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Evaluation of Pedestrian Level of Service at Signalised Intersections from the Elderly Perspective

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ABSTRACT

The crossing decisions and behaviour of elderly pedestrians are affected by the pedestrian level of service (PLOS). In this paper, an evaluation model was established to analyse the relationship between the traffic environment and the perceived evaluation of elderly pedestrians. Firstly, the characteristic parameters of the selected intersections and the perceived evaluation data of elderly pedestrians at the synchronisation scenery were extracted using manual recording and questionnaire-based truncation methods. The correlation between the perceived evaluation data of elderly pedestrians and the traffic parameters were tested with respect to the dimensions of safety, convenience and efficiency. Then, the significant parameters affecting PLOS were recognised. Based on the traffic characteristic parameters, the PLOS evaluation model from the elderly perspective was established using the fuzzy linear regression method. PLOS classification thresholds were obtained using the fuzzy C-means clustering algorithm. The data from two intersections were used to validate the model. The results show that the difference between the actual and the predicted PLOS values of the two crosswalks were 0.2 and 0.1, respectively. Thus, the proposed PLOS evaluation model in this paper can be used to accurately predict the PLOS from the elderly perspective using the traffic data of signalised intersections.

KEYWORDS

urban traffic; pedestrian level of service; fuzzy linear regression; signalised intersection; elderly pedestrian.

1. INTRODUCTION

By the end of 2021, the number of elderly people ≥ 60 years and ≥ 65 years accounted for 18.9% and 14.2% of the total population in China, respectively [1]. China has almost become a moderately aging society, with a gradually increasing degree of aging. The increase in the elderly population causes an annual increase in the proportion of elderly people in travel. Thus, lack of attention to elderly people's travel is set to bring about major hidden traffic hazards in China. Relevant data show that 24,000 elderly people died from traffic accidents in 2020. Particularly, elderly people who died in traffic accidents at urban road intersections accounted for 29.4%. Walking is the main travel mode for elderly people in China [2]. In walking travel, signalised intersections are the most complex nodes of traffic conditions faced by elderly pedestrians. With increasing age, the physical function of elderly people generally declines [3]. Thus, this can result in poorer body posture control, higher falling risk [4], more time spent looking at the ground [5], more focus on maintaining body posture stability and lack of attention to the surrounding traffic environment when elderly pedestrians cross streets [6]. When crossing streets with two-way traffic, elderly people tend to focus on the nearside lane and ignore traffic information in the farside lane [7]. Compared to young and middle-aged people, elderly people have lower traffic safety awareness [8], require longer decision-making time [9] and show a higher rate of making wrong crossing decisions [10]. In addition, elderly people have longer start-up time and lower walking speeds at signalised intersections [11]. Thus, they are subjected to higher exposure risks at intersections.

Pedestrians' crossing decisions and final crossing behaviour are influenced by their perceptions and judgments of the crossing environment. Pedestrian level of service (PLOS) is an important evaluation index reflecting the operation of crosswalks at signalised intersections. PLOS can be evaluated from the perspective of users. Therefore, the study of PLOS evaluation methods has been an important research aspect worldwide. In terms of PLOS study at signalised intersections, HCM2000 first proposed a PLOS concept based on pedestrian crossing delays [12]. Since then, parameters such as average pedestrian occupied space, pedestrian flow rate, pedestrian walking speed and the ratio of pedestrian flow rate to traffic capacity at crosswalks have been included as the evaluation indexes based on pedestrian flow characteristics [13, 14]. It is easy to obtain the data of single indicators that characterise pedestrian flow characteristics. However, they do not consider the effects of vehicles and traffic facilities on the PLOS [15]. Thus, studies based on single indicators still exhibit some limitations. Current studies on the impact of motor vehicle traffic flow on PLOS have focused on factors such as vehicle travel speed [16], vehicle traffic volume [17–19] and pedestrian-vehicle conflicts [20–23]. Studies on the impact of traffic facilities on PLOS have commonly used evaluation indicators, including crosswalk length or the number of lanes [21, 24], pedestrian safety islands [22] and pavement conditions [25]. Thus, HCM2010 proposed an evaluation method for PLOS at signalised intersections by considering pedestrian delays, channelisation, traffic characteristics and control schemes [12]. HCM2016 followed the PLOS evaluation method presented by HCM2010 [26].

In summary, with the rapid increase of aging population in China, the PLOS evaluation at signalised intersections from the elderly perspective can provide a direct evaluation method of PLOS at signalised intersections for elderly pedestrians. Thus, this may facilitate the design of pedestrian crossing facilities and the adjustment of crossing measures at signalised intersections in an aging society. Therefore, this paper analysed the relationship between static/dynamic traffic characteristics data and the evaluation results of elderly people's perceptions. Then, based on the traffic facilities, traffic management and traffic flow operation conditions of signal intersections, important variables for the PLOS evaluation of elderly pedestrians were identified. A PLOS evaluation model was established. In addition, field surveys were conducted to obtain sample data in order to establish and solve the evaluation model. The thresholds for classifying PLOS were recommended. The PLOS evaluation model can provide a reference for studying traffic safety improvement strategies in the aging context.

2. FIELD SURVEY

2.1 Selection of influencing factors

The review studies of Bansal et al. [15] and Raad et al. [27] were taken as references. The questionnaire survey at the initial installation stage of crossing facilities for elderly pedestrians was analysed. Then, pedestrian characteristics, traffic characteristics, geometric characteristics and pedestrian-signal design at signalised intersections were selected as the influencing factors for the PLOS evaluation of elderly pedestrians at signalised intersections. The detailed characteristics are shown in *Table 1*.

