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Original Research Paper

Pedestrian walking speed at un-signalized midblock crosswalk and its impact on urban street segment performance

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HIGHLIGHTS

- Statistical analyses to examine measured free-flow pedestrian walking speeds at un-signalized midblock crosswalks.
- Measurement of pedestrian walking speeds by age group.
- Theory of gap-acceptance on pedestrian crossing behavior on urban street segments.
- The Highway Capacity Manual (HCM) methodology for evaluating level of service urban street segments.
- Relationship between pedestrian walking speed and urban street level of service.

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ABSTRACT

The Urban Street Segment Chapter of the Highway Capacity Manual (HCM) includes a methodology for evaluating the level of service urban street segments provide to automobile users. The methodology does not account for pedestrian activity at un-signalized midblock crosswalk on an urban street segment. Pedestrian activity at un-signalized midblock crosswalk on urban street segments causes friction conditions between automobiles and pedestrians. As a consequence, the average time it takes vehicles to travel along the segment is increased. Increasing segment running time decreases both the travel speed of automobiles and the level of service provided to automobile users. There is an inverse relationship between the delay incurred by interrupted vehicles and the speeds at which pedestrians walk while crossing at midblock. To account for this delay, there is a need to investigate pedestrian walking speeds at un-signalized midblock crosswalks. This study measured pedestrian walking speeds by age-group at two un-signalized midblock crosswalks on urban street segments. The first objective of this paper is to perform statistical analyses to examine the measured free-flow pedestrian walking speeds. The second objective is to demonstrate how the findings of this study can be incorporated into the Urban Street Segment Analysis Chapter of the HCM. Pedestrian walking speeds were recorded and analyzed for 2937 pedestrians. The results show teenagers walk at an average speed of 1.45 m/s, young adults walk at an average speed of 1.55 m/s, middle age

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pedestrians walk at a speed of 1.45 m/s, older pedestrians walk at speed of 1.09 m/s, and elderly or physically disabled pedestrians walk at a speed of 1.04 m/s.

1. Introduction

1.1. Background

The average walking speed of pedestrians while crossing within designated crosswalks on urban streets is a very important parameter for different traffic engineering applications. It is applied in designing signal timings for pedestrians, and to evaluate the level of service an urban street facility provides to both pedestrian and automobile modes. Two key factors that influence the walking speeds of pedestrians on un-signalized midblock crosswalks are vehicular traffic and the age of pedestrians. Elderly pedestrians would tend to be more safety conscious when crossing on un-signalized midblock crosswalks, and therefore would tend to react more strongly on street segments with relatively high traffic volume and traffic speeds. Furthermore, the flow of vehicles on urban street segments with un-signalized midblock crosswalks is most often interrupted by pedestrians as they cross at midblock. Pedestrian interference at midblock causes friction, which increases the travel time of vehicles traveling along the segment. As a consequence, the average travel speed and the level of service along the segment are lowered. The Urban Street Segment Analysis Chapter of the 2010 Highway Capacity Manual (TRB, 2010) also presents a methodology to evaluate the performance of urban street segment and facility to pedestrian traffic. The methodology presents an equation that estimates average pedestrian walking speeds on sidewalks of urban street segments based on free-flow walking speeds. The application of this equation may be limited to sidewalks, and may not be applicable in estimating the average pedestrian walking speeds on midblock crosswalks on urban street segments. The speed at which pedestrians walk on sidewalks and on crosswalks at signalized intersections may differ from the speed at which they cross at un-signalized midblock crosswalks. Pedestrians would tend to be more safety conscious while crossing at un-signalized midblock crosswalks due to frequent arrivals of vehicles that are not controlled by traffic signals.

In addition, the HCM methodology for evaluating the level of service urban street segments provide to automobile users, in part, applies a segment running time equation to estimate the travel time of vehicles between upstream and downstream signalized intersections. The segment running time is estimated based on operational and geometric characteristics of the segment. The segment running time equation includes component that accounts for delays due to sources along the segment (e.g., curb parking, pedestrian activity at midblock crosswalks, etc.). However, one of the limitations of the HCM urban street segment analysis methodology is that it does not account for midblock pedestrian activity. Therefore, the manual does not provide specific value to adjust the segment running time for delays incurred by automobile user during midblock pedestrian interference. There is an inverse relationship between the delay incurred by vehicles at midblock due to pedestrian interference on an urban street segment, and the walking speed of the pedestrians crossing within the midblock crosswalk. Therefore, to adequately estimate this delay, there is a need to investigate the walking behavior of pedestrians while crossing within un-signalized midblock crosswalks on urban street segments. Furthermore, extensive research has been conducted on pedestrian walking speed and behavior on sidewalks, and on crosswalks at signalized intersections. However, not many studies have investigated pedestrian walking speeds by age group at un-signalized midblock crosswalks on urban street segments, and rigorously analyze the difference in walking speeds for the different age groups.

1.2. Objectives

The first objective of this study is to perform statistical analyses to examine measured free-flow pedestrian walking speeds on un-signalized midblock crosswalks by age group. The second objective is to demonstrate how the findings of this research can be incorporated into the Urban Street Segment Analysis Chapter of the HCM.

2. Literature review

2.1. Gap acceptance and pedestrian crossing behavior on urban streets

The theory of gap-acceptance that describes pedestrian crossing behavior on urban street segments states that there is a critical gap between vehicular traffic that pedestrians accept before crossing. The theory further states that this gap consists of the time it takes to cross and a safety margin. The safety margin is defined as the difference in time between the time for a pedestrian to cross and the arrival time of the next vehicle. According to Chu and Baltes (2003), the length of time for a pedestrian to cross is based on the length of the crosswalk, the walking speed of the pedestrian and whether the median treatment permits two-stage pedestrian crossing. It is further stated that on urban street segments with median treatment that allows a pedestrian to make a two-stage crossing, the number of gap accepted would tend to increase due to decrease in the time to cross. A study by Kadali et al. (2014) examined pedestrian gap acceptance behavior by employing an artificial neural network (ANN) model for understanding the decision making process of pedestrians, i.e., acceptance or rejection of vehicular gaps at a midblock location. The results showed that pedestrian rolling gap, frequency of attempt, vehicular gap size, pedestrian speed change condition and vehicle speed have major role in pedestrian gap acceptance. Marisamynathan and Perumal (2014) analyzed crossing behavior of pedestrians such as crossing speed, compliance with signal, and pedestrian–vehicular interaction under mixed traffic conditions. The Pearson's correlation coefficient test, ANOVA test, and student *t* test were performed to identify the influencing factors affecting traffic signal compliance by pedestrians. The study also investigated factors influencing pedestrian crossing speed.

