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Research Article

Estimating Safety Effects of Green-Man Countdown Devices at Signalized Pedestrian Crosswalk Based on Cellular Automata

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Safety effects of Green-Man Countdown Device (GMCD) at signalized pedestrian crosswalks are evaluated. Pedestrian behavior at GMCD and non-GMCD crosswalks is observed and analyzed. A microsimulation model is developed based on field observations to estimate safety performance. Simulation outputs allow analysts to assess the impacts of GMCD at various conditions with different geometric layout, traffic and pedestrian volumes, and the green time. According to simulation results, it is found that the safety impact of GMCD is affected by traffic condition as well as different time duration within green-man signal phase. In general, GMCD increases average walking velocity, especially during the last few seconds. The installation of GMCD improves safety performance generally, especially at more crowded crossings. Conflict severity is increased during last 10 s after GMCD installation. Findings from this study suggest that the current practice, which is to install GMCD at more crowded crosswalks or near the school zone, is effective. Moreover, at crosswalks with GMCD, longer all red signal phase is suggested to improve pedestrian safety during intergreen period.

1. Introduction

For an urban environment as Singapore, conflicts between pedestrians and vehicles occur frequently at the signalized pedestrian crosswalks. There are more than 1,400 signalized road intersections in Singapore, most with pedestrian crosswalks. Over a period of five years (2008 to 2012), there was an average of 82 accidents each year involving pedestrians or cyclists and vehicles at the pedestrian crosswalks; on average, 3 pedestrians were killed and 55 were injured in these accidents per year [1]. In Singapore, several crosswalks have been installed with Green-Man Countdown Device (GMCD) to indicate the amount of time left in the pedestrian crossing phase. These are usually installed at signalized pedestrian crosswalks near schools and at busy intersections [2].

A number of studies have observed pedestrians' behavior at signalized crosswalks. A local study by Koh and Wong [3] found that the decision to cross at red-man signal is affected by the headway between vehicles in the conflicting stream. According to a questionnaire study by Sisiopiku and Akin [4], 45% of pedestrian respondents agreed that they will cross the road if there exists sufficient gap. Several studies found that characteristics of pedestrians themselves and whether they are walking in a group also affect their decision-making and crossing behavior [5, 6]. Koh et al. [7] developed a logistic regression model to estimate the probability of red-man crossing based on observed pedestrian behavior; the model includes number of crossing lanes, being accompanied or not, gender, crossing length, accepted waiting time, standing position of subject, number of passing vehicles, and number of violating pedestrians.

Several studies have found that pedestrian countdown timers increase the number of late starters who managed to finish crossing before red-man phase and to increase the crossing speeds of pedestrians. It is found that as remaining time of green-man signal is provided to pedestrians, it may cause some negative consequences regarding compliance [8–11]. It is also observed that, with the installation of GMCD, a slightly increased number of pedestrians run out of time after the implementation of countdown timers as

Table 1: Statistics of the 6 survey sites.

Site	GMCD	Width	Cycle time/Green-man (s)	Pedestrian volume (ped/h/way)	Vehicle volume (veh/h/lane)	AADT (s)
1	Non-GMCD	25.5 m	110/23	283	211	49.3
2	Non-GMCD	28.7 m	108/23	273	193	40.6
3	Non-GMCD	25.1 m	99/22	194	270	37.2
4	GMCD	27.4 m	103/24	302	156	39.0
5	GMCD	30.4 m	89/25	231	129	47.9
6	GMCD	30.6 m	123/28	148	176	48.8

well as an increased number of late starters (those who enter during flashing light indication) when the countdown timer was graphic and not numerical [12]. However, most studies are based on field observations of vehicle movement characteristics or recording the number of offences. The safety effect, favorable or unfavorable, of GMCD remains unclear. Therefore, the aim of this study is to find out whether installation of GMCD affects safety performance. Moreover, the study also aims to identify under what kind of traffic conditions GMCD is favorable to pedestrian safety.

This study applies a simulation-based approach to estimate quantitative safety impacts of GMCD under various traffic conditions. Cellular Automata (CA) models, which are often applied for modeling and simulating complex traffic scenarios, are applied to model vehicle and pedestrian movements at signalized crosswalks [12]. Compared to other microscopic simulation models, CA models allow analysts to define flexible transition rules to replicate various traffic scenarios. As traffic performance of signalized pedestrian crosswalk is affected by both traffic conditions and crosswalk design, a microsimulation model provides a quick and user-friendly tool to undertake safety assessment under various conditions. Moreover, whereas conventional safety assessment approach relies on historical crash data (which requires adequate accident counts, hence lengthy occurrence period, for numerical stability), the proposed CA approach simulates traffic movements to generate severity-graded traffic conflicts as the performance indicator.

