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Research Article

Analysis on Illegal Crossing Behavior of Pedestrians at Signalized Intersections Based on Bayesian Network

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Pedestrians do not always comply with the crossing rules of when and/or where to cross the road at signalized intersections. This risky behavior tends to undermine greatly the effectiveness of safety countermeasures at such locations. Thus, it is very important to understand illegal behavior to develop more effective and targeting measures. In order to address the problem, this paper aimed to analyze characteristics of illegal crossings and their impact on behavior choice. Firstly, illegal crossing behaviors at signalized intersections were classified into two categories, including "crossing at a red light" and "crossing outside of a crosswalk". Secondly, two sets of data were collected to understand the behaviors. One set of data was collected from video-based observation conducted at 3 signalized intersections in Guangzhou, China, capturing 3334 valid illegal crossing cases in total. Another set of data, from a questionnaire survey conducted online, resulted in 275 valid responses. Finally, presentational characteristics of illegal crossings at signalized intersection were analyzed and two Bayesian network-based behavior models were developed to investigate the characteristics and their impacts on the two types of illegal crossing behaviors, "crossing at a red light" and "crossing outside of a crosswalk," respectively. Findings reveal that, (i) illegal crossings occur at various types of signalized intersections, with a higher probability for "crossing outside of a crosswalk" compared to "crossing at a red light;" (ii) Arc routing crossing has the highest probability to occur at signalized intersections compared to other types of out-side-crosswalk crossings. (iii) The location of origin and destination of a pedestrian has a significant effect on crossing outside of a crosswalk, the location of origin and destination of "one is inside of a crosswalk and another is outside of a crosswalk" has a highest proportion. These findings provide better understanding of illegal crossings and their impact factors so that the effectiveness of management and control of pedestrians at signalized intersections can be improved.

1. Introduction

The National Highway Traffic Safety Administration (NHTSA) reports that during the 10-year period of 2008–2017, the number of pedestrian fatalities in the U.S. increased by 35 percent, from 4,414 deaths in 2008 to 5,977 deaths in 2017. While pedestrian deaths have been increasing, the number of all other traffic deaths combined decreased by six percent (ghsa.org/resources/Pedestrians19). In China, illegal crossing at signalized intersections is a serious problem. In 2014, there were 2242 pedestrian accidents in China, with 1247 deaths, averaging 3.42 deaths per day due to various illegal and risky pedestrian actions on the road. Illegal crossings mainly include pedestrians crossing at red lights or outside of marked crosswalks, with the latter usually being ignored. This hazardous behavior may cause incidents between them and drivers. Therefore, it is necessary to analyze pedestrian violation behaviors at signalized intersections to reduce them.

2. Literature Review

Existing studies on illegal crossing of pedestrians mainly focus on factors affecting crossing behavior of pedestrian, data collection, illegal crossing behavior and research methods, which are summarized in Table 1 and described afterwards.

2.1. Factors Affecting Crossing Behavior of Pedestrian. Most previous studies concerning crossing behavior impact factors mainly focus on pedestrian attributes, traffic conditions, road conditions and so on. Firstly, in terms of pedestrian attributes, age and gender are two main factors considered to describe

Table 1: Literature review on illegal crossings of pedestrians.

Study focus	Literature review		
	Pedestrian attributes	Traffic conditions	Road conditions
Factors	Age [1], gender [2], crowd size [3], clothing [3], luggage [4], cultural backgrounds [5], alcohol use [6, 7], social psychology [2, 8–10], etc.	Pedestrian flow [11], waiting time [12], left-turn ratio of vehicle [13], etc.	Distance of crosswalk [14], countdown displays [15], intersection type [16], etc.
Data collection	Data from video recording [1, 17–20], data from questionnaire survey [2, 8], virtual reality experimental data [21], reported data from police [22], database [6], etc.		
	Characteristics of illegal crossings	Influence mechanism of factors	Safety analysis of pedestrian
Illegal behaviors	Process of crossing in various states [3], crossing pattern [23], statistical analysis of violation [5], parameters of crossing [14], etc.	Analysis on relation between crossing at a red light and factors [5, 15, 24]	The gap acceptance of illegal crossing [1, 25] and risk of pedestrian-vehicle collisions [22, 26]
Research methods	Descriptive statistical method [27–30]; regression analysis methods: binary regression analysis [8], polynomial regression analysis [31], logical regression analysis [11] and hierarchical regression analysis [5]. Difference significance analysis: one-way ANOVA [32, 33] and T test [34]. Disaggregated method [35–37]; Structural equation model [38]; Petri Nets (PN) model [39] and traffic flow model [40]		

the pedestrians. It is shown that the male and middle-aged pedestrians have a high probability to cross the streets illegally [1, 2, 19]. Besides, crowd size [3, 23], clothing [3], and luggage [4] are also employed to explain the different crossing speeds and waiting time. In addition, culture is considered as another important factor impacting differences in crossing behaviors [5]. Psychological factors such as comfort perception, willingness to bypass, conformity, carelessness, anxiety, and personal preference are also analyzed in previous studies [2, 8–10]. A few studies take alcohol use into account to analyze risk of pedestrian-motor vehicle collisions [6, 7].

Secondly, as for traffic conditions, the relative studies mainly focus on vehicle flow, traffic density, pedestrian flow, phase time and so on. The results show that the proportion of crossing at a red light decreases with the increase of vehicle flow and pedestrian flow at signalized intersections [11], and the probability of crossing at a red light increases while the waiting time of pedestrian is too long to exceed their tolerance limit [12]. Besides, the left-turn ratio of vehicles is a key parameter usually used to analyze the probability of pedestrian-vehicle collisions [13].

Lastly, factors of road conditions, including crosswalk distance, countdown displays, type of intersection, illumination and so on, are also considered to analyze pedestrian crossings. Some results suggest that it has a negative correlation between the proportion of compliance with traffic rules and crosswalk distance; countdown displays significantly reduce pedestrian crossing behavior at a red light [15], and factors appear to have different influence on illegal crossings at different intersections [16]. Except for the factors above, weather [6], and social economics [35] are used to analyze the preference of crossings in a few studies.

The effect of pedestrian attributes, traffic conditions, and road conditions on pedestrian crossings, are usually considered. As for pedestrian attributes, apart from the factors mentioned, education, and income level are added in this paper to analyze illegal crossing behavior, from a more diversified perspective. More effective improvement measures or educational programs are developed to target different groups by learning their socioeconomic backgrounds. Besides, on road conditions, it is shown that safety island and location of traffic attractions are rarely involved in the previous studies, so this paper makes an exploratory analysis of these two factors because it can help to formulate design and restraint schemes of facilities in some important intersections after learning the influence of safety island and location of traffic attractions.

