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Emergency Traffic Evacuation Control based on the Orthogonal Experimental Design Method *

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Abstract—**Evacuees' behaviors have a significant impact on evacuation efficiency. Evacuation clearance time is one of the key indicators in the evacuation planning and management. Evacuees' departure time choice, destination choice and route choice behavior based on real-time traffic information are three crucial factors used to estimate evacuation clearance time. In this paper, we use the orthogonal experimental design method to determine values of these three factors simultaneously, which can reduce evacuation clearance time significantly. Once we obtain these values, we can guide evacuees' departure time choice, destination choice and route choice behavior to approximate these values and evacuation efficiency will improve greatly. The dynamic traffic evacuation process is modeled using a rule-based multi-agent microscopic traffic simulation system called TransWorld. The simulation experiment results illustrate the effectiveness and reliability of the proposed method. The proposed methodology, computational results and discussions can be used for future emergency evacuation planning and management.**

I. Introduction

Emergency traffic evacuation is an effective strategy to mitigate damage of man-made or natural disasters. With the increasing size and frequency of disasters, studies of emergency traffic modeling and control strategies have become important research areas. In particular, the evacuee behavior related evacuation modeling has been attracting a lot of researcher's attention, because evacuee behavior has a significant impact on emergency evacuation planning, management and control.

Stern and Sinuany-Stern were believed to firstly develop a simulation model incorporating behavioral factors including the diffusion time of the evacuation instructions and individual's evacuation decision time in emergency planning [1]. In the analysis of the impact of household decisions on evacuation in Hurricane Floyd, Dow and Cutter considered the timing of departure and the role of information in the selection of specific evacuation routes [2]. Murray-Tuite developed one linear integer programming model to describe a family's meeting location selection process and another one linear integer programming model to assign trip chains for drivers to pick up family members who may not have access to vehicles [3]. Stopher et al. and Alsnih et al. used multinomial and mixed logit models to determine when a household would evacuate due to bush fires, respectively [4]-[5]. Lazo et al. presented the stated-choice valuation method to study households' evacuation decision [6]. Chiu et al. developed a real-time traffic management system for evacuation, in which they considered evacuee behavior responses to management strategies [7]. Further, Chiu et al. proposed a behavior-robust feedback information routing strategy to improve evacuation efficiency [8]. Li et al. simulated pedestrian evacuation using Vissim, where they considered the spatial distribution of pedestrians [9]. Hu et al. proposed a minimum-safety-distance-based evacuation car-following model based on the Gipps car-following model, in which they incorporate driver mental and behavioral reaction under emergency conditions [10]. Lindell and Prater introduced the principal behavioral variables affecting hurricane evacuation time estimates [11]. Pel et al. developed the macroscopic evacuation traffic simulation model EVAQ and analyzed the impact of trip generation, departure rates, route flow rates, road capacities, and maximum speeds on evacuation by applying EVAQ [12]. Pel et al. also reviewed travel behavior modeling in dynamic traffic simulations for evacuation [13]. However, most previous research uses only a deterministic set of parameters to represent realistic evacuee behavior, i.e. they view evacuee behavior as constant. They do not consider the impact of variation of evacuee behavior on evacuation clearance time. Therefore, new emergency evacuation management and control strategies from the perspective of evacuee behavior cannot be proposed.

Evacuees' departure time choice, destination choice and route choice behavior based on real-time traffic information are three crucial factors to affect evacuation clearance time. Different combinations of values of these three factors result in different evacuation clearance time. In this paper, we present our work on determining optimal or good enough values of these three factors simultaneously based on the orthogonal experimental design method, which can reduce evacuation clearance time significantly. Once we obtain these values, we can guide evacuees' departure time choice, destination choice and route choice behavior to approximate these values and evacuation efficiency will improve greatly.

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Experiments are done based on a rule-based multi-agent traffic simulation system called TransWorld. Experimental results show the effectiveness and reliability of the proposed method for emergency traffic evacuation control.

The main contribution of this paper is to investigate emergency traffic evacuation control from the perspective of evacuee behavior based on design of experiments. It is different from the control strategies obtained based on mathematical programming models. The proposed method can save a lot of time and resources in determining emergency traffic evacuation control strategies.

The rest of this paper is as follows. Section II presents the methodological framework, TransWorld, and the orthogonal experimental design method. The experiment design, results and discussions are given in Section III. Conclusions are given in Section IV.

