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HETEROGENEOUS PEDESTRIAN TRAFFIC FLOW MODELLING AT SIGNALISED INTERSECTIONS

ABSTRACT

Different types of pedestrians exhibit different speed characteristics and heterogeneity. In the case of mixed pedestrian flow at signalised intersections, pedestrian traffic flow modelling is important in research of the conditions at signalised intersections and the evaluation of services for pedestrians. The characteristics of pedestrian traffic flow at signalised intersections were investigated in this study against the background of pedestrian heterogeneity using videos of pedestrians crossing three signalised intersections in Chongqing recorded in a field survey. The pedestrian walking speeds were manually extracted from the videos and used as the data basis for distinguishing pedestrian heterogeneity. The walking speed data of three types (young, middle-aged, and elderly) of pedestrians at different pedestrian flows were obtained by using a microsimulation software. Based on this, a pedestrian traffic flow model for mixed-type pedestrians at signalised intersections was established and verified by actual cases. In comparison with the HCM model, the model outperforms the HCM model overall in practical applications, indicating its strong applicability and reliability.

KEYWORDS

pedestrian; pedestrian traffic flow models; pedestrian heterogeneity; signalised intersections; pedestrian flow.

1. INTRODUCTION

Pedestrians are vulnerable at signalised intersections. The inadequate consideration of the behaviour characteristics of pedestrians, especially slow pedestrians such as elderly pedestrians, frequently leads to accidents [1]. Therefore, in-depth research on pedestrian crossing behaviour at signalised intersections in different age groups and investigation of the pedestrian traffic flow model for mixed-age pedestrians at signalised intersections is conducive to improving pedestrian crossing facilities at signalised intersections and improving the level of service for pedestrians [2].

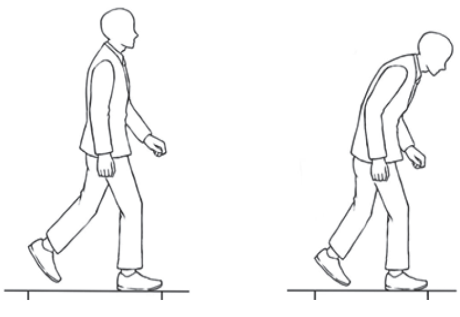
In most existing pedestrian traffic flow studies, research scenarios were limited to sidewalks, and the pedestrian traffic flow models were constructed using the pedestrian speed, flow, and density collected in the field surveys. The Highway Capacity Manual 2010 (HCM2010) of the U.S. [2], Tanaboriboon et al. in Singapore [3], and Polus et al. [4] in Israel analysed the walking speed data of pedestrians on sidewalks, established the relationship between pedestrian flow and walking speed, which were all parabolic, and found that the pedestrian walking speed and density were linearly correlated. However, the parameters of these models differed greatly due to the different geographical locations. In the studies of pedestrian flows at signalised intersections, no consensus has been reached regarding the relationships among pedestrian speed, flow, and density. Lam et al. used the Bell model, which they believed could fit the collected real-life data well, to obtain a pedestrian traffic flow model and comparatively analysed pedestrian flow characteristics in different countries [5]. Das et al. found that the relationship between pedestrian speed and density at signalised intersections followed Greenberg's logarithmic model rather than the linear relationship found for sidewalks [6]. However, previous literature mostly regarded pedestrians as homogenous without individual characteristics and did not consider pedestrian heterogeneity. Sharifi et al. analysed the heterogeneity exhibited by disabled pedestrians in pedestrian flow and established a density-speed model for two-way pedestrian flows at walking facilities with different angle intersections to explore the characteristics of heterogeneous pedestrian flow [7]. In addition, Wu et al. found that the traffic capacities of stairs and escalators in metro stations were not fixed and varied with the heterogeneous compositions of pedestrians [8]. Other studies have found that under the same pedestrian density, the walking speed of elderly pedestrians is always slower than that of young pedestrians, and the proportion of elderly pedestrians also affects the overall pedestrian walking speed [9]. Gates et al. found that an increase in the proportion of elderly people leads to a decline in pedestrian walking speed [10]. Zhang analysed the relationship between the proportion of elderly pedestrians and the pedestrian walking speed through simulation, and found that the higher the proportion of elderly pedestrians, the greater their impact on pedestrian walking speed [11].

In summary, the existing pedestrian traffic models at signalised intersections did not consider the impact of pedestrian heterogeneity on pedestrian traffic flow and thus need to be improved. Therefore, a pedestrian traffic flow model for mixed-type pedestrians at signalised intersections was established in this study and validated through actual cases to improve the existing pedestrian traffic models.

2. ANALYSIS OF PEDESTRIAN HETEROGENEITY

2.1 Pedestrian characteristics

In real-life pedestrian traffic situations, the pedestrian flow is heterogeneous, namely, completely distinguishable individual pedestrians are present with different traffic characteristics and traffic decision-making abilities due to their different individual attributes or traffic behaviour preferences [8]. Due to the influence of various factors, pedestrians at signalised intersections exhibit different walking characteristics, such as stride length and frequency, as shown in *Figure 1*.



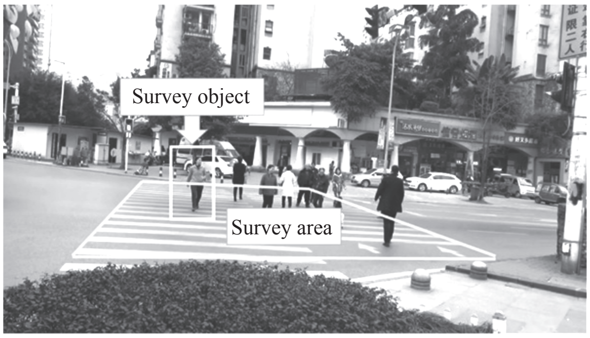
a) Adult *b) Elderly*

Figure 1 – Pedestrian stride length for different age groups

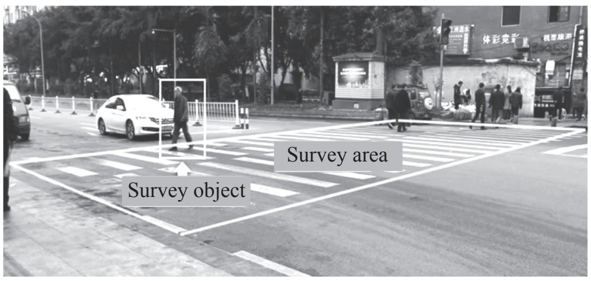
The differences in pedestrian walking characteristics are ultimately reflected in the differences in pedestrian walking speed [12]. Therefore, when pedestrians of all ages are treated as identical individuals, i.e., homogenous pedestrians, the differences in the speed of pedestrians at different ages are ignored in the pedestrian traffic flow models, resulting in deviations between simulated data and measured data.

