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Analysis on context change and repetitive travel mode choices based on a dynamic, computational model

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ABSTRACT

Research on individual decision-making process is fundamentally critical to explore the macroscopic behavioral rules for travel mode choice. In this paper, a behavioral experiment under different contexts was designed by a process-tracing method to obtain data regarding repetitive travel mode choices. Based on the Decision Field Theory, a stochastic, dynamic model was proved to be reliable and used to reproduce and analyze the repeated decision-making process. It is concluded that in a stable context, travelers would gradually establish and use some new decision rules to make a travel mode choice during the repetitive decision-making process. When travelers have developed a travel mode habit, environmental cues become the key factors that trigger travelers to make travel mode choices. Context change and traffic policies can make travelers consider, weigh and compare the relevant information again and interrupt their previous habitual choice behavior, enhancing the use of Park and Ride. Meanwhile, travelers with a faster learning speed and better memory develop a travel mode habit in a stable context and change the existing car use habit in a new context more quickly. These results would help to enrich the existing theoretical study of travel behavior and provide an interesting starting point for the development of practical strategies to promote the use of public transport instead of a private car. Traffic management techniques such as congestion pricing, along with behavior intervention and guidance strategies for different groups can strengthen this effect.

1. Introduction

In recent years, with the rapid economic development and the acceleration of the urbanization process, urban transportation problems have become increasingly prominent. Based on previous experiences of urban transportation system development, public transport has the advantages of high efficiency, energy saving, and environmental sustainability. Giving priority to public transport and improving its service levels can attract more car travelers to use public transport. These strategies play an important role in mitigating traffic problems and facilitate the development of cities. The research of travelers' mode choice behavior is an important foundation for travel demand analysis. Travel mode choice behavior is often influenced by travel environment, information regarding travel modes, individual socio-economic and psychological factors. Travelers may repeat the daily commuting-mode choice behavior and demonstrate different macroscopic behavioral characteristics such as mode preferences and habitual travel choices. However, Verplanken et al. (1997, 2008) are two of few studies that

have approached this issue from a microscopic perspective. The primary goal of this research is to investigate the mechanisms of travelers' psychological decision-making process for repetitive travel mode choices. The forming process of mode preference or travel habit and the influence of psychological factors on travel behavior need to be clarified. The mechanism between the travel environment and mode choice behavior can be explored. Effective policies along with behavior intervention and guidance strategies for different groups can be further formulated to reduce travelers' car dependence and guiding travelers to use public transport. Meanwhile, the research will help deeply understand the behavioral rules for travel mode choice from a microscopic perspective.

In this research, car travelers are taken as the research object. The decision-making process data for repetitive travel mode choices was obtained by an experiment designed by a new process-tracing method. This method is often used to analyze the effect of various psychological factors on dynamic decision-making behaviors. Then, the travelers' behavioral characteristics for repetitive travel mode choices were

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analyzed. A dynamic, computational model was further established to reproduce the forming process of travel mode choice habit.

2. Literature review

Several scholars have conducted research on the effects of many factors such as travel experience, motivation, intention and habits on travelers' mode choice. Betsch et al. (2001, 2002) reviewed the research methods of routinized decision-making behavior and proposed different behavioral models considering the influence of routines on choice. Based on the Theory of Planned Behavior (TPB), Donald et al. (2014) and Kaewkluengklom et al. (2017) analyzed the important factors influencing travelers' travel mode choices. Their research results indicated that car use is determined by intention and habit. Travelers with a strong car use habit are less likely to use public transport. The research by Klockner and Matthies (2004) showed that there is no direct relationship between car choice habits and travel mode choice, and habit strength has an indirectly moderating effect on the relationship between personal norm and travel mode choice. Chen and Lai (2011) applied the discrete choice model and the TPB to reveal that psychological factors have larger effects on mode choice behaviors than socioeconomic factors. Gardner (2009) studied the relationship among habits, motivation, and travel mode choice in stable decision contexts. It was concluded that motivation does not affect the choice behavior of commuters who have strong travel choice habits. Hélène et al. (2018) used structural equation modeling (SEM) and exploratory factor analysis to study mode choice habits. The research results showed that environmental concern has an indirect influence on mode choice habits but perceptions and feelings towards public transport partially mediate this effect. Lanzini and Khan (2017) conducted a meta-analysis of studies on travel mode choice and suggested that intentions, habits and past use can better predict travel mode choice. Hoang-Tung et al. (2017) explored the relationship between automatic intention and habits for travel mode choice. The results suggested that travelers' bus use intention for trips is affected by service quality and habits.