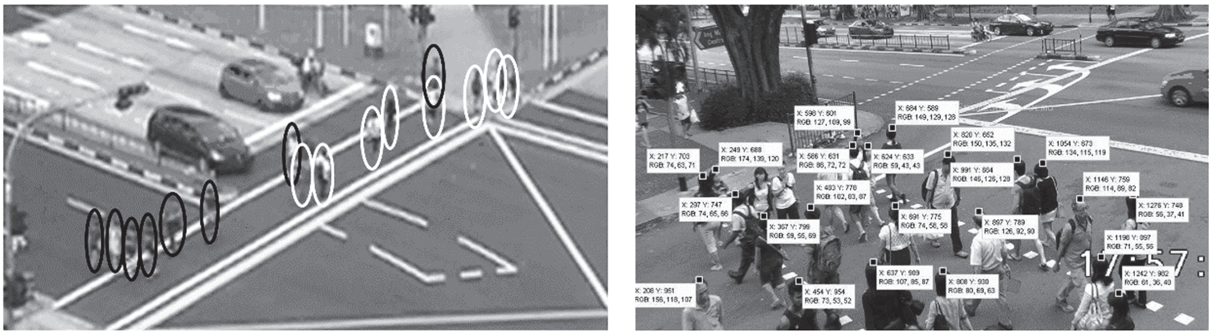
2. Methodology

A simulation-based approach to estimate the safety impacts of GMCD is proposed in this study. Pedestrian movements at signalized crosswalks were studied based on field observations. Based on observed movement characteristics, a CA model was developed to simulate conflicts between pedestrians and vehicles at crosswalks. Safety performance was estimated by computing occurrences and severity of simulated conflicts.

2.1. Field Observations of Pedestrian Movements

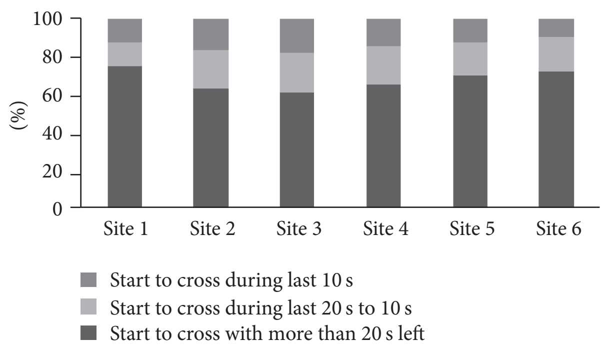
2.1.1. Survey Sites and Data Collection Techniques. Field observations were conducted at 6 pedestrian crosswalks at signalized road intersections in Singapore with similar geometrical layouts and same vehicular signal sequences. These crosswalks were selected based on their locations, at least 1 km away from each other and around 1 km away from schools and transit stations for moderate pedestrian volume. Each pedestrian crossing is 3 m in width and 25.1–30.6 m in length (average = 27.95 m, stand deviation = 2.37 m) and green-man time ranges from 21 s to 28 s (average = 24.16 s, stand deviation = 2.13 S). Among the 6 survey sites, 3 are installed with GMCD. There is no traffic red-light camera (RLC) at these intersections. The field observations were made on 6:00-7:00 pm peak hour during weekdays. Automatic classification and tracking technologies are used to record pedestrian's position, velocity, and forwarding direction, as shown in Figure 1(a). The applied classification and tracking method is validated through comparison with computer-aided manual tracking by labeling pedestrians' position at each video frame, as shown in Figure 1(b). Observed pedestrian and vehicle volumes at the 6 survey sites are summarized in Table 1. Overall accuracies of the automatic tracking approach are found to be 94% for pedestrian trajectory, 93% for velocity profile, and 100% for forwarding direction over a sample of 10,589 pedestrians at the 6 sites [13]. Observed proportions of pedestrians starting to cross, crossing velocity, and cross times are shown in Figure 2. In Singapore, the last 10 s of green signal is flashing at most signalized crosswalks without GMCD, including the 3 survey sites chosen in this study. However, for signalized crosswalks with GMCD, both green light and the countdown timer are flashing. According to Figure 2, in general, a larger proportion of pedestrians (60–80%) start to cross with more than 20 s left. Means and standard variations of velocity and cross time vary among the 6 survey sites. Such variation can be caused by cross width, cycle length, pedestrian volume, and vehicle volume.