2.2 Data acquisition and analysis

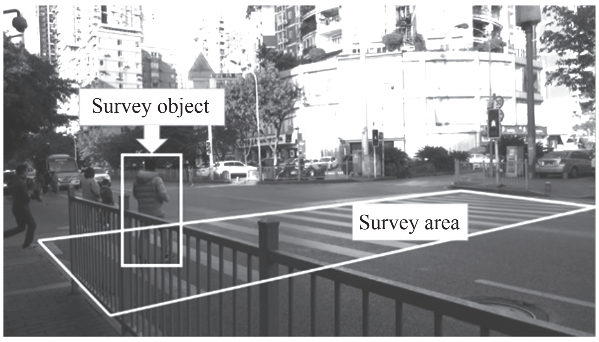
Through field surveys, video recordings, and manual extraction, walking speed data of pedestrians walking freely through crosswalks without interference from surrounding people and objects are obtained, as shown in *Figure 2*. *Table 1* lists the details of each survey site. The survey was conducted from 22 to 24 July 2019, and from 20 to 22 November



a) Nanhu Road - Qinglong Road



b) Xuefu Road - Qinglong Road



c) Jinzhi Street – Nanhu Road

Figure 2 – Extraction object schematic

Table 1 – Details of survey site

Crosswalk feature \ Position		Nanhu Road – Qinglong Road	Xuefu Road – Qinglong Road	Jinzhi Street – Nanhu Road
Countdown		Y	Y	Y
Pedestrian refuge island		N	N	N
Crosswalk signal cycle [s]		95	100	96
Pedestrian green light duration [s]		15	17	12
Pedestrian green flash time [s]		5	5	5
Crosswalk length [m]		20	18	15
Crosswalk width [m]		6	6	6
One-way pedestrian traffic [p/h]	Young	213	327	86
	Middle-aged	134	935	104
	Elderly	129	246	243
Vehicle speed limit [km/h]		40	60	40

2019, during the weekday daytime peak hours of 7 a.m. to 8 a.m. and 5 p.m. to 6 p.m., and during the non-peak hours of 10 a.m. to 11 a.m. and 3 p.m. to 4 p.m., to allow for sufficient sample size for subsequent manual extraction.

Pedestrians were preliminarily divided into three types in this study: young, middle-aged, and elderly pedestrians. By referring to previous literature [13], young pedestrians are pedestrians between 18 and 30 years of age, middle-aged pedestrians are pedestrians between 30 and 60 years of age, and elderly pedestrians are pedestrians over 60 years of age. Minors are excluded from this study since most minors travel together, spend most of their time in schools, and spend much less time on crosswalks than adults. The ages of the pedestrians in the videos are estimated by the experimenter. In order to increase the estimation precision of young, middle-aged, and elderly pedestrians, the observer was asked to estimate the age of young, middle-aged, and elderly pedestrian in the video, which was then verified by asking the pedestrian's age, and then the observer gained the experience to extract the data. Pedestrians whose type cannot be clearly distinguished were not counted. The pedestrian walking speed can be calculated by *Equation 1*. The length of the crosswalks at the above three signalised intersections was measured on site, and the time taken by the survey respondents to enter and leave the signalised intersections was extracted by watching the video at a later stage to calculate the time taken by the survey subjects to cross the crosswalks. The walking speed of each survey subject through the crosswalk was obtained in this way.

$$V = \frac{L}{T} \tag{1}$$

where V is the walking speed (m/s) of the pedestrian in the crosswalk, L is the length (m) of the crosswalk, T is the time (s) required for pedestrians to pass the crosswalk.

The pedestrian walking speed data were statistically analysed to obtain the mean speed, standard deviation, extreme value, 15th and 85th percentile walking speed, as shown in *Table 2*. The cumulative frequency distribution curves for the walking speeds of different types of pedestrians crossing the crosswalks was obtained through statistical analysis, as shown in *Figure 3*.

A one-way analysis of variance (ANOVA) was applied to find no significant difference in the walking speed of the three types of pedestrians at the investigated signalised intersections (p (young pedestrian)=0.972>0.05, p (middle-aged pedestrians)= 0.802>0.05, p (elderly pedestrians)=0.523>0.05). *Table 2* shows that the average walking speed is 1.24 m/s for young pedestrians, 1.18 m/s for middle-aged pedestrians, and 1.08 m/s for elderly pedestrians. The results of one-way ANOVA show significant differences between the walking speeds of young, middle-aged, and elderly pedestrians (p=0.000<0.05), indicating heterogeneity among these three types of pedestrians.

Table 2 – Statistics of pedestrian walking speeds

Position	Pedestrian type	Number of records	Mean speed [m/s]	SD	Minimum [m/s]	Maximum [m/s]	15th percentile walking speed [m/s]	85th percentile walking speed [m/s]
Nanhu Road – Qinglong Road	Young	396	1.24	0.24	0.86	2.66	1.05	1.35
	Middle-aged	165	1.18	0.19	0.78	2.65	1.00	1.38
	Elderly	132	1.07	0.11	0.77	1.42	0.96	1.19
Xuefu Road – Qinglong Road	Young	232	1.24	0.18	0.80	2.56	1.08	1.40
	Middle-aged	479	1.18	0.18	0.84	2.54	1.03	1.33
	Elderly	248	1.07	0.10	0.80	1.42	0.97	1.17
Jinzhi Street – Nanhu Road	Young	103	1.24	0.18	0.94	2.45	1.03	1.35
	Middle-aged	100	1.19	0.21	0.78	2.62	0.98	1.37
	Elderly	212	1.08	0.11	0.80	1.50	0.97	1.20
Young		731	1.24	0.20	0.80	2.66	1.04	1.39
Middle-aged		744	1.18	0.19	0.78	2.65	1.00	1.35
Elderly		592	1.08	0.11	0.77	1.50	0.96	1.18

3. TRAFFIC FLOW MODEL FOR SIGNALISED INTERSECTIONS

3.1 Traffic flow characteristics of different types of pedestrians

The VISSIM simulation model is used in this study to construct the scenarios to analyse pedestrian walking speed characteristics under different pedestrian flows since it is difficult to control pedestrian type and flow in the real world. Therefore, a crosswalk with a length of 20 m and width of 6 m was established on the VISSIM simulation platform. The cycle of the pedestrian traffic signal was set as 60 s, with the duration of green signal at 20 s and the duration of the flashing green at 5 s. For each pedestrian type, the cumulative frequency distribution curves for the walking speeds in *Figure 3* are input into the model to correct the pedestrian traffic behaviour data. Pedestrian crossing scenarios with the same pedestrian type but different flows are constructed using the corrected simulation platform. Three random numbers are set up for simulation under the same pedestrian flow to increase the universality of simulation (the initial value of the random speed is 100 and increments by 1000 each time). Through the simulation platform, the relationships between the walking speed and flow for different types of pedestrians were obtained, as shown in *Figure 4*.

