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ROUTE CHOICE MODEL BASED ON GAME THEORY FOR COMMUTERS

ABSTRACT

The traffic behaviours of commuters may cause traffic congestion during peak hours. Advanced Traffic Information System can provide dynamic information to travellers. Due to the lack of timeliness and comprehensiveness, the provided information cannot satisfy the travellers' needs. Since the assumptions of traditional route choice model based on Expected Utility Theory conflict with the actual situation, a route choice model based on Game Theory is proposed to provide reliable route choice to commuters in actual situation in this paper. The proposed model treats the alternative routes as game players and utilizes the precision of predicted information and familiarity of traffic condition to build a game. The optimal route can be generated considering Nash Equilibrium by solving the route choice game. Simulations and experimental analysis show that the proposed model can describe the commuters' routine route choice decision exactly and the provided route is reliable.

KEY WORDS

route choice model; game theory; commuters; reliability; dynamic route guidance system;

1. INTRODUCTION

With the improvement of national economy and the acceleration of urbanization, the range of urban residents becomes larger, and the employment range expands as well. This phenomenon leads to more commuting travels and higher complication of commuting behaviours [1]. The commuting travel is the most basic and important urban travel which influences all aspects of urban life. Especially, due to the commuting behaviour concentrated on certain periods and certain districts, it often causes traffic congestion during peak hours. The peak hour congestion becomes one of the most prominent problems; it restricts the social and economic developments.

The research of commuting behaviour will remit the traffic congestion during peak hours [2]. Abane [3] utilized polynomial Logit model to analyse the travel mode of commuters which indicated that the affection of travel mode choice includes the factors such as commuter's age, gender and income. Golob [4] analysed factors of travel chain quantity, behaviour remaining time, travel time and their relationship using structure equation model. Xuanyu et al. [5] improved the precision of commuters' travel mode prediction with the consideration of choice set and individual difference. Luan et al. [6] researched the interactions of commuters' travel model choice and travel chain choice based on Nested Logit model. The above studies focus on commuters' travel behaviour including travel mode choice and travel chain. The goal is to provide sufficient proof to transportation planning such as traffic congestion charging and staggered rush hour plan.

Shen et al. [7] introduced the commuting elasticity into the commuting behaviour research. They defined four commuting dimensions, such as time elasticity, space elasticity, mode elasticity and route elasticity, and they also analysed their interactions and relationships. They found that the fixed route ratio of private car is the lowest. Particularly, influenced by traffic uncertainty, commuters might choose an alternative route under the instruction of relative information. Therefore, researchers conducted a number of relevant studies in this field.

The traditional route choice model in route guidance system established the route choice model in so far as to evaluate the alternative routes. In route guidance system, in order to evaluate the alternative routes, the traditional route choice model is established by the route choice model through Expected Utility Theory with geometrical distance or travel time to maximize the utility [8, 9]. The route choice model based on the Expected Utility Theory assumes that the road section information is completely known, each driver is a perfectly rational human and always pursues utility maximization [10]. However, the traffic condition is complex and uncertain, which makes it hard for the drivers to understand the current traffic situation and avoid traffic accidents. The assumption of a perfectly rational human is a kind of ideal state which is quite different from the reality. Consequently, the conclusions obtained by the route choice model based on the Expected Utility Theory are usually incompatible with the drivers' real decision-making behaviour, such as the famous Allais and Ellsberg Paradox.

Simon [11] put forward a concept of limited rationality in decision-making issue. He indicated that the rationality of decision-making must take the limitations of cognition, motivation, and ability caused by the lack of omniscient and omnipotent into account. With the concept of strengthening gradually, the paradigm in decision-making research began to change. The model emphasizes the explanation and the prediction of actual decision-making behaviour appeared. The most representative models are Rank-Dependent Utility Theory Model (Quiggin) [12] and Prospect Theory Model (Kahneman and Tversky) [13]. However, most of the subsequent studies are in the stage of simple imitation of the standard model.