2.2. Data Collection. Data, on illegal crossings used for analysis, are usually obtained from video-based observation and questionnaire survey. Data from video-based observation is used to analyze characteristics of crossings, including crossing speed, crossing pattern, etc., and quantify some factors of pedestrian attributes, traffic conditions and road conditions [1, 17–20]. Data from questionnaire surveys are mainly used to obtain pedestrian psychological factors, behavioral reasons, preferences and so on [2, 8]. Applications of data are mainly divided into three categories: data of video recording used alone, data of questionnaire survey used alone, and the combination of them. The majority of studies use the two sources of data to analyze illegal crossings, however, they are usually used alone, only a few studies combine them into the model [24], while the subjects of the questionnaire are pedestrians who are recorded on the video. Also, a few studies on pedestrian crossings, applied virtual reality experimental data [21], reported data from police [22], and database [6] to their analysis.

Data from video-based observation and questionnaires are contained in some previous studies. However, these two sets of data are usually used separately, and only data from questionnaire survey are used for modeling, such as, regression analysis, while in a few papers, the subject of questionnaire survey was the pedestrians who were recorded in the video, but the contents of the questionnaire are mainly the reasons and psychology for illegal crossing, which was statistically analyzed without considering surrounding factors. It is said that in these papers it is difficult to model by combining data from video-based observation with questionnaire survey. In this paper, data from questionnaire survey in which the scenes of pedestrians crossing the streets were augmented by respondents recalling their recent crossing experiences were mainly used to model pedestrian illegal crossings considering factors of pedestrian attributes, traffic conditions and road conditions. Additional data from video recordings were only

used to analyze superficial characteristics of illegal crossings, it was not used in the illegal crossing model. Therefore, the subjects of the questionnaire survey are not necessarily the pedestrians, recorded on video in this paper, according to the objectives.

2.3. Illegal Crossing Behavior. According to the environment, illegal crossing behaviors can be divided into three categories of mid-block streets, signalized intersections, and unsignalized intersections. However, illegal crossing behavior at signalized intersections is important and difficult. Characteristics of illegal crossings, the influence mechanism of the factors and safety analysis of pedestrians are usually analyzed in the previous studies. Analyses on illegal crossing characteristics include process of crossing in various states [3], crossing pattern [23], statistical analysis of violation [5], parameters of crossing [14] and so on. Research of influence mechanisms mainly focuses on analysis on crossing behavior at a red light on which the effects of factors of pedestrian attributes, traffic conditions, and road conditions are analyzed [5, 15, 24]. As for pedestrian safety, the gap acceptance of illegal crossing [1, 25] and risk of pedestrian-vehicle collisions [22, 26], are analyzed.

In previous studies, research on illegal crossing behavior at signalized intersections mainly focuses on crossings at a red light, while behavior of crossing outside of a crosswalk in the spatial dimension is only statistically analyzed in a few studies, and it is especially lacking analysis on the relationship between behavior of crossing outside of a crosswalk and additional factors, however, it is a significant improvement to the design of pedestrian crossing facilities. This paper analyzes characteristics of illegal crossings and the influence mechanism of factors from temporal and spatial dimensions to fill in the gap of the research, by adding analysis on behaviors of crossing outside of a crosswalk.

2.4. Research Method of Illegal Behavior. The research methods used to analyze behaviors of illegal crossings mainly include descriptive statistical method, regression analysis method, significant difference analysis, disaggregated method, structural equation model, traffic flow model, and as utilized in previous studies. Descriptive statistical method is typically used to count the frequency of items of field observations and questionnaires [27–30]. Compared to descriptive statistical method, regression analysis, difference significance analysis and disaggregated method can reflect the relation between behaviors and factors. Binary regression analysis [8], polynomial regression analysis [31], sequence regression analysis [8], logical regression analysis [11] and hierarchical regression analysis [5] are the main regression analysis methods used to analyze relation between behaviors of illegal crossing and factors while correlation analysis is used to analyze the relation between the factors [21]. Difference significance analysis, including one-way ANOVA [32, 33] and T test [34] is used to analyze the differences between different dimensions of factors, and disaggregated method is mainly used to analyze the relationship between pedestrian crossing modes and influencing factors [35]. However, part of the research establishes structural equation models to study decision-making of pedestrians from the psychological perspective [38]. In terms of safety, part of the research establishes models based on the Petri Nets (PN) model [39] and traffic flow model [40], or applies GIS software [41] to analyze pedestrian-vehicle collisions.

The methodology of regression analysis, difference analysis, and nonaggregate method has become mature, which is helpful to understand pedestrian crossing behavior. In this paper, Bayesian network is proposed to analyze illegal crossings for its advantage in describing the relationship of illegal crossings and its influencing factors, forming a graphical network to intuitively reveal influencing mechanism of the factors, to make up for the shortcomings of relevant research methods.

In order to analyze illegal pedestrian crossings at signalized intersections, some work has been carried out in this paper: (i) The research data were collected from two sources of video recording and questionnaire surveys; (ii) Presentational characteristics of illegal crossings were analyzed from temporal and spatial dimensions based on data from video recording; (iii) Two models of crossing at a red light and crossing outside of a crosswalk are established based on Bayesian network to deeply reveal the causal relationship of illegal crossings and influencing factors based on data questionnaire surveys, by adding factors of education, income level, safety island, and location of traffic attractions.

3. Data Collection

This paper aimed to understand characteristics of illegal pedestrian crossings at signalized intersections and the influence mechanism of factors. To understand characteristics of illegal crossings, a video-based observation was conducted to record the whole crossing process at three signalized intersections in Guangzhou, China; and to further understand the relationship between illegal crossings and factors, an online questionnaire survey was conducted. The questionnaire survey and video-based observation were not conducted concurrently in this paper.

3.1. Video-Based Observation. In this observation, crossings at each of the selected signalized intersections were recorded for one hour, from 11:20 am to 12:20 pm on May 2, 2017 and on October 5, 2017 respectively. The observation time was chosen to cover the noon peak when pedestrian activities are more likely to be frequent. Characteristics of observed pedestrian crossings are shown in Table 2. After the videos were collected, data collectors reviewed the recordings to record information about the number of pedestrians, pedestrians crossing at a red light, pedestrians crossing outside of a crosswalk, and pedestrians occupying crosswalks during red lights, in each signal cycle. In total, there were 22-cycle recordings with 3334 pedestrian crossing cases that were processed and will be used to analyze characteristics of illegal crossings. Since panorama view was not available at signal intersections, this study only focuses on one-way pedestrian crossings.

3.2. Online Surveys. Another source was acquired from the online questionnaire survey on pedestrian crossings at signalized intersections. The online questionnaire aimed to

Table 2: Characteristics of observed pedestrian crossings.