Travel context also influences travelers' travel mode choice. Related research shows that travelers may form the behavior patterns of environmental stimulus-response in a long-term stable travel environment (Aarts and Dijksterhuis, 2003). In this case, travelers would make travel mode choices mainly based on an unconscious, habitual decisionmaking process (Ben-Zur, 1998). As indicated by Wood and Tam (2005), changes in circumstances affect behavioral intentions, whereas changes in intentions alone cannot make a complete explanation for the disruption of habits. Verplanken et al. (2008) did a comparative analysis of travel mode choices among university employees. Their research results showed that participants who have recently changed their residences pay more attention to environmental changes and are less likely to use the car for commuting. Bamberg et al. (2003) analyzed the influence of a free public transport ticket on travel mode choices of car travelers who moved to new residences. The results showed that for travelers who have a higher frequency of car use in the past, the intervention such as a free public transport ticket affects attitude, subjective norm and perceived behavioral control, resulting in changes in their travel mode choices. Klinger (2017) conducted a survey for people who recently moved houses and found that people are more inclined to use multimodal transport when they move to a public transport- or bicycle-oriented city. Sun et al. (2017) and Ettema and Nieuwenhuis (2017) explored the effect of built environment on travel mode choice. Their research results showed that commute behavior is more influenced by the built environment at residences than at workplaces.

The above studies mainly focused on the relationship among travel environment, habit, motivation, intention, and travel mode choice by using the TPB, the structural equation model and the utility theory. In daily life, some travel choice behaviors are repeatedly performed and may become habitual, such as commute travel and school travel. Some scholars have done some research on repetitive travel choices. For

example, Verplanken et al. (1994) used a script-based survey to collect the travelers' multi-day mode choice data and analyzed their travel habits based on the frequency of using travel modes and the degree of their willingness to use the modes. Friedrichsmeier et al. (2013) obtained travelers' choice preferences for public transport during two oneweek periods based on a script-based survey. It was concluded that a stable context and frequently performed behavior are often a matter of habit. Aarts et al. (1998) concluded that repetitive travel behavior in the past often leads to habitual behavior. The attitude-behavior model could be a good method for analyzing habitual travel behaviors. Thøgersen (2006) used panel survey data for the everyday use of public transport by Danish residents to conclude that current attitudes, perceptions and behavior changes are consistent for travelers without a car. The research mentioned above mainly used a script-based or repeated travel surveys at a specified time interval to conduct the study of repetitive travel choice. These surveys largely rely on personal records by investigators or respondents. Therefore, it is difficult to implement the surveys and collect the behavioral data in a longer time interval, especially in the changing travel context such as changes in residences and workplaces. Experimental approaches may be effective for repetitive travel behavior analysis. The related research we can find is by Verplanken et al. (1997). They designed three experiments for repetitive travel mode choices. The statistical analysis method was used to conclude that for travelers with strong and weak habits, the amount of information and decision strategies used during the repeated decision trials are different.

In theoretical research, a few studies have investigated the repetitive choice behaviors from a microcosmic perspective of the decision-making process. The dynamic decision theory as a dynamic-cognitive approach can be used to analyze people's underlying deliberation process. The Decision Field Theory (DFT), the main method of this dynamic decision theory, can model human decision-making based on psychological principles. The DFT was initially proposed as a deterministic, dynamic model and later was developed as a stochastic, dynamic model (Busemeyer and Johnson, 2004). Some researchers have explored individual decision-making behavior under risks and uncertainties and proposed that the DFT could analyze simple effect, attractive effect and compensation effect under multiple choice scenarios as well as the complex interaction among these effects (Roe et al., 2001; Busemeyer and Diederich, 2002; Johnson and Busemeyer, 2010; Diederich and Busemeyer, 2003; Diederich, 2003; Dai et al., 2018). In this way, DFT can better explain travelers' decision-making behaviors in a complex environment. Recently, increasing attention has been given to the applications of DFT in the field of transportation. Johnson and Busemeyer (2005) developed a dynamic, computational model to analyze the travelers' decision-making process. This process transited from more deliberative strategies to automatic strategies. The results showed that repetitive decisions can lead to habitual behaviors. Qin et al. (2013) used DFT to analyze the behavioral phenomena such as simple decision, indecision, and preference reversal during the decision-making process for travel mode choices. Hancock et al. (2018) used route choice data collected by a stated preference survey to make a comparison between the DFT and the Multinomial Logit (MNL) models. It is found that the improved DFT has greater flexibility and better fit in estimation and forecasting.