Another study by Mamidipalli et al. (2015) analyzed empirical observations and developed pedestrian gap acceptance models at midblock crossings. The study found that an increase in gap length was associated with an increased probability that a pedestrian would cross, where as a lag event had a negative coefficient; which meant that a pedestrian was less likely to accept a lag than a gap, given the same length in seconds. Alver and Onelcin (2018) investigated gap acceptance of pedestrians at overpass locations. The study applied Raff's method (deterministic approach) to estimate the critical gap. The collected data were then evaluated by a binary logit model (probabilistic approach) to estimate time gaps. The safety margin of 377 pedestrians was evaluated by analysis of variance (ANOVA) analysis to identify the significant factors. The ANOVA results showed that interactions of gender, age, and vehicle position, items carrying, group size had significant effects on safety margin. Naser et al. (2017) modelled pedestrian gap crossing index under mixed traffic condition. The study focused on the gaps accepted by pedestrians and their decision for street crossing. Data from the observation at an uncontrolled midblock and multiple linear regression (MLR) and binary logit model (BLM) techniques were applied to analyze the results. It was concluded that pedestrians' decision to cross on street segments depends on the age of the pedestrian, rolling gap, vehicle type, and size of traffic gap. Sahani et al. (2017) studied the gap acceptance behaviour of pedestrians to establish safety margins while crossing at un-signalized intersections. Equilibrium probability method and maximum likelihood method were adopted for the estimation of critical gap of pedestrians on the basis of different demographic factors. The study found that the average critical gap for a young pedestrian is (5.31 s) less than that for a middle-aged (6.49 s) or old pedestrian (6.09 s). It has been noted that with increase in critical gap, the crossing time increases logarithmically. The study also determined that critical gap and crossing time had significant effect on the safety margin of the pedestrian.

2.2. *Pedestrian walking speed on urban street segments*

According to Coffin and Morrall (1996), personal attributes, such as age are good indicators of walking speed. Median treatments, crossing location, group size of pedestrian, and trip purpose also influence the speed at which pedestrian walk on urban street segments. According to Bowman and Vecellio (1994), the average walking speed is higher for roadways with two-way left turn lanes than for undivided roadways, and pedestrians tend to walk faster at midblock locations than at signalized intersections. Knoblauch et al. (1996) conducted a series of field studies to quantify the walking speed and the start-up time of pedestrians of various age groups under different conditions. Data were collected on pedestrians who appeared to be 65 years of age or older and a control group of pedestrians under age 65 years. A value of 1.51 m/s obtained for younger pedestrians (less than 65 years old) and 1.25 m/s for older pedestrians (65 years and older). A 15th percentile walking speed of 1.25 m/s obtained for younger pedestrians and 0.97 m/s for older pedestrians. Gates et al. (2006) recommended walking speeds for timing of pedestrian clearance intervals using data collected for 1947 pedestrian crossing events measured at 11 intersections in Madison and Milwaukee, Wisconsin. The data was analyzed to determine the effect of age and disability, intersection traffic control condition, group size, and gender on walking speed. Average pedestrian walking speed of 1.22 m/s was obtained for all pedestrians, and 1.16 m/s for pedestrians 65 years or older. While 15th percentile walking speed value of 1.15 m/s for all pedestrians, 1.27 m/s for pedestrians under 30 years old, 1.22 m/s for pedestrians between 30 and 64 years of age, and 0.92 m/s for pedestrians 65 years or older.

A study by Monutar et al. (2007) investigated the normal walking speed of pedestrians and the speed when crossing a street. Data were collected on older pedestrians (those who appeared to be 65 years and older) and younger pedestrians (those who appeared to be between 20 and 64 years of age). Pedestrians were timed from the instant they stepped onto the crosswalk to the instant they left the crosswalk. The study obtained average pedestrian walking speed values of 1.61 m/s for younger pedestrians and 1.36 m/s for older pedestrians. Chapter 17 of the HCM 2010 recommends average free-flow walking speeds for different age groups of pedestrians traveling along the segment subject direction. Chapter 18 of the manual also recommends different average (50th percentile) pedestrian walking speeds based on different age groups to evaluate corner and crosswalk performance at signalized intersections. The manual describes free-flow speed as the walking speed under conditions in which there are negligible pedestrian-to-pedestrian conflicts and negligible adjustments in a pedestrian walking path to avoid other pedestrians. Average free-flow walking speed is 1.34 if 0–20% of pedestrian are elderly (65 years or older), and is 1.01 if more than 20% of pedestrians are elderly (65 years or older). Rastogi et al. (2011) investigated pedestrian walking speeds at midblock crosswalks taking into consideration traffic volume, width of roadway, gender, age, and pedestrian group size. The study found that pedestrian speed increases with increasing traffic volume up to 2000 passenger car units per hour (pcu/h). Another finding of the study was that pedestrian walking speeds reduce with increasing age and increasing size of the pedestrian group. Huang and Ma (2012) determined that the walking speeds of pedestrians are normally distributed regardless of gender or age group. The study found that the average walking speed of younger pedestrians significantly greater than that of older pedestrians. Patil and Pawar (2015) investigated pedestrian temporal and spatial gap acceptance at midblock crosswalks on urban street segments. Findings of the study show a 50th percentile temporal gap of approximately 4.1–4.8 s. The 50th percentile spatial gaps was approximately 67–79 m. The study also found the 85th percentile temporal and spatial gaps of approximately 5.0–5.8 s and 82–95 m, respectively. Bak and Kiec (2012) studied the influence of various types of midblock pedestrian crossings on road capacity. Pedestrian crossings were analyzed at zebra crossings, crossings with refuge median islands, and signalized crosswalks. The results of the study showed that the willingness to give right of way on urban streets influences capacity reduction and delays.