Intersection	Direction	Length (m)	Width (m)	Number of lanes	Green ratio
Tianhe road-tiyudong road	South	15	6	8	0.21
	East	40	6	11	0.26
Tianrun road-longkou east road	South	7	3	2	0.34
	East	15	3	4	0.12
	North	10	3	2	0.34
	West	11	3	2	0.12
Huasui road-huacheng avenue	South	15	3	4	0.14
	East	27	3	6	0.40

collect data of personal attributes, traffic conditions and road facilities by acquiring pedestrian feedback. It was conducted in Guangzhou and distributed online between September 27, 2017 and October 3, 2017, resulting in 275 valid respondents. The respondents had to fill in the questionnaires by recalling their newest crossings. This could avoid inauthentic information caused by pedestrians in a hurry at intersections. Table 3 shows the statistics of the survey respondents. People aged 18–30 account for a high proportion, 43.27%, while that of other age groups are approximately 20% each. Education has an even distribution in each sub-group, with a proportion about 20–30%. However, respondents whose income is less than three thousand Chinese Yuan accounts for over 50%, with that of respondents earning three thousand to six thousand at approximately 21%. Regarding the conditions under which illegal crossing happened, about 60% of the respondents reported that they were "in a hurry" to their next destination. About 41% of the people were crossing alone, and 30% of the people cross the streets with one additional pedestrian.

Table 3: Statistics of questionnaire survey.

Variable	Item	Frequency	Percentage
Age	<18	58	21.09%
	18~30	119	43.27%
	31~45	46	16.72%
	>45	52	18.91%
Education	Middle school and below	52	18.91%
	High school	64	23.27%
	Bachelor's	92	33.5%
	Master's and above	69	25.09%
Monthly Income (Yuan)	<3 thousand	139	50.55%
	3–6 thousand	60	21.82%
	6–10 thousand	45	16.36%
	>10 thousand	31	11.27%
Being in a Hurry	Not hurried	74	26.91%
	Moderately hurried	163	59.27%
	Very hurried	38	13.82%
The Number of Companions	0	115	41.82%
	1	82	29.82%
	2	44	16%
	>2	34	12.36%

4. Analysis on Pedestrian Illegal Crossings at Signalized Intersections

Observations show that pedestrian crossings at a red light, pedestrians standing on crosswalks during red lights, and crossings outside of a crosswalk at signalized intersections are recorded. Illegal crossings are analyzed from temporal and spatial dimensions.

4.1. Temporal Dimension. Analysis on illegal crossings in the timing dimension included crossing at a red light and pedestrians intruding into the crosswalk while waiting at the red light which is shown in Figure 1(a). From the observation statistics in Table 4, it is shown that about 17 pedestrians on average cross at a red light every signal cycle, with a proportion of 11.5%, and pedestrian standing on crosswalks during red lights accounts for 3.5%. On long crosswalks pedestrians cross at a red light when the vehicle volume is getting fewer and they choose to cross at the end of green signals, when the signal light turns red rapidly before those pedestrians reach the opposite sides. On the other hand, on short crosswalks, pedestrians choose to cross immediately when they reach the intersection no matter what the signal light is, while a few people cross after stopping for a little time.

Table 4: Statistics on illegal crossings.

Illegal crossings	Mean (person)	SD	Proportion
Crossing at a red light	17	1.041	11.5%
Crossing out of crosswalks	40	5.368	27%
Standing on crosswalks during waiting time	5	4.110	3.5%

4.2. Spatial Dimension. The results show that pedestrian crossing outside of a crosswalk is a serious phenomenon among illegal crossings in Figure 1(b), with a proportion up to 27% in Table 4. If the trajectories of crossings are depicted for each pedestrian, it is easy to find that there are specific types of routes that are taken by pedestrians while crossing at the signalized intersections. Figure 2 displays three types of crossing routes, including "Arc-routing", "Broken line-routing", and "Straight line-routing". And it is also shown that pedestrian took different routes at different types of crosswalks.

(a) (b)

Figure 1: Pedestrian illegal crossings. (a) Standing on crosswalks during waiting time. (b) Crossing outside of crosswalk.

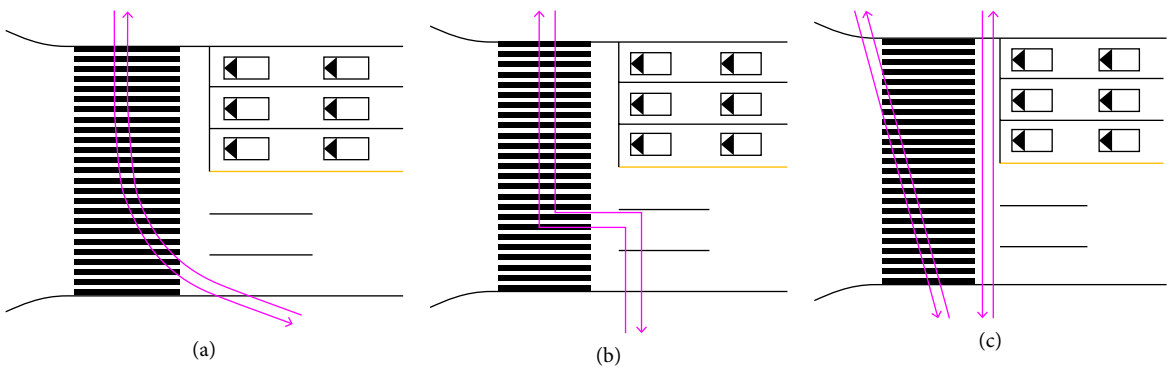

Figure 2: Classification of pedestrian crossing outside of a crosswalk. (a) Arc-routing. (b) Broken line-routing. (c) Straight line-routing.

Table 5: Proportion of three types of crossing outside of a crosswalk.

Classification	Mean (person)	SD	Proportion
Arc-routing crossing	23	8.65	58%
Broken line-routing crossing	3	1.602	8%
Straight line-routing crossing	14	4.272	34%

It is shown that some differences exist in the three illegal crossings of the location dimension in Table 5. Arc-routing crossing occupies the highest proportion of 58%, and straight line-routing crossing ranks the second, accounting for 34%. Broken line-routing crossing rarely occurs compared to other two illegal crossings. It can be concluded from statistical analysis that crossing outside of a crosswalk which is easily ignored by people has a higher probability than crossing at a red light, especially arc routing crossing.

The pairs of location of origin and destination of single pedestrians crossing the streets are classified into 4 categories, namely "both inside of the crosswalk", "both outside of a crosswalk and in the same side", "both outside of a crosswalk and in the different side", "one is inside of a crosswalk and another is outside of a crosswalk." Distribution of origin and destination of pedestrians crossing the streets is shown in Figure 3, where the lines with different colors denote different pairs of origin and destination. 640 samples of crossing outside of a crosswalk are statistically analyzed, the results are shown in

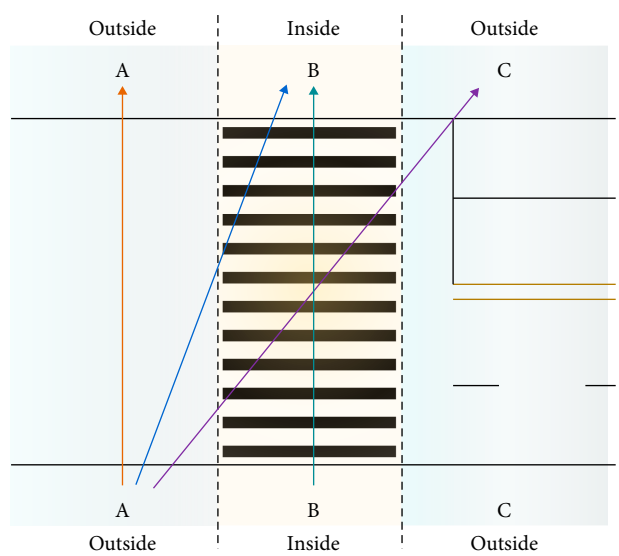

Figure 3: Distribution of origin and destination of pedestrian crossing the streets.