II. METHODOLOGY

A. *Model Framework*

There are many measures of evacuation efficiency, such as evacuation clearance time, average evacuation travel time. In this paper, we use evacuation clearance time as the evacuation efficiency measure. The objective of behavior-based emergency traffic evacuation control is to find behavior patterns that can improve or maximize the evacuation efficiency. We use the orthogonal experimental design method to obtain these behavior patterns. We choose evacuees' departure time choice, destination choice and route choice behavior based on real-time traffic information as behavior factors affecting emergency traffic evacuation process. We create orthogonal tables to arrange experiments. The emergency traffic evacuation process is modeled in TransWorld. After conducting experiments, we complete the data analysis to determine the effect of different factors on the performance measure and the optimal behavior pattern. This procedure is illustrated in Fig.1.

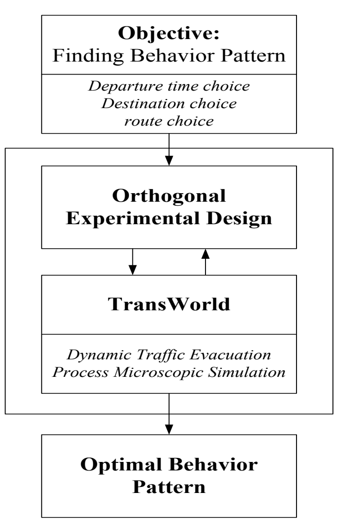

Figure 1. Model framework

B. *TransWorld*

TransWorld is a state-of-the-art of artificial transportation system for modeling and computational experiments that was developed at the Complex Adaptive Systems for Transportation (CAST) Laboratory, Institute of Automation, Chinese Academy of Sciences. We used the agent programming technology and object-oriented techniques to develop TransWorld, which can easily integrate human social behavior and traffic behavior. A generic individual behavior model in TransWorld is shown in Fig. 2. The features of TransWorld are: 1) it can grow artificial traffic behavior from bottom to up by using only population statistics and behavioral models, which is useful to test and validate transportation applications. 2) It provides a hierarchical multi-resolution traffic modeling and analysis from microscopic, mesoscopic, and macroscopic to logic emulations. 3) It is a computational experimental platform for the analysis and synthesis of transportation systems.

TransWorld is composed of network construction module, artificial population generator module, route planner module, microscopic traffic simulation module, computational results analysis module, two-dimensional and three-dimensional animation module, feedback module. TransWorld's system architecture and major components are shown in Fig. 2. Implementation details of TransWorld can be found in [14]. Other information on TransWorld can be found in [15] - [19].

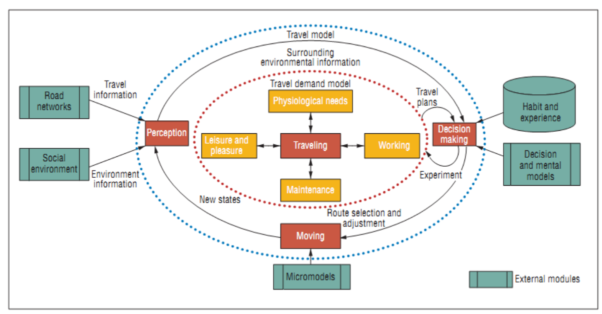

Figure 2. A generic individual behavior model in TransWorld

There is an activity type named "evacuation" in TransWorld to represent evacuee behavior. Each individual's activity is denoted as follows:

$$A_{ij}=(AT_{ij},D_{ij},ST_{ij},ET_{ij},P_{ij},M_{ij})$$

Where,

AT_{ij} : Activity type of individual i's j^{th} activity performed.

D_{ij} : Destination of individual i's j^{th} activity.

ST_{ij} : Start time of individual i's j^{th} activity.

ET_{ij} : End time individual i's jth activity.

P_{ij} : Travel paths of individual i's j^{th} activity.

M_{ij} : Travel mode for individual i's j^{th} activity.

The departure time choice behavior of evacuees is represented by a probability distribution. The destination choice mechanisms in TransWorld are two commonly used principles for describing evacuees' destination choice behavior. They are: 1) Evacuees choose the closest safe location as their destinations. 2) Evacuees choose a safe destination at random because of panic. Two kinds of evacuees are classified according to whether they can receive real-time traffic information or not. We assume that evacuees who can receive real-time traffic information will change the prescribed route en-route and follow the route with the shortest time the moment when they receive the information; Evacuees who cannot receive real-time traffic information will follow the prescribed route with the shortest time and cannot change routes while en-route. The shortest path problem is solved by using the Dijkstra algorithm.

C. Orthogonal Experimental Design Method

The orthogonal experimental design (OED) is a kind of optimal experimental method for multi-factor experiments [20]. It was developed by Dr. Genichi Taguchi of Japan, so it is also called Taguchi Method. The OED method uses orthogonal tables to organize experiments. The multi-factor and multi-level experiments are very common in practice. Times , money and other resources for experiments will explode if all possible combinations like the factorial design are tested to find optimal schemes. The OED method is an effective way to settle such a problem, which uses representative points instead of all points.