2.1.2. Pedestrian Behavior at Non-GMCD and GMCD Crosswalks. To test the significance of the results from observed GMCD and non-GMCD crosswalks, a test for the differences in population proportions was used. This test was performed to evaluate if the differences in the behavior indicators, such as velocities and proportions of crossing, observed between non-GMCD and GMCD crosswalks are statistically significant, thereby indicating whether the pedestrian countdown signals have influenced pedestrian behavior. The null hypothesis (H_0) tested in all cases is that there is no difference of the tested statistics between non-GMCD and GMCD crosswalks, with the alternate hypothesis that there is a difference. The

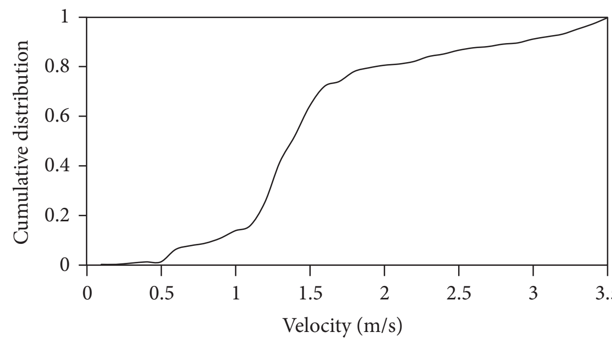


(a) Automatic tracking (b) Computer-aided manual tracking

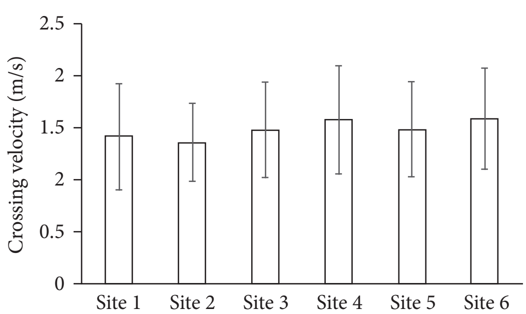
Figure 1: Automatic and manual pedestrian tracking methods.



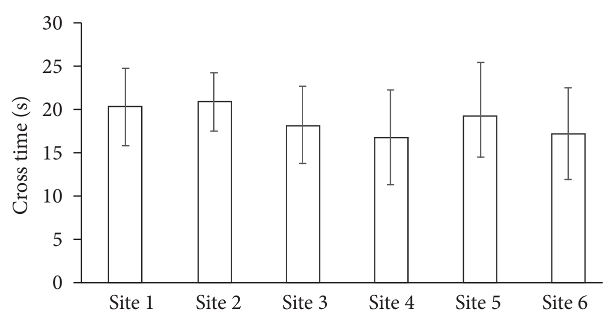
(a) Proportions of pedestrians starting to cross



(b) Cumulative distribution of crossing velocity (site 1)



(c) Means and standard deviations of crossing velocity



(d) Means and standard deviations of cross time

Figure 2: Observed pedestrian movement characteristics.

tested statistics are differences of proportions (start to cross with more than 20 s left; start to cross during last 20 s; start to cross during last 10 s) and differences of means (average velocity of pedestrians) of the population. The hypothesis testing was based on the z statistic of a normal distribution, since a large number of pedestrians were observed at each site.

A two-tailed z test was performed at a confidence level of 95%. Positive z-values indicate that the measurement is decreased at GMCD crosswalks. The reverse is true for negative values, which indicate that the measurement has increased at GMCD crosswalks. The calculated z-values and p values for each behavior indicators are shown in Tables 2–4, at confidence level of 95%. Cases with significant differences are denoted by bold font in Tables 2–4. In Table 2, each value represents z-value of a pair of two sites, one GMCD and one non-GMCD. Average z-values over the 9 different combinations are also computed. As the z-values and p values are computed between two different sites, it is not applicable to test two same sites. Such cells are then represented with dashes.

From Table 2, it is seen that the proportions of pedestrians who started to cross when the remaining green-man time is less than 10 s tended to be significantly lower (positive z-value) at GMCD crosswalks than at non-GMCD crosswalks.

Table 2: Calculated z-values/p values of behavior indicators (between non-GMCD and GMCD crosswalks).