The main research aim of this paper is to investigate travelers' repetitive decision-making behaviors for commute mode choice from a microscopic point of view. The innovations of this paper include: 1) We further extended the traditional research method for repetitive travel mode choices and designed a behavioral experiment using a processtracing method. Meanwhile, a computer programming language was used to implement the user interface design of the experimental contents. The psychological decision-making process data in different hypothetical contexts was automatically obtained. 2) For a deeper understanding of the mechanisms of repetitive travel choice behaviors, a dynamic, computational model was established to reproduce the

Table 1

Information for travel mode choice based on different influencing factors.

Hypothetical scenarios	Optional travel modes	Travel time (min)			Travel cost (Yuan)		Comfort level	Number of transfers
		Driving time	Transfer, walking and waiting time	Riding time	Parking fee and fuel cost	Bus or subway ticket cost		
Travel context one	Car	50	3	0	15	0	Comfortable	0
	Bus and subway	0	10	60	0	7	Very crowded	2
	Park and Ride	20	8	30	7	5	Crowded	1
Travel context two	Car	70	3	0	20	0	Comfortable	0
	Bus and subway	0	13	70	0	8	Very crowded	2
	Park and Ride	25	9	35	9	6	Crowded	1

forming process of mode choice preference or habit in a stable context and the behavioral changes in a changed context. 3) Compared to previous studies, our research pays more attention to analyze some key psychological factors, aiming to attract more car travelers to use public transport. 4) The influences of context change and traffic policies on travel mode choice behavior were identified and some policy recommendations were given to promote a switch from car commuting to public transit.

3. Experimental design and data analysis for repetitive travel mode choices

3.1. Experimental design and implementation

In this research, we develop user interfaces for the electronic questionnaire to collect the decision-making process data. The main contents of the behavioral experiment include the following five parts.

Part one of the experiment is designed to collect the travelers' socioeconomic information, such as gender, age, occupation, and average monthly income.

Part two of the experiment is composed of questions designed to collect personal travel information including daily travel modes used for commuting to work, mode choice during the odd-even license plate number driving restriction in Beijing.

Part three of the experiment is about a measure of the habit of travel mode choice.

Methods for measuring the travel mode habit include self-reported frequency of past behavior, trip diary, and the Self-Report Habit Index (SRHI) (Verplanken and Orbell, 2003). Among these methods, the SRHI uses mental representations of activities with potential habitual acts to explain habits (Verplanken et al., 1997). Due to its simplicity and easy implementation, the SRHI is used in this research. Participants are presented with eight daily travel activities (e.g. going to a supermarket, visiting a friend). For each activity, participants are requested to respond as quickly as possible to the first mode that comes to their mind. The available travel modes include *Car*, *Bus and Subway*, *Park and Ride*, *Taxi* and *Others* for each travel activity. The frequency of choices for each travel mode across the stimulus activities serves as a measure of habit strength for that mode.

Part four of the experiment is evaluating the importance of influencing factors on travel mode choice. The influencing factors included in this research are driving time, transfer, walking and waiting time, riding time, bus or subway ticket cost, parking fee and fuel cost, comfort, the number of transfers, traffic condition and smog. All these factors are evaluated in five levels, ranging from "very unimportant" (1) to "very important" (5).

Part five of the experiment is the repeated mode choices experiment.

A screenshot of the electronic map of Beijing is used to create a travel decision-making scenario where the home place, i.e. a new town in TONGZHOU district, and the workplace, i.e. the central business district (CBD) of Guomao, are marked. The travel distance between

these two locations is about 25 km. There is Ba-Tong Subway Line in this direction of travel. A park-and-ride facility at Beiyuan subway station on the Line is about 8 km away from the home place. The available modes of commuting are *Car*, *Bus* and *Subway*, *Park and Ride*.

According to the results from a pilot survey conducted on the factors influencing car travelers' mode choices in October 2016 in Beijing, two travel contexts were established based on the important factors including traffic conditions, smoggy conditions, and congestion pricing.

- Travel context *one* has a light level of traffic congestion and no smog. Travel mode choice in this environment was repeated seven times. Each time to make a choice is considered a trial. These trials were assumed to be from the first day to the seventh day. The collected data would be used to analyze the characteristics of travelers' repetitive choice behaviors in a stable context.
- Travel context *two* has serious traffic congestion and smog red alert (high density of smog in the air), while implementing a congestion pricing with ten Yuan per time in the urban central area and encouraging the use of public transport. In this environment, the number of times to repeat travel mode choice was three. These trials were assumed to be from the eighth day to the tenth day in this experiment. The effect of context change and traffic policies on travel mode choice would be analyzed based on the collected data.

