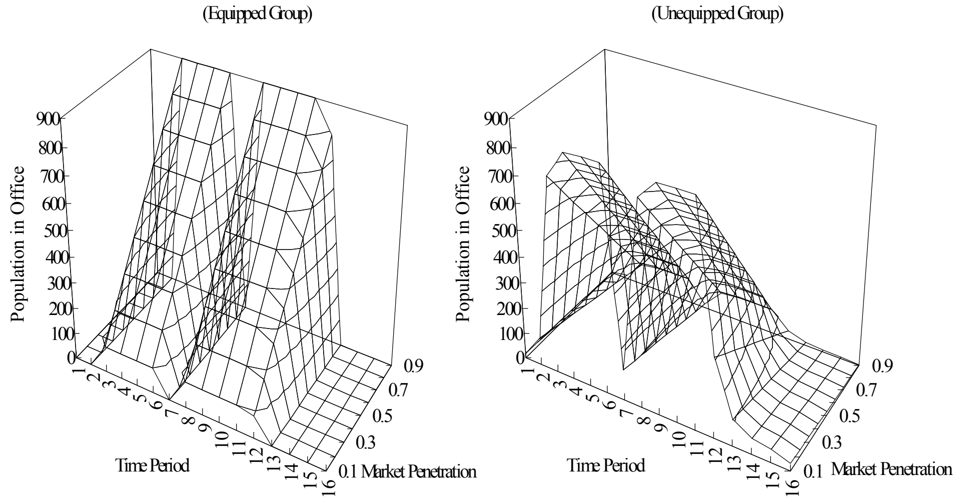

Modelling Commuter Behaviour in Networks with ATIS for Combined Activity/Destination/Route Choice Problem

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Modelling commuter behaviour in networks with ATIS for combined activity/destination/route choice problem

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Abstract

It is well known that the use of advanced traveler information systems (ATIS) can alleviate traffic congestion and enhance the performance of road networks through guiding commuters' route and departure time choices. It has also been recognised that ATIS can help destination and activity choices in determining why, where and when various activities are engaged in. This paper attempts to model the activity/destination/route choice behaviour in a time-dependent network with ATIS. Commuters are divided into two groups, one equipped with ATIS and another unequipped, being different in evaluating travel time and comprehensive utility. This multi-class activity/destination/route choice problem is formulated as an equivalent mathematical programming model. It is a time-dependent model that can be used for analysing the long-term effects by ATIS. Finally, the impacts of ATIS on an example network are investigated under various levels of ATIS market penetration.

Keywords

Activity/destination/route choice behaviour, Advanced traveler information systems, Multinomial logit formula, Stochastic user equilibrium, International Conference on Travel Behaviour Research, IATBR

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1. INTRODUCTION

Advanced Traveler Information Systems (ATIS) have experienced a rapid growth in the past decade, as an alternative to alleviate traffic congestion and enhance the performance of road networks. Proliferation of new implementations and expansion in number of ATIS users impose urgent challenges to transportation researchers for assessing their impacts. Modeling user behaviors under ATIS and evaluating of ATIS benefits are required so as to investigate the feasibility, effects and uncertainty of ATIS technologies. Dozens of researchers have devoted themselves to filling in the gap between the practice and theory for assessing ATIS impacts, and substantial results have been achieved through approaches of laboratory experiments, mathematical and computer simulation models and even field deployments (Yang, 1998).

Most of the previous analytical models that aimed for benefit evaluation of ATIS are deficient in two aspects. One is, these models do not consider some important ATIS impacts such as changes in activity and destination choices (Lam and Huang, 2002). Apart from the information related to traffic conditions, the prevailing ATIS also provides commuters social and business information. As a result, it can help travelers in making destination and activity choices so as to determine why, where and when various activities are engaged in. The other is, these models are based on a strong assumption that the network travel time is deterministic for a given flow pattern. However, in reality, road travel time is intrinsically random due to traffic incidents and traveler's perceptive error.

In this paper, all the commuters are divided into two groups; namely commuters equipped and unequipped with ATIS. A mathematical programming model is proposed to examine the interactions among equipped and unequipped commuters on the combined problem of activity, destination and route choices over a time-dependent network. In order to assess network performances and individual welfare changes, such as total (individual) travel time, total (individual) disutility and time utilization at various levels of market penetration of ATIS, the proposed model can be used to quantify properly the potential benefits of ATIS implementations and to analyze their impacts on commuters' behavior.

In contrast to the traditional trip-based approach, the activity-based approach is adopted in this paper. This approach studies travel patterns in the context of structure of activities, of the individual or household, with a framework emphasizing the importance of time and space constraints (Goodwin, 1983). Comprehensive review on this activity-based approach can be found in Damm (1983) and Jones et al. (1990). Axhausen (1990) combined an activity chain simulation model with a traffic flow simulation model, to achieve a simultaneous simulation of activity chains and traffic flows. Fellendorf et al. (1995) presented an activity-based demand forecasting process in which trip chains are generated from given activity chains and travel demands are allocated to various transport modes by a multinomial logit model. Kitamura et al. (1996) proposed a dynamic and integrated micro-simulation forecasting system which was referred to as a sequenced activity mobility simulator.

Concerning the trip chaining problems, there is a number of studies investigating the effects of non-work activities (i.e., the ones carried out on the way to or from work) on the basic home-work-home trip chain. Oster (1979) emphasized the "second role" of the work trip that is to provide the opportunity to link non-work trips. Damm (1982) developed a theoretical model to examine whether someone participates in a non-work activity and if so, for how long. Kondo and Kitamura (1987) investigated whether a commuter will make the non-work stop during the commuting trip or, alternatively, will pursue the non-work activity by making a separate trip chain from home. Nishii et al. (1990) made an empirical analysis of trip chaining behavior.

However, speaking frankly, the current development of this activity-based approach lacks rigidly structured, quantitative methods or analytical models (Lam and Yin, 2001; Lam and Huang, 2002). In addition, most of the related models are static and deterministic in nature. Clearly, the dynamic or time-dependent and stochastic activity-based models may represent more accurately the real time traffic conditions in a transportation network. In this paper, a conceptual time-dependent model is proposed for studying the stochastic activity/destination/ route choice problem. The proposed model is aimed to assess coherently the long-term strategic effects of ATIS on activity/destination/route choice behaviors.

In this paper, an equivalent mathematical programming model is presented to examine the impacts of ATIS on the combined activity/destination/route choice problem. It is a time-dependent multi-class model for long-term assessment of the benefits of ATIS. The activity/destination choices are based on multinomial logit formulae and, the route choice is governed by the stochastic user equilibrium (SUE) principle. The solution algorithm is proposed and applied to a numerical example for demonstration. It is shown that the proposed modeling approach provides a powerful tool for assessing the complex travel behavior in networks with ATIS.

In the next section, we firstly describe some basic considerations for the model formulation and then present the time-dependent multi-class model. In Section 3, we develop a solution method for the proposed model. Section 4 provides a numerical experiment to evaluate the impacts of ATIS. A summary is given in Section 5 together with recommendations for future research.

2. BASIC CONSIDERATIONS

In this section, the assumptions adopted for the proposed model are firstly discussed. It follows with formulation of the multinomial logit-based activity/destination choice problem. The formula is then developed to involve the stochastic user equilibrium condition for route choice. Finally, an equivalent mathematical programming is proposed for the time-dependent and stochastic activity/destination/route choice problem.

2.1 Assumptions

A general urban transportation network consists of nodes and directed links. Let a represent a link and p a path (or route). An origin node, which generates trips, may also be a destination node that attracts trips from other origin nodes, and *vice versa*. For a specified time period, a path that connects an origin r and a destination s, is simply an acyclic ordered set of links. In order to facilitate the presentation of the essential ideas without loss of generality, the following assumptions are made in this paper.