Due to the controversy surrounding the construction of the pedestrian traffic flow model at signalised intersections in previous studies, this paper obtains the fitting equations for the relationship between pedestrian speed of each pedestrian type and pedestrian flow referring to the pedestrian flow-speed relationship in HCM2010 [2].

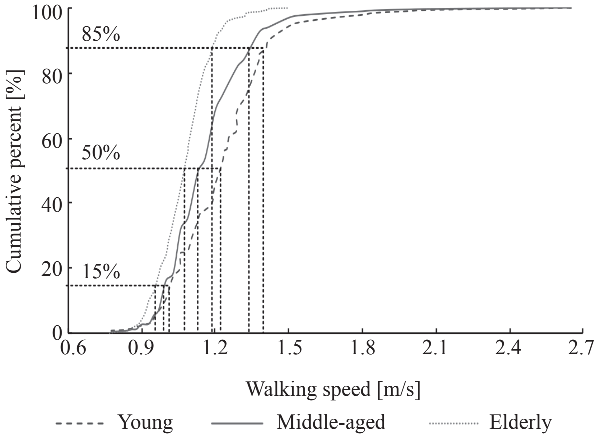


Figure 3 – Cumulative frequency distribution curves of walking speed

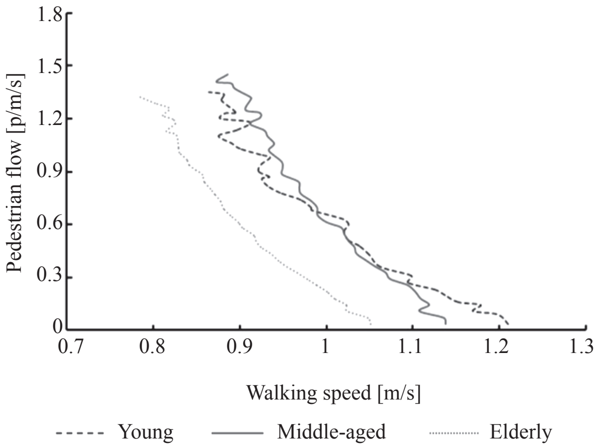


Figure 4 – Simulation data for different types of pedestrians

Young pedestrians:

$$q'_1 = 4.976u'_1 - 4.223u'^2_1 \tag{2}$$

Middle-aged pedestrians:

$$q'_2 = 6.838u'_2 - 6.093u'^2_2 \tag{3}$$

Elderly pedestrians:

$$q'_3 = 6.306u'_3 - 6.118u'^2_3 \tag{4}$$

where q'_1, q'_2, and q'_3 are the pedestrian flows (p/m/s) of young, middle-aged, and elderly pedestrians, respectively, and u'_1, u'_2, u'_3 are the average walking speeds (m/s) of young, middle-aged, and elderly pedestrians, respectively.

The coefficients of determination (R^2) of curve fitting are 0.91 for young pedestrians, 0.95 for middle-aged pedestrians, and 0.935 for elderly pedestrians. The chi-square coefficients are 0.01 of all three types of pedestrians. This indicates that the three fitting equations can realistically reflect the relationship between the average pedestrian walking speed and pedestrian flow for all three types of pedestrians, as shown in *Figure 5*.

Figure 5 shows that (1) the curves for different types of pedestrians have completely different parabolic shapes but that they are all similar to the pedestrian flow-speed relationship curve in HCM2010. (2) When the pedestrian flow is saturated, the walking speed and flow of young pedestrians are 0.59 m/s and 1.466 p/m/s, respectively, those of middle-aged pedestrians are 0.56 m/s and 1.919 p/m/s, respectively, and those of elderly pedestrians are 0.52 m/s and 1.625 p/m/s, respectively. This indicates that the walking speed is not linearly correlated with the saturated flow, as it is also related to pedestrian type. The saturated flow of young pedestrians is lowest among the three types of pedestrians because young pedestrians exhibit the fastest walking speeds and need the largest dynamic space. (3) Under the same flow of undersaturation, the walking speeds of elderly pedestrians are always lower than those of middle-aged and young pedestrians. But when the flow is oversaturated, young pedestrians have the lowest walking speed at the same flow.

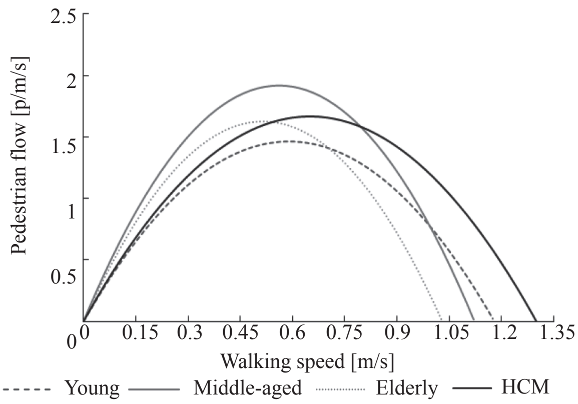


Figure 5 – Fitted result

3.2 Construction of the heterogeneity-based traffic flow model

Hypothesis: (1) There is a scenario of types of pedestrians crossing a signalised intersection with a known proportion of each pedestrian type, as shown in *Equation 5*; (2) based on the above analysis, we find that although the pedestrian flow-speed relationship curves for different types of pedestrians have different parameters, they are still parabolic. Therefore, if the pedestrian types and proportion of each pedestrian type are determined, the pedestrian flow-speed relationship should follow the parabolic shape in HCM2010 [2], as shown in *Figure 6*.

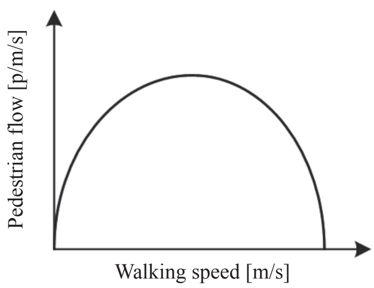


Figure 6 – Pedestrian flow-speed relationship

To determine a parabola, we need to know the coordinates of at least 3 points on it. It is known that this parabola must go through the origin, so this paper focuses on finding the other x-intercept (a zero-flow point other than the origin) and the inflection point (saturation point) of the parabola.

$$Q = [(q_1,k_1),(q_2,k_2),\ldots,(q_i,k_i)] \tag{5}$$

where Q is the pedestrian flow parameter set, q_i is the flow of type-i pedestrians, and k_i is the proportion of type-i pedestrians.