Table 1 shows the complete information for travel mode choice. The information search interface with a 2-D matrix was developed by using the Information Display Board (IDB). Each row of the information matrix represents travel modes including *Car*, *Bus and Subway*, and *Park and Ride* and each column represents influencing factors.

Fig. 1 shows an example of this interface for the first day where each matrix element is invisible by default. Based on the given travel context, the participants can search, inspect, compare and analyze various information as required before choosing a travel mode for commuting trips. When the respondents need to inspect the information, they can click the header of the affecting factor on the interface and the corresponding information for all travel modes would be shown. When they click to inspect the next factor, the previous factor information would be hidden. There is no time limit for the whole decision-making process during which the respondents are free to inspect and reinspect the available information until they are convinced to make a decision. At this time, the mode choice interface would be represented and the respondents must choose one mode. Then, a pop-up window would prompt the respondent for the outcome as to whether he/she can arrive at the workplace on time by this chosen mode. Afterward, he/she can proceed to make a travel mode choice for the next day.

Table 2 shows choice outcomes for each travel mode in two travel contexts. In order to avoid the experimental error caused by people's habit of viewing information, the order of influencing factors is randomly presented on the information search interface for daily travel mode choice.

In order to quantitatively analyze the changes of choice intents during the repeated decision-making process, participants needed to



Fig. 1. Graphical user interface (GUIs) for travel mode choice.

Table 2	
Outcomes for mode choice in different travel contexts.	

Chosen travel modes	The situation of arriving at the workplace			
	Travel context one	Travel context two		
Car Bus and Subway Park and Ride	On time Likely to be late On time	Late Likely to be late On time		

give the preference degree for three travel modes before the first and second mode choices and after the last mode choice in each travel context. The available preference degrees are "no intention", "weak", "moderate" and "strong." In addition, the participants were asked to give the outcome for the first mode choice from memory after finishing the second mode choice in two travel contexts. The collected data would be used to analyze the influence of learning and memory on repetitive mode choice behaviors.

The above contents of the experiment were converted into the GUIs using a computer programming language. These GUIs have necessary explanations and text descriptions for experimental operation. The options for each question are presented as buttons. The respondents needed to finish travel mode choices for ten times or days on their own computer. The results were automatically recorded in a specified file and were required to be sent back at a designated time.

The respondents chosen to participate in this experiment should have at least one car in their household and have experiences in driving cars for commuting. All respondents were recruited through campus interviews and local networking events. The custom program package was emailed to each respondent. The experiment was conducted from March to July in 2017 and December in 2018, in Beijing. During the experiment, 230 samples were received and the number of effective samples was 201.

3.2. Analysis of experimental data

3.2.1. Personal information and travel information

Based on the data collected throughout the experiment, 64% of the respondents were male and 36% were female. Respondents aged between 21 and 30 account for 34% and 48% of the respondents were

within 30–40 years old. Most travelers were technical personnel accounting for 39%, followed by governmental personnel and management personnel accounting for 34% and 15% respectively. The majority of samples were middle and high-income earners. 28% of the respondents had an average monthly income of between 5000 Yuan to 7000 Yuan and 68% had an average monthly income above 7000 Yuan.

Besides the *Car* used for commuting, *Subway*, *Bus and Subway*, *Taxi* were also commonly used by car travelers, accounting for 41%, 38% and 23% respectively. The respondents mainly switched from *Car* to *Bus* and *Subway* during the odd-even license plate number driving restriction in Beijing. The choice proportions were 34% and 24% respectively. The average frequency of car use under eight daily travel activities was 5.60, indicating that these travelers had a higher initial choice preference for *Car*.

3.2.2. Analysis of repetitive travel mode choices

Fig. 2 shows travel mode choice proportions across the ten trials. In travel context *one*, it can be seen that the choice proportions for *Car* are clearly dominant in the first several trials since car travelers have a strong initial preference for *Car*. With the increase of repetition times for travel mode choice, namely from trials 2 to 4, the car travelers gradually found that besides *Car*, *Park* and *Ride* can also have them arrive at their workplaces on time by inspecting and weighing the information. Some car travelers may switch to *Park* and *Ride*, and weaken



Fig. 2. Travel mode choice proportions across all trials.



Fig. 3. The number of inspected information and deliberation time across all trials.

their initial car use preference. At the same time, the proportions of choosing *Park and Ride* gradually increase, while the proportions of choosing *Car* gradually decrease. During this phase, the number of inspected factors and deliberation time of travelers significantly decrease with their increasing familiarity with the travel environment, as shown in Fig. 3. From the fifth to the seventh decisions, the choice proportions for travel modes as well as the corresponding number of inspected factors and deliberation time have minor changes. It indicates that multiple, repeated travel mode choices in a stable context can make travelers gradually accumulate travel experiences and develop a new mode choice preference.

