# MODELING ACTIVITY AND TRAVEL CHOICE BEHAVIOUR FOR LAND USE AND TRANSPORT OPTIMIZATION PROBLEMS

OUYANG LIANQUN

Ph.D
The Hong Kong
Polytechnic University
2014

The Hong Kong Polytechnic University
Department of Civil and Environmental Engineering

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**OUYANG Lianqun**

A thesis submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy

October 2013

# CERTIFICATE OF ORIGINALITY

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Ouyang Lian Qun (Name of Student)

# ABSTRACT

There has been a growing recognition in recent years that the transport models which use the activity-based approach could provide better understanding of user travel choice behaviour, when compared to the conventional transport models which use the traditional trip-based approach. The traditional trip-based transport models usually focus on a single trip with the assumption that all trips are independent to each others. Activity-based transport models, however, investigate the underlying activity choices which generate trips, interdependence of trips, scheduling of activities and trips regarding time and space, as well as relationships between inter-personal activities and trips. Thus, as can be seen, activity-based transport models describe user travel choice behaviour comprehensively.

In addition, due to the strong interactions between land use and transport, it is widely believed that there is a need to develop integrated land use and transport models to simultaneously model user (residential/employment) location and travel choice behaviours. In view of the potential merits of the activity-based approach in modeling user travel choice behavior together with their close relationships between user residential/employment location and activity choices, it is highly desirable to move forward by developing integrated land use and transport models using the activity-based approach.

Land use and transport have a strong interactive relationship; hence the development of sustainable land use and transport optimization models could be an important step

to relieve traffic congestion problems in fast-growing cities. Examples of problems resulting from such growth are currently seen in China. The growing activity demands due to such rapid development, in addition, are causing grim traffic air-pollution problems. Urban development resulting from too rapid economic growth and without the foresight of comprehensive and well structured planning in efficient clean transport can negatively affect human physical and mental health, and unnecessarily, interrupt economic progress. How to balance the economic development and environmental pollution associated with sustainable land use and transport policies, is frequently one of the most acute problems with which authorities of fast-growing cities are concerned.

With the above urban problems in mind, the overall focus of this research is developing models for modeling user travel choice behaviour more accurately so that transport-related or land use polices which enable efficient and clean movement within a city could be explored. In this regard, this research offers three major contributions.

1. The user daily activity scheduling problem under two scenarios (in congested road networks and in general road networks) is studied; two activity-based transport models are proposed and provide the first contribution of this research. The first model focuses on the user daily activity scheduling network equilibrium problem in congested road networks. It is formulated as an equivalent user equilibrium (UE) assignment problem for an expanded Activity-Time-Space (ATS) queuing network. The second model is an extension of the first and deals with the user daily activity scheduling network

equilibrium problem in general road networks (i.e. both congested and non-congested road networks) and incorporates users' different perception variations on activity utilities and travel times. It is shown to be a stochastic user equilibrium (SUE) assignment solution to the urban road network for solving the user daily activity scheduling network equilibrium problem.

In the proposed two activity-based transport models, the motivation of making trips, unlike the previous trip-based transport models, the relationships between trips, and the time and space coordinates are investigated explicitly. In addition, the activity sequences and activity durations are endogenously generated in the proposed models. Thus, the user travel choices are examined in a more comprehensive framework by comparing to the relevant activity-based transport studies appearing in recent years in the literature. Some properties of the equilibrium solution are also investigated and discussed. Efficient solution algorithms without the prior Daily Activity-Travel Pattern (DATP, i.e. user daily activity scheduling result) enumeration are developed for solving the above two models. In addition, the proposed activity-based transport model for general road networks allows different perception error variations of utilities/disutility across various activities and travel. It is noted that these variations are usually assumed to be identical in the previous activity-based related studies.

2. The development of an activity-based land use and transport model to investigate the combined user residential location and travel choice problem is the second contribution of this research. The users' combined residential

location choice and travel choice problem is formulated as a stochastic user equilibrium network model. Users are assumed to pursue the perceived maximum difference between benefit and cost of selecting a residential location. The benefit of selecting a residential location is equal to the total utility obtained from participating in activities minus the travel costs needed for activity participations in the study time horizon. The cost of choosing a residential location is the housing price or rent in the study time horizon.

In this research, the developed activity-based land use transport model extends the existing relevant models in the literature by considering both user residential location choices and user travel choices with the use of the activity-based approach. The close interrelationship between user residential location choice and user DATP choices is revealed in this developed model. The inconsistency problem that may appear in some existing relevant models is avoided in the developed model. This extension offers a new avenue of research on network equilibrium analysis for examining the interactions between land use and transport.

3. As far as the third contribution of this research is concerned, a novel activity-based land use and transport optimization model using the bi-level programming technique is proposed to solve the sustainable land use and transport optimization problem. The upper level of the proposed model is to optimize the residential/employment location developments and road link capacity expansions with a budget constraint so that the maximum network social welfare is achieved while satisfying the network-wide traffic emission

control level. The lower level of the proposed model is a network equilibrium model which models combined user residential/employment location and daily activity/travel choice (i.e. DATP choice) behaviour.

The user location and travel choice behaviours are accurately captured with the use of the activity-based approach in the lower level of the proposed model. The proposed bi-level programming model is able to optimize the land use development and transport system improvement in a consistent way.

# PUBLICATIONS ARISING FROM THE THESIS

Journal papers:

1. Ouyang, L.Q., Lam, W.H.K., Li, Z.C., and Huang, D. (2011). Network user equilibrium model for scheduling daily activity travel patterns in congested networks. *Journal of the Transportation Research Board*, 2254, 131-139.

2. Ouyang, L.Q., and Lam, W.H.K. (2009). An activity-based land use and transportation optimization. *Journal of the Eastern Asia Society for Transportation Studies*, 8.

3. Chan, K.S., Lam, W.H.K., Ouyang, L.Q., and Wong, S.C. (2007). Simultaneous estimation of the pedestrian origin-destination matrix and parameter of the activity/destination choice model. *Journal of the Eastern Asia Society for Transportation Studies*, 7.

Conference papers:

1. Ouyang, L.Q., and Lam, W.H.K. (2009). A Combined Location and Travel Choice Model---An Activity-based Approach. *Proceedings of the 88th Annual Meeting of the Transportation Research Board*, Washington, D.C., 09-3361.

2. Ouyang, L.Q., Lam, W.H.K., Tam, M.L, Li, Z.C. (2008). Simultaneous Estimation of Origin-Destination Matrix and Parameters of Activity and Destination Choice Model. *Proceedings of the 87th Annual Meeting of the Transportation Research Board*, Washington, D.C., 08-1929.

3. Ouyang, L.Q., and Lam, W.H.K. (2008). An Activity-Based Approach for Modeling Travel and Residential Location Choices. *Proceeding of the 13th International Conference of Hong Kong Society for Transportation Studies*, Hong Kong, 697-716.

4. Ouyang, L.Q., and Lam, W.H.K. (2007). Estimation of Pedestrian Time-Dependent Trip Matrix: An Activity-Based Approach. *Proceeding of the 12th International Conference of Hong Kong Society for Transportation Studies*, Hong Kong, 89-98.

# ACKNOWLEDGEMENTS

I wish to express my sincerely appreciation to my chief supervisor, Prof. William H.K. Lam, for his excellent guidance, strong sense of responsibility during my study and preparation of this thesis. His conscientious and meticulous working attitude has benefitted both in this research and is a lesson for me in the future.

Special thanks must be given to Prof. H.J. Huang from Beihang University, for his encouragement throughout the course of my PhD study. I also wish to thank Mrs. Elaine Anson for her help in proofreading this thesis. I would like to greatly thank Prof. David P. Watling, Prof. D.G. Wang and Prof. C.W. Li for their time and efforts to be the committee members of my PhD examination. Their valuable comments and suggestions are very much appreciated.

Grateful thanks should also be given to Dr. Z.C. Li, Dr. A. Sumalee, Dr. H. Shao, Dr. Z. J. Tan, Dr. K.S. Chan, Dr. M. L. Tam, Dr. B.Y. Chen, D. Liu, Y.Q. Zhang, Y.L. Xiong, D.J. Ye, and X. Fu. Discussions with them have benefited my research. Grateful appreciation should be extended to Dr .Q. Tian, Dr. T.Q.Tang, Dr. T.L. Liu, Dr. Shang, H.Y. Dr. W.X. Wu, Dr. C.Q. Mei, Dr. R.Y.Guo, Dr. J. C. Long, Dr. J.X. Ding, Dr. L.J. Tian, Y. Zhang, Dr. Y.J. Chen, and my other good friends who offered great help to me.

Special thanks should be given to my parents, my elder sister, my elder brother, and Dr. D. Huang for their great help and encouragement in completing my PhD study.

Finally, I sincerely acknowledge the financial support from the Hong Kong Polytechnic University through a HKPU studentship for three years.

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# NOTATIONS

The following notations are used throughout this thesis unless otherwise specified.

*Sets*

| | |
|---|---|
| $J$ | the set of activities |
| $\hat{G}=(S,B)$ | base network only used in Chapter 3 |
| $G=(N,A)$ | the expanded Activity-Time-Space (ATS) network in Chapter 3; transport network in the other chapters |
| $S$ | the set of all nodes, including all nodes for activity participations in base network |
| $B$ | the set of all directed road links in base network |
| $N$ | the set of all nodes |
| $K$ | the set of all time intervals |
| $A$ | the set of all directed links of the transport network; the set of all links of the ATS network in Chapter 3 |
| $P$ | the set of all routes of the transport network; the set of all paths of the ATS network in Chapter 3 |
| $I$ | the set of all feasible daily activity-travel patterns(DATPs) |
| $H$ | the set of all feasible housing/residential locations |
| $W$ | the set of all feasible employment locations |

| | |
|---|---|
| $A_e^1$ | the set of activity link in ATS network |
| $A_e^2$ | the set of travel link in ATS network |
| $A_e^3$ | the set of queue link in ATS network |
| $A_e^4$ | the set of dummy start link in ATS network |
| $A_e^5$ | the set of dummy end link in ATS network |
| $A_e^{4,1}$ | the set of exit links which connect to the tail of a road link in ATS network |
| $A_e^{4,2}$ | the set of the other exit links which connect to the head of exit links(see Figure 3.2a) in ATS network; $A_e^{4,1} \cup A_e^{4,2} = A_e^4$ |
| $F_a$ | the set of the queue links with $a' = \left(l_b^{i',k'-1}, l_b^{i',k'}\right)$, $k' = k$, $1 \le i' \le i-1$, $a' \in A_e^3$ (see Figure 3.2b) in ATS network |
| $\Omega$ | the set of feasible variables that are defined by Equations(3.3) |
| $\Omega I$ | the set of feasible variables that are defined by Equations(4.9)-(4.18) |
| $\Omega II$ | the set of feasible variables that are defined by Equations(5.5)-(5.8) |
| $\Omega III$ | the set of feasible variables that are defined by Equations(5.16)-(5.20) |
| $\Omega i$ | the set of feasible variables that are defined by Equations(6.5) |
| $\Omega ii$ | the set of feasible variables that are defined by Equations(6.9) |

*Matrices and Vectors*

| | |
|---|---|
| $\mathbf{x}$ | vector of $x_a$ |
| $\mathbf{f}$ | vector of $f_p$ |

| | |
|---|---|
| $\mathbf{V}(\mathbf{x})$ | matrix of $V_a$ |
| $\mathbf{V}'(\mathbf{x})$ | Jacobian matrix of $\mathbf{V}(\mathbf{x})$ |
| $\mathbf{q}$ | vector of $q_i$ |
| $\mathbf{P}$ | vector of $P_i$ |
| $\hat{\mathbf{V}}$ | vector of $\hat{V}_i$ |
| $\hat{\mathbf{t}}$ | vector of $\hat{t}_a(k)$ |
| $\mathbf{q}^{mh}$ | vector of $q_i^{mh}$ |
| $\mathbf{t}$ | vector of $t_a(k)$ |
| $\mathbf{P}^{mh}$ | vector of $P_i^{mh}$ |
| $\mathbf{V}^{mh}$ | vector of $V_i^{mh}$ |
| $\vec{\mathbf{q}}$ | vector of $q_{mh}$ |
| $\vec{\mathbf{P}}$ | vector of $P_{h/m}$ |
| $\vec{\boldsymbol{\Pi}}$ | vector of $\Pi_{mh}$ |
| $\Delta\mathbf{S}$ | vector of $\Delta S_h$ |
| $\Delta\mathbf{G}$ | vector of $\Delta G_w$ |
| $\Delta\mathbf{C}$ | vector of $\Delta C_a$ |

*Variables*

| | |
|---|---|
| $k$ | time interval |
| $k_-$ | the time a little earlier than $k$ under the continuous time scenario |

| | |
|---|---|
| $k_+$ | the time a little later than $k$ under the continuous time scenario |
| $j$ | an activity of the network |
| $s$ | an activity location of the network; a single node in base network in Chapter 3; a destination node when used with an origin node $r$ |
| $r$ | an origin node |
| $h$ | a housing/residential location |
| $w$ | an employment location |
| $b$ | a road link in base network only used in Chapter 3 |
| $a$ | a road link; a link of the ATS network in Chapter 3 |
| $p$ | a route choice of the transport network; a path choice of the expanded ATS network or activity chain network (ACN) |
| $i$ | a daily activity-travel pattern (DATP) |
| $m$ | a household group (i.e. a user class) |
| $u_{j,s}(k)$ | the marginal utility of the participation of activity $j$ at location $s$, at time interval $k$ |
| $u_{j,s}^{mh}(k)$ | the marginal utility of the participation of activity $j$ at location $s$, at time interval $k$ of users in group $m$ with residential location $h$ |
| $u_{j,s}^{hw}(k)$ | the marginal utility of the participation of activity $j$ at location $s$, at time interval $k$ of users with residential location $h$ and employment location $w$ |
| $\overline{U}_{j,s}(k)$ | the actual utility of performing activity $j$ at location $s$ for one interval with a start time interval $k$ |
| $\overline{U}_{j,s}^{mh}(k)$ | the utility of performing activity $j$ at location $s$ for one interval with start time interval $k$ of users in group $m$ with residential location $h$ |

| | |
|---|---|
| $\overline{U}_{j,s}^{hw}(k)$ | the utility of performing activity $j$ at location $s$ for one interval with start time interval $k$ of users with residential location $h$ and employment location $w$ |
| $\tau_{j,s}^{k}$ | the activity duration for the activity $j$ participation happened at location $s$ and start at time interval $k$ |
| $U_{j,s}(k,\tau_{j,s}^{k})$ | the actual utility of performing activity $j$ at location $s$ for activity duration $\tau_{j,s}^{k}$ with start time interval $k$ |
| $\hat{V}_{j,s}(k)$ | the perceived utility of performing activity $j$ at location $s$ for one interval with start time interval $k$ |
| $\xi_{j,s}(k)$ | the perception errors on the utility $\overline{U}_{j,s}(k)$ |
| $\xi_{mh}$ | the perception errors on the utility $U_{mh}$ |
| $\hat{V}_{i}$ | the perceived utility of DATP $i$ |
| $V_{i}^{mh}$ | the utility, of DATP $i$ for household in group $m$, with residential location $h$ |
| $V_{i}^{hw}$ | the utility obtained from conducting DATP $i$ of users with the selected housing location $h$ and employment location $w$ |
| $t_{a}(k)$ | the actual link travel time of link $a$ at time interval $k$ |
| $\hat{t}_{a}(k)$ | the perceived link travel time of link $a$ at time interval $k$ |
| $t_{r,s}^{p}(k)$ | the route travel time of route $p$ of departure at time interval $k$ from origin $r$ to destination $s$. |
| $\hat{t}_{r,s}^{p}(k)$ | the perceived route travel time of route $p$ of departure at time interval $k$ from origin $r$ to destination $s$. |

| | |
|---|---|
| $\xi_a(k)$ | the perception errors on the link travel time $t_a(k)$ |
| $x_a(k)$ | the link flow at time interval *k* on link *a* |
| $f_{r,s}^{p}(k)$ | route flow at time interval *k* on route *p* which connects origin *r* to destination *s* |
| $q_i$ | the flow of taking DATP *i* |
| $q_{r,s}^{i,p}(k)$ | the flow of choosing route *p*, departure from origin *r* to destination *s* at time interval *k* and in DATP *i* |
| $q_{r,s}^{i}(k)$ | the flow of departure from origin *r* to destination *s* at time interval *k* and in DATP *i* |
| $q_{r,s}(k)$ | the flow of departure from origin *r* to destination *s* at time interval *k* |
| $q_s^{j}(k)$ | the flow who conducts activity *j* at location *s* at time interval *k* |
| $q_s(k)$ | the flow at location *s* at time interval *k* |
| $q_i^{mh}$ | the number of households in group *m* with residential location *h*, who take DATP *i* |
| $q_i^{hw}$ | the number of users with residential location *h* and employment location *w*, who take DATP *i* |
| $q_{r,s}^{mh,i}(k)$ | the flow in group *m* (or class *m*) with residential location *h* departure from origin *r* to destination *s* at time interval *k* and in DATP *i* |
| $q_{r,s}^{hw,i}(k)$ | the flow with residential location *h* and employment location *w* departure from origin *r* to destination *s* at time interval *k* and in DATP *i* |
| $q_{r,s}^{mh,i,p}(k)$ | the flow in group *m* with residential location *h* choosing route *p*, departure from origin *r* to destination *s* at time interval *k* and in DATP *i* |

| | |
|---|---|
| $q_{r,s}^{hw,i,p}(k)$ | the flow with residential location *h* and employment location *w* choosing route *p*, departure from origin *r* to destination *s* at time interval *k* and in DATP *i* |
| $q_{r,s}^{mh}(k)$ | the flow in group *m* with residential location *h* departure from origin *r* to destination *s* at time interval *k* |
| $q_{r,s}^{hw}(k)$ | the flow with residential location *h* and employment location *w* departure from origin *r* to destination *s* at time interval *k* |
| $q_{j,s}^{mh}(k)$ | the flow in group *m* with residential location *h*, who conducts activity *j* at location *s* at time interval *k* |
| $q_{j,s}^{hw}(k)$ | the flow with residential location *h* and employment location *w*, who conducts activity *j* at location *s* at time interval *k* |
| $q_{s}^{mh}(k)$ | the flow in group *m* with residential location *h* at location *s* at time interval *k* |
| $q_{s}^{hw}(k)$ | the flow with residential location *h* and employment location *w* at location *s* at time interval *k* |
| $f_{r,s}^{mh,p}(k)$ | the route flow in group *m* with residential location *h* at time interval *k* on route *p* which connects origin *r* to destination *s* |
| $f_{r,s}^{hw,p}(k)$ | the route flow with residential location *h* and employment location *w* at time interval *k* on route *p* which connects origin *r* to destination *s* |
| $x_{a}^{mh}(k)$ | the link flow in group *m* with residential location *h* on link *a* at time interval *k* |
| $x_{a}^{hw}(k)$ | the link flow with residential location *h* and employment location *w* on link *a* at time interval *k* |

| | |
|---|---|
| $q_h$ | the demands of population who choose to reside at location $h$ |
| $q_m$ | the number of households in group $m$ |
| $q_{mh}$ | the demands of households in group $m$ residing at location $h$ |
| $q_{hw}$ | the number of population who choose location $h$ as the housing place and location $w$ as the employment venue |
| $P_{h/m}$ | the probability of households in group $m$ resides at location $h$ |
| $\hat{\Pi}$ | the maximum perceived utility of DATPs at SUE condition; $\hat{\Pi} = \max_i \hat{V}_i$ |
| $\hat{\Gamma}_{r,s}(k)$ | the minimum perceived trip time for the trip from origin $r$ to destination $s$ with departure time $k$ at SUE condition; $\hat{\Gamma}_{r,s}(k) = \min_p \hat{t}_{r,s}^{p}(k)$ |
| $\Pi_{mh}$ | the equilibrium utility of the DATP choices based on the selected residential location $h$ for household group $m$; $\Pi_{mh} = \max_i V_i^{mh}$ |
| $\Pi_{hw}$ | the equilibrium utility of DATP choices for users who choose location $h$ as the housing place and location $w$ as the employment venue; $\Pi_{hw} = \max_i V_i^{hw}$ |
| $U_{mh}$ | the utility of selecting residential location $h$ for households in class $m$ |
| $\hat{U}_{mh}$ | the perceived utility of selecting residential location $h$ for households in class $m$ |
| $\hat{b}_m$ | the maximum perceived utility of the feasible residential location choice of household group $m$ at SUE condition (i.e. the equilibrium perceived utility); $\hat{b}_m = \max_h \left\{ -\frac{1}{\theta} \ln q_{mh} + U_{mh} - \gamma_h \right\}$ |
| $\Psi$ | the network social welfare |

| | |
|---|---|
| $\delta_{rs}^{apk}(l)$ | $\delta_{rs}^{apk}(l)=1$ if the flow from origin $r$ to destination $s$ entering route $p$ at interval $k$ arrives link $a$ at interval $l$; otherwise $\delta_{rs}^{apk}(l)=0$ |
| $\delta_{j,s}^{i,k}$ | $\delta_{j,s}^{i,k}=1$ if the one-interval duration participation process of performing activity $j$ at location $s$ with the start time interval $k$, is included in DATP $i$, and $\delta_{j,s}^{i,k}=0$ otherwise |
| $\delta_{r,s,p}^{i,k}$ | $\delta_{r,s,p}^{i,k}=1$ if the travel departure from origin $r$ to destination $s$ at time interval $k$ with route choice $p$, is included in DATP $i$ and $\delta_{r,s,p}^{i,k}=0$ otherwise |
| $\delta_{r,s}^{i,k}$ | $\delta_{r,s}^{i,k}=1$ if the trip departure from origin $r$ to destination $s$ at time interval $k$, is included in DATP $i$ and $\delta_{r,s}^{i,k}=0$ otherwise |
| $r_h$ | the daily housing price/rent for residing at location $h$ |
| $P_i$ | the probability that a user/household on the network chooses DATP choice $i$ |
| $P_i^{mh}$ | the probability that a user in household group $m$ and residing at location $h$ chooses DATP choice $i$ |
| $\delta_a^p$ | the link-path incidence |
| $\hat{w}$ | a feasible route choice for the specific trips only used in Chapter 3 |
| $n_s^k$ | a node in ATS network where $k$ is the number of time intervals, and $s$ is the node in base network(see Figure 3.1) used in Chapter 3 |
| $l_b^{g,k}$ | a node in ATS network where $g$ represents the time interval of traffic entering road link $b$ and $k$ represents the current time interval(see Figure 3.1) used in Chapter 3 |

| | |
|---|---|
| $V_a$ | the implicit utility/disutility of link *a* in ATS network used in Chapter 3 |
| $\tau_b(k)$ | the queuing time of traffic who enters road link *b* at interval *k* in base network used in Chapter 3 |
| $t_b(k)$ | the total link travel time of traffic who enters road link *b* at interval *k* in base network used in Chapter 3 |
| $\Gamma_p$ | the utility of path *p* in ATS network used in Chapter 3 |
| $\Gamma^*$ | the maximum utility of the paths at UE condition; $\Gamma^* = \max_{p \in P} \{\Gamma_p\}$ in ATS network used in Chapter 3 |
| $x_a$ | the flow of link *a* in ATS network used in Chapter 3 |
| $x_a^*$ | the equilibrium flow of link *a* in ATS network used in Chapter 3 |
| $f_p$ | the flow of path *p* in ATS network used in Chapter 3 |
| $f_p^*$ | the equilibrium flow of path *p* in ATS network used in Chapter 3 |
| $d_a$ | the Lagrange multiplier associated with capacity constraints of Equation (3.3c) used in Chapter 3 |
| $\gamma_h$ | the Lagrange multiplier associated with capacity constraints of Equation (5.8) |
| $\hat{h}_{\hat{w}}(k)$ | the route traffic flow with departure time $k$ used in Chapter 3 |
| $\Theta_{\hat{w}}(k)$ | the user equilibrium queuing time of the trip with the departure time $k$, and route choice $\hat{w}$ used in Chapter 3 |
| $T_{\hat{w}}$ | the free-flow travel time of the trip of the route choice $\hat{w}$ used in Chapter 3 |

| | |
|---|---|
| $d_{\hat{w}}(k)$ | the sum of the equilibrium Lagrange multipliers associated with capacity constraints of road links experienced by the trip of the departure time $k$ and route $\hat{w}$ (measured in time) used in Chapter 3 |
| $\rho_a(k)$ | the time-dependent link emissions of traffic entering link $a$ at time interval $k$ |
| $v_a(k)$ | the link inflow at time interval $k$ on road link $a$ |
| $e$ | the total traffic emissions |
| $\Delta q$ | the increased population |
| $\Delta S_h$ | the residential allocation ability improvement |
| $\Delta G_w$ | the employment allocation ability improvement |
| $\Delta C_a$ | the link capacity expansion |
| $F_h\left(\Delta S_h\right)$ | the money cost functions for residential allocation ability improvement |
| $F_w\left(\Delta G_w\right)$ | the money cost functions for employment allocation ability improvement |
| $F_a\left(\Delta C_a\right)$ | the money cost functions for link capacity enhancement |

*Constants*

| | |
|---|---|
| $q$ | the total population on the study network |
| $T$ | the study time horizon |
| $\bar{t}_a$ | free-flow travel time of link $a$ |
| $C_a$ | the capacity of road link $a$ |
| $q_0$ | the initial population on the study network |

| | |
|---|---|
| $S_h$ | the total housing supply of residential location *h* |
| $l_a$ | the length(in kilometers) of road link *a* |
| $L$ | the length of one time interval |
| $C_{a0}$ | the initial capacity of road link *a* |
| $C_a^{\max}$ | the maximum link capacity expansion |
| $S_{h0}$ | the initial housing supply of residential location *h* |
| $S_h^{\max}$ | the maximum housing supply improvement |
| $G_w$ | the total job supply of employment location *w* |
| $G_{w0}$ | the initial job supply of employment location *w* |
| $G_w^{\max}$ | the maximum employment allocation ability improvement |
| $M$ | the total available money budget |
| $E$ | the permissible traffic emission level |
| $\overline{K}$ | the number of time intervals into which the whole study time horizon is equally divided |
| $\overline{W}$ | the maximum tolerable queuing time during a trip |
| $\overline{m}$ | the number of feasible activity choices |
| $\overline{g}$ | the number of links in base network |
| $\overline{N}$ | the number of nodes in base network |
| $\theta$ | the perception variation parameter |
| $\sigma$ | the utility parameter of time |
| $\sigma^m$ | the utility parameter of one minute for users in group *m* |
| $\alpha_m$ | the utility unit of one money for household group *m* |
| $\varepsilon$ | the convergence criteria parameter |

| | |
|---|---|
| $\hat{r}$ | the penalty parameter |
| $\bar{t}_b$ | free-flow travel time of link $b$ in base network used in Chapter 3 |
| $\overline{V}_a$ | the utility/disutility of link $a$ in ATS network used in Chapter 3 |
| $Q_b$ | capacity of road link $b$ in base network used in Chapter 3 |
| $\zeta$ | the decreasing parameter $\zeta$ ($0<\zeta<1$)used in solution algorithm in Chapter 3 |

*Symbols*

| | |
|---|---|
| "*" | the equilibrium conditions |
| $\overline{O}$ | the dummy start node |
| $\overline{D}$ | the dummy end node |

The following acronyms are used throughout this thesis:

ACN(s) /ATS /ATP(s) /BPR /CBD /CNDP /DATP(s) / DNDP/ GA/ GF/ GP/ NDP/ MNDP/ MSA/ OD/ PF/ SPFA/ SUE/ UE/ VI/ VOT/"H"/ "R" /"S"/"W"/[H] /[ER]/ [S]/ [W]/ [EW]

| | |
|---|---|
| ACN(s) | Activity Chain Network(s) |
| ATP(s) | Activity-Time-Pattern(s) |
| ATS | Activity-Time-Space |
| BPR | Bureau-Public-Road |

| | |
|---|---|
| CBD | Central Business District |
| CNDP | Continuous Network Design Problem |
| DATP(s) | Daily Activity-Travel Pattern(s) |
| DNDP | Discrete Network Design Problem |
| GA | Genetic Algorithm |
| GF | Gap Function |
| GP | Gradient Projection |
| NDP | Network Design Problems |
| MNDP | Mixed Network Design Problem |
| MSA | Method of Successive Averages |
| OD | Origin-Destination |
| PF | Penalty Function |
| SPFA | Shortest Path Faster Algorithm |
| SUE | Stochastic User Equilibrium |
| UE | User Equilibrium |
| VI | Variational Inequality |
| “H” | Home/residential area |
| “R” | Restaurant area |
| “S” | Shop area/School |
| “W” | Work place |
| [H] | at Home activity |
| [ER] | Eating at Restaurant |
| [S] | Shopping at shop |
| [W] | Work at work place |
| [EW] | Eating at Work place |

# 1 INTRODUCTION

## 1.1 BACKGROUND AND MOTIVATIONS

An important purpose of transport modeling is the achievement of better estimation of user travel choice behaviour so that various transport planning policies and infrastructure projects can be more accurately evaluated or assessed. This research is devoted to exploring transport models and integrated land use and transport models with advanced activity-based approaches for the better understanding of user travel choice behaviour.

### 1.1.1 THE NEED OF DEVELOPING ACTIVITY-BASED TRANSPORT MODELS

The transport model, most widely used and adopted in practice, is the four-step sequential transport model which deals with the four steps (① trip generation and attraction, ② trip distribution, ③modal split, and ④ assignment) sequentially, or its combined model which simultaneously deals with more than one of those steps to avoid inconsistency problems possible existing in the four-step sequential model. The four-step sequential/combined transport model is classified, basically, as a trip-based transport model.

The trip-based transport models only consider the simple trips which may leads to biased estimations of the impact on user travel choice behaviour of a transport policy.

Figure 1.1 gives such an example. Figure 1.1 illustrates user travel choice changes resulting from a new highway opened. The highway connects home and the work place directly, and not passes the shop area. The aim of opening this highway is to reduce the travel times of users' trips of traveling to work and returning home after work.

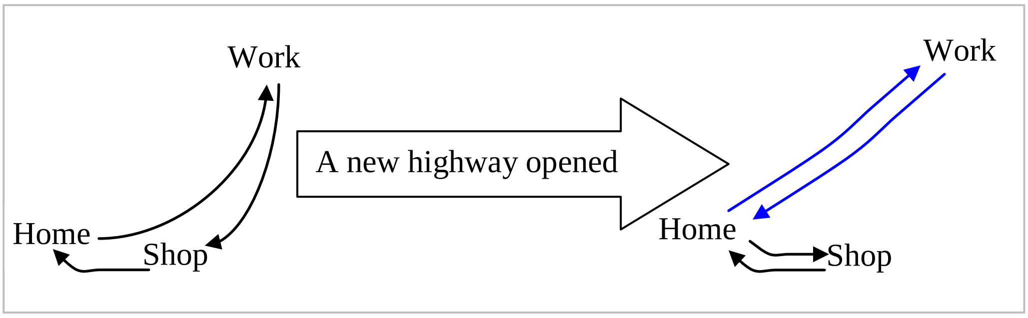


**Figure 1.1 Travel Choice Behaviour Changes to a New Highway Opened**

After such a highway opened, users would adjust their travel choice behaviour. From Figure 1.1, it can be seen that, before the highway opened, the daily travel choices of a user include driving from home to work place for work in the morning, making a stop to shop during the trip from work place to home and returning home in the afternoon. After the highway opened, the user may directly return home after work without any stop on the way. Shopping takes place in the afternoon after his return home. This latter response is rooted in a need to do the shopping activity.

In such a case, a conventional trip-based transport model which ignores activity demand, would fail to predict the changes of user daily travel choices, which in this case involves a newly generated auto evening trip from home to the shop. Failures, such as this may occur widely when evaluating the effects of other transport-related policies such as infrastructure improvement schemes, road pricing, and parking management policies, using the trip-based transport model.

The weaknesses and limitation of trip-based transport models have been discussed by many researchers (Kitamura et al., 1996; Timmermans, 2005) in the past decades, and can be briefly summarized as: (1) ignorance of travel as a demand derived from activity participation desire or need; and (2) focus on individual trips, ignoring the spatial and temporal interrelationship between all trips and activities.

These theoretical deficiencies of trip-based transport models probably result in biased understanding of user travel choice behaviour in transport policy evaluation, despite their acceptable performance in certain well-defined situations (Algers et. al., 2005). As McNally (2000) stated: “trying to infer underlying travel behaviour from the observation of person or vehicle trips only is somewhat akin to trying to understand the behaviour of an octopus by examining only the individual tentacles (perhaps by Kitamura)”.

Travel demands are derived from the desire or need to conduct various activities such as work, shopping and eating. Transport models are able to accurately capture user travel choice response to different transport policies only when a way is found to answer the basic questions that how user schedule activities and travels, is answered. In the recent past decades, transport researchers and practitioners found that transport models with the use of the activity-based approach offer a promising avenue for better understanding of user travel choice behaviour.

The activity-based approach necessitates an investigation into the activity and travel schedule mechanism, i.e. what activity is to be conducted, when and where, how long, with whom, in what sequence, how and what household activities are assigned to family members, and how all of activities and travels interrelate in the context of constrained time and space (Kitamura, 1988). The aim of the acknowledgement of this set of decisions is to determine the maximum benefits (utility) obtained by households or individual users from the activity conduction.

To simplify the presentation of the work, the models with the use of the activity-based approach are named as activity-based models while the models with the use of the trip-based approach are named as trip-based models throughout this research. When transport researchers realize the advantage of the activity-based transport models in examining user travel choices, they also find that the complexity of the activity-based analysis increases due to the multi-dimensional considerations (Timmermans, 2005).

Some activity-based analytical transport models which provide valuable insight for improving the understanding of users' travel behaviour have appeared in the past few decades. However, most of these models were conducted with some selected constraints such as ignoring network congestion, considering user activity choices in different discrete time periods as separate, and focusing on the predetermined activity sequences and/or predetermined activity durations. There is scarce study which offers a comprehensive representation of user travel choices as the expected that the activity-based approach could do.

In addition, the algorithms proposed in most of these analytical models require a prior enumeration of all feasible combinational activity and travel choice sets. This inhibits the application of analytical activity-based studies in practice since that requirement leads to exponential growth in combinatorial choices and burdensome computation.

### 1.1.2 THE NEED OF DEVELOPING INTEGRATED LAND USE AND TRANSPORT MODELS WITH ADVANCED ACTIVITY-BASED APPROACHES

Strong interactions exist between land use and transport. Such interactions can be summarized by the following two perspectives: (1). Users' residential/employment location choices are based on the estimation of transport accessibility, costs and environment, all of which depend on both the land use system and transport system; and (2). Users' travel choices are influenced not only by the transport system (the transport infrastructure, facilities, and policies) but also by the activity location distribution which is determined by the land use system.

A change in either the land use or the transport system will impact the user residential/employment location choice and/or travel choice behaviour. For better modeling/estimating the user travel (and/or residential/employment location) choices, it is necessary to examine these choices under the integrated system of land use and transport and to investigate the relationships between these choices.

The problems related to examining interaction between land use and transport has attracted the attention of many researchers over the past decades, and sequentially integrated land use and transport models have been proposed (Hunt et. al., 2005; Chang, 2006). The conventional integrated land use and transport model mainly involves a nested set of a land use model which investigates user residential/employment location choice and a trip-based transport model which studies user travel choice. The interaction between user location choice and travel choice is investigated through an iteration operation in that nested set of models.

However, the inconsistency of users' choices and associated utility (or cost), may occur in the iteration process. In view of the limitations of the trip-based approach, the conventional integrated model may also cause improper evaluation of users' location and travel choice behaviour. The following discussion provides such examples.

Figure 1.2 gives two residential locations "Home 1" and "Home 2" with different land use topologies but the travel times to the work place and to the shop area are the same (0.5 hour). Other attributes such as residential location environments are assumed as the same.

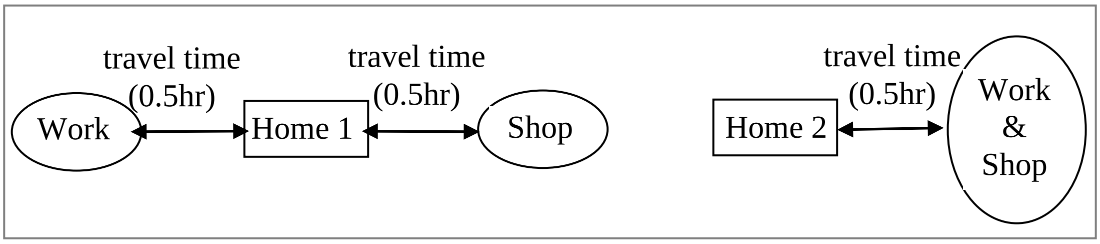


**Figure 1.2 Two Residential Locations with Different Land Use Topologies**

In this example if users consider the trips separately, they should have the same possibility to reside at “Home 1” or reside at “Home 2”, as travel times of all trips for users residing at “Home 1” are the same with those of trips for them residing at “Home2”. However, in fact, users likely prefer to reside at “Home2”. The reason is that they have the possibility of combining trips (e.g. combining the trips from home to work and home to shop into one trip) when residing at “Home 2”. With such a combination, some travel time can be saved. This example implies that the trip-based approach which investigates trips separately probably fails to capture users’ residential location choice and travel choice behaviour response to various land use policies.

In the example shown in Figure 1.2, assume that the shop area is replaced by a school, then how different group households will choose their residential locations? For households with children of school age who have two household activity options: work and school, are likely prefer to reside at “Home 2”. As the above discussions, when residing at “Home 2”, they can combine trips and save travel times while they are unable to do this if residing at “Home 1”. In contrast, however, for households without children of school age, work is their sole relevant activity. Such households can reside at “Home 1” or “Home 2” without being compromised as regards as the travel times of trips for work. This example illustrates that users’/households’ activity demands not only generate users’ travel choices but also make the direct influence on their residential location choices.

Users’ activity demands and the interdependence among users’ travels should not be ignored when analyze the impact of a certain land use/transport policy on users’ behaviour of residential/location choice and travel choice, as well as examine the interaction between these two choices. The conventional integrated land use and transport models should be improved with advanced activity-based approaches.

In recent years, there appeared some integrated land use and transport models where the activity-based approach is adopted to investigate user travel choice behaviour (Hunt et. al., 2004). However, the activity-based approach is seldom applied to simultaneously analyze user residential/employment location choice behaviour and user travel choice behaviour in the literature.

The study of transport network design which deals with adding/deleting road links problems and or enhancing road link capacity problems is an important topic in transport research for solving traffic congestion problems. The land use policy which determines the development of residential/employment locations and other activity locations, plays a crucial role in the urban sustainable development.