(i) The activity/destination/route choice problem is investigated in a fixed study horizon, T, generally a whole day. The T is divided equally into a number of time periods, k $(=1,2,\cdots,K)$. Since the time-dependent model proposed in this paper is used for long-term assessment purpose, the period duration is set to be reasonably long, such as one hour, so that most path flows departing from their origins can finish their journey in one period.

(ii) In each period, people face alternatives of choice: what to do (activity choice, *i*), where to do it (destination choice, *s*), and by which path to go (route choice, *p*). The transport mode choice is not considered in this paper in order to simplify the presentation of the essential ideas and the car occupancy is fixed and equal to one person per car.

(iii) There are two groups of commuters, one equipped with ATIS and another one without ATIS. Both groups of commuters have no perfect knowledge of traffic conditions throughout the whole network and make their route choice decisions according to the logit-based stochastic user equilibrium (SUE) principle. However, the group of commuters equipped with ATIS would have less perception error in computing route travel time than the other group.

(iv) A comprehensive utility is used to quantify the satisfaction level perceived by a commuter who selects a route to a destination and performs an activity there. This comprehensive utility is associated with travel time, destination and activity. Each commuter equipped with ATIS has less perception error in computing comprehensive utility than the one unequipped with ATIS.

(v) The time to traverse a link in period *k*, is simply given by a BPR (Bureau of Public Road) function: $t_a(k) = t_a^0[1+150(u_a(k)/s_a)^4]$, where t_a^0 is the free-flow travel time (minutes) on link *a*, s_a is the link capacity (veh/hr) and $u_a(k)$ is the traffic flow on link *a* in period *k*.

2.2 Activity and Destination Choices

Define $U_i^{rs}(k)$ and $\tilde{U}_i^{rs}(k)$ as the comprehensive utilities obtained by an equipped commuter and an unequipped commuter, respectively, who depart from zone *r* in period *k* for destination *s*, and perform activity *i* there. We can write

$$U_i^{rs}(k) = V_i(k) - \alpha \cdot c^{rs}(k) + V^s + V_i^s + \varepsilon_i^{rs}(k), \qquad \forall r,s,i,k \tag{1}$$

$$\tilde{U}_i^{rs}(k) = V_i(k) - \alpha \cdot \tilde{c}^{rs}(k) + V^s + V_i^s + \tilde{\varepsilon}_i^{rs}(k), \qquad \forall r,s,i,k \tag{2}$$

where $V_i(k)$ is the utility value of activity *i* that is intended in period *k*, $c^{rs}(k)$ and $\tilde{c}^{rs}(k)$ are the average travel times (minutes) of equipped and unequipped commuters respectively who depart from *r* in period *k* for *s*, α is a parameter for converting travel time to disutility, V_s represents the systematic component of utility common to all elements with destination *s* (such as area, population, employment and parking facilities, which are independent of activities), V_i^s represents the systematic component of utility depending on both activity *i* and destination *s* (such as business area, food quality and service level, for an eating activity in a particular location), $\varepsilon_i^{rs}(k)$ and $\tilde{\varepsilon}_i^{rs}(k)$ are the random terms in computing utilities.

Suppose that for each group of commuters, all the random terms are separately identically and independently Gumbel distributed variables with mean zero and identical standard deviation, then the joint probability of selecting destination *s* and activity *i* can be estimated by a multinomial logit formula (Ben-Akiva and Lerman, 1985). i.e.,

$$P_i^{rs}(k) = \frac{\exp[\theta(V_i(k) - \alpha c^{rs}(k) + V^s + V_i^s)]}{\sum_{s'}\sum_{i'} \exp[\theta(V_{i'}(k) - \alpha c^{rs'}(k) + V^{s'} + V_{i'}^{s'})]}, \qquad \forall r,s,i,k \tag{3}$$

for commuter group equipped with ATIS, and

$$\tilde{P}_i^{rs}(k)=\frac{\exp[\tilde{\theta}(V_i(k)-\alpha\tilde{c}^{rs}(k)+V^s+V_i^s)]}{\sum_{s'}\sum_{i'}\exp[\tilde{\theta}(V_{i'}(k)-\alpha\tilde{c}^{rs'}(k)+V^{s'}+V_{i'}^{s'})]}\ , \qquad \forall r,s,i,k \tag{4}$$

for commuter group unequipped with ATIS. In (3)-(4), the positive parameters θ and $\tilde{\theta}$ are used to reflect the uncertainty degrees in computing comprehensive utilities. As their values approach infinity, the uncertainty vanishes; as their values are close to zero, people would choose activities and destinations randomly. Hence, $\theta > \tilde{\theta}$ holds according to the assumption made on the behaviors of the two groups of commuters. This means that the equipped commuters can compute the utility more accurately than the unequipped commuters since the ATIS can help them get more exact information associated with destinations, activities and travel routes.

The marginal choice probability that destination s is chosen, can be written as

$$P^{rs}(k)=\frac{\exp[\theta(V^s-\alpha c^{rs}(k)+V^s(k))]}{\sum_{s'}\exp[\theta(V^{s'}-\alpha c^{rs'}(k)+V^{s'}(k))]}\ , \qquad \forall r,s,k \tag{5}$$

for commuter group equipped with ATIS, where $V^s(k)=(1/\tilde{\theta})\ln\sum_i \exp[\tilde{\theta}(V_i(k)+V_i^s)]$; and

$$\tilde{P}^{rs}(k)=\frac{\exp[\tilde{\theta}(V^s-\alpha\tilde{c}^{rs}(k)+\tilde{V}^s(k))]}{\sum_{s'}\exp[\tilde{\theta}(V^{s'}-\alpha\tilde{c}^{rs'}(k)+\tilde{V}^{s'}(k))]}\ , \qquad \forall r,s,k \tag{6}$$

for commuter group unequipped with ATIS, where $\tilde{V}^s(k)=(1/\tilde{\theta})\ln\sum_i \exp[\tilde{\theta}(V_i(k)+V_i^s)]$.

So, the activity/destination choices for both commuter groups have been formulated in (3)-(6). Equations (3) and (5) are related to the probabilities of both groups of commuters that individuals choose destination s to perform activity i. Equations (4) and (6) are the probabilities that individuals choose destination s to perform the activities of concerns, but not necessary confined to a particular activity.

Suppose that within each origin zone r, at the end of period k–1 there are a number of potential travelers, $N^r(k-1)$ with ATIS and $\tilde{N}^r(k-1)$ without ATIS, who will choose their destinations and complete their travels in the next period k, according to the probabilities given by equations (5) and (6), respectively. Of course, perhaps the destination chosen by them is the origin zone itself, this means that they will stay at home continuously. Hence, the aggregate departure flow of equipped commuters in period k from origin r to destination s can be expressed as

$$d^{rs}(k)=N^r(k-1)P^{rs}(k)=N^r(k-1)\frac{\exp[\theta(V^s-\alpha c^{rs}(k)+V^s(k))]}{\sum_{s'}\exp[\theta(V^{s'}-\alpha c^{rs'}(k)+V^{s'}(k))]}\ , \qquad \forall r,s,k \tag{7}$$

and that of unequipped commuters is

$$\tilde{d}^{rs}(k)=\tilde{N}^r(k-1)\tilde{P}^{rs}(k)=\tilde{N}^r(k-1)\frac{\exp[\tilde{\theta}(V^s-\alpha\tilde{c}^{rs}(k)+\tilde{V}^s(k))]}{\sum_{s'}\exp[\tilde{\theta}(V^{s'}-\alpha\tilde{c}^{rs'}(k)+\tilde{V}^{s'}(k))]}\ , \qquad \forall r,s,k \tag{8}$$

where $N^r(0)=x\bar{N}^r(0)$ and $\tilde{N}^r(0)=(1-x)\bar{N}^r(0)$ herein x is called the initial market penetration of ATIS and $\bar{N}^r(0)$ is a predetermined constant representing the number of seed individuals in zone r at the initial time of the study horizon. For each group of commuters, these people will constitute the potential travelers in the coming sequential periods through the period-by-period trip distribution/assignment process (presented in the next sub-section).