In actual travel process, the drivers do not change their routes easily, even if they found a route with maximum utility [14]. However, there is a tolerance limitation for drivers. When an evaluation index is over the acceptable range, the drivers may choose an alternative route rationally. Shiftan et al. [15] established the route choice model with the parameters of personal attribute, family attribute and travel characteristic. They found that the drivers are not willing to change their routes when they get insufficient traffic information or information not familiar with the traffic situation. Even when they got enough information, they preferred to choose the route with lower average travel time but greater variance. Drivers pursued the maximum benefits of their own [16]. They do not concern the influence on the entire traffic condition, which agrees with the example of individual rationality and collective rationality in Game Theory. Because in this situation everyone makes the decision according to their own benefit, but the final result is collective outcome suffering [17]. This game indicates the contradiction between individual rationality and collective rationality. Moreover, the individual rationality has inherent contradiction in itself as well. Sometimes, the individual rationality behaviour does not realize the maximum individual benefit, but leads to the contrary result which is called crowded drift phenomenon in the traffic problem.

Although researchers did a great work in travel behaviour influence for traffic information and route choice under uncertain environment. These studies mainly focus on single behaviour factor which separated the key behaviour factors, such as information search, learning, cognitive update and scheme generation. The separation of the related and restricted relationship of the behaviour factors resulted in unsystematic and discontinuous analysis which affected the precision of demand prediction. Therefore, it is necessary to establish the heuristic decision-making model under bounded rationality. Therefore, a commuter route choice game model is proposed to obtain Nash Equilibrium based on guidance information in this paper to provide reliable optimal commuting route.

2. GAME THEORY AND NASH EQUILIBRIUM

Game Theory is to study how to make an equilibrium decision under the interactions of all aspects of the decision body. It solves, namely, the restricted decision-making and equilibrium problem in the case of interaction and mutual influence of individuals.

The so-called equilibrium is the most optimal strategy set by all players. The result produced by the game of all players is an end of the equilibrium. It cannot be the maximum benefit for each player in the game, but rather an inevitable result under the given information and knowledge. Hence, any changing of the player's strategy will cause a variation of the equilibrium so as to lead to a worse result in itself.

There are several basic elements in a game, such as player, information, action, strategy, payoff, outcome, and equilibrium. However, player, strategy and payoff are the minimum elements of a game. The purpose of the game is to determine the equilibrium using the game principles.

The core model in Game Theory is Nash Equilibrium. Nash Equilibrium refers to an equilibrium state caused by the interaction process of individuals in a game. No individual can increase their payoff by changing its strategy unilaterally under this situation [18].

In general, a game can be described as G. If G consists of n participants, the alternative strategy sets of each player are called strategy space, which can be expressed as $S_1, S_2, \ldots, S_n$, respectively. $s_{ij} \in S_j$ indicates the strategy j of player i, where j can either be a finite number (called finite strategy game), or an infinite number (called infinite strategy game). The payoff of player i can be indicated as ui, which is a multivariate function of each player. Hence, a game with n players is usually written as *Equation 1,*

$$G=\{S_1, S_2, \ldots, S_n; u_1, u_2, \ldots, u_n\} \quad (1)$$

In a strategy-expressed game with n players $G=\{S_1, S_2, \ldots, S_n; u_1, u_2, \ldots, u_n\}$, if in a certain strategy set consisting of each strategy $(S_1^*, S_2^+, \ldots, S_n^*)$ of each player, the strategy S_i^* of each player i is the best strategy of the strategy set of the rest of the players $(S_1^*, S_2^*, \dots, S_{i-1}^*, S_{i+1}^*, \dots S_n^*)$ as *Equation 2,*

$$u(S_1^*, S_2^*, \dots S_{i-1}^*, S_{i+1}^*, \dots S_n^*) \geq \\ \geq u(S_1^*, S_2^*, \dots S_{i-1}^*, S_{ij}^*, S_{i+1}^*, \dots S_n^*) \quad (2)$$

For each $s_{ij} \in S_j$, *Equation 2* is always found, then $(S_1^*, S_2^*, \dots, S_n^*)$ is a Nash Equilibrium of *G*.

