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Pedestrians' Speed Analysis at Signalized Crosswalks

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Abstract

Pedestrian speed is essential for designing signal timings as well as for understanding pedestrian safety issues. This paper presents analysis of three types of pedestrian speeds (entry speed, crossing speed, and exit speed) at three signalized crosswalks in the State of Qatar. Pedestrian movements were tracked using *TrafficAnalyzer* software and data were analyzed to determine the effect of signal indications, crosswalk length, and crossing direction on pedestrian speeds. The results of this analysis showed that only 23.69% pedestrians crossed legally, during pedestrian green or pedestrian flashing green interval. Moreover, the pedestrian entry speeds were significantly affected by the pedestrian signal indications. Furthermore, the crossing speeds were positively correlated with crosswalk length for pedestrians crossing on green and red indications while pedestrian exit speeds were independent of crosswalk length but significantly affected by crossing direction.

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Keywords: Signalized crosswalk; Arabian Gulf countries; pedestrian entry speed; pedestrian exit speed; pedestrian crossing speed; State of Qatar

1. Background

Design of pedestrian signal timings at signalized crosswalks is based on the pedestrians' crossing speed. The 15th percentile crossing speed is commonly used for design purposes; an accurate estimation of pedestrian speeds is essential for optimum design of signals. Furthermore, pedestrian speeds are vital for pedestrian simulation purposes as well. With the advances in the modelling and simulation, pedestrian simulation has gained attention in recent

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years to assess the safety and the efficiency of pedestrian facilities. For pedestrian movements simulation, pedestrian speeds at entry, exit, and while crossing are required to develop realistic pedestrian maneuvers. In past, very few studies have studied entry and exit speeds. This study specifically analyses the distribution of various pedestrian speeds and determines factors affecting them. To the best of the authors' knowledge, this study is the first of its kind focusing on Arabian Gulf countries. Previously, pedestrian crossing speed at marked crosswalk was analyzed[1], but the speeds at signalized crosswalks remain unexplored. The two research objectives investigated, in this paper, are stated as below:

- Assess the effect of crosswalk length on pedestrians' entry speed, crossing speed, and exit speed.
- Investigate the effect of crossing direction on pedestrians' entry speeds, crossing speeds, and exit speed.

2. Literature review

Pedestrians' overall crossing speeds were widely analyzed by researchers at microscopic level with specific emphasis on analyzing effect of pedestrian characteristics on overall crossing speed. Pedestrians' crossings data at 27 crosswalks in Jordan were analyzed to determine the factors affecting pedestrian crossing speed. The single factor to multi factor ANOVA results indicated that gender, age, group size, and street width affected pedestrian crossing speed[2]. Pedestrians' crossing speed study at four signalized intersections in Melbourne city showed that generally, the crossing speeds on weekdays were lower than that of weekends and speed of unqueued pedestrians was lower than queued pedestrians[3]. Fitzpatrick et al. used crossing speeds at 42 sites in USA having different treatments to determine the value for design of pedestrian signal times. Statistical test revealed that the 15th percentile speeds for gender and age groups were statistically different. Practically, speeds were different for age, group size, and five-minute vehicle volume[4]. Further, pedestrian movements at eleven crossings in Wisconsin, USA were videotaped to determine the various factors related pedestrian crossing speeds. The multi-factor ANOVA indicated that the crossing speeds were different for disability and age, group size, and pedestrian signal condition. Pedestrians walked fastest during don't walk phase, faster during flashing phase, and with average speed during walk phase[5]. Site observations were undertaken to study the effect of time of day (lighting conditions) on crossing speed in Kuala Lumpur, Malaysia using 907 cases at signalized crosswalk. The crossing speed was found to be statistically different for type of crosswalk, gender, and age groups and it was similar for race and time of day (day and night)[6].