Table 1 – Selection and classification of influencing factors

Dimensions	Pedestrian characteristics	Traffic characteristics	Geometric characteristics	Pedestrian-signal design
Safety		Volume of right-turning traffic without signal control	Length of the crosswalk Crossing island Buffer setting	
Convenience	Pedestrian flow		Curb ramp setting	Pedestrian crossing speed
Efficiency	Average pedestrian delay			

2.2 Data acquisition

In order to analyse the influence of different factors on PLOS, the abovementioned influencing factors should have different parameter levels and incorporate a certain number of elderly pedestrians. Signalised intersections were selected according to the following requirements:

1) It is necessary to ensure that a certain number of elderly pedestrians pass through the crosswalk at the selected signal intersection; thus, they can complete the questionnaire about the pedestrian level of service.

2) The traffic data of each selected signal intersection crosswalk should be different, so as to ensure that the research is not limited to a certain type of pedestrian crossing scene, in order for the research results to have a certain applicability.
3) The selected survey sites can cover common and typical pedestrian crossing scenes at signalised intersections as far as possible, so as to ensure that the research conclusions have to be applied to other signal crosswalks.
4) The area around the signalised intersection is open and flat, which is convenient for setting up cameras to record video.

Then, based on field pre-survey and screening, 12 crosswalks at six signalised intersections in Chongqing, China, were finally selected as data collection locations. For each of the selected crosswalks, dynamic parameters such as motor vehicle flow rate, pedestrian crossing flow rate and pedestrian crossing delay were recorded and extracted for 2-hour datasets. The selected 12 survey locations were arranged as follows: ten for constructing the evaluation model (i.e. the modelling group) and two for validating the evaluation model (i.e. the validation group). The location information of each crosswalk is shown in *Table 2*. All the intersections where the crosswalks are located have signal control for both straight and left-turning vehicles.

Table 2 – Information on survey sites

Number	Location	Number	Location
A (Modelling group)	West approach of Qinglong Road - Nanhu Road intersection	G (Validation group)	West approach of Dashi Road - Qinglong Road intersection
B (Modelling group)	North approach at Qinglong Road - Nanhu Road intersection	H (Validation group)	South approach of Dashi Road - Qinglong Road intersection
C (Modelling group)	West approach of Huilong Road - Qinglong Road intersection	I (Modelling group)	West approach of Lanhua Road - Huilong Road intersection
D (Modelling group)	South approach of Huilong Road - Qinglong Road intersection	J (Modelling group)	South approach of Lanhua Road - Huilong Road intersection
E (Modelling group)	East approach of Ertang Road - Huilong Road intersection	K (Modelling group)	West approach of Jinzi Street - Nanhu Road intersection
F (Modelling group)	South approach of Ertang Road - Huilong Road intersection	L (Modelling group)	South approach of Jinzi Street - Nanhu Road intersection

For these 12 locations, information on intersection channelisation and timing schemes was recorded through on-site surveys. Data on motor vehicles, pedestrian flow and pedestrian delay were obtained by manually extracting recorded videos. The elderly pedestrians' perceptions of PLOS were investigated using an intercept survey method and synchronised with video shooting. Questionnaires were allocated to elderly pedestrians after they crossed the street. The questionnaire contained information on basic individual characteristics (such

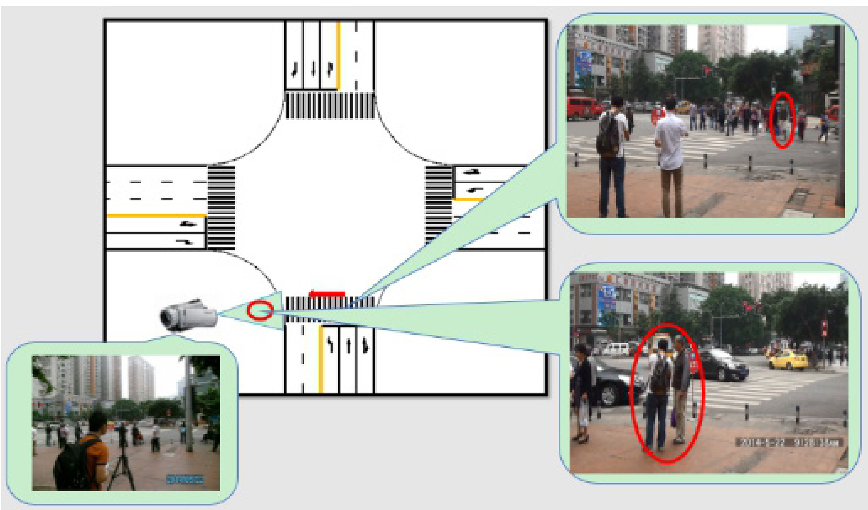

Figure 1 – Crossing video recording and the elderly pedestrian field questionnaire collection

as gender and age) and three questions on elderly pedestrians' perceptions of the safety, convenience and efficiency of the crosswalks. A five-point positive scale was used to record the survey data (i.e. a score of 5 indicates "very safe"). During the survey, when the elderly respondents had difficulty reading and writing, trained surveyors were responsible for explaining the questionnaire and completing the survey. The survey method is shown in *Figure 1*.

2.3 Data analysis

Traffic data. Static and dynamic traffic data for ten crosswalks in the modelling group and two crosswalks in the validation group were obtained based on the field survey and manual data extraction, respectively. *Table 3* shows the statistical description of these traffic data.