Zero-flow point

Theoretically, the zero-flow point other than the origin does not exist, and the curve is only approaching this point. Therefore, we set the pedestrian flow q approaching 0. The sum of the walking speeds of the type-i pedestrians is as follows.

$$u_i = u_{i1} + u_{i2} + \ldots + u_{in} = \sum_{n=1}^{q_i} u_{in} = q\bar{u} \tag{6}$$

where u_i is the sum of the walking speeds of type-i pedestrians, u_{in} is the walking speed of the nth pedestrian of the type-i pedestrians, $\bar{u}_i$ is the average walking speed of the type-i pedestrians, q is flow of all type pedestrians, and q_i is the flow of the type-i pedestrians.

Then, if i types of pedestrians simultaneously cross the intersection, the average pedestrian walking speed is as follows.

$$\bar{u} = \frac{\sum_{n=1}^{q1} u_{1n} + \sum_{n=1}^{q2} u_{2n} + \cdots + \sum_{n=1}^{qi} u_{in}}{q_1 + q_2 + \cdots q_i} \tag{7}$$

Using the average speed of each pedestrian type $\bar{u}_i$, *Equation 7* is rewritten as follows.

$$\begin{aligned}\bar{u} &= \frac{q_1\bar{u}_1 + q_2\bar{u}_2 + \cdots + q_i\bar{u}_i}{q_1 + q_2 + \cdots + q_i} \\ &= \frac{q_1}{q_1 + q_2 + \cdots + q_i}\bar{u}_1 + \cdots + \frac{q_i}{q_1 + q_2 + \cdots + q_i}\bar{u}_i\end{aligned} \tag{8}$$

Using the proportion of each pedestrian type, *Equation 8* is further simplified as follows.

$$\bar{u} = k_1\bar{u}_1 + k_2\bar{u}_2 + \cdots + k_i\bar{u}_i \tag{9}$$

where $\bar{u}_i$ is the average walking speed of the type-i pedestrians, and k_i is the proportion of type-i pedestrians.

The average pedestrian walking speed can be calculated using *Equation 8* if the proportion of pedestrians of each type and the average walking speed of pedestrians of each type under this pedestrian flow are known. The flow of each pedestrian type q_i is approaching 0; therefore, pedestrians are not affected by each other; i.e., the average walking speed of the type-i pedestrians in the scenario where the flow of type-i pedestrians alone (q_i) is approaching 0 is approximately equal to the average walking speed of the type-i pedestrians in the scenario where the flow of mixed-type pedestrians (q_i) is approaching 0. The average walking speed of each pedestrian type ($\bar{u}_i$) in the scenario where the flow is approaching zero can be easily obtained by using data collected beforehand and simulation, as shown in *Figure 5*.

Saturation point

The x-coordinate of the saturation point is the saturated flow of mixed-type pedestrians (q_c), and its y-coordinate is the corresponding pedestrian walking speed (u_{q_c}). According to the characteristics of a parabola, the saturation point is located on the axis of symmetry of this parabola:

$$u_{q_c} = \frac{u_{q\to 0}}{2} \tag{10}$$

where u_{q_c} is the overall pedestrian speed of mixed-type pedestrians in the saturated state, and $u_{q\to 0}$ is the overall pedestrian speed when the flow of mixed-type pedestrians is approaching 0.

The theoretical model proposed by Huber [13] is used in this study to determine q_c. The theoretical model method is used to study the relationship between the traffic flow in the scenario of single-type pedestrians (single-flow scenario) and the traffic flow in the scenario of mixed-type pedestrians with a proportion of p (mixed-flow scenario). According to the corresponding relationship between the level of service (LOS) and flow, the flows under the single-flow and mixed-flow scenarios are q_b and q_m at a given LOS, respectively, as shown in *Figure 7*.

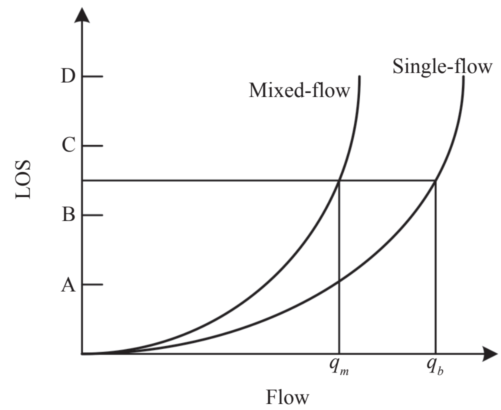


Figure 7 – Relationship between flow and LOS

Huber believed that under the same LOS, the traffic flow in a single-flow scenario should be equivalent to the traffic flow in a mixed-flow scenario, i.e.,

$$q_b = q_m \cdot p \cdot \theta + q_m \cdot (1 - p) \tag{11}$$

where q_b is the traffic flow in a single-flow scenario corresponding to a certain LOS, q_m is the traffic flow in a mixed-flow scenario corresponding to a certain LOS, p is the proportion of a certain type of pedestrian, and θ is the coefficient of equivalence. *Equations 12 and 13* can be derived from *Equation 10*.

$$\theta = \frac{\left(\frac{q_b}{q_m} - 1\right)}{p} + 1 \tag{12}$$

$$q_m = \frac{q_b}{p \cdot (\theta - 1) + 1} \tag{13}$$

The pedestrian saturation condition is used as the equivalent LOS to calculate q_c. The steps are as follows:

Step 1: Calculate the coefficient of equivalence in the scenario of type-1 pedestrians crossing the intersection with type-*i* pedestrians. Type-1 pedestrians are mixed with type-2 pedestrians, type-3 pedestrians,..., type-*i* pedestrians. Let p=1; i.e., the proportion of type-1 pedestrians is 100%. The following formula can be derived from *Equation 12*.

$$\theta_{1i} = \frac{q_{ci}}{q_{c1}} \quad (14)$$

where θ_{1i} is the coefficient of equivalence in the scenario of type-1 pedestrians crossing the intersection with type-*i* pedestrians, q_{ci} is the saturated flow of type-*i* pedestrians, and q_{c1} is the saturated flow of the type-1 pedestrians.

Step 2: Calculate the saturated flow in the scenario of type-1 pedestrians crossing the intersection with type-*i* pedestrians, with the proportion of the type-1 pedestrians being k_1:

$$q_{c1i} = \frac{q_{ci}}{k_1(\theta_{1i} - 1) + 1} \quad (15)$$

where q_{c1i} is the saturated flow in the scenario of type-1 pedestrians crossing the intersection with type-*i* pedestrians, θ_{1i} is the coefficient of equivalence in the scenario of type-1 pedestrians crossing the intersection with type-*i* pedestrians, and q_{ci} is the saturated flow of type-*i* pedestrians.