Although strong interaction between land use and transport exists, little attention has been paid to integrate deal with the transport network design and urban land use allocation strategy (Yim 2011). At the same time, increasing activity demands have caused grim traffic air-pollution in many urban areas. There is a growing recognition that traffic emission control should be incorporated in plans for urban sustainable development. Thus, it is meaningful to explore models where transport network design and land use development are consistently optimized under a local traffic emission control policy.

## 1.2 OBJECTIVES

In the light of the above discussions, the major objectives of this research are:

1) To develop novel analytical activity-based transport models by fully examining user daily activity scheduling problems
    - ✧ to provide a more comprehensive framework of understanding user travel choice behaviour,
    - ✧ to improve the potential application of analytical activity-based transport studies by exploring efficient solution algorithms, and
    - ✧ to find some features of the user daily activity scheduling results at equilibrium conditions.

2) To explore an analytical activity-based land use and transport model
    - ✧ to consistently capture users' residential location choice behaviour and travel choice behaviour under a land use and transport system, and
    - ✧ to better understand the interactions between land use and transport.

3) To formulate an activity-based land use and transport optimization model
    - ✧ to enable more accurate representation of users' response behaviour of residential/employment location choices and travel choices to government land use and transport optimization policies, and
    - ✧ to enable the exploration of efficient and integrated land use and transport optimization policies by applying the developed model, for both urban development purposes and also the procurement of environment protection.

## 1.3 OUTLINE OF THE RESEARCH

The research is composed of seven chapters. The organization structure of this research is illustrated in Figure 1.3.

Chapter 1 gives a brief introduction of the research presented in the thesis. Relevant literature on activity-based transport models, integrated land use and transport models, and transport network design problems, are reviewed in Chapter 2.

The main body of the research comprises four chapters. Chapter 3 and Chapter 4 focus on exploring novel activity-based transport models. Chapter 5 is engaged in developing an activity-based land use and transport model. Chapter 6 devotes to proposing an activity-based sustainable land use and transport optimization model. Chapter 3, Chapter 4, and Chapter 5 contribute to modeling user choice behaviour. Chapter 6 investigates the development of optimization policies for government use.

Chapter 3 concentrates specifically on developing an activity-based transport model for dealing with the user daily activity scheduling problems in congested road networks. An activity-time-space (ATS) network expansion approach is introduced to explicitly model the interdependency between user activity and travel choices. An activity-based network user equilibrium (UE) model is formulated. An efficient solution algorithm without explicit daily activity-travel pattern (DATP) enumeration is developed to solve the proposed model.

Chapter 4 extends the UE model formulated in Chapter 3 to investigate user daily activity scheduling problems in general road networks (i.e. both congested and uncongested road networks) and incorporates the stochastic dimensions of users' choices. An activity-based network stochastic user equilibrium (SUE) model is formulated. An efficient solution algorithm without explicit DATP enumeration is also developed to solve the SUE model. The UE daily activity scheduling problem in general road networks, a special case of the SUE problem with the ignorance of the stochastic dimensions, is also discussed.

Chapter 5 extends the work of Chapter 4 to study the combined user residential location and travel choice problem. An activity-based land use and transport model is formulated as a SUE model to deal with that combined problem. The relationships between users' residential location choice and their daily activity/travel choices (i.e. DATP choice) are revealed in the model. A multi-class DATP UE model in general road networks is embedded in the SUE model. A heuristic solution algorithm is explored for solving the combined problem.

In Chapter 6, an activity-based bi-level model is proposed, to enable the investigation of sustainable land use and transport optimization problems. The upper level simultaneously determines residential/employment location development and road link capacity expansion authorized by the government for maximizing the social benefit under the constraint of local traffic emission control. The lower level models user behaviour of combined user residential/employment location and DATP choices in response to the decisions of the upper level. Similar to the work of Chapter 5, user response behaviour is captured by an activity-based framework. The difference is that users’ employment location choices are examined in Chapter 6 whereas Chapter 5 only considers users’ residential location choices. A doubly constrained gravity model is adopted to deal with user combined choices in Chapter 6. A heuristic solution algorithm is designed for solving the proposed bi-level problem.

Finally, a summary of the major findings of this thesis and several suggestions for future research are presented in Chapter 7.

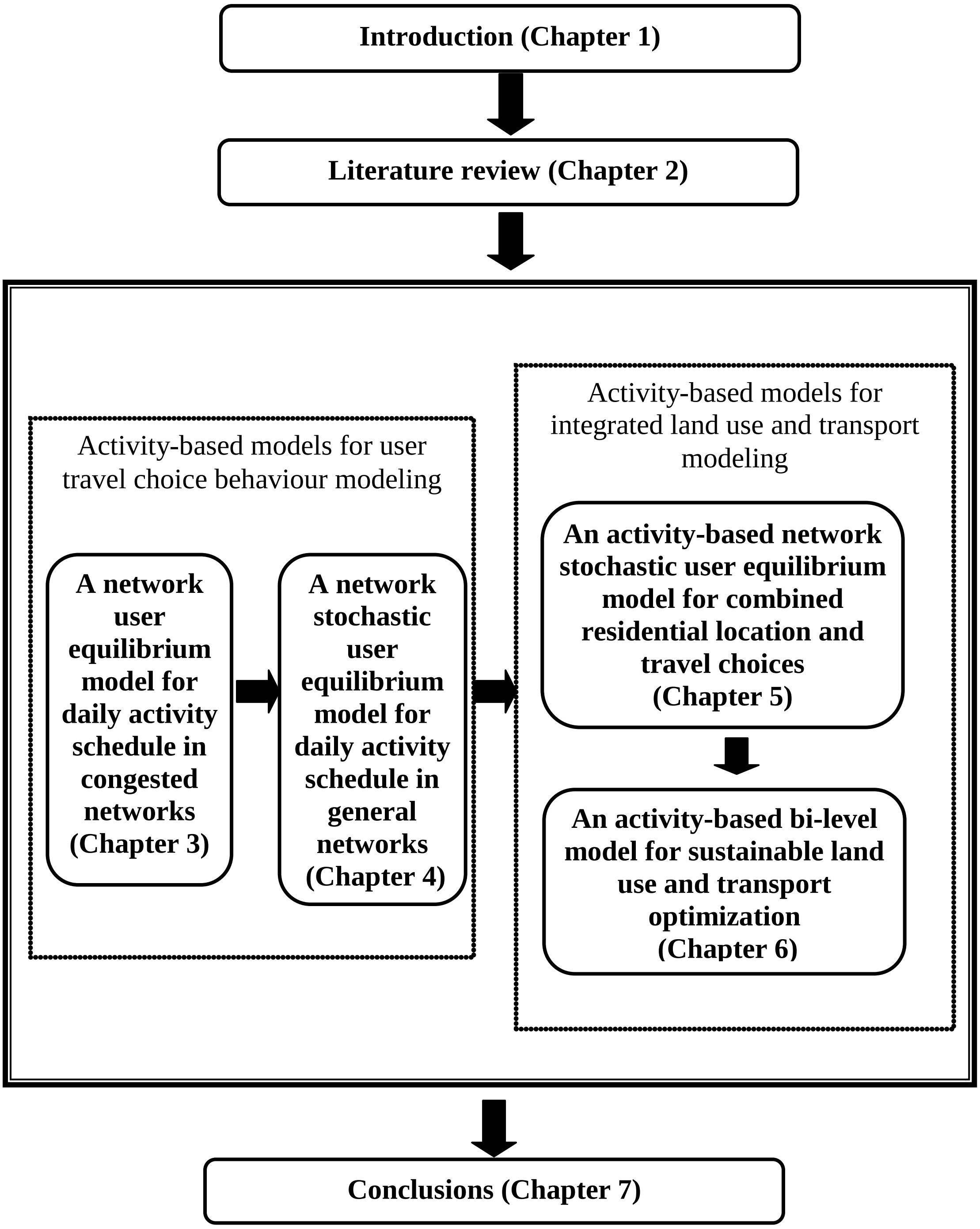


**Figure 1.3 The Structure of the Thesis**

# 2 LITERATURE REVIEW

In this chapter, an extensive literature review is given to identify the need for and the potential of achieving the research target indicated in Chapter 1. This chapter is organized as follows. The concept of the activity-based approach is discussed in Section 2.1. Previous activity-based transport studies are summarized in Section 2.2. Literature, relevant to integrated land use and transport studies is reviewed in Section 2.3. Studies of transport network design problems are briefly reviewed in Section 2.4. A summary of key points concludes the chapter.

## 2.1 The Concept of the Activity-based Approach

The fundamental tenet of the activity-based approach is that travels are driven by the desire or need to participate in compulsory and non-compulsory activities such as work, eating and shopping (Jones et. al., 1990). The activity-based approach investigates the problems of users' activity choices which generate users' travels.

When making an activity choice, users have to decide such as 1) when to start, 2) from where to start, 3) to which destination (activity location), 4) what travel mode to use, 5) what travel route to follow, 6) which activity to conduct, and 7) how much time will be spent on the activity(Kitamura, 1988). In another words, in a simple user activity choice problem, individuals' decisions including the departure time choice, origin choice, destination choice (activity location choice), mode choice, route choice, activity choice, and activity duration choice, are investigated.

Furthermore, the problems of users how to schedule their activities and generated travels under the coordination of time and space constraints are also examined in the activity-based approach. The desired/needed activities on the agenda are expected to be completed in the study time horizon (for instance, a day or a week). Activities could only be conducted at the corresponding activity locations. The distribution of activity locations is governed by the land use policies. The activity scheduling of users in the study time horizon results in an activity-travel pattern (ATP). Similarly, the daily activity scheduling of users results in a daily activity-travel pattern (DATP).

A user's daily activity schedule is always influenced by the daily activity schedule of others, particularly members of the same household. The user should adjust his travels if he wants to share a car with other members in the family. Household food shopping is probably not included in the target user's daily activity schedule when it is done by another family member. Such kind of interdependence between users' daily activity schedule is also studied in the activity-based approach.

Figure 2.1 illustrates a household activity decision structure and the corresponding individual user activity decisions. In summary, a broader spectrum of factors derived from social, demographic and economic changes, which influence user travel choices, are incorporated in the activity-based approach.

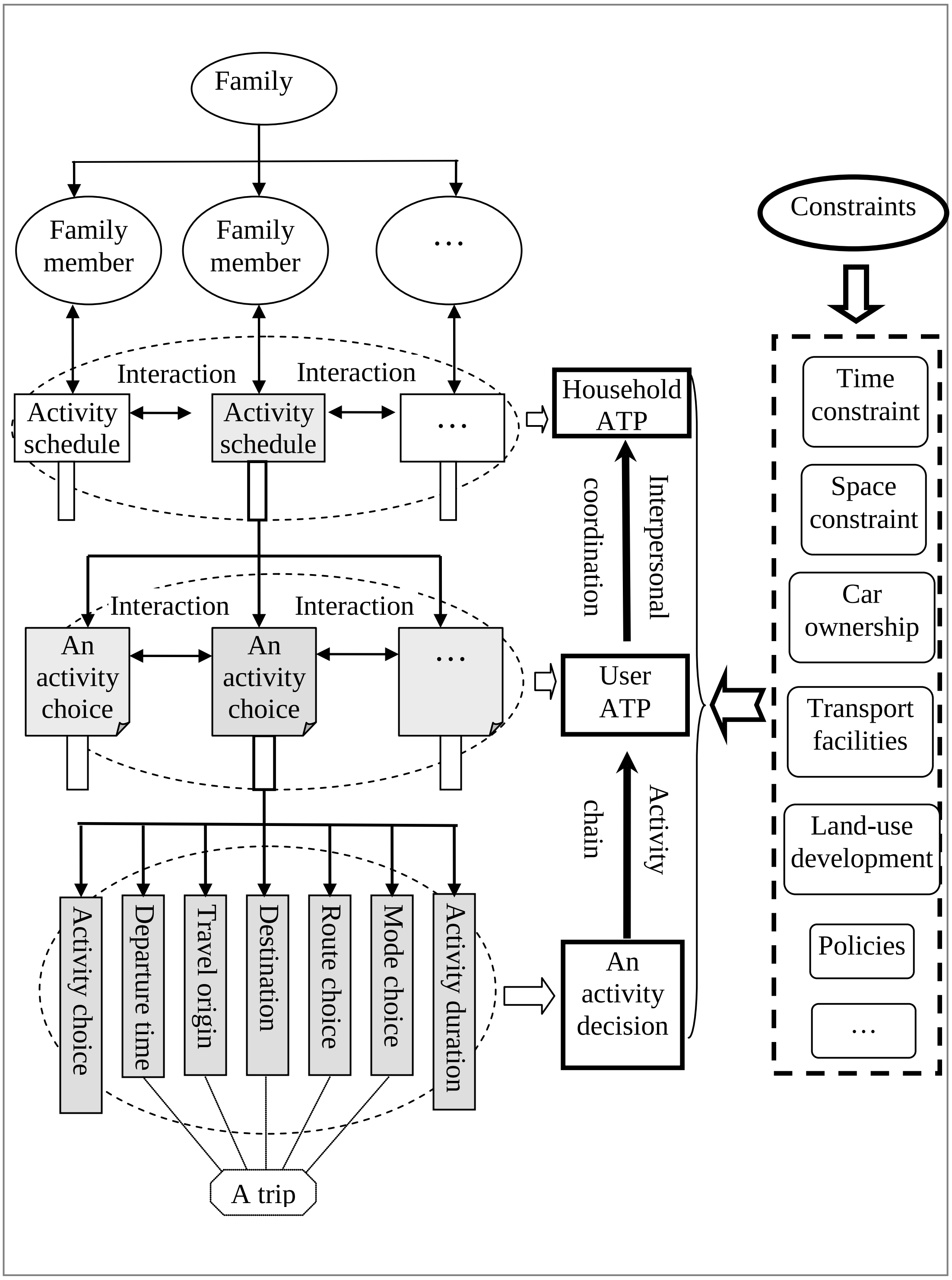


**Figure 2.1 A Household Activity Decision Structure**

## 2.2 The Activity-based Transport Models

The intellectual root of exploring activity-based transport models for user travel choice behaviour study goes back to the 1950's (Mitchell and Rapkin, 1954), and the later seminal works on activity-based transport modeling. The latter include those of Hägerstrand (1970), Jones (1979), Kitamura (1984), Hirsh et al. (1986), Recker et al. (1986a, b), Mahmassani et al. (1986), Pas(1988), Supernak(1990).

A complete review of the initial works on activity-based transport analysis is provided by Kitamura (1988), Jones et. al. (1990), and Axhausen and Gärling(1992). Much progress has been made over the past decades in the modeling of user travel choice behaviour by activity-based transport models. The reader is recommended to refer to MacNally (2000), Algers et. al. (2005), and Timmermans (2005) for a comprehensive review of the recent studies. In general, the existing activity-based transport models can be categorized into three approaches; namely, simulation models, econometric models and mathematical analytical models. Table 2.1 gives a summary of the classification of previous activity-based transport models.

Simulation models envisage computer simulation as a viable modeling tool to analyze user activity and travel choice behaviour. Simulation models are regarded as the most operational activity-based transport models. The simulation method saves the step, to establish mathematical models to represent relationships in the daily activity scheduling process.

**Table 2.1 The Classification of Activity-Based Transport Models**

| | |
|---|---|
| Simulation models | Jones, 1983; Recker et al., 1986 a, b; Ettema and Timmermans, 1995; Kitamura, 1996; Arentze and Timmermans, 2000, 2004; Arentze et al., 2003; Timmermans and Zhang, 2009; Ronald et al., 2012; Nijland et al., 2013. |
| Econometric models | Bowman and Ben-Akiva, 1997; Golob and McNally, 1997; Golob, 2000, 2003; Dissanayake, 2002; Vakratsas and Bass, 2002; Lee and Timmermans, 2007; Wang and Li, 2009. |
| Mathematical analytical models | Becker, 1965; Ghez and Becker, 1975; Winston, 1982; Hirsh et al., 1986; Recker, 1995; Lam and Yin, 2001; Lam and Huang, 2002; Lam and Huang, 2003; Huang and Lam, 2005; Zhang et al., 2005; Hoogendoorn and Bovy, 2004; Gan and Recker, 2008; Adnan et al., 2009; Ramadurai and Ukkusuri, 2010; Li et al., 2010; Ramadurai and Ukkusuri, 2011; Chow and Recker, 2012; Fu and Lam, 2013. |
| | This research. |

A variety of econometric models, traditionally used in the analysis of social behaviour, has been adapted to model joint relationships between variables in the ATP generation process under the transport system (Timmermans, 2005). Wang and Li (2009) proposed a regression model to examine the impact of hiring a domestic helper on household DATP in Hong Kong. Their analysis was based on trip diary data from the Hong Kong Travel Characteristic Survey (2002). Econometric models hold many distinct advantages such as a well-established theoretical basis, a mature methodology, and professional familiarity.

Despite the presence of relevant information in the literate, little attention has been devoted to the development of mathematical analytical models. The widely used and adapted conceptual mathematical analytical models for user activity behaviour analysis are based on the economic theory of consumer choice (Lancaster, 1966), extended in a theory of household's time allocation, as first advocated by Becker (1965), Ghez and Becker (1975) and later by Winston (1982), Hoogendoorn and Bovy (2004). Following on from the economic theory of choice, a basic assumption is that time allocation entails decisions made according to the principle of utility maximization. Hirsh et al. (1986) developed a dynamic weekly activity pattern model based on the utility maximization theory.

Activity scheduling modeling which addresses modeling problems of simultaneous activity and travel choices in the context of constrained time and space is a key feature of analytical activity-based transport models. Recker (1995) optimized the daily activity sequence and trip chain of an individual and a household, using an integer programming method. Similarly, Gan and Recker (2008) investigated the rescheduling problem of an individual or a household. Chow and Recker (2012) recently proposed an inverse optimization model to calibrate the household activity pattern problem. In these three studies (Recker, 1995; Gan and Recker, 2008; Chow and Recker, 2012), the traffic congestions were not considered since these studies focused on individual or household choice problems instead of network problems.

Lam and Yin (2001) proposed an activity-based network equilibrium model for a single class of users. Users were assumed to choose an activity which had the maximum utility at each discrete time interval. This approach was extended to include stochastic dimension (Huang and Lam, 2005) and for congested road networks with delays (Lam and Huang, 2002). It should be noted that users' activity choices at different discrete time interval were regarded as separate choices in the study of Lam and Yin (2001) and in the later two extensions.

Other related studies were mainly conducted under pre-determined activity sequences. Zhang et al. (2005) studied the interactions between work duration and departure time choice of work-related travel under the nonadjustable activity sequence of home-work-home. Adnan et al. (2009) investigated the scheduling problem of the home–work tour. They found that the consideration of only time-of-day dependent marginal utility profiles of activities in the utility function did not appropriately integrate activities and travel within the tour. Li et al. (2010) investigated activity-based transit timetable scheduling problem with given activity sequences. Recently, Fu and Lam (2013) considered user activity and travel choice behaviours in multi-modal transit networks with behaviourally homogeneous or heterogeneous groups but the in-vehicle travel times of transit modes were pre-determined and fixed.

Various solution algorithms with a prior enumeration of combinational activity and travel choice sets, to solve the user activity scheduling network problems, were also developed in these previous related studies (Lam and Huang, 2002, 2003; Huang and Lam, 2005; Ramadurai and Ukkusuri, 2010; Zhang et al., 2005; Li et al. 2010). These algorithms, however, are difficult to implement even for moderately sized networks since the multi-dimensional activity scheduling problem leads to exponential growth in combinatorial choices.

In addition to the above models, there is also a scare literature on the comprehensive activity scheduling problems. Ramadurai and Ukkusuri (2010) developed a cell-based transmission model in an attempt to study the whole activity scheduling problem. Later, they proposed an algorithm without a prior enumeration of ATPs, the B-dynamic solution algorithm, to solve that problem (Ramadurai and Ukkusuri, 2011). The equilibrium solution, provided by their model could not, however, be guaranteed since the topology of their introduced activity-travel supernetwork was always be changed during the iterations. The solution might not converge and be stable particularly when networks were very congested.

Compared to the development of activity-based econometric models and activity-based simulation models, the development of activity-based mathematical analytical models is seriously lagging. This situation primarily arises from the difficulty of analyzing complicated interdependency between variables in household activity schedule processes. As stated above, few mathematical analytical models exist. Even in these few, there is still some way to go before the satisfactory development of a comprehensive framework for investigating complex user daily activity scheduling problems is achieved. Almost all are limited to one or maybe several specific problems but under selected ideal assumptions. Chapter 3 and Chapter 4 of this research are devoted to exploring a more comprehensive activity-based analytical framework to deal with user daily activity scheduling problems.

## 2.3 Integrated Land Use and Transport Model

A city can considered as a network with land use building nodes s and transport channel links. Figure 2.2 shows a simple such city network. The function of the buildings is to provide activity locations to satisfy residential needs as well as activity requirements such as those related to work, eating and shopping. Transport channels are opened to cover the distance between different activity locations.

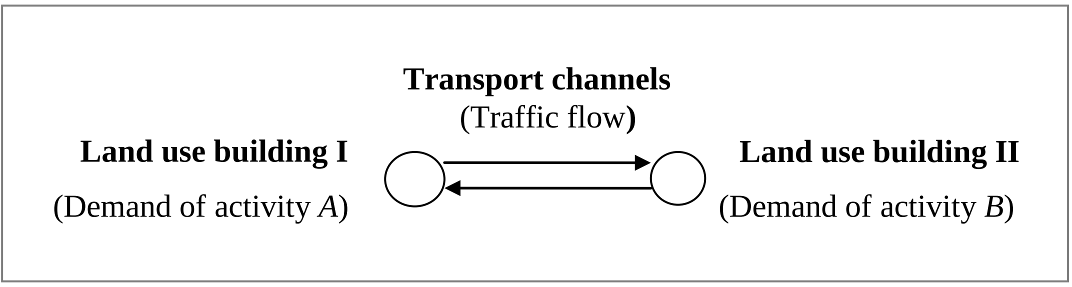


**Figure 2.2 A Simple City Network**

Nodes (land use buildings) and links (transport channels) of the city networks are activity linked. Travel demands are derived from the need of or the desire for activity participation at different activity locations on the networks. Such activity location distribution is defined by the land use system. Transport systems enable the execution of travel demands. Thus, activity and travel decisions are determined based on the integrated land use and transport system, and there are strong interactions between land use and transport.

The interaction problems between land use and transport have attracted great attention of academic researchers over the past decades (Boyce, 1986; Meng et al., 2000; Chang and Mackett, 2006). The integrated land use and transport studies which simultaneously investigate user travel choice behaviour, and location (usually residential location or/and employment location) choice behaviour have been appeared. In these studies, attempts have been made to gain insights into the effects of changes in urban land use on traffic conditions and the impact of changes in transport accessibility on population distribution of the locations. The structure of a typical conventional land use and transport model is illustrated in Figure 2.3.

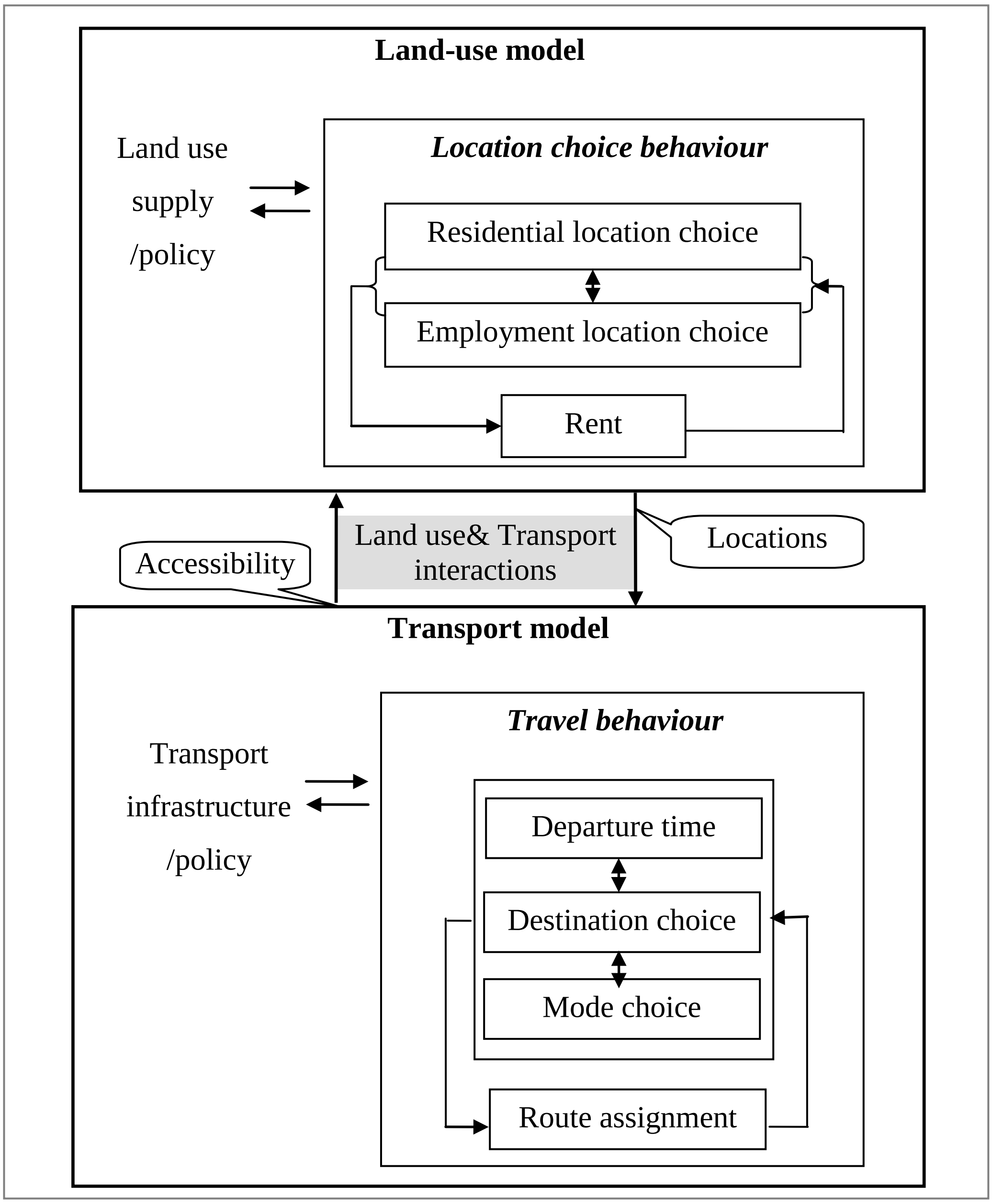


**Figure 2.3 The Structure of a Typical Land Use and Transport Model**

Previous integrated land use and transport models and methods can be classified based on four influential approaches (Hunt et. al., 2005; Chang, 2006): these are spatial interaction (gravity) models (Wong et al., 1998; Wong et al., 1999; Wong et al., 2001), discrete choice models (Maat et al., 2005), bid-choice models (Chang and Mackett, 2006), and mathematical analytical models (Boyce and Mattsson, 1999).

Lowry (1964) proposed the most operational spatial interaction model: the Lowry model. The Lowry model focuses on the spatial characteristics of an urban area in terms of three board sectors of activity: employment in basic industries, employment in population-serving industries, and household or population sectors. The Lowry model is considered a remarkable accomplishment and has been rapidly accepted and developed by many other researchers (Wilson, 1977; Yang and Meng, 1998a; Meng et al. 2000; Wong et al, 1999; Wong et al, 2001).

The spatial interaction models have the dual advantages of being conceptually simple but comprehensive. These models, however, because of their deterministic and aggregate structure, do not address the unique characteristics of residential/employment location and the households' decision-making process. Additionally, the interaction between transport and land-use is not revealed explicitly. The discrete choice model uses the random utility theory to describe the interactions between user travel choice and user residential/employment location choice. Earlier models have considered the methodological foundation using a joint or nested logit framework. The discrete choice model has been applied to a wide range of topics: exploring the user residential location choices using aggregate data (Anas, 1981); investigating the joint choice of residential location and employment location

(Abraham and Hunt, 1997); and using combined data of stated and revealed preferences (Earnhart, 2002). These models effectively represent the residential/employment location characteristics using a set of components. Aadditionally, they suggest a high degree of behavioural validity.

Alonso (1964) proposed a bid choice model in which residential location is assigned to the highest bidder in terms of a bid-auctioning process. This model has been associated with the hedonic theory (Rosen, 1974) and a stochastic framework (Ellickson, 1981). The probabilistic bid-rent model has been applied empirically (Gross, 1988) and incorporated into comprehensive land-use transport models RURBAN. The hedonic interpretation of the bid-rent model is a useful insight into examining the user residential location decisions. However, it is difficult to establish the explicit interaction between user residential location choice and travel choice behaviour (Chang and Mackett, 2006).

Martínez (1992) compared the discrete-choice random-utility theory with the bid-rent theory proposed by Alonso (1964), and demonstrated that in perfectly competitive land markets both approaches are equivalent in all respects, and therefore should be understood to be complementary rather than alternatives. A more comprehensive bid-choice land use mode for examining user residential location choice problems was proposed by Martínez(1992). Later, that model was extended to study static land use equilibrium problems by Martínez and Henríquez (2007).

Mathematical analytical models are designed to solve the combined user residential/employment location choice and travel choice problems. The aggregate structure of mathematical analytical models presents difficulties in representing systematic residential/employment location properties and the behavioural context of decision-makers. Earlier models from this group have been formulated using linear programming (Herbert and Stevens, 1960); later, combined models, which have integrated a spatial interaction model with a traffic assignment model, have been developed (Boyce and Southworth, 1979; Boyce and Mattsson, 1999; Briceño et.al., 2008; Bravo et.al., 2010). The combined model is effective in the examination of the interaction between land use and transport.

Regarding overall model structure, the existing integrated land use and transport models can also be categorized as two groups, namely unified models and composite models. The unified model which exams combined user residential/employment location and travel choice problems, links land use systems and transport systems as tightly consistent units. The composite model which employs a nested set of a land use model investigating user residential/employment location choice problems and a traditional trip-based transport model studying user travel choice problems, loosely links land use systems and transport systems. The user location and travel choices are simultaneously examined through the iteration operation of that nested set. The composite models may have inconsistency problems since the user choices and associated utility or cost may not be consistent within that assumed in the iteration process. The majority of mathematical analytical models search for a unifying principle, while most spatial interaction models, the bid choice models and the discrete choice models are composite frameworks.

The main difficulty met when attempting to reveal the relationship between land use and transport, are how to accurately capture the influence of land use systems on user travel choice behaviour and how to exactly represent the impact of transport systems on user residential/employment location choice behaviour. In most existing integrated land use and transport models(Boyce, 1986; Yang and Meng, 1998a; Boyce and Mattsson, 1999; Meng et al., 2000; Chang and Mackett, 2006), the impact of transport system on user residential/employment location choices is represented by a transport accessibility term such as the travel time/cost from users' selected residential location to their selected employment location, for all users in the attraction functions employed in the spatial models and bid choice models, or in the utility functions used in the discrete choice models. This method possibly leads to biased results.

For example, the travel time/cost from home to school is given. Household with children of school age are sensitive to this cost, while for families without children, this cost may not be a priority in their residential location choice. When make residential location choice, households only care of the travel time/cost from that residential locations to the activity locations where their families members want go to conduct activities. The transport accessibility of a residential/employment location may mean different for households with different activity participation desires/needs. It is thus necessary to investigate user activity scheduling problem when dealing with user residential/employment location choice problems. In Chapter 5 of this research, an analytic activity-based land use and transport model was developed in which the relationship between user short-term daily activity scheduling and user long-term residential location choice was revealed.

## 2.4 Transport Network Design

The network design problem (NDP) is widely recognized as one of the most difficult and challenging problems in transport research. A vast amount of literature has focused on formulation and solution algorithms for network design problems. The formulated models can be divided into three classes: the continuous network design problem (Gershwin and Tan, 1979; Suwansirikul et al., 1987; Suh and Kim, 1992; Gao et. al., 2005), the discrete network design problem (Bruynooghe, 1972; Steenbrink, 1974; Poorzahedy and Turnquist, 1982; Boyce and Janson, 1980; Gao et.al., 2005), and the mixed network design problem (Yang and Bell, 1998).

The continuous network design problem (CNDP) aims to determine the set of link capacity expansions. The discrete network design problem (DNDP) is concerned with modification of transport by adding new road links or deleting road links. The mixed network design problem (MNDP) aims to simultaneously study the capacity expansions and road link addition/deletion.

The NDP is usually represented as a leader-follower game, the players being the transport planning departments as the leaders, with users acting the followers, who can freely choose such as the route, mode, and departure time. The NDP is usually formulated as a bi-level model. The upper level determines leaders' decisions to optimize the objective such as minimization of the social travel time. The lower level represents users' response behaviour under the decisions from the upper level. Various bi-level network design models with different upper-level objectives and lower-level travel models have been developed.

In view of the strong interactions between land use systems and transport systems, it has been realized that the study of NDP should not be solely confined to the transport system and it should be studied in the integrated land use and transport systems. The transport network improvement should be correlated and consistent with the urban land use development strategy. However, few studies are devoted to integrated land use and transport optimization problems (Yim et. al., 2011).

In view of the advantage of the activity-based approach in examining the interactions between land use and transport as discussed above; this research poses a first attempt to investigate the sustainable land use and transport optimization problems by an activity-based approach. Details are given in Chapter 6 of this research.

## 2.5 Summary

From a review of the above literature, it is found that it is necessary to adopt the activity-based approach for user travel choice behaviour analysis, combined user residential/employment location and travel choice behaviour analysis, and integrated land use and transport optimization policy development,. In this research, based on previous related work, activity-based approaches have been developed to solve ① network travel choice equilibrium problems, ②combined user residential location choice and travel choice problems, and ③simultaneous land use development and road link expansion problems for sustainable land use and transport planning purposes.

It should be pointed out that, due to the complex interactions between activity choice behaviour and travel choice behaviour, this research concentrates only on exploring activity-based approaches for individuals.  However, to more completely understand user travel choice behaviour and/or user residential/employment location choice behaviour, household activity-based models, where the inter-personal interactions among family members are examined, should be established, as part of the ongoing research.

# 3 A NETWORK USER EQUILIBRIUM MODEL FOR DAILY ACTIVITY SCHEDULE IN CONGESTED NETWORKS

In this chapter, the user daily activity scheduling problem in congested networks is studied. Bearing in mind previous relevant studies, this chapter extends existing theories by developing a more comprehensive framework. This framework simultaneously considers the impact of traffic congestion, interactions between activities at different discrete time intervals, flexible activity durations, and flexible activity sequences in user daily activity scheduling problems. A solution algorithm which is convergent and obviates the enumeration of daily activity-travel patterns (DATPs) is developed for solving the user daily activity scheduling problems in congested networks.

## 3.1 INTRODUCTION

Users' desire or need of activity participation generates individual travel choices such as trip chain choice, departure time choice, and destination choice. In turn, travel choices influence the user's provision of opportunities to enable activity participation, activity duration choice (i.e. activity start/end time), and activity location choice. As previously indicated, a better understanding of user travel choice behaviour can be achieved only when the scheduling problem of users' activity choices under the constraints time and space is solved.

In this chapter, the user daily activity scheduling problem in congested networks is dealt with. As the discussion of the abstract of this chapter, comparing to the previous relevant studies (Recker, 1995; Lam and Huang, 2002 2003; Huang and Lam, 2005; Zhang et al 2005; Adnan et al. 2009; Li et al. 2010; Ramadurai and Ukkusuri, 2010; Ramadurai and Ukkusuri, 2011), the interdependencies of user daily activity and travel choices are more comprehensively investigated in this chapter.

The main contributions of the work presented in this chapter are summarized as follows: (1) An activity-travel-space(ATS) network expansion approach, which explicitly addresses the relationship between users' activity choices and users' travel choices, is proposed; (2) An activity-based UE model is presented as a variational inequality(VI) problem which enables the formulation of the daily activity scheduling problem endogenously; (3) A polynomial-time algorithm is developed for solving the activity-based UE problem; (4) Sensitivity analyses to evaluate the effects of various transport and land use policies by applying the proposed model, are carried out.

The remainder of this chapter is organized as follows. Basic assumptions and concepts are firstly given in Section 3.2. An ATS network expansion approach is introduced in Section 3.3.  In Section 3.4, a UE model is formulated as a VI problem over the ATS network for studying the daily activity scheduling problem, and the properties of the equilibrium flow are discussed. A diagonalization algorithm is developed for solving the VI problem in Section 3.5. Numerical results are illustrated in Section 3.6. Finally, in Section 3.7, conclusions are drawn together with suggestions for further research.

## 3.2 BASIC ASSUMPTIONS AND CONCEPTS

### 3.2.1 ASSUMPTIONS

To facilitate the presentation of the essential ideas of this chapter, the basic assumptions are given below.

A3.1 The study horizon $[0,T]$ is 24 hours. This period is divided into a number of equally-spaced time intervals $\{k : k = 1,2,\ldots \overline{K}\}$. Let $K$ denote the set of all time intervals. A similar assumption was adopted by Lam and Yin (2001) and Lam and Huang (2002). The longer the time interval, the shorter the computational time is required. However, the shorter the time interval, the more accurate is the solution closing to the dynamic decision process.

A3.2 Link flow is constrained by the link capacity within the road network. The time spent by a vehicle on a link consists of a fixed free-flow travel time (measured in units of intervals) and a queuing time (measured in units of intervals) at the exit of that link (Bell, 1995; Yang and Meng, 1998b). Considering that users’ tolerable queuing time is limited, the maximum user tolerable queuing time on a road link is assumed to be $\overline{W}$ time intervals.

A3.3 Once the activity is chosen, at least one interval time should be occupied by participation in the selected activity.

A3.4 It is reasonable to assume that the marginal utility of any feasible activity participation at locations, is greater than the marginal disutility of traveling or queuing on road links.

A3.5 The focus of this chapter is on individual activity and travel scheduling behaviour analysis (Lam and Yin, 2001; Zhang et. al., 2005; Ramadurai and Ukkusuri, 2010; Li et. al., 2010; Ramadurai and Ukkusuri, 2011). Activity interdependency of household members is not considered. It is further assumed that vehicle occupancy is one person per vehicle.

A3.6 Users schedule the activity choices on the basis of a trade-off between utility obtained from activity participation and travel disutility so as to maximize the total utility during the whole day.