Table 3 – Statistical description of traffic data

The crosswalk number	A	B	C	D	E	F	G	H	I	J	K	L
Number of lanes	5	5	5	5	5	7	4	5	8	7	2	5
Pedestrian crossing length [m]	20	16	26	24	30	38	16	22	30	24	9	16
Curb ramp setting	0	1	0	1	0	0	0	1	1	0	1	1
Buffer facilities	0	0	0	1	1	0	1	1	1	1	1	1
Safety island	0	0	0	0	0	1	0	1	0	0	0	0
Pedestrian signal cycle [s]	105	105	100	100	110	110	110	110	115	115	96	96
Pedestrian red-light duration [s]	87	85	78	69	83	92	92	83	90	85	81	81
Pedestrian crossing speed [$m \cdot s^{-1}$]	1.11	0.80	1.18	0.77	1.11	0.78	0.89	0.81	0.83	0.80	0.60	1.07
Pedestrian flow [$ped \cdot h^{-1}$]	162	189	421	771	82	202	94	698	343	134	230	92
Non-motor vehicle traffic volume [$veh \cdot h^{-1}$]	0	2	6	2	0	0	3	36	11	6	3	2
Motor vehicle traffic volume [$veh \cdot h^{-1}$]	811	1806	1397	1183	1465	2624	1139	3897	1056	981	243	1585
Volume of right-turning traffic without signal control [$veh \cdot h^{-1}$]	91	0	258	0	228	255	0	0	89	89	0	0
Average pedestrian delay [$s \cdot ped^{-1} \cdot cycle^{-1}$]	23.2	23.8	26.6	23.4	9.8	47.5	26.9	30.0	37.9	44.7	34.2	29.3

Note: In the three traffic parameters of Curb ramp setting, Buffer facilities and Safety island, 1 means 'yes' or 'have', 0 means 'no' or 'none'.

Sample data. A questionnaire survey on the perception of PLOS was conducted for elderly pedestrians crossing the street. A total of 515 questionnaires were completed at the 12 crosswalks, with 457 valid questionnaires (369 for the modelling group and 88 for the validation group).

Based on *Table 1*, correlation analyses were conducted between the results of the perceived safety, convenience and efficiency ratings and the data of the corresponding variables at each dimension. This was aimed to identify the variables that elderly pedestrians consider important in influencing PLOS at signalised intersections among the possible influencing factors. Based on the sample data of the 12 crosswalks, Spearman's rank correlation test was applied to categorical variables (e.g. whether there were curb ramps at both ends of crosswalks), and the Pearson correlation test was applied to other variables. The correlation results show that the crosswalk length and the volume of right-turning traffic without signal control were strongly correlated with the safety dimension of PLOS. The pedestrian crossing speed and the existence of curb ramps at both ends of the crosswalks were strongly correlated with the convenience dimension of PLOS. The average pedestrian delay was strongly correlated with the efficiency dimension of PLOS. The results are shown in *Table 4*.

Table 4 – Correlation test results

Dimension	Variables	Relative degree	ρ_p	ρ_s
Safety	Pedestrian crossing length	Strong correlation	0.679*	
	Volume of right-turning traffic without signal control	Strong correlation	0.794**	
Convenience	Pedestrian crossing speed	Highly relevant	0.889***	
	Curb ramp setting	Highly relevant		-0.869**
Efficiency	Average pedestrian delay	Highly relevant	0.947***	

*Note: *P<0.05, **P<0.01, ***P<0.001.*

Therefore, the above five variables were considered as important variables for evaluating PLOS perceived by elderly pedestrians at signalised intersections.

3. MODEL METHODOLOGY

3.1 Evaluation model

The perceived PLOS evaluation data of signalised intersections obtained from the questionnaire-based survey were subjective. These data were based on personal judgments of elderly pedestrians via linguistic description. Thus, these data were fuzzy, while the static and dynamic traffic parameters of intersections were quantitative. The fuzzy liner regression (FLR) method based on the likelihood distribution is more suitable for dealing with such subjective qualitative data [28]. Thus, the FLR model was adopted for modelling in this paper.

The evaluation model is expressed as

$$\tilde{y}=\tilde{a}_0+\tilde{a}_1x_1+\tilde{a}_2x_2+\cdots+\tilde{a}_nx_n=\langle a_0,\alpha_0,\beta_0\rangle_{LR}+\langle a_1,\alpha_1,\beta_1\rangle_{LR}x_1+\cdots+\langle a_n,\alpha_n,\beta_n\rangle_{LR}x_n \quad (1)$$

where $\tilde{y}$ is the composite score of pedestrian level of service perceived by elderly pedestrians expressed as LR-type fuzzy numbers in the FLR model; x_n is the n^{th} independent variable, which is the traffic characteristics of signalised intersections verified by significance tests, i.e. crosswalk length (L_c), the volume of right-turning traffic without signal control (Q_r), pedestrian crossing speed (V_p), curb ramp setting (R_c) and the average pedestrian delay (D_p); $\tilde{a}_n$ is the regression coefficient of the n^{th} independent variable expressed as LR-type fuzzy numbers in the FLR model.

If the score is lower, the PLOS is better [12], so the five-point positive scale score data of the sample were backward processing (i.e., a score of 5 indicates "very unsafe"). And according to the questionnaire results of perceived evaluation by elderly pedestrians, the data of ten crosswalks in the modelling group were used to demonstrate the score distribution in each dimension, as shown in *Figure 2*.

To solve such FLR models by referring to the relevant literature [29], let the regression coefficients be $\tilde{a}_n=\langle a_n,\alpha_n,\beta_n\rangle_{LR}$ and the dependent variables $\tilde{y}_n=\langle s_n,p_n,q_n\rangle_{LR}$, where s is the mean value of the perceived sample data of the modelling group; p is the left extension; q is the right extension. The regression coefficients and dependent variable matrices can be expressed as

$$\begin{cases}\boldsymbol{A}=(a_0,a_1,a_2,\dots,a_n)^T\\ \boldsymbol{\alpha}=(\alpha_0,\alpha_1,\alpha_2,\dots,\alpha_n)^T\\ \boldsymbol{\beta}=(\beta_0,\beta_1,\beta_2,\dots,\beta_n)^T\\ \boldsymbol{X}=(1,x_1,x_2,\dots,x_n)^T\\ \boldsymbol{S}=(s_0,s_1,s_2,\dots,s_n)^T\\ \boldsymbol{P}=(p_0,p_1,p_2,\dots,p_n)^T\\ \boldsymbol{Q}=(q_0,q_1,q_2,\dots,q_n)^T\end{cases} \quad (2)$$