When the travel context turned to serious traffic congestion, smog red alert, and congestion pricing, travelers' mode choice behaviors changed accordingly. For the eighth decision, the proportions of choosing *Bus and Subway* and *Park and Ride* increase significantly while the choice proportion for *Car* decreases significantly. At the same time, the number of inspected information items and deliberation time spent on mode choice increase accordingly. With an increase in repetitions for travel mode choice, the proportions of choosing *Park and Ride* continue to increase rapidly because only by using *Park and Ride* can travelers arrive at their work places on time. It implies that travelers would consider, compare and weigh the relevant information to choose a travel mode with gain when facing a new travel context and traffic policy. During this process, they would change their pre-existing mode choice preference or habit.

4. Decision Field Theory

4.1. Rule-based Decision Field Theory

The development of cognitive skills through experiences has been a topic of interest for cognitive psychologists. Anderson and Lebiere (2012) proposed the ACT-R model to explore the cognitive process of human beings. Anderson assumed that problem-solving strategies began with slow, deliberative processes that are changed with experiences into faster procedural routines. During the repeated decisionmaking process, travelers may gradually reduce their focus on information about choice situations and choice options, and then establish and use simple rules to make decisions. The decision rule refers to the degree of accumulated choice preference for options in a certain circumstance. Based on the learning and feedback process, the decision rule as a whole gains (or loses) strength based on its performance experienced after each decision. If the environment changes, the earlier rules may no longer work, and the deliberative process may resume again. On the basis of these considerations, the rule-based Decision Field Theory (DFT) is more suitable to analyze the decision-making process for travelers' repetitive choice behaviors (Johnson and Busemeyer, 2005).

In this research, there are two levels of dynamics. One is the deliberation process within a single choice, denoted by *t*, and the other is a learning process based on the outcomes across the multiple, repeated choices, denoted by *n*. The decisions for a short-term scale usually last a few moments or minutes and the decisions for a long-term scale can take place over learning trials spanning minutes, days, weeks, or years. Once the preference accumulated for an option reaches the deliberation state threshold, it is regarded as the final choice and the decision-making process for the task stops. The accumulation of preferences for the available options is based on the information related to the options and decision rules. On the basis of the sequential sampling mechanism, the model of rule-based DFT is shown as follows (Johnson and Busemeyer, 2005).

During the *n*-th deliberation process, the momentary relative valence vector of the weighted utility for all options at time t is shown in formula (1).

$$V(t) = CM(n)W(t)$$
⁽¹⁾

Where *C* is the contrast matrix. Its diagonal elements are 1 and the offdiagonal elements are -1/(u - 1). *u* is the number of options. *M*(*n*) is the information matrix for the *n*-th decision. *W*(*t*) is the momentary attention weights at time *t*. According to these weights, only one single attribute or factor is selected from *M*(*n*) to calculate the relative valence.

Then the momentary preference vector P(t) for all options at time t is shown in formula (2):

$$P(t) = SP(t-1) + V(t)$$
(2)

Where *S* is the feedback matrix. Its diagonal elements s_{ii} are the self-feedback coefficients whose value are 0.915 in this research. The other elements s_{ik} are negative lateral feedback coefficients. These coefficients are assumed to be related to the conceptual distance between option *i* and *k* (Qin et al., 2013).

The information matrix that affects the *n*-th decision consists of two parts:

$$M(n) = [M|X(n)] \tag{3}$$

Where *M* is the information matrix for the attributes or factors related to all options, as shown in Table 1. X(n) is the assessment of all options according to decision rules. Its elements $x_{il}(n)$ is the preference for option *i* if rule z_l is used in period *n*.

$$w_1 = [...w_{j...}]$$
 (4)

$$w_2 = [...Pr(z_l)...]$$
 (5)

$$w(n) = [\alpha \cdot w_1 | w_2] = E_n(W(t)) \tag{6}$$

$$\alpha = 1 - \sum_{l} \Pr(z_l) \tag{7}$$

Where w_j in the vector w_1 is the attention weight for attribute or factor *j*. Pr(z_l) in the vector w_2 is the probability of using decision rule z_l , just as the weight w_j exists for attribute or factor *j*. α is the probability of using attributes rather than rules. When Pr(z_l) reaches or approaches one, people make a decision mainly based on the advice of an established decision rule instead of attributes. At this time, people's decisionmaking behaviors are close to a temporal stable state.