The orthogonal table has the following attributes:

1. in each column of the table each element occurs the same number of times;
2. in any two columns of the table each pair (1,1), ..., (1, a), (2,1), …, (a, a) occurs the same number of times.

The orthogonal table is denoted as $L_n(a^p)$, where L is the symbol for the orthogonal table, n is experiment times, a is the number of levels of factors, p is the number of columns of the orthogonal table. One example for the orthogonal table, called $L_9(3^4)$ is shown in Table 1.

Table 1. $L_9(3^4)$ table

Column Number / Sequence Number	1	2	3	4
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

The OED method consists of five steps:

Step 1. Determine the target of experiments. We have to analyze the purpose of experiments and choose proper system measurements for experiments.

Step 2. Determine the experimental factors and levels. Factors are variables within the process that affect the performance measure such as evacuation clearance time, temperature. Levels for each factor are the parameters should be varied at. The experimental factors and levels must be specified.

Step 3. Select the right orthogonal table. The selection of orthogonal tables is based on the number of factors and the levels of variation for each factor.

Step 4. Conduct the experiments according to the orthogonal table selected in Step3, and collect experimental.

Step 5. Analyze experiment data and draw experiment conclusions.

III. Computational Experiment design

A. Test Bed Data

Zhongguancun area is selected as the test bed for the proposed method. It is located in Haidian District, Beijing, China. The selected area, which covers 15.3 km^2, west to Wanquanhe Road, east to Xueyuan Road and Xitucheng Road, north to North 4th Ring Road, and south to 3rd Ring Road, is a central business and educational district (see Fig. 3.). An artificial transportation system is constructed for the selected area using TransWorld, as shown in Fig. 4. The area includes eighty two sites, which are directly related to traffic generation: twelve residential communities, twenty-eight office buildings, four schools, fifteen shopping malls, five recreational parks, three sport facilities, four restaurants and hotels, two hospitals, and nine shelters. The shelters are safe destinations for evacuees and located surrounding the area.

Figure 3. Location of Zhongguancun area

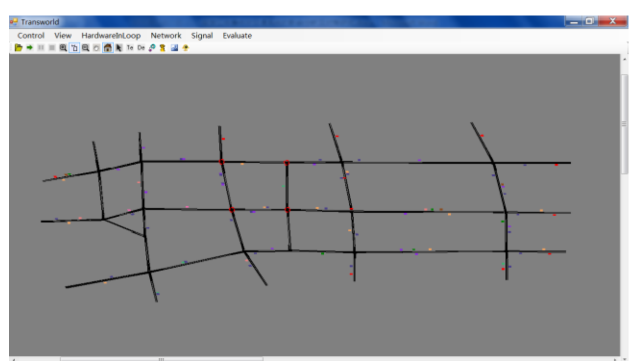

Figure 4. Artificial Transportation System for Zhongguancun area

B. Experimental Design

A hypothetical terrorist attack was assumed to happen in the selected area. Ten thousand people in this area need to be evacuated. We choose evacuees' departure time choice, destination choice and route choice behavior based on real-time traffic information as factors affecting emergency traffic evacuation process. We want to obtain the optimal behavior pattern for these three behaviors, and guide evacuees to achieve the pattern to improve evacuation efficiency. The computational experiments conducted in this study follow the three basic principles of experimental design which are replication, randomization, and blocking.

Evacuation clearance time is the performance measure in this study. We denote evacuees' departure time choice distribution as A, percentages of evacuees selecting destinations based on different principles as B, and percentages of evacuees choosing the route with the shortest time based on real-time traffic information as C. Each factor has three levels, as shown in Table 2, Table 3 and Table 4. We choose the $L_9(3^4)$ orthogonal table to arrange experiments, as shown in Table 5.

Table 2. Factors and Levels

Level	Factor		
	A	***B***	***C***
1	A1	B1	C1 = 0.3
2	A2	B2	C2 = 0.4
3	A3	B3	C3 = 0.7

Table 3. Specific value for A1, A2 and A3

	Distributtion	**Min Value**	**Max Value**
A1	Uniform Distribution	5:30	6:10
A2	Uniform Distribution	5:15	6:10
A3	Uniform Distribution	5:00	6:10