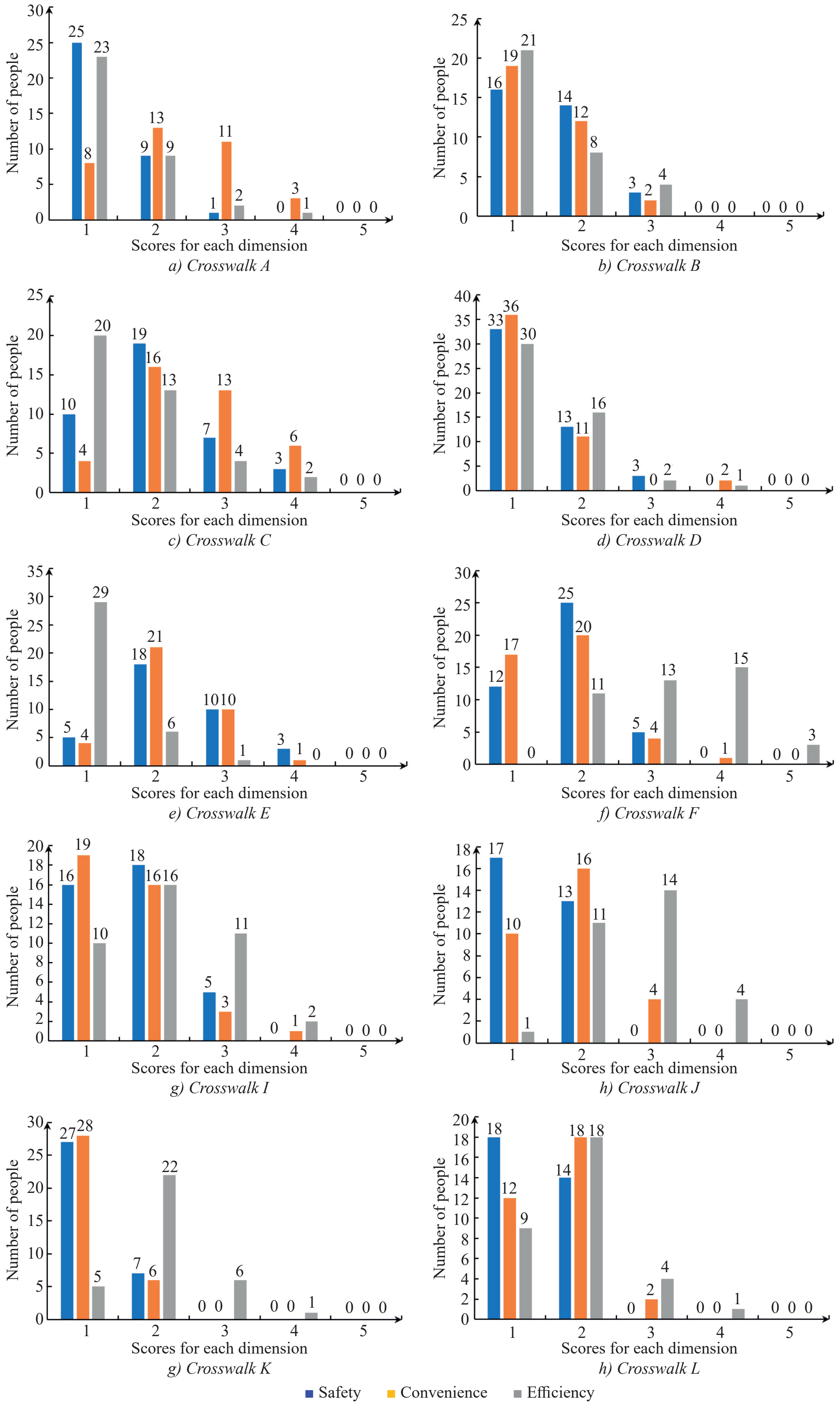

Figure 2 – The distribution of scores for each dimension of the crosswalks

The mean value, the left extension and the right extension for the perceived sample data of elderly pedestrians are written as:

$$s=\frac{1}{N_1}\cdot\sum_{j=1}^{N_1}y_{ij}^{(d)} \tag{3}$$

$$p=s-\frac{1}{N_2}\cdot\sum_{j=1}^{N_2}y_{ij}^{(d)}\left(y_{ij}^{(d)}\le s\right) \tag{4}$$

$$q=\frac{1}{N_3}\cdot\sum_{j=1}^{N_3}y_{ij}^{(d)}-s\left(y_{ij}^{(d)}>s\right) \tag{5}$$

where $y_{ij}^{(d)}$ is the perceived evaluation score of the j^{th} respondent at the i^{th} crosswalk in the d^{th} dimension; N_1 is the total amount of data on the perceived evaluation values at the i^{th} crosswalk; N_2 is the amount of data smaller than s; N_3 is the amount of data larger than s.

The regression coefficients of the FLR model are solved by

$$\begin{bmatrix}\boldsymbol{X}^T\boldsymbol{X}\boldsymbol{A}\\ \boldsymbol{X}^T\boldsymbol{X}\boldsymbol{\alpha}\\ \boldsymbol{X}^T\boldsymbol{X}\boldsymbol{\beta}\end{bmatrix}=\begin{bmatrix}\boldsymbol{X}^T\boldsymbol{S}\\ \boldsymbol{X}^T\boldsymbol{P}\\ \boldsymbol{X}^T\boldsymbol{Q}\end{bmatrix} \tag{6}$$