However, very few studies were found on detailed analysis of various pedestrian speeds at signalized crosswalks. Detailed analysis would be of interest because these are precise and can capture the minor variation in the speed and provide robust results. In addition, the actual distance walked by a pedestrian is used as opposed to the length of the crosswalk. The effect of pedestrian signal timing (green intervals, flashing green time, and red indication), crossing direction, and crosswalk length were investigated on various pedestrian speeds using data from three signalized crosswalks in Nagoya city. The Pedestrian Green (PG) was divided into three intervals; to find that as PG passes the entry speed and crossing speed of the pedestrian increases. Further, at longer crosswalks greater crossing speeds were observed[7]. Subsequently, pedestrians' sudden changes in crossing speeds were analyzed using multinomial logit models for the pedestrian movements at five signalized crosswalks at three intersections in Nagoya City. The effect of crosswalk geometry and signal timing was studied on sudden speed changed along with its timing and locations. The results indicated that speed change choices were affected by entering speed and crosswalk length[8&9]. In another study, a traffic signal optimization strategy for isolated intersections that considers pedestrian and vehicle delays was developed. In this study, a fixed pedestrian speed was assumed regardless of pedestrian characteristic and crosswalk geometry. It was found that the pedestrian speed was a primary factor affecting optimization function[10]. Authors extended the optimization function to consider coordination of vehicle and pedestrian flows simultaneously[11]. It was concluded that the settings of pedestrian walking speed on the sidewalk and crossing speed were essential for developing efficient pedestrian coordination strategies.

3. Pedestrian speeds

Firstly, it is important to specify the pedestrian's crossing direction. The pedestrians crossing from the side where vehicles are exiting the intersection are considered as near side pedestrians while those crossing from the opposite side are considered as far side pedestrians (Fig. 1). Authors acknowledge the fact that some pedestrians cross near the crosswalk, all the pedestrians starting and completing crossing in the designated area were considered in analysis (red rectangle in Fig. 1).

- Entry speed (v_{en}): The instantaneous speed with which a pedestrian enters the crosswalk.
- Exit speed (v_{ex}): The instantaneous speed with which a pedestrian exits the crosswalk.
- Crossing speed (v_c): The crossing speed of a pedestrian is the average travel speed along the entire crosswalk. It is calculated by dividing total distance traveled while crossing by the time spent by the pedestrian to cross the crosswalk from entry point to exit point (Equation 1). For staged crossings, two crossing speeds are calculated, first and second half of crossing (v_{c1} and v_{c2}), as shown in Equation 2 and 3 respectively, because pedestrians often cross half the distance and wait at the median before starting crossing the second half of the crosswalk.

$$v_c = \frac{\sqrt{(y_c - y_a)^2 + (x_c - x_a)^2}}{(t_c - t_a)} \quad \text{between A \& C} \qquad (1)$$

$$v_{c1} = \frac{\sqrt{(y_b - y_a)^2 + (x_b - x_a)^2}}{(t_b - t_a)} \quad \text{between A \& B} \qquad (2)$$

$$v_{c2} = \frac{\sqrt{(y_c - y_b)^2 + (x_c - x_b)^2}}{(t_c - t_b)} \quad \text{between B \& C} \qquad (3)$$