There are several research conclusions in route optimization and route choice behaviour based on Game Theory. Yang et al. [19] analysed customer equilibrium, system equilibrium, and Nash equilibrium models. The Nash Equilibrium model and relevant algorithm were established based on an assumption, i.e. drivers make a decision by knowing the other drivers' route choice decisions. Li [20] proposed a route choice model based on evolutionary game theory under guidance information. He analysed the payoffs of different combinations of acceptance and rejection of guidance information to formulate different route choice strategies. An et al. [21] considered the characteristics of the interaction of system optimum and user optimum in route choice process, and introduced the game theory to coordinate the conflicts of the system and the user to establish a route choice game model between the administrator of road network system and the drivers. They found the model not only met the needs of drivers, but also improved the entire road network performance. Guan et al. [22] proposed a route choice model based on the evolutionary game theory under the situation of incomplete information and limited rationality. The model proved that the obtained evolution state is equivalent to the equilibrium state obtained in random utility theory and traffic assignment theory in case of two or *n* independent routes. With mathematical induction as a tool, this paper proves the suitability of evolutionary approach for the analysis of drivers' route choice behaviour. It is found that for two and up to n routes, the evolutionary stable state derived from the above-mentioned approach is exactly equivalent to the equilibrium derived from the traffic assignment theory and stochastic utility theorem.

Under the guidance information situation, the commuters consider the travel time cost. At the same time, they also care about the reliability of the travel time. Therefore, after the guidance system providing the travel time of the optimal route, which is usually calculated according to the real-time information or predicted information, the commuters judge the reliability of the provided optimal route according to their experience to determine whether they will follow the system instructions. A commuter route choice game model is proposed based on the precision of predicted information and familiarity of traffic condition to find the Nash Equilibrium so as to provide a reliable optimal route choice.

3. GAME MODEL ESTABLISHMENT

3.1 Optimization Goal Analysis

The commuting routes are relatively fixed, and commuters are familiar with their routine commuting routes. Therefore, the route choice game model makes the routine commuting route and the k shortest routes with the minimum travel time as the players in the game model. The parameter *k* is usually 3 to 4. If the model does not get the routine commuting route, *k*=4, otherwise *k*=3.

The *k* shortest routes can be described as follows: sets v_i and v_j are two vertices of assignment graph *G*. Here *r* represents a route from v_i to v_j, and its travel time is *z*(*r*). All the different routes from v_i to v_j consist of the route set $R(G,v_i,v_j)$, which is expressed as *Equation 3*, and is called the route set from v_i to v_j in graph *G*.

$$R(G, v_i, v_j) = \{r_1, r_2, \dots r_Q\} \quad (3)$$

According to the magnitude of travel time value, the arrangement of $R(G, v_i, v_j)$ is as follows:

$$r_1, r_2, \dots r_Q \,|\, z(r_1) \leq z(r_2) \leq \dots z(r_Q) \quad (4)$$

where r_1 is the first shortest route from v_i to v_j in graph *G*, that is the optimal route in general; r_2 is the second shortest route from v_i to v_j in graph *G; r_Q* is Q^{st} shortest route from v_i to v_j in graph *G*.

The *k* shortest route issue is to calculate the first of the $\boldsymbol{k}^{st}$ (k≤*Q*) shortest routes from v_i to v_j in graph *G* .

The game strategy is established using the precision of the predicted information *PId* and traffic condition familiarity *DAf*, and their payoffs in consideration of travel time are also calculated. Provide the optimal route by solving the game and calculating the Nash Equilibrium of the games, described as *Equation 5* and *Equation 6*.

$$G = \{R_1, R_2, \dots R_n; u_1, u_2, \dots u_n\}, \quad (5)$$

$$s.t. u(r_1^*, r_2^*, \dots, r_{i-1}^*, r_i^*, r_{i+1}^*, \dots r_n^*) \geq \\ \geq u(r_1^*, r_2^*, \dots, r_{i-1}^*, r_{ij}^*, r_{i+1}^*, \dots r_n^*) \quad (6)$$

where R_i represents the feasible alternative routes; u_i indicates the payoff of R_i, and r_{ij} indicates the strategy of R_i.