Ma et al. (2013) studied the characteristics of pedestrian crossing speeds within designated crosswalks on urban street segments. Several factors that influence pedestrian crossing speeds were analyzed including, condition of the urban street, pedestrian signals, and pedestrian flow characteristics. Data for this study were collected from five different land use areas including, business district, transport hub, neighborhood, university campus, and comprehensive land use. Li et al. (2013) carried out a study on walking speeds of elderly pedestrian crossings at midblock crosswalks, at signalized intersections, and at un-signalized intersections. Pedestrian walking speed was calculated as the measured curb-to-curb distance divided by the time taken to walk from one curb to the other. A mean speed value of 1.00 m/s was recorded at midblock crosswalks and signalized intersections close to seniors and nursing homes, and a value of 1.20 m/s at other signalized intersections. Hussein and Sayed (2015) conducted a study on microscopic pedestrian behavior during several interactions, with pedestrian walking speed and gait parameters (step frequency and length) as variables. Pedestrian trajectories at a signalized intersection in Vancouver, British Columbia, Canada, were extracted from video recordings by means of computer vision techniques. Walking speed and gait parameters were estimated by analyzing pedestrian speed profiles. The study provided detailed analysis of seven interactions. The variations in walking speed and gait parameter values across group size and gender during the seven interactions were also investigated. Peters et al. (2015) investigated pedestrian crossing behavior at signalized intersections in New York City. The study focused on pedestrian reaction times and the effect of pedestrian characteristics and walking environments on walking speed. Reaction times were studied for two pedestrian groups, (a) those who waited on the sidewalk and (b) those who waited in the crosswalk. The study also examined the effect of pedestrian walking speed on gender, location, pedestrian arrival, and pedestrian position at the beginning of the walk, time of day, baggage handling, and walking in groups. Yang et al. (2016) presented a multiobjective evaluation method to estimate the performance of various midblock crosswalk treatments on urban streets. The objectives included traffic operation, traffic safety, environmental impacts, and costs. VISSIM simulation models were developed and calibrated using field data to evaluate the operational and environmental impacts of various midblock crosswalk treatments. For the impact of various treatments on traffic operation, the total control delay to vehicles on the major streets and pedestrians were estimated.

Another study by Zhao et al. (2016) investigated the impact of pedestrian gender and age, the presence of a pedestrian group, vehicle interference and crossing direction, on the time it takes for pedestrians to cross at non-signalized midblock crosswalks. The findings of the study show that pedestrian walking speed ranges from 1.0 to 1.1 m/s. The time it takes pedestrians to cross was found to increase with increasing age, while pedestrian walking speeds increase when the gap between pedestrians and approaching traffic decreases. Russo et al. (2018) carried out a study on pedestrian behavior at signalized intersection crosswalks. The main aim was to study the factors associated with distracted walking, pedestrian violations, and walking speed. A total of 3038 pedestrians were observed across four signalized intersections in New York and Arizona using high-definition video cameras. The video data were reduced and summarized, and an ordinary least squares (OLS) regression model was estimated to analyze factors affecting walking speeds.

2.3. *Modeling pedestrian activities on urban streets*

Chu and Baltes (2003) developed a statistically estimated model of pedestrian quality of service for midblock street crossings as part of the Florida Department of Transportation Multimodal Quality of Service Program. The model was to be used in evaluating the level of service of street segments for pedestrian street crossing. Golani and Damti (2007) proposed a model for estimating crossing times at high-occupancy crosswalks. The model variables included the following components of the crossing time of a platoon of pedestrians: start-up time, walking speed, and pedestrian headways (lag) as a function of the size of the dominant platoon and the opposite platoon separately. The model was calibrated based on data extracted from video recordings of pedestrian crossings at crosswalks. Schroeder and Rouphail (2011) used event-based modeling of driver yielding behavior at un-signalized crosswalks. The research investigated factors that are associated with driver yielding behavior at un-signalized pedestrian crossings and developed predictive models for yielding by using logistic regression. The results provide new insights into the complex interaction of pedestrians and vehicles at un-signalized intersections and have implications for future work toward predictive models for driver yielding behavior. Song et al. (2015) developed a model for calculating the total crossing time of a platoon of pedestrians at signalized intersections. The study took into consideration the condition of bidirectional pedestrian interference, the number of pedestrians, pedestrian directional split ratio, and crosswalk width and length. Total crossing time was divided into three parts: the discharging time of a pedestrian platoon, the objective pedestrian's basic crossing time, and the frictional delay caused by pedestrians moving in the opposite direction.

Yu et al. (2015) proposed an integrated model for optimizing the quantity, locations and signal settings of midblock crosswalks simultaneously to best trade-off the operational performances between pedestrians and vehicles. Pedestrian behavior of choosing crosswalks is captured under a discrete demand distribution. Cantillo et al. (2015) modeled pedestrian crossing behavior in urban streets based on a latent variable approach. The latent variables were determined by socioeconomic characteristics of the individual (age, gender, level of study) and conditioned by the circumstances of the trip (main mode of transport, walking or not with children). The study proposed a hybrid framework to analyze pedestrians' choice on how to cross an urban street, where three crossing options are available: crossing directly, crossing by using a pedestrian bridge or using a crosswalk at a signalized intersection. Zhao and Liu (2017) proposed a pedestrian control delay model that considers the diagonal crossing and moving paths of pedestrians. The proposed model was validated using field measurements. It was found that the delay of diagonal crossing increases with increase in the time gap of the green light between the two adjacent crosswalks and an increase in the green time length of the crosswalk. Iryo-Asano and Alhajyaseen (2017) modeled pedestrian crossing speed profiles considering speed change behavior as they cross signalized crosswalks under uncongested conditions. Pedestrian speed profiles were collected from empirical data and speed change events were extracted assuming that the speed profiles were stepwise functions. A speed change event was described by a discrete choice model as a function of the necessary walking speed to complete crossing before the red interval ends, current speed, and the presence of turning vehicles in the conflict area.

While all of these studies measured pedestrian walking speeds of pedestrians within crosswalks at midblock or at the signalized intersections on street segments, this study however, goes further by performing rigorous statistical analyses to investigate how significantly different the walking speeds are by age group. This study also demonstrates how the measured walking speeds can be incorporated into the Urban Street Segment Analysis Chapter of the HCM.

2.4. *Estimating average travel speed on urban street segment*

HCM 2010 considers travel speed as the key metric to measure the performance of automobile mode on urban street segments. It is used to determine the level of service at which the segment operates. The manual computes the travel speed for the subject direction of travel along the segment as follows

$$s_{T,seg} = \frac{3600L}{1609(t_R + d_t)} \tag{1}$$

where $s_{T,seg}$ is travel speed of through vehicles for the segment (mph), L is segment running time (m), t_R is segment running time (s), d_t is through delay (s/veh).