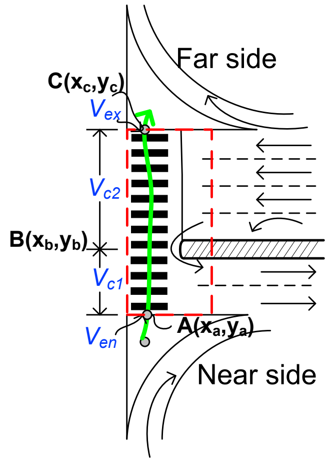


Fig. 1 Illustration of pedestrian speeds

4. Methodology

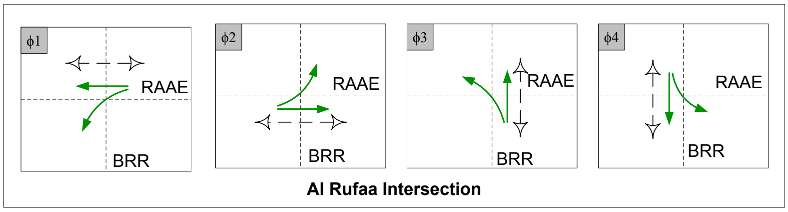
4.1. Site description

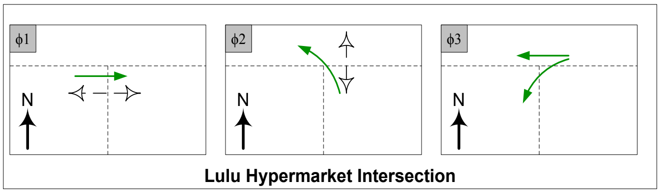
Conventionally, Doha city observes fewer walking trips, in order to obtain pedestrians data at busy intersections; two signalized intersections in Doha City were videotaped. Both intersections were located near busy commercial complexes. The first site is Al Rufaa intersection, a four-legged junction, which is used by many residents to access the nearby commercial complex by foot. The south approach crosswalk at Al Rufaa intersection was selected since it has significant movement of pedestrians. Further, two crosswalks located at the east and south approaches of Lulu Hypermarket intersection, a three-legged junction, were selected for the analysis. The characteristics of these intersections are listed in Table 1 while the phasing information and signal timings are shown in Fig. 2. All the signal timings are controlled by Sydney Coordinated Adaptive Traffic System (SCATS). The green time for vehicle movements vary based on the demand but timings for pedestrian signal indications remain the same.

Table 1. Characteristics of selected crosswalks.

Intersection	Approach	Abbreviation	Date of recording	N_{entry}	N_{exit}	N_m	M_w (m)	L_c (m)	W_c (m)	$N_{PG\ \&\ PFG}$	N_R	N_{ip}
Al Rufaa Intersection	South	AR(SA)	21/03/ 2017	4	2	1	0.9	24.50	3.0	18	80	14
Lulu Hypermarket Intersection	East	LH(EA)	30/03/ 2017	5	3	2	2.5	37.65	3.0	24	37	27
	South	LH(SA)		2	2	1	1.9	18.10	3.0	8	44	18

Note: N_{entry} is number of entry lanes, N_{exit} is number of exit lanes, N_m is number of medians, M_w is median width, L_c is length of crosswalk, W_c is width of crosswalk, $N_{PG\ \&\ PFG}$ is number of pedestrians crossing during PG & PFG, N_R is number of pedestrians crossing during R, N_{ip} is number of pedestrians following illegal path





Crosswalk	Phase	PG (s)	PFG (s)	Cycle Length (s)
AR(SA)	ϕ1	8	12	140-235
LH(EA)	Φ2	7	21	167-240
LH(SA)	ϕ1	10	26	167-240

Note: PG is pedestrian green interval and PFG is pedestrian flashing green interval.

Fig.2. Phase diagrams and signal timings for studied intersections.

4.2. Data collection

Both sites were videotaped for twelve hours on a typical weekday from nearby high-rise buildings to cover the entire intersection. Data was extracted for one hour from 5 pm to 6 pm for Al Rufaa Intersection and 5 pm to 6:15 pm for Lulu Hypermarket Intersection. Pedestrian movements were tracked using *TrafficAnalyser* software[12] at one second interval. The point representing a pedestrian's center of body on the ground is recorded as reference point. All the local coordinates were converted to realworld coordinates using projective transformation. A sample of the tracked pedestrian's path is shown in Fig. 3. The view of the intersection was calibrated using the real world coordinates extracted from GIS database obtained. Table 2 shows the details of calibration. Further, pedestrians crossing direction and pedestrian as well as vehicle signal indication at the entry and exit time of the pedestrian were also recorded. Data for pedestrians that were obtained from videos has 121 pedestrians crossing from far side and 90 crossing from near side. Additionally, data for 59 pedestrians, who crossed away from selected crosswalk, was not considered in the analysis because they followed illegal path. This included pedestrians crossing far away from crosswalk or crossing in such a way that making their entry or exit points or complete path was invisible. It should be noted that out of 211 pedestrians used for analysis; only 50 (23.69%) pedestrians crossed during PG or Pedestrian Flashing Green (PFG). Higher proportion of pedestrians crossing during red signal (R) indication and illegal path is the major concern for transport planners. The number of pedestrians in Table 1 indicates that the pedestrians' data relates to uncongested condition and crowded/congested condition does not occur at the observed crosswalks.