The LR-type fuzzy number addition algorithm shown in *Equation 7* was used to sum the scores $\tilde{y}_i^{(s)}$, $\tilde{y}_i^{(c)}$ and $\tilde{y}_i^{(e)}$ in the three evaluation dimensions (safety, convenience and efficiency). Thus, a three-dimensional composite score for the perceived evaluation of elderly pedestrians was obtained:

$$\begin{aligned}\tilde{y}_i^{(s)}+\tilde{y}_i^{(c)}+\tilde{y}_i^{(e)}&=\left\langle s_i^{(s)},p_i^{(s)},q_i^{(s)}\right\rangle_{LR}+\left\langle s_i^{(c)},p_i^{(c)},q_i^{(c)}\right\rangle_{LR}+\left\langle s_i^{(e)},p_i^{(e)},q_i^{(e)}\right\rangle_{LR}\\ &=\left\langle s_i^{(s)}+s_i^{(c)}+s_i^{(e)},p_i^{(s)}+p_i^{(c)}+p_i^{(e)},q_i^{(s)}+q_i^{(c)}+q_i^{(e)}\right\rangle_{LR}\end{aligned} \tag{7}$$

Based on *Figure 2*, the FLR model was used to obtain the scores in each dimension and the composite scores from elderly pedestrians. The score results are shown in *Table 5*.

Table 5 – LR typed fuzzy coefficients representation of dependent variable perceptual evaluation score

Crosswalk	Safety score	Conveniency score	Efficiency score	Comprehensive score
A	<1.31,0.31,0.79>	<2.26,0.64,0.20>	<1.46,0.46,0.88>	<5.03,1.41,1.86>
B	<1.55,0.55,0.63>	<1.48,0.48,0.66>	<1.48,0.48,0.85>	<4.52,1.52,2.14>
C	<2.08,0.42,1.22>	<2.54,0.74,0.78>	<1.69,0.69,0.73>	<6.31,1.85,2.73>
D	<1.39,0.39,0.80>	<1.35,0.35,0.96>	<1.47,0.47,0.74>	<4.20,1.20,2.50>
E	<2.31,0.52,0.93>	<2.22,0.38,0.87>	<1.22,0.22,0.92>	<5.75,1.13,2.71>
F	<1.83,0.83,0.33>	<1.74,0.74,0.50>	<3.24,0.70,0.93>	<6.81,2.27,1.76>
I	<1.72,0.72,0.50>	<1.64,0.64,0.61>	<2.13,0.51,1.03>	<5.49,1.87,2.13>
J	<1.43,0.43,0.57>	<1.80,0.80,0.40>	<2.70,0.78,0.52>	<5.93,2.02,1.49>
K	<1.21,0.21,0.79>	<1.18,0.18,0.82>	<2.09,0.27,1.05>	<4.47,0.66,2.67>
L	<1.44,0.44,0.56>	<1.69,0.69,0.41>	<1.91,0.91,0.37>	<5.03,2.03,1.34>

The five significant variables of the ten crosswalks in the modelling groups in *Table 3* and the composite PLOS score data in *Table 5* were extracted to obtain the matrices $\boldsymbol{X}$, $\boldsymbol{S}$ and $\boldsymbol{P}$ of the perceived PLOS evaluation. The parameter estimates of the FLR model were calculated. Then, the composite evaluation model of PLOS at signalised intersections was obtained:

$$\begin{aligned}\tilde{y}&=\left\langle 2.5664,-2.4067,4.9533\right\rangle_{LR}+\left\langle 0.0052,0.0324,-0.0306\right\rangle_{LR}x_1+\left\langle 0.0055,-0.0017,0.0066\right\rangle_{LR}x_2\\ &+\left\langle 1.0823,2.2983,-2.0371\right\rangle_{LR}x_3+\left\langle -0.0382,0.1648,0.4859\right\rangle_{LR}x_4+\left\langle 0.0382,0.0418,-0.0391\right\rangle_{LR}x_5\end{aligned} \tag{8}$$

The evaluation data can be obtained using *Equation 8*. However, the general PLOS evaluation value is one score. Thus, the data can be solved using the centroid method:

$$\hat{y}_i = \frac{1}{3}\left(\tilde{y}_{i(L)} + \tilde{y}_{i(M)} + \tilde{y}_{i(U)}\right) \tag{9}$$

where $\hat{y}_i$ denotes the score of pedestrian level of service for the i^{th} crosswalk; $\tilde{y}_{i(L)}$, $\tilde{y}_{i(M)}$ and $\tilde{y}_{i(U)}$ are the lower, middle and upper value, respectively. Thus, the data of the perceived PLOS evaluation by the elderly pedestrians at the corresponding static and dynamic characteristic parameters of the signalised intersections can be obtained.

3.2 Determination of level threshold

Considering the fuzzy nature of the collected evaluation sample data, the fuzzy C-means (FCM) clustering algorithm was used to perform clustering and classify the PLOS. The FCM algorithm has natural and non-probabilistic characteristics. More sample data were obtained for clustering to make the classification results more accurate. With reference to relevant literature [30–34], different value ranges and linear intervals are determined for each independent variable. The ranges and intervals were assigned to the crosswalk length, the volume of right-turning traffic without signal control, pedestrian crossing speed, whether to set a curb ramp and pedestrian delay. The details are shown in *Table 6*.

Table 6 – The independent variable takes a random value

Variables	Value range	Interval
L_c [m]	[7,42]	7
Q_r [veh·h^{-1}]	[0,800]	50
V_p [m·s^{-1}]	[0.60,1.20]	0.05
R_c	[0,1]	1
D_p [s·ped^{-1}·cycle^{-1}]	[0,90]	5

Using *Equation 9*, a sample dataset $\boldsymbol{Y} = \left\{\hat{y}_1, \hat{y}_2, \cdots, \hat{y}_j\right\}$ of the perceived PLOS evaluation values at signalised intersections was obtained from the elderly perspective. The division criterion of the FCM algorithm is to iteratively calculate the membership matrix $\boldsymbol{U} = \left[u_{ij}\right]_{k\times n}$ of the sample dataset and the cluster centre vector $\boldsymbol{C} = \left[c_1,\ c_2,\ \cdots,\ c_k\right]$ of each PLOS to minimise the objective function $J\left(u_{ij}, c_i\right)$. The FCM algorithm can be expressed as

$$\begin{cases} \min\ J\left(u_{ij}, c_i\right) = \sum_{i=1}^{k}\sum_{j=1}^{n} u_{ij}^{m} \left\| \hat{y}_j - c_i \right\|^2,\ 1 \le m < +\infty \\ \sum_{i=1}^{k} u_{ij} = 1,\ j = 1, 2, \cdots, n \end{cases} \tag{10}$$

where c_i is the cluster centre of the i^{th} level of PLOS; m is the weighted index to control the fuzzy degree of the membership matrix, taken as 2; u_{ij} is the membership degree of the j^{th} sample data to the i^{th} level of PLOS.