Note that the OD market penetrations of ATIS implemented in sequential periods may not equal to x since $d^{rs}(k)/[d^{rs}(k)+\tilde{d}^{rs}(k)]\neq x$ in general, except $\theta=\tilde{\theta}$ and $c^{rs}(k)=\tilde{c}^{rs}(k)$, i.e., the fundamental behavior difference between the two groups of commuters disappears. This is exactly what we want to investigate in this study, i.e., may the initial market penetration of ATIS not remain unchanged with the flow evolution in time and space dimensions.

Equations (7) and (8) indicate that the travel demands between an OD pair in period k are dependent on the utility functions and the average travel times associated with period k. The average travel times, in turn, are dependent on the OD travel demands because of the traffic assignment effect on the network. For each group, there is an inter-relationship between the trip distribution/assignment results in a period and the number of potential travelers available for the next period. Commuters of two groups experience the same traffic condition, i.e., the same link flows on the network, but perceive the travel times in different manners. Hence, the proposed model can be regarded as a strategic tool to forecast the time-dependent OD demands of commuters with and without ATIS.

2.3 Activity/Destination/Route Choices and Combined Model

In this subsection, we first formulate the multi-class route choice problem and then combine it with the activity/destination choice problem presented in the last subsection, so as to form an equivalent mathematical programming problem. As supposed before, both commuters with ATIS and without ATIS make route choices according to the stochastic user equilibrium (SUE) principle. Let $t_p^{rs}(k)$ be the objective travel time on path p from r to s in period k, $T_p^{rs}(k)$ and $\tilde{T}_p^{rs}(k)$ be the subjective path travel time perceived by equipped and unequipped commuters, respectively. With the requirements for generating a logit-based SUE assignment, let

$$T_p^{rs}(k)=t_p^{rs}(k)+\frac{1}{\beta}\xi_p^{rs},\qquad \forall r,s(\neq r),p,k \tag{9}$$

and

$$\tilde{T}_p^{rs}(k)=t_p^{rs}(k)+\frac{1}{\tilde{\beta}}\tilde{\xi}_p^{rs},\qquad \forall r,s(\neq r),p,k \tag{10}$$

where ξ_k^{rs} and $\tilde{\xi}_k^{rs}$ are random terms in perceiving the travel times by the two groups of commuters respectively, β and $\tilde{\beta}$ are the corresponding dispersion parameters relating to the perception variances, $\beta>\tilde{\beta}$. Suppose that all random terms are separately identically and independently Gumbel distributed variables, it can then be shown that $E[T_p^{rs}(k)]=E[\tilde{T}_p^{rs}(k)]=t_p^{rs}(k)$, $Var[T_p^{rs}(k)]=\pi^2/6\beta^2$ and $Var[\tilde{T}_p^{rs}(k)]=\pi^2/6\tilde{\beta}^2$. From the utility maximization principle of path choice, the probability of selecting path p is

$$P_p^{rs}(k)=\Pr(T_p^{rs}(k)\leq T_l^{rs}(k),\forall l)=\frac{\exp(-\beta t_p^{rs}(k))}{\sum_l \exp(-\beta t_l^{rs}(k))},\qquad \forall r,s(\neq r),p,k \tag{11}$$

for equipped commuters, and

$$\tilde{P}_p^{rs}(k) = \Pr(\tilde{T}_p^{rs}(k) \le \tilde{T}_l^{rs}(k), \forall l) = \frac{\exp(-\tilde{\beta} t_p^{rs}(k))}{\sum_l \exp(-\tilde{\beta} t_l^{rs}(k))}, \qquad \forall r, s(\ne r), p, k \qquad (12)$$

for unequipped commuters.

The path flows of equipped and unequipped commuters are given by

$$f_p^{rs}(k) = d^{rs}(k) P_p^{rs}(k) \qquad \forall r, s(\ne r), p, k \qquad (13)$$

and

$$\tilde{f}_p^{rs}(k) = \tilde{d}^{rs}(k) \tilde{P}_p^{rs}(k), \qquad \forall r, s(\ne r), p, k \qquad (14)$$

respectively. Clearly, for commuter group equipped with ATIS, with the definition on path choice probability, the equation (13) automatically leads to

$$\sum_p f_p^{rs}(k) = d^{rs}(k), \qquad \forall r, s(\ne r), k \qquad (15)$$

$$f_p^{rs}(k) \ge 0, \qquad \forall r, s(\ne r), p, k. \qquad (16)$$

The set of path flows satisfying conditions (15)-(16) is called logit-based SUE assignment. Similarly, for commuter group unequipped with ATIS we have

$$\sum_p \tilde{f}_p^{rs}(k) = \tilde{d}^{rs}(k), \qquad \forall r, s(\ne r), k \qquad (17)$$

$$\tilde{f}_p^{rs}(k) \ge 0, \qquad \forall r, s(\ne r), p, k. \qquad (18)$$

In this paper, we assume that link travel times are continuous and strictly increasing functions of link flows and period duration is large enough such that it covers the whole journey of each path flow in a period. It is expected that the path travel time in a time period is depending on the path flows in that period only. Hence, for each period and a given OD demand pattern we are in fact dealing with a static logit-based SUE traffic assignment problem with two classes of commuters. It is easy to show that such assignment problem can be characterized as a solution of the following convex mathematical programming problem

$$\min \sum_a \int_0^{u_a(k)} t_a(w) \mathrm{d}w + \frac{1}{\beta} \sum_r \sum_{s(\ne r)} \sum_p f_p^{rs}(k) \ln f_p^{rs}(k) + \frac{1}{\tilde{\beta}} \sum_r \sum_{s(\ne r)} \sum_p \tilde{f}_p^{rs}(k) \ln \tilde{f}_p^{rs}(k), \quad \forall k \qquad (19)$$

subject to (20)-(22) and

$$t_p^{rs}(k) = \sum_a t_a(u_a(k)) \delta_{ap}^{rs}, \qquad \forall r, s(\ne r), p, k \qquad (20)$$

$$t_a(k) = t_a^0 [1 + 150(u_a(k)/s_a)^4], \qquad \forall a, k \qquad (21)$$

$$u_a(k) = \sum_r \sum_{s(\ne r)} \sum_p [f_p^{rs}(k) + \tilde{f}_p^{rs}(k)] \delta_{ap}^{rs}, \qquad \forall a, k \qquad (22)$$

where $\delta_{ap}^{rs} = \{1$, if path p from r to s contains link a; 0, otherwise$\}$. After solving the logit-based SUE assignment problem, we can compute the path choice probabilities by equations (11)-(12), and get the average OD travel times based on the equations (1)-(6), as follows

$$c^{rs}(k) = \sum_p P_p^{rs}(k) t_p^{rs}(k), \qquad \forall r, s(\ne r), k \qquad (23)$$

for commuter group equipped with ATIS, and

$$\tilde{c}^{rs}(k) = \sum_p \tilde{P}_p^{rs}(k) t_p^{rs}(k), \qquad \forall r, s(\ne r), k \qquad (24)$$

for commuter group unequipped with ATIS.