(a) Start to cross with more than 20 s left

Non-GMCD sites	GMCD sites Site number 4	GMCD sites Site number 5	GMCD sites Site number 6
Site number 1	**$-9.23/6.00 \times 10^{-5}$**	**$3.79/1.60 \times 10^{-4}$**	**$8.79/6.00 \times 10^{-5}$**
Site number 2	**$9.49/6.00 \times 10^{-5}$**	**$8.21/6.00 \times 10^{-5}$**	**$11.32/6.00 \times 10^{-5}$**
Site number 3	**$8.25/6.00 \times 10^{-5}$**	**$8.30/6.00 \times 10^{-5}$**	**$3.89/1.00 \times 10^{-4}$**
Average			**$5.32/6.00 \times 10^{-5}$**

(b) Start to cross during last 20 s (inclusive of last 10 s)

Non-GMCD sites	GMCD sites Site number 4	GMCD sites Site number 5	GMCD sites Site number 6
Site number 1	**$-4.64/6.00 \times 10^{-5}$**	$-0.93/3.52 \times 10^{-1}$	**$2.31/2.09 \times 10^{-2}$**
Site number 2	$1.56/1.19 \times 10^{-1}$	**$2.93/3.38 \times 10^{-3}$**	**$-6.45/6.00 \times 10^{-5}$**
Site number 3	$1.68/9.30 \times 10^{-2}$	$-0.49/6.24 \times 10^{-1}$	**$4.23/6.00 \times 10^{-5}$**
Average			**$-0.50/6.17 \times 10^{-1}$**

(c) Start to cross during last 10 s

Non-GMCD sites	GMCD sites Site number 4	GMCD sites Site number 5	GMCD sites Site number 6
Site number 1	**$8.76/6.00 \times 10^{-5}$**	**$-3.23/1.24 \times 10^{-3}$**	**$-15.8/6.00 \times 10^{-5}$**
Site number 2	$-1.67/9.49 \times 10^{-2}$	**$-13.21/6.00 \times 10^{-5}$**	$-0.32/7.49 \times 10^{-1}$
Site number 3	**$-12.32/6.00 \times 10^{-5}$**	**$-10.1/6.00 \times 10^{-5}$**	**$-3.45/5.60 \times 10^{-4}$**
Average			**$-5.70/6.00 \times 10^{-5}$**

(d) Average velocity of pedestrians

Non-GMCD sites	GMCD sites Site number 4	GMCD sites Site number 5	GMCD sites Site number 6
Site number 1	**$3.53/4.20 \times 10^{-4}$**	**$3.83/1.20 \times 10^{-4}$**	$1.23/2.19 \times 10^{-1}$
Site number 2	$1.85/6.43 \times 10^{-2}$	$-0.82/4.12 \times 10^{-1}$	$-0.23/8.18\times10^{-1}$
Site number 3	**$4.20/6.00 \times 10^{-5}$**	$0.12/9.04 \times 10^{-1}$	**$5.21/6.00 \times 10^{-5}$**
Overall			**$2.10/3.57 \times 10^{-2}$**

However, average walking velocity tended to be significantly higher (negative z-value) at GMCD crosswalks than at non-GMCD crosswalks.

It is noted in Tables 3 and 4 that the hypothesis test of proportions of pedestrians entering crosswalk during last 10 s is significant between two different locations for some combinations. This might be affected by several factors such as pedestrian volume, vehicle volume, and signal length. To obtain probability of a categorical outcome, a logistic regression model was therefore calibrated to compute these two features. The variables include whether it is a GMCD crosswalk (A, 0 = non-GMCD, 1 = GMCD), pedestrian volume (B), vehicle volume (C), and time to onset of red-man (D). The crossing propensity of pedestrians, p_c, was modeled by the following equation. Correlation coefficients (R), standard errors, and p values for chi-square test ($p_r > \chi^2$ not less than 0.05) for the estimated parameters of each independent variable are shown in Table 5.

$$p_c = \left[1 + \exp\left\{-\left(-4.01 - 0.17A + 0.91B - 0.64C + 0.42D\right)\right\}\right]^{-1}. \tag{1}$$

In general, a positive estimated parameter means when the independent variable increases, the probability of cross will also increase and vice versa. For discrete variable (whether it is a GMCD crosswalk), a positive estimated parameter means the particular level increases with cross probability. As expected, a pedestrian is found to be more likely to cross when there is a longer time to the onset of red-man and when pedestrian volume is lower.

Chi-square test was conducted and a statistically significant relationship was obtained with $\chi^2 = 31.231$ and $p < 0.0001$ at a confidence level of 95%. With four degrees of freedom, this indicates a good fit of the logistic regression model.