The Lagrangian operators were introduced to transform the extreme value problem with membership constraints into the unconstrained condition problem.

The input parameters in the objective function (u_{ij} and c_i) were derived to obtain the necessary conditions for the objective function to reach the minimum value:

$$\begin{cases} u_{ij} = \dfrac{1}{\sum_{i=1}^{k}\left(\left\|\hat{y}_j - c_i\right\| \big/ \left\|\hat{y}_j - c_l\right\|\right)^{\frac{2}{m-1}}} \\ c_i = \sum_{j=1}^{n} u_{ij}^{m} \cdot \hat{y}_j \Big/ \sum_{j=1}^{n} u_{ij}^{m} \end{cases} \tag{11}$$

where c_l is the cluster centre of the l^{th} level of PLOS. When $i = l$, *Equation 11* can be used to solve for c_l.

The iterative computation process of the FCM algorithm includes the following three steps:

Step 1: Parameter initialisation. The following parameters are initialised: the fuzzy weighted index m, the error threshold ε and the number of clusters k of the membership matrix $\boldsymbol{U}$. The error threshold is used as the condition to determine the iteration termination, taken as $1\times e^{-5}$. The PLOS is classified as A~F in this paper; thus, the number of clusters was taken as 6.

Step 2: Using *Equation 11* to calculate the membership matrix $\boldsymbol{U}$ of PLOS evaluation data and the clustering centre vector $\boldsymbol{C}$ of each PLOS.

Step 3: Determining whether the iteration is terminated. The termination conditions of the iteration are expressed as

$$\max_{ij}\left\{\left|u_{ij}^{(k+1)}-u_{ij}^{(k)}\right|\right\}<\varepsilon \tag{12}$$

If *Equation 12* holds, the objective function is minimised, and the iteration is terminated. Then, the membership matrix $\boldsymbol{U}$ and the cluster centre vector $\boldsymbol{C}$ are obtained. If *Equation 12* does not hold, then k=k+1 and return to *Step 2* for iterations.

According to the iterative calculation process of the FCM algorithm, the ten sample datasets of PLOS evaluation values were clustered and solved in turn. The average PLOS classification boundary values in the ten clustering results were taken to obtain the recommended PLOS classification thresholds (*Table 7*).

Table 7 – Proposed threshold values for PLOS classification

PLOS classification	Threshold
A	[3.0,5.2)
B	[5.2,6.4)
C	[6.4,7.6)
D	[7.6,8.8)
E	[8.8,10.1)
F	[10.1,15.0]

3.3 Model error check

The accuracy of the FLR-based PLOS evaluation model was checked using mean absolute error (MAE), root mean square error (RMSE), mean absolute percentage error (MAPE) and goodness of fit (R^2). The model error check results (*Table 8*) show that the error between the questionnaire-based true PLOS and the FLR-based predicted PLOS was insignificant. The model generally exhibited high goodness of fit (R^2=0.9794).

Table 8 – Error test result

Model	MAE	RMSE	MAPE	R^2
FLR model	0.0897	0.0735	0.80%	0.9794

3.4 Clustering performance analysis

The standard FCM clustering algorithm can only guarantee that the solution is locally optimal but not the overall optimal solution. Thus, it is necessary to evaluate the clustering performance of the FCM algorithm. Three evaluation indicators are commonly used, including classification coefficient F, average fuzzy entropy H and standard FCM classification success rate v:

$$F=\frac{1}{n}\sum_{j=1}^{n}\sum_{i=1}^{k}u_{ij}^{2} \tag{13}$$

$$H=-\frac{1}{n}\sum_{j=1}^{n}\sum_{i=1}^{k}u_{ij}\ln u_{ij} \tag{14}$$

$$v=w/10 \tag{15}$$

where u_{ij} denotes the membership degree of the j^{th} sample data to the i^{th} level of PLOS; w denotes the number of times the cluster centres are successfully obtained by running the standard FCM ten times.

The arithmetic mean of each clustering performance evaluation index was obtained using the results of ten runs of the standard FCM algorithm. The results show that the FCM algorithm has good clustering performance, with F=0.75, H=0.51 and v=100%.

4. MODEL VALIDATION

The traffic data of the two crosswalks in the validation group were used to validate the established evaluation model. The actual PLOS scores obtained from the questionnaire and predicted PLOS scores were compared and analysed. The results are shown in *Figure 3*.

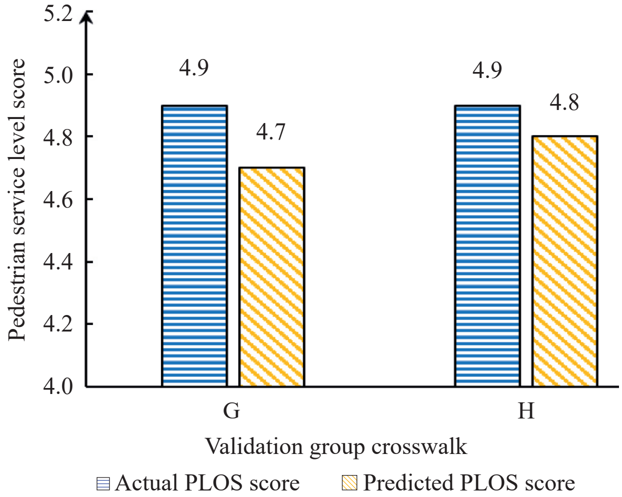

Figure 3 – Model validation results

From *Figure 3*, the actual and predicted PLOS score for Crosswalks G (4.9 and 4.7) and H (4.9 and 4.8) were classified as Level A according to the recommended threshold for classification of pedestrian service level in *Table 7*. The differences between the actual and predicted PLOS scores for Crosswalks G and H were 0.2 and 0.1, indicating smaller errors and good consistency. So, the divided threshold in the paper can be used to classify the group. In addition, the evaluation model for pedestrian level of service at signalised intersections from the elderly perspective can be used to predict the evaluation conditions from the viewpoint of elderly pedestrians according to signalised intersection traffic data.