3.2 Game model

According to the factors affecting the drivers' decision-making procedure and their relationship, the route choice game model is proposed. The model involves two parameters, including the precision of the predicted travel time and traffic condition familiarity.

The model assumes that: 1) drivers strictly follow the predicted travel time to select the departure time with the travel time prediction of each feasible alternative route; 2) the lower the traffic condition familiarity, the lower are their intentions to choose, and vice versa.

3.2.1 Game participants

First of all, to establish a game is to select the game players. The game players of the route choice game model are the routine commuting route and the alternative k shortest routes.

The routine commuting route can be acquired by the data analysis of the GPS unit. The alternative *k* shortest routes are calculated in the *k* shortest route algorithm mentioned above. The parameter *k* is usually three to four. Based on the adjustment of parameter *k* in the course of simulation and experimental analysis, if the model doesn't get the routine commuting route, *k* is equal to four, otherwise *k* is equal to three.

3.2.2 Game strategy

a) Precision of Predicted Information

Generally speaking, the parameter which is used to search the optimal route in calculating the shortest route is real-time or predicted information. However, the real travel time of the optimal route is often different from that of the model provided. However, the real travel time cannot be known before the drivers' travel, or even their arrival. Moreover, due to the variable factors such as driving preferences and signal intersections, there must be a deviation between the predicted information and the real information. Therefore, the route choice model which only depends on the assumed travel time to provide optimal route may help drivers who are unfamiliar with the traffic condition. However, this does not work with the commuters.

The route choice game model utilizes the precision of predicted travel time *PId* as one of the game parameters to establish the route choice model. The *PId* is calculated in Equation 7 and Equation 8.

$$PI = \frac{1}{n}\sum(\alpha_1, pi_1 + \alpha_2, pi_2 + ...\alpha_n, pi_n), \tag{7}$$

where pi_n is the predicted travel time of route for each player, and α_n is the weight-coefficient.

$$PId = \frac{|PI - RI|}{RI}, \tag{8}$$

where *PI* represents the predicted travel time of the route; *RI* stands for the real travel time of the route, and *α* is the time payoff parameter.

b) Familiarity of traffic condition

The commuters may not get the complete information of the entire network before the travel, and the traffic conditions continuously change during their travel. Hence, commuters can only get a part of information. When the model provides commuters with one optimal route or alternative routes, the commuters usually choose their familiar route instead of the optimal one in the situation of lacking complete information acquisition or face unknown and uncertain alternative routes. Therefore, the other parameter *DAf*, which is the familiarity of traffic condition in the route choice game model can be described as follows:

$$DAf = \frac{1}{n}\sum(\gamma DA_i + \lambda RG_i + \varepsilon), \tag{9}$$

where DA_i represents the drivers' preferences of road section *i*; RG_i indicates the grade of road section *i*, and ε indicates the random factor which belongs to the range [-1, 1].

3.2.3 Game payoffs

Commuters usually have an arrival time limitation. Due to the traffic variation, the travel time of the same route at different departure time will be different, especially during the peak hours. Consequently, the calculation of game payoffs to determine the payoffs depend on the travel time, the arrival time limitation, signal intersection and traffic condition. The methods of payoff calculations are different for each parameter.

a) Precision Payoffs

Due to the relationship between the predicted information and departure time, the calculation of predicted information precision payoff U_{PId} consists of two factors, including the travel time and arrival time.

$$U_{PId}=u_{AT}+u_{TT} \text{ ,} \qquad 10)$$

where u_{AT} represents the payoff of arrival time. When the arrival time is before the specified moment, its value is positive, otherwise is negative. The calculation of u_{AT} can be described as Equation 11. u_{TT} indicates the travel time payoff, which is equal to the value of *PId*.

$$u_{AT} = \begin{cases} x^{-\alpha x}, x \le T_b \\ T_b^{\alpha Tb} - x^{-\beta x}, T_b < x \le T_r, \\ -\lambda x^{\gamma}, x > T_r \end{cases} \tag{11}$$

where Tb_w indicates the best arrival time, and T_r is the specified commuting time. The values of parameters α, β, γ, and λ are 0.88, 1.2, 1.78, and 2.25, respectively [23].

