MODELLING THE EFFECTS OF MULTI-MODAL TRAVELER INFORMATION SYSTEMS

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Abstract: This paper proposes a multi-class probit-based stochastic user equilibrium model for assessing the effects of multi-modal traveler information systems (MTIS) on a multi-modal transport network. It can be formulated as a fixed-point problem and solved by a simulation-based heuristic solution algorithm. It is assumed in this paper that the travelers equipped and unequipped with MTIS would make their travel choices following a probit-based stochastic manner when considering alternative paths or modes according to their perceived utilities. The proposed model and solution algorithm can be used to evaluate explicitly the impacts of MTIS services. Numerical results show that the introduction of MTIS would improve the network performance and promote the utilization of public transit under certain market penetration and congestion levels.

Key Words: multi-modal traveler information systems, stochastic user equilibrium, fixed point problem

1. INTRODUCTION

It is widely recognized that advanced traveler information systems (ATIS) is a core component of intelligent transportation systems (ITS). ATIS can enhance a more efficient decision making for travelers’ trips by providing related and sufficient transportation information (e.g. travel time estimation). Thus, the next-generation advanced traveler information systems, i.e. multi-modal traveler information systems (MTIS), have gained considerable interests from both transportation professionals and academics (Adler and Blue, 1998; Chorus et al., 2006). The systems can provide travelers at anytime all relevant travel information for their journeys in a multi-modal transport network.

There are many countries and regions involved in the development of the multi-modal traveler information systems. For instance, the “511” system in USA, as an outset of MTIS, can provide travelers with the real-time information on the most effective travel modes and the shortest routes through the phone, internet or Dial-a-Ride system. Other cases include the system provided by Transport for London in the UK (http://www.tfl.gov.uk/tfl/); integrated transportation information platform of Beijing in China (Li et al., 2005) and the eFinder
service developed for multi-modal transit network in Hong Kong (Lo et al., 2005).

In the past decade, the main focus is on the evaluation of the impacts of ATIS on a single transport mode (Chorus et al., 2006). However, in reality most trips made in metropolitan areas are multi-modal trips. Several studies have considered the multi-modal network equilibrium problems but without ATIS (Nagurney, 1984; Uchida et al., 2005; Li et al., 2007).

Harris and Konheim (1995) investigated the impacts of MTIS on the choice-making behaviors of travelers. They carried out a telephone survey among peak hour travelers in the USA on the travelers’ attitudes to the future provision of travel information services. They concluded that timely and reliable MTIS services would encourage transit use in replacement of car. Fujiwara et al. (2004) evaluated the effects of multi-modal travel information by using the principle of relative utility maximization. Based on the data collected in Japan, they reported that the multi-modal travel information can reduce the car users and increase the transit users. Similar works were conducted by Neuherz et al. (2000), Yim and Miller (2000) and Abdel-Aty and Abdalla (2006). However, most of these studies adopted either statistical or experimental simulation approaches to investigate the impacts of MTIS. There has not yet been any integrated theoretical network model developed or proposed for modelling the effects of MTIS under different network conditions.

In this paper, a new multi-class stochastic user equilibrium (SUE) model is proposed for modelling the impacts of MTIS on travelers’ choice behaviors in a multi-modal transport network. In the proposed model, different information components of MTIS are considered explicitly. To facilitate the presentation of the essential ideas in this paper, we consider a multi-modal transport network with three transport modes, i.e. auto, Mass Transit Railway (MTR) and Park-and-Ride (P&R). Both travelers, equipped and unequipped with MTIS, are assumed to make travel choices according to their perceived travel disutility considering implicitly their habitual or personal preferences.

The remainder of this paper is organized as follows. The next section describes some basic considerations for the model formulation. Section 3 proposes a fixed-point problem for modelling the stochastic user equilibrium in multi-modal network with MTIS. Section 4 presents a heuristic solution algorithm for solving the proposed model. It follows with a numerical example in Section 5. Finally, conclusions are given in Section 6 together with recommendations for further study.

2. BASIC CONSIDERATIONS

2.1 Assumptions

A number of basic assumptions for modelling formulation are adopted in this paper as follows:

A1 The study period is assumed to be a one-hour period, such as the morning peak hour period. The static modelling approach is also assumed since the proposed model is developed to assess the long-term effects of MTIS.
A2 It is assumed that the commuters can complete their journeys within the given period by any three alternative single or combined modes: auto, MTR and P&R with auto-MTR.

A3 There are two user classes: travelers with and without MTIS services. It is assumed that both the equipped and unequipped travelers’ mode and route choices behaviors follow a probit-based stochastic user equilibrium (SUE). The travel mode, transfer node and route (or path) is considered as a component of the travel choice. Thus, the travelers are assumed to make their travel choices simultaneously on mode, route (or path) and in some cases transfer node if necessary.

A4 It is assumed that three types of travel information provided by the MTIS including: (i) route guidance information for equipped car users providing the road traffic condition; (ii) parking information for equipped car users providing information about parking fee and available parking space by locations, e.g. the central business district (CBD), suburban areas and P&R sites; (iii) transit information for equipped transit passengers including schedules/frequencies and fares of MTR transit routes. The qualities of these three types of travel information are different. It is assumed that the parking information is more accurate and its information quality is therefore the best. Comparatively, the quality of route guidance information service is the worst since the road traffic condition is less predictable. In addition, the market penetration of the information services is assumed to be varied by origin-destination (OD) pair.