Table 6. As it is shown that "one is inside of a crosswalk and another is outside of a crosswalk" has a highest proportion of 77.97% among the 4 categories. "Both outside of a crosswalk and in the same side" ranks second, with a proportion of 21.72%. "Both inside of the crosswalk" and "both outside of a crosswalk and in the different side" have a very small proportion.

Table 6: Statistics on location of origin and destination of crossing outside of a crosswalk.

Classification	Origin	Destination	Frequency	Total
Both inside of the crosswalk	B	B	0.01%	0.01%
Both outside of a crosswalk and in the same side	A	A	5.47%	21.72%
	C	C	16.25%	
Both outside of a crosswalk and in the different side	A	C	0.15%	0.30%
	C	A	0.15%	
One is inside of a crosswalk and another is outside of a crosswalk	A	B	5.47%	77.97%
	C	B	60.78%	
	B	A	3.91%	
	B	C	7.81%	

Table 7: Variable definition of factors influencing illegal crossings.

Category	Variable	Definition and value
Personal attributes	Age (x_1)	1: <18 (state 4); 2: 18~30 (state 1); 3: 31~45 (state 2); 4: >45 (state 3)
	Education (x_2)	1: Middle school and below (state 4); 2: High school (state 1); 3: Bachelor's (state 2); 4: Master's and above (state 3)
	Income (x_3)	1: <3thousand Yuan (state 4); 2: 3~6 thousand Yuan (state 1); 3: 6~10 thousand Yuan (state 2); 4: >10 thousand Yuan (state 3)
	The number of companions (x_4)	1: 0 (state 4); 2: 1 (state 1); 3: 2 (state 2); 4: >2 (state3)
	Hurry (x_5)	1: not hurried (state 3); 2: moderately hurried (state 1); 3: very hurried (state 4)
Traffic conditions	Vehicle volume (x_6)	1: small (<300pcu/h∗lane) (state 3); 2: medium (250~550pcu/h∗lane) (state 1); 3: large (>500pcu/h∗lane) (state 2)
	Waiting time (x_7)	1: short (<30 s) (state 3); 2: medium (20~60 s) (state 1); 3: long (>50 s) (state 2)
	Pedestrian flow (x_8)	1: small (<40ped/circle) (state 3); 2: medium (35~60ped/circle) (state 1); 3: large (>55ped/circle) (state 2)
Road conditions	Crossing distance (x_9)	1: 1~2 lanes (state 3); 2: 3~4 lanes (state 1); 3: 5~6 lanes (state 2)
	Safety island presence (x_{10})	1: Yes (state 2); 2: No (state 1)
	Countdown device presence (x_{11})	1: Yes (state 2); 2: No (state 1)
	Location of traffic attractions (x_{12})	1: On anterolateral side of crosswalk (state 2); 2: On right ahead of crosswalk (state 1)
Crossing	Signal light color (x_{13})	1: Red (state 2); 2: Green (state 1)
	Crossing track (x_{14})	1: Part/not in the crosswalk (state 2); 2: Completely in the crosswalk (state 1)

5. Correlation Analysis on Factors Influencing Illegal Crossings

5.1. Variable Definition and Value. Personal attributes, traffic conditions, and road conditions are considered to have certain influence on illegal pedestrian crossings [1, 22, 42]. Personal attributes include age, education, income, and the number of companions, etc. Traffic conditions include vehicle volume, waiting time, and pedestrian volume. Road conditions include crossing distance, safety island presence and so on. The definition and value of each variable used in this study are shown in Table 7.

5.2. Correlation Analysis. Correlation analysis on factors influencing illegal crossings can help select the significant ones before modeling illegal crossings. GeNIe software is used to model behavior of illegal crossings, which internally get the optimal network after automatically finishing component analysis according to results of correlation analysis on the factors [43].

Correlation analysis is used to examine whether there is a significant relationship between two variables. And it indicates that two variables are significantly correlated when P value is less than 0.05, and they are correlated more significantly when P value is less than 0.03. In this part, crossing at a red light (x_{13}) and crossing outside of a crosswalk (x_{14}) are used to have correlation analysis with other variables (x_n, $n = 1, ..., 12$), the results are shown in Tables 8 and 9.

6. Modeling Illegal Crossings Based on Bayesian Network

Bayesian network has proven to be an effective method for representation and reasoning of uncertain knowledge [44], with the advantages of overcoming the difficulties in conceptual definition and computation based on rule relations and being able to learn causality. Bayesian uses graphical networks to reveal structures of one variable to another, so it can better describe the relationship of behavior and various factors, as well as one factor to another. Therefore, this paper tentatively proposes a new method to analyze pedestrian illegal crossings based on Bayesian network model, which can be used to analyze the mechanism between illegal crossings and related factors.

Table 8: Results of correlation analysis between variables (including crossing at a red light).

	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}	x_{13}
x_1			**								**
x_2			*								
x_3	**	*			**						**
x_4								**			
x_5											**
x_6							**		*	*	**
x_7						**		**			*
x_8				**			**				
x_9						*					
x_{10}						*					
x_{13}	**		**		**	**	*				

Notes: **Significant at 0.01 level; *Significant at 0.05 level; x_n ($n = 1$–14) see Table 7.

Table 9: Results of correlation analysis between variables (including crossing outside of a crosswalk).

	x_1	x_2	x_3	x_4	x_5	x_9	x_{12}	x_{14}
x_1			**					*
x_2			*					
x_3	**	*			**			*
x_4								*
x_5			**					*
x_9								**
x_{12}								**
x_{14}	*		*	*	*	**	**	

Notes: **Significant at 0.01 level; *Significant at 0.05 level; x_n ($n = 1$–14) see Table 7.

6.1. Theories. A Bayesian network is a relationship network that uses statistical methods to represent probability relationships between different elements. Its theoretical foundation is the Bayes rule [45].

$$p(h|e) = \frac{p(e|h) \cdot p(h)}{p(e)}, \tag{1}$$

$p(h)$ is the prior probability of hypothesis h; $p(e)$ is the prior probability of evidence e; $p(h|e)$ is the probability of h given e; $p(e|h)$ is the probability of e given h.

Bayesian network is a graphical network based on probabilistic reasoning, which includes directed acyclic graph (DAG) and conditional probability table (CTP). DAG is the qualitative process to estimate the structure of illegal crossings and CTP is the quantitative process to get the probabilities of one variable to another.

6.1.1. Bayesian Network Structure. Based on a complete data set, three methods are usually used to build Bayesian network structure. That is, (i) modeling based on expert knowledge; (ii) obtaining from database learning. (iii) creating from a knowledge base. These methods are synthetically used to model Bayesian network, with expert knowledge as the dominant. However, in the absence of expert knowledge and knowledge base, it is an effective method to model Bayesian network structure from database learning.