b) Familiarity Payoffs

With the consideration of arrival time limitation, the factors affecting the traffic situation payoffs are signal intersections and familiarity with traffic condition. Due to the driving preference of different drivers, the crossing signal intersection quantity is larger, the volatility of intersection delay is greater. Especially during the morning peak hours, the driving preference will cause great intersection delay. Moreover, the traffic condition is another critical factor which affects the travel time, even for the situation caused by different departure time. Hence, the calculation of traffic condition familiarity payoff U_{DAf} includes the payoffs of traffic and signal intersections.

$$U_{DAf}=u_{TC}+u_{SC} \tag{12}$$

where u_{SC} indicates the payoffs of signal intersection and u_{TC} indicates the traffic payoffs; $u_{SC}=\rho N_{sc}$, where N_{sc} indicates the signal intersection quantity; u_{TC} is equal to the value of *DAf*.

3.3 Game analysais and procedure

There are many methods to analyse the route choice game in complete information static game. Since the players in this model are only two and the choices of the player are limited, the model adopts simple scribing method to solve the route choice game. This method is simple and easy to solve with the help of a computer. Moreover, the choices are limited, so that the calculation amount is rare. The game procedure of the model is as follows:

Step 1: Provide the *k* shortest routes from the origin to the destination so as to consist of alternative route sets as the players in addition of the routine commuting route.

Step 2: Calculate the parameters *PId* and *DAf* so as to establish the game strategies and calculate the payoffs of different strategy sets.

Step 3: Utilize the scribing method to calculate the biggest payoffs in each row and column to solve the route choice game to ensure the optimal route.

4. SIMULATION AND EXPERIMENTAL ANALYSIS

The proposed model will be simulated and verified in a real urban road network. Choose parts of the urban road network for convenience as shown in *Figure 1*. The road network topology contains 17 nodes and 26 road sections, where 12-15 stands for the expressway. There are three one-way streets, which are 13-6, 17-12, and 6-5-13.

Assume the commuting origin is Node 1 and destination is Node 12. The routine commuting route is 1-2-3-4-9-12. The k shortest routes from Node 1 to Node 12 at 7:35 (Departure Time, DT) are OP1, OP2, and OP3, respectively, including the routine commuting route OP1, shown in *Figure 2*.

Table 1 lists the parameters of the alternative routes. The optimal route is OP1 in solving the route choice game to obtain the Nash Equilibrium. However, the travel time of OP2 is smaller than the one of OP1. OP1 is the routine commuting route with a high *DAf* in the restricted time, while OP2 is an alternative route with lower *DAf*. For commuters, compared with the alternative route, they are more familiar with the routine commuting route OP1. Therefore, they prefer to choose OP1 in the restricted time. The results agree with the principles that the drivers will not change the route; otherwise, the travel time will save up to 27% in reference [11]

Once the departure time is 7:45, the parameters of alternative routes are changed as listed in *Table 2*. At this moment, the optimal route given by the game model is OP2. Regarding travel time, OP2 is the only route that can take the commuter to the destination on time. Maybe OP4 will also make the commuter drive to the destination on time, but it has a larger PId than that of OP2. Although its *DAf* is larger, the drivers usually tend to risk aversion in this situation so as to choose a more reliable route.