It should be noted in the above logit-based SUE assignment that the OD demand for each time period is assumed to be given. However, the OD demand of each time period should be solved from the last time period's trip generation at origin zones by using the equations (7) and (8) in which the average path travel times for both groups are provided from solving the current logit-based SUE assignment. Hence, a fixed point problem for OD demand is formulated for this case.

Now, we examine the OD flow conservation constraints and their evolutions between neighborhood time periods. Note that in equations (7) and (8), we allow for $s = r$. So, the OD demands solved from these two equations satisfy

$$\sum_{s(\neq r)} d^{rs}(k) + d^{rr}(k) = N^{r}(k-1), \qquad \forall r,k \tag{25}$$

for commuter group equipped with ATIS, and

$$\sum_{s(\neq r)} \tilde{d}^{rs}(k) + \tilde{d}^{rr}(k) = \tilde{N}^{r}(k-1), \qquad \forall r,k \tag{26}$$

for commuter group unequipped with ATIS, where the boundary values for $N^{r}(0)$ and $\tilde{N}^{r}(0)$, $\forall r$, are given. The variables in the left-hand sides of (25)-(26) are obtained from solving the fixed point problem mentioned above. As a result, $d^{rr}(k)$ and $\tilde{d}^{rr}(k)$ respectively represent the numbers of equipped and unequipped trips who still stay in origin r till the end of period k, $d^{rs}(k)$ and $\tilde{d}^{rs}(k)$ respectively represent the numbers of equipped and unequipped trips who has already arrived at zone s by the end of period k. These persons are regarded as the potential travelers who will continue to go for their activities and travel in the next period, k+1. Hence, the potential travelers for continuous travel at the end of period k, can be written as

$$N^{r}(k) = d^{rr}(k) + \sum_{r'} d^{r'r}(k), \quad \forall r,k. \tag{27}$$

for commuter group equipped with ATIS, and

$$\tilde{N}^{r}(k) = \tilde{d}^{rr}(k) + \sum_{r'} \tilde{d}^{r'r}(k), \quad \forall r,k. \tag{28}$$

for commuter unequipped group. Clearly, $\sum_{r} N^{r}(k) = \sum_{r} N^{r}(0)$ and $\sum_{r} \tilde{N}^{r}(k) = \sum_{r} \tilde{N}^{r}(0)$ for all periods, i.e., at the end of each period all persons gather at zones.

Up until now, we have already formulated all the conditions required for the time-dependent multi-class model in which activity/destination/route choices are combined. In this model, the activity choices are governed by (3)-(4), the destination choices by (7)-(8), the route choices by (11)-(12), and the evolution of travel potential by (27)-(28). It is easy to show that seeking a solution $\{f_p^{rs*}(k), \tilde{f}_p^{rs*}(k), d^{rs*}(k), \tilde{d}^{rs*}(k), N^{r*}(k), \tilde{N}^{r*}(k)\}$ for all k, satisfying these conditions, is equivalent to

$$\begin{aligned} \min\ Z(\cdot) = & \sum_{k}\sum_{a}\int_{0}^{u_a(k)} t_a(w)\mathrm{d}w + \sum_{k}\sum_{r}\sum_{s(\neq r)}\sum_{p}\Big[\frac{1}{\beta} f_p^{rs}(k)\ln f_p^{rs}(k) + \frac{1}{\tilde{\beta}}\tilde{f}_p^{rs}(k)\ln \tilde{f}_p^{rs}(k)\Big] \\ & + \frac{1}{\alpha}\sum_{k}\sum_{r}\sum_{s}\Big[\frac{1}{\theta} d^{rs}(k)\ln d^{rs}(k) + \frac{1}{\tilde{\theta}}\tilde{d}^{rs}(k)\ln \tilde{d}^{rs}(k)\Big] \\ & - \frac{1}{\alpha}\sum_{k}\sum_{r}\sum_{s}\Big\{[V^{s} + V^{s}(k)]d^{rs}(k) + [V^{s} + \tilde{V}^{s}(k)]\tilde{d}^{rs}(k)\Big\} \end{aligned} \tag{29}$$

subject to

$$\sum_p f_p^{rs}(k) = d^{rs}(k), \qquad \forall r, s(\neq r), k \qquad (30)$$

$$\sum_p \tilde{f}_p^{rs}(k) = \tilde{d}^{rs}(k), \qquad \forall r, s(\neq r), k \qquad (31)$$

$$\sum_{s(\neq r)} d^{rs}(k) + d^{rr}(k) = N^r(k-1), \qquad \forall r, k \qquad (32)$$

$$\sum_{s(\neq r)} \tilde{d}^{rs}(k) + \tilde{d}^{rr}(k) = \tilde{N}^r(k-1), \qquad \forall r, k \qquad (33)$$

$$N^r(k-1) = d^{rr}(k-1) + \sum_{r'} d^{r'r}(k-1), \qquad \forall r, k(\geq 2) \qquad (34)$$

$$\tilde{N}^r(k-1) = \tilde{d}^{rr}(k-1) + \sum_{r'} \tilde{d}^{r'r}(k-1), \qquad \forall r, k(\geq 2) \qquad (35)$$

$$\{f_p^{rs}(k), \tilde{f}_p^{rs}(k), d^{rs}(k), \tilde{d}^{rs}(k), N^r(k), \tilde{N}^r(k)\} \geq 0 \qquad \forall r, s, p, k \qquad (36)$$

where $t_a(w)$ and $u_a(k)$ are defined by

$$t_a(k) = t_a^0[1 + 150(u_a(k)/s_a)^4], \qquad \forall a, k$$

$$u_a(k) = \sum_r \sum_{s(\neq r)} \sum_p [f_p^{rs}(k) + \tilde{f}_p^{rs}(k)]\delta_{ap}^{rs}, \qquad \forall a, k$$

respectively, and the boundary values for $N^r(0)$ and $\tilde{N}^r(0), \forall r$, are given. Note that in the third and fourth summation terms of (29), the superscript *s* covers *r*. The above mathematical programming problem can be split into *K* one-period sub-problems and solved by the variants of the standard convex combination algorithm (Sheffi, 1985). For each sub-problem, for example the one in period *k*, the travel potential within origin, $N^r(k-1)$ and $\tilde{N}^r(k-1)$, are given by the last period sub-problem's solution, i.e., computed by (34)-(35).

3. SOLUTION METHOD

The algorithm for solving the mathematical programming problem (29)-(36) is described as follows. In this algorithm, Step 2.3 for reducing objective function (29) is based on path flow variables, so that all OD demand variables (except the case of $s = r$) are replaced by path flow variables using (30)-(31).

Step 1. Let $k = 1$ and prepare $N^r(0)$ and $\tilde{N}^r(0), \forall r$.

Step 2. Solve the multi-class model for current period *k*.

2.1. Set the iteration index $n = 1$ and choose an initial feasible OD demands $\{d^{rs,n}(k)\}$ and $\{\tilde{d}^{rs,n}(k)\}$. On the base of path travel times corresponding to free-flow network, compute the initial path choice probabilities by (11)-(12) and then determine the initial feasible path flows $\{f_p^{rs,n}(k)\}$ and $\{\tilde{f}_p^{rs,n}(k)\}$ by (13)-(14).

2.2. Set $u_a^n(k) = \sum_r \sum_{s(\neq r)} \sum_p [f_p^{rs,n}(k) + \tilde{f}_p^{rs,n}(k)]\delta_{ap}^{rs}$. Compute link travel times and then path travel times $\{t_p^{rs,n}(k)\}$.