### 3.2.2 SOME USEFUL CONCEPTS

***Definition 3.1:*** A ***Daily activity-travel pattern (DATP)*** is the result of user daily activity scheduling and it is defined as a decision relating to the user's all activity-related and travel-related choices along the time of a day, such as: which activity sequence to choose (activity sequence choice), where to perform the activities (activity location choice), when to start and end an activity (activity start/end time choice), how long to spend on each activity (activity duration choice), when to depart from origin (trip departure time choice), and which route to choose for trip (route choice of the trip).

Travel is motivated by a need to participate in activities. Activity participation and travel are subject to time and space constraints within the study network. Users schedule the activities based on a tradeoff between utility obtained from activity participation and travel disutility.

***Activity utility:*** Let $u_{j,s}(k)$ denote the marginal utility of the participation of activity *j* at location *s*, at time interval *k*. Readers may refer to Figure 3.5 for examples of marginal utility functions. The utility of performing activity *j* at location *s* for one interval with a start time interval *k*, can be expressed as:

$$\overline{U}_{j,s}(k) = \int_{k}^{k+1} u_{j,s}(\omega) d\omega \,. \tag{3.1}$$

***Travel disutility:*** From A3.2, travel disutility includes free-flow travel time and queuing time caused by link flows exceeding link capacity. Assume that queuing time depends on the number of vehicles in the queue at the time interval that users join the queue, rather than on the physical length of the queue. Let $\bar{t}_b$ denote free-flow travel time of link *b*. Let $\tau_b(k)$ denote the queuing time of traffic that enters road link *b* at interval *k*. The total link travel time $t_b(k)$ can then be expressed as

$$t_b(k) = \bar{t}_b + \tau_b\left(k + \bar{t}_b\right). \tag{3.2}$$

## 3.3 ACTIVITY-TIME-SPACE NETWORK EXPANSION APPROACH

In this section an ATS network expansion approach is introduced, to represent the daily activity and travel choice behaviour of users over a network. This approach is an extension of the space-time expanded network method, adopted by many previous dynamic traffic studies (Drissi-Kaïtouni, 1993; Bell, 1995; Bell and Iida, 1997; Yang and Meng 1998b; Carey and Subrahmanian, 2000; Liao et al., 2013).

### 3.3.1 ATS NETWORK EXPANSION APPROACH

Consider an urban road transport network (base network) $\hat{G} = (S, B)$, where *S* is a set of all nodes, including all those for activity participation, and *B* is a set of all directed road links. Let *s* denote a single node, $s \in S$ and *b* denote a road link, $b \in B$. Let $Q_b$ denote the capacity of road link *b*. Let *J* represent the set of activities, and *j* an activity, $j \in J$. Let *q* be the total study network population.

Readers may refer to Appendix for the step-by-step procedure of an ATS network expansion. Figure 3.1 gives an example of such a network. The network expansion approach is summarized as follows.

Each feasible activity location choice node $n_s$ in the base network is expanded to $\overline{K}+1$ nodes, and $\overline{K}$ (or $2\overline{K}$) activity links for each feasible activity at this location. Each road link $b$ in the base network is expanded to $\pi_1$ nodes, $\overline{K}+1-\bar{t}_b$ travel links,

$\pi_2$ queue links, and $\pi_1$ exit links, where $\pi_1 = (\bar{K}+1-\bar{W}-\bar{t}_b)(\bar{W}+1)+\sum_{g=1}^{\bar{W}} g$ and $\pi_2 = (\bar{K}-\bar{W}-\bar{t}_b)\bar{W}+\sum_{g=1}^{\bar{W}} g$ .

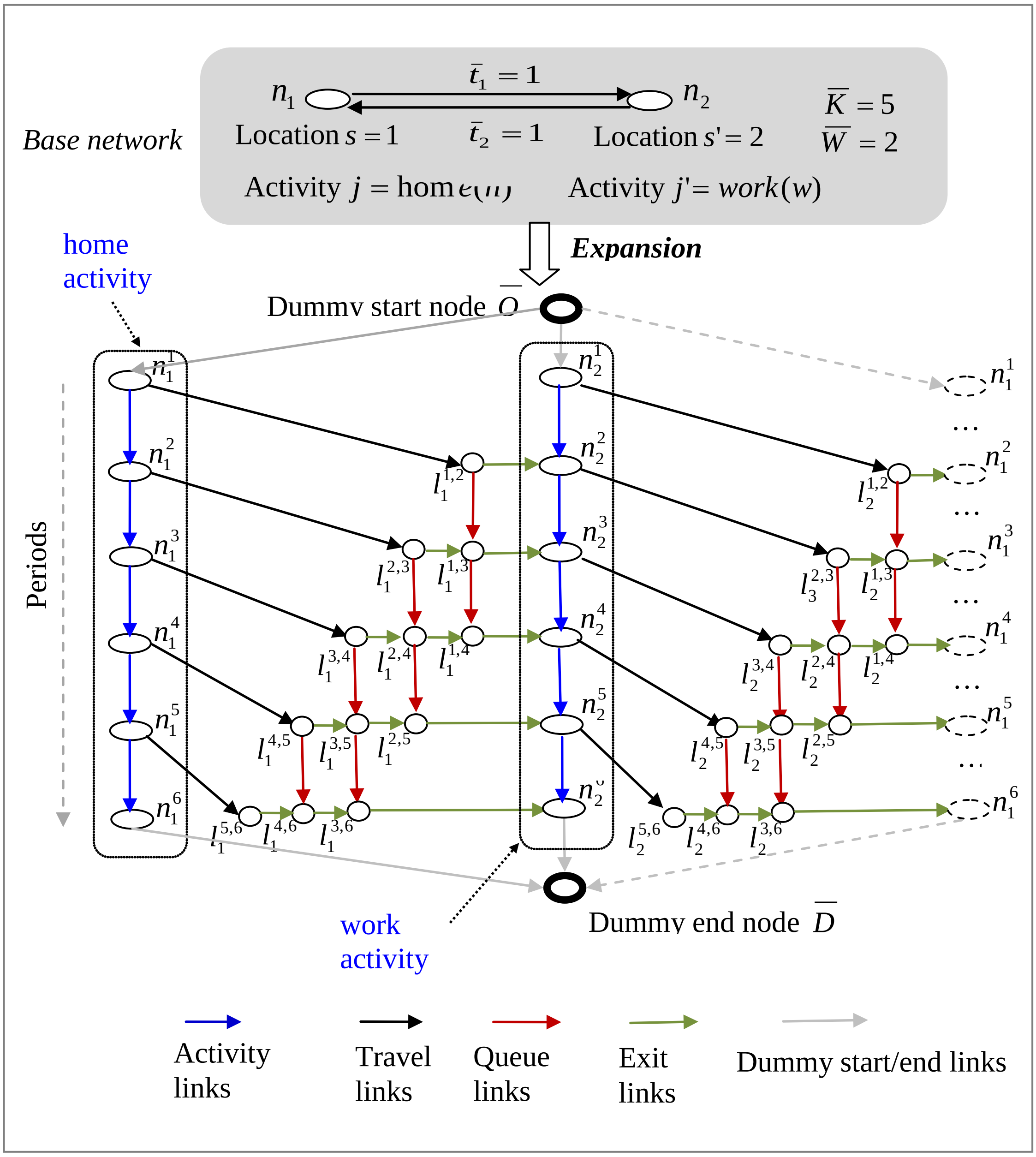


**Figure 3.1 An Illustrative Example of Activity-Time-Space Network**

***Activity links***: An activity link indicates the process of one-interval activity participation, which connects an activity location node from one interval to the next. Such a link contains information of activity type, activity location, and activity duration of one interval.

***Travel links:*** A travel link represents the free-flow condition travel process on a road link. From A3.2, a user enters a road link, and then he/she must take free-flow travel times when traveling on that link and may later either exit the link or join a queue on that link. At each time interval, the user continuously faces a choice of exiting the road link or joining the queue. A travel link connects a node which is one of the nodes expanded from that at the head of the road link to the node at the head of an exit link and/or a queue link (Referring to Figure 3.1). A travel link contains the information of the entry time and the free-flow travel time of the road link. Such a link may also indicate the departure time of a trip, if the head of the road link is the origin node of that trip.

***Queue links:*** A queue link represents a one-interval queuing process, which connects a certain node from one time interval to the next time interval. The queuing process is caused by congestion. Congestion, in turn prevents immediate exit from the road link, owing to the capacity constraints. The queue links are constructed on the assumption (refer to A3.2) that the longest queuing time on a road link is $\overline{W}$ time intervals. Results will not be affected if $\overline{W}$ is set as a large number.

***Exit links:*** An exit link represents the exit process of users. After a travel process or a queuing process, users may exit the road link if there are spare capacities. Each exit link connects the tail of a travel or queue link to either the tail of the road link or the head of another exit link. Exit links may imply the arrival time of a trip if it connects to the tail of the road link and if that tail is the destination node of the trip.

***Dummy start and end links:*** Dummy start links which connect an introduced dummy start node $\overline{O}$ to each activity location node at the beginning of the study time horizon, correspond to the process of entering the ATS network. Dummy end links which connect each activity location node at the end of the study time horizon to an introduced dummy end node $\overline{D}$, correspond to the process of exiting the ATS network.

Let $G = (N, A)$ represent the expanded ATS network, where $N$ is the set of all nodes, and $A$ is the set of all directed links. Let $a$ represent a link, $a \in A$. Let $\overline{V}_a$ and $C_a$, respectively, represent the utility/disutility and capacity of link $a$. Let $P$ represent the set of paths, and $p$ a path, $p \in P$ .Let $\Gamma_p$ represent the utility of path $p$. Let $x_a$ represent the flow of link $a$, and $f_p$ the flow of path $p$. Let $A_e^1$ denote the activity link set, $A_e^2$ the travel link set, $A_e^3$ the queue link set, $A_e^4$ the exit link set, and $A_e^5$ the dummy start/end link set, respectively.

### 3.3.2 LINK UTILITY/DISUTILITY AND LINK CAPACITY

Before setting the (dis)utility/capacity of each link in the ATS network, the exit link set $A_e^4$ is classified into two link sets $A_e^{4,1}$ and $A_e^{4,2}$ .

***Definition 3.2:*** Define $A_e^{4,1}$ as the set of exit links which connect to the tail of a road link (i.e. a location) $n_s^k$ (where $k$ is the number of time intervals, and $s$ is the node), and define $A_e^{4,2}$ as the set of all other exit links which connect to the head of the exit links (see Figure 3.2a). $A_e^{4,1} \cup A_e^{4,2} = A_e^4$.

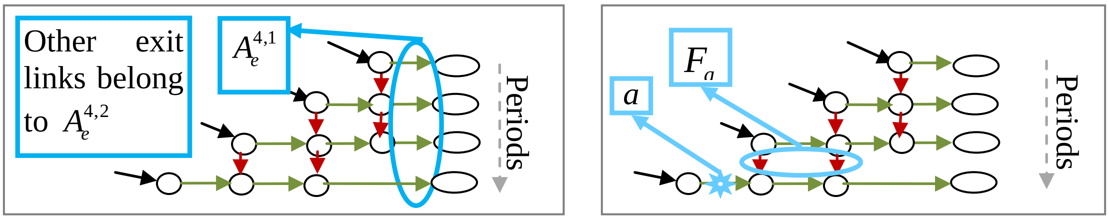


**Figure 3.2(a) The Classification of Exit Link; (b) An Example of $F_a$ Set**

***Definition 3.3:*** For an exit link $a = \left(l_b^{g,k}, l_b^{g-1,k}\right)$, $a \in A_e^{4,2}$ (where $g$ represents the time interval of traffic entering road link $b$ and $k$ represents the current time interval, referring to Figure 3.1), define $F_a$ as the set of queue links $a' = \left(l_b^{g',k'-1}, l_b^{g',k'}\right)$, where $k' = k$, $1 \le g' \le g-1$, $a' \in A_e^3$ (see Figure 3.2b).

Traffic on these queue links $a'$, $a' \in F_a$, should take priority when exiting the road link $b$, $b \in B$, over the traffic on that exit link $a$, since traffic on links $a'$ enters road link $b$ before the time interval $g$ in view of $1 \le g' \le g-1$, earlier than time interval $g$ that traffic on the link $a$ enters link $b$.

The capacity, as well as the (dis)utility, of each type of links in ATS network, is set out as below:

***Link utility/disutility:***

- ✓ Let $\overline{V}_a = 0$, $a \in A_e^4 \cup A_e^5$, so that the utility of exit links and dummy links is zero.
- ✓ Let $\overline{V}_a = \overline{U}_{j,s}(k) - \sigma L$, $a \in A_e^1$ (where $\sigma$ is the utility parameter of time and $L$ is the length of one time interval). It implies that the utility of activity links is the utility obtained from one time interval activity participation.
- ✓ Let $\overline{V}_a = -\sigma \bar{t}_b$, $a \in A_e^2$, such that the disutility of travel links is the equivalent disutility of free-flow travel time on that link.
- ✓ Let $\overline{V}_a = -\sigma L$ , $a \in A_e^3$. It means the disutility of queue links is the equivalent disutility of one interval queuing time.

***Link capacity:***

- ✓ Let $C_a = \infty$, $a \in A_e^1, A_e^2, A_e^3, A_e^5$.
- ✓ Let $C_a = Q_b$, $a \in A_e^{4,1}$ and; let $C_a = Q_b - \sum_{a' \in F_a} x_{a'}$, $a \in A_e^{4,2}$.

The capacity of an exit link $a$ , $a \in A_e^{4,1}$ only depends on the capacity of the corresponding road link $b$, $b \in B$. The capacity of an exit link $a$, $a \in A_e^{4,2}$ not only depends on the corresponding road link capacity, but also relates to the total traffic flow on queue links $a', a' \in F_a$.

## 3.4 THE MODEL

### 3.4.1 DAILY ACTIVITY-TRAVEL PATTERN ON THE EXPANDED ATS NETWORK

According to the ATS network expansion approach introduced previously, the activity choices and travel choices can be explicitly represented by the respective activity links and the travel/queuing/exit links of the ATS network. The daily time-dependent activity and travel choices are then represented by link choices over time intervals $k = 1,2,...,\overline{K}$. The relationships between these choices as well as the time and space constraints are reflected by the ATS network topology. Each path from the dummy start node $\overline{O}$ to the dummy end node $\overline{D}$ on the ATS network denotes a feasible DATP, and all feasible DATPs are represented by the path set between $\overline{O}$ and $\overline{D}$. Users schedule their activity and travel plans to maximize utility. This is equivalent to finding the longest path on the ATS network. Therefore, the network user equilibrium problem for daily activity scheduling is transformed into a static traffic assignment problem over the ATS network. This resultant assignment problem is confined to a single origin-destination (OD) pair in which all users depart from node $\overline{O}$ and finish at node $\overline{D}$. The OD demand relates to the total population within the study network.

The network user equilibrium conditions of the daily activity scheduling problem are given as follows.

***Definition 3.4*** *The DATP choices on the network reach user equilibrium (UE) if the following conditions hold: No user can improve his utility by unilaterally changing his DATP choice to any other feasible one.*

### 3.4.2 MODEL FORMULATION

The DATP choice UE problem can be regarded as a typical static traffic network equilibrium assignment problem over the ATS network $G = (N, A)$. The assignment over the expanded ATS network must be done in a way such that the traffic flow conservation, capacity and nonnegative constraints are satisfied:

$$\sum_{p \in P} f_p = q , \quad p \in P , \tag{3.3a}$$

$$f_p = \sum_{a \in A} \delta_a^p x_a , \quad a \in A, p \in P , \tag{3.3b}$$

$$x_a \le C_a , \quad a \in A , \tag{3.3c}$$

$$x_a , f_p \ge 0 , \quad a \in A , \ p \in P , \tag{3.3d}$$

where $\delta_a^p$ is the link-path incidence. Let $\Omega$ be the set of feasible path/link variables defined by Equations (3.3).

The user equilibrium condition of Definition 3.4 can be formulated as

$$\sum_{a \in A} \left( \overline{V}_a \right) \delta_a^p + \sum_{a \in A_e^4} d_a \delta_a^p = \Gamma^* , \qquad if \quad f_p > 0 , \tag{3.4a}$$

$$\sum_{a \in A} \left( \overline{V}_a \right) \delta_a^p + \sum_{a \in A_e^4} d_a \delta_a^p \le \Gamma^* , \qquad if \quad f_p = 0 , \tag{3.4b}$$

where $\Gamma^* = \max_{p \in P} \left\{ \Gamma_p \right\}$ is the maximum utility of the paths from node $\overline{O}$ to node $\overline{D}$ at UE condition (i.e. the equilibrium utility), given the total population as $q$ on network $G$, and $d_a$ is the Lagrange multiplier associated with capacity constraints of Equation (3.3c).

The equivalent VI formulation of problems (3.4) is given below.

***Theorem 3.1.*** *The DATP choices (i.e. path choices on ATS network) reach the UE state if and only if it satisfies the following VI condition:*

$$\sum_p \Gamma_p(f_p^*)(f_p^* - f_p) \geq 0 \,, \tag{3.5}$$

*where* $f_p \in \Omega, f_p^* \in \Omega$ *and* $f_p^*$ *is an equilibrium path flow .*

***Proof.*** For the proof, the reader is referred to Smith (1979) on the path VI formulation for the static traffic assignment problem. □

The VI problem (3.5) can be further written as a link-based formulation as shown below.

***Theorem 3.2.*** *The time-dependent daily activity and travel choices (i.e. link choices on the ATS network) reach the UE state if and only if it satisfies the following VI condition:*

$$\sum_a \overline{V}_a(x_a^*)(x_a^* - x_a) \geq 0 \,, \tag{3.6}$$

*where* $x_a \in \Omega, x_a^* \in \Omega$ *and* $x_a^*$ *is an equilibrium link flow.*

***Proof.*** For the proof, the reader is referred to Smith (1979), link VI formulation for the static traffic assignment problem. □

The existence of a solution to VI (3.5) or (3.6) can be easily proved. It is worth noting that some of the link utility/disutility is constant. Sequentially, the link utility/disutility or path utility/disutility may be not strictly concave with the link flow. Therefore, the solution to VI (3.5) or (3.6) may be non-unique.

### 3.4.3 SOME PROPERTIES OF THE ATS NETWORK UE FLOW

Properties and/or characteristics of the network UE flow on the ATS network are given in this section. Let $l_b^{g,k}$ denote the head of an exit link in the ATS network.

Consider a specific trip (i.e. with determined origin and destination choices) required in a DATP on the base network: Let $\hat{w}$ denote a feasible route choice for the trip, and $\hat{h}_{\hat{w}}(k)$ be the route traffic flow with departure time $k$. Let $\Theta_{\hat{w}}(k)$ denote the equilibrium queuing time of the trip with the departure time $k$, and route choice $\hat{w}$. Let $T_{\hat{w}}$ denote the free-flow travel time of the trip with the route choice $\hat{w}$. Let $d_{\hat{w}}(k)$ (measured in time) denote the sum of the equilibrium Lagrange multipliers associated with capacity constraints of road links experienced by the trip with the departure time $k$ and route $\hat{w}$. Let $c = \min_{\hat{w}}\{T_{\hat{w}} + \Theta_{\hat{w}}(k) + d_{\hat{w}}(k)\}$, $c_{\hat{w}}^1(k) = T_{\hat{w}} + \Theta_{\hat{w}}(k)$, and $c_{\hat{w}}^2(k) = \Theta_{\hat{w}}(k) + d_{\hat{w}}(k)$.

At the network UE conditions, the following properties hold.

***Proposition 3.1.*** *At the network UE conditions, for each trip, included in the DATPs, with departure time $k$, no user can decrease his trip time by unilaterally changing his route choice to any other feasible one, which is,*

$$T_{\hat{w}} + \Theta_{\hat{w}}(k) + d_{\hat{w}}(k) = c, \qquad \text{if} \qquad \hat{h}_{\hat{w}}(k) > 0, \tag{3.7a}$$

$$T_{\hat{w}} + \Theta_{\hat{w}}(k) + d_{\hat{w}}(k) \geq c, \qquad \text{if} \qquad \hat{h}_{\hat{w}}(k) = 0. \tag{3.7b}$$

***Proof.*** From A3.4 and A3.6, for each trip, users pursue the route with the shortest time and try to arrive at the destination as early as possible, to obtain greater utility by allocating the saved travel time on activity participations. Thus, Proposition 3.1 holds. □

***Lemma 3.1.*** *At the network UE conditions, a user at a node* $l_b^{g,k}$ *in ATS network,* $b \in B, g \in K, k \in K$ *, has only two choices: either waiting on the connected queue link when* $C_{I'} = 0$ *, or passing a number of exit links and immediately exiting road link* $b$ *when* $C_{I'} > 0$ *. Link* $I'$ *is the exit link which is out from node* $l_b^{g,k}$ *.*

***Proof.*** See Figure 3.3a. According to the capacity setting, we have link $III' \in A_e^{4,1}$, $C_{III'} = Q_b$ ; link $II' \in A_e^{4,2}$ , $F_{II'} = \{link1\}$ , $C_{II'} = Q_b - x_1^*$ ; and link $I' \in A_e^{4,2}$ , $F_{I'} = \{link1, link2, ..., link\hat{m}\}, C_{I'} = Q_b - \sum_{a'=1}^{\hat{m}} x_{a'}^*$ . It is noticed that $x_a^* \geq 0, \forall a \in A$, then $C_{I'} \leq ... \leq C_{II'} \leq C_{III'}$ . If $C_{I'} = 0$, traffic at node $l_b^{g,k}$ has to wait on the queue link and follow path 1. If $C_{I'} > 0$, it means there is spare capacity at node $l_b^{g,k}$ enabling traffic to pass link $I'$, and it is also possible for that traffic to pass other exit links along path 2 to immediately arrive at the tail of link $b$ , in view of $C_{I'} \leq ... \leq C_{II'} \leq C_{III'}$ . It is highly probable that this traffic will follow path 2. However, assume that this traffic does not follow path 2, but enters the queue link e.g. follows path 3. As travel time is shorter on path 2 than on path 3, traffic on path 3 is likely to switch to path 2 to take advantage of a prospective shorter journey. This move is in accordance with Proposition 3.1. Thus traffic at node $l_b^{g,k}$ will only choose waiting in the queue link when $C_{I'}=0$, or choose to pass a number of exit links to successfully exit the road link $b$ when $C_{I'}>0$. □

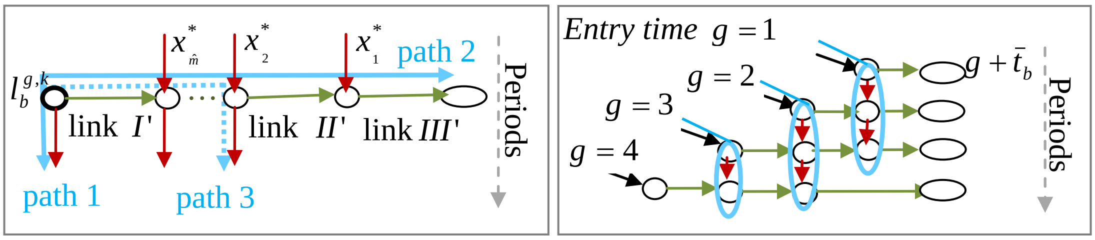


**Figure 3.3(a)Two Choices for Traffic at Node $l_b^{g,k}$; (b)Queues Separated by Entry Time.**

***Lemma 3.2.*** *At the network UE conditions, queues on a road link $b$, $b\in B$ are distinguished in terms of entry times $g$ in the ATS network: Users entering a road link $b$ at time interval $g$, $b\in B, g\in K$, may and only may queue at links which belong to the their own queue link set of links $a=\left(l_b^{g,k}, l_b^{g,k+1}\right)$, $g+\bar{t}_b\le k\le \overline{K}$.*

***Proof.*** See Figure 3.3b. A user who enters a road link $b$ at time interval $g$ may either pass the exit link or enter the queue link $\left(l_b^{g,g+\bar{t}_b}, l_b^{g,g+\bar{t}_b+1}\right)$ at time interval $g+\bar{t}_b$. If he chooses to pass the exit link, he will directly arrive at the end node of road link $b$ by passing a number of exit links according to Lemma 3.1. If he chooses to enter the queue link, he again faces a choice of passing the exit link or entering the queue link $\left(l_b^{g,g+\bar{t}_b+1}, l_b^{g,g+\bar{t}_b+2}\right)$ after one time interval. The process is repeated until he chooses the exit link. It is found that such a user may only queue at queue links $a=\left(l_b^{g,k}, l_b^{g,k+1}\right)$, $g+\bar{t}_b\le k\le \overline{K}$, during the repeated processes. □

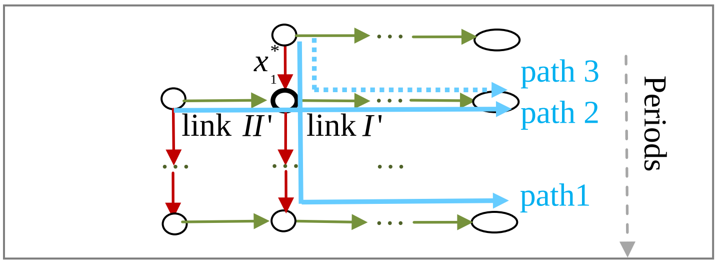


**Figure 3.4 First-In-First-Out Principle**

***Proposition 3.2.*** *At the network UE conditions, the first in first out (FIFO) principle holds in the ATS network: the first user enters a road link* $b$, $b \in B$, *is the first that exits.*

***Proof.*** It is noticed that the queue link sets distinguished by the entry times (refer to Lemma 3.2 and Figure 3.3b) are arranged from left to right in accordance with the entry time $g = \overline{K} + 1 - \bar{t}_b, \ldots, 4, 3, 2, 1$. In Figure 3.4, traffic on path 1 then enters the road link $b$ earlier than traffic on path 2. The FIFO is ensured if the equilibrium path flow on path 1 and path 2 satisfies $f_1^* \cdot f_2^* = 0$.

1) If $f_2^* = 0$: $f_1^* \cdot f_2^* = 0$.

2) If $f_2^* > 0$ : According to the capacity setting, in Figure 3.4, we have that $F_{II'} - F_{I'} = link1$ and $C_{II'} = C_{I'} - x_1^*$. If $f_2^* > 0$, it means that the capacity of each link along path 2 is greater than zero i.e. $C_{II'} > 0$ and $C_{I'} > x_1^*$. Assume $f_1^* > 0$. From Lemma 3.2, we get $x_1^* \geq f_1^*$. Then, $C_{I'} > x_1^* \geq f_1^* > 0$. Following Proposition 3.1 and in view of $C_{I'} > f_1^* > 0$, when the traffic $f_1^*$ on link 1 arrives at the bold node in Figure 3.4, this traffic will follow path 3 instead of path 1. Thus $f_1^* = 0$ and $f_1^* \cdot f_2^* = 0$.

This completes the proof of Proposition 3.2. □

Let $j=1$ and $s=1$ denote the respective activity and activity location of the start of the trip. Let $j=2$ and $s=2$ denote the respective activity and activity location of the end of the trip. Let $k_-$ and $k_+$ denote the time a little earlier and later than $k$ under the continuous time scenario.

***Proposition 3.3.*** *At the network UE conditions, for a trip, for $\forall w$ where $\hat{h}_{\hat{w}}(k) > 0$ (here k is the departure time choice of the trip), the marginal activity utility of the start of the trip and that utility of the end of the trip satisfy:*

*(i)* $\int_{k-1}^{k} u_{1,1}(\omega)d\omega - \sigma c_{\hat{w}}^{2}(k) \geq \int_{k-1+c_{\hat{w}}^{1}(k-1)}^{k+c_{\hat{w}}^{1}(k)} u_{2,2}(\omega)d\omega - \sigma c_{\hat{w}}^{2}(k-1)$,

*and* $\int_{k}^{k+1} u_{1,1}(\omega)d\omega + \sigma c_{\hat{w}}^{2}(k) \leq \int_{k+c_{\hat{w}}^{1}(k)}^{k+1+c_{\hat{w}}^{1}(k+1)} u_{2,2}(\omega)d\omega + \sigma c_{\hat{w}}^{2}(k+1)$;

*(ii)* $u_{1,1}(\omega)d\omega \geq \int_{k+c_{\hat{w}}^{1}(k_-)}^{k+c_{\hat{w}}^{1}(k)} u_{2,2}(\omega)d\omega - \sigma c_{\hat{w}}^{2}(k_-) + \sigma c_{\hat{w}}^{2}(k)$,

*and* $u_{1,1}(\omega)d\omega \leq \int_{k+c_{\hat{w}}^{1}(k)}^{k+c_{\hat{w}}^{1}(k_+)} u_{2,2}(\omega)d\omega + \sigma c_{\hat{w}}^{2}(k_+) - \sigma c_{\hat{w}}^{2}(k)$, *if* $\overline{K} \to \infty$;

*(iii)* $u_{1,1}(k) = u_{2,2}(k+T_{\hat{w}})$, *if* $\overline{K} \to \infty$ *and no congestion on the network;*

*(iv)* $u_{1,1}(k) = u_{2,2}(k)$, *if* $\overline{K} \to \infty$ *and the location for these two activities is the same one.*

***Proof.***

(i) From Proposition 3.2, we have $k-1+c_{\hat{w}}^{1}(k-1) \leq k+c_{\hat{w}}^{1}(k) \leq k+1+c_{\hat{w}}^{1}(k+1)$. Since $k$ is the optimal departure time of the trip, it means that departure at $k$ is not worse than departure at $k-1$ and departure at $k+1$, then

$\int_{k-1}^{k} u_{1,1}(\omega)d\omega - \sigma c_{\hat{w}}^{2}(k) \geq \int_{k-1+c_{\hat{w}}^{1}(k-1)}^{k+c_{\hat{w}}^{1}(k)} u_{2,2}(\omega)d\omega - \sigma c_{\hat{w}}^{2}(k-1)$, and

$$\int_{k}^{k+1} u_{1,1}(\omega)d\omega + \sigma c_{\hat{w}}^{2}(k) \le \int_{k+c_{\hat{w}}^{1}(k)}^{k+1+c_{\hat{w}}^{1}(k+1)} u_{2,2}(\omega)d\omega + \sigma c_{\hat{w}}^{2}(k+1)\,.$$

(ii) Following Proposition 3.3(i), it is easy to demonstrate that Proposition 3.3(ii) hold.

(iii) If no congestion on the network, $d_{\hat{w}}(g) = 0$ and $\Theta_{w}(g) = 0$, for $g = k, k_{-}, k_{+}$. Hence following Proposition 3.3(ii), we have $u_{1,1}(k) = u_{2,2}(k + T_{\hat{w}})$.

(iv) From Proposition 3.3(iii) and $T_{\hat{w}} = 0$, we have $u_{1,1}(k) = u_{2,2}(k)$.

This completes the proof of Proposition 3.3. □

## 3.5 THE SOLUTION ALGORITHM

### 3.5.1 SOLUTION ALGORITHM

The solution, of the link-based VI problem (3.6) which is equivalent to the daily activity scheduling problem, is addressed in this section. Note that the capacity $C_a$ of link $a$, $a \in A_{e}^{4,2}$ depends on the flow of link $a'$, $a' \in F_a$, where the definition of $F_a$ is given in the previous section. The implicit link utility $V_a$ of link a in the ATS network may not only be related to the flow of that link itself, but also to the flows of other links. Hence, the VI problem (3.6) can be decomposed into a sequence of sub-problems $VI^{y}$, $y = 1,2,...$, by using the diagonalization or Jacobian method. Each sub-problem $VI^{y}$ can be defined as follows.

$$VI^{y}: \sum_{a} V_{a}^{y}(x_{a}^{*})(x_{a}^{*} - x_{a}) \ge 0,\ \forall x_{a} \in \Omega, \tag{3.8}$$

where $V_a^y(x_a) = V_a(x_1^y, x_2^y, ..., x_a, x_{a+1}^y, ..., x_{|A|}^y) = V_a(C_a^y, x_a)$ and $x_a^* \in \Omega$ is the equilibrium link flow.

It is noted that each sub-problem $VI^y, y = 1,2,...,$ is separable, so each sub-problem has an equivalent optimization problem as shown below.

$$\max Z(x_a) = \sum_{a \in A} \int_0^{x_a} V_a(\omega) d\omega, \qquad x_a \in \Omega. \tag{3.9}$$

The solution algorithm of the VI problem (3.6) is transformed to solve a sequence of maximization problems (3.9). In the remainder of this section, we will then focus on the solution of the equivalent optimization problem (3.9).

Note that the optimization problem (3.9) is subject to link capacity constraints in the ATS network. Here an inner penalty approach is used to relax the capacity constraint (Yang and Yagar, 1994; Yang and Meng, 1998b). Similar to the study of Yang and Yagar (1994), the implicit link utility which incorporates the impacts of the capacity constraints, is defined as follows:

$$V_a = \overline{V}_a - \hat{r} / (C_a - x_a), \qquad a \in A_e^4, \tag{3.10}$$

where $\hat{r} \in \overline{R}^+$ is the penalty parameter.

The equivalent optimization problem (3.9) with relaxed capacity constraints is:

$$\max Z(x_a) = \sum_{a \in A} \overline{V}_a \cdot x_a + \hat{r} \sum_{a \in A} \left[ \log(C_a - x_a) - \log C_a \right], \quad x_a \in \{\Omega - eq.(3.3c)\} \tag{3.11}$$

where the item $\sum_{a \in A} \left[ \log(C_a - x_a) - \log C_a \right]$ is the penalty function(PF) defined by Yang and Yagar(1994), and $\partial Z / \partial x_a = V_a$. Let $PF = \sum_{a \in A} \left[ \log(C_a - x_a) - \log C_a \right]$.

The problem (3.11) is equivalent to a typical static traffic assignment problem without capacity constraints on the expanded ATS network. The Gradient Projection (GP) algorithm is regarded as one of the most efficient algorithms for solving this type of traffic network assignment problem (Chen et al. 2000; Chen et al., 2002; Nie et al., 2004). In this chapter, the GP algorithm is adopted to solve the resultant uncapacitated optimization problem (3.11) and the Shortest Path Faster Algorithm (SPFA) is used to find the path (i.e. DATP choice) with the maximum utility in the iterations.

The proposed solution algorithm is outlined as follows:

**Step 0.** Initialization: let $n$ = 1 (outer iteration) and find a feasible solution as the initial solution $\mathbf{x}^{(1)}$; set decreasing parameter $\zeta$ ($0<\zeta<1$), and convergence criteria $\varepsilon^{(n)}$; set $\hat{r}^{(n)}$ ($\hat{r}^{(n)}>0$).

**Step 1.** Solve the resultant uncapacitated optimization problem (3.11) using the GP algorithm to obtain link flow $\mathbf{x}^{(n)}$ and path flow $\mathbf{f}^{(n)}$, let z= 1 (inner iteration):

Step 1.1: Perform GP iteration and obtain $\mathbf{f}^{(n,z)}$ .

Step 1.2: Update $\varepsilon^{(n)}$ by Equation (3.12).

Step 1.3: Convergence test. If the convergence criterions (the assignment result of the sub-problem satisfies the user equilibrium condition; in the other words, the utility of all DATPs with non-zero flows almost equals to each other) is met, go to Step 2; Otherwise, set z = z+1, and go to Step 1.1.

**Step 2.** Convergence test: If the gap function GF ≤ ε1, then stop. Otherwise, let $\hat{r}^{(n+1)} = \varepsilon^{(n)}\zeta$ , and $n$ = $n$+1, and go to Step1.

Let

$$\varepsilon^{(n)} = \frac{\hat{r}^{(n)}}{\vartheta \cdot \max(-\overline{V}_a + \hat{r}^{(n)} / (C_a - x_a))}, \ a \in A, \tag{3.12}$$

where $n$ is the iteration time and $1 \leq \vartheta \leq 100$, and $\hat{r}^{(n)}$ is the penalty parameter at *n*th iteration . Define gap function (GF) as

$$GF = PF / \left(q \times \Gamma^{*}\right). \tag{3.13}$$

For the details of the GP iteration in Step 1.1, readers can refer to Chen et al. (2000, 2002).

### 3.5.2 ANALYSIS OF THE TIME COMPLEXITY OF SOLUTION ALGORITHM

The computation time of the solution algorithms for solving the traffic assignment problems is required when searching the shortest path in each iteration. In the following, the time complexity of the solution algorithm that is presented above is investigated.

As discussed in the Section 3.1, most of the existing activity-based network models require an explicit enumeration of DATPs or ATPs. Suppose that there are $\overline{m}$ feasible activity choices, $\overline{K}$ intervals, $\overline{g}$ links and $\overline{N}$ nodes in the base network. The time complexity of those methods with explicit enumeration of the DATPs is $O[\left(\overline{m}\overline{K}\overline{g}\overline{N}\right)^{\overline{m}\overline{K}\overline{g}\overline{N}}]$ since the number of combinational patterns may reach to $\left(\overline{m}\overline{K}\overline{g}\overline{N}\right)^{\overline{m}\overline{K}\overline{g}\overline{N}}$. Therefore, the algorithm requiring a prior enumeration of DATPs leads to burdensome computation of exponential-time growth. In practice, this inhibits the use of the potential application of the activity-based approach.

In Section 3.5.1, a link-based solution algorithm which does not need an explicit enumeration of DATPs is proposed to solve the daily activity scheduling problem. The SPFA is employed to find the path with maximum utility. The time complexity of SPFA for finding longest path on a network with $\overline{g}$ links and $\overline{N}$ nodes, is O[ $\overline{g}$ ]. Thus, the time complexity of SPFA for solving the daily activity scheduling problem on the ATS network is O[ $2\overline{\mathrm{K}}\overline{\mathrm{m}} + \overline{\mathrm{K}}\overline{\mathrm{g}} + 2\overline{\mathrm{K}}\overline{\mathrm{W}}\overline{\mathrm{g}} + \overline{\mathrm{K}}\overline{\mathrm{N}} + 2\overline{\mathrm{N}}$ ], because the maximum number of links on the expanded ATS network is O[ $2\overline{\mathrm{K}}\overline{\mathrm{m}} + \overline{\mathrm{K}}\overline{\mathrm{g}} + 2\overline{\mathrm{K}}\overline{\mathrm{W}}\overline{\mathrm{g}} + \overline{\mathrm{K}}\overline{\mathrm{N}} + 2\overline{\mathrm{N}}$ ] in terms of the expansion method presented in Section 3.3.1. As such, the solution algorithm proposed in Section 3.5.1 is a polynomial-time algorithm.