A5 In the road network, the traffic flows are quantified in vehicular units, while the flows in transit network are in passenger units. Similar to Li et al. (2007), the concept of car occupancy rate is adopted in this paper to convert passenger units (or person trips) into vehicular units. We denote this conversion parameter as $\gamma_w$, where $w$ is a given OD pair.

2.2 Notations
Consider a multi-modal transport network $G=(N, A)$, which consists of a typical road sub-network $G^a=(N^a, A^a)$, a MTR sub-network $G^b=(N^b, A^b)$, and transfer nodes termed as interchanges or transfer points and walk links between these nodes. For ease of reference, the notations used throughout this paper are listed as follows:

Indices

- $w$: Origin-Destination pair $w=(r, s)$
- $i$: The parking site nearby destination $s$
- $t$: The P&R site nearby the MTR station $t'$
- $m$: Mode $m \in \{a, b, c\}$, where $a$ represents auto mode, $b$ represents MTR mode, $c$ represents auto-MTR or P&R mode
- $n$: The user class, $n=1$ for the equipped travelers, $n=2$ for the unequipped travelers

Sets

- $W$: The set of OD pairs, $w \in W$
- $I_w$: The set of all feasible parking sites between OD pair $w$, $i \in I_w$
- $T_w$: The set of all possible P&R sites between OD pair $w$, $t \in T_w$
- $P_w^a$: The set of routes from $r$ to $i$ between OD pair $w$ in the auto sub-network
- $P_w^b$: The set of paths between OD pair $w$ in the MTR sub-network
The set of the combined auto-MTR paths between OD pair $w$ via P&R site $t$

$P_{w,t}^{c}$

The set of routes/paths between OD pair $w$ using mode $m$, $P_{w}^{(a)} = P_{w,a}^{u}$, $P_{w}^{(b)} = P_{w}^{b}$

and $P_{w}^{(c)} = P_{w,t}^{c}$, denoted $P_{w} = \bigcup_{m} P_{w}^{(m)}$

Variables

$U_{w,p}^{m}$ The actual travel disutility on path/route $p$ between OD pair $w$ using mode $m$

$U_{w,p}^{ma}$ The perceived travel disutility of path/route $p$ between OD pair $w$ using mode $m$ for user class $n$

$q_{w}$ The travel demand between OD pair $w$

$q_{w}^{n}$ The demand of the equipped ($n=1$) and unequipped ($n=2$) travelers between OD pair $w$

$f_{n,p}^{w}$ The flow on path/route $p$ between OD pair $w$ by user class $n$, $p \in P_{w}$

$\pi_{w}$ The market penetration of MTIS services by OD pair $w$

3. MODEL FORMULATION

3.1 Actual Travel Disutility

The actual travel disutility for using different modes of transport consists of different cost components. The cost of travelers by auto mode may include: travel time from origin to parking location, searching time for an available parking space, parking charge, walking time from parking site to destination and monetary travel cost such as gasoline cost. The travelers by MTR mode would consider the following cost components: access time from origin to the nearby MTR station, waiting time on the MTR station, in-vehicle time, egress time from MTR station to the destination and the MTR fare. The P&R mode is a combined mode. Thus, the cost by this mode is made of three components: the travel cost by auto from origin to P&R site, the transfer cost and the travel cost by MTR from transfer point to destination. The actual travel disutility, $U_{w,p}^{m}$, by mode $m$ can be formulated as the weighted sum of all costs related to that mode and defined as below.

When travelers with OD pair $w$ choose auto mode (i.e. $m = a$) and the parking site $i$, their actual travel disutility, $U_{w,p}^{a}$, via route $p \in P_{w,i}^{a}$ can be expressed as:

$$U_{w,p}^{a} = \alpha_{1} T_{w,p}^{a} + \alpha_{2} d_{i} + \alpha_{3} z_{i} + \alpha_{4} \Gamma_{p}^{a} + \Delta^{a}, \quad \forall p \in P_{w,i}^{a}, i \in I_{w}, w = (r,s) \in W$$

(1)

where $T_{w,p}^{a}$ is the travel time on route $p$ from origin $r$ to parking site $i$; $d_{i}$ is the searching time on the parking site $i$; $z_{i}$ is the parking charge and the consumption of fuel that can be shared by the passengers in the same car; $\Gamma_{p}^{a}$ represents the walking time related to mode $a$ via path $p$, such as, walking from parking site $i$ to destination $s$; $\Delta^{a}$ is the bias parameter for choosing mode $a$. The car occupancy rate, $\gamma_{w}$, is for converting the cost from vehicular units to passenger units. The coefficients ($a$) are the reciprocal substitution factors between different cost components.

The actual travel disutility, $U_{w,p}^{b}$, for the travelers by MTR mode (i.e. $m=b$) between OD pair $w$ via path $p \in P_{w}^{b}$ can be quantified as:
where $T_{r'}$ is the waiting time at the nearby MTR station $r'$; $T_{w, p}^b$ is the in-vehicle travel time between OD pair $w$ via path $p$; $z_{w, p}$ is the MTR fare of using path $p$ for travel between OD pair $w$; $\Gamma_{p}^b$ is total walking time associated with using mode $b$ via path $p$, including walking from origin $r$ to nearby MTR station, walking from final MTR station to the destination $s$; $\Delta^b$ is the bias parameter for choosing mode $b$. The coefficients ($\beta$) are the reciprocal substitution factors between different cost components.

