residential area) and two destination TAZs (e.g., downtown employment centers). The multimodal network consists of metro links, auto links, and connecting links (PNR or walk access to transit station and walk access to destination). For the sake of simplicity, the travel modes for TSA and AOZ are limited to: walk-metro, PNR, and auto. Other potential modes, such as feeder bus and bike-metro, are not considered in the paper, which can be added in the mode choice model in the future extensions. The land in TSA can be fully or partially used for TOD or PNR, for which the general development areas are shown in Figure 1b.

本文暂且只考虑walk-metro、P+R、auto等三种出行方式在我个人的博士论文中，第四章、第五章和第六章中，为了简化处理，也只做这三种方式的考虑。不过，在博士论文的第二张、第三章中，需要增加feeder bus和bike-metro的出行方式

The deployment of TOD or PNR leads to the relocation of the existing households between AOZ and TSA. Note that relocation of businesses is also possible *(27)*, but it is not considered in this study. Instead, we assume that the AOZs and TSAs are suburban residential areas. The TOD community with better accessibility (e.g., shorter travel time and lower travel cost compared to those on the congested roadways) may attract more households moving in from AOZ; while the PNR turning partial station-area land into parking lots may drive households out to the AOZ. After the residential relocation, the derived travel demand can be simulated by the conventional four-step travel demand models. The assigned network and resulting traditional new travel pattern in turn affect the households' residential location choices due to the varying accessibility caused by the change in travel times. These iterative interactions can be depicted in Figure 2, illustrating two modules i.e., land use and travel demand modules, where exogenous inputs include station-area land use, transportation network, and socioeconomic data. As oppose to conventional TAZ-based metropolitan regional models, the proposed analysis framework incorporates a neighborhood-scale land use model (based on residential relocation model) and thus is capable of capturing the above-stated interactions between station-area land use and transit system.

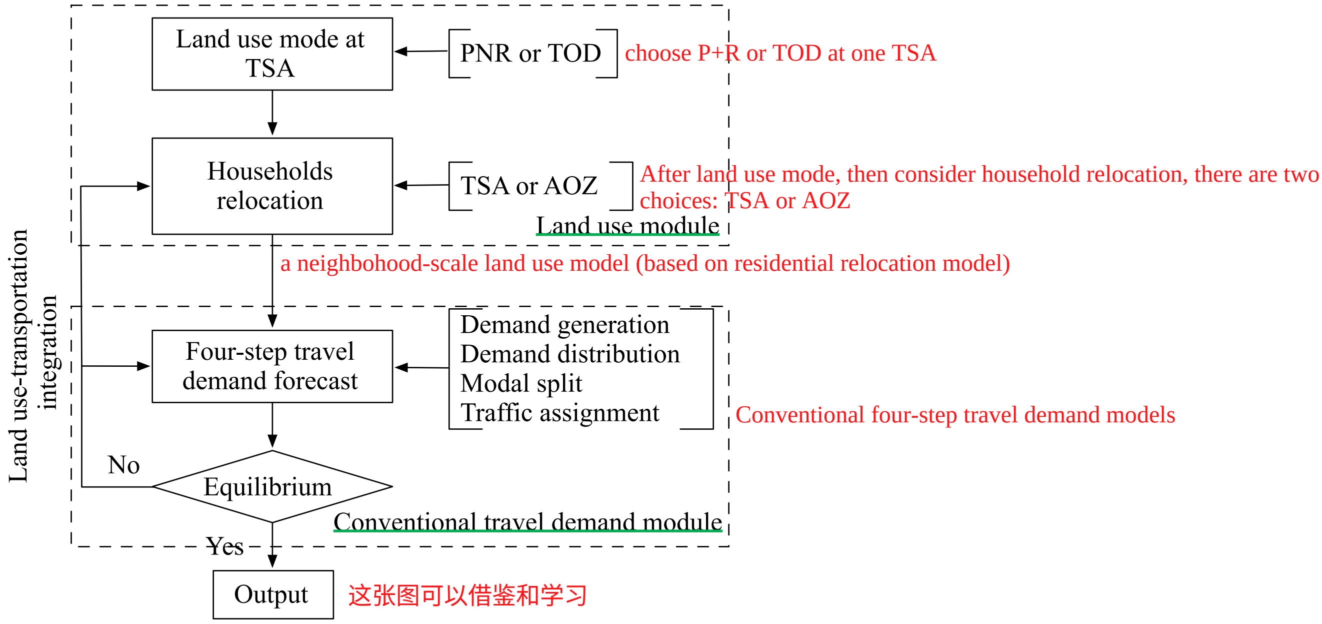


FIGURE 2 Analysis framework.

The notation used in this paper is provided in Table 1.

TABLE 1 Notation and definitions.