Step 3: Calculate the coefficient of equivalence in the scenario of type-2 pedestrians crossing the intersection with type-1 and type-*i* pedestrians. Type-2 pedestrians are mixed with type-1 pedestrians and type-*i* pedestrians (the proportion of type-1 pedestrians is k_1, i>2). Let p=1-k_1; i.e., the sum of the proportions of type-1 and type-2 pedestrian is 100%. The following formula can be derived from *Equation 12*:

$$\theta_{2i} = \frac{\frac{q_{c1i}}{q_{c12}} - 1}{1 - k_1} + 1 \quad (16)$$

where θ_{2i} is the coefficient of equivalence in the scenario of type-2 pedestrians crossing the intersection with type-1 and type-*i* pedestrians, and q_{c12} is the saturated flow in the scenario of type-1 pedestrians crossing the intersection with type-2 pedestrians.

Step 4: Calculate the saturated flow in the scenario of type-2 pedestrians crossing the intersection with type-1 and type-*i* pedestrians, with the proportions of type-1 and type-2 pedestrian being k_1 and k_2, respectively. The following formula can be derived from *Equation 13*.

$$q_{c2i} = \frac{q_{c1i}}{k_2 \cdot (\theta_{2i} - 1) + 1} \quad (17)$$

where q_{c2i} is the saturated flow in the scenario of type-2 pedestrians crossing the intersection with type-1 and type-*i* pedestrians, θ_{2i} is the coefficient of equivalence in the scenario of type-2 pedestrians crossing the intersection with type-1 and type-*i* pedestrians, and q_{ci} is the saturated flow of type-*i* pedestrians.

The coefficients of equivalence and q_c of all scenarios of mixed-type pedestrians can be obtained by progressive computing. The relevant flowchart is shown in *Figure 8*.

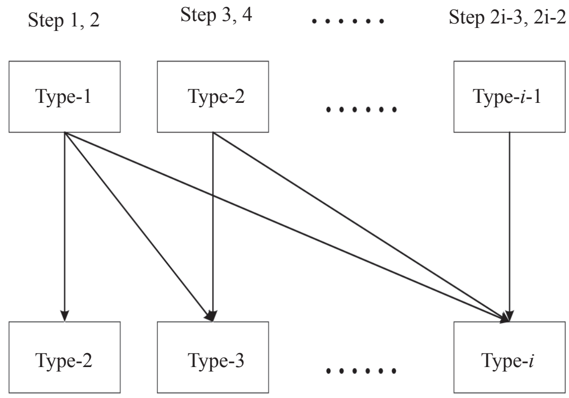


Figure 8 – Calculation flowchart

The parabolic relationship between pedestrian walking speed and pedestrian flow in the scenario of mixed-type pedestrians crossing the signalised intersection is determined based on three feature points on the parabola, namely, the origin (0, 0), zero-flow point ($u_{q\to 0}$, 0), and saturation point (u_{q_c}, q_c):

$$q = \frac{2q_c}{u_{q_c}}u - \frac{q_c}{u_{q_c}^2}u^2 \quad (18)$$

where q is the pedestrian flow in the scenario of mixed-type pedestrians crossing the signalised intersection, and u is the pedestrian speed in the same scenario.

The relationship between three macroscopic parameters, namely, pedestrian flow q, density r, and speed u [2], can be expressed by *Equation 19*.

$$q = r \cdot u \quad (19)$$

Then, the derived density-speed relationship is as follows:

$$r = \frac{2q_c}{u_{q_c}} - \frac{q_c}{u_{q_c}^2}u \quad (20)$$

where r is the pedestrian density in the scenario of mixed-type pedestrians crossing the signalised intersection, and u is the pedestrian speed in the same scenario.

4. VERIFICATION OF A TRAFFIC FLOW MODEL

4.1 Derivation of the application model

In this paper, the simulation data obtained in section 3.1 are used to construct a traffic flow model for three types (young, middle-aged, and elderly) of pedestrians crossing a signalised intersection. We let the proportions of young, middle-aged, and elderly pedestrians in the mixed-type pedestrians be k_1', k_2' and k_3', respectively.

Step 1: Calculate the zero-flow point. *Figure 5* shows that young, middle-aged, and elderly pedestrians exhibit walking speeds of 1.178 m/s, 1.122 m/s, and 1.031 m/s, respectively, when the flow is approaching 0. *Equation 21* can be obtained by substituting these working speeds into *Equation 9*:

$$u_{q\to 0} = 1.178k_1' + 1.122k_2' + 1.031k_3' \tag{21}$$

where k_1' is the proportion of young pedestrians, k_2' is the proportion of middle-aged pedestrians, and k_3' is the proportion of elderly pedestrians.

Step 2: Calculate the saturation point. Based on *Equation 10*, the pedestrian speed in the saturated state u_{q_c} can be expressed as follows:

$$u_{q_c} = \frac{u_{q\to 0}}{2} = 0.589k_1' + 0.561k_2' + 0.515k_3' \tag{22}$$

According to the steps for calculation of q_c, the young pedestrians are first mixed with the middle-aged pedestrians (*Figure 9a*) and elderly pedestrians (*Figure 10a*). Let p=1; i.e., the proportion of young pedestrians is 100%, meaning that the pedestrians in these two scenarios are all young pedestrians, as shown in *Figure 9b and Figure 10b*.

Figure 4 shows that the saturation flow is 1.446 p/m/s for young pedestrians, 1.919 p/m/s for middle-aged pedestrians, and 1.625 p/m/s for elderly pedestrians. The coefficient of equivalence for the scenario of mixed young, and middle-aged pedestrians crossing the intersection (θ_{12}'=1.327) and the coefficient of equivalence for the scenario of mixed young and elderly pedestrians crossing the intersection (θ_{13}'=1.124) can be calculated using *Equation 14*. The proportion of young pedestrians (k_1') can be obtained using *Equation 15*.