For those travelers using P&R mode (i.e. $m=c$), their actual travel disutility, $U_{w, p}^c$, between OD pair $w$ with the transfer point $t$ via combined path $p \in P_{w, t}$, can be computed as:

$$U_{w, p}^c = \kappa_2 T_{w, p}^c + \kappa_3 T_{t} + \kappa_4 T_{w, p}^c + \kappa_5 d_i + \kappa_6 l_i + \kappa_7 \Gamma_{p}^c + \Delta^c , \ \forall p \in P_{w, t}^c, w = (r, s) \in W$$

where $T_{w, p}^c$ is the travel time by auto on route $p$, from origin $r$ to P&R site $t$; $T_{t}$ is the in-vehicle travel time on path $p_{t}^c$ from MTR station $t$ to destination $s$; $z_{p_{t}^c}$ is the MTR fare along path $p_{t}^c$. The transfer cost consists of three parts: (i) the waiting time on the MTR station $t$, denoted by $T_{t}$; (ii) the searching time on the P&R site $t$, denoted by $d_i$; and (iii) the parking charge and the consumption of fuel that can be shared by the passengers in the same car, denoted by $z_i$. Note that the parking and fuel costs will be converted from vehicular units to passenger units by the occupancy rate $\gamma$. $\Gamma_{p}^c$ is the total walking time required for travelling by mode $c$ via a combined path $p$, which includes walking trips from P&R site $t$ to MTR station $t'$ and from final MTR station to destination. $\Delta^c$ is the bias parameter (alternative specific constant) for choosing mode $c$. The coefficients ($\kappa$) are the reciprocal substitution factors between different cost components.

Note that due to the effects of the combined P&R mode on the multi-modal transport network, the flows on the auto sub-network affect those on the MTR sub-network and vice versa. As a result, the inter-relationship between the flows on the paths/routes and the flows on links becomes more complicated due to their interaction. Set $v_l$ and $v_k$ are the flows on auto link $l$ and MTR link $k$, respectively, then

$$v_l = \sum_{w \in \mathcal{W}} \frac{1}{w} \left( \sum_{p \in P_{w, l}, \delta_{lp}^w} f_{w, p}^a \delta_{lp}^w + \sum_{p \in P_{w, l}, \delta_{lp}^w} f_{w, p}^c \delta_{lp}^w \right) , \ l \in A^a , \ (4)$$

and

$$v_k = \sum_{w \in \mathcal{W}} \left( \sum_{p \in P_{w, k}, \delta_{lp}^w} f_{w, p}^b \delta_{lp}^w + \sum_{p \in P_{w, k}, \delta_{lp}^w} f_{w, p}^c \delta_{lp}^w \right) , \ k \in A^b , \ (5)$$

where $\delta_{lp}^w$ and $\delta_{lp}^w$ are link-route and link-path indicator variables respectively. $\delta_{lp}^w = 1$ if link $l$ on route $p$ and $\delta_{lp}^w = 0$ otherwise. Similar conditions are applicable to the MTR link/path indicator variable, $\delta_{lp}^w$. $f_{w, p}^a$ is the auto flow between OD pair $w$ on auto route $p$ using the pure auto mode, in passenger units. $f_{w, p}^c$ is the passenger flow choosing the combined P&R mode,
in passenger units, on path $p$. Note that these flow demands can be converted into vehicular units by using the car occupancy rate. $f^a_{w,p}$ is the passenger flow between OD pair $w$ on auto route $p$ using the MTR mode, in passenger units. Using Eqns. (4) and (5), we can compute the in-vehicle travel times in (1)-(2) as:

$$T^a_{w,p} = \sum_{l \in A} t_l(v_l) \delta^w_{lp} \quad \forall p \in P^a_w, i \in I_w, w = (r,s) \in W, \quad (6)$$

$$T^b_{w,p} = \sum_{k \in A} t_k(v_k) \delta^w_{kp} \quad \forall p \in P^b_w, w = (r,s) \in W. \quad (7)$$

If $p = p_n \times p_{ri}, t \in T_w, w = (r,s) \in W$, for mode $c$

$$T^{c}_{w,p_n} = \sum_{l \in A} t_l(v_l) \delta^w_{lp_n}, \quad (8)$$

and

$$T^{c}_{w,p_{ri}} = \sum_{k \in A} t_k(v_k) \delta^w_{kp_{ri}}, \quad (9)$$

where $v_l$ and $v_k$ are expressed in Eqns. (4) and (5), respectively. $\delta^w_{lp} = 1$ if link $l$ is on the route $p_n$ connecting $r$ and $i$, and $\delta^w_{lp} = 0$ otherwise. $t_l(v_l)$ is the travel times on auto link $l$ which can be estimated by following BPR-type function:

$$t_l(v_l) = t^0_l (1 + \alpha \left( \frac{v_l}{C_l} \right) ^\beta), \quad (10)$$

where $t^0_l$ is the free-flow travel time, $C_l$ is the capacity of the link concerned.

In reality, the in-vehicle travel time $t_k(v_k)$ on the MTR link $k$ can be pre-specified by its timetable. To capture the crowding effect in MTR, the modified in-vehicle travel time function often used to model the passengers’ discomfort. We adopt a BPR-type function, similar to Eqn. (10), to model the discomfort effect on travelers’ disutilities (Lo et al., 2003):

$$t_k(v_k) = t^0_k (1 + \alpha \left( \frac{v_k}{C_k} \right) ^\beta), \quad (11)$$

where $t^0_k$ is the free-flow travel time, $C_k$ is the capacity of the link concerned.