2.3. Find the direction for reducing the value of objective function (29). Solve

$$\min \tilde{Z}(\cdot)=\sum_r\sum_{s(\neq r)}\sum_p\left(\frac{\partial Z(\cdot^n)}{\partial f_p^{rs}(k)}h_p^{rs}(k)+\frac{\partial Z(\cdot^n)}{\partial \tilde{f}_p^{rs}(k)}\tilde{h}_p^{rs}(k)\right)$$
$$+\sum_r\left(\frac{\partial Z(\cdot^n)}{\partial d^{rr}(k)}q^{rr}(k)+\frac{\partial Z(\cdot^n)}{\partial \tilde{d}^{rr}(k)}\tilde{q}^{rr}(k)\right) \qquad (37)$$

subject to

$$\sum_{s(\neq r)}\sum_p h_p^{rs}(k)+q^{rr}(k)=N^r(k-1)\ , \qquad \forall r \qquad (38)$$

$$\sum_{s(\neq r)}\sum_p \tilde{h}_p^{rs}(k)+\tilde{q}^{rr}(k)=\tilde{N}^r(k-1)\ , \qquad \forall r \qquad (39)$$

$$h_p^{rs}(k)\geq 0,\ q^{rr}(k)\geq 0,\ \tilde{h}_p^{rs}(k)\geq 0,\ \tilde{q}^{rr}(k)\geq 0, \qquad \forall r,s,p. \qquad (40)$$

Denote the solution as $\{h_p^{rs,n}(k),q^{rr,n}(k),\tilde{h}_p^{rs,n}(k),\tilde{q}^{rr,n}(k)\}$. Compute

$$q^{rs,n}(k)=\sum_p h_p^{rs,n}(k), \qquad \forall r,s(\neq r) \qquad (41)$$

$$\tilde{q}^{rs,n}(k)=\sum_p \tilde{h}_p^{rs,n}(k), \qquad \forall r,s(\neq r). \qquad (42)$$

2.4. In (29), Replace path flow variables by $f_p^{rs,n}(k)+\lambda(h_p^{rs,n}(k)-f_p^{rs,n}(k))$ for commuter group equipped with ATIS and $\tilde{f}_p^{rs,n}(k)+\lambda(\tilde{h}_p^{rs,n}(k)-\tilde{f}_p^{rs,n}(k))$ for commuter group unequipped with ATIS, OD flow variables by $d^{rs,n}(k)+\lambda(q^{rs,n}(k)-d^{rs,n}(k))$ for equipped and $\tilde{d}^{rs,n}(k)+\lambda(\tilde{q}^{rs,n}(k)-\tilde{d}^{rs,n}(k))$ for unequipped, and link flows by $u_a^n(k)+\lambda(v_a^n(k)-u_a^n(k))$ where $v_a^n(k)=\sum_r\sum_{s(\neq r)}\sum_p[h_p^{rs,n}(k)+\tilde{h}_p^{rs,n}(k)]\delta_{ap}^{rs}$ and $0\leq\lambda\leq 1$.

Solve the resulted line search problem for generating an optimal step size, λ^n.

2.5. Update variables, let

$f_p^{rs,n+1}(k)=f_p^{rs,n}(k)+\lambda^n(h_p^{rs,n}(k)-f_p^{rs,n}(k))$ for all *r*, *s*, *p*,
$\tilde{f}_p^{rs,n+1}(k)=\tilde{f}_p^{rs,n}(k)+\lambda^n(\tilde{h}_p^{rs,n}(k)-\tilde{f}_p^{rs,n}(k))$ for all *r*, *s*, *p*,
$d^{rs,n+1}(k)=d^{rs,n}(k)+\lambda^n(q^{rs,n}(k)-d^{rs,n}(k))$ for all *r*, *s*,
$\tilde{d}^{rs,n+1}(k)=\tilde{d}^{rs,n}(k)+\lambda^n(\tilde{q}^{rs,n}(k)-\tilde{d}^{rs,n}(k))$ for all *r*, *s*.

Set *n* = *n*+1, if some termination criterion is satisfied, go to Step 3; otherwise, go to Step 2.2.

Step 3. Compute

$$N^r(k)=d^{rr,n}(k)+\sum_{r'}d^{r'r,n}(k), \qquad \forall r \qquad (43)$$

$$\tilde{N}^r(k)=\tilde{d}^{rr,n}(k)+\sum_{r'}\tilde{d}^{r'r,n}(k), \qquad \forall r. \qquad (44)$$

Step 4. If *k* = *K*, stop; otherwise, set *k* = *k*+1 and go to Step 2.

In order to improve the convergence, a modified method can be used as follow. Following Step 2.2, we use (11)-(12) to compute the path choice probabilities and then obtain the average path travel times by (23)-(24), i.e., $c^{rs,n}(k)=\sum_p t_p^{rs,n}(k)P_p^{rs,n}(k)$ for commuter group equipped with ATIS and $\tilde{c}^{rs,n}(k)=\sum_p t_p^{rs,n}(k)\tilde{P}_p^{rs,n}(k)$ for commuter group unequipped with

ATIS. In Step 2.3, instead of solving a linear programming problem, we use the multinomial logit formulation to compute the auxiliary OD demand, i.e.,

$$q^{rs,n}(k) = N^r(k-1)\frac{\exp[\theta(V^s - \alpha c^{rs,n}(k) + V^s(k))]}{\sum_{s'}\exp[\theta(V^{s'} - \alpha c^{rs',n}(k) + V^{s'}(k))]} \quad , \qquad \forall r,s \qquad (45)$$

$$\tilde{q}^{rs,n}(k) = \tilde{N}^r(k-1)\frac{\exp[\tilde{\theta}(V^s - \alpha \tilde{c}^{rs,n}(k) + \tilde{V}^s(k))]}{\sum_{s'}\exp[\tilde{\theta}(V^{s'} - \alpha \tilde{c}^{rs',n}(k) + \tilde{V}^{s'}(k))]} \quad , \qquad \forall r,s \qquad (46)$$

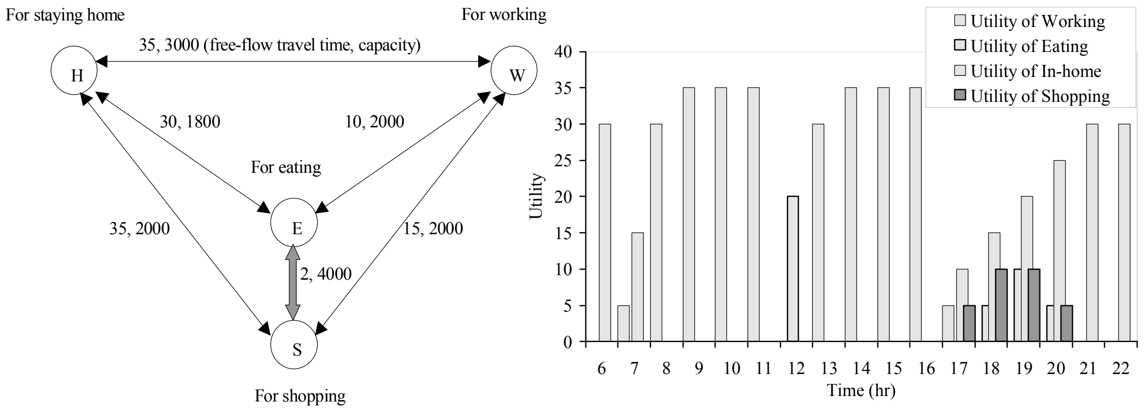
and use the logit-based SUE assignment to get the auxiliary path flows, i.e.,

$$h_p^{rs,n}(k) = q^{rs,n}(k)P_p^{rs,n}(k) = q^{rs,n}(k)\frac{\exp(-\beta t_p^{rs,n}(k))}{\sum_l \exp(-\beta t_l^{rs,n}(k))} \qquad \forall r,s,p \qquad (47)$$

$$\tilde{h}_p^{rs,n}(k) = \tilde{q}^{rs,n}(k)\tilde{P}_p^{rs,n}(k) = \tilde{q}^{rs,n}(k)\frac{\exp(-\tilde{\beta} t_p^{rs,n}(k))}{\sum_l \exp(-\tilde{\beta} t_l^{rs,n}(k))} \qquad \forall r,s,p\,. \qquad (48)$$

All the other steps of the algorithm remain unchanged. In solving the standard logit-based SUE problem, Sheffi (1985) provided the proof for the convergence of this variant.