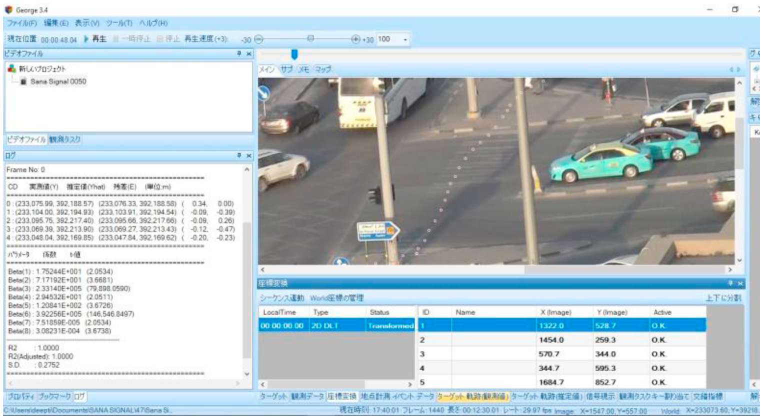


Fig. 3. Screenshot of tracked pedestrians using *TrafficAnalyzer*

Table 2. Co-ordinate transformation results

Intersection	Approach	Abbreviation	R^2 adjusted	SD	Absolute coordinate transformation error (m)		
					Minimum	Maximum	Average
Al Rufaa Intersection	South	AR(SA)	1.000	0.2752	0.00	0.47	0.219
Lulu Hypermarket Intersection	East	LH(EA)	1.000	0.4030	0.000	0.98	0.2657
	South	LH(SA)					