The calculation of the possibilities of using decision rules and their update process are as follows:

$$\Pr(z_l) = \frac{\exp(q_{l,n})}{\sum_l \exp(q_{l,n}) + K}$$
(8)

$$q_{l,0} = \Delta \tag{9}$$

$$q_{l,n} = \beta. \ q_{l,n-1} + F_{l,n} \tag{10}$$

$$F_{l,n} = \begin{cases} \Delta \cdot r & \text{if } z_l \text{ successful at } n-1 \\ 0 & \text{if } z_l \text{ not used at } n-1 \\ -\Delta \cdot p & \text{if } z_l \text{ unsuccessful at } n-1 \end{cases}$$
(11)

Where $q_{l,n}$ is the strength for using decision rule z_l in period *n*. $q_{l,n}$ is updated after each repetitive decision. *K* is the parameter for relative attention advantage. The parameter determines how much attention is assigned to the rule relative to attribute processing. Δ is the learning rate for feedback to rule. β is the memory coefficient for the past successful decision. $F_{l,n}$ is the feedback function, *r* is the reinforcement strength for a successful outcome, while *p* is the punishment strength for an unsuccessful outcome. In addition, with the increasing repetitions for decisions, people tend to fix their choice on one option with gain. Meanwhile, $F_{l,n}$ continuously increase during this process.

In this research, the learning and feedback process in the model borrows from the research of Busemeyer and Myung (1992). Based on the experimental data in Section 3, the improved formula (8) was adopted for calculating the probability of using a decision rule.

4.2. Model parameter estimation

According to the data collected in the experiment, the model parameters were estimated and the rule-based DFT model for multiple, repeated decision-making process would be established.

(1) Attention weights w_i for the influencing factors

The weights represent the average amount of attention the traveler allocates to each factor. The shifting of attention of the traveler is assumed to be a static stochastic process based on w_j . Based on the data collected in **Part four** of the experiment, the attention weights were calculated as the total score for each factor divided by the sum of the scores for all factors, as shown in Table 3.

(2) Memory coefficient β for the past successful decision

By comparing the outcomes leading to gains for the first mode choice with the ones remembered by the respondents after finishing the second mode choice, the memory coefficient was obtained by the proportion with the same results. The memory coefficient β_1 is 0.93 in travel context *one* and β_2 is 0.87 in travel context *two*.

(3) Feedback parameters r, p for the past decision

Based on the collected choice intents for three travel modes before the first and second decisions, the changes of intents between these two decisions in gain and loss situations were calculated respectively. Then the reinforcement strength r and the punishment strength p are about 0.30 and 0.36 respectively in travel context *one*, and 0.45 and 0.35, respectively in travel context *two*.

(4) Other parameters

The learning rate Δ is set as 1. The relative attention advantage K_1 , K_2 are 9 and 8 in travel context *one* and *two* respectively. The deliberation state threshold is set as 7.

In this research, the Matlab^{*}-based simulation method is used to implement the prediction model with the calibrated parameters. In order to model and reproduce the long-term repeated decision-making process by simulation, the travel mode choice is repeated 70 times in travel context *one* and 30 times in travel context *two*. 20,000 simulation runs are executed for each travel mode choice. Each trial represents a new repetitive encounter of the mode choice problem.



Fig. 4. Travel modes choice probabilities across all trials.

5. Analysis of decision-making process for repetitive travel mode choices

5.1. The repeated decision-making process using the rule-based DFT

Fig. 4 shows the predicted choice probabilities for three travel modes across all trials by using the rule-based DFT. The overall average error between theoretical predictions and experimental results for the decisions in two travel contexts is 6.50%. The maximum error is 13%, while the minimum error is 0.32%. Furthermore, 82% of the absolute errors is below 10%. Therefore, the dynamic, computational model has been proved reliable and the model parameters are appropriately estimated. The proposed rule-based DFT can be used to further analyze the travelers' decision-making process for repetitive travel mode choices.

As shown in Fig. 4, in travel context one, travelers have significantly higher choice probabilities for Car at the beginning of the repetitive decisions. Meanwhile, the choice probabilities for Park and Ride increase with the increasing repetition for travel mode choice. And during this phase, travelers gradually establish and use a decision rule to make the choice of travel mode. Meanwhile, the probabilities of using decision rule 1 increase accordingly and the deliberation time decrease gradually as shown in Figs. 5 and 6. In this case, the traveler attends to the influencing factors for each option or the advice of an established decision rule. After the travel mode choice is repeated for about 30 times, the choice probabilities for three travel modes tend to be stable. The choice probabilities for Car and Park and Ride are around 50% because both of these two modes can make travelers arrive at their workplaces on time. And during this phase, deliberation time is basically unchanged and reduces to a minimum. The accumulated probabilities of using decision rule 1 are higher and close to or over 0.8. Travelers mainly attend to the advice of an established decision rule to make a decision and pay little attention to the information on influencing factors for each option. It indicates that travelers have developed a Car and Park and Ride use habit from the multiple, repeated decisions in a stable context. The environmental or contextual cues become the key factors that trigger travelers to make the choice of travel mode.