Figure 1 Exampled network and simplified temporal utility profiles of activities

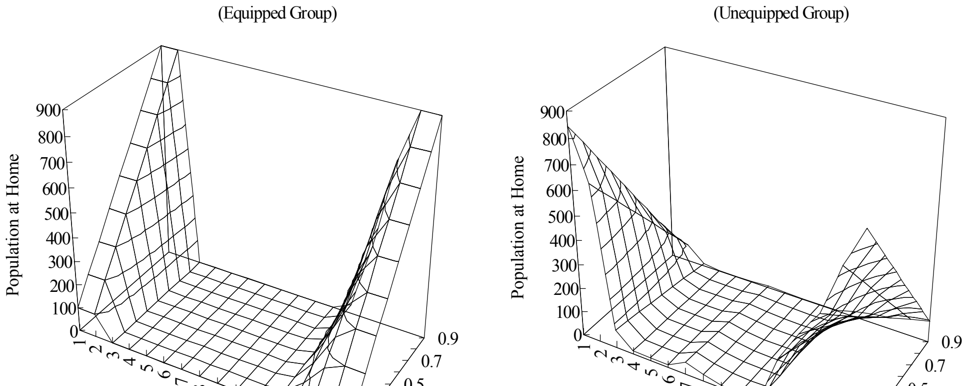


4. NUMERICAL EXAMPLE

Figure 1 shows an example transportation network consisting of 4 zones and 12 one-way links. For each link, the free-flow travel time (minutes) and the capacity (vehicles per hour) are given in this figure. The free-flow travel time and link capacity are identical in each direction of one link. Four types of activities are considered; namely staying home, working, shopping and eating. These four activities are performed within the four zones as shown in Figure 1 together with their temporal utility profiles. The study horizon is ranged from 6:00am to 10:00pm and is divided into 16 hourly periods. It is assumed in this example that there is only one "Home" zone, H, with 1000 seed travellers (population), i.e., $N^H(0) + \tilde{N}^H(0)$ =1000, $N^W(0) + \tilde{N}^W(0)$ =0, $N^E(0) + \tilde{N}^E(0)$ =0 and $N^S(0) + \tilde{N}^S(0)$ =0. Subsequently, the respective conditions of equipped and unequipped commuters are dependent on an initial market penetration of ATIS within zone H only, $N^H(0)/[N^H(0)+\tilde{N}^H(0)]$. Other parameters required by the proposed model are: α=0.25, θ=0.8, $\tilde{\theta}$=0.1 and β=1.2, $\tilde{\beta}$=0.3; explanations to these parameters are given below (1)-(4) and (9)-(10), respectively.

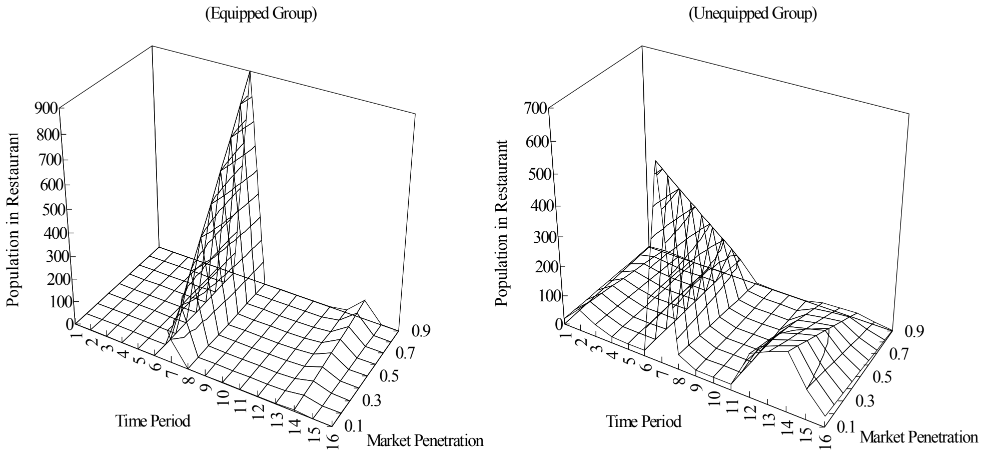
Figures 2-5 show the populations within the four zones by the four types of activities respectively in view of variation of time period and initial market penetration of ATIS. These populations are the potential travelers who will travel to other zones for performing their activities by time period. From these figures, we can investigate the people's activity pattern on the network temporarily and spatially, and evaluate the impacts on activity choices. Figure 2 indicates that in the first two periods all equipped people choose to stay at home, in the last two periods most of them come back and only few go for shopping (see Figure 4); however, the decisions by unequipped commuter are not so clever due to their randomness in perceiving the activity utilities and travel times (see the right-hand-side of these figures that are referred to the impacts on commuter group unequipped with ATIS). Figures 3-5 give the same results that at each level of ATIS market penetration, in comparison with the commuter group unequipped with ATIS there are more equipped commuters who perform the activities with high utility. This says, they work from 3rd to 6th period, have lunch at the 7th period, work again from 8th to 11th period, and then go to shop and return home subsequently. An interesting finding is that some people (more commuters from the group unequipped with ATIS) go for shopping in the 8th period since Zone S is very closed to zone E so that a new route for going back W after having lunch (from W to E to S to W) is generated.

Figure 2 Populations at home by time and ATIS market penetration



Figures 3-5 give the same results that at each level of ATIS market penetration, in comparison with the commuter group unequipped with ATIS there are more equipped commuters who perform the activities with high utility. This says, they work from 3rd to 6th period, have lunch at the 7th period, work again from 8th to 11th period, and then go to shop and return home subsequently. An interesting finding is that some people (more commuters from the group unequipped with ATIS) go for shopping in the 8th period since Zone S is very closed to zone E so that a new route for going back W after having lunch (from W to E to S to W) is generated.