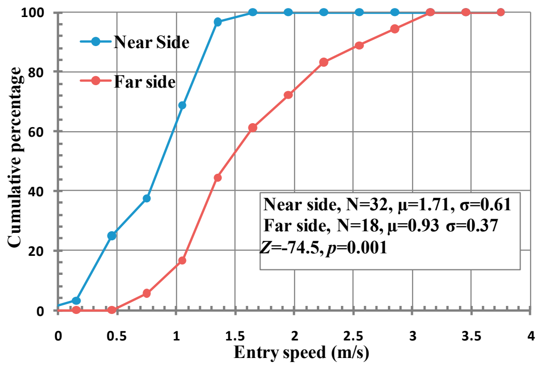


Fig. 4 Distribution of v_{en} for pedestrians crossing during PG & PFG

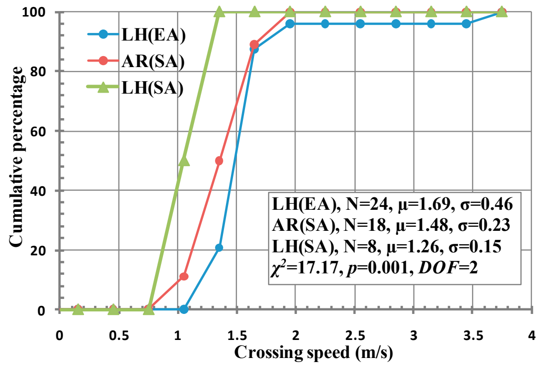


Fig. 5 Distribution of v_c for pedestrians crossing during PG & PFG

5. Results and discussion

The pedestrian movements data obtained from *TrafficAnalyzer* were compiled to calculate various pedestrian speeds. In addition, statistical analysis was done using IBM SPSS Statistics 23.0 where the confidence interval was set at 95%. Initially, the pedestrians speed data were analyzed based on the pedestrian signal indications while entering the crosswalk. In the State of Qatar, most intersections are equipped with pedestrian push buttons to activate pedestrian green phase. However, as observed, some pedestrians during their phase did not call for green signal and crossed while the pedestrian signal was red, probably because they knew their phase where they do not have conflicts with vehicles. Subsequently, three pedestrian entry signal indications were noted, Pedestrian Green (PG), Pedestrian Flashing Green (PFG), and Red (R); here R included the pedestrians who waited for conflicting traffic but did not call for pedestrian phase. ANOVA tests for pedestrians entry speeds showed that the entry speeds were significantly different during different pedestrian signal indications ($\chi2$=8.049, p=0.018, *DOF*=2). Hence, the analyses for pedestrian speeds were divided into two categories; pedestrians crossing in PG and PFG, and pedestrians crossing in R. Authors acknowledge the fact that the pedestrian speeds during PG and PFG may be different but due to lack of sample size these two categories were combined for this study. Further, when pedestrians crossing speeds were analyzed, it was found that the crossing speed during PG and PFG (N=50, μ=1.5455m/s) and single staged crossing during R (N=85, μ=1.5143m/s) was not significantly different (Z=-1.180, p=0.238). Usually, pedestrians crossing speed during R is more than the speed during PG and PFG, hence this contradictory finding needs to be investigated further in future research.

5.1. Pedestrian speed during PG & PFG

5.1.1. Entry speed (v_{en})

ANOVA tests suggested that the pedestrians' entry speeds were not statistically different between the sites ($\chi2$=4.898, p=0.086, *DOF*=2). This might be attributed to the lack of sample size. Furthermore, the statistical test revealed far side pedestrians have significantly higher entry speeds compared to near side pedestrians (Z=74.500, p=0.001). The lower entry speeds for near side pedestrians can be justified because they have to be cautious for the vehicles clearing the intersection during all red period. The distribution of pedestrians' entry speed based on the crossing direction is shown in Fig. 4.

5.1.2. Crossing speed (v_c)

Fig. 5 shows the distribution of pedestrians crossing speeds during PG and PFG for three crosswalks. It should be noted that all pedestrians crossed in one stage when they started crossing during PG or PFG intervals; no two-stage crossings were observed. Estimated crossing speeds were significantly different between three crosswalks ($\chi2$=17.172, p=0.001, *DOF*=2). The variation in overall crossing speeds is attributed to the variation in the length of

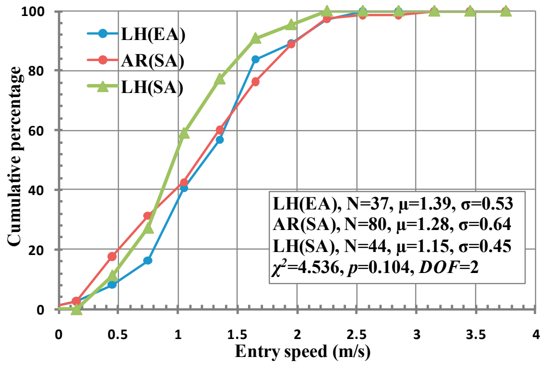


Fig. 6 Distribution of v_{en} for pedestrians crossing during R

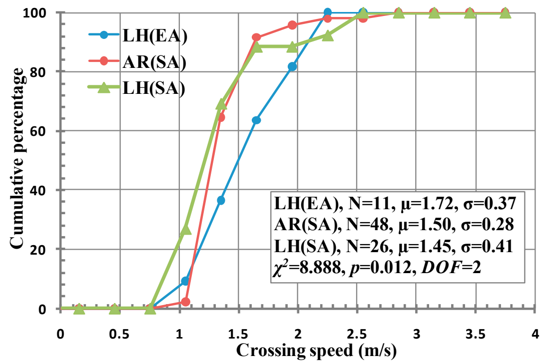


Fig. 7 Distribution of v_c for pedestrians crossing during R

the crosswalks with higher speeds for the longest crosswalk [LH(EA)] and lower speeds for shorter crosswalks [AR(SA) and LH(SA)]. This is in accordance with previous analysis on pedestrian data from Japan[7].