Notations	Description	Unit
$A_{i(x)}, A_{i(y)}$ accesibility	Accessibility of spatially correlated TSA and AOZ	-
$D_{i(\cdot)j}(\cdot), D^{-1}(\cdot)$ demand	inverse function of travel demand Actual travel demand between OD pair and the corresponding inverse function of travel demand	Trips/hour
$De_{i(x,y)}, De_{i(T)}$ density	Dwelling unit density of common community of TSA /AOZ and residential TOD community at *i*th TAZ	Du/km^2
$Du_{i(x)}$ dwelling units	Total amount of dwelling units at TSA *x* of *i*th TAZ	Dwelling units
E_j employment	Employment at the *j*th TAZ	Jobs
$h_{i(T)}, h_{i(P)}$ household	The relocating demand of households under TOD and PNR development at *i*th TAZ, respectively	Households
$H_{i(x)}, H_{i(y)}$ Households	The amount of households at TSA and AOZ	Households
i ith TAZ	TAZ consisting of spatially correlated TSA and AOZ	-
$i(x)$, $i(y)$ TSA AOZ	The TSA and AOZ that are spatially correlated at *i*th TSA 这里应该写错了，应该是TAZ，不是TSA	-
l, r and $\hat{l}, \hat{r}$	Auto link and route; and metro link and route l, link; r, route	-
auto metro L_x, L_y, L_T, L_P land area	Land area of TSA, AOZ, TOD, and PNR	km^2
m mode	Travel mode, m=[a, b, c], where a refers to auto, b metro, and c PNR	-

a, auto; b, metro; c, P+R

$M_{i(x)j}, M_{i(y)j}$ modes	The set of travel modes between OD pairs $(i(x), j)$ and $(i(y), j)$ i j, TAZ; x, TSA; y, AOZ	-
N	Set of TAZs	-
$R_{i(x)j}, R_{i(y)j}$ routes	Set of all routes between OD pairs $(i(x), j)$ and $(i(y), j)$	-
t_l, t_{l0}, v_l, C_l auto travel time free-flow travel time volume capacity	Experienced auto travel time (hour), free-flow travel time (hour), volume (vehicles/hour), and capacity (vehicles/hour) at auto link l	-
t_p, t_{p0}, v_p, C_p search time minimum search time volume capacity	Experienced search time (hour), minimum search time (hour), volume (vehicles/hour), and capacity (vehicles/hour) at PNR/parking lot p	-
$\hat{t}_{\hat{l}}, \hat{v}_{\hat{l}}$ transit travel time volume	Door-to-door transit travel time (including train operating time, walk time, and station wait time) (hour) and volume (passengers/hour) at metro link	-
$T^m_{i(x)j}, T^m_{i(y)j}$ generalized travel cost	Generalized travel cost of mode m between OD pairs $(i(x), j)$ and $(i(y), j)$	Dollars
$T^m_{i(x)j,r}, T^m_{i(y)j,r}$ generalized travel cost	Generalized travel cost of path r via mode m between OD pairs $(i(x), j)$ and $(i(y), j)$	Dollars
X_i	The set of TSAs that are spatially correlated with the same AOZ. x, TSA; y, AOZ	-
α	Proportion of potential relocating demand	-
β	Parameter in location choice model, reflecting the elasticity of household relocating demand against accessibility	-
λ, μ	Parameters in travel demand function	-
θ	Parameter in modal choice model	-

parameter

Residential relocation model A logit-type of household residential relocation demand model

The TOD land use plan, if adopted, will lead to higher density of dwelling units in TSAs than in neighboring suburbs. ($De_{i(T)} > De_{i(x,y)}$). So there is a potential to accommodate additional households who are willing to move in the TSA area due to better accessibility. Households' residential location choices are likely influenced by a variety of factors such as mobility, housing price, school quality, air quality, pleasantness resulting from agreeable conditions amenities *(27)*. In this study, we only focus on the accessibility as a measure of mobility. Following the work by McFadden *(28)*, we introduce a logit-type of household residential relocation demand model ($h_{i(T)}$), as a function of accessibility ($A_{i(\cdot)}$):

$$h_{i(T)} = \alpha H_{i(y)} \frac{\exp\left(\beta A_{i(x)}\right)}{\exp\left(\beta A_{i(x)}\right) + \exp\left(\beta A_{i(y)}\right)} \quad \text{possibility} \tag{1}$$

Subject to:

$$h_{i(T)} \le Du_{i(x)} - H_{i(x)} \tag{1a}$$

$$Du_{i(x)} = L_{i(T)} De_{i(T)} + \left(L_{i(x)} - L_{i(T)}\right) De_{i(x,y)} \tag{1b}$$

where equation (1a) sets the upper-limit constraint for the accommodation capacity at the TSA area; and equation (1b) estimates the total dwelling units at the TSA area with development of TOD. Similar model structure had been applied to predict the residential location demand in the literature *(29-31)*.

Following the accessibility measures developed by Handy and Niemeier *(32)*, and Kwan et al. *(33)*, the accessibilities of TSA and AOZ at the *i*th zone are defined as a function of the number of job opportunities accessible (E_j) at all other zones and the travel impedance ($T_{i(\cdot)j}$) between OD pairs ($i(\cdot)$, j), given as:

阻抗

$$A_{i(\cdot)} = \sum_j \frac{E_j}{T_{i(\cdot)j}}, i(\cdot) \in [i(x), i(y)], j \neq i(x), j \in N \tag{2}$$

where E_j can be obtained from local surveys or forecasted socioeconomic data; and $T_{i(\cdot)j}$ reflects the generalized travel costs of travelers between OD pair ($i(\cdot)$, j), expressed as:

$$T_{i(\cdot)j} = \ln\left(\exp\left(\sum_m T^m_{i(\cdot)j}\right)\right), m \in M_{i(\cdot)j}, i(\cdot) \in [i(x), i(y)] \tag{3}$$

$$T^m_{i(\cdot)j} = \min_r \left(T^m_{i(\cdot)j,r}\right), r \in R_{i(\cdot)j}, i(\cdot) \in [i(x), i(y)] \tag{4}$$

Equations (3-4) represent travelers' mode and route choice behaviors, respectively (given in Section Network equilibrium model).