The searching time $d_i$ and $d_t$ is the function of the capacity of parking site $i$ and P&R site $t$, denoted by $C_i$ and $C_t$ respectively and the auto parking volume, denoted by $v_i$ and $v_t$. Similar to Lam et al. (1999), the BPR searching time-flow function can be modified as follow for quantifying the relationships between parking delay and demand:

$$d_i(v_i) = d^0_i (1 + \alpha' \left( \frac{v_i}{C_i} \right) ^{\beta'}), \quad (12)$$

$$d_t(v_t) = d^0_t (1 + \alpha' \left( \frac{v_t}{C_t} \right) ^{\beta'}), \quad (13)$$

where $d^0_i$ ($d^0_t$) is the free-flow parking access time at parking site $i$ (P&R site $t$), the parameter $\beta'$ is used as a measure on the degree of parking capacity restraint. The auto parking volume, $v_i$ ($v_t$), in vehicular units, can be formulated as:
\[ v_i = \sum_{w \in W} \frac{1}{q^{a}_{w,i}}, \]  
\[ v_i = \sum_{w \in W} \frac{1}{q^{c}_{w,i}}, \]

where \( q^{a}_{w,i} (q^{c}_{w,i}) \) is the parking demand on parking site \( i \) (P&R site \( t \)) for travel between OD pair \( w \). The waiting time \( T_r' \) and \( T_t' \) on MTR station \( r' \) and \( t' \), in Eqns.(2) and (3), respectively, can be computed by \( T_r' = \frac{\theta_{w}}{p_{w}} \) and \( T_t' = \frac{\theta_{w}}{p_{w}} \), where \( \phi_r' \) and \( \phi_t' \) are the parameters depending on the distributions of MTR vehicle headway and passenger arrival at each of the MTR stations. A value of 0.5 is commonly used implying that a uniform random passenger arrival distribution and a constant headway between MTR vehicles (De Cea and Fernandez, 1993; Lam et al., 2002).

### 3.2 Modelling Route Choice Behavior Under MTIS

Let \( \Psi^{mn}_{w,p} \) be the perceived travel disutility of user class \( n \) \((n = 1, 2)\) by mode \( m \) \((m = a, b, c)\) along route/path \( p \) between OD pair \( w \). It can be formulated as the sum of a systematic component and a perception error term, i.e.,

\[ \Psi^{mn}_{w,p} = U^{mn}_{w,p} + \xi^{mn}_{w,p}, \]

where \( \xi^{mn}_{w,p} \) is the perception error term, which is the sum of the perception errors of the travelers on the (auto or MTR) link travel time and the parking search time. Let \( \xi^{n}_{l} \), \( \xi^{n}_{k} \), \( \xi^{n}_{t} \) and \( \xi^{n}_{i} \) denotes the perception errors of user class \( n \) on the travel or searching times of auto link \( l \), MTR link \( k \), P&R site \( t \) and parking site \( i \) respectively. \( l \in A^a \), \( k \in A^b \), \( t \in \cup T_w \) and \( i \in \cup I_w \) represents auto link, MTR link, parking site and P&R site, respectively. Different assumptions on the distributions of these four random variables may lead to different choice models.

According to assumption A3, all travelers, including those equipped and unequipped with MTIS, make their travel choice decisions in a probit-based SUE manner. The equipped travelers have lower variation on their perceived travel disutilities compared to those of the unequipped travelers due to the MTIS services. It is assumed in this paper that \( \xi^{n}_{l} \), \( \xi^{n}_{k} \), \( \xi^{n}_{t} \) and \( \xi^{n}_{i} \) are normally distributed with zero mean, respectively, i.e.

\[ \xi^{n}_{l} \sim N(0, \sigma^{n}_{l}(v_{l})), \quad \xi^{n}_{k} \sim N(0, \sigma^{n}_{k}(v_{k})), \quad \xi^{n}_{t} \sim N(0, \sigma^{n}_{t}(v_{t})), \quad \xi^{n}_{i} \sim N(0, \sigma^{n}_{i}(v_{i})). \]

\( \sigma^{n}_{l}(v_{l}), \sigma^{n}_{k}(v_{k}), \sigma^{n}_{t}(v_{t}), \sigma^{n}_{i}(v_{i}) \) are the standard derivations of the travel times of user class \( n \) on auto link \( l \), MTR link \( k \), P&R site \( t \) and parking site \( i \) respectively which are functions of flows of those links. Similar to Yin and Lam (2002), in this paper, we assume \( \sigma^{n}_{l}(v_{l}) = \rho^{1}_{l}t_{l}(v_{l}), \quad \sigma^{n}_{k}(v_{k}) = \rho^{2}_{k}t_{k}(v_{k}), \quad \sigma^{n}_{t}(v_{t}) = \rho^{3}_{t}t_{t}(v_{t}), \) and \( \sigma^{n}_{i}(v_{i}) = \rho^{4}_{i}t_{i}(v_{i}) \). This implies a higher level of travel time variation on the link when it is more congested. \( \rho^{n}_{l}, \rho^{n}_{k} \) and \( \rho^{n}_{i} \) represents dispersion level of the perception of travel time variation. For the equipped travelers (i.e. user class 1), these parameters reflect the information quality provided by the MTIS as mentioned in A4. The smaller the value of \( (\rho^{1}_{l}, \rho^{2}_{k}, \rho^{4}_{i}) \), the higher the quality of the MTIS information provided for
user class 1. The condition $\rho_{\mu}^1 < \rho_{\mu}^2$, $\mu \in \{1,2,3\}$, should be satisfied, which implies that the equipped travelers have more accurate knowledge on the expected travel disutility than the unequipped travelers.