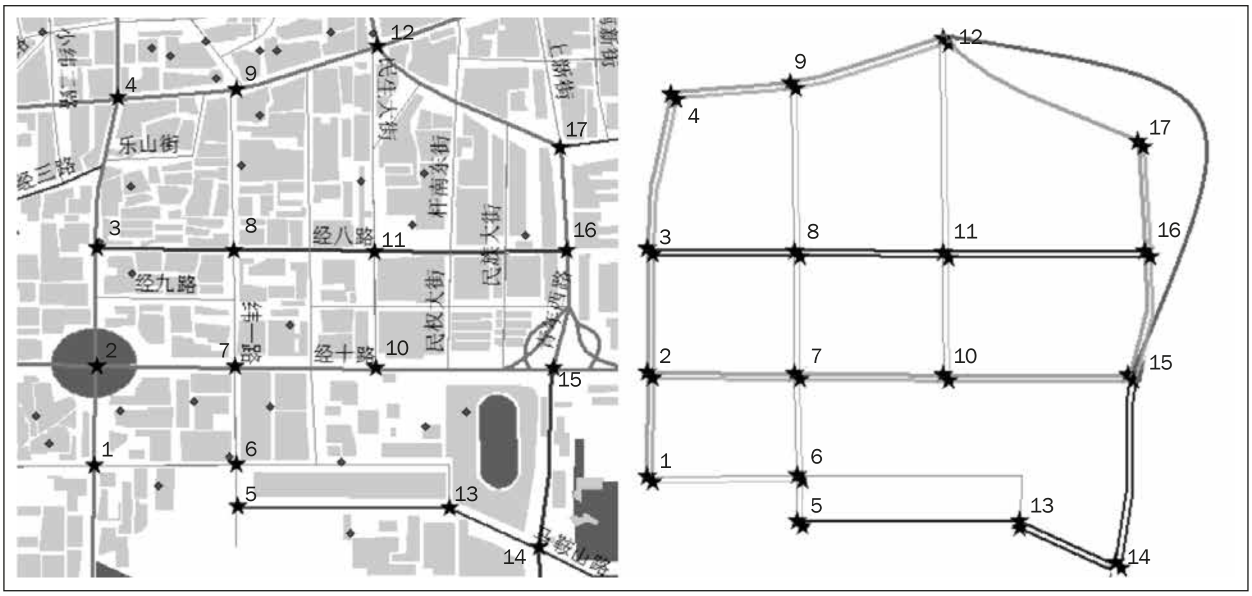

Figure 1 – Simulated Road Network Topology

Figure 2 – Alternative routes at 7:35

Figure 3 – Alternative routes at 7:45

Table 1 – Parameters of alternative routes at 7:35

DT Route	7:35 Length	TT*	*PId*	*DAf*	AT
OP1	2.0456	13.53	0.433	0.945	7:49
OP2	3.5771	10.06	0.055	0.688	7:46
OP3	2.2469	16.23	0.125	0.843	7:44

Table 2 – Parameters of alternative routes at 7:45

DT Route	7:45 Length	TT*	*PId*	*DAf*	AT
OP1	2.0456	16.03	0.171	0.945	8:02
OP2	3.5771	10.74	0.033	0.688	7:56
OP4	3.35	15.53	0.061	0.796	8:01

Table 3 – Precision comparison of alternative routes

	OP1	OP2	OP3	OP4
7:35	0.433	0.055	0.125	0.033
7:45	0.171	0.033	0.119	0.061
Average	0.103	0.093	0.083	0.053

Simulate the above road network topology in VISSIM. The simulation time range is from 6:00 to 9:30. Choose the simulation data from 6:30 to 9:00 as real information so as to compare it with the travel time given by the model. Comparisons are shown in *Figure 4* to *Figure 7*, respectively.

Figures 4 to *7* show that the predicted travel time given by the model is larger than the real information in peak hours, respectively. On the one hand, the predicted information has prediction error. On the other hand, considering the sensitiveness of time to drivers, the calculation of the predicted travel time has certain redundancy. Therefore, the predicted travel time is close to the real travel time simulated in VISSIM. The travel time is not only as close as the real information, but also has a certain surplus. *Figure 5* and *Figure 7* show that the real travel times of OP2 and OP4 during the simulation performance are smoother, since most of the routes pass through the expressway. Moreover, the error between the predicted travel time and the real information of OP2 during the simulation is the smallest of all, that is, the predicted information of OP2 is closest to the real information. Hence, the optimal route OP2 is more reliable.