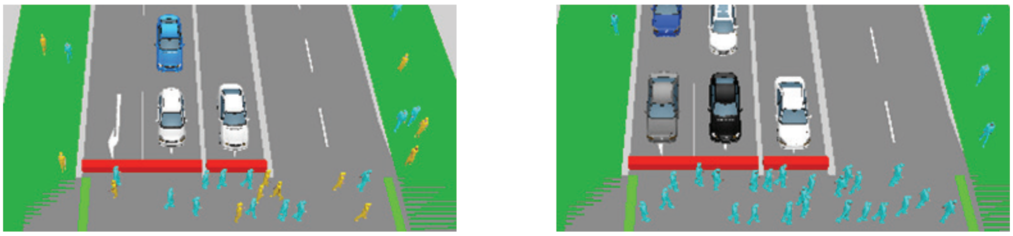
The saturation flow for the scenario of mixed young and middle-aged pedestrians crossing the intersection:

$$q_{c12}' = \frac{1.919}{0.327k_1' + 1} \tag{23}$$

The saturation flow for the scenario of mixed young and elderly pedestrians crossing the intersection:

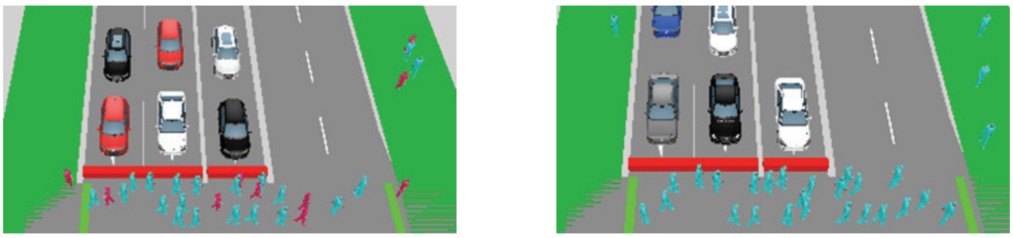
$$q_{c13}' = \frac{1.625}{0.124k_1' + 1} \tag{24}$$

Then, the middle-aged pedestrians are put in a scenario of mixed young and elderly pedestrians crossing the intersection, with the proportion of middle-aged adults with the proportion of young pedestrians being k_1', as shown in *Figure 11a*. Let the proportion of middle-aged pedestrians be p=1-k_1'; that is, the middle-aged pedestrians replace the elderly pedestrians, transforming the scenario of mixed young and elderly pedestrians crossing the



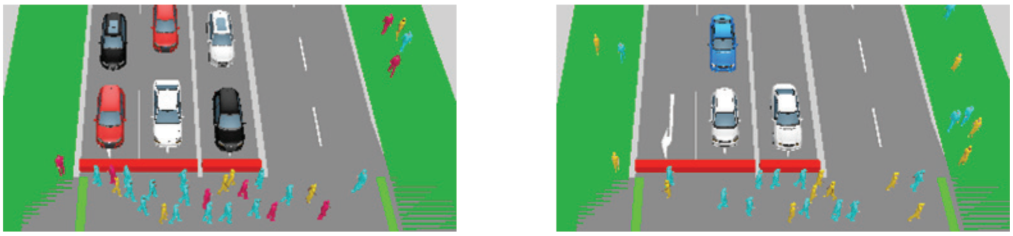
a) Young and middle-aged *b) All young*

Figure 9 – Young blending into the middle-aged population



a) Young and elderly *b) All young*

Figure 10 – Young mixed with the elderly population



a) Young, middle-aged and elderly *b) Young and middle-aged*

Figure 11 – Middle-aged mixed the young and elderly population

Table 3 – Details of different types of signalised intersections

Position	Xuefu RD – Ertang RD	Chongqing 110 High School	Nanhu RD – Qinglong RD	Jinzhi Street – Nanhu RD
Countdown	Y	N	Y	Y
Pedestrian refuge island	Y	Y	N	N
Crosswalk length [m]	24	24	20	15
Crosswalk width [m]	6	6	6	6
Crosswalk signal cycle [s]	112	100	95	96
Pedestrian green light duration [s]	25	19	15	12
Pedestrian green flash time [s]	5	5	5	5

intersection to a scenario of mixed young and middle-aged pedestrians crossing the intersection, as shown in *Figure 11b*.

Equation 24 can be derived from *Equations 16, 23, and 24*:

$$\theta'_{23} = \frac{\frac{q'_{c13}}{q'_{c12}} - 1}{1 - k'_1} + 1 \tag{25}$$

When the percentages of young and middle-aged pedestrians are k'_1 and k'_2, respectively, q_c is derived from formula in *Equation 16*:

$$q_c = \frac{q'_{c13}}{k'_2(\theta'_{23} - 1) + 1} = \frac{3.118k'_1 - 3.118}{0.238k'^2_1 - 0.293k'_1k'_2 + 1.681k'_1 + 0.294k'_2 - 1.919} \tag{26}$$

Step 3: When the proportions of young, middle-aged, and elderly individuals at signalised intersections are k'_1, k'_2, and k'_3, respectively, the pedestrian traffic flow model is derived from *Equations 18 and 20*:

$$\begin{cases} q = \dfrac{2\varphi(k'_1,k'_2)}{\gamma(k'_1,k'_2,k'_3)}u - \dfrac{\varphi(k'_1,k'_2)}{\gamma^2(k'_1,k'_2,k'_3)}u^2 \\ r = \dfrac{2\varphi(k'_1,k'_2)}{\gamma(k'_1,k'_2,k'_3)} - \dfrac{\varphi(k'_1,k'_2)}{\gamma^2(k'_1,k'_2,k'_3)}u \\ \varphi(k'_1,k'_2) = \dfrac{3.118k'_1 - 3.118}{0.238k'^2_1 - 0.293k'_1,k'_2 + 1.681k'_1 + 0.294k'_2 - 1.919} \\ \gamma(k'_1,k'_2,k'_3) = 0.589k'_1 + 0561k'_2 + 0.515k'_3 \end{cases} \tag{27}$$

The parameters in this formula have the same meanings as above.

4.2 Verification with actual cases

To verify the reliability and applicability of the model, it is compared with the HCM model and field data. The field data of pedestrians crossing different types of signalised intersections (signalised intersections with or without pedestrian countdown signals, with or without pedestrian refuge islands, and with different crosswalk lengths at non-peak and peak hours) are collected in field surveys. *Table 3* lists the details of each survey site.

Ten signal periods are randomly selected at each of the signalised intersections above for the non-peak time period (five signal periods) and the peak time period (five signal periods). At each signal cycle, the flow, the ratios of pedestrian types, and the average speed of pedestrian traffic flow are extracted manually. With the manual extraction method in subsection 2.2, the number of young, middle-aged, and elderly pedestrians, as well as the walking speed of each pedestrian, are calculated in each signal cycle. The collected data are compared with the simulated data, as shown in *Table 4*, *Table 5*, *Table 6*, and *Table 7*.