2.2. Cellular Automata Model for Signalized Pedestrian Crosswalk

2.2.1. Cell Space. The CA model was established to simulate a typical cross-intersection with pedestrian crosswalks. Different cell sizes were used to build the spatial framework in the simulation model according to size and movement

Table 3: Calculated z-values/p values of behavior indicators among non-GMCD sites.

(a) Proportions of pedestrians starting to cross with more than 20 s left

Non-GMCD sites	Non-GMCD sites Site number 1	 Site number 2	 Site number 3
Site number 1	—	$-0.32/7.49 \times 10^{-1}$	$-1.19/2.34 \times 10^{-1}$
Site number 2	$0.32/7.49 \times 10^{-1}$	—	$-0.39/6.96 \times 10^{-1}$
Site number 3	$1.19/2.34 \times 10^{-1}$	$0.39/6.96 \times 10^{-1}$	—

(b) Proportions of pedestrians starting to cross during last 20 s (inclusive of last 10 s)

Non-GMCD sites	Non-GMCD sites Site number 1	 Site number 2	 Site number 3
Site number 1	—	$0.55/5.82 \times 10^{-1}$	$-1.07/2.82 \times 10^{-1}$
Site number 2	$-0.55/5.82 \times 10^{-1}$	—	$0.14/8.88 \times 10^{-1}$
Site number 3	$1.07/2.82 \times 10^{-1}$	$-0.14/8.88 \times 10^{-1}$	—

(c) Proportions of pedestrians starting to cross during last 10 s

Non-GMCD sites	Non-GMCD sites Site number 1	 Site number 2	 Site number 3
Site number 1	—	$2.70/6.94 \times 10^{-3}$	$\mathbf{2.30/2.20 \times 10^{-2}}$
Site number 2	$-2.70/6.94 \times 10^{-3}$	—	$-0.39/6.96 \times 10^{-1}$
Site number 3	$\mathbf{-2.30/2.20 \times 10^{-2}}$	$0.39/6.96 \times 10^{-1}$	—

(d) Average velocity of pedestrians

Non-GMCD sites	Non-GMCD sites Site number 1	 Site number 2	 Site number 3
Site number 1	—	$\mathbf{-2.40/1.64 \times 10^{-2}}$	$\mathbf{-2.34/1.93 \times 10^{-2}}$
Site number 2	$\mathbf{2.40/1.64 \times 10^{-2}}$	—	$-0.04/9.68 \times 10^{-1}$
Site number 3	$\mathbf{2.34/1.93 \times 10^{-2}}$	$0.04/9.68 \times 10^{-1}$	—

(e) Proportions of pedestrians running

Non-GMCD sites	Non-GMCD sites Site number 1	 Site number 2	 Site number 3
Site number 1	—	$\mathbf{-3.07/2.14 \times 10^{-3}}$	$-5.54/6 \times 10^{-5}$
Site number 2	$\mathbf{3.07/2.14 \times 10^{-3}}$	—	$-0.26/3.95 \times 10^{-1}$
Site number 3	$5.54/6 \times 10^{-5}$	$0.26/3.95 \times 10^{-1}$	—

of the road users. According to field observations of previous studies, all interactions are performed at fairly low speeds so there is less differential in acceleration/deceleration characteristics among all the vehicles at intersections than along links [14]. Therefore, homogeneous vehicle flow (cars only) was simulated in this study. Through observation of approach and departure lanes, the average space headway of 397 queuing cars (speed = 0) at the 6 selected signalized intersections is 7.10 m (minimum 6.85 m), with an average gap of 2.24 m (minimum 1.94 m). This suggests the minimum practical space headway of two adjacent vehicles within one lane is around 7.0 m. When traffic stream is moving, the space headway will not be smaller than stand-still situation. Therefore, a cell length of 7.0 m can be used at approach and departure lanes to reduce the complexity of computation. At intersection-box area, a square cell size of 3.5 m × 3.5 m was chosen to simulate relatively slower moving velocity and also to represent the squared geometry at that area. This means when a particular cell is occupied, rear and alongside cells could not be occupied.

To determine the cell size of a crossing pedestrian, firstly, the average transversal direction space of a pedestrian has been established as being 0.45 m in Asian countries. According to Highway Capacity Manual (HCM) 2000, the average thickness of pedestrian is 0.3 m and the dynamic space is 0.6–0.8 m [15]. Field observations conducted in Singapore suggest that a pedestrian tends to follow the front person closely and the minimum gap is found as 0.29 m. As a result, a cell size of 0.4 m × 0.4 m was chosen for a crossing pedestrian. A gap tolerance rule was also built in such that the forward (moving direction) minimum gap is 1 cell (3.5 m) and lateral minimum gap is 0 to ensure the minimum space headway of 7.0 m. These smaller cells are always occupied pair-wise. This means when a particular cell is occupied, rear and alongside cells could not be occupied. Specific scenarios for simplified lanes within intersection-box area are illustrated in Figure 3.