The perception error term in Eqn. (16), $\xi_{w,p}^{mn}$, can be expressed as:

$$\xi_{w,p}^{mn} = \sum_{l \in L^c} \xi_{l}^{m} \delta_{lp}^{mw} + \sum_{k \in L^c} \xi_{k}^{n} \delta_{kp}^{mw} + \sum_{j \in L^c} \xi_{j}^{n} \delta_{jp}^{mw},$$

$$\forall p \in P_{w}^{(m)}, w \in W, n = 1,2, m \in \{a,b,c\},$$

where $\delta_{lp}^{mw}$ is the link/route indicator variable, $\delta_{lp}^{mw} = 1$ if link $l$ is on the route $p$ and $p \in P_{w}^{(m)}$; $\delta_{lp}^{mw} = 0$ otherwise. Similar conditions are applicable to $\delta_{kp}^{mw}$, $\delta_{kp}^{mw}$ and $\delta_{l\mu}^{mw}$.

Let $\Pr_{w,p}^{n}$ be the probability that the user class $n$ choose the path/route $p \in P_{w}$ for travel between the OD pair $w$. Then, the probit-based route/path flow of user class $n$ in a multi-modal transport network can be determined by:

$$f_{w,p}^{n} = q_{w,p}^{n} \Pr_{w,p}^{n}, \forall p \in P_{w}, w \in W, n = 1,2,$$

where $q_{w,p}^{n}$ is the demand of user class $n$ between OD pair $w$, and

$$\sum_{n} q_{w}^{n} = q_{w}^{w}, \forall w \in W.$$

$q_{w}$ in Eqn. (19) is the total demand between OD pair $w$. And if the market penetration of MTIS, $\pi_{w}$, is given, then

$$q_{w}^{1} = \pi_{w} q_{w},$$

$$q_{w}^{2} = (1 - \pi_{w}) q_{w}.$$ (20)

Path/route flows $f_{w,p}^{n}$ satisfy the following conservation condition:

$$\sum_{p \in P_{w}} f_{w,p}^{n} = q_{w}^{n}, n = 1,2, w \in W.$$ (22)

The path/route choice probabilities, $\Pr_{w,p}^{n}$, for user class $n$ using path/route $p \in P_{w}^{(m)}$ between OD pair $w$ in Eqn. (18) are governed by the following probit-based formulae:

$$\Pr_{w,p}^{n} = \Pr\{\Psi_{w,p}^{n} \leq \Psi_{w,p}^{n'}, \forall p' \in P_{w}\}.$$ (23)

Note that the path/route $p$ and $p'$ may belong to different path sets with different modes, such as $p \in P_{w}^{(m)}$, $p' \in P_{w}^{(m')}$, thus $\Psi_{w,p}^{n}$ and $\Psi_{w,p}^{n'}$ in Eqn. (23) can be computed by modes and denoted as $\Psi_{w,p}^{mn}$ and $\Psi_{w,p}^{mn'}$, respectively.

From Eqns. (1)-(3), (16) and (17), path/route choice probabilities, $\Pr_{w,p}^{n}$, are the functions of systematic components of costs on all paths/routes, which are in turn the functions of $f_{w,p}^{n}$ as defined in Eqns. (4)-(15). Hence, the path/route choice probabilities, $\Pr_{w,p}^{n}$, are the functions of path/route flows $f_{w,p}^{n}$. Let $f^{n}$ denote the vector of path/route flows for the user class $n$ and define the set of feasible path/routes flows as: $\Omega = \{f^{1}, f^{2}\}$, where $f^{1} \geq 0$, $f^{2} \geq 0$ and satisfy Eqns. (19)-(22). Let $x$ denote an element in this set, i.e., $x = (f^{1}, f^{2}) \in \Omega$, then the multi-class probit-based stochastic user equilibrium condition (17) can be further formulated as the
following fixed-point problem:

$$\mathbf{x}^* - q \mathbf{Pr}(\mathbf{x}^*) = 0, \quad \mathbf{x}^* \in \Omega,$$  

(24)

where \(q\) and \(\mathbf{Pr}\) are the vectors of travel demand and path/route choice probability, respectively. According to the Brouwer’s fixed-point theory, there exists at least one solution to the problem (24) since \(\Omega\) is compact and \(\mathbf{Pr}\) is a continuous vector function. However, the uniqueness of the solution may not be guaranteed.

To assess the benefit of multi-modal traveler information systems, we make use of the relative reduction of total network travel disutility. The total network travel disutility (\(TNTD\)) is defined as:

$$TNTD = \sum_{\mathbf{w}} \sum_{\mathbf{p}} (f_{\mathbf{w},\mathbf{p}}^1 + f_{\mathbf{w},\mathbf{p}}^2)U_{\mathbf{w},\mathbf{p}},$$  

(25)

where \(U_{\mathbf{w},\mathbf{p}}\) is the travel disutility via path/route \(p\) for OD pair \(w\). Note that the path \(p\) may belong to path set with different modes, i.e. \(p \in P^{(m)}_w\), thus \(U_{\mathbf{w},\mathbf{p}}\) can be computed by mode and denoted as \(U_{\mathbf{w},\mathbf{p}}^m\). A related measure, so-called the relative reduction in \(TNTD\), is suggested to capture the change in \(TNTD\) before and after the provision of MTIS services. That is,

$$\text{Relative Reduction in } TNTD = \frac{TNTD^a - TNTD^b}{TNTD^b} \times 100\%,$$  

(26)

where the superscripts “b” and “a” refer to the cases of “before” and “after” introduction of MTIS, respectively.