Note that for the PNR development at the TSA, households at the land area occupied by the PNR lot are directly relocated to the adjacent AOZ, and the relocating demand is given by:

要注意的是

$$h_{i(P)} = -L_{i(P)} De_{i(x,y)} \tag{5}$$

Travel demand model

常识补充：交通需求是派生需求，是基于一定的出行目的，如上学、购物、上班等而衍生出来的一种需求，直接理解可以是没有人为了达到这个这样的目的而去出行。

The travel demand generated by the integrated land use and transportation model is a derived demand, governed by the socioeconomic characteristics (e.g., households and jobs) of OD pairs ($i(\cdot)$, j), represented by:

派生需求

$$D_{i(\cdot)j} = \lambda H_{i(\cdot)} \frac{E_j \exp\left(-\mu T_{i(\cdot)j}\right)}{\sum_k E_k \exp\left(-\mu T_{i(\cdot)k}\right)}, k \neq i, k \in N \tag{6}$$

Derived travel demand function

The derived travel demand ($D_{i(\cdot)j}$) in equation (6) is directly affected by the relocation change of household demand (equation #1 or #5), which are revised for the TSA and AOZ as:

$$H'_{i(x)} = H_{i(x)} + h_{i(\cdot)} \tag{7a}$$

The revised amount of households at TSA

$$H'_{i(y)} = H_{i(x)} - h_{i(\cdot)} \tag{7b}$$

The revised amount of households at AOZ

It is noted that the travel demand ($D_{i(\cdot)j}$) in equation (6) is also dictated by the travel impedance ($T_{i(\cdot)j}$) between OD pairs ($i(\cdot)$, j), which is obtained from the loaded network results, described next.

If one thing dictates another, the first thing causes or influences the second thing. Here, dictate means influence.

Network equilibrium model

According to the work by Sheffi *(34)*, a minimization formulation is given to represent the equilibrium state in a transportation network taking into account the elastic demand (due to the varying station-area land use and travel impedance) and multiple travel modes (i.e., auto, metro, and PNR):

Consider elastic demand (varying station-area land use and travel impedance) and multiple travel modes (auto, metro and P+R)

$$\min G = \frac{1}{\theta} \sum_{i(\cdot)j} \sum_m v^m_{i(\cdot)j} \left(\ln\left(\frac{v^m_{i(\cdot)j}}{D_{i(\cdot)j}}\right) - 1 \right) - \sum_{i(\cdot)j} \int_0^{D_{i(\cdot)j}} D^{-1}(w)\,dw + \sum_l \int_0^{v_l} t_l(v)\,dv + \sum_{\hat{l}} \hat{t}_{\hat{l}} \hat{v}_{\hat{l}} \tag{8}$$

Subject to:

be capable of capturing the interactions between station-area land use and travel demand

$$\sum_{m} v_{i(\cdot)j}^{m} = D_{i(\cdot)j} \tag{8a}$$

a set of flow conservation constraints

$$\sum_{r} v_{i(\cdot)j,r}^{m} = v_{i(\cdot)j}^{m} \tag{8b}$$

$$v_{i(\cdot)j,r}^{m} \geq 0 \tag{8c}$$

a set of non-zero constraints for network flow solution

$$v_{l} = \sum_{i(\cdot)j}\sum_{m}\sum_{r} v_{i(\cdot)j,r}^{m}\delta_{l,r}^{i(\cdot)j}, m=[a,b] \tag{8d}$$

the definitional constraints indicating the additive relationship between route flow and link flow in the auto and metro networks

$$\hat{v}_{\hat{l}} = \sum_{i(\cdot)j}\sum_{r} v_{i(\cdot)j,r}^{m}\delta_{\hat{l},r}^{i(\cdot)j}, m=[b,c] \tag{8e}$$

where equations (8a, b) are a set of flow conservation constraints, which state that the flow of all modes between each OD pair has to equal the OD trip demand, and the flow on all routes connecting the OD pair via mode *m* has to equal the corresponding trip demand of mode *m* between the OD pair. Equation (8c) is a set of non-zero constraints for network flow solution. Equations (8d, e) are the definitional constraints indicating the additive relationship between route flow and link flow in the auto and metro networks, respectively. $\delta_{l,r}^{i(\cdot)j}, \delta_{\hat{l},r}^{i(\cdot)j} = 1$, when link l ($\hat{l}$) belongs to route r; otherwise $\delta_{l,r}^{i(\cdot)j}, \delta_{\hat{l},r}^{i(\cdot)j} = 0$. It can be proved that the first-order conditions of the minimization model (equation 8) are identical to the equilibrium conditions. Detailed equivalence proof can be found in Sheffi *(34)*. Things that are identical are exactly the same.