5. CONCLUSIONS

In this paper, the perceived evaluation of elderly pedestrians was obtained using a questionnaire survey. The static traffic facilities and dynamic traffic parameters of signalised intersections were collected. A PLOS evaluation model was established, with the intersection traffic characteristics parameters as input and the perceived PLOS evaluation of elderly pedestrians at signal intersections as output. The main findings are as follows:

1) Analysis of significant factors affecting the PLOS evaluation of elderly pedestrians. The subjective evaluation of elderly pedestrians with respect to three dimensions (safety, convenience and efficiency) of signalised intersections was correlated with pedestrian crossing characteristics, traffic characteristics, intersection geometric design and pedestrian-signal design at the intersection, respectively. The results show that the perceived PLOS evaluation of elderly pedestrians was mainly related to the crosswalk length, the volume of right-turning traffic without signal control, pedestrian crossing speed, the presence of curb ramps at both ends of the crosswalks and average pedestrian delay at the intersection.
2) Establishment of the PLOS evaluation model based on elderly pedestrians' perceptions. The traffic characteristic parameters significantly affecting the PLOS evaluation by the elderly at signalised intersections were used as inputs. Based on the fuzzy linear regression model, the PLOS evaluation model from the elderly perspective was established. The model parameters were calibrated using the traffic environment data collected from ten crosswalks and the perceived evaluation results of elderly pedestrians.
3) Analysis and validation of model thresholds. The elderly pedestrians' evaluation and objective traffic parameters in the modelling group were collected. Based on the fuzzy C-means clustering algorithm, the thresholds for PLOS classification were recommended. Then, the evaluation and classification of the mod-

el were validated using the data of the two crosswalks in the validation group. The results show insignificant differences between the predicted and actual (perceived) PLOS values at the two crosswalks. The proposed model exhibited good prediction performance.

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REFERENCES

[1] National Bureau of Statistics. *Statistical Communiqué of the PRC on the 2021 National Economic and Social Development*. 2021. http://www.stats.gov.cn/tjsj/zxfb/202202/t20220227_1827960.html. [Accessed 20th Jan. 2021].

[2] Lu SD, Xu ZQ, Wu XF. Analysis of travel characteristics of the elderly in Nanchang. *Proceedings of the 2017 Annual National Planning Conference, 9 Jun. 2017, Shanghai, China*. 2017. p. 2312-2319.

[3] Tournier I, Dommes A, Cavallo V. Review of safety and mobility issues among older pedestrians. *Accident Analysis & Prevention*. 2016;91:24-35. DOI: 10.1016/J.AAP.2016.02.031.

[4] Vieira E, et al. Temporo-spatial gait parameters during street crossing conditions: A comparison between younger and older adults. *Gait & Posture*. 2015;41(2):510-515. DOI: 10.1016/j.gaitpost.2014.12.001.

[5] Avineri E, Shinar D, Susilo Y. Pedestrians' behaviour in crosswalks: the effects of fear of falling and age. *Accident Analysis & Prevention*. 2012;44(1):30-34. DOI: 10.1016/j.aap.2010.11.028.

[6] Zito GA. Cazzoli D, Scheffler L. Street crossing behavior in younger and older pedestrians: An eye- and head-tracking study. *BMC Geriatrics*. 2015;15(1):1-10. DOI: 10.1186/s12877-015-0175-0.

[7] Dommes A, et al. Crossing a two-way street: comparison of young and old pedestrians. *Journal of Safety Research*. 2014;50:27-34. DOI: 10.1016/j.jsr.2014.03.008.

[8] Feng ZX, Ji NY, Luo Y, Zhao C. Questionnaire survey-based evaluation of public traffic safety awareness. *China Journal of Highway and Transport*. 2020;33(06):212-223. DOI: 10.19721/j.cnki.1001-7372.2020.06.020.

[9] Loo BPY, Tsui KL. Contributory factors to critically wrong road-crossing judgements among older people: An integrated research study. *Hong Kong Journal of Emergency Medicine*. 2016;23(1):13-24. DOI: 10.1177/102490791602300102.

[10] Dommes A, Cavallo V. The role of perceptual, cognitive, and motor abilities in street-crossing decisions of young and older pedestrians. *Ophthalmic and Physiological Optics.* 2011;31(3):292-301. DOI: 10.1111/j.1475-1313.2011.00835.x.

[11] Knoblauch RL, Pietrucha MT, Nitzburg M. Field studies of pedestrian walking speed and start-up time. *Transportation Research Record*. 1996;1538(1):27-38. DOI: 10.3141/1538-04.

[12] Transportation Research Board. *Highway capacity manual 2010.* Washington: Transportation Research Board, National Research Council; 2010.

[13] Banerjee A, et al. A review of pedestrian flow characteristics and level of service over different pedestrian facilities. *Collective Dynamics*. 2018;3(A17):1-52. DOI: 10.17815/CD.2018.17.

[14] Lee JY, Goh PK, Lam WH. New level-of-service standard for signalized crosswalks with bi-directional pedestrian flows. *Journal of Transportation Engineering*. 2005;131(12):957-960. DOI: 10.1061/(ASCE)0733-947X(2005)131:12(957).