6.1.2. Bayesian Network Parameter Learning. Maximum likelihood estimation, Bayesian estimation, and maximum expectation algorithm (EM algorithm) are usually used for probabilistic reasoning. In this paper, EM algorithm is used to estimate parameters because the data sample is incomplete.

Let X denote the set of observed variables, Z denote the set of the hidden variables, and Θ denote parameters of model, the maximum likelihood estimation is as follows,

$$LL(\Theta|X, Z) = \ln P(X, Z|\Theta). \tag{2}$$

Starting from the initial value Θ^0, the following steps can be iterated until convergence:

Step E: estimating the distribution of the hidden variable based on the current parameter of Θ^t, then calculating expectation of $LL(\Theta|X, Z)$, that is,

$$Q(\Theta|\Theta^t) = E_{Z|X,Q^t} LL(\Theta|X, Z). \tag{3}$$

Step M: search for maximized expectation likelihood of parameter, that is,

$$\Theta^{t+1} = \arg\max_{\Theta} Q(\Theta|\Theta^t). \tag{4}$$

$$LL(\Theta|X) = \ln P(\Theta|X) = \ln \sum_{Z} P(X, Z|\Theta). \tag{5}$$

6.2. Modeling. Two important steps were taken to establish Bayesian network models on influencing on illegal crossings of the factors, including structure learning and parameter learning.

GeNIe2.1 software is used to study Bayesian network structure of illegal crossings in this paper. In the absence of expert knowledge and knowledge base, database learning is used to model Bayesian network structure in this paper. Firstly, the database from questionnaires is imported into the software, and structure learning is completed by greedy search method (GTT) and K2 algorithm. Initial Bayesian network structures of crossing at a red light and crossing outside of a crosswalk are obtained. Secondly, the network structures are modified according to results of correlation analysis finished above. Finally, after many iterations, component analysis is finished in the software to obtain the optimal Bayesian network structures of illegal crossings shown in Figures 4 and 5.

Parameter learning is the second step to study Bayesian network to get the joint probability distribution. Firstly, an EM (Expectation Maximization) algorithm is used for parameter learning which is completed on the GeNIe2.1 software after obtaining the network structures. Secondly, marginal probabilities of father nodes of crossing at a red light and crossing outside of a crosswalk are calculated by using joint tree algorithm. The marginal probability is the summation of a set of probabilities of a factor which affects illegal crossings under several other factors. Finally, results of parameter estimation of crossing at a red light and crossing outside of a crosswalk are obtained in Tables 10 and 11.

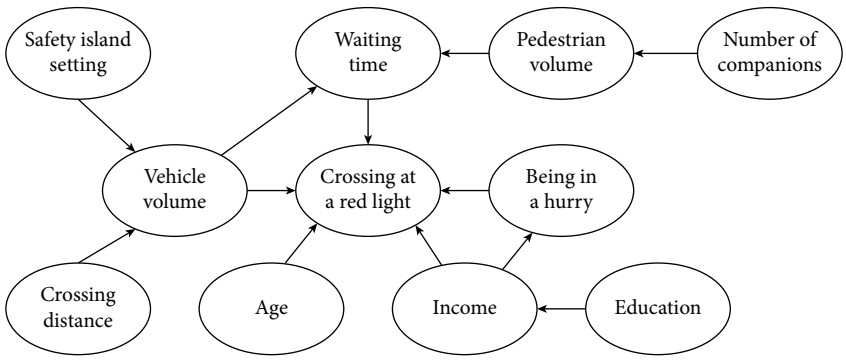

Figure 4: Bayesian network structure of pedestrian crossing at a red light.

6.3. Results

6.3.1. Bayesian Network Structure of Illegal Crossings. A father node is the starting node of an arrow in the graphical network. According to structure learning, age, monthly income, being in a hurry, vehicle volume, and waiting time have a direct influence on crossing at a red light. Crossing distance, safety island setting, education, number of companions, and pedestrian volume have an indirect influence on crossing at a red light shown in Figure 4.

Father nodes of crossing outside of a crosswalk include age, monthly income, education, being in a hurry, number of companions, crossing distance, and location of traffic attraction, which have a direct influence on crossing outside of a crosswalk, which is shown in Figure 5.

6.3.2. Parameter Estimation of Bayesian Network. The results of parameter estimation of Bayesian network of crossing at a red light and crossing outside of a crosswalk are obtained after parameter learning. The probabilities of different dimensions of the father nodes to cross at a red light and cross at a green light are listed in Table 10. Besides, the probabilities of different dimensions of the father nodes to cross inside of a crosswalk and cross outside of a crosswalk are listed in Table 11. Analysis on results of parameter estimation is analyzed in detail in the next section.

7. Analysis on the Results

This paper establishes models of influence on illegal crossings of factors based on Bayesian network, and finishes parameter learning to understand how factors influence illegal crossings. Bayesian network can intuitively indicate the probability of illegal crossings under joined factors (father nodes), and probabilities of different states of father nodes can be obtained as well. Modeling illegal crossings based on Bayesian network can not only predict illegal crossings, but also reveal relationship between illegal crossings of factors.

7.1. Discussion Model of Crossing at a Red Light. From Bayesian network structure, it is indicated that a child node is influenced by its joint father nodes. Figure 6 shows that age, income, being in a hurry, vehicle volume, and waiting time

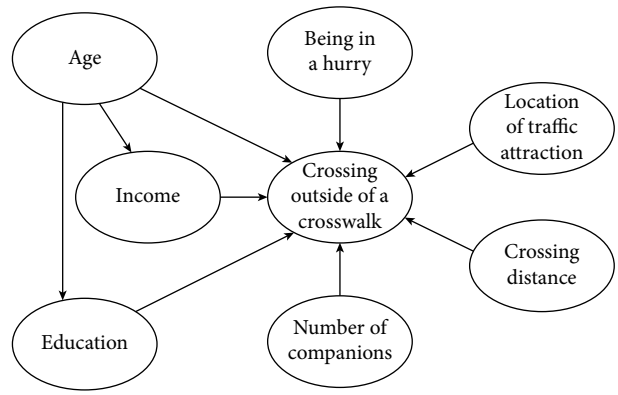

Figure 5: Bayesian network structure of crossing outside of a crosswalk.

have significant effect on crossing at a red light. And Figure 5 shows the probability distribution of different dimensions for each variable, in which the variables are influenced by their father nodes at the same time.

(i) *Age*. According to Figure 6(a), it has a highest probability of 14% to cross at a red light among people who are younger than 18 years old, and it shows that the younger the people are, the higher probability it is to cross at a red light.

(ii) *Income*. From Figure 6(b), pedestrians with different incomes have almost the same probability of crossing at a red light.

(iii) *Being in a hurry.* As it is shown in Figure 6(c) that the probability of crossing at a red light when people are in a hurry is 42%, which is much higher than that when people are not in a hurry or a little hurry.