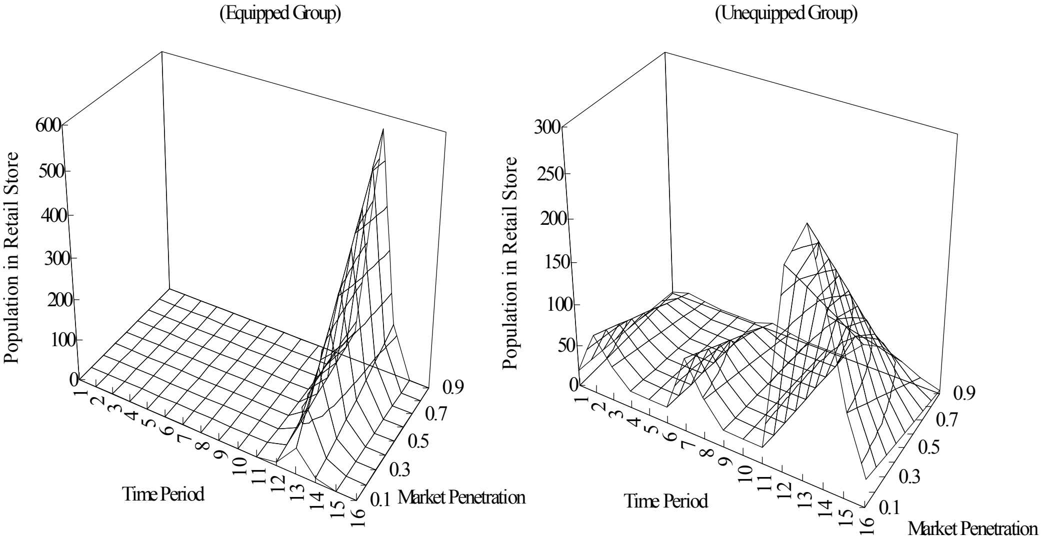
Figure 3 Populations in restaurant by time and ATIS market penetration



(Equipped Group)

(Unequipped Group)

Figure 4 Populations in retail store by time and ATIS market penetration



(Equipped Group)

(Unequipped Group)

Figure 6 depicts the activity utilities (on average) of each commuter equipped and unequipped with ATIS, subject to different time period and initial market penetration of ATIS. Figure 7 illustrates the average travel times of the two groups during the study horizon. In the same period and at the same level of market penetration, the average activity utility implemented by commuter group equipped with ATIS is larger than that by commuter group unequipped with ATIS, but its average travel time is shorter except in the 3rd period. In the 3rd period, all people leave home for office and select the path from W to H directly so as to result in high congestion on this link. These two figures can be used to analyze the temporal changes of the two measures (i.e., activity utility and average travel time) at different ATIS market penetrations. Basically, the ATIS market penetration does not result in great influences on these two average measures.

Figure 5 Populations in office by time and ATIS market penetration

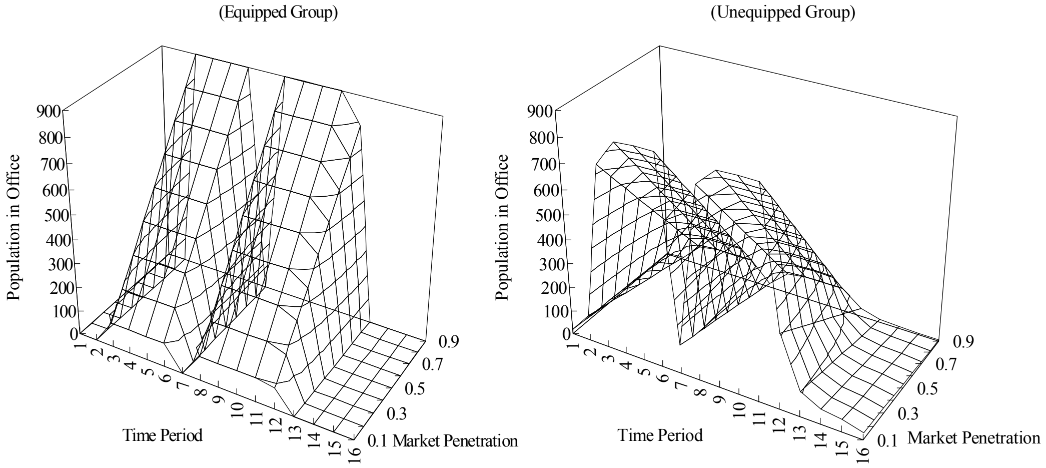


Figure 6 Variation of activity utilities by time and ATIS market penetration

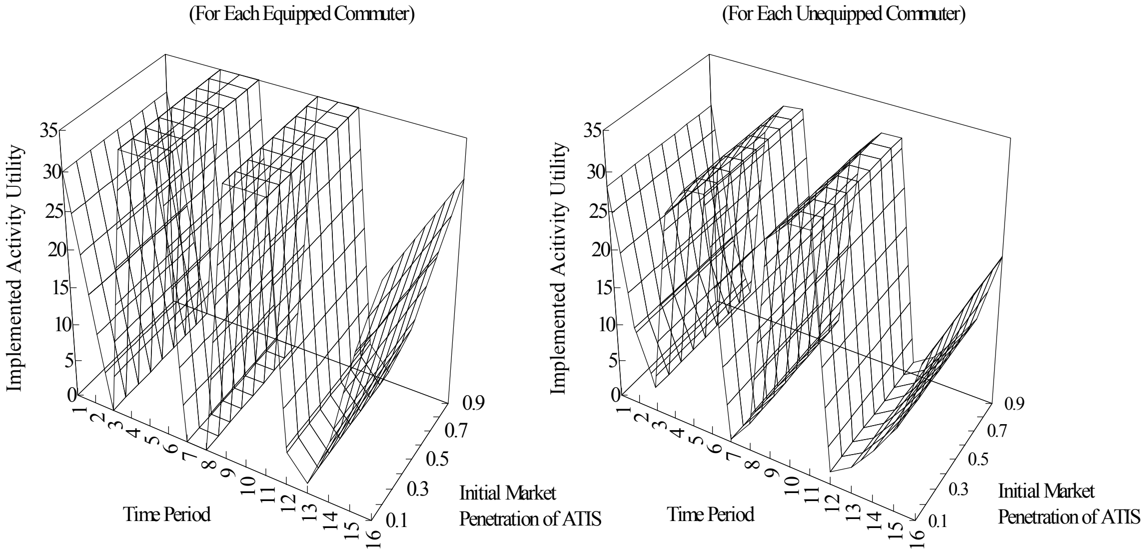


Figure 8 depicts the implemented activity utilities and travel times of each equipped commuter, each unequipped commuter and all commuters under various levels of ATIS market penetration, respectively; all these results shown in Figure 8 are referred to the total values of the two measures during the study horizon. It is intuitive to see that the activity utility obtained by each equipped commuter is larger than that by each equipped commuter and his travel time is smaller than that of each unequipped commuter. This observation is due to the fact that the specific ATIS can help equipped commuters to choose the activities with higher utility and paths with less travel time. The left-hand-side of Figure 8 shows that the implemented activity utility of each equipped or unequipped commuter decreases slightly with increasing the ATIS market penetration. As a result, the utility of all commuters goes up steadily when the ATIS market penetration is increasing. On the other hand, the right-hand-side of

Figure 8 indicates that the average travel time of each equipped or unequipped commuter increases with the ATIS market penetration. It leads to the result that the average travel time of all commuters decreases with increasing the ATIS market penetration until more than 70% of commuters equipped with ATIS. Then, the average travel time of all commuters starts to go up when the ATIS market penetration is greater than 70%. This means that before the market penetration is reached to a certain value, the gain of the whole system from ATIS is increasing with the market penetration, but it may become negative after exceeding the particular value.