[15] Bansal A, Gayal T, Sharma U. Level of service of pedestrian facilities in an urban area (a critical evaluation of factors). *Journal of Engineering Technology*. 2018;7:416-434. https://www.researchgate.net/publication/333668531. [Accessed 20th Jan. 2021].

[16] Petritsch TA, et al. Level-of-service model for pedestrians at signalized intersections. *Transportation Research Record*. 2005;1939(1):54-62. DOI: 10.1177/0361198105193900107.

[17] Hubbard SM, Bullock DM, Mannering FL. Right turns on green and pedestrian level of service: Statistical assessment. *Journal of Transportation Engineering*. 2009;135(4):153-159. DOI: 10.1061/(ASCE)0733-947X(2009)135:4(153).

[18] Bian Y, et al. Pedestrians' level of service at signalized intersections in China. *Transportation Research Record*. 2009;2114(1):83-89. DOI: 10.3141/2114-10.

[19] Nagraj R, Vedaipi P. Modeling pedestrian delay and level of service at signalized intersection crosswalks under mixed traffic conditions. *Transportation Research Record*. 2013;2394(1):70-76. DOI: 10.3141/2394-09.

[20] Zhang L, Prevedouros P. Signalized intersection level of service incorporating safety risk. *Transportation Research Record*. 2003;1852(1):77-86. DOI: 10.3141/1852-11.

[21] Steinman N, Hines DK. A methodology to assess design features for pedestrian and bicyclist crossings at

signalized intersections. *Transportation Research Record*. 2004;1878(1):42-50. DOI: 10.3141/1878-06.

[22] Ling Z, et al. Evaluating pedestrian level of service at signalized intersections in China: Intercept survey method. *Transportation Research Record*. 2015;2519(1):75-84. DOI: 10.3141/2519-09.

[23] Marisamynathan S, Vedagiri R. Modeling pedestrian level of service at signalized intersection under mixed traffic conditions. *Transportation Research Record*. 2017;2634(1):86-94. DOI: 10.3141/2634-13.

[24] Jensen S, Ren U. Pedestrian and bicycle level of service at intersections, roundabouts, and other crossings. *92nd Annual Meeting of the Transportation Research Board, 13-17 Jan. 2013, Washington DC, USA.* 2013. p. 43-51. https://trid.trb.org/view/1240737. [Accessed 20th Jan. 2021].

[25] Ahmed T, et al. A new pedestrian crossing level of service (PCLOS) method for promoting safe pedestrian crossing in urban areas. *International Journal of Environmental Research and Public Health*. 2021;18(16):1-20. DOI: 10.3390/IJERPH18168813.

[26] Transportation Research Board. *Highway capacity manual 2016.* Washington: Transportation Research Board, National Research Council; 2016.

[27] Nowar R, Burke MI. What are the most important factors for pedestrian level-of-service estimation? A systematic review of the literature. *Transportation Research Record.* 2018;2672(35):101-117. DOI: 10.1177/0361198118790623.

[28] Chen Y, Wei LL. Parameter estimation of the fuzzy logistic regressive model with LR typed fuzzy coefficients. *Operations Research and Fuzziology*. 2016;6(1):27-35. DOI: 10.12677/ORF.2016.61004.

[29] Wang HD, Guo SC, Yue LZ. An approach to fuzzy multiple linear regression model based on the structured element theory. *System Engineering Theory and Practice*. 2014;34(10):2628-2636. DOI: 10.12011/1000-6788(2014)10-2628.

[30] Chen F. *Research on pedestrian-vehicle conflict discrimination and resolution at crosswalk for autonomous vehicles*. M.Eng. thesis. Wuhan University of Technology; 2019.

[31] Hubbard SM, Bullock DM, Mannering FL. Right turns on green and pedestrian level of service: Statistical assessment. *Journal of Transportation Engineering*. 2009;135(4):153-159. DOI: 10.1061/(ASCE)0733-947X(2009)135:4(153).

[32] Zhao J, Zheng Z, Hang Y. Delay and optimal cycle length model for tandem intersections. *China Journal of Highway and Transport*. 2019;(03):135-144. DOI: 10.19721/j.cnki.1001-7372.2019.03.015.

[33] He YQ. *Study on pedestrian traffic organization methods of signalized intersection on urban arterial.* Harbin: Harbin Institute of Technology; 2006.

[34] Liu GX, Li KP, Sun J. Research on pedestrians waiting time at signal control intersection. *China Safety Science Journal*. 2009;19(09):159-166+179. DOI: 10.16265/j.cnki.issn1003-3033.2009.09.026.

张惠玲，张德凯，王瑞浩

老年视角的信号交叉口行人服务水平评价研究

摘要
老年人对信号交叉口行人服务水平评价将直接影响老年人的过街决策及行为。为了分析交叉口的交通环境与老年人对信号交叉口的过街评价之间的关系，建立了交通客观因素和老年人的主观感受之间的关系模型。首先，利用同时段人工现场记录及截断式问卷调查的方法，得到了同步情况下交叉口的客观交通参数和过街老年人的主观认知评价数据；从安全、便利和效率三个方面对老年人认知主观评价情况和对应的交通特征参数进行了相关性分析，识别出了影响老年人主观评价行人过街服务水平的重要变量；应用模糊线性回归模型，从老年视角建立了现场交通特征参数对应下的信号交叉口行人服务水平评价型，并通过模糊C均值聚类算法得到了不同服务水平等级划分的建议阈值；应用2条人行横道的数据对模型的应用情况进行了验证，结果表明：行人服务水平得分实际值和模型预测值差值分别为0.2和0.1，表明预测模型能够根据信号交叉口现场的交通数据较为准确地预测出老年人对信号交叉口行人服务水平的评价值。

关键词
城市交通；行人服务水平；模糊线性回归；信号交叉口；老年人