(iv) *Vehicle volume.* It shows in Figure 6(d) that people have a 40% probability to cross at a red light when the vehicle volume is in the medium level at intersections, which is the result of vehicle volume and its father nodes influence on crossing at a red light.

(v) *Waiting time.* It is shown in Figure 6(e) that the longer people wait at intersections, the larger the probability of crossing at a red light is, and the probability can be up to 53% when people wait for a long time.

Table 10: Results of parameter estimation of Bayesian network of crossing at a red light.

State	Age				Income (thousand Yuan)			
	<18	18–30	0–45	>45	<3	3–6	6–10	>10
Green[1]	59%	66%	67%	69%	67%	63%	67%	66%
Red[2]	41%	34%	33%	31%	33%	37%	33%	34%
State	Being in a hurry			Vehicle volume			Waiting time		
	Not	Moderately	Very	Small	Medium	Large	Short	Medium	Long
Green	63%	70%	58%	66%	60%	70%	67%	63%	48%
Red	37%	30%	42%	34%	40%	30%	33%	37%	52%

[1]Means crossing at a green light. [2]Means crossing at a red light.

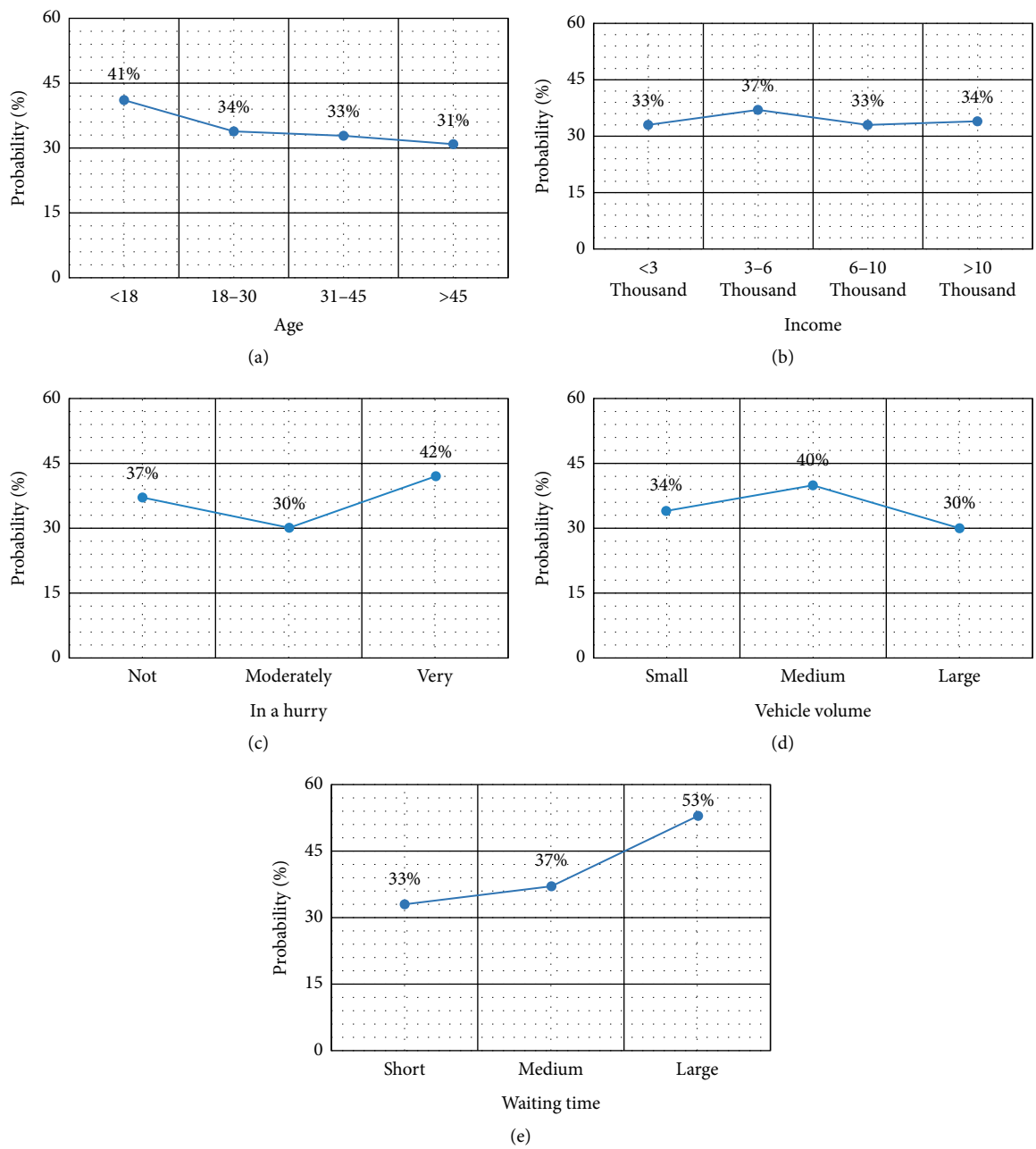

Figure 6: Probability distribution of father node to crossing at a red light. (a) Age, (b) Income, (c) Being in a hurry, (d) Vehicle volume and (e) Waiting time.

Table 11: Results of parameter estimation of Bayesian network of crossing outside of a crosswalk.

State	Age				Education			
	<18	18-30	30-45	>45	1	2	3	4
A	47%	49%	46%	48%	47%	49%	47%	46%
B	53%	51%	54%	52%	53%	51%	53%	54%
State	Income (thousand Yuan)				Number of companions			
	<3	3-6	6-10	>10	0	1	2	>2
A	46%	46%	48%	49%	48%	47%	47%	46%
B	54%	54%	52%	51%	52%	53%	53%	54%

State	Being in a hurry			Crossing distance (lanes)			Location of traffic attractions	
	Not	Moderately	Very	1-2	3-4	5-6	Front side	Right ahead
A	47%	46%	50%	48%	47%	47%	48%	46%
B	53%	54%	50%	52%	53%	53%	52%	54%

A means crossing outside of a crosswalk. B means crossing inside of a crosswalk.