precise, decided, express, specific

In equation (8), travelers' modal choice behavior is assumed stochastic, while route choice is assumed deterministic. The stochastic modal choice assumption reflects the users' complex decision process, which is influenced by the quantitative factors (i.e., travel costs of different travel modes) and a large number of qualitative factors including personal preferences, vehicle ownership, and context-dependent conditions (e.g., weather and destination activity). The modal split can be formulated as a logit function:

Quantitative factors: travel costs of different travel modes
Qualitative factors: personal preferences, vehicle ownership and weather, destination activity

$$v_{i(\cdot)j}^{m} = D_{i(\cdot)j}\frac{\exp\left(-\theta T_{i(\cdot)j}^{m}\right)}{\sum_{m}\exp\left(-\theta T_{i(\cdot)j}^{m}\right)}, m \in M_{i(\cdot)j} \tag{9}$$

The modal split can be formulated as a logit function

As for the route choice, it is reasonably hypothesized for long-term planning that travelers have the well-informed knowledge about the transportation network from their day-to-day traveling experiences or intelligent information guidance system. Thus, the user equilibrium of route choices on auto and metro network can be expressed as:

假设; 猜测

$$\begin{cases} v_{i(\cdot)j,r}^{m}\left(T_{i(\cdot)j,r}^{m} - \min_{r}\left(T_{i(\cdot)j,r}^{m}\right)\right) = 0 \\ T_{i(\cdot)j,r}^{m} - \min_{r}\left(T_{i(\cdot)j,r}^{m}\right) \geq 0 \end{cases}, r \in R_{i(\cdot)j} \tag{10}$$

The user equilibrium of route choices on auto and metro network, UE conditions

Note that the route travel cost ($T_{i(\cdot)j,r}^{m}$) is the sum of all travel costs (travel times are converted to monetary terms) on the intermediate links (e.g., auto/metro, PNR, and walk links) of route *r*. The travel time (t_l) along auto link *l* is expressed in the Bureau of Public Roads (BPR) form as follows:

$$t_{l} = t_{l0}\cdot\left(1+0.15\cdot\left(v_{l}/C_{l}\right)^{4}\right), \tag{11a}$$

BPR function, Bureau of Public Roads
Travel time along auto link l

PNR facility or parking lot at the destination TAZ can be treated as a virtual auto link with a BPR-form parking search time *(35)*:

$$t_{l} = t_{l0}\cdot\left(1+0.4\cdot\left(v_{l}/C_{l}\right)^{2}\right), l = p \tag{11b}$$

a BPR-form parking search time

Travel times on other network links are treated as constants ($\hat{t}_{\hat{l}}$), consisting of 常量 train operating time, walking time, and station waiting time at metro links ($\hat{l}$) (walk links are virtualized as the metro connectors).

The equilibrium model (equation #8) is capable of capturing the interactions between station-area land use and travel demand. When the equilibrium state is reached, the flows in the auto and metro network satisfy the UE conditions (equation #10), and the relocated household demand, travel demand, and modal split in the integrated system meet the requirements stated in equations (1 or 5), (6), and (9), respectively.

The deployment of troops, resources, or equipment is the organization and positioning of them so that they are ready for quick action

SOLUTION ALGORITHM

Given that the deployment of TOD and PNR is known at the TSA from the exogenous 部署 having an external origin station-area land use plans, the paper applies the method of successive averages MSA (MSA) to find solutions to the above-given minimization model (equation #8). The solution algorithm steps are summarized as:

Step 1: Initialization. Set loop variable $k=1$. Initialize the network flows (e.g., $v_{i(\cdot)j,r}^{m(k)}=0$) and obtain the corresponding travel costs ($T_{i(\cdot)j,r}^{m(k)}$).

Step 2: Land use deployment. Substitute network performance ($T_{i(\cdot)j,r}^{m(k)}$) under current network flow solutions to equations (1, 5) and estimate the relocating demand.

Step 3: Transportation system responses.

Step 3.1: Travel demand generation. Estimate travel demand by equation (6).

Step 3.2: Modal split: Estimate modal demand by equation (9).

Step 3.3: Traffic assignment. Compute auxiliary network flows ($av_{i(\cdot)j,r}^{m(k)}$) to satisfy 辅助的 equation (10) and apply the MSA to update the flow solution:

$$v_{i(\cdot)j,r}^{m(k+1)} = v_{i(\cdot)j,r}^{m(k)} + \left(av_{i(\cdot)j,r}^{m(k)} - v_{i(\cdot)j,r}^{m(k)}\right)/k \tag{12}$$

Step 4: Convergence criteria. Terminate the algorithm if the loop variable (k) reaches the pre-specified iteration limit (e.g., k=1000) or the following convergence criteria is satisfied:

$$\frac{\sum_{l}\left|v_{l}^{(k)}-v_{l}^{(k-1)}\right|}{\sum_{l} v_{l}^{(k)}}+\frac{\sum_{\hat{l}}\left|\hat{v}_{\hat{l}}^{(k)}-\hat{v}_{\hat{l}}^{(k-1)}\right|}{\sum_{\hat{l}} \hat{v}_{\hat{l}}^{(k)}} \le \varepsilon \tag{13}$$

Output the optimal solution; otherwise, set $k=k+1$ and go to Step 2.