Table 4 – Verification results for Xuefu RD – Ertang RD

Time Period	Walking speed [m/s]	Pedestrian ratio			Pedestrian flow [p/m/s]			Absolute value error [p/m/s]	
		Young	Middle-aged	Elderly	True	HCM	Model	HCM	Model
Non-peak	1.08	34.1%	22.4%	43.5%	0.153	0.938	0.121	0.785	0.032
	1.04	23.3%	25.1%	51.6%	0.223	1.067	0.275	0.844	0.052
	1.05	13.5%	38.7%	47.8%	0.243	1.036	0.215	0.793	0.028
	1.03	24.2%	12.0%	63.8%	0.359	1.098	0.267	0.739	0.092
	1.12	66.7%	0.0%	33.3%	0.495	0.796	0.046	0.301	0.449
Peak	0.89	45.2%	42.4%	12.4%	1.211	1.440	1.112	0.229	0.099
	0.86	36.4%	39.3%	24.3%	1.246	1.493	1.176	0.247	0.070
	0.94	63.4%	21.3%	15.3%	1.056	1.336	0.909	0.280	0.147
	0.98	61.7%	28.5%	9.8%	0.843	1.238	0.785	0.395	0.058
	0.81	54.2%	28.2%	17.6%	1.398	1.566	1.299	0.168	0.099

Table 5 – Verification results for Chongqing 110 High School

Time Period	Walking speed [m/s]	Pedestrian ratio			Pedestrian flow [p/m/s]			Absolute value error [p/m/s]	
		Young	Middle-aged	Elderly	True	HCM	Model	HCM	Model
Non-peak	1.07	25.0%	20.0%	55.0%	0.127	0.971	0.091	0.844	0.036
	1.06	13.6%	31.8%	54.5%	0.136	1.004	0.119	0.868	0.017
	1.04	19.0%	38.1%	42.9%	0.381	1.067	0.312	0.686	0.069
	1.10	30.4%	34.8%	34.8%	0.062	0.868	0.042	0.806	0.020
	1.05	16.7%	37.5%	45.8%	0.265	1.036	0.234	0.771	0.031
Peak	0.95	51.1%	20.0%	28.9%	1.013	1.312	0.824	0.299	0.189
	0.98	58.7%	26.1%	15.2%	0.984	1.238	0.762	0.254	0.222
	0.86	68.1%	14.9%	17.0%	0.973	1.493	1.144	0.520	0.171
	0.92	39.6%	47.9%	12.5%	1.153	1.380	1.016	0.227	0.137
	0.91	32.7%	49.0%	18.4%	1.211	1.401	1.036	0.190	0.175

Table 6 – Verification results for Nanhu RD – Qinglong RD

Time Period	Walking speed [m/s]	Pedestrian ratio			Pedestrian flow [p/m/s]			Absolute value error [p/m/s]	
		Young	Middle-aged	Elderly	True	HCM	Model	HCM	Model
Non-peak	1.09	26.7%	26.7%	46.7%	0.029	0.903	0.024	0.874	0.005
	1.06	43.8%	25.0%	31.3%	0.356	1.004	0.313	0.648	0.043
	1.04	11.8%	35.3%	52.9%	0.263	1.067	0.241	0.804	0.022
	1.06	22.2%	16.7%	61.1%	0.123	1.004	0.108	0.881	0.015
	1.07	5.3%	52.6%	42.1%	0.117	0.971	0.103	0.854	0.014
Peak	0.91	52.5%	15.0%	32.5%	1.011	1.401	0.954	0.390	0.057
	0.93	68.3%	14.6%	17.1%	1.021	1.358	0.932	0.337	0.089
	0.86	28.6%	52.4%	19.0%	1.326	1.493	1.214	0.167	0.112
	0.88	30.2%	55.8%	14.0%	1.275	1.459	1.166	0.184	0.109
	0.92	34.1%	45.5%	20.5%	0.954	1.380	0.987	0.426	0.033

Table 7 – Verification results for Jinzhi Street – Nanhu RD

Time Period	Walking speed [m/s]	Pedestrian ratio			Pedestrian flow [p/m/s]			Absolute value error [p/m/s]	
		Young	Middle-aged	Elderly	True	HCM	Model	HCM	Model
Non-peak	1.05	30.0%	0.0%	70.0%	0.164	1.036	0.139	0.872	0.025
	1.04	18.2%	36.4%	45.5%	0.249	1.067	0.296	0.818	0.047
	1.07	25.0%	16.7%	58.3%	0.063	0.971	0.073	0.908	0.010
	1.05	30.8%	7.7%	61.5%	0.221	1.036	0.185	0.815	0.036
	1.06	14.3%	35.7%	50.0%	0.156	1.004	0.146	0.848	0.010
Peak	0.97	34.3%	48.6%	17.1%	0.832	1.263	0.799	0.431	0.033
	0.93	77.8%	8.3%	13.9%	1.011	1.358	0.935	0.347	0.076
	0.92	37.8%	54.1%	8.1%	1.056	1.380	1.037	0.324	0.019
	0.89	42.1%	44.7%	13.2%	1.243	1.440	1.115	0.197	0.128
	0.86	33.3%	51.3%	15.4%	1.229	1.493	1.219	0.264	0.010

5. RESULTS AND DISCUSSION

As shown in *Figure 12*, (1) the HCM model produces a larger mean absolute error when the signalised intersection is in non-peak hours, which is due to the fact that the pedestrian walking speed is less constrained by traffic when pedestrian traffic is low and pedestrian walking speed is mainly influenced by local culture. In contrast, the pedestrian database of the model in this paper can be constructed by surveying the walking speed characteristics of local pedestrians, therefore, the mean absolute error is much smaller than that of the HCM model during non-peak hours. (2) During the peak hours of signalised intersections, the mean absolute error of both the HCM model and the model of this paper are smaller, but the model of this paper considers the heterogeneity of pedestrians in pedestrian traffic flow, so the mean absolute error is lower than that of the HCM model. The model in this paper not only takes into account the heterogeneity of pedestrians, but can also construct a suitable pedestrian traffic flow model for signalised intersections according to the walking speed characteristics of different local pedestrian types. In addition, the model in this paper has the lowest mean absolute error of 0.039 (the pedestrian crossing length is 15m) and 0.050 (the pedestrian crossing length is 20m) at intersections without pedestrian refuge islands and with countdown (the data collection for the three pedestrian types is at this type of signalised intersections), and the mean absolute error at other types of signal intersections is 0.082 at signalised intersections with countdown and pedestrian refuge islands and 0.107 at signalised intersections without countdown and with pedestrian refuge islands. This indicates that pedestrian crossing lengths, countdowns, and pedestrian refuge islands could affect the model. Therefore, in order to better apply the