4. SOLUTION ALGORITHM

In this section, a heuristic solution algorithm is presented to solve the fixed-point problem (24) for a given market penetration of MTIS. This proposed solution algorithm combines the Monte Carlo simulation method and the method of successive averages (MSA). The step-by-step procedure of the proposed solution algorithm is outlined as below.

Step0. Set iteration \(e=1\). Choose initial route/path flows \(f_{\mathbf{w},\mathbf{p}}^{1(e)}\) and \(f_{\mathbf{w},\mathbf{p}}^{2(e)}\) for given demands \(q_{\mathbf{w}}^n, n = 1, 2\) between OD pair \(w\).

Step1. Sampling. Set \(j=1\).

Step2. Based on Eqns. (4) -(14) and current link flows, compute the actual auto link time, \(t_i\), MTR link time, \(t_k\), searching time of parking site in CBD, \(d_i\), and the searching time of P&R site, \(d_i\).

Step3. Performing the Monte Carlo simulation to sample \(\xi_i^{(e)} \sim N(0, \rho_i^{(e)} t_i)\), \(\xi_k^{(e)} \sim N(0, \rho_k^{(e)} t_k)\), \(\xi_i^{(e)} \sim N(0, \rho_i^{(e)} d_i)\) and \(\xi_i^{(e)} \sim N(0, \rho_i^{(e)} d_i)\) for each auto link, MTR link and parking site.

Step4. Calculating the path/route \(p\) with minimum disutility for all modes and all routes/paths according Eqns.(1)-(3).

Step5. All-or-nothing assignment.

Assign the OD demands \((q_{\mathbf{w}}^1, q_{\mathbf{w}}^2)\) to the path/route \(p\) by performing all-or-nothing loading, then yield the auxiliary route/path inflows \(\mathbf{g}_{\mathbf{w},\mathbf{p}}^{1(j)}\) and \(\mathbf{g}_{\mathbf{w},\mathbf{p}}^{2(j)}\).
for equipped and unequipped travelers, respectively.

Step6. Using the method of successive averages to update the path/route flows,

\[ g_{w,p}^{(j)} = \frac{(j-1)g_{w,p}^{(j-1)} + g_{w,p}^{(j)}}{j} \] for equipped travelers and

\[ g_{w,p}^{2(j)} = \frac{(j-1)g_{w,p}^{2(j-1)} + g_{w,p}^{2(j)}}{j} \] for unequipped travelers.

Step7. Stopping test for sampling loop.

If the sample number \( j \) is less than a pre-specified sample size, then set \( j = j + 1 \) and go to Step2; Otherwise set \( \hat{f}_{w,p}^{(j)} = g_{w,p}^{(j)} \) and \( \hat{f}_{w,p}^{2(j)} = g_{w,p}^{2(j)} \).

Step8. Flow averaging using MSA

\[ f_{w,p}^{(e)} = \frac{(e-1)f_{w,p}^{(e-1)} + \hat{f}_{w,p}^{(e)}}{e} \] and \( f_{w,p}^{2(e)} = \frac{(e-1)f_{w,p}^{2(e-1)} + \hat{f}_{w,p}^{2(e)}}{e} \).


If the equilibrium conditions (24) are achieved, then stop and report the solution; otherwise, set \( e = e + 1 \), go to Step1.

Let \( \Pr^{(e-1)}(x) \) denote the probabilities as calculated by the Monte Carlo (MC) simulation in Steps 1-7, where \( x^{(e-1)} \) is the input path/route-flow vector for the MC simulation. Thus

\[ \hat{x}^{(e)} = q\Pr^{M}(x^{(e-1)}) \] (27)

where \( \hat{x}^{(e)} \) is the auxiliary path/route-flow vector computed by Step 7. In Step 8, we can also obtain:

\[ \hat{x}^{(e)} = ex^{(e)} - (e-1)x^{(e-1)}. \] (28)

From Eqns. (27) and (28), we can obtain:

\[ x^{(e-1)} - q\Pr^{M}(x^{(e-1)}) = e(x^{(e)} - x^{(e-1)}) = x^{(e-1)} - \hat{x}^{(e)} \] (29)

If Eqn. (29) converges to zero for all paths, user classes and OD pairs, then fixed-point condition in (24) is satisfied. Thus, a gap function of the fixed-point condition can be defined as:

\[ \Theta(e) = \max_{n,p,w} \left\{ \frac{f_{n,p}^{(e)} - \hat{f}_{n,p}^{(e)}}{f_{n,p}^{(e)}} \right\}, \quad n = 1,2, \quad p \in P_{w}, \quad w \in W. \] (30)

If \( \Theta(e) \to 0 \), the path flows computed from the proposed solution algorithm approach to the solution of Eqn. (24). Note that a sufficient sampling numbers of MC are required to ensure the convergence of the solution algorithm. Thus, the method may be too time-consuming. Other analytical approximation methods for the path choice probability calculation, such as Mendell-Elston method (Kamakura, 1989), can be employed instead of the MC simulation to reduce the computational time.