The through delay d_t, in Eq. (1) is the sum of control and geometric delays. The control delay in is due to traffic control at the boundary intersection. The geometric delay that is due to negotiation of intersection geometry. The HCM computes the segment running time (t_R) by taking into consideration the control type at the upstream intersection, the free flow speed, vehicle proximity, and various mid-segment delay sources. The segment running time is shown as follows

$$t_R = \frac{6 - l_1}{0.0025L} f_x + \frac{3600L}{5280S_f} f_v + \sum_{i=1}^{N_{ap}} d_{ap,i} + d_{other} \tag{2}$$

where l_1 is start-up lost time (2.0 for signal control), f_v is vehicle proximity adjustment factor (1.0 for no mid-segment access point), L is segment length (ft), S_f is free flow speed (mph), f_x is control-type adjustment factor (1.0 for signal control), $d_{ap,i}$ is delay due to left and right turns from the street into access point intersection i (s/veh), N_{ap} is number of influential access point approaches along the segment, d_{other} is delay due to other sources along the segment (e.g., curb parking, pedestrians) (s/veh). All variables are defined in detail in the HCM.

3. Description of study sites

The walking speed of pedestrians was measured at two un-signalized midblock crosswalks on urban street segments in downtown Newark, New Jersey. The description of each site is provided in Table 1 below. Study sites 1 and 2 are shown in Figs. 1 and 2, respectively. As part of the second objective, this paper analyzes four different scenarios of pedestrian-vehicle interference at un-signalized midblock crosswalk on two-lane and four-lane urban street segments similar to the lane configuration of study sites 1 and 2, respectively.

4. Field measurement of pedestrian walking speeds

The measurement of pedestrian walking speeds by age group was carried out in two steps. The first step was to video record pedestrians while crossing within the midblock crosswalk at the study sites. At study site 1, the video camera was mounted at an altitude of about 4 m overlooking the midblock crosswalk. Pedestrian and vehicular activity at this site was recorded for three consecutive days. Data collection at study site 2 was carried out by positioning a video camcorder at an elevation of about 18 m to record vehicular and pedestrian

Table 1 – Description of study sites.

Description	Study site 1	Study site 2
Route name	Warren street	Martin Luther King Jr. Blvd
Number of lane in study direction	1	2
Length of crosswalk (m)	9	28
Posted speed limit (mph)	25	25
Average pedestrian volume (ped/h)	182	135
Average vehicular volume (veh/h)	186	313

Fig. 1 – Study site 1.

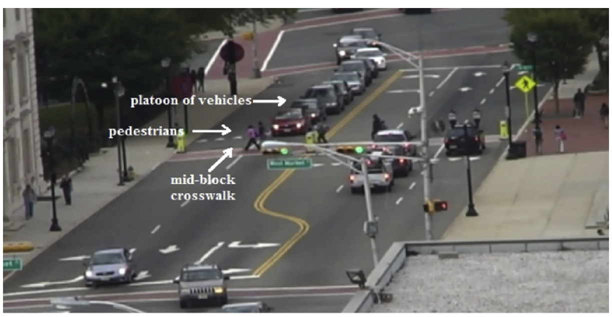

Fig. 2 – Study site 2.

activities. Data was recorded for a total of 22 h, on different days of the week. Once the field data recording was completed, the second step was to carefully and meticulously review and summarize the video recordings. A stop watch was used to record the time it took a pedestrian to walk from curb-to-curb. Based on this walking time, the walking speed of a pedestrian was obtained by dividing the measured walking time by the distance of the crosswalk. The use of video camera provided an advantage of recording and eventually measuring every crossing and the time it took to cross. Furthermore, the use of video recording technique in the field study, in part, was to address potential issues, such as incorrectly classifying pedestrians into their respective age groups. It presented an opportunity to analyze each pedestrian more than once by replaying the video over and over to ensure they were correctly classified and walking times accurately measured.

Each pedestrian was classified by one of the following age groups:

- Child (age 0–12)
- Teen (age 13–18)
- Young adult (age 19–30)
- Middle (age 31–60)
- Older (age older than 60 but not classified as "elderly or physically disabled")
- Elderly or physically disabled (e.g., using crutches, a self-propelled wheelchair, etc.)
- Age uncertain

5. Analysis of measured pedestrian walking speeds

The distribution of mean pedestrian walking speed by age group is in Fig. 3. A statistical summary of the data for study sites 1 and 2 is presented in Table 2. The table shows a total of 431 pedestrians recorded at study site 1 and 2506 pedestrians were recorded at study site 2. Of the 431 pedestrians at study site 1, 359 (83%) were young adults, 40 (9%) were middle age, and 32 (7%) were those whose age could not be determined. No other age group was recorded at this site. Of the 2506 pedestrians recorded at the second site, 2457 (98%) were observed to be "walking", while the remaining 49 (2%) were observed to be either running or both walking and running during crossing. These 49 data points were not included in the final dataset. A breakdown of the 2457 pedestrians who were walking shows, 268 (11%) were teenagers, 294 (12%) were young adults, 1645 (67%) were middle age, 149 (6%) were older, 60 (2%) were elderly or physically disabled, and 41 (1.7%) were those whose age

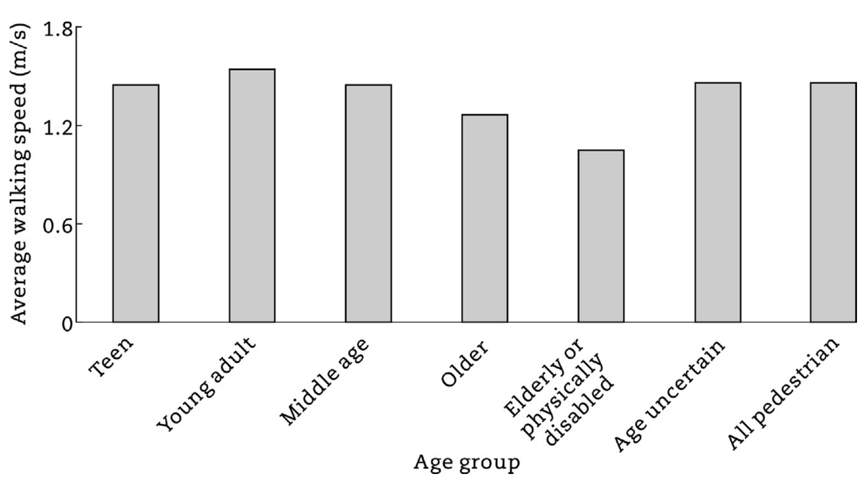

Fig. 3 – Distribution of mean pedestrian walking speed by age group.

Table 2 – Summary statistics of pedestrian walking speeds by age group.