## 3.6 NUMERICAL EXAMPLES

In this section, two numerical examples are used to illustrate the application of the proposed model and solution algorithm. The purpose of the first simple numerical example is to show the merits of the proposed activity-based model by comparing the results of this model with those of other activity-based models and the trip-based model. The numerical example is also used to evaluate the effects of the transport policy on users' activity and travel choice behaviour. The second numerical example, which is based on the Sioux Falls network, aims to indicate the potential capability of implementing the proposed model and solution algorithm in a medium-size transport road network. It is also used to estimate the effects of the land use policy on users' activity and travel choice behaviour.

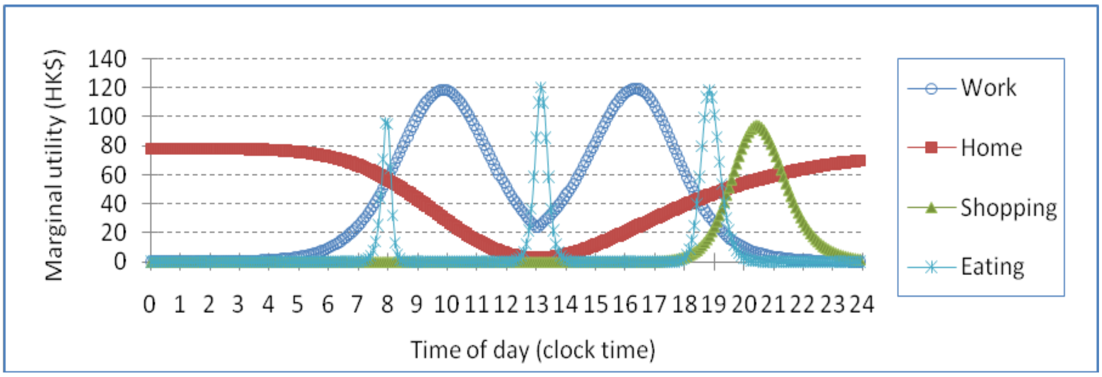


**Figure 3.5 Marginal Utility Functions**

The entire study time period is from 6:00 to 24:00 equally divided into 108 time intervals (i.e. 10 minutes per time interval). Suppose that $\sigma$ =HK$60/hour. The used activity marginal utility functions $u_{j,s}(k)$ for $\forall s$, are given in Figure 3.5 without special statement (Lam and Huang, 2002, 2003; Huang and Lam, 2005; Zhang et al., 2007; Li et al. 2010). The parameters used in the solution algorithm are given as follows: $\hat{r}^{(1)} = 1$, $\varepsilon 1 = 0.0001$, and $\zeta = 0.9$. The computer program for the proposed solution algorithm was coded in Matlab (2009a version) and run on a laptop with CPU 2.80GHz.

### 3.6.1 EXAMPLE 1: A FOUR-NODE NETWORK

Figure 3.6 is a simple road network which consists of ten directional links and four nodes. The four nodes represent four zones, namely, home/residential area ("H"), restaurant area ("R"), shop area ("S"), and work place ("W"), respectively. There are six bottlenecks in this network. The link free-flow travel times and link capacities are given in Table 3.1. In this study network, the total population is assumed to be 3500.

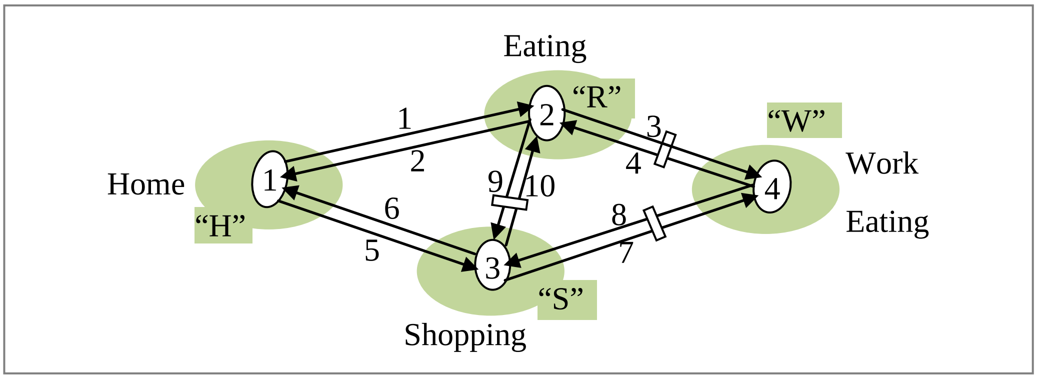


**Figure 3.6 Base Network**

**Table 3.1 Link Free-Flow Travel Time and Capacity for the Base Network**

| Link | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Free-flow travel time (min) | 30 | 30 | 20 | 20 | 30 | 30 | 20 | 20 | 20 | 20 |
| Capacity(veh/hour) | N/A | N/A | 1800 | 1800 | N/A | N/A | 1500 | 1500 | 1800 | 1800 |

Four activities, namely home, work, shopping and eating activities, can be performed within the four nodes in the example network. The marginal utility profiles of these activities are the same as those shown in Figure 3.5, but for following differences: (1) Parking fees of HK$15/hour at "R" and "S", and HK$25/hour at "W", are incorporated (Note that US$ 1.00 = HK$ 7.8). (2) It is assumed that for eating activity at "W", only lunch is served. Considering that it is difficult to distinguish the exact start times and end times of different activities conducted at "H", eating activity at "H" and home activity are not differentiated, and are combined as home activity. The temporal marginal utility of eating at "H" and "W", is 0.6 times of that of eating shown in Figure 3.5. (3) Late departure penalty functions are employed to make sure that users depart from H for work in the morning no later than 7:40. The readers may refer to the studies (Nguyen et. al, 2001; Yang and Meng, 1998b) to consider other late departure penalty functions or early/late arrival penalty functions.

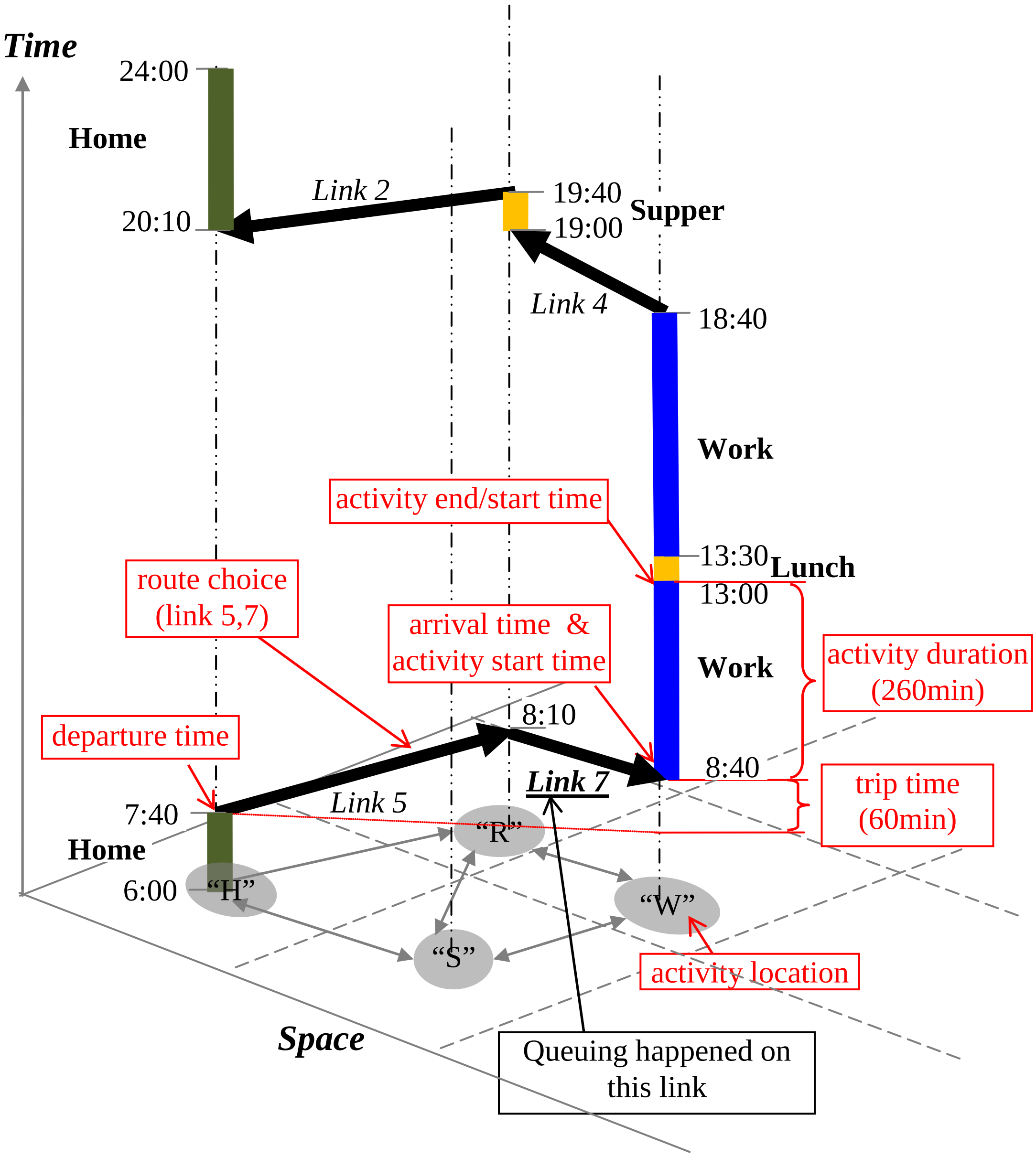


**Figure 3.7 An Example of the Resultant Daily Activity-Travel Patterns**

Figure 3.7 presents a DATP example which is endogenously derived from the network model proposed in this chapter. The number of the DATPs taken by the whole population is 34 and 250 users take the DATP presented in Figure 3.7. It can be seen that the activity sequence of this DATP is home-work-lunch-work-supper -home. Three trips are included: the trip from “H” to “W”, the trip from “W” to “R”, and the trip from “R” to “H”. The other activity-related choices and travel choices can also be traced in the DATP as shown in Figure 3.7. Note that the trip time from “H” to “W” is 60 minutes, which is greater than the sum (50 minutes) of the free-flow travel times of link 5 and link 7. The implication is that each user choosing this DATP, queues for 10 minutes to exit link 7.

The results of the proposed model in this chapter are compared with the results of other activity-based models and the trip-based model. Table 3.2 shows the main results of these models.

Presented in this chapter is Model I, an activity-based model where activity durations and activity-travel patterns are endogenously generated. Model II is an activity-based model with given activity durations (refer to Recker, 1995; Ramadurai and Ukkusuri, 2010) where the duration of eating, shopping and work is respectively, 0.5 hour, 1 hour and 8.5 hours. Model III is an activity-based model with given activity sequences (refer to Zhang et.al., 2005; Li et. al., 2010) in which two activity sequences, home-work-eating at R-home, and home-work-shopping-home, are considered. Model IV is a trip-based model with early/late arrival penalty functions (see Yang and Meng, 1998b). In this example, four trips, “H”-“W”, “W”-“R”, “R”-“S”, and “S”-“H”, are considered in Model IV. The best start time for work(i.e. the expected arrival time of trip "H”-“W"), eating(i.e. the expected arrival time of trip

"W”-“R"), shopping(i.e. the expected arrival time of trip "R”-“S") and best home return arrival time in the evening(i.e. the expected arrival time of trip "S”-“H"), is 8:30, 18:50, 19:30, and 21:00, respectively. It is pointed out that the trip-based model cannot model activity durations. For comparison, it is assumed that, in Model IV, the stay duration at locations, obtained by the analysis of departure time choices of trips, is the activity duration.

Table 3.2 shows that the model, (Model I), proposed and presented in this chapter is the most efficient of the three activity-based models, as it leads to the highest equilibrium daily utility of 630 HK$/user. The lower equilibrium daily utility of Model II or Model III is caused by an assumption of fixed activity durations or given activity sequences. Both hinder users from selecting optimal DATP choices.

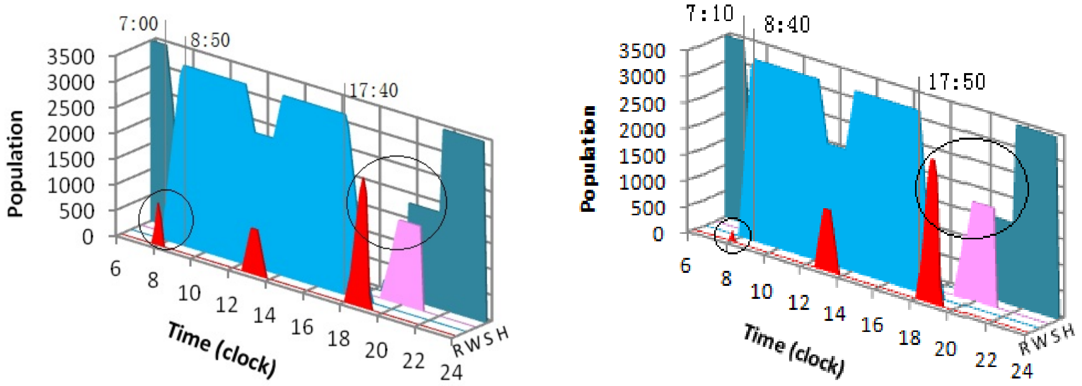
**Table 3.2 Comparison of the Results of Four Different Models**

| | Model I | Model II | Model III | Model IV |
|---|---|---|---|---|
| Equilibrium daily utility (HK$/user) | **630** | **522** | **571** | N/A |
| Travel demand of different trip chains | | | | |
| “H”-“W”-“R”-“H” | 1343 | 1451 | **2300** | N/A |
| “H”-“W”-“S”-“H” | 745 | 997 | **1200** | N/A |
| “H”-“W”-“R”-“W”-“R”-“S”-“H” | 591 | 0 | N/A | N/A |
| “H”-“R”-“W”-“R”-“W”-“R”-“S”-“H” | 300 | 0 | N/A | N/A |
| “H”-“R”-“W”-“R”-“H” | 300 | 0 | N/A | N/A |
| “H”-“R”-“W” -“H” | 221 | 300 | N/A | N/A |
| “H”-“W” -“H” | 0 | 752 | N/A | N/A |
| Average durations of different activities (hour/user) | | | | |
| home | 4.7 | 5.79 | 5.50 | 4.23 |
| work | 9.24 | **8.50** | 9.37 | 10.08 |
| out-of-home eating | 1.19 | **0.50** | 0.45 | 0.11 |
| shopping | 0.81 | **1.00** | 0.86 | 0.64 |
| Average travel time | 2.06 | 1.71 | 1.82 | 2.63 |
| Total time (hour/user) | 18 | 18 | 18 | **17.69** |

The resulting demand of different trip-chains by the above four models are also compared in Table 3.2. It is seen that trip-chains cannot be examined by the trip-based model (Model IV) and the trip chains generated in Model I cannot be fully observed by the other two activity-based models (Model II, III). From Table 3.2, it is also found that the four models offer significant time allocation differences for users. In addition, it is noted that the total time (17.69 hours) which user allocates on activities and travels by Model IV is inconsistent with the length of the study time horizon (18hours). This inconsistency is caused by trips having been dealt with separately, and trip relationships having been ignored in Model IV. For example, in Model IV, the situation that a user departs “R” of the trip “R”-“S” at a time earlier than the time he arrives at “R” of the trip “W”-“R”, may appear. Then inconsistency problem happens.

In summary, a comparison of the results as shown in Table 3.2, indicates that the proposed activity-based model in this chapter provides a more comprehensive framework for examining user daily activity scheduling problems and also offers better understanding of user daily travel choice behaviour.

Suppose that a transport policy exists, designed to expand the road link capacities of bottlenecks to 2400 veh/hour (Policy I). Figure 3.8 depicts the impact of that policy on the resulting population distributions at different activity locations of user DATP choices.



**(a)Before Policy I** **(b)After Policy I**

**Figure 3.8 Effects of Road Link Capacity Expansion (Policy I) on Population Distribution**

Users' daily activity and travel choices change as a result of Policy I. Some changes, such as changes in trip departure time and arrival time and the demands of activities, are pointed out in Figure 3.8. For example, it is noticed that users depart "H" later and arrive at "W" earlier in the morning after Policy I. The reason is probably that after capacity expansion the trip time from "H" to "W" decreases. From Figure 3.8, it is also found that more users can enjoy lunch at "R" and shop at "S" after Policy I. This result is also probably due to the decreased travel times of trips after capacity expansion. Users can now allocate the saved travel times on conducting these two activities. Another change is in eating at "R" in the morning. This activity is cancelled after Policy I by most users. This change occurs because before Policy I some users have to depart "H" earlier for work to avoid congestion, and it is too early for them to have breakfast at "H" before the departure, so these users choose to have breakfast at "R".

### 3.6.2 EXAMPLE 2: SIOUX FALLS NETWORK

The application of the proposed model and solution algorithm on the well known medium sized Sioux Falls network as shown in Figure 3.9 is examined in the following paragraphs.

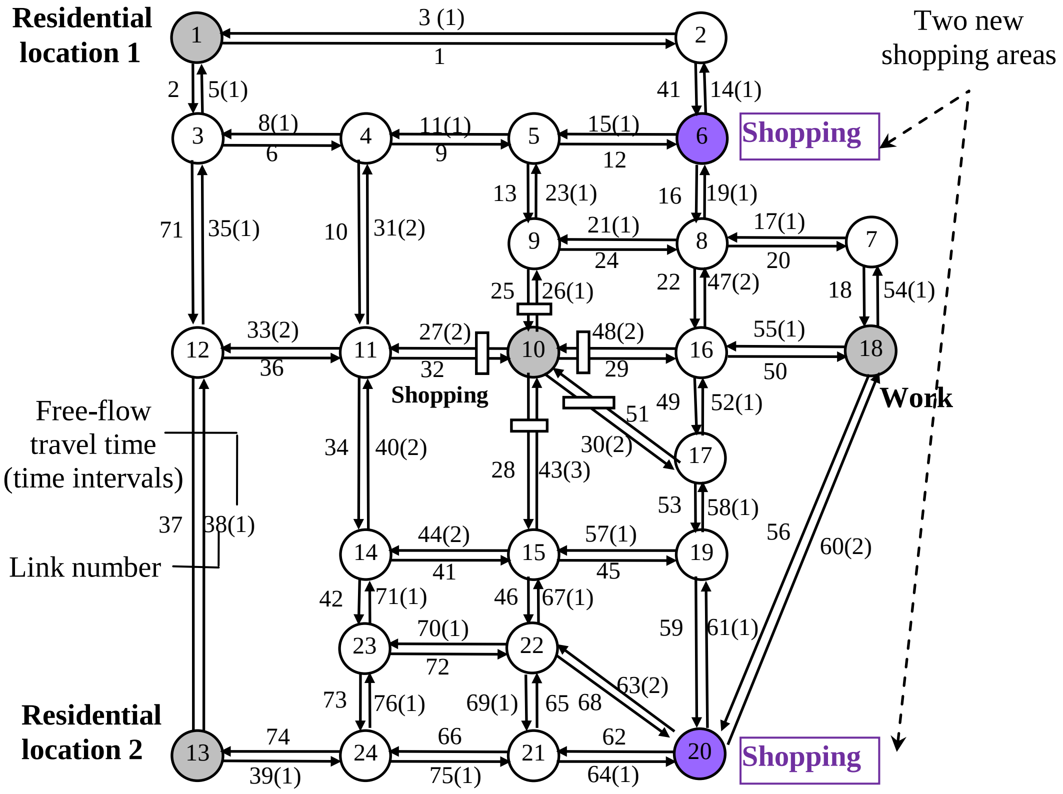


**Figure 3.9 Sioux Falls Network**

On the Sioux Falls network, Node 1 and Node 13 are assumed as two residential locations. The total population is considered to be 6000, with and 3000 users at each residential location. Users are assumed to perform home activities at their own residential location. Activities namely, work is feasible at Node 18 and shopping is feasible at Node 10. Assume that links connected to Node 10 are bottlenecks and the capacity constraint at each bottleneck is 1800 veh/hour. The free-flow travel time in time intervals of each road link is given in Figure 3.9. The free-flow travel times of links connecting the same two nodes but in opposite directions are the same.

Firstly, the convergence performance of the proposed solution algorithm is examined and shown in Figure 3.10. It is seen that after the first main iteration, the gap function value reaches less than 0.001. After 15 iterations, the gap function value decreases to less than the convergence tolerance 0.0001.

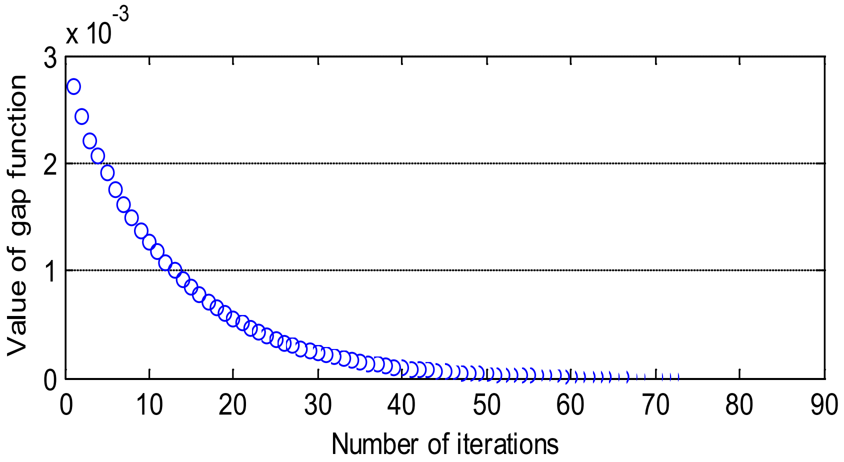
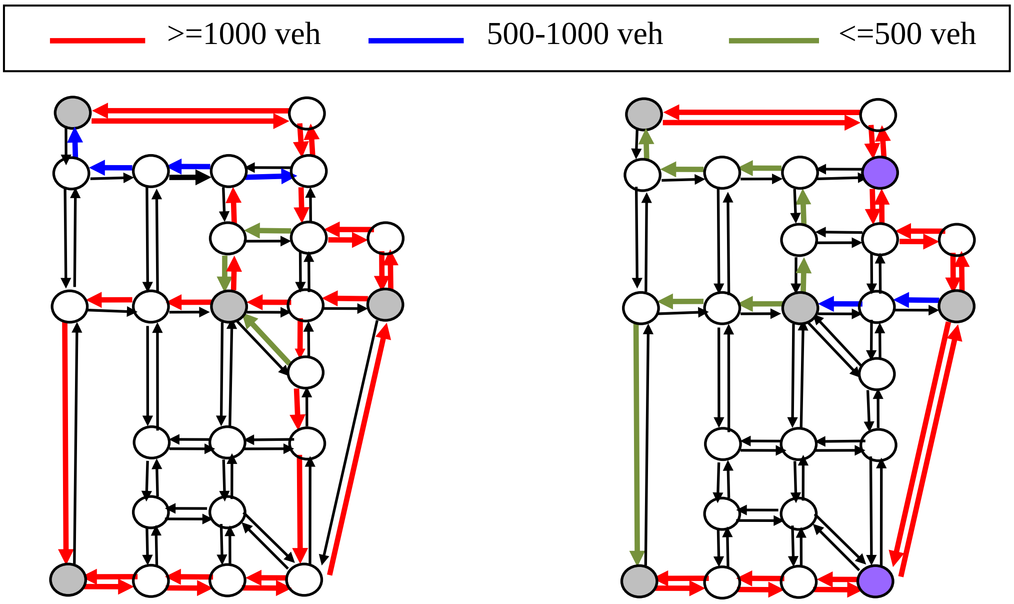


**Figure 3.10 The Convergence of the Proposed Solution Algorithm**

Secondly, the proposed model is applied to estimate the effects of a land use policy (Policy II) on user activity and travel choice behaviour. Suppose that new shopping areas are developed at Node 6 and 20. The marginal utility functions of shopping at these two areas are, 0.6 times of that function of shopping given in Figure 3.5.

The ranges of accumulated link flow throughout the whole day on each link before and after Policy II of users' DATP choice results are indicated by different color lines in Figure 3.11. It is seen that there are significant changes in the accumulated link flows. Policy II has a significantly impact on users' activity choices. The number of users who choose DATP including shopping activity increases from 2098 to 4651 after Policy II.



**(a)Before Policy II**

**(b)After Policy II**

**Figure 3.11 Effects of Developing Two New Shopping Areas (Policy II) on the Accumulated Link Flows within a Day**

## 3.7 SUMMARY

In this chapter, an ATS network expansion approach has been introduced to explicitly address the relationships between user daily activity choices and travel choices. The daily activity scheduling problem on a congested road network with queues was transformed into a typical static traffic assignment problem on the expanded ATS network. An activity-based UE traffic assignment model was formulated as a series of link-based VI sub-problems. A diagonalization solution algorithm without a prior DATPs enumeration was developed to solve the daily activity scheduling problem on congested road networks with queues. The SPFA was embedded into the proposed solution algorithm for searching the maximum-utility path in the ATS network. The time complexity of the proposed solution algorithm was also analyzed.

To facilitate the presentation of the essential ideas of this chapter, the study were presented with some constraints such as the ignorance of queuing problems at activity locations, and flexible durations for all activities while sometimes existing fixed durations for some activities(e.g. 8 hours for work) in practice. However, the study of this chapter should not be confined to these constraints and it can also be adopted to deal with activity scheduling problems where these constraints are relaxed. Similar to the method of considering queuing problems on road links, queuing problems at activity locations could be examined through constructing queuing links in the ATS network expansion approach. It is also easy to extend the study of this chapter to deal with relevant activity scheduling problems but some of the activities can be predetermined with fixed durations, if appropriate penalty strategies are designed to force users to select the fixed durations for these particular activities in due course.

The results from two numerical examples showed that the users' daily activity and travel choice behaviour can be reproduced well by the proposed model. In particular, the first numerical example illustrates the merits of the proposed model in predicting the allocation of users' activity participation time during a day and in evaluating the effects of the transport policy on the users' activity and travel choice behaviour. The second numerical example shows that the proposed model and solution algorithm can be used to assess the effects of land use policies, and offers potential for solving the daily activity scheduling problem in a medium-scale and real network.

It should be pointed out that only individual activity-travel choices are considered in this chapter. Future work should be carried out in the following aspects: (a) to extend the proposed model to consider the interactions of the activity and travel choice behaviour of inter-personal dependence among household members, (b) to study user activity and travel choice behaviour in a multi-modal transport network with behaviourally homogeneous or heterogeneous groups (some relevant work have been conducted by Fu and Lam (2013) but for multi-modal transit network only), (c) to calibrate and validate the parameters of the activity utility functions in the proposed model with empirical data, (d) to investigate user daily activity scheduling problems in general networks, and (e) to consider the stochastic dimensions in user daily activity scheduling problems. Some extension work of (d) and (e) are carried out in this research and described in the next chapter.

# 4 A NETWORK STOCHASTIC USER EQUILIBRIUM MODEL FOR DAILY ACTIVITY SCHEDULE IN GENERAL NETWORKS

This chapter extends the proposed method described in Chapter 3 to general road networks and incorporates the stochastic dimensions on user choices. In this chapter, an activity-based transport model is formulated as a SUE traffic assignment model for investigating user daily activity scheduling problems in general road networks. Note that the UE is a special case of the SUE in that the stochastic dimensions are ignored. Thus, the relevant UE traffic assignment model can be easily developed on the basis of this formulated SUE model.

## 4.1 INTRODUCTION

In many studies (Hirsh et al. 1986; Recker, 1995; Ettea and Timmermans, 2003; Lam and Yin, 2001; Adnan et al. 2009; Ramadurai and Ukkusuri, 2010) which investigate user daily activity scheduling problems, it is usually, assumed that users schedule their daily activity choices to ensure maximum utility can be obtained from activity participation and a minimum travel disutility. Utility and disutility, however, cannot be observed or measured directly, especially activity utility. Therefore it is reasonable to treat both activity utility and travel disutility as random. This means that users’ perception errors on activity utility and travel disutility should not be ignored when considering user daily activity and travel choice scheduling problems.

Recently, some studies (Lam and Yin, 2001; Huang and Lam, 2005; Zhang et al., 2005; Li et al., 2010) have developed SUE models where such perception errors on activity utility and travel disutility have been considered. In these studies the perception error variations of utilities/disutility across various activities (compulsory activities and noncompulsory activities) and travel are assumed to be identical. Hence, in these studies, a logit-based model or a multinomial logit model is formulated, with the use of the random utility theory, for investigating user daily activity and travel choice problems.

However, users probably have different perception error variations of utilities/disutility on different activities and travel, in accordance with their individual expectations. For example, users’ utility perception errors regarding compulsory activities are usually small, since the utilities gained from these activities could be measured more strictly by indexes such as salary and company regulations. Similarly users’ perception errors of travel disutility are probably small as the disutility is likely to be measured by travel time or travel cost. In contrast, users’ utility perception errors regarding non-compulsory activities may be high, as the utilities obtained from these activities mainly depend on users’ satisfaction with the service which influenced by emotion. Therefore, it is necessary to consider different perception error variations of utility/disutility across various activities and travel when investigating user daily activity scheduling problems.

In this chapter, a SUE model is formulated to investigate user daily activity scheduling problems in general road networks. A remarkable merit of the formulated is that it allows different perception error variations of utilities/disutility across various activities (compulsory activities and noncompulsory activities) and travel. In the previously analytical activity-based approach (Lam and Yin, 2001; Huang and Lam, 2005; Zhang et al., 2005; Li et al., 2010), however, these variations are usually assumed to be identical. The properties of the SUE solution of user DATP choices are also examined in this chapter. A heuristic solution algorithm that allows an automatic generation of the DATPs is developed to solve the user daily activity scheduling SUE problems, while the enumeration of such patterns has often been required in many previous related studies(Huang and Lam, 2005; Zhang et al., 2005; Li et al., 2010).

The remainder of this chapter is organized as follows. The basic considerations such as assumptions and notations are given in Section 4.2. The user daily activity scheduling problem in general road networks is discussed in Section 4.3. In Section 4.4, the user daily activity scheduling problem is formulated as a SUE model. The properties of the stochastic equilibrium solutions of the user daily activity scheduling problem are discussed in Section 4.5. A solution algorithm developed for solving the problem follows in Section 4.6. The special case of the daily activity scheduling problem (i.e. UE case) is discussed in Section 4.7. In Section 4.8, a numerical example is presented to illustrate the application of the proposed model and solution algorithm. Finally, conclusions are drawn in Section 4.9.

## 4.2 BASIC CONSIDERATIONS

### 4.2.1 THE DATP CONCEPT AND ASSUMPTIONS

The definition of DATP used in Chapter 3(i.e. Definition 3.1) is employed in this chapter. To simplify the presentation of the essential ideas of this chapter, the following assumptions are made.

A4.1 Assumptions A3.1, A3.3, and A3.5 given in Chapter 3, are carried on into this chapter. Let $L$ denote the duration of one time interval.

A4.2 It is reasonable to assume that the perceived marginal utility obtained from any feasible activity participation at any location and at any time is greater than the perceived marginal disutility of traveling on road links.

A4.3 Users schedule their daily activities so as to obtain the maximum perceived utility by optimizing their activity participations and travels within the whole day.

### 4.2.2 SOME NOTATIONS

Consider an urban road transport network $G = (N, A)$, where $N$ is the set of all nodes, including the nodes of activity locations, and $A$ is the set of all directed road links. Let $s$ denote a single node, $s \in N$ and $a$ denote a single road link, $a \in A$. Let $J$

represent the set of activities, and *j* represent an activity, $j \in J$ . Let *i* and *I*, respectively, denote a feasible DATP and the DATP set.

Let $x_a(k)$ denote the link flow at time interval *k* on road link *a*. Let *p* and *P* respectively denote a route and the route set, $p \in P$ . Let $f_{r,s}^{p}(k)$ denote route flow at time interval *k* on route *p* which connects origin *r* to destination *s*. Let *q* be the total population on the study network. Let $q_i$ denote the flow of taking DATP *i*. Let $q_{r,s}^{i,p}(k)$ denote the flow of choosing route *p*, departure from origin *r* to destination *s* at time interval *k* and in DATP *i*. Let $q_{r,s}^{i}(k)$ denote the flow of departure from origin *r* to destination *s* at time interval *k* and in DATP *i*. Let $q_{r,s}(k)$ denote the flow of departure from origin *r* to destination *s* at time interval *k*. Let $q_s^j(k)$ be the flow who conducts activity *j* at location *s* at time interval *k*, and $q_s(k)$ be the flow at location *s* at time interval *k*.

## 4.3 THE DAILY ACTIVITY SCHEDULING PROBLEM

According to A4.3, users optimize their DATPs to obtain the maximum perceived utility by activity participations and travels. This means that users make their DATP choices based on a tradeoff between the perceived utility obtained from activity participations and the perceived travel disutility.

### 4.3.1 ACTIVITY UTILITY AND TRAVEL DISUTILITY

Let $u_{j,s}(k)$ denote the marginal utility of the participation of activity *j* at location *s*, at time interval *k*. Let $\tau_{j,s}^{k}$ be the activity duration for the activity *j* participation at location *s* and start at time interval *k*. Let $U_{j,s}(k,\tau_{j,s}^{k})$ denote the actual utility of participating in activity *j* at location *s* for activity duration $\tau_{j,s}^{k}$ with start time interval *k*, and it can be calculated by the marginal utility, i.e.

$$U_{j,s}(k,\tau_{j,s}^{k}) = \int_{k}^{k+\tau_{j,s}^{k}} u_{j,s}(\omega)d\omega. \tag{4.1}$$

Let $\overline{U}_{j,s}(k)$ denote the actual utility of performing activity *j* at location *s* for one interval with start time interval $k$, and it is given by Equation (3.1).

The perceived utility $\hat{V}_{j,s}(k)$ of performing activity *j* at location *s* for one interval with start time interval *k*, can be expressed as:

$$\hat{V}_{j,s}(k) = \overline{U}_{j,s}(k) + \xi_{j,s}(k), \tag{4.2}$$

where $\xi_{j,s}(k)$ is the perception errors on the utility of conducting activity *j* at location *s* with start time interval *k* for one interval time duration. In this chapter, $\xi_{j,s}(k)$ is assumed to be a random noise with finite support and to be normally distributed with zero means, i.e. $\xi_{j,s}(k) \sim N\left(0,\left(\theta_{j,s}\overline{U}_{j,s}(k)\right)^{2}\right)$, where $\theta_{j,s}$ captures the perception variations of users on the activity utility. The value of parameter $\xi_{j,s}(k)$ reflects the familiarity degree of users to activity participation conditions.

Let $t_a(k)$ denote the actual link travel time and which is given by the bureau-public-road (BPR)-type link travel time function, i.e.

$$t_a(k) = \bar{t}_a\left(1.0 + 0.15\left(x_a(k)/C_a\right)^4\right), \tag{4.3}$$

where $\bar{t}_a$ is the free-flow travel time; $x_a(k)$ is the link flow at time interval $k$; and $C_a$ is the link capacity.

The perceived link travel time $\hat{t}_a(k)$, is given by the sum of the actual link travel time and the perception error on the travel time at time interval $k$:

$$\hat{t}_a(k) = t_a(k) + \xi_a(k), \tag{4.4}$$

where $\xi_a(k)$ is the perception errors on the link travel time. It is assumed that $\xi_a(k)$ is a random noise with finite support and follows a normally distribution with zero means, i.e. $\xi_a(k) \sim N\left(0, \left(\theta_a t_a(k)\right)^2\right)$, where $\theta_a$ captures the perception variations of users on the link travel time. The value of parameter $\xi_a(k)$ reflects the familiarity degree of users to traffic conditions.

Let $\hat{t}^p_{r,s}(k)$ denote the perceived route travel time of route *p* of departure at time interval *k* from origin *r* to destination *s*. The perceived route travel time is calculated using the nested function. Assume that $p = \{a_1, a_2, ..., a_n\}$, then $\hat{t}^p_{r,s}(k)$ can be expressed as

$$\hat{t}^p_{r,s}(k) = \hat{t}_{a1}(k) + \hat{t}_{a2}(k + \hat{t}_{a1}(k)) + ... + \hat{t}_{an}(k + \hat{t}_{a1} + \hat{t}_{a2} + ... + \hat{t}_{an-1}). \tag{4.5}$$

where $\hat{t}_{a1} = \hat{t}_{a1}(k)$, $\hat{t}_{a2} = \hat{t}_{a2}(k + \hat{t}_{a1}(k))$ ,..., for short. Equation (4.5) could be rewritten as

$$\hat{t}^{p}_{r,s}(k) = \sum_{a \ on \ route \ p} \sum_{l(\geq k) \in K} \hat{t}_{a}(l) \delta^{apk}_{rs}(l) . \tag{4.6}$$

Thus, the value (1 or 0) of $\delta^{apk}_{rs}(l)$ depends on both the topology of the transport network and traffic conditions on the network.

In view of A4.1 and A3.1, and to simplify the calculations without losing the essential ideas of this chapter, the perceived route travel time $\hat{t}^{p}_{r,s}(k)$ is measured in units of one time interval. If the perceived route travel time obtained by Equation (4.5) or (4.6) is not in integer times of one time interval, it should be replaced by its closest value which is in integer times of one time interval.

As discussed in Section 4.1, the normal distributions of the perception errors on compulsory activities, non-compulsory activities, and travel times are probably different. Let $\theta^{c}_{j,s}$ and $\theta^{nc}_{j,s}$ , respectively, indicates the perception variation on compulsory activities such as work and noncompulsory activities such as shopping. Usually, we have $\theta^{c}_{j,s} < \theta_{a} < \theta^{nc}_{j,s}$ .

### 4.3.2 THE DAILY ACTIVITY SCHEDULING PROBLEM

Let $\sigma$ denote the utility parameter of time. The perceived utility, $\hat{V}_{i}$, of taking DATP $i$ is the sum of the perceived utility obtained from activity participations minus the perceived disutility of travels, and is expressed as

$$\hat{V}_{i} = \sum_{j} \sum_{s} \sum_{k} \delta^{i,k}_{j,s} \hat{V}_{j,s}(k) - \sigma \sum_{r} \sum_{s} \sum_{k} \sum_{p} \delta^{i,k}_{r,s,p} \hat{t}^{p}_{r,s}(k) , \tag{4.7}$$

where $\delta_{j,s}^{i,k} = 1$ if the one-interval duration participation process of performing activity *j* at location *s* with the start time interval *k*, is included in DATP $i$, and otherwise $\delta_{j,s}^{i,k} = 0$ ; $\delta_{r,s,p}^{i,k} = 1$ if the travel departure from origin *r* to destination $s$ at time interval $k$ with route choice $p$, is included in DATP *i* and otherwise $\delta_{r,s,p}^{i,k} = 0$.