In addition, in a large-scale multi-modal transport network, the definition of feasible path set should be required (Lo et al., 2003). In our multi-modal transport network, the path between an OD pair is considered viable if it includes only one consecutive sequence of MTR mode, or only one consecutive sequence of private mode with origin node O (Bielli et al., 2006). Lozano and Storchi (2001) started to investigate passenger transfer behaviors in multi-modal transport networks. They proposed a method to generate a pareto-optimal path set based on transfer numbers and generalized link costs. Their method can be adapted to generate effective or viable path set in this paper.

5. NUMERICAL STUDIES
An example multi-modal network is adopted in this paper to illustrate the application of the proposed model and solution algorithm. Figure 1 shows this example network which consists of three modes, two OD pairs (1-3 and 2-3) and eleven nodes. Suppose that travel demands are given in person trips or passenger units for the two OD pairs. The demand from origin 1 to destination 3 is denoted as $q_{13}=4000$ (passenger/hr) and the demand from origin 2 to destination 3 is denoted as $q_{23}=2400$ (passenger/hr).

The parameters in BPR-type functions (9)-(11) are defined as: $\alpha = 0.15, \beta = 4$ and $\alpha' = 0.31, \beta' = 4.03$ (Lam et al., 1999; Li et al., 2007). The values of free-flow travel time and capacity of each roadway link are presented in Table 1. Table 2 shows the parameters related to parking site A and P&R site on node 5 adopted in the test. Table 3 displays the travel times of walk links and MTR links.

In this example, it is assumed that the MTR fares on MTR links 11 and 12 are $4$ and $8$ respectively. The vehicle capacity and dispatching frequency of the MTR line are 200 passengers per vehicle and 6 trains per hour respectively. Each train consists of two vehicles, thus the capacity of each train is 400 passengers. The average walking speed of travelers is assumed to be 5.0 km/h. The car occupancy rate $\gamma_w$ is assumed to be 1.0. Other model parameters are $\alpha_1=1.0, \alpha_2=1.4, \alpha_3=0.1, \alpha_4=1.8; \beta_1=2.0, \beta_2=1.0, \beta_3=0.1, \beta_4=1.8; \kappa_1=1.0, \kappa_2=2.0, \kappa_3=1.8; \kappa_4=0.1, \kappa_5=1.4, \kappa_6=0.1, \kappa_7=1.8; \phi_1=\phi_6=0.5 ; \Delta^a=0.1, \Delta^b=1, \Delta^c=0.5$. In addition, $\rho_1^2=5$ for all auto links, $\rho_2^2=1$ for all MTR links and $\rho_3^2=0.1$ for parking sites and P&R sites. Thus the triple $u=(\rho_1^2, \rho_2^2, \rho_3^2)$ reflects the perception errors of the unequipped travelers on network travel disutility. For simplicity, we assume that the level of service quality of MTIS can be measured by multiplying $\nu$ and $u$ with $\nu \in (1,0)$. Such as, if $\nu=0.3$, the

![Figure 1 The example network](image-url)
triple \((\rho^1, \rho^2, \rho^3) = (1.5, 0.3, 0.03)\), which represents the parameters related to the perception errors of the equipped travelers. Obviously, the services quality of MTIS will decrease with a higher value of \(\nu\). It is assumed in this example that the MTIS market penetration, \(\pi_w = \pi\), is a constant for all OD pairs and takes the value between 0 and 1.

Table 2 The parameters of parking site and P&R site

<table>
<thead>
<tr>
<th></th>
<th>Free-flow parking access time(hr)</th>
<th>Parking fee($)</th>
<th>Parking capacity(veh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P&amp;R site (Node 5)</td>
<td>0.05</td>
<td>2</td>
<td>800</td>
</tr>
<tr>
<td>Parking site (A)</td>
<td>0.1</td>
<td>12</td>
<td>1350</td>
</tr>
</tbody>
</table>

Table 3 The travel time of the walk links and MTR links

<table>
<thead>
<tr>
<th>Link</th>
<th>Travel time(hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Walk links</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>0.60</td>
</tr>
<tr>
<td>14</td>
<td>0.50</td>
</tr>
<tr>
<td>15</td>
<td>0.05</td>
</tr>
<tr>
<td>16</td>
<td>0.20</td>
</tr>
<tr>
<td>17</td>
<td>0.10</td>
</tr>
<tr>
<td>MTR links</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>0.15</td>
</tr>
<tr>
<td>12</td>
<td>0.60</td>
</tr>
</tbody>
</table>

The MC sampling size is 5000 in this numerical example. The convergence of \(\Theta(e)\) with MTIS market penetration \(\pi = 0.3\) and information quality \(\nu = 0.3\) is shown in Figure 2. From Figure 2, \(\Theta(e)\) converges to zero, and thus \(f_{w,p}^{n(x)}\) approaches to the solution of the fixed-point problem in (24).

Figure 2 Convergence of the proposed solution algorithm

Figure 3 shows the corresponding relative reduction in total network travel disutility, in percentage term, with various combinations of MTIS market penetration and information quality. It can be observed that the relative reduction can be decreased by providing better information quality at each given market penetration of MTIS. A similar result also occurs when MTIS market penetration is increased but the information quality is fixed. It should be noted that for a given and fixed information quality, the increasing trend of the relative reduction slows down with the increase of market penetration, as illustrated in Figure 3. From the model results, when market penetration, \(\pi\), is larger than about 0.67 and the value of \(\nu\) is
lower than 0.25, the maximum value of relative reduction is up to 93%. This requires a majority of travelers to be equipped with the perfect MTIS services. The numerical example shows that the MTIS services can improve the network performance and reduce the total network travel disutility.