Table 4: Calculated z-values/p values of behavior indicators among GMCD Sites.

(a) Start to cross with more than 20 s left

GMCD sites	GMCD sites		
	Site number 4	Site number 5	Site number 6
Site number 4	—	$-1.83/6.72 \times 10^{-2}$	$-0.11/9.12 \times 10^{-1}$
Site number 5	$1.83/6.72 \times 10^{-2}$	—	$1.12/2.62 \times 10^{-1}$
Site number 6	$0.11/9.12 \times 10^{-1}$	$-1.12/2.62 \times 10^{-1}$	—

(b) Start to cross during last 20 s (inclusive of last 10 s)

GMCD sites	GMCD sites		
	Site number 4	Site number 5	Site number 6
Site number 4	—	$\mathbf{2.06/3.94 \times 10^{-2}}$	$-1.59/1.12 \times 10^{-2}$
Site number 5	$\mathbf{-2.06/3.94 \times 10^{-2}}$	—	$0.38/7.04 \times 10^{-1}$
Site number 6	$1.59/1.12 \times 10^{-2}$	$-0.38/7.04 \times 10^{-1}$	—

(c) Start to cross during last 10 s

GMCD sites	GMCD sites		
	Site number 4	Site number 5	Site number 6
Site number 4	—	$1.48/1.38 \times 10^{-2}$	$0.42/6.74 \times 10^{-1}$
Site number 5	$-1.48/1.38 \times 10^{-2}$	—	$\mathbf{4.03/6 \times 10^{-5}}$
Site number 6	$-0.42/6.74 \times 10^{-1}$	$\mathbf{-4.03/6 \times 10^{-5}}$	—

(d) Average velocity of pedestrians

GMCD sites	GMCD sites		
	Site number 4	Site number 5	Site number 6
Site number 4	—	$0.024/9.81 \times 10^{-1}$	$\mathbf{-4.21/6 \times 10^{-5}}$
Site number 5	$-0.024/9.81 \times 10^{-1}$	—	$\mathbf{-4.25/6 \times 10^{-5}}$
Site number 6	$\mathbf{4.21/6 \times 10^{-5}}$	$\mathbf{4.25/6 \times 10^{-5}}$	—

(e) Running

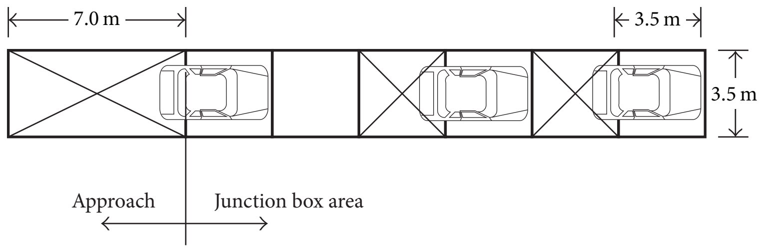
GMCD sites	GMCD sites		
	Site number 4	Site number 5	Site number 6
Site number 4	—	$1.93/5.36 \times 10^{-2}$	$\mathbf{-3.20/1.38 \times 10^{-3}}$
Site number 5	$-1.93/5.36 \times 10^{-2}$	—	$\mathbf{-1.99/4.66 \times 10^{-2}}$
Site number 6	$\mathbf{3.20/1.38 \times 10^{-3}}$	$\mathbf{1.99/4.66 \times 10^{-2}}$	—

Table 5: Results of the estimated parameters for each independent variable.

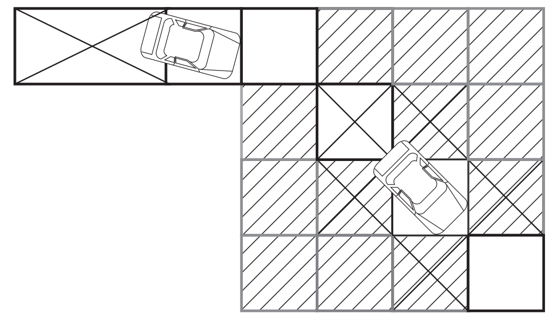
Variables	Estimate	Correlation coefficient	Standard error	p value
Whether it is a GMCD crosswalk	−0.17	0.40	0.216	0.001
Pedestrian volume	0.91	0.21	0.024	0.002
Vehicle volume	−0.64	−0.63	0.016	0.0057
Time to onset of red man	0.42	0.37	0.025	0.0103