NUMERICAL STUDIES

Two examples are designed (a single station site and multiple station sites) to validate the above-proposed models and algorithm. We will discuss the policy implications for station-area land use alternatives, i.e., building a PNR lot adjacent to metro station, TOD replacement of an existing PNR, and a new TOD at the entire TSA area.

Single metro site scenario analysis

The multimodal network (i.e., metro and auto network shown in Figure 1b) is taken as the experimental network, of which the basic settings are given in Table 2. In the base case, TSA and AOZ are indifferent within the suburban residential areas. Parameters used in the models are given as, $\alpha=0.9$, $\beta=0.1$, $\theta=1$, $\mu=0.9$, and $\lambda=0.1$, which remain unchanged for all scenarios. Note that although it is common in studies to pre-specify the model parameters, in practice they have to be calibrated and validated based on the survey data at each stage of model building *(36)*.

TABLE 2 Variables settings of the base case.

Parameters	Values	Units	Descriptions
C_l	4,000	Vehicles/h	Capacity of auto links
$C_{\hat{l}}$	15,000	Passengers/h	Capacity of metro links
C_p	1,000	Vehicles/h	Parking capacity of PNR facility
	8,000	Vehicles/h	Parking capacity at destination
De_1, De_2	2,500	h/km^2	Existing household density
E_9, E_{11} *	60	jobs/unit area	Employment at destination
L_1	15	km^2	Area of auto reliance zone
L_2	2**	km^2	Area of station area land
t_{l0}	0.15	Hour	Free flow travel time at auto links
t_{p0}	0.05	Hour	Minimum parking search time
$\hat{t}$	0.14	Hour	Operating time at metro links
	0.05	Hour	Walking time at walk links
	0.05	Hour	Waiting time at metro stations

Note: *The value is set to yield a proper amount of OD travel demand that can be accommodated by the simplified network with a limited capacity and simultaneously has the tendency of using metro due to the traffic congestion on the roadway network. **The area is the coverage of a metro station with a radius (i.e., walking-accessible range) of 800m.

Three scenarios (i.e., a PNR lot, a TOD replacement, and a new TOD) are designed: It is assumed that the PNR scenario proposes to occupy a portion (as illustrated in Figure1b) of the metro station-area land (2 km^2) to build a surface parking lot and the occupancy area can be estimated by multiplying its parking capacity (i.e., 1,000 parking spaces) with the unit area (including parking spots and public area) per parking (i.e., 32 m^2/space adapted from studies by Burgess *(24)* and VTPI *(37)*). Under the TOD replacement scenario, the development of a TOD area (with the density of 7,500 du/km^2) is restrained within the existing PNR area (i.e., 0.03 km^2), reflecting realistic land availability for the transit agencies (e.g., BART). The new TOD scenario suggests to utilize the entire station area (i.e., 2 km^2) for the intensive residential development (i.e., 7,500 du/km^2), which may be reasonable in the long-term transit-oriented planning for vacant area.

Applying these data to the proposed models and solution algorithm under the base case and the three scenarios, we obtain the following results presented in Table 3. Table 3 summarizes the main results of network performances under the base case and three scenarios, including demand split (DS), modal split (MS), metro patronage (MP), VKT, and VHD. The varied demand splits of AOZ and TSA among the base case and three scenarios can be explained as a result of the household relocation. Significant travel demand changes are achieved under the new TOD scenario, which is understandable since the entire station-area land is developed as a high-density residential TOD. As for the modal split, the deployment of a PNR facility at the TSA attracts a considerable demand shift from auto mode to PNR at AOZ. The modal shares in the TSA appear to fluctuate slightly and be less impacted by different scenarios.

TABLE 3 System performances. AOZ, auto oriented zone; TSA, transit station area

	Items		Base case	PNR lot	TOD replacement	New TOD
Demand split	DS (%)	AOZ	86.0%	86.2%	85.6%	66.7%
		TSA	14.0%	13.8%	14.4%	33.3%
Modal split	MS (%)	AOZ*	[100, 0]	[88, 12]	[100, 0]	[100, 0]
		TSA**	[45, 55]	[47, 53]	[45, 55]	[46, 54]
Metro patronage	MP (trips/h)		1,183	2,707	1,216	2,791
Vehicle kilometers traveled	VKT (kms)		488,613	414,899	482,485	414,001
Vehicle hours of delay	VHD (hours)		3,490	2,182	3,435	1,623
	Percent changes (%)					
Metro patronage		MP	-	129%	3%	136%
Vehicle kilometers traveled		VKT	-	-15%	-1%	-15%
Vehicle hours of delay		VHD	-	-37%	-2%	-53%