According to A4.3, the network SUE conditions of the daily activity scheduling problem can be given as follows:

***Definition 4.1*** *The DATP choices on the network reach SUE if the following conditions hold: No user can improve his perceived utility by unilaterally changing his DATP choice to any other feasible one.*

Definition 4.1 could be mathematically expressed as,

$$\hat{V}_i = \hat{\Pi}, \qquad if \qquad q_i > 0. \tag{4.8a}$$

$$\hat{V}_i \le \hat{\Pi}, \qquad if \qquad q_i = 0. \tag{4.8b}$$

where $\hat{\Pi} = \max_i \hat{V}_i$ is the perceived equilibrium utility of DATP choices.

## 4.4 THE MODEL

In this section, a SUE traffic assignment model which is equivalent to Equations (4.8) is formulated for examining the user daily activity scheduling problems in general road networks. Before that, the network constraints of the user daily activity scheduling problems are discussed.

### 4.4.1 NETWORK CONSTRAINTS

The constraint set for the user daily activity scheduling problem is summarized by the following Equations (4.9)-(4.18), and it is denoted by $\Omega I$ :

Flow conservation constraints at activity locations:

$$q_s^j(k) = \sum_i \delta_{j,s}^{i,k} q_i \ , \tag{4.9}$$

$$q_s(k) = \sum_j q_s^j(k) \cdot \tag{4.10}$$

Flow conservation constraints on road links:

$$q_{r,s}^i(k) = \sum_p \delta_{r,s,p}^{i,k} q_i = \sum_p q_{r,s}^{i,p}(k) \ , \tag{4.11}$$

$$q_{r,s}(k) = \sum_p f_{r,s}^p(k) = \sum_i q_{r,s}^i(k) \ , \tag{4.12}$$

$$f_{r,s}^p(k) = \sum_i q_{r,s}^{i,p}(k) \ , \tag{4.13}$$

$$x_a(k) = \sum_{rs} \sum_p \sum_{l(\le k) \in K} \delta_{rs}^{apl}(k) f_{r,s}^p(l) \ \cdot \tag{4.14}$$

Flow conservation constraint over the network and nonnegative constraints:

$$q = \sum_i q_i \ , \tag{4.15}$$

$$q_{r,s}^{i,p}(k) \ge 0 \ , \tag{4.16}$$

$$q_i \geq 0 \ . \tag{4.17}$$

From Equations (4.9)-(4.14), when Equation (4.16) and Equation (4.17) are effective, all flow variables are nonnegative.

For any DATP choice, the following time conservation constraint should be satisfied：

$$\sum_j \sum_s \sum_k \delta_{j,s}^{i,k} L + \sum_r \sum_s \sum_k \sum_p \delta_{r,s,p}^{i,k} \hat{t}_{r,s}^{p}(k) = T \qquad \forall i \tag{4.18}$$

where $T$ is the length of the study time horizon.

Note that the activity duration $\tau_{j,s}^{k}$ could be given by the following equation:

$$\begin{aligned} &\tau_{j,s}^{k} = \left(\delta_{j,s}^{i,k+1} + \delta_{j,s}^{i,k+2} \ldots + \delta_{j,s}^{i,k+n}\right) L \\ &\quad when\, \delta_{j,s}^{i,k+1} \ldots = \delta_{j,s}^{i,k+n} = 1, \delta_{j,s}^{i,k} = 0, \delta_{j,s}^{i,k+n+1} = 0, \qquad k \in [1, \overline{K} - n - 1] \end{aligned} \tag{4.19}$$

### 4.4.2 MODEL FORMULATION

Let $P_i$ represent the probability that a user on the network chooses DATP $i$. According to Equations (4.8) the user optimizes the DATP choice based on the maximum perceived utility, i.e.:

$$P_i = P\left(\hat{V}_i > \hat{V}_{\vec{i}} \mid \forall \vec{i} \in I, \vec{i} \neq i\right) . \tag{4.20}$$

The DATP choice demand is then given by

$$q_i = qP_i \qquad \forall i \ . \tag{4.21}$$

It can be inferred from Equations (4.3)-(4.7) and Equations (4.20)-(4.21), that DATP choice flow $q_i$ is a function of $\hat{V}_i$, which is a function of the perceived link travel times $\hat{t}_a(k)$, which are, in turn a function of $q_i$ in terms of Equations(4.11)-(4.14).As a result, the daily activity scheduling SUE problems of (4.8) is equivalent to a fixed-point problem as below. Let"*" denote the SUE condition.

***Theorem 4.1.*** *The DATP choices reach the SUE state if and only if it satisfies the following fixed-point formulation: find* $\mathbf{q}^* \in \Omega I$ *such that for all* $\mathbf{q} \in \Omega I$ *,*

$$\mathbf{q}^* = q\mathbf{P}\left(\hat{\mathbf{V}}\left(\hat{\mathbf{t}}(\mathbf{q}^*)\right)\right), \tag{4.22}$$

*where* $\mathbf{q}$ *is the vector of* $q_i$, $\mathbf{P}$ *is the vector of* $P_i$, $\hat{\mathbf{V}}$ *is the vector of* $\hat{V}_i$, *and* $\hat{\mathbf{t}}$ *is the vector of* $\hat{t}_a(k)$.

The existence of a solution to the fixed-point problem (4.22) can be easily proved. The indicator variable in Equation (4.5), however, depends on the link travel times, which in turn depend on the time-dependent link flow. Consequently, the route travel times are non-linear and non-convex. This means the fixed-point SUE model (4.22) is non-convex and multiple local solutions may exist (Chen and Hsueh 1998).

## 4.5 SOME FEATURES OF THE EQUILIBRIUM SOLUTION

In this section features of the SUE condition of user daily activity scheduling problems are discussed. The feature of route choices at the SUE condition in the daily activity scheduling problem is discussed below Proposition 4.1.

***Proposition 4.1.*** *At the SUE condition of the user* daily activity *scheduling problems, the route choice for each trip included in the DATPs, satisfies the following contention: no user can decrease his perceived trip time by unilaterally changing his route choice to any other feasible one, which is,*

$$\hat{t}_{r,s}^{p}(k) = \hat{\Gamma}_{r,s}(k), \qquad if \qquad f_{r,s}^{p}(k) > 0\,, \tag{4.23a}$$

$$\hat{t}_{r,s}^{p}(k) \geq \hat{\Gamma}_{r,s}(k), \qquad if \qquad f_{r,s}^{p}(k) = 0\,. \tag{4.23b}$$

*where* $\hat{\Gamma}_{r,s}(k) = \min_{p} \hat{t}_{r,s}^{p}(k)$ *is the equilibrium perceived trip time.*

***Proof.*** From A4.2 and A4.3, for each trip, users will pursue the route with the shortest perceived travel time and try to arrive at the destination as early as possible, so that they can obtain more perceived utility by allocating the saved time on activity participations. Thus, Proposition 4.1 holds. □

According to Proposition 4.1, Equation (4.7) could be rewritten as

$$\hat{V}_i = \sum_{j}\sum_{s}\sum_{k} \delta_{j,s}^{i,k} \hat{V}_{j,s}(k) - \sigma \sum_{r}\sum_{s}\sum_{k} \delta_{r,s}^{i,k} \hat{\Gamma}_{r,s}(k) \tag{4.24}$$

where $\delta_{r,s}^{i,k} = 1$ if the trip departure from origin $r$ to destination $s$ at time interval $k$, is included in DATP $i$ and $\delta_{r,s}^{i,k} = 0$ otherwise.

The features of activity choices and activity location choices at the SUE condition in the daily activity scheduling problem are discussed in Proposition 4.2 and Proposition 4.3.

Define

$$F_1\left[\chi(\omega),\rho_1,\rho_2\right]=\begin{cases}\sum_{\rho_1}^{\rho_2}\chi(\omega)d\omega, & \text{if } \overline{K} \text{ is an integer}\\ \int_{\rho_1}^{\rho_2}\chi(\omega)d\omega, & \text{if } \overline{K}\to\infty\end{cases}.$$

***Proposition 4.2.*** *In view of any three sequential activity and activity location choices{(j1,s1),(j2,s2),(j3,s3) } included in a DATP choice at the SUE condition , for* $\forall(j,s)$ *where* $j\neq j2$, $s\neq s2$, *we have that:*

*(i) if* $k+\hat{\Gamma}_{s1,s}(k)+\hat{\Gamma}_{s,s3}(k_2)<k'$,

$$\begin{aligned}F_1\left[\hat{V}_{j2,s2}(\omega),k+\hat{\Gamma}_{s1,s2}(k),k'-\hat{\Gamma}_{s2,s3}(k_1)\right]-\sigma\hat{\Gamma}_{s1,s2}(k)-\sigma\hat{\Gamma}_{s2,s3}(k_1)\geq\\ F_1\left[\hat{V}_{j,s}(\omega),k+\hat{\Gamma}_{s1,s}(k),k'-\hat{\Gamma}_{s,s3}(k_2)\right]-\sigma\hat{\Gamma}_{s1,s}(k)-\sigma\hat{\Gamma}_{s,s3}(k_2)\end{aligned};$$

*(ii) if* $k+\hat{\Gamma}_{s1,s}(k)+\hat{\Gamma}_{s,s3}(k_2)\geq k'$,

$$\begin{aligned}F_1\left[\hat{V}_{j2,s2}(\omega),k+\hat{\Gamma}_{s1,s2}(k),k'-\hat{\Gamma}_{s2,s3}(k_1)\right]-\sigma\hat{\Gamma}_{s1,s2}(k)-\sigma\hat{\Gamma}_{s2,s3}(k_1)\geq\\ F_1\left[\hat{V}_{j3,s3}(\omega),k+\hat{\Gamma}_{s1,s3}(k),k'\right]-\sigma\hat{\Gamma}_{s1,s3}(k_2)\end{aligned}.$$

*Note that* $k$ *denotes the departure time of the trip from s1 to s2, and* $k'$ *denotes the start time of participating activity j3 at location s3 in the DATP choice.* $k_1=k'-\hat{\Gamma}_{s2,s3}(k_1)$ *and* $k_2=k'-\hat{\Gamma}_{s,s3}(k_2)$.

***Proof.***

(i) If $k+\hat{\Gamma}_{s1,s}(k)+\hat{\Gamma}_{s,s3}(k_2)<k'$ : Since the sequential activity and activity location choices *{(j1,s1),(j2,s2),(j3,s3) }* of the DATP choice are the optimum choice, from

Definition 4.1 the utility of the activity sequence segment $\{(j1,s1),(j2,s2),(j3,s3)\}$ should not be less than the utility of the activity sequence segment $\{(j1,s1),(j,s),(j3,s3)\}$, *where* $j \neq j2$, $s \neq s2$ .Therefore, Proposition 4.2(i) holds.

(ii) If $k+\hat{\Gamma}_{s1,s}(k)+\hat{\Gamma}_{s,s3}(k_2) \geq k'$: users have no time to conduct activity *j* at *s,* since there is insufficient time for travelling from *s1*with the departure time *k*, passing location *s*, and finally arriving at location *s3* for participation in activity *j3* before time $k'$ . Thus they have to cancel activity *j,* and follow the activity sequence segment {(*j1, s1*), (*j3, s3*)}. From A4.2and Definition 4.1, the utility of the activity sequence segment $\{(j1,s1),(j2,s2),(j3,s3)\}$ should not be less than the utility of the activity sequence segment $\{(j1,s1),(j3,s3)\}$. Therefore Proposition 4.2(ii) *holds.*

This completes the proof of Proposition 4.2. □

***Proposition 4.3.*** *In view of any activity and activity location choice (j1,s1) at time interval k included in a DATP choice at the SUE condition, for* $\forall j$ *which available at location s1, we have that:*

*(i) when* $\overline{K}$ *is an integer:* $\hat{V}_{j1,s1}(k)=\max_{j}\left\{\hat{V}_{j,s1}(k)\right\}$;

*(ii) when* $\overline{K} \rightarrow \infty$: $u_{j1,s1}(k)+\frac{\partial \xi_{j1,s1}(\omega)}{\partial \omega}|_{k}=\max_{j}\left\{u_{j,s1}(k)+\frac{\partial \xi_{j,s1}(\omega)}{\partial \omega}|_{k}\right\}$.

***Proof.*** Proposition 4.3 is the special case of Proposition 4.2(i). Follow Proposition 4.2(i), and assume that *s2=s1,* for $\forall j$ where activity *j* is then, available at location *s1,* we have:

(i) when $\overline{K}$ is an integer: $\hat{V}_{j1,s1}(k) \geq \hat{V}_{j,s1}(k)$;

(ii) when $\overline{K} \rightarrow \infty$: $u_{j1,s1}(k)+\frac{\partial \xi_{j1,s1}(\omega)}{\partial \omega}|_{k} \geq u_{j,s1}(k)+\frac{\partial \xi_{j,s1}(\omega)}{\partial \omega}|_{k}$.

Hence Proposition 4.3 holds. □

The feature of departure time choice for each trip (or activity start/end time choice, or activity duration choice for each activity) at the SUE condition in the daily activity scheduling problem is discussed in Proposition 4.4.

Define

$$F_2[\chi(\omega),\rho_1,\rho_2]=\begin{cases}\sum_{\rho_1}^{\rho_2}\chi(\omega), & if \quad \rho_1<\rho_2\\ 0, & if \quad \rho_1=\rho_2\\ -\sum_{\rho_2}^{\rho_1}\chi(\omega), & if \quad \rho_1>\rho_2\end{cases},$$

and $F_3[\chi(\omega),\rho_1,\rho_2]=\begin{cases}\int_{\rho_1}^{\rho_2}\chi(\omega)d\omega, & if \quad \rho_1<\rho_2\\ 0, & if \quad \rho_1=\rho_2\\ -\int_{\rho_2}^{\rho_1}\chi(\omega)d\omega, & if \quad \rho_1>\rho_2\end{cases}.$

Let $(j1,s1)$ denote the activity and activity location of the start of the trip, and $(j2,s2)$ denote the activity and activity location of the end of the trip. Let $k_{-}$ and $k_{+}$ denote the time a little earlier and later than $k$ under the continuous time scenario.

***Proposition 4.4.*** *At the SUE condition, for each trip included in the DATPs where* $q_{s1,s2}(k)>0$*: in view of the departure time choice(i.e. the end time choice of the activity at the start of the trip, k), the marginal utility of participation in activity* $j1$ *and that utility of participation in activity* $j2$ *satisfy:*

*(i)* $$\begin{aligned}&\hat{V}_{j1,s1}(k-1)-\sigma\hat{\Gamma}_{s1,s2}(k)\ge\\&\qquad F_2\left[\hat{V}_{j2,s2}(\omega),k-1+\hat{\Gamma}_{s1,s2}(k-1),k+\hat{\Gamma}_{s1,s2}(k)\right]-\sigma\hat{\Gamma}_{s1,s2}(k-1)\end{aligned},$$

*and* $$\begin{aligned}&\hat{V}_{j1,s1}(k)-\sigma\hat{\Gamma}_{s1,s2}(k+1)\le\\&\qquad F_2\left[\hat{V}_{j2,s2}(\omega),k+\hat{\Gamma}_{s1,s2}(k),k+1+\hat{\Gamma}_{s1,s2}(k+1)\right]-\sigma\hat{\Gamma}_{s1,s2}(k)\end{aligned}.$$

*(ii) when* $\overline{K}\to\infty$*:*

$$u_{j1,s1}(k)+\frac{\partial\xi_{j1,s1}(\omega)}{\partial\omega}|_k\ge F_3\left[\hat{\hat{V}}_{j2,s2}(\omega),\hat{\Gamma}_{s1,s2}(k_-),\hat{\Gamma}_{s1,s2}(k)\right]-\sigma\hat{\Gamma}_{s1,s2}(k_-)+\sigma\hat{\Gamma}_{s1,s2}(k),$$

*and*

$$u_{j1,s1}(k)+\frac{\partial\xi_{j1,s1}(\omega)}{\partial\omega}|_k\le F_3\left[\hat{V}_{j2,s2}(\omega),\hat{\Gamma}_{s1,s2}(k),\hat{\Gamma}_{s1,s2}(k_+)\right]-\sigma\hat{\Gamma}_{s1,s2}(k)+\sigma\hat{\Gamma}_{s1,s2}(k_+)$$
.

*(iii) when* $s1=s2:\hat{V}_{j1,s1}(k)\le\hat{V}_{j2,s2}(k)$.

*(iv) when* $\overline{K}\to\infty$ *and* $s1=s2\ :u_{j1,s1}(k)+\frac{\partial\xi_{j1,s1}(\omega)}{\partial\omega}|_k=u_{j2,s2}(k)+\frac{\partial\xi_{j2,s2}(\omega)}{\partial\omega}|_k$.

***Proof.***

(i) Since $k$ is the optimal departure time of the trip, the departure at $k$ is not worse than departure at $k-1$ or departure at $k+1$, Proposition 4.4(i) then holds. Note that Proposition 4.4(i) could also be proved by discussing the optimum activity duration choice of activity *j1*.

(ii) By following Proposition 4.4(i), it is easy to demonstrate that Proposition 4.4(ii) holds.

(iii) When $s1=s2$, $k$ means the end time choice of activity *j1* or the start time choice of activity *j2*. From Definition 4.1, we have $\hat{V}_{j1,s1}(k)\le\hat{V}_{j2,s2}(k)$.

(iv) From Proposition 4.3(iii) and $\overline{K} \to \infty$, it is then seen that the marginal perceived activity utility at time $k$ should be equal to each other for these two sequential activities at the same location. Thus, Proposition 4.4(iv) holds.

This completes the proof of Proposition 4.4. □

## 4.6 SOLUTION ALGORITHM

In this section, a heuristic solution algorithm without the need of prior DATP enumeration is developed to solve the fixed-point problem (4.22), whereas explicit enumeration of DATPs are required in most of the existing activity-based stochastic studies. To avoid the requirement of all feasible DATP choice enumeration, an activity-chain network (ACN) generation approach is introduced.

### 4.6.1 ACTIVITY CHAIN NETWORK GENERATION APPROACH

In this section, the generation approach of an ACN is introduced. The topology of an ACN explicitly represents the relationships between activity choices and travel choices in the daily activity scheduling problems in general networks. Figure 4.1 shows an ACN construction based on the transport network of Figure 3.6. It should be pointed out that only a small number of the trip links are constructed and shown in Figure 4.1.

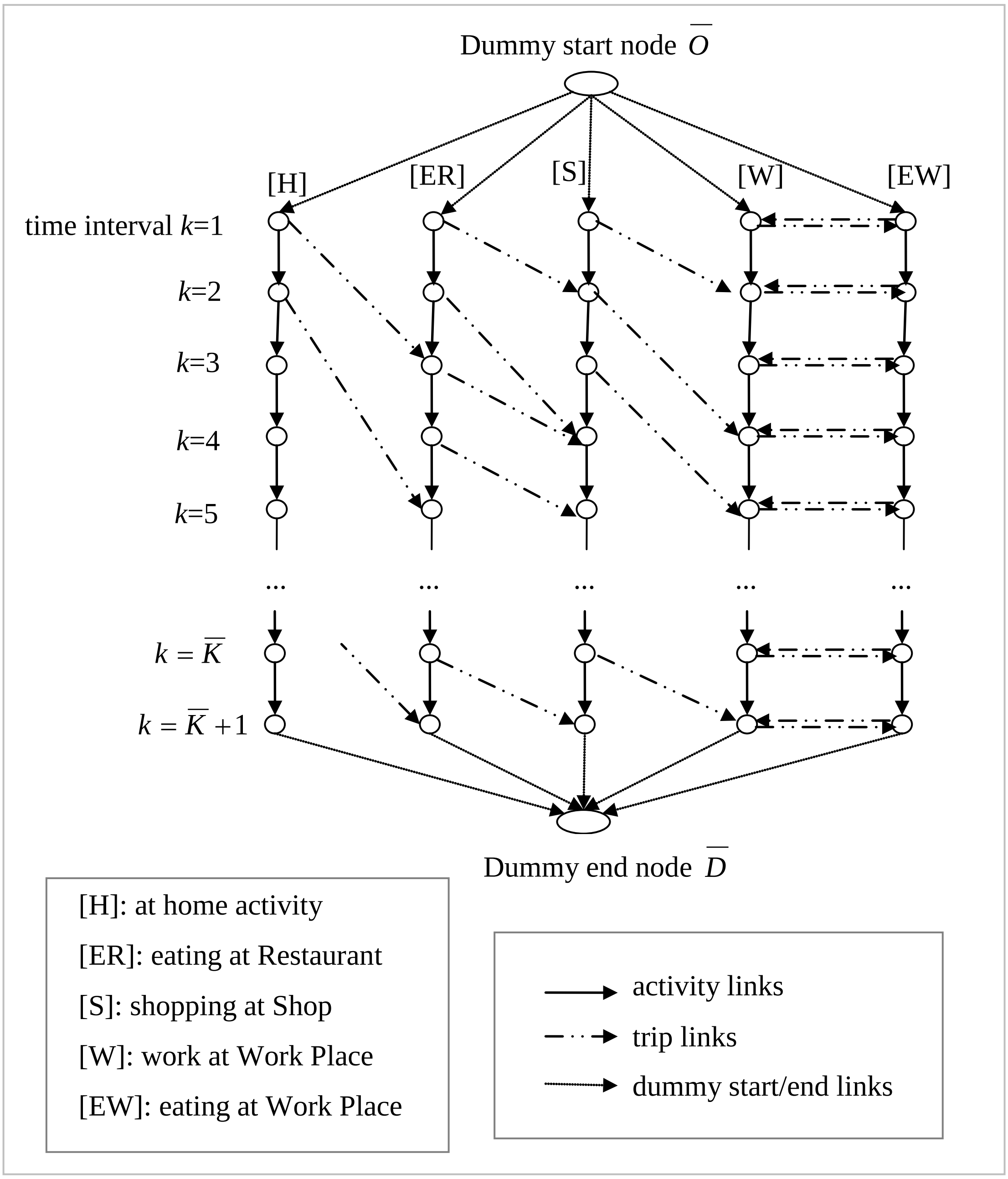


**Figure 4.1 An Illustrative Example of Activity Chain Network**

The ACN is constructed in such a way that each activity/location node is expanded to ($\overline{K}+1$) nodes, where $\overline{K}$ is the number of time intervals into which the whole study time horizon is equally divided. Each activity link represents one-interval activity participation process with the activity choice *j*, activity start time *k*, and activity location choice *s* and activity duration of one interval. Each trip link represents the travel process from the origin *r* to the destination *s* with departure time *k* but ignoring the specific route choice on the transport network. Note that the number of intervals crossed by a trip link equals the time-dependent equilibrium perceived trip time $\hat{\Gamma}_{r,s}(k)$ on the transport network. Dummy start/end links are employed to illustrate the entry/end process of the DATP choices.

It is not difficult to find that each path from the dummy start node $\overline{O}$ to dummy end node $\overline{D}$ on the ACN is a specific activity chain or a specific DATP that ignores route choices of trips. All feasible DATPs without consideration of route choices of trips are represented by the path set between $\overline{O}$ and $\overline{D}$.

It is also found that the values of $\delta_{j,s}^{i,k}$ and $\delta_{r,s}^{i,k}$ in Equation (4.24) indicate the connection relationship between links and paths on the ACN. If $\delta_{j,s}^{i,k} = 1$, the corresponding activity link which represents participation in activity *j* with the start time *k* at activity location *s* for one interval duration is included in the path which represents a DATP *i* with the ignorance of route choices; otherwise not included. If $\delta_{r,s}^{i,k} = 1$, the corresponding trip link representing the travel process from the origin *r* to the destination *s* with departure time *k* but ignoring the specific route choice on the transport network is included in the path representing DATP *i* with the ignorance of route choices; otherwise not included.

Users optimize DATPs to maximize their perceived utility value. This is operation is equivalent to a two-stage problem. The first stage is finding the path with the maximum perceived utility value from $\overline{O}$ to $\overline{D}$ on the ACN, then the optimum

DATP but ignoring the route choice problem of each trip in the DATP, is identified. The second stage is finding the route with the minimum perceived travel disutility on the base transport network for each trip. The route choice problem of each trip in the DATP is then solved. After following these two stages, the optimum DATP is identified.

The SPFA could be used to find the required path on the generated ACN in the first stage. The Dijkstra algorithm could be employed to find the required route on the transport network in the second stage. Thus, with the use of ACN generation approach, there is no need to enumerate all DATPs to find the optimum DATPs in the solution algorithms for solving user daily activity scheduling problems.

Note that the structure, of the generated ACN, changes with the equilibrium perceived trip time $\hat{\Gamma}_{r,s}(k)$. When the generated ACN is stable, and both the path choices on the stabilized ACN and route choices on the base transport network reach SUE conditions, the daily activity scheduling SUE condition is realized.

### 4.6.2 SOLUTION ALGORITHM

Based on the above introduced ACN generation approach, a heuristic solution algorithm without the need of enumerating all feasible DATPs is proposed to solve the fixed-point problem (4.22). The procedure of the heuristic algorithm is outlined as follows.

**Step 0.** Initialization.

Set $n = 1$. According to the free-flow travel time and given activity marginal utility functions, generate an ACN. Find the path with the maximum utility on the generated ACN by the SPFA and find the route with the minimum time-dependent travel time on the transport network by the Dijkstra algorithm for each trip required by the DATPs. The optimum DATP is then, obtained. Use the all-or-nothing method to assign the total population $q$ on the optimum DATP, and obtain the initial DATP choice demand $q_i^{(n)}$,

**Step 1.** Outer loop operation.

Set the sample number $z = 1$. Let $d'^{(z)}_i = q_i^{(n)}$.

**Step 2.** Inner loop operation (network loading loop).

***Step 2.1:*** Calculate the time-dependent link travel time at time interval $k$.

***Step 2.2:*** Perform the Monte Carlo Simulation by sampling the random link travel time and marginal activity utility, and the corresponding perception errors. Calculate the perceived activity utility and perceived travel disutility by Equation (4.3) and Equation (4.4).

***Step 2.3:*** Generate an ACN according to the perceived activity utility and perceived travel time.

***Step 2.4:*** Find the path with the maximum perceived utility on the generated ACN by SFPA and search the route with the minimum perceived time-dependent travel time on the transport network with the use of the Dijkstra algorithm for each trip required by the DATP. The optimum DATP is then, obtained.

***Step 2.5:*** Assign the total population on the optimum DATP by performing all-or-nothing loading, and then yield the auxiliary DATP flow pattern $\tilde{d}'^{(z)}_i$.

***Step 2.6:*** Update the DATP flow pattern, $d'^{(z+1)}_i = d'^{(z)}_i + \left(\tilde{d}'^{(z)}_i - d'^{(z)}_i\right)/z$.

**Step 3.** Convergence test for the inner loop operation.

If the sample number $z$ is less than a pre-specified sample size, set z = z+1, go to Step 2.1; otherwise, set $d'^{(n)}_i = d'^{(z)}_i$ and go to Step 4.

**Step 4.**Method of successive averages (MSA) replacement.

Update the DATP flow pattern, $q^{(n+1)}_i = q^{(n)}_i + \left(d'^{(n)}_i - q^{(n)}_i\right)/n$.

**Step 5.** Convergence test for the outer loop operation.

If the DATP choice SUE conditions (4.8) or equivalently the fixed-point problem (4.22) are satisfied, then stop; otherwise, set *n* = *n+1* and go to Step 1.

The above proposed solution algorithm without the requirement of DATP enumerations dramatically decrease the computation time for solving user daily activity scheduling problems while the algorithm requiring a prior enumeration of DATPs leads to burdensome computation of exponential-time growth. The dramatic decreased computation time of the solution algorithm promotes the potential application of the proposed model in analyzing user daily activity scheduling problems in practice.

Note that, in practice, the government and transport planners may only be interested in the resulting time-dependent flow on the activity location nodes and road links from user DATP choices, instead of the specific DATP choices. Thus, during the above iteration process of the solution algorithm, there is no need to record the optimum DATP choices. It is only necessary to assign and update the flow on the activity location nodes and road links according to the optimum DATP choices. The computational time of the solution algorithm for solving the daily activity scheduling problems is then further decreased.

## 4.7 THE SPECIAL CASE OF THE DAILY ACTIVITY SCHEDULING PROBLEM

As discussed in section 4.3.1, the perception error terms in Equation (4.2) and Equation (4.4) represent user familiarity degree to activity participation conditions and traffic conditions. Assume that the ideal case exists where users have perfect knowledge of activity participation conditions and traffic conditions over the network. In this special case, users have determined activity utility and travel disutility for their DATP choices. This means that the perception errors in Equation (4.2) and Equation (4.4) are equal to zero. The network equilibrium problem of user daily activity scheduling in this special case becomes a UE problem.

The UE conditions of the daily activity scheduling problem are given as follows:

***Definition 4.2*** *The DATP choices on the network reach UE if the following conditions hold: No user can improve his utility by unilaterally changing his DATP choice to any other feasible one.*

The daily activity scheduling UE problem is a special case of the daily activity scheduling SUE problem, where user activity utility and travel disutility perception errors are ignored. Thus, ①the proposed SUE model, ②the properties of the equilibrium flow at SUE condition, and ③ the developed solution algorithm discussed in this chapter could also be used for investigating user daily activity scheduling UE problems. However, the UE condition is an ideal case which probably does not exist in the real world, as discussed in Section 4.1.

## 4.8 NUMERICAL EXAMPLE

The purpose of the following numerical example is: (i) to illustrate the application of the proposed model and solution algorithm; (ii) to demonstrate the merits of the proposed SUE model by comparing the results with those of the UE model; (iii) by conducting a sensitivity analysis of the parameters of $\theta_{j,s}^{c}$, $\theta_{j,s}^{nc}$, and $\theta_a$ to show the merits of distinguishing the perception error variations onactivity utilities and travel disutility .

### 4.8.1 BASIC INPUT DATA

The entire study time period is from 6:00 to 24:00 equally divided into 108 intervals (i.e. 10 minutes per interval). The total population is assumed to be 2000. In this example, work is the compulsory activity. Shopping, eating and at home activity are noncompulsory activities. Let $\theta_{j,s}^{c} = 0.1$ and $\theta_{j,s}^{nc} = 0.6$ for $\forall j, s$. Let $\theta_a = 0.3$ for $\forall a$.

Suppose that $\sigma$ =HK$60/hour. The sample size in the Monte Carlo simulation is 2000.

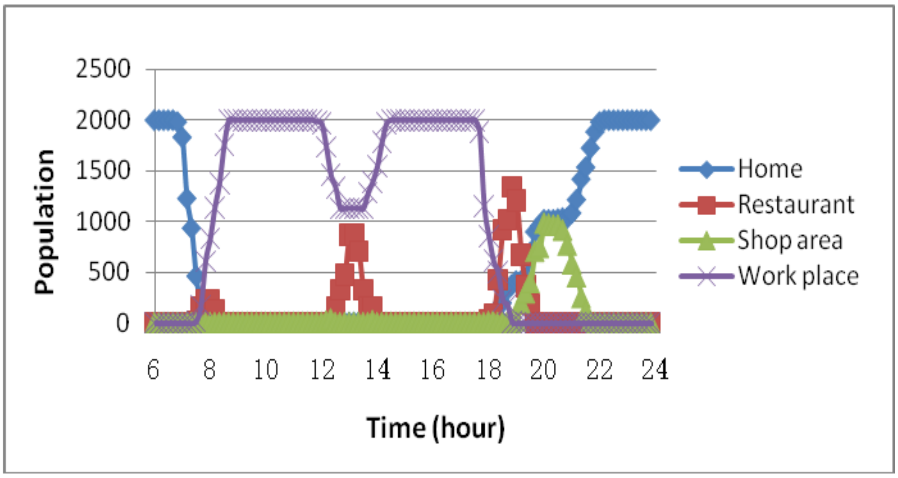
The simple road network, presented in Figure 3.6 of Chapter 3, is the network, considered. Assume that the free-flow travel times are 20 mins (i.e. 1/3 hour) and the link capacities are 1800 veh/hour for all links. Other input data, without special mention here, such as the feasible activity/location choice set, marginal activity utilities, and parking fees, are assumed to be the same as those given in Example 1 presented in Section 3.6 of Chapter 3. The case with the above settings is termed the "SUE base case".

### 4.8.2 COMPARISON OF THE RESULTS UNDER SUE AND UE CONDITIONS

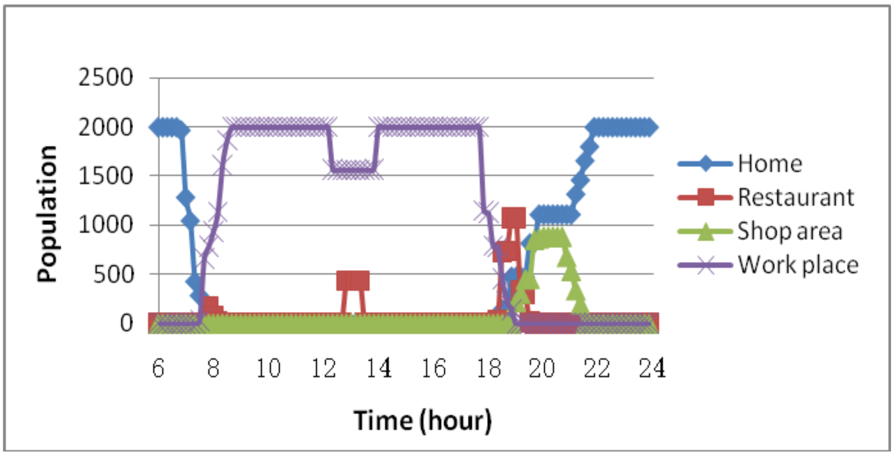
The SUE results are compared with those under the UE condition. In the UE, it is assumed that there are no perception errors on activity utilities and travel times. This means that $\theta_{j,s}^{c} = \theta_{j,s}^{nc} = \theta_{a} = 0$, for $\forall j, s, a$ .

Figure 4.2 presents the population distribution at activity locations of Home (“H”), Restaurant (“R”), Shop area (“S”), and Work place (“W”) during the study time period under the SUE and UE condition. It is noticed that the lines of the temporal population distribution at locations in Figure 4.2(a) drops or rises more smoothly than those lines shown in Figure 4.2(b). This implies that users have a greater variety of trip departure time choices, activity start time choices, and activity duration choices under the SUE condition than that available in the UE condition. From

Figure 4.2, it is also found that more users conduct eating activity and shopping activity in their DATP choices under the SUE condition than that under the UE condition.



**(a) SUE results**



**(b) UE results**

**Figure 4.2 The Temporal Population Distribution at Locations**

Characteristics, such as the equilibrium DATP utility and trip chain demands of the results under the SUE and UE conditions are summarized in Table 4.1. It should be noted that breakfast at “R”, lunch at “R”, supper at “R”, and supper at “W”, are regarded as individual out-of-home activities, while work in the morning and in the afternoon are regarded as one activity(i.e. work activity), as shown in Table 4.1.

**Table 4.1 Selected Characteristics of Daily Activity Scheduling Results**

| | SUE results | UE results |
|---|---|---|
| Average actual DATP utility (HK$/user) | **687.07** | **747.45** |
| Perceived equilibrium DATP utility (HK$/user) | **803.17** | N/A |
| Average number of out-of-home activities per user | **3.99** | **3.01** |
| Average number of trips per user | **4.86** | **3.55** |
| Percentage of travel demands for different trip chains | | |
| “H”-“R”-“W”-“R”-“W”-“R”-“S”-“H” | **42.90%** | 0.79% |
| “H”-“W”-“R”-“W”-“H” | **17.07%** | 3.97% |
| “H”-“R”-“W”-“R”-“S”-“H” | 8.64% | 2.38% |
| “H”-“W”-“R”-“S”-“H” | 8.27% | **13.89%** |
| “H”-“W”-“H” | 2.51% | **17.06%** |
| “H”-“W”-“R”-“H” | 0.05% | **22.62%** |
| “H”-“W”-“S”-“H” | 0.01% | **14.68%** |
| Others | 20.55% | 24.61% |

Note: 7.8 HK$=1.0 US$

Table 4.1 indicates that the average actual DATP utility (687.07HK$) per user under the SUE condition is lower than that (747.45HK$) under the UE condition, though the perceived equilibrium DATP utility per user(803.17HK$) under SUE condition is the highest. This is caused by the allowance of perception errors on activity utilities and travel times under the SUE condition. The allowance of perception errors prevents some users from selecting the ideal optimum DATP choices. It is found that the average number of out-of-home activities (3.99) and that number of trips (4.86) per user under the SUE condition are larger than those (3.01 and 3.55) under the UE condition. This suggests that users under the SUE condition are likely to schedule their DATPs with more activities and more journeys, while users under UE condition prefer to schedule their DATPs with fewer activities and fewer journeys in this example. This conclusion is consistent with that indicated by the statistics percentage of travel demands for different trip chains under the SUE and UE conditions.

### 4.8.3 SENSITIVITY ANALYSIS OF PERCEPTION VARIATION PARAMETERS

In this section, the results of cases which allow different perception variations on the utilities of compulsory activities and noncompulsory activities, and travel times are compared. The following three cases are considered: the SUE base case where $\theta_{j,s}^{c} < \theta_a < \theta_{j,s}^{nc}$ and $\theta_{j,s}^{c} = 0.1$, $\theta_{j,s}^{nc} = 0.6$ and $\theta_a = 0.3$ (Case I), the case where $\theta_{j,s}^{c} = \theta_{j,s}^{nc} < \theta_a$ and $\theta_{j,s}^{c} = 0.1$, $\theta_{j,s}^{nc} = 0.1$ and $\theta_a = 0.3$ (Case II), and the case where $\theta_{j,s}^{c} = \theta_{j,s}^{nc} > \theta_a$ and $\theta_{j,s}^{c} = 0.6$, $\theta_{j,s}^{nc} = 0.6$ and $\theta_a = 0.3$ (Case III).

The Daily activity scheduling results of the three cases are summarized in Table 4.2. Table 4.2 shows that the difference of the mean start time of activities among the three cases is wild. Table 4.2 also shows that the number of users who take the compulsory activity (i.e. work activity in this example) in their DATPs remains the same (i.e. 2000) in the three cases. In contrast, the number of users who take noncompulsory activities such as Lunch at “R” and shopping in their DATPs is different in the three cases. For example, the number of users who have lunch at “R” is 798 in Case I, while the number who have lunch becomes 696 in Case II and 1478 in Case III. These results are probably due to the different attributes of the compulsory and noncompulsory activities. Compulsory activities are those which users are required to perform in the user DATP choice, so that the number of users who take the compulsory activity may not change or only have a wild change when the values of perception variation parameters change. The noncompulsory activities are those which users have free choice as to whether perform or not. Then, the demands of noncompulsory activities probably change greatly in line with changes in the values of perception variation parameters.