Age group	Sample size		Mean (m/s)	Std. dev (m/s)	Min. (m/s)	Max. (m/s)
	Study site 1	Study site 2				
Teen (age 13–18)	0	268	1.45	0.23	0.81	3.35
Young adult (age 19–30)	359	294	1.55	0.23	0.91	2.51
Middle age (age 31–60)	40	1645	1.45	0.20	0.85	2.48
Older (more than 60 but not classified as elderly)	0	149	1.26	0.20	0.85	2.17
Elderly or physically disabled	0	60	1.04	0.14	0.67	1.44
Age uncertain	32	41	1.46	0.15	1.22	1.83
All pedestrian	431	2457	1.45	0.23	0.67	3.35

Table 3 – Percentile walking speeds by age group.

Age group	Sample size	Walking speed (m/s)	
		15th percentile	50th percentile
Teen (age 13–18)	268	1.24	1.44
Young adults (age 19–30)	653	1.35	1.58
Middle (age 31–60)	1685	1.24	1.45
Older (more than 60 but not classified as elderly)	149	1.09	1.24
Elderly or physically disabled	60	0.91	1.02
Age uncertain	89	1.26	1.45
All pedestrian	2904	1.24	1.45

groups could not be determined. The statistical summary of the data shows pedestrians in the young adult age group walked the fastest, at a mean speed of 1.55 m/s. While pedestrians in the elderly or physically disabled age group walked the slowest, at a mean speed of 1.04 m/s.

In addition to the mean pedestrian walking speed, 15th and 50th percentile speeds of pedestrians were also obtained. These percentile speeds indicate the speeds below which 15% and 50% of the pedestrians walked while crossing at midblock. Table 3 shows the 15th and 50th percentile walking speeds by age group. The table shows 85% of older and elderly or physically disabled pedestrians walked at speeds greater than 1.09 m/s and 0.91 m/s respectively. It also shows 85% of young adults walked at speeds greater than 1.35 m/s, and 85% of teenagers and middle age pedestrians walked at speeds greater than 1.24 m/s.

The cumulative frequency distribution curves presented in Figs. 4 and 5 indicate the 15th and 50th percentile walking speeds by age group as shown in Table 3. The curves show the percentage of pedestrians and their corresponding walking speeds. Fig. 4(a) and (b) show the cumulative frequency curves plotted for all walking speed values for teenagers and young adults, respectively. The curve for teen age group shows a 15th percentile (50th percentile) walking speed of 1.24 m/s (1.44 m/s). The curve for young adults shows 15th percentile (50th percentile) walking speeds of 1.35 m/s (1.58 m/s).

Fig. 4(c) and (d) show the cumulative frequency distribution curves for all walking speed values for middle age and older pedestrians, respectively. The curve for middle age pedestrians shows a 15th percentile walking speed of 1.24 m/s and a 50th percentile speed of 1.45 m/s. The curve for older pedestrians shows a 15th percentile walking speed of 1.09 m/s and a 50th percentile speed of 1.24 m/s.

Fig. 4(e) and (f) show the cumulative distribution curves of pedestrian walking speeds for elderly or disabled pedestrians and those pedestrians whose ages could not be determined, respectively. The curve for elderly or disabled pedestrians shows a 15th percentile walking speed of 0.91 m/s and a 50th percentile walking speed of 1.02 m/s. The curve shows 85th percentile of elderly or physically disabled pedestrians walked at speeds greater than 1.22 m/s; while 100% of all elderly or disabled pedestrians walked at speeds below 1.52 m/s. The curve for uncertain age group shows 85% of pedestrian whose age groups could not be determined walked at speeds greater than 1.26 m/s, and 50% walked at speeds greater or less than 1.45 m/s.

Fig. 5 shows the cumulative distribution curve of walking speeds of all the pedestrians recorded at both study sites. It is shown that 85% of all pedestrians walked at speeds greater than 1.24 m/s. While 50% of all pedestrians walked at speeds greater or less than 1.45 m/s.

6. Results

Two statistical tests were performed to compare the walking speed between the different age groups. The analysis of variance (ANOVA) test and the independent two-sample *t*-test were performed to compare the walking speed between the different age groups. The ANOVA test was performed to statistically analyze the measured free-flowing pedestrian walking speeds to accommodate all combinations of the pedestrian age groups. The result of this test is shown in the Tables 4 and 5. Table 5 shows a *p*-value less than the significance level of 0.05, and a calculated *F* value that is far greater than the critical value. This indicates a statistically significant difference between the mean values of at least two age groups. ANOVA test, however, does not specify which of the age groups. This, therefore, warrants conducting multiple *t*-tests to determine which age groups have statistically significant difference between their means. In Table 5, SS, df and MS are the sum of squares, degrees of freedom and mean squares, respectively. The sum of squares (SS) is the sum of the square of variation, where variation is the spread between each individual value and mean. The mean square gives an indication of the differences between the sample means. Degrees of freedom