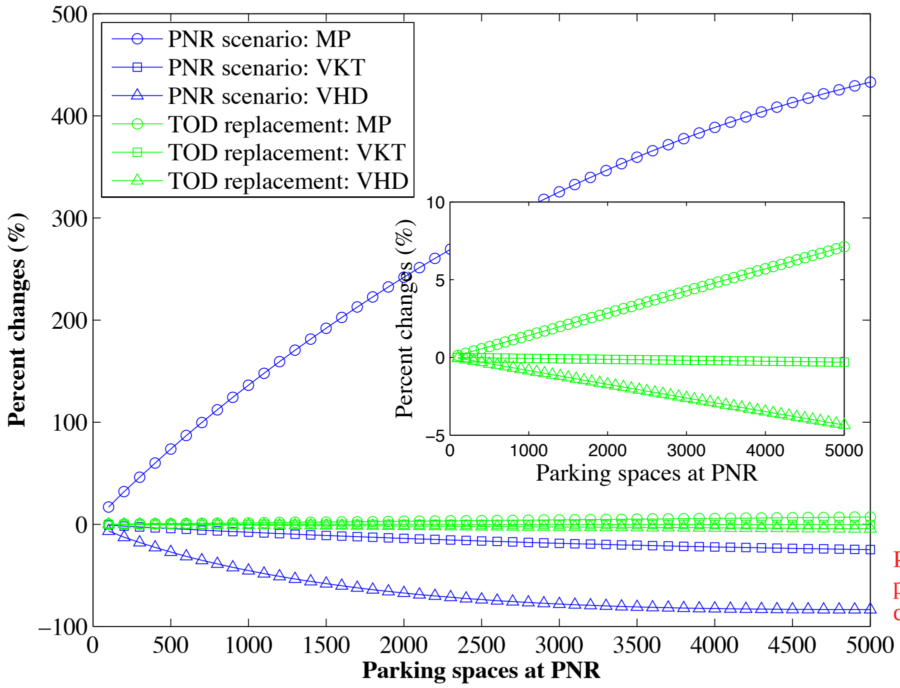
Note: *values in bracket 括号 indicate modal split between auto and PNR at AOZ; and **values in bracket indicate modal split between auto and metro at TSA.

Higher MP and lower VKT and VHD are consistently observed in three scenarios compared to the base case, but the percentage changes differ considerably for the three scenarios. A new PNR facility significantly increases the MP and thus reduces the VKT and VHD due to the induced 诱发的 PNR trips. Relatively, the TOD replacement project results in a considerable loss in the MP as opposed 与...截然相反 to the PNR and more VKT and VHD occur on the auto network. The degradation of the system performance under the TOD replacement scenario can be explained by the limited TOD development scale (i.e., 0.03 km^2, land area occupied by existing PNR), which attracts few households moving in and shifting to metro mode from auto mode. When the TOD is deployed on the entire TSA (i.e., 2 km^2), the new TOD scenario has the maximum MP for the metro lines and correspondingly the minimum VKT and VHD for the auto network.

灵敏度分析，在第七章：公交与用地一体化政策评价方法与指标，可能用得到

Furthermore, we conduct a sensitivity analysis to explore the impacts of two key variables: the parking capacity (spaces) of a PNR facility and the development density (dwelling unit per square kilometers) of TOD. The results are shown in Figures 3 and 4, respectively. It can be seen in Figure 3 that although the percentage changes of MP, VKT, and VHD increase with the amount of parking spaces under both PNR and TOD replacement scenarios, the former appears to be much more sensitive to the parking capacity than the latter P+R given other conditions unchanged. It is demonstrated that compared to the TOD TOD with the same land usage area (i.e., TOD replacement scenario), the PNR facility appears to be much more effective in expanding the transit market and mitigating 缓和，减轻 the vehicular traffic congestion.

灵敏度分析这块思路和想法，也可以在博士论文中有所体现



P+R appears to be much more sensitive to the parking capacity than the TOD given other conditions unchanged

FIGURE 3 Sensitivity of performances against parking spaces of PNR.

Figure 4 depicts 描述 how MP, VKT, and VHD change with the varying TOD density. It is observed that the TOD density plays a positive role in improving the system performances (the linearly increased MP and reduced VKT and VHD); however, the effectiveness of the TOD replacement scenario is limited by the available land use (i.e., the existing PNR lot). It is also noted that for the new TOD scenario the curves of MP, VKT and VHD turn flat beyond a threshold point (i.e., 6,722) as shown in Figure 4. The threshold is dictated by the demand of the household residential relocation (equation #1), which depends on the accessibility advantage of TSA: at equilibrium state, both TSA and AOZ's accessibilities stabilize and result in finite 有限的 household relocation demand; and thus the growing TOD density with the incremental 增加的，增值的 accommodation capacity (dwelling units) for relocating households will not continuously produce more TOD benefits.