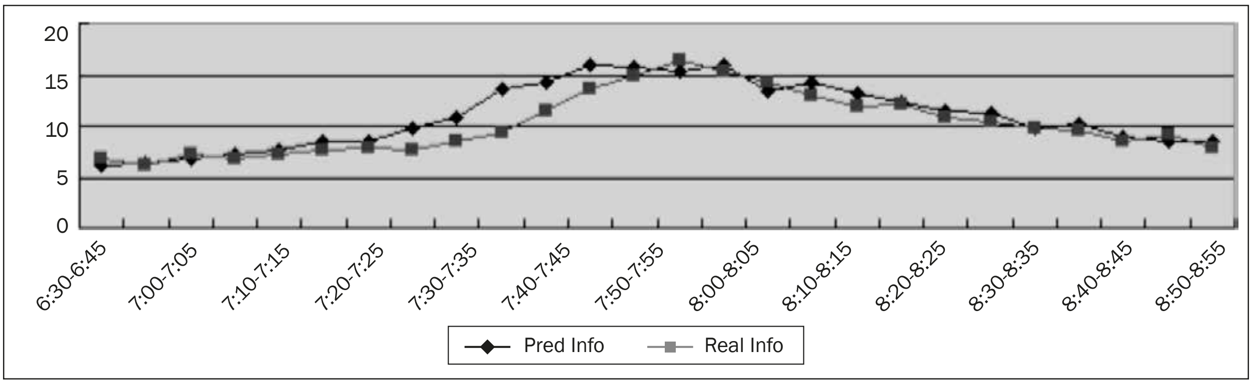

Figure 4 – Travel time comparison of alternative route OP1

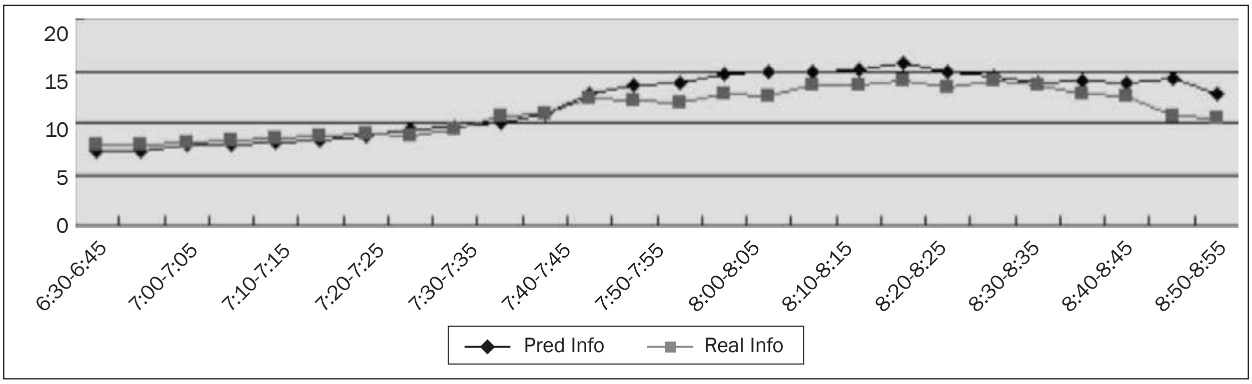

Figure 5 – Travel time comparison of alternative route OP2

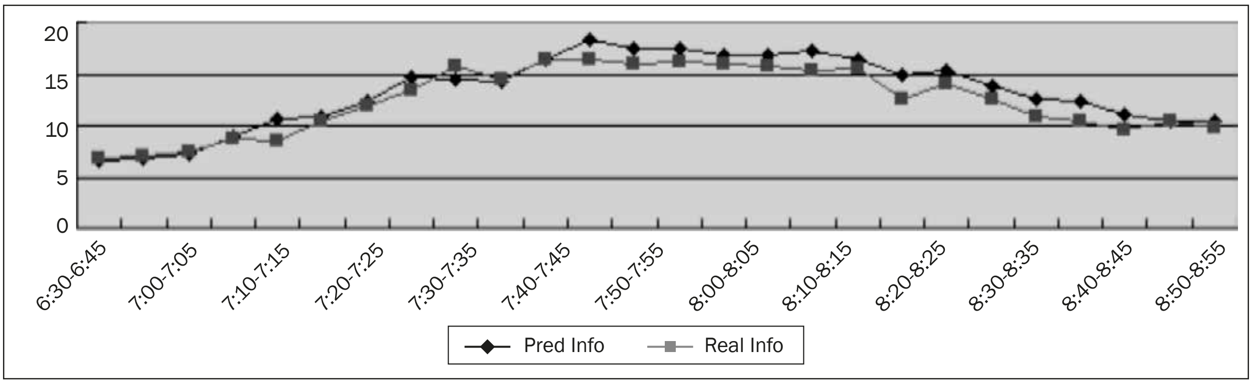

Figure 6 – Travel time comparison of alternative route OP3

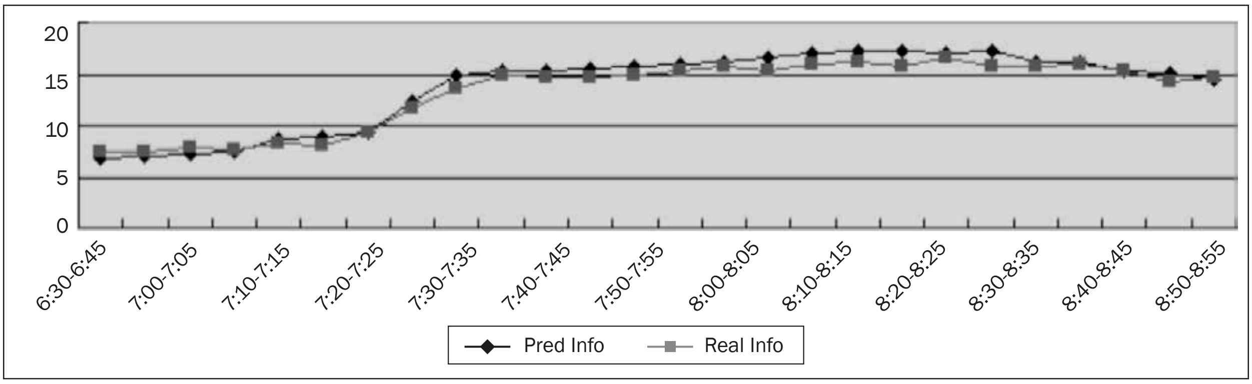

Figure 7 – Travel time comparison of alternative route OP4

5. CONCLUSIONS

The existing route guidance systems are insufficient in the aspects of continuous variation of time characteristics and individual preference characteristics. The guidance strategies are made according to the instantaneous state of the whole route at a certain time point. The corresponding routes choice is established according to the accumulated experienced time rather than real traffic situation, which leads to the choice results with great deviation relative to the facts. Based on the traditional route choice model with travel time parameter, the proposed Game Theory-based route choice model introduces the parameters of precision of predicted information and familiarity of traffic condition. The model provides reliable optimal routes to commuters by discussing the factors and their relations of commuters' decision-making procedure.