Being shared usage with vehicle, pedestrian crosswalk was gridded with small cells (3.5 m × 3.5 m each cell, as shown shaded in Figure 4). The crosswalk is usually 3 m wide, as shown in Figure 4. However, pedestrians are given priority during the pedestrian signal cycle. When at least one of the pedestrian cells (0.4 m × 0.4 m) at the pedestrian crosswalk is occupied, the cell (3.5 m × 3.5 m) covering that area will be regarded as being "occupied" and unavailable to the vehicles. On the other hand, when a small cell (3.5 m × 3.5 m) on the crosswalk is occupied by a vehicle, pedestrians will not be allowed to occupy any of the pedestrian cells (0.4 m × 0.4 m) within that vehicle footprint.

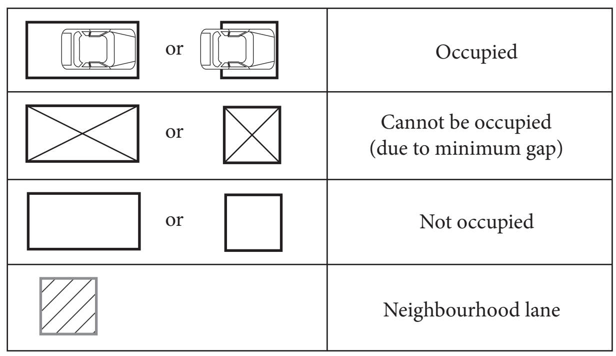
2.2.2. Pedestrian Movements. Transition rules for pedestrians were modified from a CA model for bidirectional walkways proposed by Blue and Adler [16]. Each time step was subdivided as two substeps, as forwarding and lateral movements. At each time step, the following rules were applied in parallel in updating the position and velocity of each pedestrian. Assume all pedestrians are moving along



(a) Gap tolerance for straight-through or left-turn



(b) Gap tolerance for right-turn



(c) Cell states

Figure 3: Gap tolerance rules of vehicle movements.

x direction. Positions of each pedestrian in forwarding and lateral directions were defined as x_p and y_p.

(i) Forwarding Rules

Rule 1. Front gap (g_{p1}) is computed for each subject pedestrian (p_1) as

$g_{p1} = v^p_{\max}$ cells if front pedestrian (p_2) is moving in the same direction;

$g_{p1} = \text{INT}(0.5 * |y_{p1} - y_{p2}|)$ if front pedestrian is moving in opposite direction.

Rule 2 (update velocity). $v_{p1} = \min(g_{p1}/\Delta t, v^p_{\max})$.

Rule 3 (overtaking). If $g_{p1} = 0$ or 1, p_1 will pass p_2 in the next time step; therefore $v_{p1} = \min(g_{p1}/\Delta t + 1, v^p_{\max})$.

Rule 4 (update position). $x_1 = x_1 + v_{p1} \times \Delta t$.

(ii) Lateral Rules. p_1 and p_2 (moving in opposing directions) in the same lateral lane are required to side step to avoid conflicting with each other. According to Blue and Adler [16], pedestrian p_1 will side step if the front gap (g_{p1}) to an opposing pedestrian p_2 is within 3.2 m (8 cells). Both p_1 and p_2 have a 0.5 possibility of side stepping with a lateral velocity of $v^l_{p1} = 1$ cell/s. If an additional conflict is detected after side stepping, pedestrian(s) will sidestep again to make sure no further conflict exists. If conflict with other pedestrians occurs after the subject pedestrian has already side stepped 2 cells within one time step, the subject pedestrian will not side step and instead, the opposing pedestrian will side step to avoid conflict with 100% probability.