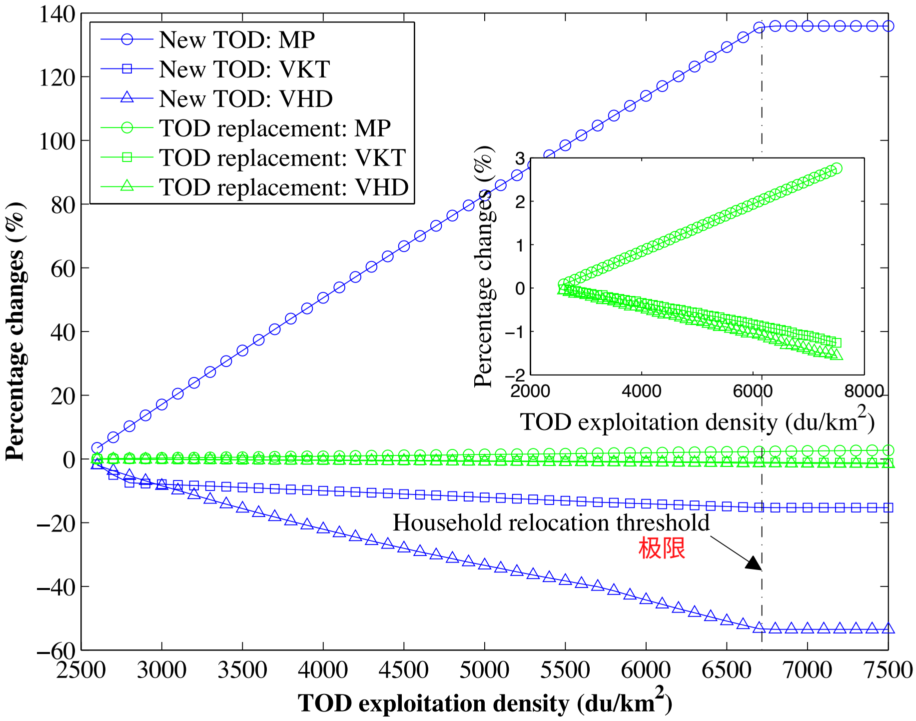


FIGURE 4 Sensitivity of performance changes against TOD exploitation density.

How MP, VKT, and VHD change with the varying TOD density

In this numerical study, several policy implications can be drawn: (i) when the policy-makers decide to replace an existing PNR facilities with a TOD, attentions should be given to the potential losses in terms of reduced transit patronage and increased VKT and VHD; (ii) when developing new TOD plans, transit agencies should be more cautious about the development density, because a higher-density TOD causes a higher investment cost and does not necessarily guarantee better benefits if they fail to attract sufficient residents; and (iii) possible solutions to enhance the TOD effectiveness include expanding the TOD area, coordinating the residential demand and development scale at the TSA, and conferring significant transit accessibility advantage.

Multiple metro sites scenario analysis

In reality, transit agencies may develop the station-area land use at multiple sites along transit lines. To represent this scenario, in addition to one pair of AOZ-TSA at nodes 1 and 2, two more AOZ-TSAs are added at nodes 12, 13 and 14, 15 along with the connecting auto and access links, as shown in Figure 5. The multiple TSAs (i.e., nodes 2, 13, 15 with area of 2, 0.79, 0.28 km^2, respectively) and AOZs (nodes 1, 12, 14 with area of 15, 10, 5 km^2, respectively) represent low- (2,500 h/km^2), median- (3,500 h/km^2), and high-density (4,500 h/km^2) residential locations along the metro lines from the suburban to urban area. Other conditions remain the same with the single metro site example (Figure 1b).