5.2. Pedestrian speed during R

5.2.1. Entry speed (v_{en})

It was interesting to find that between the three crosswalks, pedestrians' entry speeds were not significantly different ($\chi 2$=4.536, p=0.104, DOF=2) as shown in Fig. 6. In addition, the entry speed for near side pedestrians was lower (N=58, μ=1.1771m/s) than that for far side pedestrians (N=103, μ=1.3243m/s), although the difference was not statistically significant (Z=-1.794, p=0.073). Further, the entry speed was similar for single staged (N=85, μ=1.2969m/s) and two staged crossings (N=76, μ=1.2426m/s) (Z=-0.628, p=0.530).

5.2.2. Crossing speed

Two types of pedestrian crossing maneuvers were observed when pedestrians started crossing during R; single staged crossing and two staged crossing. The single staged crossing means that the pedestrian crossed the crosswalk without stopping on the median between two directions. While in the two staged crossing, which is the most common behavior for those crossing during pedestrian red signal indication, pedestrians cross half of the crosswalk (where traffic is stopped due to red signal) and waited at the median looking for a suitable gap between arriving traffic or waited for pedestrian green signal indication. Crossing speeds for these two maneuvers were analyzed separately.

5.2.2.1. Single-stage crossing (v_c)

Total, 85 cases were observed for pedestrians who crossed in a single stage during red signal indication for pedestrians. ANOVA showed that the crossing speeds were statistically different between the three crosswalks ($\chi 2$=8.888, p=0.012, DOF=2). The average crossing speed was inversely related to the length of crosswalk as shown in Fig. 7. Due to the lack of sample size, the impact of crossing direction was investigated only at AR(SA), where no significant difference was found between the crossing speeds of near side and far side pedestrians (Z =-0.109, p=0.913).

5.2.2.2. Two-stage crossing (v_{c1} & v_{c2})

For two staged crossing, 76 cases were identified. The ANOVA for crossing speed showed that the three crosswalks have significantly different v_{c1} ($\chi 2$=20.434, p=0.001, DOF=2). The average v_{c1} for crosswalk LH(EA), AR(SA), and LH(SA) were 1.27m/s, 1.60m/s, and 1.13m/s, respectively. Higher v_{c1} was observed for AR(SA) because pedestrians took advantage of gaps in traffic while starting to cross, which made them cross aggressively. For other crosswalks, pedestrians initiated crossing when the conflicting traffic was stopped completely as they could not find gaps in traffic due to heavy vehicle volume. The distributions of v_{c1} are shown in Fig. 8.

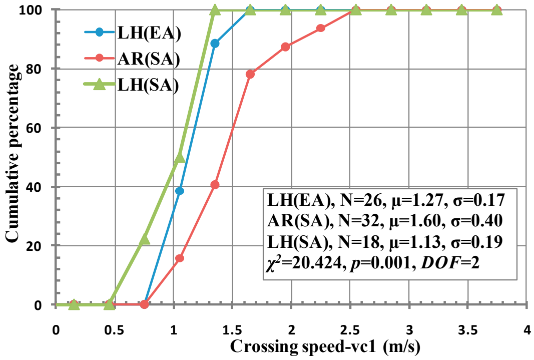


Fig. 8 Distribution of v_{c1} for pedestrians' crossing during R

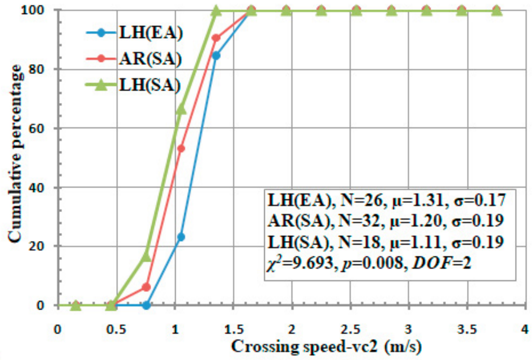


Fig. 9 Distribution of v_{c2} for pedestrians' crossing during R

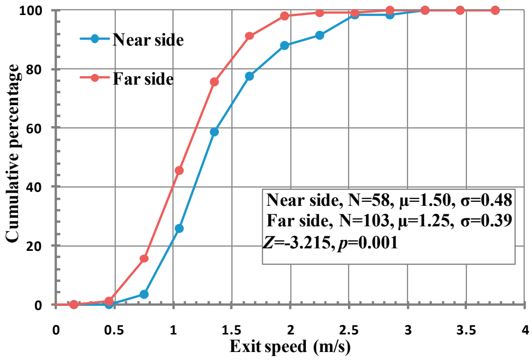


Fig. 10 Distribution of v_{ex} for pedestrians crossing during R based on crossing direction