Figure 4 depicts the effects of multi-modal traveler information systems (MTIS) on the demand shares among the three modes with respect to different information service quality and market penetration levels. Noteworthy, the results are computed at a relatively high demand level with $q_{13}=4000$ and $q_{23}=2400$. Along the direction of the arrow on Figure 4, one can notice a slight reduction of the P&R demand (shown as dotted lines) from 1010 to 970 (around 4% reduction).

From Figure 4, along the same arrow-line, the auto demand decreases much more rapidly, e.g. from 4000 to 3000 (25% reduction). The MTR demand, on the other hand, increases substantially. This result implies that a higher market penetration and a better information quality of MTIS will encourage more car users to switch to MTR mode. To investigate the effects of MTIS on the modal shift more closely, consider points A and B in Figure 4 for illustration. From A to B, the information quality, $\nu =0.35$, is fixed, and the market penetration, $\pi$, changes from 0.04 to 0.9. The demands of using auto mode, P&R demand and MTR mode then change from 4000, 1010 and 1400 to 2030, 970 and 3400 at point B respectively. The demand changes for car, P&R, and MTR are around -30%, -3%, +142% respectively. This shows clearly the switch of the demand between car and MTR modes with a relatively small change in the demand for P&R.

As mentioned earlier, this test is conducted under a highly congested condition. This implies a
high variation of car travel time perception in contrast to a less variable perceived MTR journey time. Thus, when the information quality of MTIS increases, equipped travelers are then more aware of the congestion in the road network and may decide to switch to the MTR. Similarly, the higher the quality of MTIS information, the better the awareness of the congestion at the parking site of P&R and hence the lower demand. It is possible that under a condition with a spare capacity of the parking facility of the P&R mode some demand from car mode may switch to P&R instead of the MTR. This particular result shows that MTIS can have a positive effect on the utilization of public transit, which was simulated by Neuherz et al. (2000) and also investigated by Fujiwara et al. (2004).

Figure 5 considers the effects of congestion level and market penetration on the demand splits among the three transport modes when the information quality is given ($\nu=0.3$). The input parameter (congestion level) is denoted as $\vartheta$ to represent different travel demand levels. The contour shows different modal splits with different market penetration and congestion levels.

At a low congestion level (e.g. $\vartheta \leq 0.3$, i.e. the total demand is less than 1920), the majority of travelers (above 80%) prefer to use cars. Very few travelers (less than 50) choose the MTR mode. Under such the condition, as shown in Figure 5, providing MTIS services to travelers encourages the use of car and/or P&R modes rather than the MTR mode. On the other hand, at a high congestion level $\vartheta$ (e.g. $\vartheta \geq 1.0$, i.e. the total demand is more than 6400), the auto (bolded contour) and the P&R (dotted contour) demands both decrease when the market penetration of MTIS increases. On the other hand, the number of travelers choosing MTR mode increases. This result is along the same line with the discussion regarding Figure 4. Under a relatively normal condition (e.g. congestion level locates between 0.3 and 1.0), increasing the share of population using MTIS services reduces the number of only-auto users whereas the demand for the P&R and MTR modes increases. However, note that the proportion of only-auto users with mode shift is less than that under the heavy congestion cases.

Based on this test, we may conclude that the effect of MTIS critically depends on the existing congestion condition. Under a rather mild congestion level, providing MTIS services to travelers would encourage a higher level of car uses. Some previous studies postulated that the demand switch from auto to public transit will be rather low (Yim and Miller, 2000; Abdel-Aty and Abdalla, 2006) because of their habitual behaviors of mode choice in reality, which is represented partially by the mode specific constant in Eqn. (3). On the other hand, with a relatively high level of congestion, the higher the information quality and market

Figure 5 Effects of congestion level and market penetration on demand
penetration of MTIS the higher the switch of the demands from the auto to MTR modes. The MTIS, in other words, magnifies the actual congestion level in the user’s perception which overhears the mode specific constant (representing some mode choice habit). For the P&R mode, the effect of MTIS on its demand depends on the level of congestion at the parking site.

6. CONCLUSIONS

The integrated information service, such as MTIS, is expected to have a large potential to influence travel choices particularly on mode choice in a multi-modal transport network. This paper proposed a multi-class probit-based stochastic user equilibrium (SUE) model to investigate the effects of MTIS. It was assumed that travelers are divided into two classes, those equipped and unequipped with MTIS. Travelers from both classes would make their travel choice decisions based on the probit-based SUE principle. In the proposed model, the effects of various types of information in MTIS have been considered explicitly. The multi-modal multi-class SUE problem has been formulated as a fixed-point problem and solved by a solution algorithm based on MSA and the Monte Carlo simulation.

The numerical results indicated that the introduction of multi-modal traveler information systems (MTIS) will have significant impacts on the performance of the multi-modal transport network. Specifically, a higher market penetration and a better information quality of MTIS can reduce the total network travel disutility and promote the utilization of public transit under a medium to highly congested condition. In addition, the modal choice of travelers is significantly influenced by the other factors such as information quality and market penetration of MTIS. Further investigations will be: (i) to extend the proposed model to the time-dependent or dynamic modelling paradigm; (ii) to determine the optimal market penetration of MTIS services; and (iii) to develop efficient solution algorithm for larger-scale multi-modal transport networks.

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