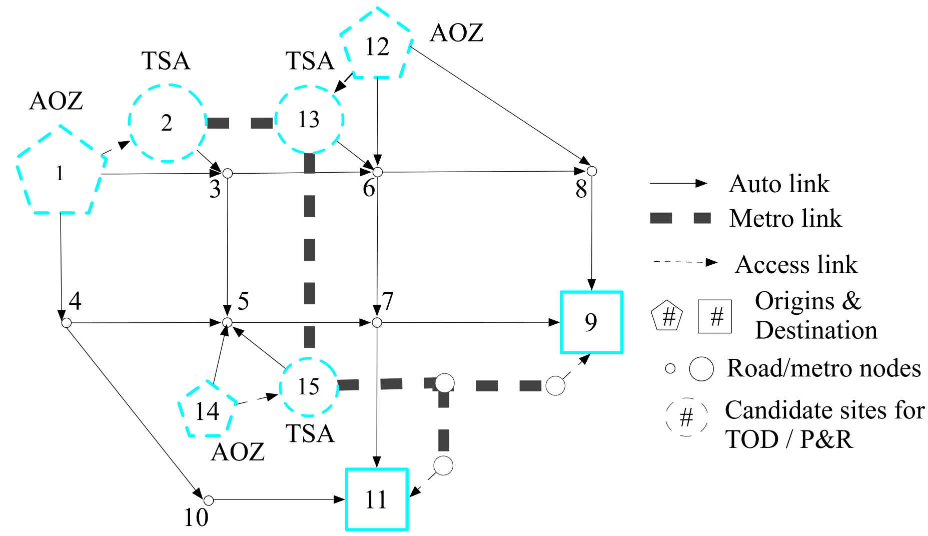


FIGURE 5 Multiple metro sites example. 此图可推广到博士论文第四章：TOD与P&R设施竞争选址模型，案例分析

Three objective criteria (i.e., MP maximization and VKT and VHD minimization) are applied to find the optimal solutions to the multiple-site land use scenario. For the sake of simplicity, the selection of station-area land use is only considered between two promising options, i.e., new TOD and PNR. Let σ_i indicate the deployment of TOD ($\sigma_i = 1$) or PNR ($\sigma_i = 0$) at TSA (i), the relocating household demand can be written as $h_{i(\cdot)} = \sigma_i h_{i(T)} + (1-\sigma_i) h_{i(P)}$. Thus, an optimization model (i.e., maximizing MP or minimizing VKT and VHD) can be established as a 0-1 integer-programming problem with the decision variable σ_i. Note that the characteristics (e.g., area, density, and capacity) of TOD and PNR in this study are assumed to be constant variables, which considerably reduce the complexity of the problem. The optimal results are summarized in Tables 4 and 5. Three objective criteria lead to consistent optimal solutions: TOD at node 2 and PNR at nodes 13 and 15. The results can be reasonably explained by the weakened effectiveness of TOD on MP maximization and VKT/VHD minimization: as its location approaches the employment centers, (i) the available land for TOD at station area reduces, (ii) the accessibility advantage (e.g., travel time savings at metro links) of TSAs decreases; and (iii) the household density differences between TOD and neighboring AOZ also diminishes.

终于找到了0-1规划模型的理论依据了，真他妈高兴，哈哈，原来真的是TOD、P+R要么一个是0、另外一个是1。所以，还是要多看论文啊，勉励一下自己

在Multiple metro sites scenario中，只考虑新建TOD或P+R

在第六章：TOD与P&R设施用地联合开发模型研究中，可通过TOD/P+R设施的面积比例来决定 Relocating hosuehold demand

减少

TABLE 4 Optimal solutions at three metro sites.

Objective criteria	TSA one (node 2)	TSA two (node 13)	TSA three (node 15)
MP	TOD	PNR	PNR
VKT	TOD	PNR	PNR
VHD	TOD	PNR	PNR

Table 5 presents the comparisons between the optimal and worst solutions for the multiple-site land use planning. It is confirmed that under the given experimental conditions the deployment of TOD or PNR at the metro sites improves the system performance compared to the base case; however, when the station-area land use plan is misguided (i.e., the worst case), the system performance may be considerably lower than that of the optimal one.

TABLE 5 Comparisons between the optimal and worst solutions.

	Indexes	Base case	Optimal solution	Worst solution	
Metro patronage	MP (trips/h)	4,561	11,116	7,830	Worst solution也比base case好
Vehicle kilometers traveled	VKT (veh km/h)	1,061,291	935,179	987,250	Worst solution也比base case好
Vehicle hours of delay	VHD (veh h /h)	550,221	221,715	393,330	Worst solution也比base case好

The above-described experiments demonstrate the necessity for transit agencies to conduct a thorough research when making metro station-area land use plans. Different from the conventional site-based analysis, the proposed network-based analysis framework helps to capture the household relocating effects at the TSA as well as travelers' travel choices (e.g., mode and route choices) on a multimodal network. Thus, more insights are provided for the selection and optimization of alternative station-area land use plans.

CONCLUSIONS

With the objective of examining two station-area land use options (i.e. TOD and PNR), the paper integrates the households' residential relocation model with the conventional four-step travel demand models to quantify the interaction between land use and travel demand. Three scenarios, i.e., building PNR lot, TOD replacement, and new TOD, are developed to analyze the effectiveness of land use policies on increasing metro patronage and reducing VKT and VHD. The results show that (i) the deployment of PNR and new TOD can make significant contributions to the total metro ridership as well as VKT/VHD reduction; but (ii) a TOD replacement of existing PNR lot appears to lead to considerable patronage loss. The proposed analysis framework can be embedded into traditional four-step travel demand models, saving considerable cost and time. In the future, we plan to apply the proposed method to Maryland Statewide Transportation Models in conjunction with the vehicle emission models (e.g., MOVES), so as to examine the large-scale traffic and air quality impacts of the regional station-area land use plan *(38)*.

It needs to point out that the study has several limitations. First, there are several types of TODs classified by the nature of the occupants, e.g., residential, office, and mixed TOD. Current study only considers the residential TOD (representing the suburban communities). In the future, business/employment relocation can be incorporated into the TOD modeling by accounting for the sophisticated land use models (e.g., Lowry model, IMREL, and ITLUP) *(15)*, and relatively more TOD-favored results are expected due to the internalized non-auto trips within the mixed/joint developed TOD area. Second, transit-access modes in this study neglect feeder bus, bike-and-park, kiss-and-ride, etc., which can be incorporated in travelers' mode choices via multinomial or nested logit models in further studies. Third, the characteristics (e.g., area, density, and capacity) of TOD and PNR are simplified as constants in the current study, which can be further relaxed by introducing an integer-programming model with the decision variables such as TOD density and PNR capacity. Heuristic algorithms (e.g., generic algorithm) can be applied to resolve the corresponding integer programming problem on a large-scale network. Additionally, the paper didn't consider the equity issues of PNR-to-TOD conversion, which may disenfranchise a high share of residents. When developing specific land use policies, economic activities of transit agencies (e.g., selling off land for TOD) merit furfure benefit-cost analysis from a financial perspective.

从范老师谈及的logit模型来看，在博士论文第二章：围绕地铁站公交与用地一体化建模核心理论中，可以考虑用multinomial or nested logit model，但我目前是准备用混合logit model来做，可以做multinomial、nested和mixed logit model

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