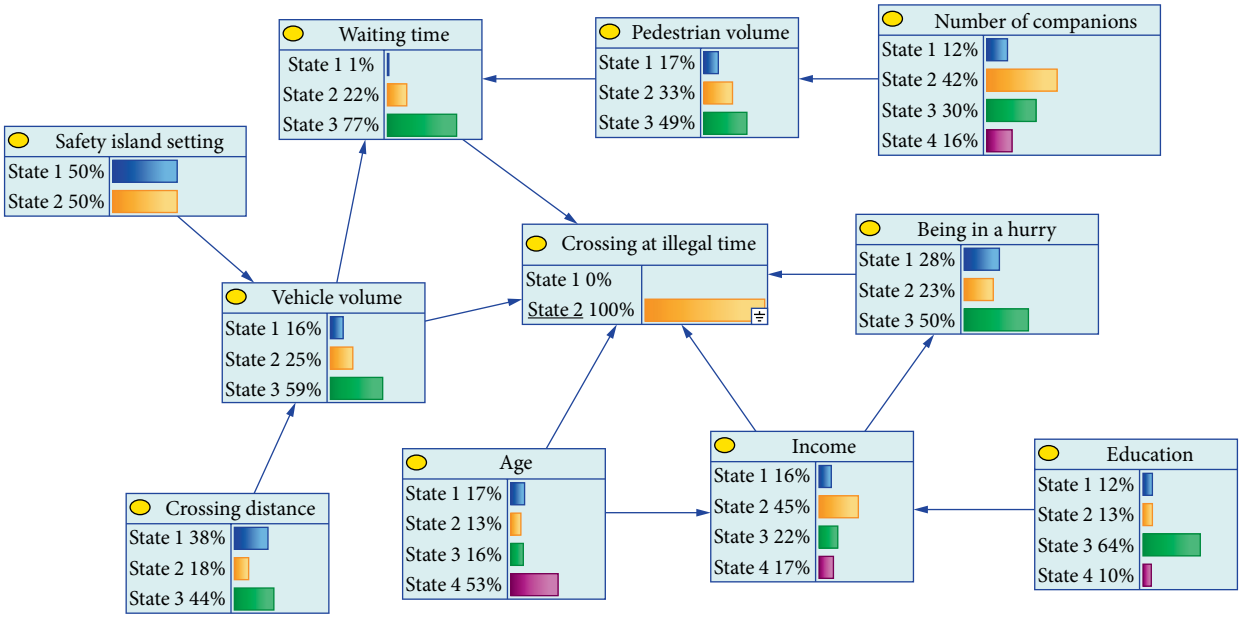

Figure 7: Probabilistic topology diagram when probability of crossing at a red light is 100%. Notes: state n ($n = 1 \sim 4$) sees Table 7. Notes: in the level of education, "1" means "Middle school and below"; "2" means "High school"; "3" means "Bachelor's"; "4" means "Master's and above."

The state of maximum probability of each father node is obtained when the probability of crossing at a red light is 100% in the Bayesian network structure in Figure 7 and Table 12. It is intuitive to see that the crossing at a red light has a higher probability to occur among people aged 31–45, with a high school education, with an income less than 3000, and with no companions, and in the medium traffic condition level of vehicle volume, pedestrian volume, and waiting time, and in a road condition of 3-4 lane-crossing distance as well.

7.2. Discussion Model of Crossing Outside of a Crosswalk. Figure 4 shows that age, education, income, number of companions, being in a hurry, and crossing distance have a significant effect on crossing outside of a crosswalk. And Figure 7 shows the probability distribution of different dimensions for each variable, as noted earlier, the variables are influenced by their father nodes at the same time.

(i) *Age*. From Figure 8(a), the probability of crossing outside of a crosswalk among people who aged 18–30 is 49%, which is higher than that of other age groups.

(ii) *Education*. It shows that people with high school education have the highest possibility to cross outside of a crosswalk. In general, people educated postgraduate and above have a lower probability to cross outside of a crosswalk.

(iii) *Income*. According to Figure 8(c), the people with an income of more than 10,000 yuan have the highest probability to cross outside of a crosswalk.

(iv) *The number of companions*. It is shown in Figure 8(d) that the more the number of companions, the lower the probability to cross outside of a crosswalk.

Table 12: The state of maximum probability of each father node when the probability of crossing at a red light is 100%.

Father node	Age	Education	Income	Number of companions	Hurry
State	31~45	High school	<3000	0	Moderately
Probability	53%	64%	47%	42%	50%
Father node	Vehicle volume	Waiting time	Crossing distance	Pedestrian volume	——
State	Medium	Medium	3~4 lanes	Medium	——
Probability	59%	77%	44%	49%	——

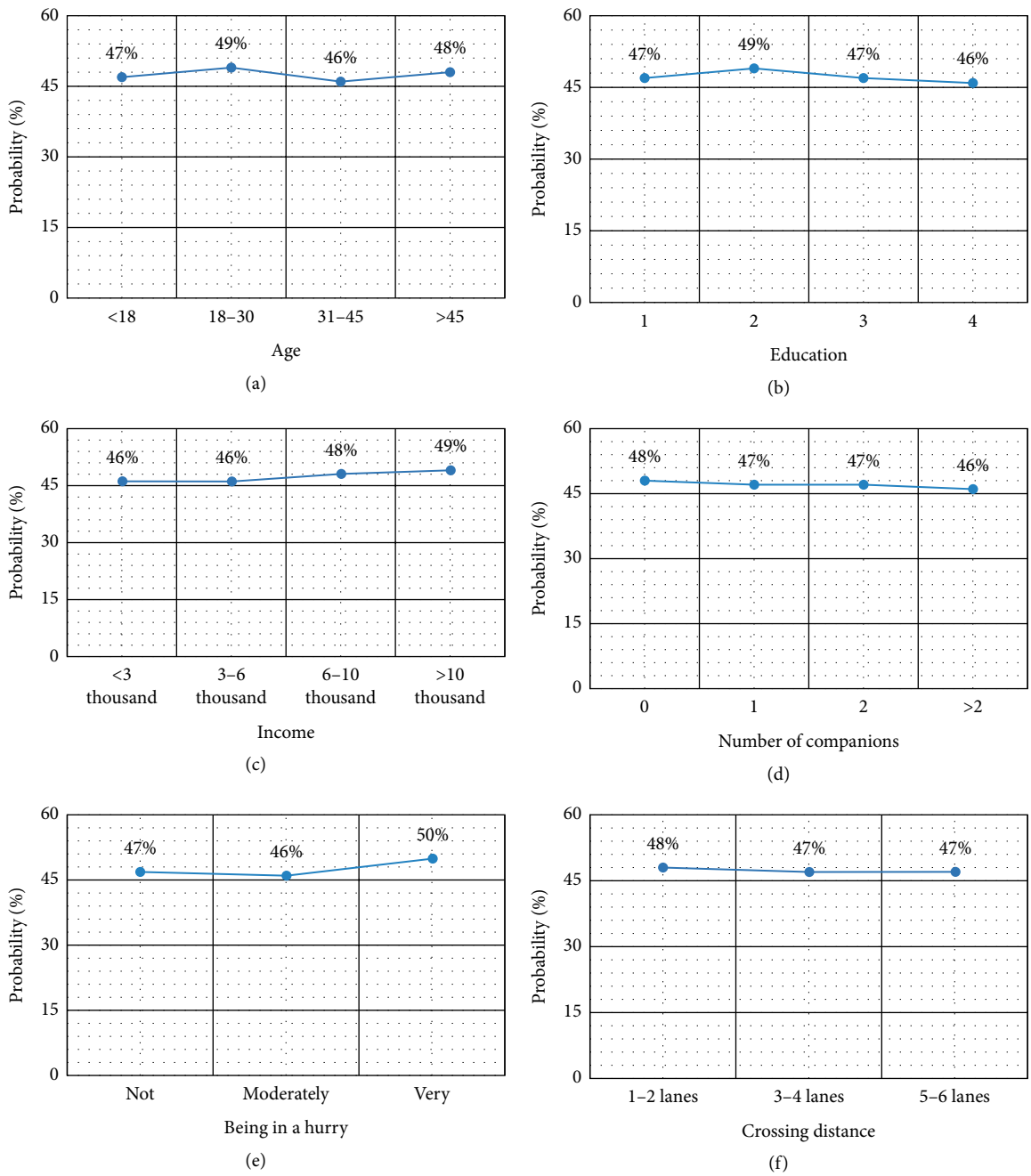

Figure 8: Probability distribution of father node to crossing outside of a crosswalk. (a) Age. (b) Education. (c) Income. (d) Number of companions. (e) Being in a Hurry. (f) Crossing distance.