**Table 4.2 Comparison of Characteristics of Daily Activity Scheduling Results**

| | | Activities | Case I (0.1,0.6,0.3)[1] | Case II (0.1,0.1,0.3) | Case III (0.6,0.6,0.3) |
|---|---|---|---|---|---|
| Start time | Mean (time o'clock) | Work | 8:22 | 8:20 | 8:12 |
| | | Lunch at “R” | 13:06 | 12:58 | 12:58 |
| | | Shopping | 19:46 | 19:47 | 19:46 |
| | Standard deviation (min) | Work | 39 | 47 | 58 |
| | | Lunch at “R” | **13** | **2** | 13 |
| | | Shopping | 17 | 14 | 17 |
| Duration | Mean (min) | Work | 533 | 539 | 529 |
| | | Lunch at “R” | 34 | 30 | 47 |
| | | Shopping | 100 | 89 | 100 |
| | Standard deviation (min) | Work | ***37*** | **46** | *55* |
| | | Lunch at “R” | 15 | 5 | 15 |
| | | Shopping | 18 | 16 | 18 |
| Population[2] | \ | Work | ***2000*** | ***2000*** | ***2000*** |
| | | Lunch at “R” | ***798*** | ***696*** | ***1478*** |
| | | Shopping | *1499* | *1335* | *1392* |

Note: 1, "(0.1, 0.6, 0.3)" represents the value of parameters $(\theta^{c}_{j,s}, \theta^{nc}_{j,s}, \theta_{a})$ for $\forall j, s, a$;
2, "Population" means the number of users who take the corresponding activity in the their DATP schedules.

Consider the results of Case I and Case II shown in Table 4.2. Note that the value of the perception variation parameter of the noncompulsory activities of Case II is 0.1 which appears to be an underestimation when compared to the 0.6 of Case I. From Table 4.2, it is found that in Case II, the standard variations of start time and duration as well as the mean duration of noncompulsory activities such as lunch at “R” and shopping are underestimated comparing to those of Case I. For example, the start time standard variation for lunch at “R” is 2 minutes of Case II while that standard variation is 13 minutes of Case I. In contrast, it is found that the standard deviations of start time and duration as well as the mean duration of compulsory activities such as work activity of Case II are overestimated comparing to those of Case I. For example, the standard deviation of duration of work is 46 minutes of Case II while that standard deviation is 37 minutes of Case I. These findings indicate that biased estimation of the value of the perception variation parameter on noncompulsory activities probably result in overestimated or underestimated results of user DATP choices.

A comparison of the results of Case I and Case III in Table 4.2 shows that a biased estimation of the value of the perception variation parameter on compulsory activities may also lead to biased results of user DATP choices. Note that the value of the perception variation parameter of compulsory activities of Case III is 0.6 which is an overestimation comparing to that of 0.1 of Case I. From Table 4.2, it can be seen that although in Case III the standard deviations of start time and duration of noncompulsory activities (shopping and lunch at “R”) are unchanged in comparison with those of Case I, the standard deviations of start time and duration of compulsory activity (work activity) are overestimated compared to those of Case I (e.g. the standard deviation of duration of work is 55 minutes of Case II while that standard deviation is 37 minutes of Case I).

Finally, the network performance of different values of perception variation parameters (where the values of $\theta_a$ and $\theta_{j,s}^{nc}$ change, and the value of $\theta_{j,s}^{c}$ keeps at 0.1) is investigated. It is seen in Figure 4.3 that the obtained equilibrium average

DATP utility per user increases with the decrease of the values of $\theta_a$ and $\theta_{j,s}^{nc}$. This means that the government may improve the network performance (i.e. increase user equilibrium DATP utility) by offering high quality traffic condition information and network activity participation conditions to users, as such offered information decreases the values of $\theta_a$ and $\theta_{j,s}^{nc}$.

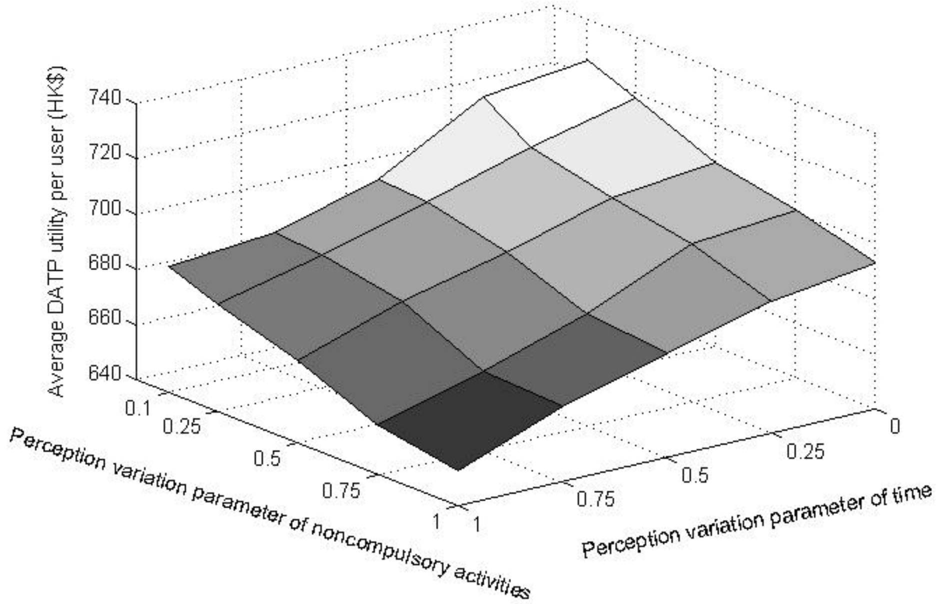


**Figure 4.3 Average DATP Utility under Different Values of Different Perception Variation Parameter Values**

## 4.9 SUMMARY

In this chapter, a SUE model for dealing with the user daily activity scheduling problems in general road networks has been proposed. The proposed model was formulated as an equivalent fixed-point problem. The properties of the equilibrium flow have been investigated. A novel approach for generating activity chain networks (ACNs) has been introduced. With the generated ACNs, a solution algorithm that allows an automatic generation of DATPs has been developed to solve the daily activity scheduling problem. The proposed model and solution algorithm could help the understanding of the interactions between activity choices and travel choices in user daily activity scheduling problems.

Similar to the study of Chapter 3, the study presented in this chapter should also not be confined to the constraints of the ignorance of congestion problems at activity locations, and flexible durations for all activities while sometimes existing activities with fixed durations (e.g. 8 hours for work) in practice. It is easy to extend the study of this chapter to deal with relevant activity scheduling problems where these constraints are relaxed.

Based on the results of the above numerical studies, the following main findings were obtained:(i) The estimation of user daily activity scheduling behaviour might be biased if the users' perception errors on activity utilities and travel disutility are ignored; (ii) A distinction should be made among the perception error variations on compulsory activity utility, noncompulsory activity utility and travel time when examine user daily activity scheduling problems, otherwise, results of DATP choices might be overestimated or underestimated.

In summary, the stochastic model proposed in this chapter provided a powerful tool for better understanding user daily activity scheduling behaviour. However, it should be pointed out that the model proposed and described in this chapter assumed that users’ daily activity scheduling was based on the given residential and employment locations. Considering the close interactions among user residential/employment location choices, activity choices and travel choices discussed in Chapter 2, the work described in this chapter could be extended to investigate user residential location choices and DATP choices simultaneously. In the next chapter, such extension work is introduced.

## 4.10 COMPARISONS BETWEEN THE ATS NETWORK EXPANSION APPROACH AND ACN EXPANSION APPROACH

In this chapter, a solution algorithm based on the ACN expansion approach was proposed. In Chapter 3, a solution algorithm based on an approach named as ATS network expansion approach was developed. Both the ATS network expansion approach and the ACN expansion approach are super-network approaches and designed for dealing with user activity scheduling network problems. With either one of these two approaches, the relationships between user travel choices and activity choices could be explicitly represented, and coordination of time and space in user ATP/DATP choices could also be explicitly captured. With the use of these two approaches, efficient solution algorithms without the requirement of prior ATP/DATP enumerations were developed for solving user activity scheduling problems.

The performance of the solution algorithms based on these two approaches, the application situations, and the characteristics of the two approaches, however, are different. The following three aspects of the ATS network expansion approach and ACN expansion approach are compared and given below:

### *(1) Application situations*

The ATS network expansion approach is designed for studying user activity scheduling problems for congested road networks with queues. Users' road link travel time is the summation of the free-flow link travel time and queuing time on the road link. Users' queuing behaviour which is caused by the limited road capacity, is denoted by the flow on the queue links of the ATS network. The ACN expansion approach is proposed for investigating user activity scheduling problems in general road networks. Users' road link travel time is obtained through any one type of functions accepted by transport researchers and practitioners for calculating road link travel times (for example, the BPR function).

### *(2) Characteristics of ATS networks and ACNs*

(2.1) An ATS network includes three kinds of nodes (expanded nodes based on nodes of the base network, expanded nodes based on the road links of the base network, and dummy start/end nodes) and five kinds of links (activity links, travel links, queue links, exit links and dummy start/end links). An ACN includes two kinds of nodes (expanded nodes based on nodes of the base network, and dummy start/end nodes) and three kinds of links (activity links, trip links and dummy start/end links). Each path from the dummy start node to the dummy end node in the ATS network represents a specific ATP in the study time horizon. Each path from the dummy start node to the dummy end node in the ACN represents a specific activity chain (i.e. an ATP except the specific route choice of each trip included in the ATP is unknown) in the study time horizon.

(2.2) The work of constructing an ATS network is heavier than the work required when generating an ACN for the same base transport road network since many more queue links, exit links and expanded nodes have to be constructed for such a network.

(2.3) The topology of the ATS network is fixed once it is constructed. In contrast, the ACN topology always changes during the iterations of the solution algorithm since trip links of the ACN should be re-constructed when trip times change.

***(3) The performances of the solution algorithm developed in Chapter 3 which is based on the ATS network expansion approach and the solution algorithm proposed in Chapter 4 which is based on the ACN expansion approach***

(3.1) Computational time: The computational time required by the solution algorithm proposed in Chapter 4 is usually less than the computational time needed by the solution algorithm developed in Chapter 3 for solving user activity scheduling problems of the same size of base transport network. For example, the computational time for solving the base case problem of the numerical example presented in Chapter 4 is around 3 minutes (in addition, the time taken for solving the UE problem of that numerical example is just around 1 minute), while the computational time for solving the base case problem of the numerical example presented in Chapter 3 is about 36 minutes. The longer computational time of the latter has two possible main reasons. They are as follows: ①The size of the expanded ATS network is much bigger than that of the expanded ACN, for the same size of base transport road network, because a greater number of nodes and links have to be constructed for a ATS network (refer to the above (2.2) ). This leads to the solution algorithm which is based on ATS network expansion approach and developed in Chapter 3, requires much more time to search optimum ATPs/DATPs in iterations. ② The solution algorithm developed in Chapter 3 needs to reach re-equilibrium after the decreasing parameter $\zeta$ ($0<\zeta<1$) is justified in each iteration of the outer loop. The number of justification iterations makes the computation time increase exponentially.

(3.2) Accuracy level and convergence: The performance of the accuracy level and convergence of the solution algorithm developed in Chapter 3 with ATS networks is generally better than that of the solution algorithm proposed in Chapter 4 with ACNs. The topology of the ATS network is fixed during the iterations of the solution algorithm. The activity scheduling problem is transferred to a traditional static traffic assignment problem. The accurate and convergent equilibrium solution could be obtained by the application of the solution algorithm developed in Chapter 3. However, the topology of ACN always changes during the iterations of the solution algorithm. Therefore, only a close equilibrium solution is achieved by the application of the solution algorithm proposed in Chapter 4. Furthermore, this solution may not converge when the traffic on the network is very congested because the topology of ACN may not be stable despite the number of iterations undergone.

(3.3) FIFO principle: The FIFO property holds in the ATS network at equilibrium solutions, while that property cannot be guaranteed in the ACN at equilibrium solutions since the specific route choice and road link choice of each trip could not be captured in the ACN.

# 5 AN ACTIVITY-BASED NETWORK STOCHASTIC USER EQUILIBRIUM MODEL FOR COMBINED RESIDENTIAL LOCATION AND TRAVEL CHOICES

Chapter 3 and Chapter 4 were devoted to developing activity-based transport models to enable better understanding user travel choice behaviour. The interactions between user daily activity choices and user daily travel choices (i.e. user daily activity scheduling problem) were examined. This chapter focuses on the exploration of an activity-based land use and transport model to enable better understanding of both user travel choice behaviour and user residential location choice behaviour. To achieve this, the relationships between user long-term residential location choices and user short-term daily activity scheduling, are investigated in road networks.

## 5.1 INTRODUCTION

User residential location selection is usually based on a tradeoff between the location selection cost such as housing price/rent and the location attributes such as size, green environment, and transport accessibility of the location (Boyce, 1986; Meng et al., 2000; Maat et al., 2005; Chang and Mackett, 2006). However, without the analysis of user daily activity scheduling problems, it is difficult to determine the impact of each residential location attribute (such as size, green environment, and transport accessibility) in influencing user residential location selection decisions. There are close interrelationships between user residential location choices and user daily activity/travel choices (Bhat et al., 2013).

It is generally believed that the most important purpose of user residential location selection is to enable the conduct of at home activity such as sleeping and eating, as comfortable as possible. The degree of comfort depends on the residential location attributes such as size, and green environment. Another critical purpose of user residential location selection is to enable the participation in needed/desired out-of-home activity such as work and shopping as convenient as possible. The convenience is largely determined by the transport accessibility. At home activities, out-of-home activities, and generated travels within a day constitute a DATP (For the definition of DATP, refer to Definition 3.1). The attractiveness of the attributes of a residential location relates to the degree of utility obtained from their DATP choices within that residential location.

In this chapter, an activity-based model is developed for the combined user residential location and travel choice analysis. In the developed model, user residential location choice is based on the consideration of users' tradeoff between the residential location selection cost and the utility of their optimum DATP choices (i.e. results of user daily activity scheduling) within the selected location.

The major contributions of this chapter are as follows: (1) the development of an activity-based equivalent optimization model for dealing with user residential location choice problems, (2) the proposal of a UE model for investigating the multi-class user daily activity scheduling problems, (3) the formulation of a SUE model presented as a fixed-point problem for studying combined user residential location and travel choice problems and, (4) the exploration of a solution algorithm to solve the combined user residential location and travel choice problems.

The remainder of this chapter is organized as follows. Basic assumptions are given in Section 5.2. User residential location choice problem and the multi-class user daily activity scheduling problem are discussed in Section 5.3. A SUE model is formulated for considering combined user residential location and travel choice problems and is given in Section 5.4. In Section 5.5, a solution algorithm is developed for solving the combined problems. In Section 5.6, a numerical example is presented to illustrate the application of the proposed model and solution algorithm. Finally, conclusions are drawn and suggestions for further research are given in Section 5.7.

## 5.2 ASSUMPTIONS

To facilitate the presentation of the essential ideas of this chapter, the following basic assumptions are made for the model developed in this chapter.

A5.1 Assumptions A3.1, A3.3, and A3.5 given in Chapter 3, are carried on into this chapter.

A5.2 Residential location choice is a household choice problem, but for simplicity it is assumed that the household behaves as a representative user (Boyce and Mattsson, 1999; Maat et al., 2005).

A5.3 Residential location choice is a long-term decision; hence the average daily cost / benefit of the residential location selection are considered (Meng et al., 2000). The average daily cost is the daily housing price/rent while the average daily benefit is the utility obtained from user DATP choice based on the selected residential location (Herz, 1983).

A5.4 It is assumed that the considered household representative users are all workers. The employment locations of the workers are assumed to be exogenously given (Yang and Meng, 1998a; Boyce and Mattsson, 1999). Workers with different values of time (VOT) are distinguished. It is further assumed that the vehicle occupancy is assumed to be one user per vehicle (Yang and Meng, 1998a; Boyce and Mattsson, 1999; Lam and Yin, 2001).

## 5.3 THE COMBINED RESIDENTIAL LOCATION AND TRAVEL CHOICE PROBLEM

### 5.3.1 THE RESIDENTIAL LOCATION CHOICE SUB PROBLEM

Assume that user residential location choice is made on the tradeoff between the cost of selecting a residential location as home and the utility obtained from the optimum

DATP choices under the selected residential location. The user choice also follows the random utility theory which means that each user chooses the residential location with the maximum expected utility. The aggregate user choices then, result in a stochastic equilibrium. The definition of the residential location choice at SUE condition is given.

***Definition 5.1.*** *Residential location choices over the urban network reach SUE condition if the following conditions hold: no household of each household group can improve his perceived utility by unilaterally changing his residential location choice to any other feasible one.*

Let $r_h$ represent the average daily housing price/rent for residing at location $h$. Define a cost function $r_h = r_h(q_h, S_h)$ for each residential location $h$, where $q_h$ is the demand of households who choose to reside at location $h$, and $S_h$ is the given supply number of alternative housing units at location $h$. It is assumed that the cost function $r_h(q_h, S_h)$ is a monotonic increasing function with the demand $q_h$. Let $m$ represent a household group (i.e. user class). Let $\Pi_{mh}$ denote the equilibrium utility of the DATP choice on a typical day based on the selected residential location $h$ for households in group $m$. The equilibrium utility $\Pi_{mh}$ is given by solving the multi-class daily activity scheduling sub problem discussed in the next section. The utility, $U_{mh}$, of selecting residential location $h$ for households in group $m$ is calculated by

$$U_{mh} = -\alpha_m r_h(q_h, S_h) + \Pi_{mh} \tag{5.1}$$

where $\alpha_m$ is the utility unit of money for household group *m* (Boyce and Mattsson, 1999).

The perceived utility of selecting residential location *h* for households in group *m* is

$$\hat{U}_{mh} = U_{mh} + \xi_{mh} \tag{5.2}$$

where $\xi_{mh}$ is an independently random part which follows the distribution of Gumbel distribution with a mean 0 and standard deviation $\frac{\pi}{\sqrt{6\theta}}$.

From the random utility theory, the probability of households in group $m$ resides at location $h$ is

$$P_{h/m} = \frac{\exp \theta U_{mh}}{\sum_h \exp \theta U_{mh}}. \tag{5.3}$$

Let $q_m$ denote the number of households in group $m$. The demands of households in group $m$ residing at location $h$, $q_{mh}$, is

$$q_{mh} = q_m P_{h/m}, \forall m \tag{5.4}$$

Considering that $\sum_h P_{h/m} = 1$, for $\forall m$, follows Equation (5.4), we then obtain the following population conservation constraint for each group.

$$q_m = \sum_h q_{mh}, \forall m. \tag{5.5}$$

The total demands of users residing at location $h$, $q_h$, can be estimated by

$$q_h = \sum_m q_{mh}, \forall h. \tag{5.6}$$

Assume that the total number of households needing to be located is $q$, the total population conservation constraint is then expressed as

$$\sum_h q_h = q. \tag{5.7}$$

In addition, the total demands of households at each residential location should satisfy the following house supply capacity constraint

$$q_h \le S_h \ \ \forall h. \tag{5.8}$$

***Theorem 5.1.*** *The SUE problem of the residential location choices is equivalent to the following optimization problem:*

$$\max_{q_{mh}} Z = -\frac{1}{\theta}\sum_m \sum_h q_{mh}\left(\ln q_{mh} - 1\right) + \sum_m \sum_h \int_0^{q_{mh}} U_{mh}(\omega) d\omega, \tag{5.9}$$

*subject to $\Omega II$, where $\Omega II$ denotes the constraint set of Equations (5.5-5.8).*

**Proof.** For the proof, the reader is referred to Sheffi (1985) on the model formulation for the logit-based SUE traffic assignment problem. □

According to problem (5.9), the residential location choice SUE condition of Definition 5.1 can be formulated as

$$-\frac{1}{\theta}\ln q_{mh} + U_{mh} - \gamma_h = \hat{b}_m \qquad if\ q_{mh} > 0, \tag{5.10a}$$

$$-\frac{1}{\theta}\ln q_{mh} + U_{mh} - \gamma_h \le \hat{b}_m \qquad if\ q_{mh} = 0, \tag{5.10b}$$

where $\hat{b}_m = \max_h \left\{ -\frac{1}{\theta} \ln q_{mh} + U_{mh} - \gamma_h \right\}$ is the maximum perceived utility of the feasible residential location choice of households in group $m$ at SUE condition (i.e. the equilibrium perceived utility), and $\gamma_h$ is the Lagrange multiplier associated with capacity constraints of Equation (5.8).

### 5.3.2 THE MULTI-CLASS DAILY ACTIVITY SCHEDULING SUB PROBLEM

In this section, the problem of household DATP choice is investigated. Assume the aggregate household DATP choices result in a UE problem. It is worth noting that at home activity is only effective at households' selected residential locations and work activity is also only effective at their given employment locations. Since, for users with different groups $m$ and/or different residential location choices $h$, the utilities of the activity participations at the same activity location with the same activity start time and activity duration may be different, the DATP choice problem is a multi-class problem. The definition of the multi-class DATP choice equilibrium condition is given below.

***Definition 5.2.*** *The multi-class DATP choices reach UE condition if the following conditions hold: no household of each household group can improve his utility by unilaterally changing his DATP choice to any other feasible one.*

Let $\overline{U}_{j,s}^{mh}(k)$ denote the utility of performing activity *j* at location *s* for one interval with a start time interval *k* of households in group $m$ with residential location $h$. It can be calculated by

$$\overline{U}_{j,s}^{mh}(k)=\int_{k}^{k+1} u_{j,s}^{mh}(\omega)d\omega, \tag{5.11}$$

where $u_{j,s}^{mh}(k)$ denotes the marginal utility of the participation of activity *j* at location *s*, at time interval *k* of households in group $m$ with residential location $h$.

Let $t_a(k)$ denote the link travel time which is given by the BPR-type link travel time function, i.e.

$$t_a(k)=\bar{t}_a\left(1.0+0.15\left(x_a(k)/C_a\right)^4\right), \tag{5.12}$$

where $\bar{t}_a$ is the free-flow travel time; $x_a(k)$ is the time-dependent link flow; and $C_a$ is the link capacity.

Let $t_{r,s}^{p}(k)$ denote the route travel time of route $p$ of departure at time interval $k$ from origin $r$ to destination $s$. Assume that $p=\{a_1,a_2,...,a_n\}$, $t_{r,s}^{p}(k)$ can then be expressed as

$$t_{r,s}^{p}(k)=t_{a1}(k)+t_{a2}(k+t_{a1}(k))+...+t_{an}(k+t_{a1}+t_{a2}+...+t_{an-1}), \tag{5.13}$$

where $t_{a1}=t_{a1}(k)$, $t_{a2}=t_{a2}(k+t_{a1}(k))$,..., in short form. Equation (5.13) could be rewritten as

$$t_{r,s}^{p}(k)=\sum_{a \quad on \quad pat \quad p}\ \sum_{l(\geq k)\in K} t_a(l)\delta_{rs}^{apk}(l), \tag{5.14}$$

where $\delta_{rs}^{apk}(l)=1$ if the flow from origin *r* to destination *s* entering route $p$ at interval *k* and arriving link *a* at interval *l*; otherwise $\delta_{rs}^{apk}(l)=0$. Thus, the value (1 or 0) of

$\delta_{rs}^{apk}(l)$ depends on both the topology of the transport network and traffic conditions on the network.

In view of A5.1 and A3.1, to simplify the calculations without losing the essential points in this chapter, the route travel time $t_{r,s}^{p}(k)$ is measured in units of one time interval. If the route travel time obtained by Equation (5.13) or Equation (5.14) is not in integer times of one time interval, it should be replaced by its closest value which is in integer times of one time interval.

Let $\sigma^{m}$ denote the utility parameter of one minute for households in group *m*. The utility, $V_i^{mh}$, of DATP $i$ for households in group $m$, with residential location $h$, is the sum of the utility obtained from activity participations in the DATP minus the disutility of generated travels in the DATP, which is expressed as

$$V_i^{mh} = \sum_j \sum_s \sum_k \delta_{j,s}^{i,k} \overline{U}_{j,s}^{mh}(k) - \sigma^m \sum_r \sum_s \sum_k \sum_p \delta_{r,s,p}^{i,k} t_{r,s}^{p}(k) \tag{5.15}$$

In Equation (5.15), $\delta_{j,s}^{i,k} = 1$ if the one-interval duration participation process of performing activity *j* at location *s* with the start time interval *k*, is included in DATP $i$, and $\delta_{j,s}^{i,k} = 0$ otherwise. In addition, in Equation (5.15), $\delta_{r,s,p}^{i,k} = 1$ if the travel departure from origin $r$ to destination $s$ at time interval $k$ with route choice $p$, is included in DATP $i$, and $\delta_{r,s,p}^{i,k} = 0$ otherwise.

Let $q_i^{mh}$ denote the number of households in group *m* with residential location *h*, who take DATP *i*. Let $q_{r,s}^{mh,i}(k)$ denote the flow in group *m* with residential location *h* departure from origin $r$ to destination $s$ at time interval $k$ and in DATP $i$. Let $q_{r,s}^{mh,i,p}(k)$ denote the flow in group $m$ with residential location $h$ choosing route p, departure from origin $r$ to destination $s$ at time interval $k$ and in DATP $i$. Let $q_{r,s}^{mh}(k)$ denote the flow in group $m$ with residential location $h$ departure from origin $r$ to destination $s$ at time interval $k$. Let $q_{j,s}^{mh}(k)$ be the flow in group $m$ with residential location $h$, who conducts activity $j$ at location $s$ at time interval $k$, and $q_{s}^{mh}(k)$ denote the flow in group $m$ with residential location $h$ at location $s$ at time interval $k$. Let $q_s(k)$ denote the total node flow at activity location $s$ at time interval $k$.

Let $f_{r,s}^{mh,p}(k)$ be the route flow in group $m$ with residential location $h$ at time interval $k$ on route $p$ which connects origin $r$ to destination $s$. Let $x_a^{mh}(k)$ be the link flow in group $m$ with residential location $h$ on link $a$ at time interval $k$. Let $x_a(k)$ be the total link flow on link $a$ at time interval $k$. Let $T$ be the length of the study time horizon of the DATP choice problem.

The constraint set for the multi-class DATP scheduling problem is summarized as follows (Equations 5.16-5.20), and is denoted by $\Omega III$ .The constraint set includes the flow conservation constraint on activity locations (Equations 5.16), the flow conservation constraints on road links (Equations 5.17-5.18), the flow conservation constraint over the network (Equation 5.19), the time conservation constraint of each DATP choice(Equation 5.20), and nonnegative constraints (Equations 5.21):

$$q_{j,s}^{mh}(k) = \sum_i \delta_{j,s}^{i,k} q_i^{mh} , \tag{5.16a}$$

$$q_s^{mh}(k) = \sum_j q_{j,s}^{mh}(k), \tag{5.16b}$$

$$q_s(k) = \sum_m \sum_h q_s^{mh}(k) . \tag{5.16c}$$

$$q_{r,s}^{mh,i}(k) = \sum_p \delta_{r,s,p}^{i,k} q_i^{mh} , \tag{5.17a}$$

$$q_{r,s}^{mh,i}(k) = \sum_p q_{r,s}^{mh,i,p}(k) , \tag{5.17b}$$

$$f_{r,s}^{mh,p}(k) = \sum_i q_{r,s}^{mh,i,p}(k) , \tag{5.17c}$$

$$q_{r,s}^{mh}(k) = \sum_p f_{r,s}^{mh,p}(k) = \sum_i q_{r,s}^{mh,i}(k), \tag{5.18d}$$

$$x_a^{mh}(k) = \sum_{rs} \sum_p \sum_{l(\le k)\in K} \delta_{rs}^{apl}(k) f_{r,s}^{mh,p}(l) . \tag{5.18e}$$

$$x_a(k) = \sum_m \sum_h x_a^{mh}(k) . \tag{5.18f}$$

$$q_{mh} = \sum_i q_i^{mh} . \tag{5.19}$$

$$\sum_j \sum_s \sum_k \delta_{j,s}^{i,k} L + \sum_r \sum_s \sum_k \sum_p \delta_{r,s,p}^{i,k} t_{r,s}^{p}(k) = T \tag{5.20}$$

$$q_{r,s}^{mh,i,p}(k) \ge 0 , \tag{5.21a}$$

$$q_i^{mh} \ge 0 . \tag{5.21b}$$

From Equations (5.16)-(5.19), when Equations (5.21) are effective, all flow variables are non-negative.

Definition 5.2 could be mathematically expressed as,

$$V_i^{mh} = \Pi_{mh}, \qquad if \qquad q_i^{mh} > 0, \tag{5.22a}$$

$$V_i^{mh} \le \Pi_{mh}, \qquad if \qquad q_i^{mh} = 0, \tag{5.22b}$$

where $\Pi_{mh} = \max_i V_i^{mh}$ is the equilibrium utility of DATP choices for household group *m* with residential location *h*.

Define $P_i^{mh} = q_i^{mh} / q_{mh}$. It can be inferred that, with the given $q_{mh}$, the DATP choice flow $q_i^{mh}$ is a function of $V_i^{mh}$ in terms of Equations (5.22); and $V_i^{mh}$ is a function of the link travel times $t_a(k)$ in terms of Equation (5.15) and Equation (5.14); in turn, $t_a(k)$ is a function of $q_i^{mh}$ in terms of Equations (5.12) and (5.16)-(5.18). As a result, the multi-class DATP choice problem leads to a fixed-point problem as below. Let "*" denote the equilibrium state.

***Theorem 5.2.*** *For the given* $q_{mh}$*, the multi-class DATP choices reach the UE state if and only if it satisfies the following fixed-point formulation: find* $\mathbf{q}^{mh*} \in \Omega III$ *such that for all* $\mathbf{q}^{mh} \in \Omega III$,

$$\mathbf{q}^{mh} * = \vec{\mathbf{q}} \mathbf{P}^{mh}\left(\mathbf{V}^{mh}\left(\mathbf{t}(\mathbf{q}^{mh*}, k)\right)\right), \qquad (5.23)$$

*where* $\mathbf{q}^{mh}$ *is the vector of* $q_i^{mh}$*;* $\vec{\mathbf{q}}$ *is the vector of* $q_{mh}$*;* $\mathbf{P}^{mh}$ *is the vector of* $P_i^{mh}$*;* $\mathbf{V}^{mh}$ *is the vector of* $V_i^{mh}$ *and;* $\mathbf{t}$ *is the vector of* $t_a(k)$.

## 5.4 MODEL FORMULATION OF THE COMBINED RESIDENTIAL LOCATION AND TRAVEL CHOICE PROBLEM

It can be inferred that, the residential location choice flow $q_{mh}$ is a function of $\Pi_{mh}$ in terms of Equations (5.1)-(5.4); and $\Pi_{mh}$ is a function of the link travel times $t_a(k)$ in terms of Equation (5.14), (5.15) and (5.22); in turn, $t_a(k)$ is a function of $q_i^{mh}$ in terms of Equations (5.12), and (5.16)-(5.18); and $q_i^{mh}$ is a function of $q_{mh}$ in terms of Equation (5.23). As a result, the combined user residential location and travel choice problem leads to a fixed-point problem as below.

***Theorem 5.3.*** *The combined residential location and travel choices reach the SUE state if and only if it satisfies the following fixed-point formulation: find* $\vec{\mathbf{q}}^* \in \Omega II$ *and* $\mathbf{q}^{mh*} \in \Omega III$ *such that for all* $\vec{\mathbf{q}} \in \Omega II$ *and* $\mathbf{q}^{mh} \in \Omega III$,

$$\vec{\mathbf{q}}^* = q\vec{\mathbf{P}}\left(\vec{\mathbf{\Pi}}\left(\mathbf{q}^{mh*}\left(\vec{\mathbf{q}}^*\right)\right)\right), \tag{5.24}$$

*where* $\vec{\mathbf{q}}$ *is the vector of* $q_{mh}$; $\vec{\mathbf{P}}$ *is the vector of* $P_{h/m}$ *and;* $\vec{\mathbf{\Pi}}$ *is the vector of* $\Pi_{mh}$.

The existence of a solution to the fixed-point problem (5.24) can be easily proved. The fixed-point problem (5.24) is non-convex, thus multiple local solutions may exist (Chen and Hsueh, 1998).

## 5.5 SOLUTION ALGORITHM

In this section, a diagonalization heuristic solution algorithm is developed to solve the fixed-point problem (5.24). The procedure of the diagonalization algorithm is outlined as follows:

**Step 1.** Initialization. Get the initial $q_{mh}$ and $q_i^{mh}$.

Set iteration $n=1$. Set a feasible set of $q_{mh}$ as the initial solution $q_{mh}^{(n)}$. Generate ACNs according to the free-flow travel time. Assign $q_{mh}^{(n)}$ on the ACNs and obtain the initial solution of $q_i^{mh(n)}$ (Refer to Chapter 4). In addition, $\Pi_{mh}^{(n)}$ is obtained after that assignment on the ACNs.

**Step 2.** Update $q_{mh}$ and $q_i^{mh}$.

***Step 2.1.*** With the obtained $\Pi_{mh}^{(n)}$ and $q_h^{(n)}$, calculate $U_{mh}^{(n)}$ by Equation (5.1). Solve the following subproblem (5.25) and obtain the residential location choice flow pattern $\tilde{q}_{mh}^{(n)}$. Subproblem:

$$\max_{\tilde{q}_{mh}} \tilde{Z} = -\frac{1}{\theta}\sum_m \sum_h \tilde{q}_{mh}\left(\ln \tilde{q}_{mh} - 1\right) - \sum_m \sum_h \alpha_m r_h(\tilde{q}_{mh}, S_h)\tilde{q}_{mh} + \sum_m \sum_h \Pi_{mh}\tilde{q}_{mh}, \tag{5.25}$$

subject to $\Omega II$ (i.e. Equations (5.5)-(5.8)) with the subproblem variables(Yang and Meng, 1998a).

***Step 2.2.*** Generate ACNs according to $\Pi_{mh}^{(n)}$. Assign $\tilde{q}_{mh}^{(n)}$ on the ACNs and obtain the solution of $\tilde{q}_i^{mh(n)}$. In addition, $\tilde{\Pi}_{mh}^{(n)}$ is obtained.

***Step 2.3.*** MSA replacement. Let $q_{mh}^{(n+1)} = q_{mh}^{(n)} + \left(\tilde{q}_{mh}^{(n)} - q_{mh}^{(n)}\right)/n$ and $q_i^{mh(n+1)} = q_i^{mh(n)} + \left(\tilde{q}_i^{mh(n)} - q_i^{mh(n)}\right)/n$.

**Step 3.** Convergence check.

If the stopping criterion is satisfied, terminate and output the solution; otherwise, set $n=n+1$ and go to step 2. The stopping criterion can be based on following two inequalities (5.26).

$$\sqrt{\sum_m \sum_h \left(q_{mh}^{(n+1)} - q_{mh}^{(n)}\right)^2} \Big/ q \le \varepsilon, \tag{5.26a}$$

$$\sqrt{\sum_{m}\sum_{h}\sum_{i}\left(q_i^{mh(n+1)} - q_i^{mh(n)}\right)^2} \Big/ q \le \varepsilon \,. \tag{5.26b}$$

where $\varepsilon$ is the pre-determined tolerance.

The method of generating ACNs introduced in Chapter 4, is employed to explicitly represent the relationship between activity choices and travel choices in solving the multi-class user daily activity scheduling problems in this chapter. Details of the ACN generation method are presented in Section 4.6.1 of Chapter 4. Note that the utilities/disutilities of activity/trip links of the generated ACNs are different for various household groups.

## 5.6 NUMERICAL EXAMPLE

The purposes of this numerical example are: (i) to illustrate the application of the proposed model and solution algorithm in studying the combined residential location and travel choice problems as well as the interactions between user residential location choices and user daily activity/travel choices ; (ii) to demonstrate the merits of applying the proposed model in evaluating the effects of various land use/transport policies on user residential location choice behaviour and user daily travel choice behaviour.

### 5.6.1 BASIC INPUT DATA

Figure 5.1 is a simple road network which consists of sixteen directional links and five nodes. Node 1 and Node 5 represent two residential zones in which users can choose to reside. The housing supply of Node 1 and Node 5 for both is 5000. Node 3 represents the employment zone. Node 4 represents the shop/restaurant area. Node 3, Node 4 and Node 5 are in the Central Business District (CBD). At home and eating activities can be performed at the selected residential zone (i.e. Node 1 or Node 5). Work and eating activities can be conducted at the employment zone (i.e. Node 3). Shopping and eating activities can be conducted at Node 4. The link free-flow travel times and link capacities are given in Table 5.1.