When the travel context changes from the 71st decision, that is serious traffic congestion, smog red alert and implementing congestion pricing, the probabilities of using decision rule 1 gradually decrease with the increase of repetitions. Meanwhile, travelers gradually establish a new decision rule 2, and increase its use probability. The probabilities of choosing *Park and Ride* increase rapidly and are clearly higher than the other two travel modes. It implies that a changed

Table 3

The attention weights of the influencing fac	ctors.
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Factors	Driving time	Transfer, walking and waiting time	Riding time	Parking fee and fuel cost	Bus or subway ticket cost	Comfort level	Number of transfers
Weights	0.17	0.14	0.15	0.14	0.11	0.15	0.14



Fig. 5. Deliberation time across all trials.



Fig. 6. The probabilities of using decision rules across all trials.

context and traffic policy can make car travelers interrupt their habitual choice behaviors and develop new travel mode habits, enhancing the use of *Park and Ride*.

5.2. The impact of psychosocial factors on repetitive travel mode choices

5.2.1. The impact of learning rate

As shown in Fig. 7, in travel context *one*, the choice probabilities for three travel modes tend to be stable after about 40 repeated decisions when the learning rate \triangle is 0.8. But only about 20 repeated decisions are needed to develop a habitual travel choice for travelers when the learning rate \triangle is 1.2. It indicates that travelers with a faster learning speed accumulate travel experiences more quickly based on the gains or losses brought by the repetitive travel mode choices. Accordingly, they change the existing car choice habit and develop a new travel mode choice habit more quickly with the increasing number of repeats for

travel mode choice. In travel context *two*, when the learning rate \triangle is 1.2, the choice probabilities for *Park and Ride* are higher than those derived when the learning rate \triangle is 0.8. Meanwhile, the choice probabilities for *Park and Ride* begin with rapid growth, then gradually tend to be stable with the increasing decision times. For travelers with a slower learning speed, they need to take longer to develop a new mode preference during the repetitive decision-making process.

5.2.2. The impact of the memory coefficient

According to formulas (8) to (10), a small change in memory coefficient β would result in a great change in the probability of rule use. Fig. 8 shows that choice probabilities for travel modes have significant differences in different memory coefficients, implying that memory coefficient has an important influence on travelers' mode choice behaviors.

Fig. 8 (a) shows that travelers with a poor memory for past decisions, that is, when β_1 is 0.91 and β_2 is 0.85, have relatively higher choice probabilities for *Car* and lower ones for *Park and Ride* in travel context *one*. In this case, travelers take longer to accumulate travel experiences, and then establish and use decision rules to develop a mode choice habit. Fig. 8 (b) shows that travelers have a good memory for past decisions when memory coefficients β_1 and β_2 are 0.95 and 0.89, respectively. As the number of repeats for travel mode choice increases, travelers reduce their car dependence quickly and gradually establish and use a decision rule to make a decision. Therefore, the probabilities of choosing *Park and Ride* increase more quickly at the beginning of the repetitive decisions in two travel contexts and the travelers' mode choice preferences or habits are constructed quickly.

5.2.3. The impact of relative attention advantage

Increasing *K* will decrease the amount of success that the decision rule accumulates to be probabilistically favored. As shown in Fig. 9, in travel context *one*, the higher the value of *K*, the greater the probabilities of choosing *Car* and the smaller the probabilities of choosing *Park and Ride* during the repeated decision-making process. When K_1 and K_2 are all 20, the choice probabilities for *Car* are obviously dominant and difficult to reach a stable state in travel context *one*. In this case, travelers' mode choice preferences or habits are developed more slowly compared with that when K_1 and K_2 are all 3.

5.3. The impact of deliberation state threshold on repetitive travel mode choices

The deliberation state threshold has an important influence on travelers' decision-making behaviors. Travelers with a lower deliberation state threshold usually make a decision quickly on the basis of a weak preference. Travelers with a higher deliberation state threshold need a long time to make a decision on the basis of a strong preference.



Fig. 7. Repetitive travel mode choices in different learning rates.



Fig. 8. Repetitive travel mode choices in different memory coefficients.