(v) *Hurry*. It has a highest probability of 50% to cross outside of a crosswalk among the people who are in a hurry.

(vi) *Crossing distance*. The probability of crossing outside of a crosswalk is the largest at 48% in a road condition of 1~2 lanes-crossing distance. The smaller the

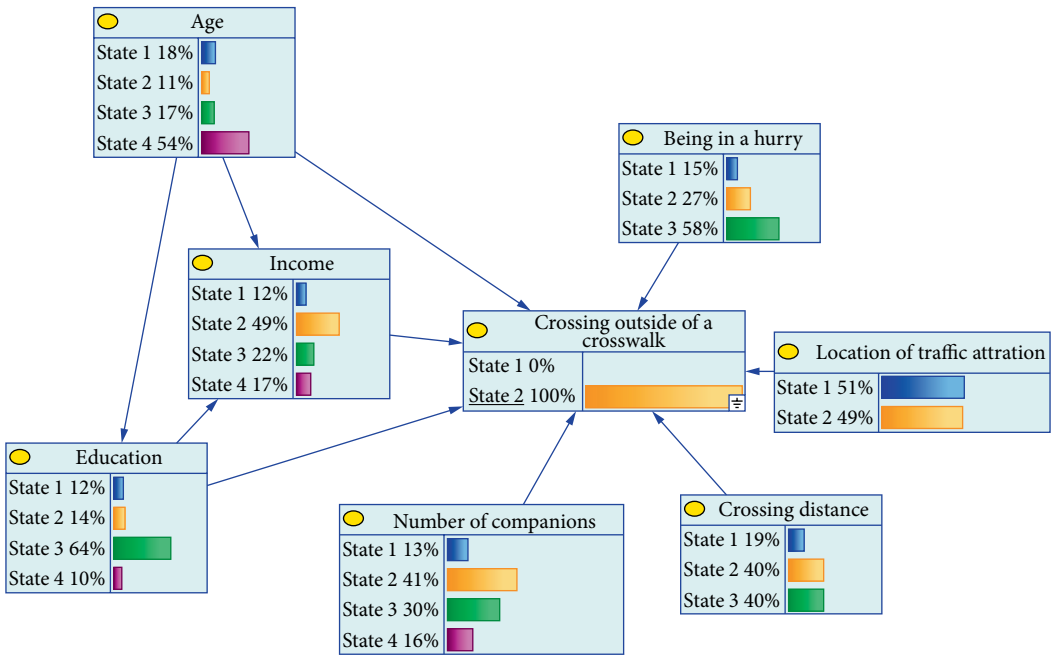

Figure 9: Probabilistic topology diagram when probability of crossing outside of a crosswalk is 100%. Notes: state n ($n = 1$–4) see Table 7.

Table 13: State of maximum probability of each father node when the probability of crossing outside of a crosswalk is 100%.

Father node	Age	Education	Income	Number of companions
State	18~30	High school	<3 thousand	0
Probability	54%	64%	49%	41%
Father node	Being in a hurry	Crossing distance	Location of traffic attraction	——
State	Moderately	1~2 lanes	Front side	——
Probability	58%	41%	51%	——

crossing distance, the higher the probability to cross outside of a crosswalk.

(vii) *Location of traffic attractions*. When the traffic attraction is on anterolateral side of crosswalk, people have a 60% possibility to cross outside of a crosswalk.

The state of maximum probability of each father node is obtained when the probability of crossing outside of a crosswalk is 100% in the Bayesian network structure in Figure 9 and Table 13. It is shown that the crossing at a red light has a higher probability to occur among people less than 30, with a high school education, and an income of less than 3,000 yuan, without any companions and in a hurry, and in a road condition of 1~2 lanes-crossing distance and in a traffic attraction on anterolateral side of crosswalk.

8. Conclusions

This paper analyzes characteristics of illegal crossings at signalized intersections and establishes models of influence on illegal crossings of factors based on data from video-based observations and a questionnaire survey. Bayesian network is used to develop models for crossing at a red light and crossing outside of a crosswalk. The results show that, (i) it has a proportion of 36.3% on average to cross outside of a crosswalk in every signal cycle at the intersections, and it occurred more frequently than crossing at a red light, of which the proportion is 27%. (ii) Arc routing crossing has a highest probability of 58% to occur at signalized intersections compared to other types of out-side-crosswalk crossings. (iii) The location of origin and destination of a pedestrian have a significant effect on crossing outside of a crosswalk, the proportions of "both outside of a crosswalk and on the same side" and "one is inside of a crosswalk and another is outside of a crosswalk" make up to about 99% among samples of crossing outside of a crosswalk. (iv) Among the five significant influencing factors, waiting time has the strongest influence on behavior of crossing at a red light. Some recommendations are provided based on the conclusions above.

(i) Waiting time is the most important factor of crossing at a red light and crossing outside of a crosswalk. Therefore, signal timing at intersections should be more considerate about pedestrians. Enough pedestrian signal time should be given to make sure that pedestrians can pass through, and each phase time should avoid an unreasonable waiting period.

(ii) Location of traffic attractions has a significant influence on crossing outside of a crosswalk. It is necessary to add some auxiliary facilities at intersections, such as

fencing, to prevent pedestrians from crossing outside of a crosswalk.

(iii) As it is shown that the probability of illegal crossings including crossing at a red light and crossing outside of a crosswalk is very high. Education is a powerful means to strengthen consciousness of traffic safety. Therefore, it is very important to provide more education on traffic safety to people, especially from childhood.

This paper analyzes illegal crossings from temporal and spatial dimensions, which provides better understanding of pedestrians' illegal crossing at signalized intersection. This paper, using Guangzhou as a case study, generates findings about characteristics of pedestrians' illegal crossing and influences mechanism of the impact factors in typical large Chinese cities. Besides, the method used in this paper, to analyze pedestrians' illegal crossing, can be transferred to solve similar problems for other countries and cities. The findings of the research in this paper could be considered as basic guidance for traffic design and management. However, there is room for improvement, including improving the questionnaire survey utilized in this paper, and combining expert knowledge with database and knowledge base to study Bayesian network by collecting diversified information.

Data Availability

The data used to support the findings of this study were supplied under license and so cannot be made freely available. Requests for access to these data should be made to [Yingying Ma, mayingying@scut.edu.cn].

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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