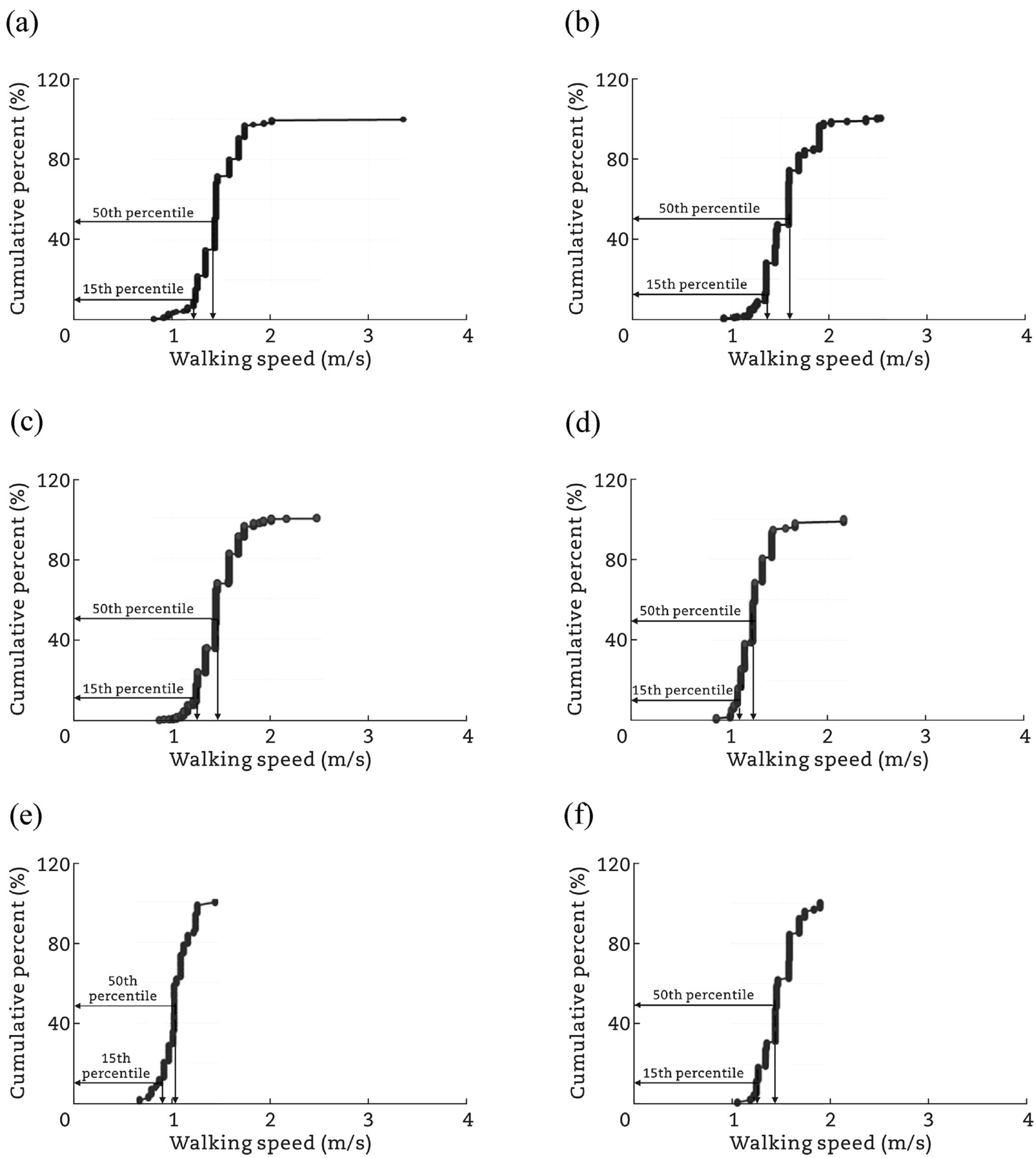

Fig. 4 – Cumulative frequency distribution of walking speeds. (a) Teen age group. (b) Young adult age group. (c) Middle age group. (d) Older age group. (e) Elderly or physically disabled age group. (f) Age uncertain age groups.

is the maximum number of logically independent values in the data sample that have the freedom to vary.

The multiple independent two-sample *t*-tests were conducted using the statistical analysis system (SAS) software (2015) with the goal of testing the null hypothesis of no statistically significant difference between the mean walking speed values by age group at a level of significance of 0.05. In conducting independent two-sample *t*-test, there is the need to test the hypothesis of equal variance using the Pooled and the Satterthwaite's methods. Therefore, two possible *t*-statistics and two different *p*-values are obtained from this test. The pooled variance estimator is used if it assumed that the two populations have equal variance. The Satterthwaite method is used when the variances are not

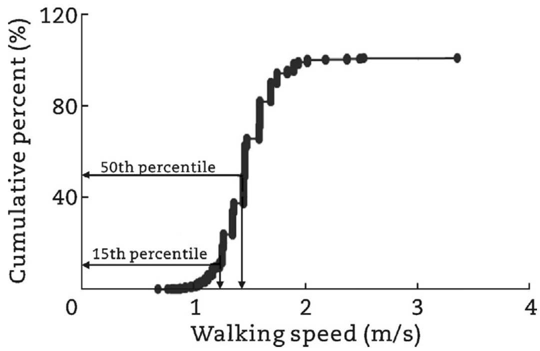

Fig. 5 – Cumulative frequency distribution of walking speeds for all pedestrians.

Table 4 – Statistics on pedestrian walking speeds by age group.

Groups	Count	Sum	Average	Variance
Teens	268	387.72	1.45	0.05
Young adult	653	1008.65	1.54	0.06
Middle age	1685	2442.86	1.45	0.04
Older	149	187.82	1.26	0.04
Elderly or physically disabled	60	62.46	1.04	0.02

Table 5 – Summary of ANOVA statistics on pedestrian walking speeds by age group.

Source of variation	SS	df	MS	*F*	*p*-value	*F* crit
Between groups	21.22	4.00	5.30	121.50	<0.0001	2.38
Within groups	122.68	2810.00	0.04			
Total	143.89	2814.00				

assumed to be equal. The *F* distribution is the ratio of the two estimates of variances. It determines whether there is significant difference in variance. The Satterthwaite method is used to interpret the *p*-value if the $Pr > F$ value is less than the critical value of 0.05. Otherwise, the Pooled method is used. The *p*-value is the probability of observing a *t*-value of equal or greater absolute value and the null hypothesis. The *p*-values ($Pr>|t|$) in Table 6 are less than the significant level of 0.05 for all age group pairs with the exception of teenage and middle age group pair. It is therefore concluded that the difference in means of walking speeds between these two age groups is not significantly different from zero. However, the differences in the mean walking speeds are statistically significant for the other age group pairs.

7. Application of the un-signalized midblock crosswalk pedestrian walking speed parameter

As a second objective, this paper demonstrates how the midblock pedestrian walking speed parameter obtained in this study could be incorporated into the HCM Urban Street methodology. As discussed previously, the HCM methodology for evaluating the level of service urban street segments provide to automobile traffic uses the segment travel speed as the performance metric to determine the level of service on street segments. The segment travel speed equation as shown in Eq. (1), in part, includes a segment running time equation shown in Eq. (2), which estimates the running time of platoon vehicles between an upstream and a downstream signalized intersection based on the segment's operational and geometric characteristics. The segment running time equation incorporates a component that accounts for delays due to different sources along the segment (e.g., curb parking, pedestrian activity at midblock, etc.). However, the manual does not provide specific values to adjust the segment running time for such delays. The delay incurred by interrupted vehicles during midblock pedestrian activity involves three components. The first component is the delay due to deceleration, which is incurred as the driver perceives and reacts to a pedestrian the instant he/she enters the crosswalk. The second delay component is due to stopping. This delay is incurred once the vehicle comes to a full stop and the driver waits for the pedestrian to cross. The third delay component is due to acceleration to normal speed. It is incurred once the pedestrian has crossed the street, and the driver starts to accelerate until it reaches the normal speed he/she was driving before the interference. The delay due to deceleration and stopping is related to the time it takes the pedestrian to cross within the designated midblock crosswalk. Therefore, increasing average pedestrian walking speed decreases the time for pedestrians to cross. Consequently, the stopped delay is decreased and the travel speed along the segment is increased. Increasing the segment's average travel speed increases the level of service along the segment. The average time it takes pedestrians to cross can be calculated as a function of the average distance pedestrians walk during a midblock interference and their average walking speed. Fig. 6 below shows the HCM urban street segment analysis methodology for automobile mode and the relationship between level of service (LOS) and average pedestrian walking speed.