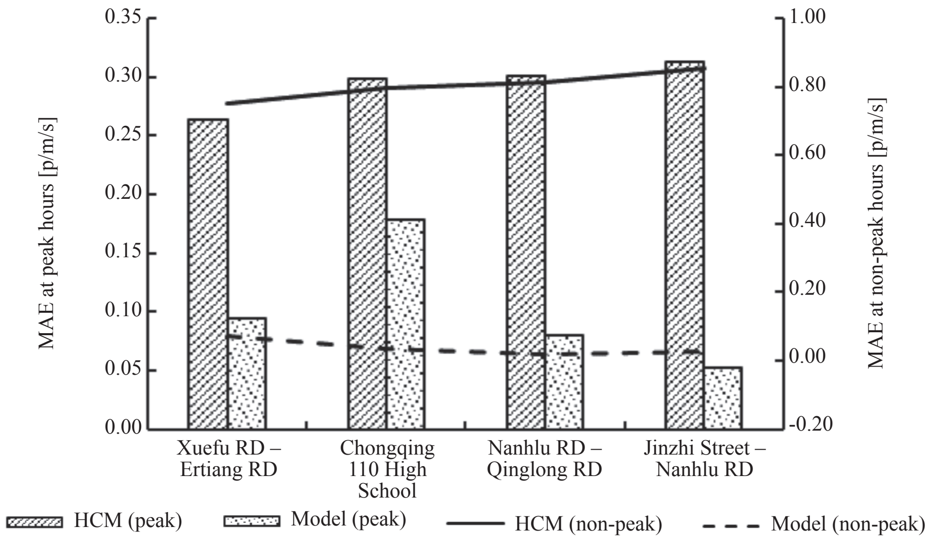


Figure 12 –Analytical chart of the mean absolute error

model to other types of signalised intersections, the basic pedestrian database needs to be updated and the pedestrian crossing walking speed characteristics should be investigated at corresponding signalised intersections.

6. CONCLUSIONS AND PROSPECTS

Different types of pedestrians exhibit different dynamic characteristics. This paper introduces the concept of pedestrian heterogeneity in model construction and analyses the heterogeneity of young, middle-aged, and elderly pedestrians when they are crossing intersections. A pedestrian traffic flow model for mixed-type pedestrians at signalised intersections is established by analysing the relationships among pedestrian flow, speed, and density. The data collected from field surveys are used to establish and calibrate the simulation platform, on which the speed-flow relationships for the mixed-type pedestrians with different proportions of young, middle-aged, and elderly pedestrians are obtained. The model is validated by data collected at four actual signalised intersections at peak and non-peak hours. The absolute error of the model in practical applications is much lower than that of the HCM model, which indicates that the model is superior to the HCM model. The model not only takes into account the heterogeneity of pedestrians, but can also be used to construct the corresponding pedestrian traffic flow models according to different types of signalised intersections. This gives the model a strong local applicability and reliability. The results of this study can further enrich the pedestrian traffic flow model at signalised intersections and provide a theoretical basis for the study of pedestrian walking speed and signal timing at signalised intersections with complex pedestrian types in China. For the geographical environment, the physical features of pedestrians and their behavioural habits, which all influence the pedestrian walking characteristics have differences, and the collected and validated data in this paper are all from Chongqing, China. So if the model is to be used in other countries, it needs to be further tested.

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张惠玲，奚邦顺

考虑行人异质性的信号交叉口行人交通流建模研究

摘要

不同类型行人的速度特征和异质特性大相径庭。在信号灯交叉口处于混合行人流的情况下，研究行人交通流模型对于分析信号交叉口的设施设置情况和评估行人服务水平至关重要。在行人异质性的背景下，利用实地调查的重庆市三个信号交叉口的行人过街视频，研究了信号交叉口的行人交通流特征。从视频中人工提取的行人步行速度数据作为区分行人异质性的数据基础。利用微观模拟软件获得了三种类型（年轻、中年和老年）的行人在不同行人流量下的步行速度数据。在此基础上，建立了不同类型行人在信号交叉口的交通流模型，并通过与HCM模型进行实例比较分析，得到该模型在实际应用中总体上优于HCM模型，这表明其具有较强的适用性和可靠性。

关键词

行人；行人交通流模型；行人异质性；
信号交叉口；行人流

REFERENCE

[1] Li B, et al. Age differences analysis of pedestrian travel demand at signalized intersection. *Journal of Wuhan University of Technology (Transportation Science & Engineering)*. 2016;40(2): 309-314. doi: 10.3963/j.issn.2095-3844.2016.02.022.

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

[3] Tanaboriboon Y, Hwa SS, Chor CH. Pedestrian characteristics study in Singapore. *Journal of Transportation Engineering*. 1986;112(3): 229-235. doi: 10.1061/(ASCE)0733-947X(1986)112:3(229).

[4] Polus A, Schofer JL, Ushpiz A. Pedestrian flow and level of service. *Journal of Transportation Engineering*. 1983;109(1): 46-56. doi: 10.1061/(ASCE)0733-947X(1983)109:1(46).

[5] Lam WHK, Morrall JF, Ho H. Pedestrian flow characteristics in Hong Kong. *Transportation Research Record*. 1995;1487: 56-62.

[6] Das S, Mukherjee D, Saha P, Roy SK. Pedestrian flow characteristics at signalized intersections in mixed traffic situations: A case study in Kolkata, India. *Procedia Computer Science*. 2018;130: 150-156. doi: 10.1016/j.procs.2018.04.024.

[7] Sharifi MS, Song Z, Esfahani HN, Christensen K. Exploring heterogeneous pedestrian stream characteristics at walking facilities with different angle intersections.

Physica A: Statistical Mechanics and Its Applications. 2020;540: 112-123. doi: 10.1016/j.physa.2019.123112.

[8] Wu HL, et al. A capacity simulation model of stairway in subway station considering pedestrian heterogeneity. *Journal of Transportation Systems Engineering and Information Technology.* 2016;16(3): 141-147.

[9] Ren X, Zhang J, Song W, Cao S. The fundamental diagrams of elderly pedestrian flow in straight corridors under different densities. *Journal of Statistical Mechanics: Theory and Experiment.* 2019;02(34): 03-21.

[10] Gates TJ, Noyce DA, Bill AR, Van Ee N. Recommended walking speeds for timing of pedestrian clearance intervals based on characteristics of the pedestrian population. *Transportation Research Record Journal of the Transportation Research Board*. 2006;1982(1): 38-47. doi: 10.3141/1982-07.

[11] Zhang HL. Threshold research on the elderly pedestrian ratio in pedestrian crossing speed setting on signalized crosswalk in China. *Promet – Traffic&Transportation*. 2020;32(1): 55-63. doi: 10.7307/ptt.v32i1.3110.

[12] Callisaya ML, et al. Cognitive status, fast walking speed and walking speed reserve—the Gait and Alzheimer Interactions Tracking (GAIT) study. *Geroscience*. 2017;39(6): 1-9. doi: 10.1007/s11357-017-9973-y.

[13] Yang WY, Zhang X, Chen H, Jin WQ. A model of pedestrian trajectory prediction for autonomous vehicles based on social force. *Journal of Highway and Transportation Research and Development.* 2020;37(08): 127-135. doi: 10.3969/j.issn.1002-0268.2020.08.016.

[14] Huber MJ. Estimation of passenger car equivalents of tracks in traffic stream. *Transportation Research Record*; 1982. p. 60-70.