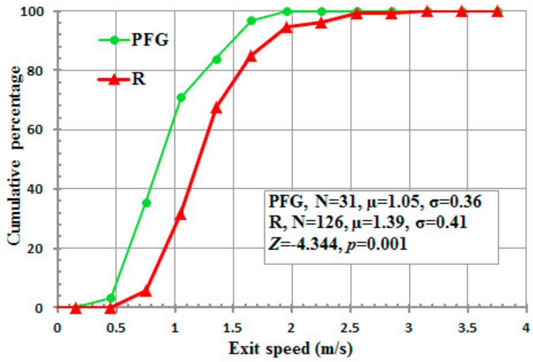


Fig. 11 Distribution of v_{ex} for pedestrians crossing during R based on pedestrian signal indication at exit

Similarly, v_{c2} was also statistically different for three observed crosswalks ($\chi2$=9.693, p=0.008, DOF=2). v_{c2} followed similar trends to v_{c1}. The distributions of v_{c2} are shown in Fig. 9. Overall, similar average speeds, v_{c1} and v_{c2} were observed for LH(EA) and LH(SA). The impact of pedestrian crossing direction could not be investigated due to the limited sample size.

5.2.3. Exit speed (v_{ex})

The v_{ex} were analyzed for 161 pedestrians who crossed during pedestrian red signal indication. The ANOVA found that v_{ex} was not statistically different between the crosswalks ($\chi2$=5.163, p=0.076, DOF=2). However, the analysis revealed that far side pedestrians have significantly lower v_{ex} compared to near side pedestrians, Fig. 10 (Z=-3.215, p=0.001). This can be attributed to the conflicts with exiting vehicular traffic at the intersections during pedestrian red signal indication. In such situations, usually exiting vehicles have high speeds, which threaten the pedestrians and push them to speed up while crossing to clear the conflict area.

Regarding the impact of two staged and single staged crossing on v_{ex} for pedestrians crossing during R, it was found that v_{ex} for single staged crossing was significantly higher (N=78, μ =1.49 m/s) than that of two staged crossing (N=48, μ=1.23 m/s) (Z=-3.454, p=0.001).

A separate analysis revealed that v_{ex} was statistically different for different signal indications at exit (Z=-4.344, p=0.001). For this analysis, PG signal indication was not included because there were only four pedestrians who started during R and finished during PG. Fig. 11 shows the distributions of v_{ex} based on the pedestrian signal indication at exit. As expected higher v_{ex} was observed for R signal indication. Further, the reason for lower exit speeds during PFG may be that these pedestrians are aware about the buffer interval which is followed by PFG.

6. Conclusions

This paper analyzed pedestrians' speeds (mainly entry speed, crossing speed, and exit speed) at signalized crosswalks in the State of Qatar. Data were collected at three signalized crosswalks located at two intersections in Doha city. The processed data showed that 23.69% of observed pedestrians crossed during PG or PFG while remaining pedestrians crossed during R. The high proportion of pedestrians crossing during R indicated higher risks undertaken due to the interactions with conflicting vehicular traffic. Crosswalk length is a major influencing factor on pedestrian crossing speed (v_c, v_{c1}, and v_{c2}) where longer crosswalks have higher crossing speeds. Furthermore, the statistical analysis showed that the pedestrians' entry speed was significantly affected by crossing direction during PG and PFG. For pedestrians crossing during R, entry speed was independent of crosswalk length and crossing direction while exit speed was significantly influenced by crossing direction. Although some interesting findings were reported in this study, the results need to be strengthened by collecting larger sample size from various sites with different geometric layouts.

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