The average time it takes for pedestrians to cross a street can be estimated as a function of the average distance pedestrians walk during a midblock interference and the average walking speed. The average pedestrian walking distance during a midblock interference on a two-lane and a four-lane urban street segment could be estimated for different scenarios of midblock pedestrian-vehicle interference as illustrated in Figs. 7 and 8, respectively. At un-signalized midblock crosswalks on urban streets, pedestrians have the right-of-way. Therefore, drivers must yield or come to a full stop for pedestrians to cross. This paper analyzes four different scenarios of pedestrian-vehicle interference at un-signalized midblock crosswalk on two-lane and four-lane urban street segments. In the first scenario, as illustrated in Fig. 7, the interference starts from the instant a pedestrian from Point A and a pedestrian from Point B enter the crosswalk. For this scenario, the average walking distance equals the critical walking distance. This critical distance is defined as the longest distance a pedestrian would have to walk during an interference. The critical walking distance on

Table 6 – Summary of *t*-test statistics of pedestrian walking speeds by age group.

Variable	Method	Equality of variances				Variance	DF	t-value	Pr > |t|
		Den DF	Num DF	F value	Pr > F				
Teen and young adult	Folded F	267	652	1.03	0.8089				
	Pooled					Equal	919	−5.75	<0.0001
	Satterthwaite					Unequal	502.86	−5.79	<0.0001
Teen and older	Folded F	267	148	1.39	0.0277				
	Pooled					Equal	415	−8.26	<0.0001
	Satterthwaite					Unequal	349.17	−8.65	<0.0001
Teen and middle age	Folded F	267	1684	1.40	0.0002				
	Pooled					Equal	1951	0.23	0.8187
	Satterthwaite					Unequal	330.64	0.20	0.8391
Teen and elderly or physically disabled	Folded F	267	59	2.73	<0.0001				
	Pooled					Equal	326	−12.99	<0.0001
	Satterthwaite					Unequal	141.43	−17.60	<0.0001
Young adult and older	Folded F	652	148	1.42	0.0089				
	Pooled					Equal	800	−13.67	<0.0001
	Satterthwaite					Unequal	253.73	−15.27	<0.0001
Young adult and middle age	Folded F	652	1684	1.43	<0.0001				
	Pooled					Equal	2336	−9.88	<0.0001
	Satterthwaite					Unequal	1023.3	−9.13	<0.0001
Young adult and elderly or physically disabled	Folded F	652	59	3.10	<0.0001				
	Pooled					Equal	711	−16.42	<0.0001
	Satterthwaite					Unequal	96.665	−25.88	<0.0001
Older and elderly or physically disabled	Folded F	148	59	1.97	0.0037				
	Pooled					Equal	207	−7.85	<0.0001
	Satterthwaite					Unequal	151.57	−9.03	<0.0001
Middle age and older	Folded F	1684	148	1.01	0.9318				
	Pooled					Equal	1832	11.25	<0.0001
	Satterthwaite					Unequal	175	11.22	<0.0001
Middle age and elderly or physically disabled	Folded F	1684	59	1.95	0.0015				
	Pooled					Equal	1743	−15.95	<0.0001
	Satterthwaite					Unequal	67.488	−21.76	<0.0001

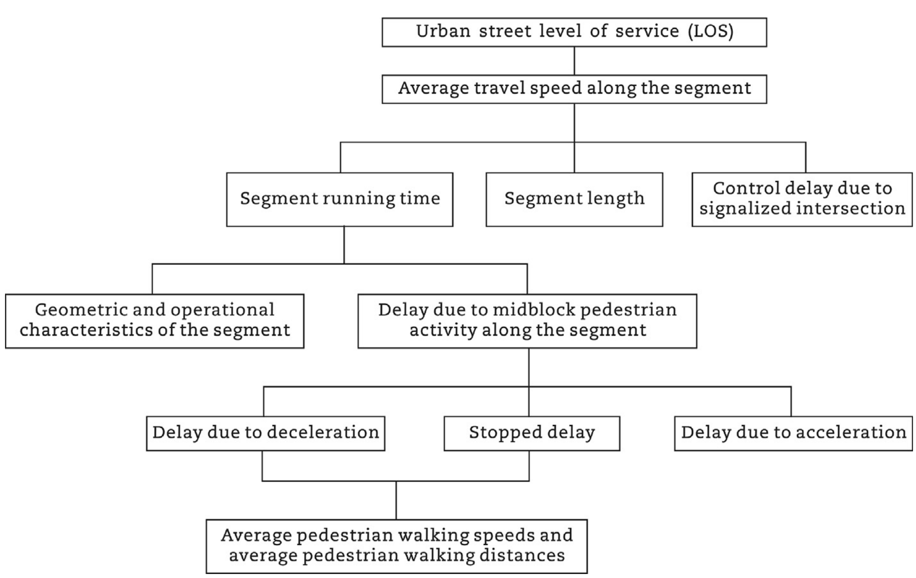

Fig. 6 – Relationship between pedestrian walking and urban street level of service to automobile.

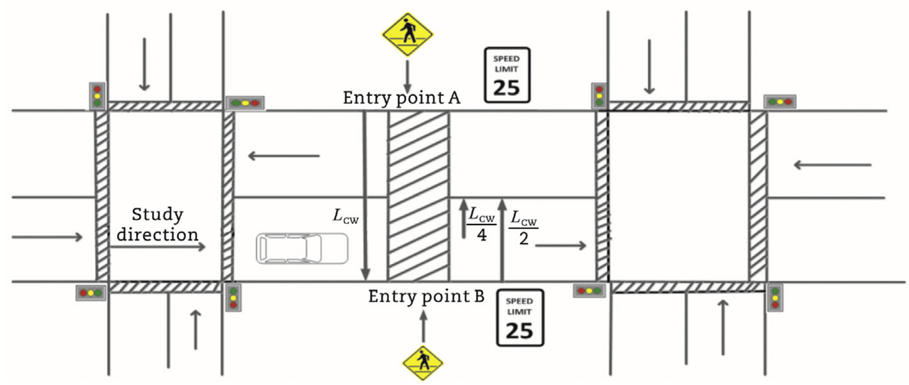

Fig. 7 – Outline of midblock crosswalk on two-lane urban street segment.