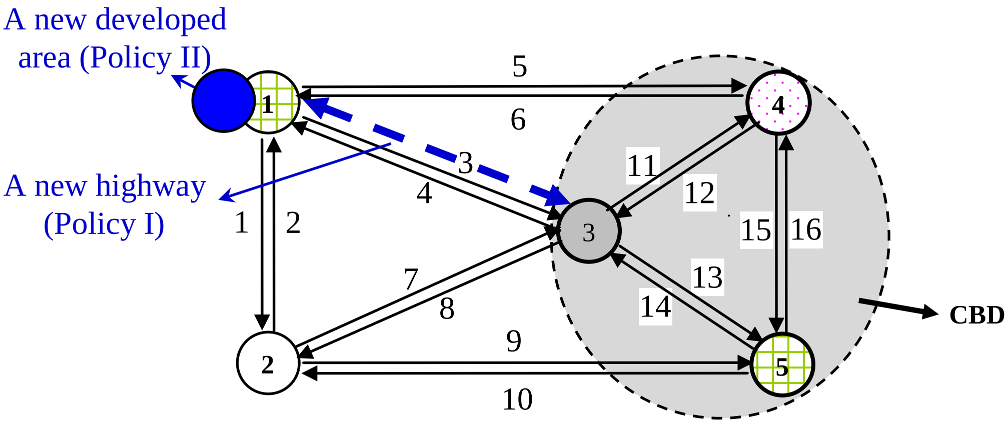


Figure 5.1 An Example Urban Network (i.e. Base Transport Network)

**Table 5.1 Link Free-Flow Travel Time and Capacity of the Transport network**

| Link | 1,2 | 3,4 | 5,6 | 7,8 | 9,10 | 11,12 | 13,14 | 15,16 |
|---|---|---|---|---|---|---|---|---|
| Free-flow travel time (min) | 10 | 30 | 50 | 40 | 50 | 10 | 10 | 10 |
| Capacity(veh/hour) | 1800 | 1800 | 1800 | 1800 | 1800 | 1800 | 1800 | 1800 |

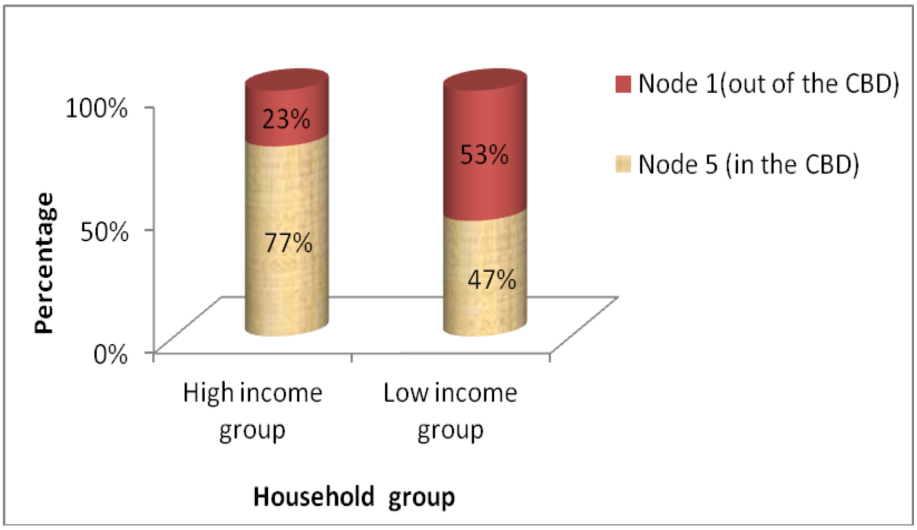
The total population in the study area is assumed to be 5000. The population is categorized into two household groups: a high income group with a higher Value of Time (VOT), and a low income group with a lower VOT, as shown in Table 5.2. The daily housing rent function of the residential location Node1 and Node5 is given by $r_1 = 150 + 0.6(q_1)^{0.6} + 120(q_1/S_1)$ and $r_5 = 220 + 0.6(q_5)^{0.6} + 120(q_5/S_5)$, respectively (refer to the study of Yang and Meng, 1998a). Assume that the dispersion parameter of user residential location choices, $\theta$, is 0.2.

**Table 5.2 The Characteristics of the Population**

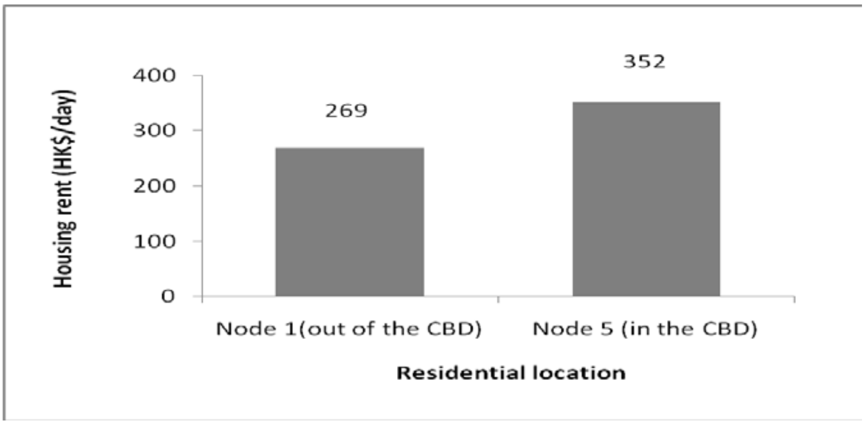
| | Number | $\alpha_m$ (utility/HK$) | VOT($\sigma^m$) (utility/min) |
|---|---|---|---|
| High income group | 1000 | 1/6 | 0.5 |
| Low income group | 4000 | 1/6 | 0.1 |

For the DATP choice sub-problem, the entire study time period is from 6:00 to 24:00 and equally divided into 108 intervals (i.e. 10 minutes per interval). The marginal utility profiles of activities are the same as those shown in Figure 3.5, but for following differences: (1) The marginal utility profile of work of the low income group is the same as that of work shown in Figure 3.5. The marginal utility profile of work of the high income group is 1.5 times that of the low income group. (2) The marginal utility profile of residents' at home activity at Node 5 and Node 1 is the same as that of at home activity shown in Figure 3.5. (3) It is assumed that for eating activity at Node 3, is only lunch. As it is difficult to distinguish the exact start/end times of different activities conducted at home, eating activity at the selected residential location and other at home activities are combined as one home activity. The temporal marginal utility of eating at residential zones and at employment zone is 0.6 times that of eating as shown in Figure 3.5. (4) Parking fees of HK$15/hour at Node 4, and HK$25/hour at Node 3, are incorporated (Note that US$ 1.00 = HK$ 7.8).

### 5.6.2 EXAMPLE RESULTS



(a) Resulting residential location choices;



(b) Generated housing rents

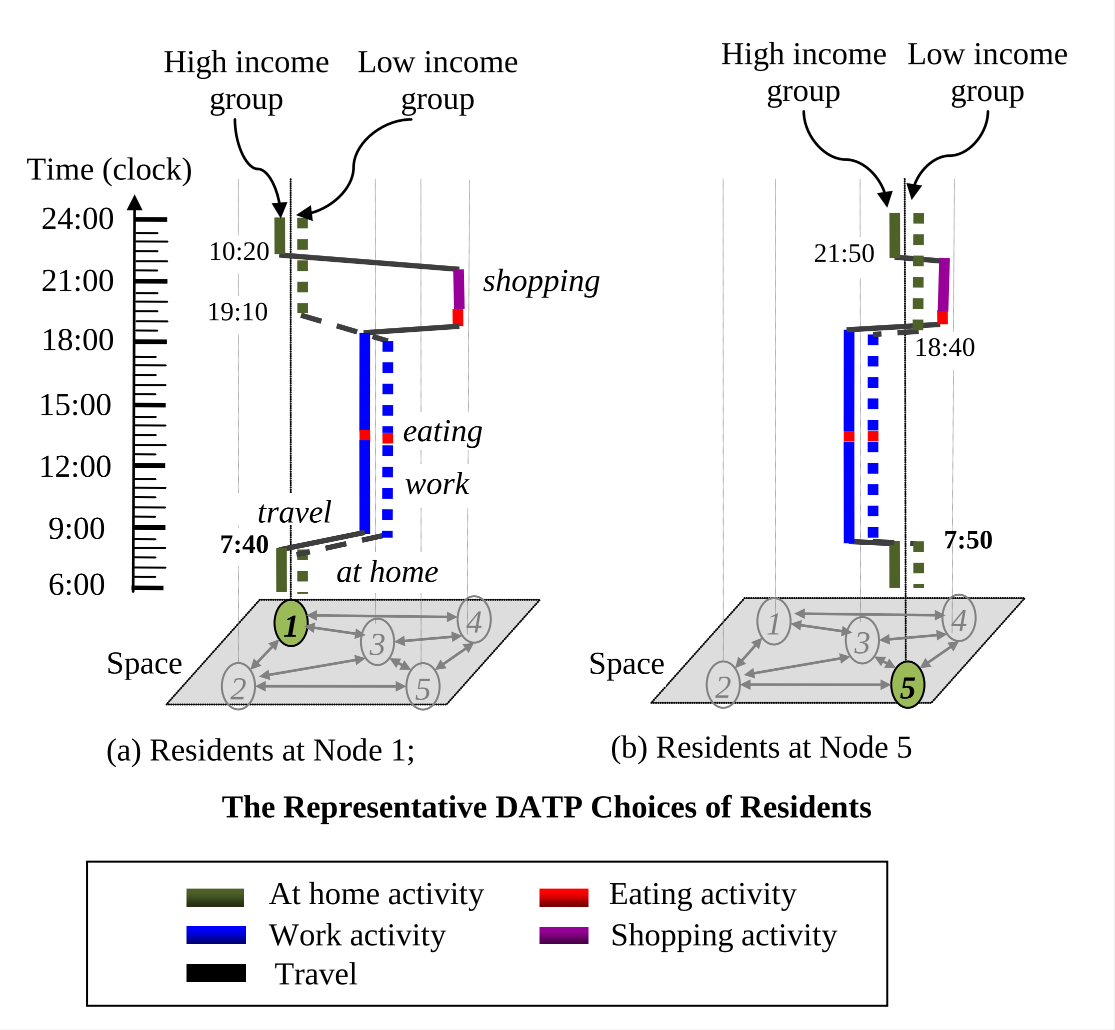
Figure 5.2 The Effects of Transport Accessibility on Residential Location Choices and Housing Rents

Firstly, the impact of transport accessibility on user residential location choices and housing rents was examined.

Figure 5.2 presents the residential location choice results based on the transport network presented above. As shown in Figure 5.2, the majority of the high income users prefer to reside at Node 5 in the CBD (77%) and pay a high daily housing rent (352HK$/day), while most low income users prefer to reside at Node 1 out of the CBD (53%) and pay a low daily housing rent (269HK$/day). The reason is possibly that the good transport condition near Node 5 enables high income users who have a higher VOT, to save more travel time and allocate that saved time on conducting other activities. In contrast, low income workers have a lower VOT and higher money value, thus they are inclined to reside at Node 1 with a low housing rent and poorer transport condition.

The impact of residential location choices and household income levels on user daily activity/travel choice behaviour such as activity sequence choices, journey departure time choice, journey travel times, and activity durations, is also investigated. Figure 5.3 gives the representative DATP choices of households in different income groups and with different residential location choices.

From Figure 5.3 it can be seen that the representative DATP choices of users with different income levels or different residential location choices are likewise, different. It is also noticed that, for residents both at Node 1 and Node 5, the representative activity sequence choices are the same for the same income level group, but different for different income level groups. As shown in Figure 5.3, high income users prefer to follow the activity sequence with activities (supper and shopping) at Node 4, while low income users are inclined to choose the activity sequence without activities at Node 4. It is also found that the majority of users residing at Node 5 (in the CBD) have a later morning departure time 7:50 from home to work, which 10-minute later than 7:40 the time of users residing at Node 1. However, users residing at Node 5 have an earlier home arrival time after work 18:40, which is 30-minute earlier than 19:10 the time of users residing at Node 1.



(a) Residents at Node 1; (b) Residents at Node 5

**The Representative DATP Choices of Residents**

**Figure 5.3 The Impact of Residential Location Choices on DATP Choices by Income Group**

Time allocation on activities of users with different income levels and different residential location choices is summarized, in detail, in Table 5.3. From Table 5.3, it is clear that, on average, the high income users spend more time working than low income users. This is caused by the higher marginal utility of work for high income users compared to that of low income users. It is also found that high income users, on average, allocate more time on shopping and out-of-home eating, but less time than low income users on at home activity. Generally, users residing at Node 5 (in the CBD) allocate more time on conducting activities such as shopping and working, and save time in traveling, than users residing at Node 1. The longer average travel time of residents at Node 1 is caused by the activity location distribution of the network, the latter being determined by the land use pattern. For example, due to the activity location distribution, residents at Node 1 probably have to spend a greater length of long time traveling from home (Node 1) to the employment zone (Node 3). In contrast, residents at Node 5 may only spend a short time traveling from home (Node 5) to their employment zone (Node 4).

**Table 5.3 The Time Allocation on Activities by Resident Group**

| Resident group | | Average duration (hour/user) | | | | |
|---|---|---|---|---|---|---|
| | | Work | Shopping & out-of-home eating | At home | Travel | Total time (6:00-24:00) |
| High income | Residents at Node 1 | 9.92 | 3.36 | 2.59 | **2.13** | 18 |
| | Residents at Node 5 | 10.05 | 3.50 | 3.50 | 0.95 | 18 |
| Low income | Residents at Node 1 | 9.19 | 0.62 | 6.32 | **1.87** | 18 |
| | Residents at Node 5 | 9.38 | 0.85 | 6.73 | 1.04 | 18 |

### 5.6.3 EVALUATION OF POLICIES USING THE PROPOSED MODEL

#### *5.6.3.1 Evaluation of transport policies using the proposed model*

A sensitivity test on the effect of transport policies on the combined user residential location and travel choices was conducted. Consider a a project (Policy I) which is a high way to be constructed connecting Node1 and Node 3 as shown in Figure 5.1. The fixed travel time by the new high-way from Node 1 to Node 3 (or from Node 3 to Node 1) is 10 minutes.

The effects of the above project as regards the changes of residential location choice results, are presented in Table 5.4. As shown in Table 5.4, after Policy I, some high and low income users (208and 267, respectively) who previously resided at Node 5 in the CBD, switched to reside at Node 1. The reason for the move is expected to be the newly decreased travel time between Node 1 and Node 3 caused by the introduction of Policy I and which thus makes Node 1 more attractive to residents. It is also noticed that more low income users (37; 267-208=37) switched to reside at Node 1. The reason is probably that the low housing rent of residing at Node 1is more attractive to the low income users than to high income users.

In summary, the housing demand of Node 1 increased due to Policy I. The underlying reason is that the equilibrium DATP choice utility of residents at Node 1 probably increases after Policy I. This utility increase is caused by that residents at Node 1 can save some travel times on journeys between Node 1 and Node 3 after Policy I and then they obtain greater utility by allocating the saved travel times on conducing other activities. The increased housing demand of Node 1 leads to the increase of the daily housing rent of Node 1 as shown in Table 5.4. In contrast, after Policy Iboth the housing demand and daily housing rent decreased for users residing at Node 5.

**Table 5.4 The Effects of Policy I/II on Residential Location Choice Results**

| | Number of high income users | | Number of low income users | | Housing rent (HK$/day) | |
|---|---|---|---|---|---|---|
| | Node 1 | Node 5 | Node 1 | Node 5 | Node 1 | Node 5 |
| Base case | 227 | 773 | 2119 | 1881 | 269 | 352 |
| Changes after Policy I | **+208** | -208 | **+267** | -267 | **+19** | **-20** |
| Changes after Policy II | +74 | -74 | +74 | -74 | +3 | -3 |

**Table 5.5 The Effects of Policy I/II on the Time Allocation on Activities**

| | Average duration (hour/user) | | | |
|---|---|---|---|---|
| | Work | Shopping & out-of-home eating | At home | Travel |
| Base case | 9.42 | 1.27 | 5.84 | 1.47 |
| After Policy I | 9.93 | 1.31 | 5.93 | 0.83 |
| Percentages of the changes after Policy I | **5%** | **3%** | **2%** | **-44%** |
| After Policy II | 9.82 | 3.73 | 3.10 | 1.35 |
| Percentages of the changes after Policy II | 4% | **194%** | **-47%** | -8% |

The effects of Policy I as regards the changes of users' time allocation on activities are presented in Table 5.5. From Table 5.5, it is found that after Policy I, the average travel time per user per day greatly decreased. Because of the saved average travel time, the average duration of various activities increased. How the saved travel time is allocated on activities may not be investigated by the integrated land use and transport models where the trip-based approach is used. In contrast, that time allocation problem could be examined in this example as illustrated in Table 5.5, due to the merits of the proposed activity-based model in this chapter.

#### *5.6.3.2 Evaluation of land use policies using the proposed model*

Suppose that based on the example urban network as shown in Figure 5.1, the government is planning to develop an area for shopping and eating at Node 1(Policy II). The marginal utilities of shopping and eating at Node 1 are the same as those of shopping and eating given in Figure 3.5. The effects of Policy II as regards the changes of residential location choice results, are presented in Table 5.4. As shown in Table 5.4, the changes of the residential choices caused by Policy II are wild. However, the activity time allocation resulting from user DATP choices change dramatically as shown in Table 5.5. The average activity duration of shopping and out-of-home eating increased greatly due to that land use policy (Policy II).

From the numerical example results analysis, it is found that the combined location and travel choice behaviour were comprehensively examined by applying the proposed activity-based SUE model. It showed that the proposed model was a valuable tool for estimating the impacts of land use/transport policies on user location choice behaviour and travel choice behaviour.

## 5.7 SUMMARY

In this chapter, an activity-based SUE traffic assignment model has been proposed for dealing with the combined residential location and travel choice problems. The proposed model was formulated as an equivalent fixed-point problem. The residential location choice depends on the average daily housing price and the equilibrium utility of the optimum DATP choice with the selected residential location. A solution algorithm was developed to solve combined user residential location and travel choice problems.

The numerical study showed that the proposed model and solution algorithm provided a comprehensive framework of the understanding of user residential location choice behaviour, user travel choice behaviour, as well as the interactions between the two. User residential location choice behaviour was significantly influenced by the accessibility of a transport network. User residential location choices and income levels, in turn, were the critical factors that influenced user DATP choices. The numerical study also illustrated that the proposed model and solution algorithm could be a useful tool to enable government evaluation of the effects of various land use and transport policies.

It should be pointed out, however, that the proposed model assumed that employment locations were given, thus the interactions between user employment location choices and user residential location choices were ignored. The housing supply and demand market clearing problem was also not investigated in this chapter. On the basis of the work described in this chapter, future work could be carried out in the following aspects: (a) to study the employment location choice, residential location choice and daily activity/travel choice simultaneously; (b) to investigate the equilibrium problems of the housing supply and demand market (Martínez and Henríquez, 2007) and; (c) to consider the integrated land use and transport optimization problems for the government; (d) to validate the housing cost function $r_h(q_h, S_h)$ by the collection of data in reality. Some relevant extension works of (a) and (c) are conducted in this research and presented in the next chapter.

# 6 AN ACTIVITY-BASED BI-LEVEL MODEL FOR SUSTAINABLE LAND USE AND TRANSPORT OPTIMIZATION

The activity-based approach has been employed to study user travel choice behaviour and user residential location choice behaviour in the previous chapters. In this chapter the activity-based approach is extended to investigate the optimization model for government use.

The air pollution problem from traffic emissions in urban areas has become increasingly serious due to the growing activity demands in the past decades. Currently a need has developed to integrate optimize the land use system and transport system in an effort to contribute to the balance of economic development and environmental pollution. In this chapter, an activity-based bi-level model is proposed to solve the optimization problem.

## 6.1 INTRODUCTION

The transport network design and urban land use allocation strategy should be consistently aligned due to the strong interactions between land use and transport. For instance, if the performance of existing transport networks is unsatisfactory, particularly in terms of unacceptable congestion, the government may find it necessary to alleviate the situation by adopting a more appropriate land use policy.

Such appropriate land use policy changes the population distribution of residential/employment locations. The changed population distribution impacts user travel demands. In this way, traffic congestions may be alleviated.

Conversely, an optimized transport network improvement strategy could be an alternative solution for improving the efficiency of the existing land use resource allocation. A transport network improvement strategy changes the transport accessibility of user residential/employment locations or other activity locations such as shopping malls and schools. The changed transport accessibility influences user residential/employment location choices. The user choices result in population distribution of residential/employment locations. In such way, the efficiency of the land use resource allocation may be improved.

An inappropriate land use development plan or an inconsistent transport network improvement scheme could have serious implications on many aspects of a community. Negative impacts include a possible mismatch between supply distribution of housing/employment locations, which in turn could lead to an overburdened urban situation, isolated rural areas and subsequent serious and socially disruptive traffic conditions. Such conditions can cause, unemployment or unfilled jobs and subsequent economic decline, Hence the development of an integrated model which simultaneously optimizes land use development and transport network enhancement would have welcome advantages (Yim et al., 2011).

In recent decades, serious air pollution from traffic emissions has emerged as one of the most acute problems that big city authorities should take strong measures to control. The air pollutants from traffic emissions include such as carbon monoxide (CO), nitrogen oxides (NOx), sulphur dioxide(SO2), and volatile organic compounds (VOCs), (Yin and Lawphongpanich, 2006). Transport is accountable for approximately 90% of the carbon monoxide and 50% of the emissions of nitrogen oxide. The system of land use and transport networks has to be sustainable and in step with both the present and expected growth. To this end, traffic emission control policies should be explored. This chapter extends the conventional transport network design to the sustainable land use and transport optimization.

The most important aspect of studying sustainable land use and transport optimization problems is how to accurately capture user residential/location choice behaviour and daily travel behaviour in response to the optimization policies. Efficient optimization policies can only be developed with user co-operation. As discussed in Chapter 5, the activity-based approach has great merit in exposing the behaviour such as residential location choices and travel choices. In this chapter, the user behaviour in response to government optimization policies is captured by an activity-based approach.

An activity-based bi-level model is proposed to deal with the sustainable land use and transport optimization problem in this chapter. In the proposed model, the upper level deals with government decisions concerning the joint residential/employment location development and road link capacity expansion in line with the population increase. Attention is given to maximizing social welfare under the local traffic emission control within a given budget constraint. The lower level deals with the user response behaviour model. This model captures combined user residential and employment location and DATP choices.

This chapter is organized as follows. The basic considerations are given in Section 6.2. In Section 6.3, an activity-based bi-level model is formulated for dealing with the sustainable optimization problem. In Section 6.4, a genetic algorithm (GA) is proposed for solving the sustainable optimization problem. Section 6.5 presents a numerical example for illustrating the applications of the proposed model and solution algorithm. Finally, the conclusions are drawn in Section 6.6 together with recommendations for further studies.

## 6.2 BASIC CONSIDERATIONS

### 6.2.1 ASSUMPTIONS

To facilitate the presentation of the essential ideas, the following basic assumptions are made in this chapter.

A6.1 The assumptions of A3.1, A3.3, A3.4, A3.5, and A3.6 given in Chapter 3 are carried on into this chapter to investigate users' DATP choice problems.

A6.2 The proposed sustainable land use and transport optimization model is mainly used for strategic planning. Assume that users' combined residential/employment location and DATP choices satisfy network equilibrium conditions.

A6.3 Although residential/employment location choice is a household choice problem, but for simplicity and similar to the assumption made in Chapter 5, assume that the household behaves as a representative individual (Boyce and Mattsson, 1999; Maat et al., 2005). Note that dissimilar to the work of Chapter 5, the focus of which is only user residential location choices, user employment location choices are also investigated in this chapter.

A6.4 The population is confined to workers with homogenous values of time. All individuals are assumed to choose residential location and employment location to obtain the maximum utility by scheduling their DATP within the selected locations.

### 6.2.2 NETWORK SOCIAL WELFARE

Let $h$ represent a feasible residential location. Let $w$ represent a feasible employment location. Let $H$ and $W$ represent the respective sets of residential locations and employment locations. Let $\Pi_{hw}$ be the equilibrium utility of DATP choices for users who choose location $h$ as the residence and location $w$ as the employment venue. Let $q_{hw}$ be the number of users who choose location $h$ as the residence and location $w$ as the employment venue. The network social welfare $\Psi$ can be estimated by

$$\Psi = \sum_{h}\sum_{w}\left(\Pi_{hw} \times q_{hw}\right). \tag{6.1}$$

### 6.2.3 USER RESIDENTIAL/EMPLOYMENT LOCATION AND DATP CHOICES

In the combined user residential/employment location and typical DATP choice problems, it is assumed that users simultaneously choose the residential location and employment location, and optimize the typical DATP choice to obtain the maximum utility from activity participations. Here, we adopt the doubly constrained gravity model of Evans (1976) to consider the combined problem. The population distribution of residential/employment locations has the close-form expression,

$$q_{hw} = A_h S_h B_w G_w \exp(\theta \Pi_{hw}), \quad \forall h, w \tag{6.2}$$

where $\theta$ is the dispersion parameter which needs to be calibrated, $S_h$ is the total housing supply of residential location *h*, $G_w$ is the total job supply of employment location *w*, and $A_h$ and $B_w$ are balancing factors determined by

$$A_h = \frac{S_h}{\sum_w B_w G_w \exp(\theta \Pi_{hw})}, \quad \forall h \tag{6.3}$$

$$B_w = \frac{G_w}{\sum_h A_h S_h \exp(\theta \Pi_{hw})}, \quad \forall w \tag{6.4}$$

Let $q$ denote the total population of the network. Regarding the problem of population distribution of residential/employment locations, the following population conservation constraints should be satisfied, $\Omega i$, Equations (6.5)

$$A_h = \sum_w q_{hw}, \quad \forall h \tag{6.5a}$$

$$B_w = \sum_h q_{hw}, \qquad \forall w \tag{6.5b}$$

$$\sum_h A_h = \sum_w B_w = q \tag{6.5c}$$

Let $i$ represent a feasible DATP choice. Let $q_i^{hw}$ denote the number of users with residential location $h$ and employment location $w$, who take DATP $i$. In the user DATP choice problem, the DATP choice flow $q_i^{hw}$ reaches the UE state "*" if and only if it solves the following VI problem:

for $\forall q_i^{hw} \in \Omega ii$,

$$\sum_h \sum_w \sum_i \Pi_{hw} \left( q_i^{hw} - q_i^{hw*} \right) \leq 0 \tag{6.6}$$

where $\Pi_{hw} = \max_i V_i^{hw}$ ; $V_i^{hw}$ represents the utility obtained from conducting DATP $i$ of users with the selected residential location $h$ and employment location $w$; and $\Omega ii$ represents the constraint set defined by Equations(6.9).

Let $t_{r,s}^p(k)$ denote the travel time of route $p$ for departure at time interval $k$ from origin $r$ to destination $s$. This can be calculated by Equation (5.14). To simplify the calculations without losing the essential ideas of this chapter, the route travel time $t_{r,s}^p(k)$ is measured in units of one time interval. If the route travel time obtained by Equation (5.14) is not in integer times of one time interval, it should be rounded to its closest value which is in integer times of one time interval.

Let $\overline{U}_{j,s}^{hw}(k)$ denote the utility of performing activity *j* at location *s* for one interval with start time interval *k* for users with residential location choice $h$ and employment location choice *w*, and it can be calculated by

$$\overline{U}_{j,s}^{hw}(k) = \int_k^{k+1} u_{j,s}^{hw}(\omega) d\omega, \tag{6.7}$$

where $u_{j,s}^{hw}(k)$ denotes the marginal utility of performing activity *j* at location *s*, at time interval *k* of users with residential location $h$ and employment location *w*.

The utility, $V_i^{hw}$, of DATP $i$ is the sum of the utility obtained from activity participations minus the disutility of travels for users with residential location $h$ and employment location $w$. This is expressed as

$$V_i^{hw} = \sum_j \sum_s \sum_k \delta_{j,s}^{i,k} \overline{U}_{j,s}^{hw}(k) - \sigma \sum_r \sum_s \sum_k \sum_p \delta_{r,s,p}^{i,k} t_{r,s}^p(k), \tag{6.8}$$

where $\delta_{j,s}^{i,k} = 1$ if the one-interval duration participation process of performing activity $j$ at location $s$ with the start time interval *k*, is included in DATP $i$, and $\delta_{j,s}^{i,k} = 0$ otherwise; $\delta_{r,s,p}^{i,k} = 1$ if the travel departure from origin $r$ to destination $s$ at time interval $k$ with route choice $p$, is included in DATP *i* and $\delta_{r,s}^{i,k} = 0$ otherwise.

Let $\delta_{r,s}^{i,k} = 1$ if the trip departure from origin $r$ to destination $s$ at time interval $k$, is included in DATP $i$ and $\delta_{r,s}^{i,k} = 0$ otherwise. The value (1 or 0) of $\delta_{j,s}^{i,k}$ and $\delta_{r,s}^{i,k}$ is characterized by the network topology of ACN. The generation approach of ACN is given in Chapter 4. Note that the topology of ACN for each user group $q_{hw}$ with different residential/employment location choices is the same, but the ACN link utility (i.e. activity utility $\overline{U}_{j,s}^{hw}(k)$ ) for that each user group may be different due to different residential/employment location choices.

Let $q_{r,s}^{hw,i,p}(k)$ denote the flow with residential location *h* and employment location *w* choosing route *p*, departure from origin *r* to destination *s* at time interval *k* and in DATP *i*. Let $q_{r,s}^{hw,i}(k)$ denote the flow with residential location *h* and employment location *w* departure from origin *r* to destination *s* at time interval *k* and in DATP *i*. Let $q_{r,s}^{hw}(k)$ denote the flow with residential location *h* and employment location *w* departure from origin *r* to destination *s* at time interval *k*. Let $q_{j,s}^{hw}(k)$ be the flow with residential location *h* and employment location *w*, who conducts activity *j* at location s at time interval *k*. Let $q_{s}^{hw}(k)$ denote the flow with residential location h and employment location *w* at location *s* at time interval *k*. Let $q_s(k)$ denote the total node flow at location *s* at time interval *k*.

Let $f_{r,s}^{hw,p}(k)$ be the route flow with residential location *h* and employment location *w* at time interval *k* on route *p* which connects origin *r* to destination *s*. Let $x_a^{hw}(k)$ be the link flow with residential location *h* and employment location *w* on link *a* at time interval *k*. Let $x_a(k)$ be the total link flow on link *a* at time interval *k*. The constraint set $\Omega ii$ for the DATP choice is summarized as following Equations (6.9).

Flow conservation constraints at activity locations:

$$q_{j,s}^{hw}(k) = \sum_{i} \delta_{j,s}^{i,k} q_i^{hw} \ , \tag{6.9a}$$

$$q_s^{hw}(k) = \sum_j q_{j,s}^{hw}(k) \cdot \tag{6.9b}$$

$$q_s(k) = \sum_{hw} q_s^{hw}(k) \tag{6.9c}$$

Flow conservation constraints on road links:

$$q_{r,s}^{hw,i}(k) = \sum_p \delta_{r,s,p}^{i,k} q_i^{hw} = \sum_p q_{r,s}^{hw,i,p}(k) \ , \tag{6.9d}$$

$$q_{r,s}^{hw}(k) = \sum_p f_{r,s}^{hw,p}(k) = \sum_i q_{r,s}^{hw,i}(k) \, , \tag{6.9e}$$

$$f_{r,s}^{hw,p}(k) = \sum_i q_{r,s}^{hw,i,p}(k) \ , \tag{6.9f}$$

$$x_a^{hw}(k) = \sum_{rs} \sum_p \sum_{l(\le k) \in K} \delta_{rs}^{apl}(k) \, f_{r,s}^{hw,p}(l) \ \cdot \tag{6.9g}$$

$$x_a(k) = \sum_{hw} x_a^{hw}(k) \ \cdot \tag{6.9h}$$

where $\delta_{rs}^{apk}(l) = 1$ if the flow from origin *r* to destination *s* entering route $p$ at interval *k* arrives link *a* at interval *l*; otherwise $\delta_{rs}^{apk}(l) = 0$. Thus, the value (1 or 0) of $\delta_{rs}^{apk}(l)$ depends on both the topology of the transport network and traffic conditions on the transport network.

Flow conservation constraint over the network and nonnegative constraints:

$$q_{hw} = \sum_i q_i^{hw} \ , \tag{6.9i}$$

$$q_{r,s}^{hw,i,p}(k) \ge 0 \ , \tag{6.9j}$$

$$q_i^{hw} \ge 0 \ \cdot \tag{6.9k}$$

From Equations (6.9a)-(6.9i), when Equation (6.9j) and Equation (6.9k) are effective, all flow variables are nonnegative.

Let $L$ denote the duration of one time interval. For any DATP choice, the following time conservation should also be satisfied：

$$\sum_j \sum_s \sum_k \delta_{j,s}^{i,k} L + \sum_r \sum_s \sum_k \sum_p \delta_{r,s,p}^{i,k} t_{r,s}^{p}(k) = T \qquad \forall i . \tag{6.9l}$$

where $T$ is the study horizon.

### 6.2.4 LOCAL TRAFFIC EMISSIONS

To simplify the presentation of this chapter, only carbon monoxide is considered. The time-dependent link emissions (in grams) $\rho_a(k)$ of traffic entering link *a* at time interval *k*, are given by the following equation (Yin and Lawphongpanich, 2006):

$$\rho_a(k) = 0.2038 * t_a(k) * \exp^{0.7962 * l_a / t_a(k)}, \tag{6.10}$$

where $l_a$ is the length (in kilometers) of road link $a$ . Note that here $t_a(k)$ is in minutes.

The total traffic emissions $e$, are estimated by the following equation:

$$e = \sum_k \sum_a v_a(k) \rho_a(k), \tag{6.11}$$

where $v_a(k)$ is the link inflow at time interval *k* on road link $a$. The time-dependent link inflow can be calculated by,

$$v_a(k) = x_a(k), \text{ for } k = 1; \tag{6.12a}$$

$$v_a(k) = x_a(k) - x_a(k-1), \text{ for } k = 2, \ldots \bar{K} . \tag{6.12b}$$

## 6.3 MODEL FORMULATION OF THE SUSTAINABLE LAND USE AND TRANSPORT OPTIMIZATION PROBLEM

In this section, an activity-based bi-level model is proposed to investigate the sustainable land use and transport optimization problem. The upper level examines the optimum residential and employment location development and road link capacity expansion so that when the population increases, the social welfare is maximized under a traffic emission control and a constraint of the budget. The lower level is an activity-based network equilibrium model for studying combined user residential/ employment location and DATP choice problem.

### 6.3.1 THE UPPER-LEVEL PROBLEM

Let $q_0$ be the initial population, $\Delta q$ be the increased population, and $q$ be the total population after the increase. Let $S_{h0}$ be the initial housing supply of residential location $h$, $\Delta S_h$ be residential allocation ability improvement. Let $G_{w0}$ be the initial job supply of employment location $w$, $\Delta G_w$ be the employment allocation ability improvement. Let $C_{a0}$ be the initial link capacity of road link $a$, $\Delta C_a$ be the road link capacity expansion, and $C_a$ be the total road link capacity after the expansion. Let $S_h^{\max}$ be the maximum residential allocation ability improvement, $G_w^{\max}$ employment allocation ability improvement and $C_a^{\max}$ road link capacity expansion. Let $\mathbf{\Delta S}$, $\mathbf{\Delta G}$ and $\mathbf{\Delta C}$ represent the vector set of $\Delta S_h$, $\Delta G_w$ and $\Delta C_a$, respectively. Let $F_h\left(\Delta S_h\right)$ be the money cost functions of residential allocation ability improvement, $F_w(\Delta G_w)$ employment allocation ability improvement and $F_a(\Delta C_a)$ road link capacity expansion. Let $M$ be the total available money budget. Let $E$ be the permissible traffic emission level.

According to the above statement, the upper-level subproblem can be formulated as

$$\max_{\mathbf{\Delta S \Delta G, \Delta C}} \sum_h \sum_w \left(\Pi_{hw} \times q_{hw}\right) \tag{6.13}$$

Subject to

(Emission control)

$$\sum_k \sum_a \left(\rho_a(k) \times v_a(k)\right) \le E \qquad k \in K, a \in A \tag{6.14}$$

(Budget constraint)

$$\sum_h F_h\left(\Delta S_h\right) + \sum_w F_w\left(\Delta G_w\right) + \sum_a F_a\left(\Delta C_a\right) \le M \tag{6.15}$$

(Minimum and maximum development/expansion constraints)

$$0 \le \Delta S_h \le S_h^{\max}, \quad \forall h \tag{6.16a}$$

$$0 \le \Delta G_w \le G_w^{\max}, \quad \forall w \tag{6.16b}$$

$$0 \le \Delta C_a \le C_a^{\max}, \quad \forall a \tag{6.16c}$$

(Population conservation constraints)

$$\sum_h \Delta S_h = \Delta q \tag{6.17a}$$

$$\sum_w \Delta G_w = \Delta q \tag{6.17b}$$

The population distribution of locations $q_{hw}$, the equilibrium utility of the combined user location and DATP choices $\Pi_{hw}$, the traffic emissions $\rho_a(k)$ and the time-dependent link inflow $v_a(k)$ are obtained by solving the lower-level problem.

### 6.3.2 THE LOWER-LEVEL PROBLEM

The lower-level problem represents the user behaviour regarding residential location choice, employment location choice, and DATP choice in response to the improved residential allocation ability, improved employment allocation ability, and expanded road link capacity given in the upper level. The combined problem of user residential and employment location choice, and DATP choice can be formulated as the following VI problem:

for $\forall q_{hw}, q_i^{hw} \in \Omega i, \Omega ii$,

$$\sum_h \sum_w \Lambda\left(q_{hw} - q_{hw}^*\right) + \sum_h \sum_w \sum_i \Pi_{hw}\left(q_i^{hw} - q_{i*}^{hw}\right) \leq 0 \tag{6.18}$$

where $\Lambda = \max_{h,w}\left(\Pi_{hw} - \frac{1}{\beta} \ln q_{hw}\right)$, and in the constraints of $\Omega i$ and $\Omega ii$, the total population, housing supply of the residential location, job supply of the employment location, and road link capacity should be calculated by

$$q = q_0 + \Delta q \tag{6.19a}$$

$$S_h = S_{h0} + \Delta S_h \tag{6.19b}$$

$$G_w = G_{w0} + \Delta G_w \tag{6.19c}$$

$$C_a = C_{a0} + \Delta C_a \tag{6.19d}$$

## 6.4 SOLUTION ALGORITHM

The sustainable land use and transport optimization problem is formulated as a bi-level programming problem and given in Section 6.3. The genetic algorithm (GA) (Yim et al., 2011) is adapted for solving the proposed bi-level programming problem. Reference can be made to other heuristic algorithms such as the Simulated Annealing Approach (SAA) (Friez et al., 1993; Ouyang et. al., 2009) for solving the proposed bi-level problem. In addition, in this chapter a heuristic algorithm is provided to solve the combined user residential/employment location and DATP choice equilibrium problem of the lower level.

### 6.4.1 A HEURISTIC ALGORITHM FOR SOLVING THE LOWER-LEVEL PROBLEM

The lower level problem is the combined user residential/employment location and DATP choice equilibrium problem. A heuristic algorithm embedded the Furness iteration technique (Lam and Huang, 1992) and the MSA is developed to solve the lower level problem.

The procedure of the heuristic algorithm is outlined as follows:

**Step 0.** Initialization.

Set $n = 1$. Set a feasible value as the initial solution of $q_{hw}^{(n)}$.

**Step 1.** Outer loop operation.

With the obtained population distribution of locations $q_{hw}^{(n)}$, solve the DATP choice equilibrium subproblem to obtain the equilibrium DATP flow $q_{i}^{hw(n)}$, the equilibrium DATP utility $\Pi_{hw}^{(n)}$, the activity location flow $q_{s}^{(n)}(k)$, and the road link flow $x_{a}^{(n)}(k)$.

Calculate $\Phi_{hw}^{(n)}$ by the following equations

$$\Phi_{hw}^{(n)} = -\Pi_{hw}^{(n)} + \frac{1}{\theta}\ln q_{hw}^{(n)} . \tag{6.20}$$

**Step 2.** Inner loop operation (Furness iteration technique). Set $z = 1$.

***Step 2.1:*** Set $A_h^{(z)} = 1, \forall h$ as the value of $A_h$. Calculate the values of $B_w^{(z)}$ by the following equations

$$B_w^{(z)} = \frac{1}{\sum_h A_h^{(z)} S_h \exp(-\theta\Phi_{hw}^{(n)})} \tag{6.21a}$$

***Step 2.2:*** Obtain the auxiliary $\tilde{A}_h^{(z)}$ by Equation (6.21b)

$$\tilde{A}_h^{(z)} = \frac{1}{\sum_w B_w^{(z)} G_w \exp(-\theta\Phi_{hw}^{(n)})} . \tag{6.21b}$$

Obtain the auxiliary $\tilde{B}_w^{(z)}$ with the auxiliary $\tilde{A}_h^{(z)}$ by Equation (6.21a).