Simulation results show that the Game Theory-based route choice model for commuters fully considers the precision of the predicted information. Compared to the model with single travel time parameters, the proposed model is advanced in the intelligent prediction of travel time information and real time selection of optimal routes, which can improve the fitness to the real information. Meanwhile, the proposed Game Theory-based model also considers individual preference affections, so that the model can translate the individual preference and experience to mathematical model, which make the model close to the way of individual thinking and meet the needs of route choice for commuters.

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基于博弈论的通勤者路径选择模型

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摘要：在交通高峰时期通勤者的出行容易引起道路交通拥堵。先进的交通信息系统可以为通勤者提供动态的交通信息。由于该系统提供的信息缺乏及时性和全面性，通畅不能满足出行的需要。针对基于期望效用理论的传统路径选择模型的假设易与实际交通局势产生冲突，本文中，提出了一种基于博弈论的路径选择模型为通勤者提供可靠的路径选择方法。所提提出模型将可选路径作为博弈者，同时利用准确的预测信息和交通条件的相似性建立博弈规则。通过求解纳什均衡产生最佳路径。仿真及实验论证表明所提模型能够准确描述通勤者的路径选择决策行为及所提供路径的可靠性。

关键字：路径选择模型；博弈论；通勤者；可靠性；动态路径诱导系统

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