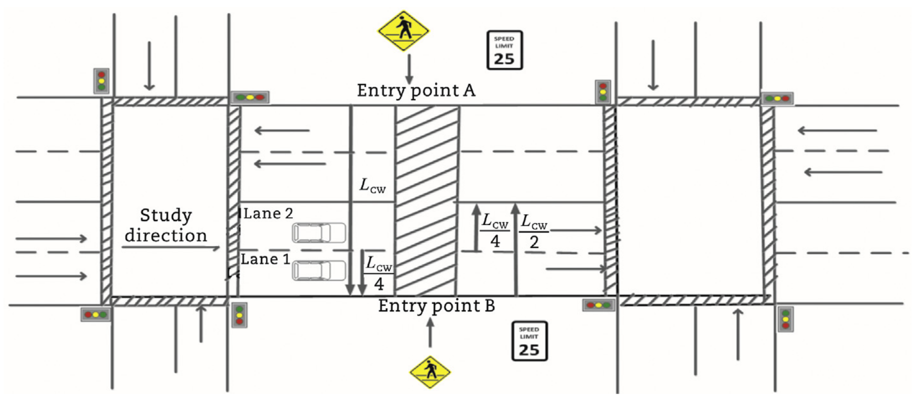

Fig. 8 – Outline of midblock crosswalk on four-lane urban street segment.

a two-lane urban street segment will be the length of the crosswalk, L_{CW}. It is the distance a pedestrian that entered the crosswalk from entry point A will have to walk. In the second scenario, the interference in the second scenario starts from the instant a pedestrian enters the crosswalk from entry Point A only. The average walking distance during the interference on both two-lane and four-lane urban street segments will be the same as the average walking distance for the first scenario.

In the third scenario, the interference starts immediately after a pedestrian enters the crosswalk from entry Point B only. Therefore, on a two-lane urban street segment, the critical walking distance is one-half the length of the segment, given as $1/2L_{CW}$. It is assumed the driver will start to accelerate once the pedestrian has crossed the single lane in the study direction (as shown in the figures). While, on a four-lane urban street segment, the critical walking distance for vehicles in Lanes 1 and 2 will be one-fourth ($1/4L_{CW}$) and one-half ($1/2L_{CW}$) the length of crosswalk,. Therefore, the average walking distance during the interference is the average of the walking distance for the driver in Lane 1 and the driver in Lane 2, and is given as three-eight the length of the crosswalk, $3/8L_{CW}$.The interference during the fourth scenario starts when the driver sees pedestrians that already entered the crosswalk from Point A and Point B, and are assumed to have walked one-fourth the length of the crosswalk. Therefore, on a two-lane urban street segment, the critical walking distance will be one-fourth ($1/4L_{CW}$) the length of the crosswalk. On a four-lane urban street segment, the critical walking distance for a vehicle in Lane 1 will be three-fourth ($3/4L_{CW}$) the length of the crosswalk. That is, the driver in Lane 1 would have to slow down or come to a complete stop for the pedestrian crossing from Point A, who has already walked one-fourth the length of the crosswalk. The critical pedestrian walking distance for a vehicle in Lane 2 would be one-half ($1/2L_{CW}$) the length of the crosswalk. The average walking distance during the interference, therefore, is given as$5/8L_{CW}$. A detailed description of these scenarios is presented by Forde and Maina (2017).

8. Discussion

This study measured and analyzed two key pedestrian walking speed parameters for midblock crosswalks on urban street segments. The first parameter is the average free-flow walking speed by age group. This paper also illustrates how this parameter could be incorporated into the Urban Street

Segment Analysis Chapter to account for one of the limitations of the methodology in evaluating the level of service urban street segments provide to automobile users under conditions of midblock pedestrian interference.

The second parameter is the percentile walking speed by age group. This parameter may be applied in designing signal timings for pedestrians crossing at midblock on urban street segments. Based on the proportion of pedestrians by age groups in the population within an urban area, pedestrian signal timings may be designed using the appropriate percentile walking speed value.

In addition, transportation agencies most often use "complete streets" policy to plan and design urban street facilities. This policy is a multi-modal planning and design approach that accounts for automobile, pedestrian, bicycle and transit modes. One of the drawbacks of this policy is its impacts to automobile users, especially at un-signalized midblock crosswalks on urban street segments, where drivers are frequently interrupted by crossing pedestrians. Interruptions to traveling motorists increase delay and reduce the performance of the street segment. Another drawback is the safety of pedestrians as they cross at midblock. Therefore, to efficiently plan and design a multi-modal urban street facility, it is critically important to understand the impact of pedestrians to determine the performance of urban street segments and to correctly assess whether the un-signalized midblock crossing should be present or replaced with a traffic signal. In addition, the midblock pedestrian walking speeds obtained in this research may be applied in determining the timing for rectangular rapid flash beacons (RRFBs).

9. Conclusions

This study measured pedestrian walking speeds by different age groups as they crossed within un-signalized midblock crosswalks on urban street segments. The measured speed data were analyzed to determine the 15th and 50th percentile walking speeds by age group. An ANOVA test was performed to compare the means of pedestrian walking speeds to accommodate all combinations of the pedestrian age groups. The results showed a p-value less than the significance level of 0.05 and a calculated F value far greater than the critical value. This indicated statistically significant difference between the means of at least two of the age groups. To determine which age group pair had statistically significant difference in means, multiple independent two-sample t-tests were performed. Results of the tests showed statistically significant difference between the mean walking speed of all age group pairs, with the exception of teenage and middle age group pair. As a second objective, this paper also demonstrated how the findings of this research could be incorporated into the HCM 2010 urban street methodology to account for the impact of midblock pedestrian activity on the level of service urban street segments provide to automobile users. Based on the findings of this study, it is therefore concluded that.

- Teen and middle age pedestrians walk at approximately the same speeds when crossing at un-signalized midblock crosswalks on urban street segments.
- Young adults walk the fastest when crossing at un-signalized midblock crosswalks on urban street segments. While elderly or physically disabled pedestrians walk the slowest.
- About 85% of all pedestrians crossing within midblock crosswalks on urban street segments walk at speeds greater than 1.24 m/s. This value maybe appropriate for designing signal timings for pedestrians crossing at midblock crosswalks. However, in urban areas with high population of elderly or physically disabled pedestrians, a value of 0.91 m/s may be is appropriate for pedestrian signal timings at midblock crosswalks. And a value of 1.26 m/s in urban areas with high population of younger pedestrians.

Conflict of interest

The authors declare that there is no conflict of interest regarding the publication of this article.

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