***Step 2.3:*** Convergence test for the inner loop operation. If the value of gap function (GF) in the inner loop

$$GFinner = \frac{\sum_h \left(\tilde{A}_h^{(z)} - A_h^{(z)}\right)^2 + \sum_w \left(\tilde{B}_w^{(z)} - B_w^{(z)}\right)^2}{\sum_h \left\|A_h^{(z)}\right\| + \sum_w \left\|B_w^{(z)}\right\|} \tag{6.22}$$

is smaller than a pre-specified tolerance, then stop the inner loop, update $A_h^{(n)} = \tilde{A}_h^{(z)}, B_w^{(n)} = \tilde{B}_w^{(z)}$, and go to Step 3. Otherwise set $A_h^{(z+1)} = \tilde{A}_h^{(z)}, B_w^{(z+1)} = \tilde{B}_w^{(z)}$, $z = z + 1$, and go to Step 2.2.

**Step 3.** Obtain the auxiliary values of $\tilde{q}_{hw}^{(n)}$ with the updated $A_h^{(n)}$ and $B_w^{(n)}$ .

**Step 4.** MSA replacement.

Update the flow pattern of population distribution of locations, $q_{hw}^{(n+1)} = q_{hw}^{(n)} + \left(\tilde{q}_{hw}^{(n)} - q_{hw}^{(n)}\right)/n$ .

**Step 5.** Convergence test for the outer loop operation.

If the value of the relative gap function (GF)

$$GF = \frac{\sum_{hw} \left( q_{hw}^{(n+1)} - q_{hw}^{(n)} \right)^2}{q} \tag{6.23}$$

is smaller than a pre-specified tolerance, then stop; otherwise, set $n = n+1$ and go to Step 1.

The time-dependent activity utilities at residential and employment locations are different for users with different residential and employment location choices, thus, solving the DATP choice equilibrium subproblem with given $q_{hw}^{(n)}$ to obtain $q_i^{hw(n)}$ in Step 1 is equivalent to solving a multi-class DATP choice UE problem. The solving of the multi-class DATP choice UE problem is given in Chapter 5.

### 6.4.2 A GENETIC ALGORITHM FOR SOLVING THE BI-LEVEL PROBLEM

Bi-level programming problems are generally difficult to solve because evaluation of the upper-level function requires the solution of the lower-level problem (Yang and Bell, 1998). Furthermore, as the lower level problem of combined user residential/employment location and DATP choice equilibrium is a non-linear problem, the bi-level problem in this chapter is a nonconvex programming problem. It is difficult to find a global optimum solution of the bi-level problem due to the nonconvexity. In view of this difficulty, the GA approach is employed to solve the bi-level programming problem in this chapter.

The basic idea of the GA approach is to code the decision variables of the upper-level problem to finite strings and calculate the fitness of each string by solving the lower-level problem. After the reproduction, crossover and mutation operations of GA, the local optimal string may be achieved.

The main steps of the GA for solving the bi-level problem of sustainable land use and transport optimization are summarized as follows:

**Step 0.** Define the parameters for the GA, including the population size, crossover rate, mutation rate, and the maximum number of generations. Code the decision variables of the upper-level problem to a finite string. Determine the transform equation to map the objective function of the upper-level problem to a fitness function.

**Step 1.** Generate an initial random population of chronmosomes. Set the generation number to $n = 1$.

**Step 2.** Evaluate the fitness functions of each chronmosome in the population by sovling the lower-level combined location and DATP choice problem (which is discussed in Section 6.4.1), and reproduce the population of chronmosomes according to the distribution of the fitness function values.

**Step 3.** Carry out the crossover operation with the crossover rate.

**Step 4.** Carry out the mutation operation with the mutation rate. Then, a new population of chronmosomes is obtained.

**Step 5.** Check the stopping criterion (the maximum number of generations). Terminate the procedure and adopt the chronmosome with the highest fitness as the optimal solution the problem, if the stopping criterion is satisfied; otherwise, set $n = n+1$ and go to Step 2.

## 6.5 NUMERICAL EXAMPLE

The purposes of the following numerical example are: (i) to illustrate the application of the proposed activity-based bi-level model and the proposed solution algorithm for solving the sustainable land use and transport optimization problem; (ii) to show the advantages of the proposed model over traditional continuous transport network design models, as an aid to improving the performance of land use and transport systems; (iii) to investigate the effects of the sustainable optimization policy on user residential/ employment location choice behaviour, and DATP choice behaviour; (iv) to illustrate the merits of the activity-based approach in providing more comprehensive characterization of user response behaviour of residential/employment location choice and daily activity/travel choice in investigating sustainable land use and transport optimization problems; (v) to study the relationships between the traffic emission control level and the sustainable optimization policy, and the interactions between traffic emission control level and user residential/employment location and DATP choice behaviour.

### 6.5.1 BASIC INPUT DATA

Figure 6.1 is a simple road network which consists of sixteen directional links and five nodes. The link free-flow travel times, the link capacities, and the link lengths are given in Table 6.1. Node 1 and Node 5 represent two residential zones in which users can choose to reside. Node 2 and Node 4 represent two employment zones in which users can choose to work. Node 4 represents the shop/restaurant area. Node 3, Node 4 and Node 5 are in the CBD zone. The existing zonal residents and workers are listed in Table 6.2.

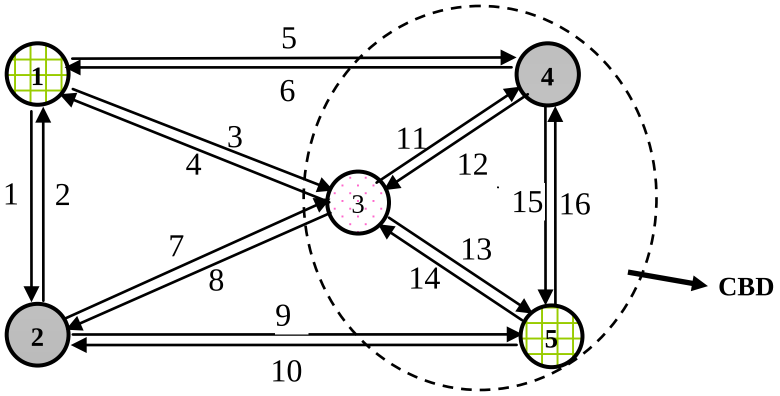


**Figure 6.1 An Example Urban Network**

**Table 6.1 Link Data of the Network**

| Link | 1,2 | 3,4 | 5,6 | 7,8 | 9,10 | 11,12 | 13,14 | 15,16 |
|---|---|---|---|---|---|---|---|---|
| Free-flow travel time (min) | 10 | 30 | 50 | 40 | 50 | 10 | 10 | 10 |
| Capacity(veh/hour) | 1800 | 1800 | 1800 | 1800 | 1800 | 1800 | 1800 | 1800 |
| Length(km) | 10 | 30 | 50 | 40 | 50 | 10 | 10 | 10 |

**Table 6.2 Existing Residents and Workers in the Network**

| Zone | Residents/Workers |
|---|---|
| Residential Node 1 | 2500 |
| Residential Node 5 | 2500 |
| Employment Node 2 | 2000 |
| Employment Node 4 | 3000 |

For the DATP choice sub-problem, the entire study time period is from 6:00 to 24:00 and equally divided into 108 intervals (i.e. 10 minutes per interval). At home and eating activities can be performed at the selected residential zone (i.e. Node 1 or Node 5). Work and eating activities can be performed at the selected employment zone (i.e. Node 2 or Node 4). Shopping and eating activities can be performed at Node 3.

The marginal utility profiles of activities are the same as those shown in Figure 3.5 but for following differences: (1) The marginal utility profile of residents' at home activity at Node 5/Node 1 is the same as that of at home activity shown in Figure 3.5. (2) The marginal utility profile of work at Node 4 is the same as that of work shown in Figure 3.5. The marginal utility profile of work at Node 2 is 0.7 times that of work shown in Figure 3.5. (3) It is assumed that for eating activity at Node 3, only lunch is served. The temporal marginal utility of eating at residential zones and the employment zones is 0.6 times that of eating as shown in Figure 3.5. (4) Parking fees of HK$18/hour at Node 2, HK$15/hour at Node 3, and HK$25/hour at Node 4, are incorporated (Note that US$ 1.00 = HK$ 7.8). As it is difficult to distinguish the exact start and end times of different activities conducted at home, eating activity at the selected residential location and other at home activities at the residential location are combined as an at home activity.

The total population in the study area is assumed to have increased from 5000 to 7000 which means that $\Delta q = 2000$. The land use development is allowed to expand up to 4000 housing/ job supply for each residential/employment zone (from Table 6.2, i.e. $0 \le \Delta S_1 \le 1500$, $0 \le \Delta S_5 \le 1500$, $0 \le \Delta G_2 \le 2000$, and $0 \le \Delta G_4 \le 1000$). The capacity of the road links is allowed to expand up to 2400 veh/hour for each link (from Table 6.1, i.e. $0 \le \Delta C_a \le 600, \forall a$ ). The costs of the residential and employment developments, and the road link capacity expansions are given by $F_h = (\Delta S_h)^2 \times 10^3$, $F_w = (\Delta G_w)^2 \times 10^3$, and $F_a = 0.3(\Delta C_a)^2 \times 10^3$, respectively. The maximum budget for the sustainable optimization project is $5.2 \times 10^9$ HK$ (i.e. $M = 5.2 \times 10^9$). The maximum permissible traffic emission level for the network is $2.5 \times 10^4$ grams/day (i.e. $E = 2.5 \times 10^4$). Suppose that $\sigma$ =HK$60/hour and the dispersion parameter $\theta = 0.8$.

The parameters used in the GA algorithm are given as follows: (1) Population size is 20; (2) The maximum number of generation is 500; (3) The crossover probability is 0.6; (4) The mutation rate is 0.0333. The computer program for the proposed solution algorithm was coded in Matlab (2009a version) and run on a laptop with CPU 2.80GHz.

### 6.5.2 THE SOLUTIONS OF THE SUSTAINABLE OPTIMIZATION PROBLEM

The model proposed in this chapter is denoted as Model I. The model is an activity-based bi-level model, the aim of which is to deal with sustainable land use and transport optimization problems. The optimization solution to the above sustainable optimization problem after the application of Model I is shown in Table 6.3.

### Table 6.3 Optimization Solutions of the Bi-level Problems

| | Model I (Proposed) | Model II (Traditional) |
|---|---|---|
| The total network social welfare(HK$/day) | 4.65x10$^{6}$ | **4.10 x10$^{6}$** |
| Total traffic emissions(grams/day) | 2.46x10$^{4}$ | **1.27 x10$^{5}$** |
| Total budget used(HK$) | 5.13x10$^{9}$ | 1.73 x10$^{9}$ |
| Budget used for land use development(HK$) | 4.10 x10$^{9}$ | N/A |
| Budget used for link capacity expansion(HK$) | **1.03 x10$^{9}$** | **1.73 x10$^{9}$** |
| Land use development | | |
| Node 1(residential location development) | 910 | N/A |
| Node 5(residential location development) | **1090** | N/A |
| Node 2(employment location development) | 791 | N/A |
| Node 4(employment location development) | **1209** | N/A |
| Link capacity expansion(veh/hour) | | |
| Link 1/ Link 2 | 274/**600** | 600/600 |
| Link 3/ Link 4 | **596**/51 | 599/600 |
| Link 5/ Link 6 | **596**/117 | 600/600 |
| Link 7/ Link 8 | 57/0 | 600/598 |
| Link 9/ Link 10 | 119/**596** | 600/600 |
| Link 11/ Link 12 | **596**/358 | 600/600 |
| Link 13/ Link 14 | **596/596** | 600/600 |
| Link 15/ Link 16 | **5956/593** | 600/598 |

Consider the results of Model I shown in Table 6.3. The main residential and employment location development is conducted in Node 5 and Node 4, respectively. These two nodes are in the CBD. This indicates that users prefer to reside or work in the CBD. The reason is probably due to the traffic network topology as shown in Figure 6.1.

The results of Model I presented in Table 6.3 also show that the main link capacity expansion is conducted at Link 1, Link 2, Link 3, Link 5 and the links in the CBD (i.e. Link 11, Link 12, Link 13, Link 14, Link 15, and Link 16). In most previous relevant studies (Boyce and Mattsson, 1999; Meng et al., 2000; Yim et al., 2011) which use the trip-based approach to capture user combined residential/employment location and travel choice behavior, it is generally believed that the road links which connect users' residential location and their employment location are critical links, the capacities of which should be more urgently expanded than that of other links. Following that belief, in this example, the capacities of Link 5 and Link 6 which connect Node 1 and Node 4 should be urgently improved. However, with the application of the proposed activity-based bi-level model, the capacities of Link 5 and Link 3 rather than Link 6 are largely improved. Another finding which may also not be revealed in previous relevant trip-based studies is that for the two links which connect the same two nodes but with different directions, the link capacity expansions might be different. For example, the link capacity expansion of Link 1 which is from Node 1 to Node 2 is 274 veh/hour while the link capacity expansion of Link 2 which is from Node 2 to Node 1 is 600 veh/hour.

In summary, the results of Model I as shown in Table 6.3 indicate that with the application of the proposed activity-based bi-level model and the proposed solution algorithm, the sustainable land use and transport optimization problems could be solved. The results also imply that, compared to previous relevant trip-based studies, more accurate and efficient land use and transport optimization policies can be explored with the application of the proposed model which adopts the activity-based approach to capture user response behaviour.

### 6.5.3 COMPARISON OF THE RESULTS OF THE PROPOSED MODEL AND A TRADITIONAL TRANSPORT NETWORK DESIGN MODEL

The results of the model (Model I) proposed in this chapter are compared with the results of a traditional transport continuous network design model (Model II). In Model II, the optimization problem of road link capacity expansion only, is studied. Such link capacity expansion is conducted within the budget constraint given above, the aim of which is to maximize social welfare. The bi-level programming technique and the GA are also adapted to deal with the optimization problem in Model II. Note that in Model II, user DATP choices in response to the optimization policy are investigated, but user residential/employment location choices are not examined. The population distribution of residential/employment locations is exogenously given and listed in Table 6.4.

**Table 6.4 Given Population Distribution of Residential/Employment Locations**

| | Residential location Node 1 | Residential location Node 5 |
|---|---|---|
| Employment location Node 2 | 500 | 1500 |
| Employment location Node 4 | 2500 | 2500 |

Consider the results of Model II as presented in Table 6.3. It is seen that almost all road link capacities are expanded to their maximum 2400 veh/hour (i.e. 1800veh/hour + 600veh/hour). The budget used for the link capacity expansion of Model II is $1.73\times10^{9}$ HK$, which is greater than $1.03\times10^{9}$ HK$ of Model I. Although the budget used for road link capacity expansion has thus increased, the total traffic emissions per day of Model II fail to decrease but, rather increase by more than 5 times that of Model I, i.e. $\left(1.27\times10^{5}\right)/\left(2.46\times10^{4}\right)=5.16$. Also of interest is the fact that the total network social welfare of Model II ($4.10\times10^{5}$ HK$/day) also decreases 12%, compared to that of Model I ($4.65\times10^{6}$ HK$/day). The results of the decreased social welfare and increased traffic emissions imply that the optimization policy provided by the traditional method of Model II, is less efficient than the optimization policy offered by the model (Model I) proposed in this chapter. Additionally, given the population distribution of residential/employment locations, the strong interactions between user residential/employment location choices and user DATP choices cannot be fully captured in Model II. Users are hindered from selecting the optimum combination of residential/employment location choice and DATP choice. The effect of this failure could also lead to social welfare decrease and/or traffic emission increase.

### 6.5.4 COMPARISON OF USER BEHAVIOUR WITH/WITHOUT THE OPTIMIZATION POLICY

To illustrate the interactions between the optimization policy from the government in the upper level of the proposed bi-level model and the residential/employment location and DATP choice behaviours of users in the lower level, the user choice behaviour results with and without the optimization policy are compared in Table 6.5.

Case I is the above case where the land use and transport network are optimized simultaneously. Case II is the case without the optimization policy. It is assumed that in Case II the residential and employment development for Node 1, Node 5, Node 2, and Node 4 is equal to each other (i.e. $\Delta S_1 = \Delta S_5 = 1000$, $\Delta G_2 = \Delta G_4 = 1000$), and there is no road link capacity expansion.

Focusing on the results of Case I and Case II shown in Table 6.5, it can be seen that the average user equilibrium utility of choices increases from 573.03 HK$/user/day to 663.76 HK$/user/day due to the optimization policy. This implies that it is necessary to optimize the sustainable land use and transport policy to have an impact on user behaviour and to further improve the efficiency of the land use and transport systems. It is also seen that the average traffic emission per user decreases dramatically due to the optimization policy. The indication is that it is also necessary to jointly optimize the land use and transport network for the purpose of sustainable development. The population distribution of residential/employment locations and user daily activity/travel choices in Case I and Case II, are also summarized in Table

6.5. It can be seen that the effects of the optimization policy on user location choices and daily activity/travel choices are significant.

**Table 6.5 The Effects of the Optimization Policy on User Behaviour**

| | Case I | Case II | Case III |
|---|---|---|---|
| Average user equilibrium utility(HK$/user/day) | **663.76** | **573.03** | **-13.97** |
| Average traffic emission(grams/user/day) | **3.53** | **4.18** | **0.60** |
| Population distribution of residential-employment locations | | | |
| Node 1-Node 2 | 2525 | 2596 | 1544 |
| Node 1-Node 4 | 885 | 904 | 1866 |
| Node 5-Node 2 | 266 | 404 | 1247 |
| Node 5-Node 4 | 3324 | 3096 | 2343 |
| Some characteristics of user daily activity/travel choices | | | |
| Number of out-of-home activities | 4.25 | 3.65 | 1 |
| Number of trips | 4.87 | 4.43 | 1 |
| Average work duration (hour/user) | 9.78 | 9.06 | N/A |
| Average travel time (hour/user) | 1.45 | 2.32 | 0.233 |

### 6.5.5 COMPARISON OF USER BEHAVIOUR REVEALED BY THE TRIP-BASED APPROACH AND BY THE ACTIVITY-BASED APPROACH

To illustrate the merits of the activity-based approach in examining user response behaviour, the user behaviour results captured by the trip-based approach under the above optimization policy are summarized in Case III of Table 6.5. In Case III, only work activity is considered and the simple trip of home to work is examined. In Case III, users choose residential and employment locations based on the minimum travel time of the trip from the selected residential location to the selected employment location instead of the maximum equilibrium utility of DATP choices.

Consider the results of Case I and Case III shown in Table 6.5. It can be seen that there are significant differences between the user behaviour results of the activity-based approach and those of the trip-based approach under the above optimization policy. In Case III, the resulting average traffic emission, number of out-of-home activities, number of trips, and the average daily travel time of users by the trip-based approach are underestimated. Furthermore, the population distribution of residential/employment locations by the trip-based approach is biased. The results demonstrate that the activity-based approach provides a way for more comprehensively capturing user response behaviour than the trip-based approach. Therefore, it can be concluded in Section 6.5.2 that more accurate and efficient land use and transport optimization policies can be explored with the application of the proposed activity-based bi-level model.

### 6.5.6 SENSITIVITY ANALYSIS

In this section, the sensitivity analyses of the budget level, and the traffic emission control level for the sustainable land use and transport optimization problems, are investigated.

Firstly, the sensitivity analysis of the budget level with a fixed traffic emission control level at $2.50 \times 10^4$ grams/day is conducted, and the optimization results of which are shown in Figure 6.2.

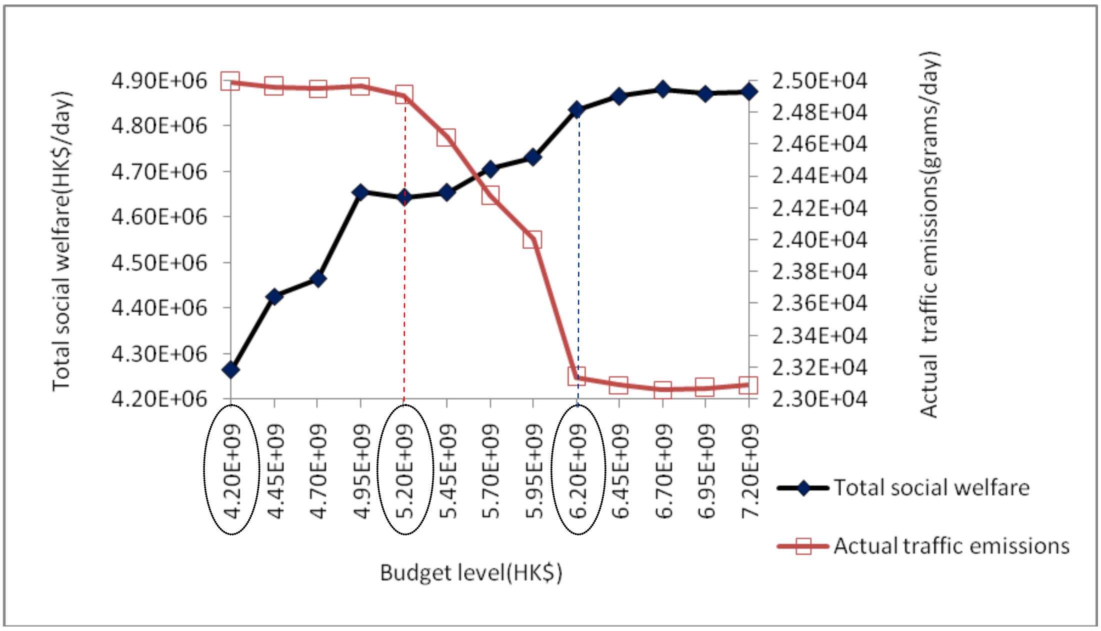


**Figure 6.2 Optimization Results on the Total Social Welfare and Actual Traffic Emissions Against Different Budget Levels**

Two main findings regarding the relationship between the network total social welfare and the budget level can be seen in Figure 6.2: (1) the network total social welfare always increases with the increasing budget level while the traffic emission control level is fixed, but not in all cases; (2) when the budget level reaches a value of $6.20 \times 10^9$ HK$, the total social welfare is maximized and stabilized.

The first finding indicates that the budget level increase is helpful for improving social welfare, in most cases. The second finding suggests that it is meaningless to increase the budget level to larger than $6.20 \times 10^9$ HK$ for the purpose of improving the total social welfare. This possibly because the capacities of the network critical links have already been expanded up to their maximum limits and the land use development have already been the optimum pattern. In such a situation, a further increase in the budget level would not enable a significant improvement in the network social welfare.

From the curve of actual traffic emissions against budget level, presented in Figure 6.2, it is seen that the actual total traffic emissions decreases with the increasing budget level. It is found the slope of this curve during the budget level interval {$4.20\times10^9 \sim 5.20\times10^9$ HK$}, is gentle. This suggests that the traffic emission control constraint is active at that budget level interval, so the actual total traffic emissions are kept around at the fixed traffic emission control level($2.50\times10^4$ grams/day). From the curve, it is also found that he actual traffic emissions remain stable while budget level reaches a value of $6.20\times10^9$ HK$. The reason is possibly the same as that discussed in the previous paragraph which causes the stabilization of the network social welfare. It is interesting to note that when the budget level is less than $4.20\times10^9$ HK$, there is no solution to the sustainable optimization problem because the actual traffic emissions tend to be larger than the settled control level.

Secondly, a sensitivity analysis of the traffic emission control level with a budget level fixed at $5.20\times10^9$ HK$, is conducted, and the optimization results of which are shown in Figure 6.3. It is found that the traffic emission control level sensitivity analysis can only be conducted on a narrow interval {$2.75\times10^4 \sim 2.35\times10^4$ grams/day} because of restraints caused by the budget level constraint. It means that if traffic emissions are expected to be controlled below $2.35 \times 10^4$ grams/day, the government should increase the budget level; otherwise the conflict between the budget level control and the traffic emission level control will appear. Therefore, the government should avoid such conflict while using the proposed model to deal with sustainable optimization problems.

From the curve in Figure 6.3 regarding traffic emission control level against total social welfare, it is seen that the impacts of traffic emission control level on the total social welfare are wild. The reason for this result could be that the sensitivity analysis is only conducted in a narrow interval of traffic control levels.

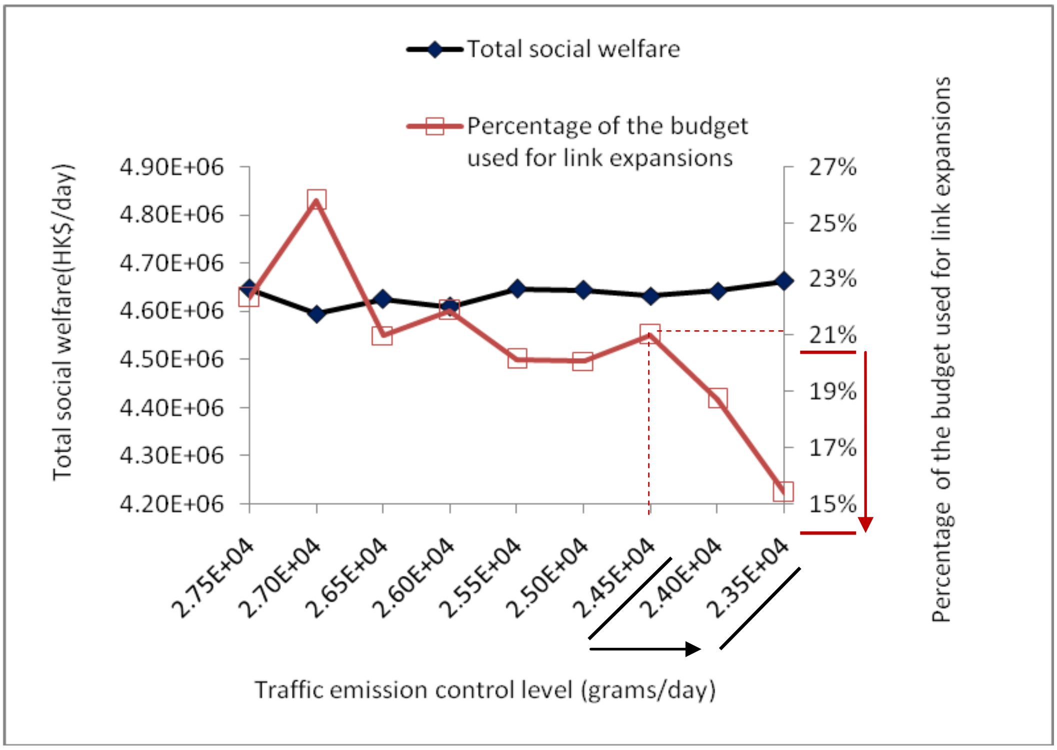


**Figure 6.3 Optimization Results on the Total Social Welfare and the Percentage of the Budget Used for Link Capacity Expansions Against Different Traffic Emission Control Levels**

Figure 6.3 also presents the percentage of the budget used for the road link capacity expansions against different traffic emission control levels. It is generally believed that with the fixed total budget level, the percentage of the budget used for link capacity expansion should increase while the traffic emission control level is decreased. It is likely to be necessary to increase the road link capacity expansion budget in order to relieve traffic congestions and to satisfy the decreased traffic emission control level.

However, as shown in Figure 6.3, it is not the fact from the information indicated by the curve of optimization results on the percentage of the budget used for link expansions against different traffic emission control levels. In Figure 6.3, the optimum percentage of the budget used for the road link capacity expansions does not increase with the decrease of the traffic emission control level in all cases. Particularly, when the traffic emission control level decreases from $2.45\times10^4$ grams/day to $2.35\times10^4$ grams/day, the percentage of the budget used for link capacity expansions does not increase but decrease from 21% to 15%. This result appears probably due to the interactions between land use and transport. Note that while the percentage of the budget used for link capacity expansions decreases from 21% to 15%, the consequence is to increase the percentage of the budget used for land use development(i.e. used for residential allocation ability improvement and employment allocation ability improvement) from 79% to 85%. The increase of the budget used for land use development would contribute to impacts on re-distribution of residential/employment locations. Such impacts make users to adjust their residential/employment locations choices subsequently. This adjustment would affect travel demands over the transport network due to the changes of origins and destinations of users' daily travels. The travel demands in turn may result in the relief of traffic congestion, hence leading to reduction in traffic emission control level. The results indicate that for solving traffic emission or traffic congestion problems, it should be not confined to the transport system. An appreciate land use development policy may be a better way to solve traffic-related problems due to the interactions between land use and transport.

## 6.6 SUMMARY

In this chapter, an activity-based bi-level model for solving the sustainable land use and transport optimization problem of the residential/employment location development and road link capacity expansion, has been proposed. In this model the activity-based approach was applied to model combined user residential/employment location and DATP choice behaviour. A solution method was developed and applied to a numerical example for illustrating the merits of the proposed model. The numerical example results demonstrated that that it was strongly meaningful to jointly optimize the residential/employment location development and road link capacity expansion for improving the performance of the land use system and transport system with the limited resources available and with the objective, also, of sustainable development. The results also revealed that the activity-based approach provided a comprehensive way for examining user behaviour in response to the sustainable optimization policies.

It should be acknowledged that, in order to present the essential ideas of this chapter, some restrictive assumptions were made and only a simple network example was provided. Further research work should be carried out in the following two aspects: (a) to consider the sustainable land use and transport optimization problem where the development of more activity locations (e.g., shopping malls and schools) is studied; (b) to investigate the sustainable land use and transport optimization problem with the realistic networks in practice.

# 7 CONCLUSIONS

This thesis aimed to develop activity-based models to enable better understanding of user travel and residential/employment location choice behaviours in order to solve the sustainable land use and transport optimization problems. The major contributions of this research consist of: (1) proposing activity-based transport models to capture user daily activity-travel choice behaviours; (2) developing an activity-based land use and transport model to investigate combined user residential location and travel choice behaviours for long-term strategic planning purposes; (3) and exploring an activity-based bi-level programming model for solving the sustainable land use and transport optimization problems.

In Chapter 3 of this thesis, an activity-based UE traffic assignment model is firstly developed to deal with the user daily activity scheduling problems in congested road networks. The developed UE model is extended in Chapter 4 to investigate user daily activity scheduling problems which incorporate the stochastic dimensions in user choices for both non-congested and congested road networks. In Chapter 5, a novel activity-based SUE model is proposed to examine user combined residential location and travel choice problems. In the proposed SUE model, users' residential location choices and daily travel choices are simultaneously examined by an activity-based approach. Finally, on the basis of the work described in Chapter 3, Chapter 4, and Chapter 5, an activity-based bi-level programming model is developed in Chapter 6 for solving the sustainable land use and transport optimization problems.

The main achievements of this research are summarized as follows:

1. Two analytical activity-based network equilibrium models have been developed for dealing with the user daily activity scheduling problems in road networks. Some analytical activity-based studies have been conducted from the information presented in the literature. The developed models in this research extend the existing work by providing a more comprehensive framework, which incorporates the impacts of traffic congestion, interactions between activities at different time intervals, flexible activity durations, and flexible activity sequences. The more comprehensive framework improves the accuracy of the estimation of user travel choice behaviour.
2. The properties of user daily activity and travel choices at the network equilibrium conditions have been discussed. These properties offer important information for better understanding of user travel choice behaviour and the relationship between user daily activity choices and user daily travel choices.
3. Heuristic algorithms have been developed for solving daily activity scheduling UE problem in congested networks and SUE problem in general road networks (i.e. both noncongested networks and congested networks). The advantage of the developed algorithms is that there is no need to enumerate DATPs. In contrast, most previous studies require a prior enumeration of DATPs. That requirement leads to the burdensome computation of exponential-time growth which inhibits the use of the potential application of the analytical activity-based models in practice.
4. An activity-based network equilibrium model and a heuristic algorithm have been proposed for dealing with the combined user residential location and travel choice problems. This activity-based model provides a better way of

understanding the close relationship between user travel choice behaviour and user residential location choice behaviour. This model also avoids the inconsistency which may have existed in previous nested land use and transport models.

5. An activity-based bi-level model and a heuristic algorithm have been developed for dealing with sustainable land use and transport optimization problems for both the economic development purpose and the traffic pollution control purpose. The activity-based model offers a powerful tool to represent the interactions between land use and transport. The application of the developed model and algorithm could improve the efficiency of resource allocation in the land use system and transport system.

The major findings of this research are listed as follows:

1. Firstly, it was found that dealing with trips separately and ignoring the relationship of trips might lead to inconsistency problems in user daily activity/travel choice problems. The constraint of fixed activity durations or given activity sequences might hinder users from selecting optimal DATP choices. Thus, it was necessary to investigate the user daily activity scheduling problems in a comprehensive way for full understanding of user travel choice behaviour.
2. Secondly, it was found that the stochastic dimensions of activity utilities and travel disutility should be considered, otherwise, the DATP choice results might be overestimated or underestimated. A distinction also should be made between the different perception variations of compulsory activities, noncompulsory

activities, and travel times; otherwise, the estimated DATP choice results would probably be biased.

3. Thirdly, it was found that user residential location choices were significantly influenced by the accessibility of a transport network. User residential location choices and income levels, in turn, were the critical factors that influenced user DATP choice behaviours. The activity-based land use and transport models were valuable tools for estimating the impacts of land use or transport policies on user residential location choice and travel choice behaviour.
4. Finally, it was found that an appreciate land use-related policy  might be a better method than transport-related policies to relieve traffic congestions, due to the interactions between land use system and transport system. Therefore, it is meaningful to jointly optimize land use development and transport network expansions.

Based on this research work, several issues merit further study:

1. It should be pointed out that only individual activity-travel choices, or household representative residential/employment location choices are considered in this research. In future studies, effects on activity/travel choice and location choice behaviour of inter-personal dependence among household members should be examined.
2. Activity utility functions have importance in activity-based studies. Thus, to apply analytic activity-based methods in real networks, work of calibrating and validating parameters of activity utility functions with empirical data, is suggested for future studies.

3. This research was conducted on the assumption that all users were car users and the assumption of one person one car. The car sharing behaviour among family members is an interesting topic for future activity-based studies. This research could also be extended to multi-modal transport networks.
4. In this research, the activity-based approach was used to investigate the combined user residential location and travel choice problems without considering the housing supply and demand market. The incorporation of the housing market clearing mechanism in the combined user residential location and travel choice problems should be included for future work.
5. The developed activity-based bi-level model for sustainable land use and transport optimization could be extended to consider the joint land use and transport optimization problems where the development of more activity locations such as schools and shopping malls, are considered.

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# APPENDIX THE STEP-BY-STEP PROCEDURE OF AN ATS NETWORK EXPANSION

The step-by-step procedures of the ATS network expansion approach presented in Section 3.3.1 of Chapter 3 is given as follows (refer to Figure 3.1).

**Nodes:**

— Each node $n_s (s \in S)$ of the base road network is expanded into $\overline{K} + 1$ nodes $n_s^k$, $k = 1,2,...,\overline{K}, \overline{K} + 1, s \in S$.

— Each road link $b = (n_s, n_{s'})$, $b \in B, s \in S, s' \in S$, for $k = \bar{t}_b + 1, \bar{t}_b + 2, ..., \overline{K}, \overline{K} + 1$, construct:

-- $k - \bar{t}_b$ nodes (i.e. $l_b^{k-\bar{t}_b,k}, l_b^{k-\bar{t}_b-1,k}$ ,..., $l_b^{1,k}$), when $1 + \bar{t}_b \le k \le \overline{W} + \bar{t}_b$;

-- $\overline{W} + 1$ nodes (i.e. $l_b^{k-\bar{t}_b,k}, l_b^{k-\bar{t}_b-1,k}$ ,..., $l_b^{k-\bar{t}_b-\overline{W},k}$), when $k > \overline{W} + \bar{t}_b$.

For constructed node $l_b^{g,k}$, $g$ denotes the interval of users entering road link $b$, $b \in B$ and $k$ denotes the current interval.

**Links:**

***Activity links:*** at each expanded node $n_s^k$, $k = 1,2,...,\overline{K}, s \in S$, construct

— one activity link $(n_s^k, n_s^{k+1})$;

***Travel/queuing/exit links:*** for each road link $b = (n_s, n_{s'})$, $b \in B, s \in S, s' \in S$, construct,

— for each constructed node $l_b^{g,k}$ , $g = 1,...,k - \bar{t}_b$ or $g = k - \bar{t}_b - \overline{W},...,k - \bar{t}_b$ , $k = 1,2,...,\overline{K} + 1$:

-- one exit link $(l_b^{g,k}, n_s^k)$ while $g = 1$, or one exit link $(l_b^{g,k}, l_b^{g-1,k})$ while $g > 1$;

-- one queue link $(l_b^{g,k}, l_b^{g,k+1})$ while $k \le \overline{K}$ ;

— for $k = 1,2,...,\overline{K}, \overline{K} + 1 - \bar{t}_b$ : one travel link $(n_s^k, l_a^{k,k+\bar{t}_b})$ .

***Start links and end links:*** In order to show how users enter and exit the expanded ATS network, one dummy node $\overline{O}$ is introduced as the start node and one dummy node $\overline{D}$ as the end node.

while $k = 1$, for each expanded node $n_s^1$ , $s \in S$ , construct

— one dummy start link $(\overline{O}, n_s^1)$;

while $k = \overline{K} + 1$, for each expanded node $n_s^{\overline{K}+1}$ , $s \in S$ , construct

— one dummy end link $(n_s^{\overline{K}+1}, \overline{D})$.

In addition, if more than one activity feasible at a location, $\overline{K}$ dummy nodes and $\overline{K}$ dummy links for each additional feasible activity $j$ ( $j \in J$ ) should be introduced to the ATS network to differentiate activities at the same location $s$ ( $s \in S$ ). The dummy nodes are denoted as $n_{s,j}^k$ for $k = 1,2,...,\overline{K}$ . The dummy links are constructed from node $n_s^k$ to dummy node $n_{s,j}^k$ for $k = 1,2,...,\overline{K}$ . For each additional feasible activity $j$ , $\overline{K}$ activity links from dummy node $n_{s,j}^k$ to node $n_s^{k+1}$ for $k = 1,2,...,\overline{K}$ , are also constructed in the ATS network to represent users' one-interval activity participation process.