Compared with Figs. 4 and 5, travelers would weigh and contrast more information to cautiously choose a relative optimal travel mode when the deliberation state threshold is 10, as shown in Figs. 10 and 11. Accordingly, travelers' deliberation time would increase with the increase of deliberation state threshold. As a result, the probabilities of choosing *Car* is higher in travel context *one*, while the probabilities of choosing *Park and Ride* is higher in travel context *two* before the formation of mode choice preference or habit. Deliberation state threshold has little effect on the speed of formation for mode choice preference or habit.

6. Conclusions

Research on individual decision-making process is an important foundation for exploring the macroscopic behavioral rules for travel mode choice. In this research, a behavioral experiment was designed by a new process-tracing method to obtain the decision-making process data for repetitive travel mode choices. Furthermore, a stochastic, dynamic model based on the DFT was established to reproduce and analyze the forming process of travelers' mode preferences or travel habits in the stable context and behavioral changes in the changed context. The effects of psychological factors on the decision-making process for repetitive travel mode choices were analyzed.

From a theoretical point of view, we find that in a travel context, travelers gradually accumulate travel experiences and use simple decision rules to make a mode choice with the increasing repetitions for travel mode choice. Meanwhile, the number of information items and deliberation time used for mode choice gradually decrease. After reaching a certain number of repetitions, the choice proportions for travel modes tend to be stable, implying that frequent repetition of behavior is critical for developing a mode choice habit. The habitual



Fig. 10. Travel modes choice probabilities across all trials when $\theta = 10$.

behavior would arise without conscious intent and deliberate evaluation. At this moment, environmental cues become the key factors that trigger the traveler to make a mode choice.

When the travel context changes to serious traffic congestion, smog red alert, and congestion pricing, travelers would consider, weigh and compare the relevant information again and the number of inspected information items and deliberation time spent on travel mode choice increase accordingly. The changed contextual factors and policy strategies can interrupt travelers' habitual car choice behaviors and enhance the use of *Park and Ride*. It indicates that strategies such as external incentives and disincentives as well as traffic demand management strategies would be effective ways to reduce habitual car use.

Comparing with experimental data, the stochastic, dynamic model based on the DFT has been proved reliable and can be used to reproduce



Fig. 9. Repetitive travel mode choices in different relative attention advantage.



Fig. 11. Deliberation time across all trials when $\theta = 10$.

and analyze the repeated decision-making process for travel mode choice. The effects of psychological factors on travel mode choice are also explored and some conclusions are obtained. Learning speed and memory coefficients have an important influence on travelers' travel mode choice. Travelers with a faster learning speed and better memory would soon reduce their car dependence and develop a travel mode habit more quickly with the increasing number of repeats of travel mode choice. Meanwhile, they change the existing car use habit more quickly in a new context and then increase the use for Park and Ride. The parameter of relative attention advantage controls the attention proportion in which travelers afford to decision rule relative to attribute processing. The larger the value, the more travelers make a mode choice mainly based on attribute processing and the slower the forming process for a travel mode habit. Travelers with a higher deliberation state threshold would weigh and contrast more information and spend more time to cautiously choose a relative optimal travel mode.

These results provide an interesting starting point for the development of practical transport strategies to promote the use of public transport instead of a private car. Changing decision contexts like traffic conditions, living environment and the place of residence would motivate individuals to change their pre-existing mode choice habits. Traffic management techniques such as congestion pricing and reward schemes, along with behavior intervention and guidance strategies for different groups can strengthen this effect and promote the use of public transport. The high-quality public transport services are probably a necessary prerequisite for the success of such measures. Providing attractive public transport will give travelers comfortable and positive experiences and induce a more modal shift from cars to public transport. Meanwhile, such strategies would be more effective for people who have a fast learning speed, good memory, and a high deliberation state threshold.

Overall, our research methods and conclusions in this research will help enrich the existing theoretical study of travel behavior and provide references for transport policymakers. Future investigations could first increase the amount of experimental data for repetitive travel mode choices to minimize variations and uncertainties of the modeling results. Moreover, it would be interesting to conduct an in-depth analysis of the relationship between repeated decisions and the related influencing factors. Third, it is very challenging to identify the policy-sensitive people such as those with a faster learning speed and better memory. Once those people are identified, formulating some transport policies along with behavior intervention and guidance strategies for the specific groups should be discussed in the future work. Fourth, maybe it would be a good starting point to profile the individual decision-making process to explore the behavioral rules for repetitive travel mode choices. Finally, future research should analyze the decision-making process for repetitive travel mode choices in a more complex travel environment.

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