Figure 7 Travel times by time period and ATIS market penetration

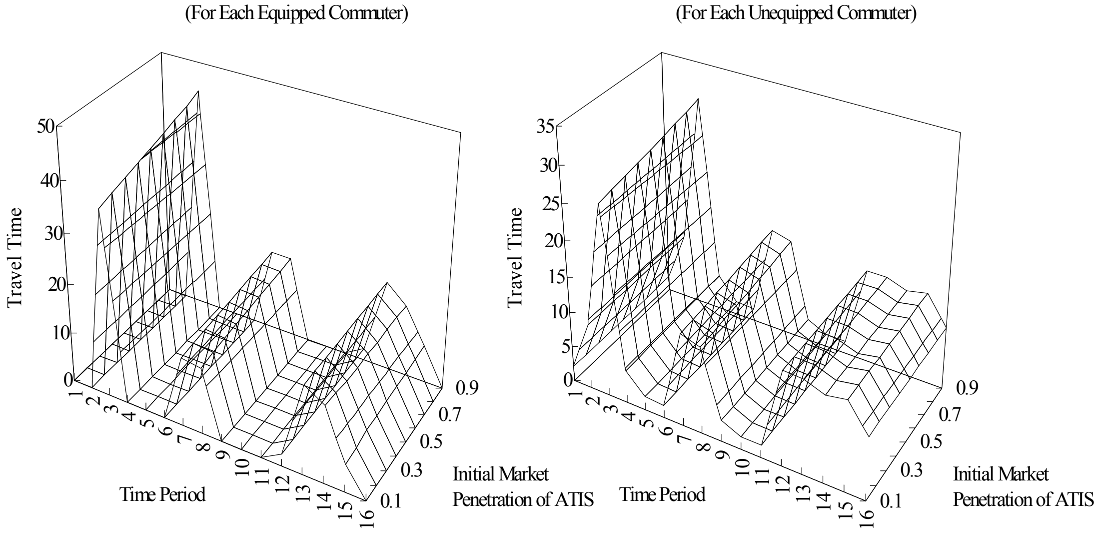


Figure 8 Implemented activity utilities and travel times in the study horizon subject to variation of ATIS market penetration

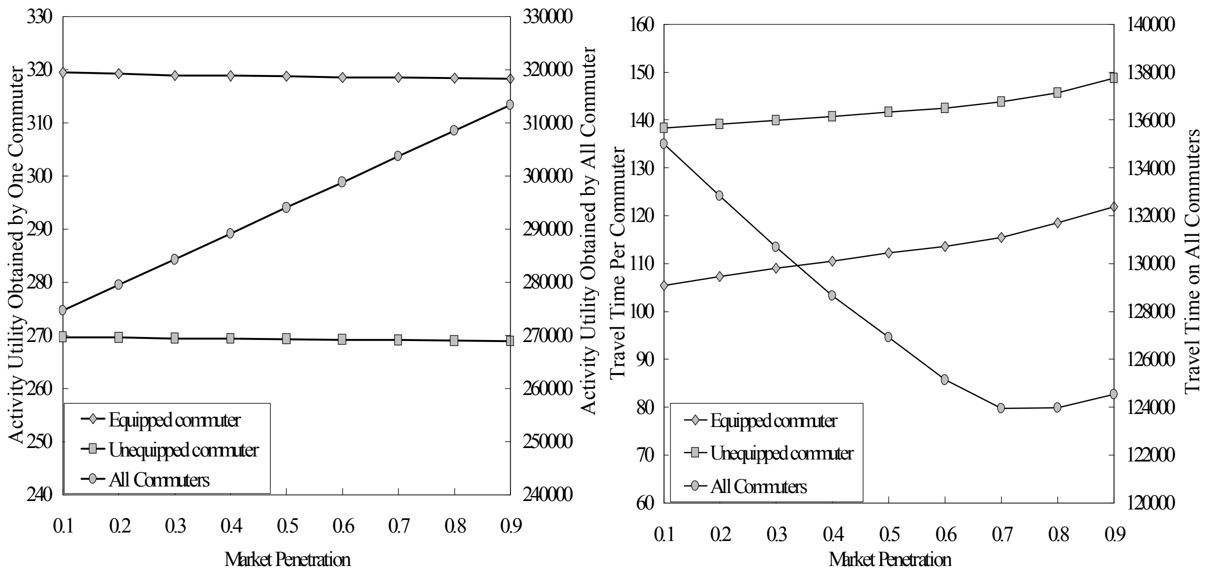


Table 1. Average duration consumed in travel and various activities

	Initial market penetration of ATIS								
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
T	1.76	1.79	1.82	1.84	1.87	1.89	1.92	1.95	1.98
$\tilde{T}$	2.30	2.32	2.33	2.35	2.36	2.37	2.39	2.41	2.43
H	4.67	4.66	4.64	4.63	4.62	4.61	4.61	4.60	4.59
$\tilde{H}$	3.85	3.85	3.85	3.85	3.85	3.85	3.85	3.85	3.85
W	8.04	8.01	7.99	7.97	7.96	7.94	7.91	7.90	7.87
$\tilde{W}$	7.34	7.33	7.31	7.30	7.29	7.28	7.27	7.25	7.24
E	0.85	0.85	0.85	0.85	0.85	0.85	0.84	0.84	0.84
$\tilde{E}$	1.41	1.41	1.41	1.40	1.40	1.40	1.39	1.39	1.38
S	0.68	0.69	0.70	0.70	0.70	0.71	0.761	0.72	0.72
$\tilde{S}$	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10
$T+H+W+E+S$	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0
$\tilde{T}+\tilde{H}+\tilde{W}+\tilde{E}+\tilde{S}$	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0

Notes: The unit (hours/person) is used for all data.

Finally, we summarize the results in Table 1. It shows how the 16 hours are consumed by the two groups of commuters in terms of travel and the four types of activities under various levels of ATIS market penetrations. The indexes appearing in Table 1 are defined by

$$\begin{cases} T_{\text{Average Travel Time}} = \sum_{k}\sum_{r}\sum_{s(\neq r)} d^{rs}(k)c^{rs}(k)/(N^{H}(0)\times 60) \\ H_{\text{Average Duration at Home}} = \sum_{k}[d^{HH}(k) + \sum_{r=E,W,S} d^{rH}(k)(1-c^{rH}(k)/60)]/N^{H}(0) \\ W_{\text{Average Duration in Office}} = \sum_{k}[d^{WW}(k) + \sum_{r=E,H,S} d^{rW}(k)(1-c^{rW}(k)/60)]/N^{H}(0) \\ E_{\text{Average Duration in Restaurant}} = \sum_{k}[d^{EE}(k) + \sum_{r=H,W,S} d^{rE}(k)(1-c^{rE}(k)/60)]/N^{H}(0) \\ S_{\text{Average Duration in Retail Store}} = \sum_{k}[d^{SS}(k) + \sum_{r=H,E,W} d^{rS}(k)(1-c^{rS}(k)/60)]/N^{H}(0) \end{cases} \tag{49}$$

for equipped group; and $\tilde{T},\tilde{H},\tilde{W},\tilde{E}$ and $\tilde{S}$ are for unequipped group, computed by the same method on the base of results associated with this group.

As shown in Table 1, it was found that in comparison with unequipped commuters, equipped commuters spend less times in travel, in restaurant for having lunch and in retail store for shopping, but spend more times for staying at home and for working in office. However, for both groups of commuters, the time durations for travel are increasing and the times spent in office are decreasing as the market penetration increases, and the durations consumed in other places do not change significantly. Hence, the equipped commuters have better use of the time than the unequipped commuters, but the marginal effect of ATIS market penetration is progressively decreasing.

5. CONCLUSIONS

In this paper, the concept of the temporal utility profile of activities is employed to study the activity and travel choice behaviors. An equivalent mathematical programming model is proposed for studying impacts of ATIS on activity/destination/route choice behaviors. It is a time-dependent multi-class model for evaluation of the benefits of ATIS. A solution algorithm is presented and applied to an example for illustration. Although the findings observed from the example may not be applicable to other cases with ATIS implementations, it is shown that the proposed modeling approach provides a powerful tool for better understanding and assessment of the complex travel-related behaviors under various levels of ATIS market penetration. By introducing the activity-based approach, we offer a new avenue of evaluating ATIS from long-term strategic viewpoint .

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