Table 4. Specific value for B1, B2 and B3

	Random	**Closest**
B1	60%	40%
B2	70%	30%
B3	80%	20%

Table 5. $L_9(3^4)$ orthogonal table for evacuation experiments

Column Number / Sequence Number	**A**	**B**	**C**	**4(blank)**
1	1(A1)	1(B1)	1(C1)	1
2	1(A1)	2(B2)	2(C2)	2
3	1(A1)	3(B3)	3(C3)	3
4	2(A2)	1(B1)	2(C2)	3
5	2(A2)	2(B2)	3(C3)	1
6	2(A2)	3(B3)	1(C1)	2
7	3(A3)	1(B1)	3(C3)	2
8	3(A3)	2(B2)	1(C1)	3
9	3(A3)	3(B3)	2(C2)	1

If we use the full factorial design method for the 3-factor, 3-level experiment, we need to conduct $3^3 = 27$ runs. However, we make only 9 runs when we use the OED method for the same experiment. It significantly reduces experiment run times.

C. Results and Discussion

We conducted 9 runs based on Table 5 by using TransWorld. Experiment results are shown in Table 6.

The mean response of each factor is shown in Table 7. The row R in Table 7 means the extremum difference for the factor A, the factor B and the factor C, respectively. From this row, we can conclude that the factor A affects emergency traffic evacuation process much more than the factor B and the factor C. Furthermore, we drew the trend chart for the factor A, the factor B and the factor C, respectively, as shown in Fig. 5. We make the same conclusion that the factor A affects emergency traffic evacuation process much more than those other two factors. We can also infer that $A_3B_3C_3$ combination is the optimal behavior pattern from Fig. 5. We further conduct the experiment based on the optimal behavior pattern $A_3B_3C_3$, and find that evacuation clearance time for $A_3B_3C_3$ is the least.

Table 6. Experiments results

Column Number / Sequence Number	**A**	**B**	**C**	**Evacuation Clearance Time (Second)**
1	1(A1)	1(B1)	1(C1)	27 318
2	1(A1)	2(B2)	2(C2)	26 305
3	1(A1)	3(B3)	3(C3)	26 489
4	2(A2)	1(B1)	2(C2)	26 383
5	2(A2)	2(B2)	3(C3)	25 924
6	2(A2)	3(B3)	1(C1)	25 701
7	3(A3)	1(B1)	3(C3)	25 689
8	3(A3)	2(B2)	1(C1)	25 695
9	3(A3)	3(B3)	2(C2)	25 521

Table 7. Mean response table

Level	**A**	**B**	**C**
1	26 704	26 463	26 238
2	26 003	25 975	26 070
3	25 635	25 904	26 034
R	1 069	560	204
Order	1	2	3

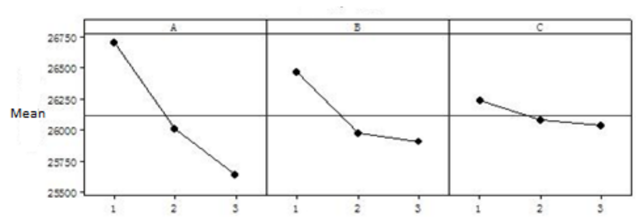

Figure 5. Main effects of mean

The analysis of variance of results is shown in Table 8. The P-value for each factor is greater than 0.05, so we cannot make the conclusion that whether the factor is significant or not. We delete the least significant factor C and conduct analysis of variance for the factor A and the factor B. The results are shown in Table 9. We can see that the P-value for the factor A is less than 0.05, so the factor A is significant for emergency traffic evacuation. The P-value for the factor B is greater than 0.05 and less than 0.20, so the factor B is minor significant.

Table 8. Analysis of variance of A, B and C

Source	**Degree**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**
A	2	2262345	2262345	1131172	9.17	0.098
B	2	451261	451261	225630	1.83	0.354
C	2	81201	81201	40600	0.33	0.752
error	2	246786	246786	123393		
total	8	3041592				

Table 9. Analysis of variance of A and B

Source	**Degree**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**
A	2	2262345	2262345	1131172	13.8	0.016
B	2	451261	451261	225630	2.75	0.177
error	4	327987	327987	81997		
total	8	3041592				

IV. CONCLUSION

Evacuee behaviors have a significant impact on traffic evacuation process. If we know the optimal behavior pattern that can optimize the evacuation efficiency, we can guide evacuees to form that pattern. In this paper, we use the orthogonal experimental design method to determine the optimal behavior pattern with three behavior factors simultaneously. The three factors are the evacuees' departure time choice behavior, destination choice behavior and route choice behavior based on real-time traffic information. The simulation experiments demonstrate the effectiveness and reliability of the proposed method. The proposed methodology, computational results and discussions can be used to emergency evacuation planning and management. This study also provides potentials of new emergency evacuation management and control strategies from the perspective of evacuee behavior.

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