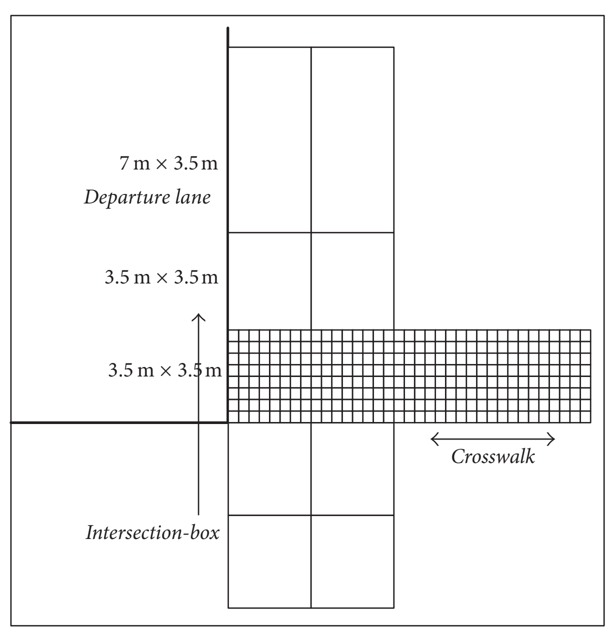


Figure 4: Layout of crosswalk mapped with small cells.

2.2.3. Vehicle Movements. For vehicle movement, as lane changing was not simulated in this study, the applicable forwarding transition rules were modified from

Table 6: Validation of proposed CA model.

Statistics		Sites 1	2	3	4	5	6	Overall
Average velocity (m/s)	Observation	1.35	1.3	1.39	1.45	1.38	1.44	
	Simulation	1.33	1.28	1.45	1.44	1.42	1.44	
	Error	–1%	–2%	4%	–1%	3%	0%	1%
Average velocity during last 10 s of green-man signal (m/s)	Observation	1.36	1.31	1.41	1.48	1.42	1.46	
	Simulation	1.38	1.31	1.43	1.47	1.44	1.45	
	Error	1%	0%	1%	–1%	1%	–1%	0%

Nagel–Schreckenberg (NaSch) model, which is an essential one-directional CA model to replicate car following [17]. Transition rules are as follows.

The velocity v of each vehicle can take one of the $v_{\max}+1$ allowed integer values $= 0, 1, \ldots, v_{\max}$. Suppose x_n and v_n denote the position and velocity, respectively, of the nth vehicle. Then, $d_n = x_{n+1} - x_n$ is the spacing between the nth vehicle and the $(n+1)$th vehicle in front of it at time t. At each time step $\rightarrow t + \Delta t$ (set as 1 s in this study), the arrangement of the N vehicles on a finite lattice of length L is updated according to the following rules.

Rule 1 (acceleration). If $v_n < v_{\max}$, the velocity of the nth vehicle is increased by $\varphi_a = 1$ cell/s (2 cells/s within intersection-box area), but v_n remains unaltered if $v_n = v_{\max}$; that is,

$$v_n \longrightarrow \min\left(v_n + \varphi_a, v_{\max}\right). \tag{2}$$

Rule 2 (deceleration (due to other vehicles)).

At Green or Amber Phase. If $d_n/\Delta t \leq v_n$, then if the subject vehicle continues moving, it will collide with the front car at next time step. Therefore, the velocity will be reduced by $\varphi_d = 1$ cell/s (2 cells/s within intersection – box area) to $d_n/\Delta t - \varphi_d$.

At Red Phase. Assume DS is the distance between a vehicle and the stop-line.

If $\min(d_n, DS)/\Delta t \leq v_n$, then if the subject vehicle continues moving, it will exceed the front car or exceed the stop-line at the next time step, and the velocity of the nth vehicle is reduced to $\min(d_n, DS)/\Delta t - \varphi_d$

$$v_n \longrightarrow \min\left(v_n, \left(\frac{d_n}{\Delta t} - \varphi_d\right), \left(\frac{DS}{\Delta t} - \varphi_d\right)\right). \tag{3}$$

Rule 3 (randomisation). In NaSch model, the first two rules (acceleration and deceleration) make sure the following vehicle will travel at the maximum possible velocity without surpassing the front vehicle. However, in reality, not all the vehicles will travel at the maximum possible velocity. Therefore, a random deceleration rule was built to reduce simulated velocity to be more close to the reality.

If $v_n > 0$, the velocity of the nth vehicle is decreased randomly by $\varphi_r = 1$ cell/s with probability p_r but v_n does not change if $v_n = 0$; that is,

$$v_n \longrightarrow \max\left(\left(v_n - \varphi_r\right), 0\right) \tag{4}$$

with probability p_r. It was found that when vehicle decelerates with probability $(p_r) = 0.2$, simulated average travel time per vehicle was close to observe values with errors within ±3% [14].

Rule 4 (vehicle movement). Each vehicle is moved forward according to its new velocity determined in Steps 1–3; that is,

$$x_n \longrightarrow x_n + v_n \times \Delta t. \tag{5}$$

2.2.4. Calibration and Validation of the Proposed Cellular Automata Model. A sensitivity analysis based on Elementary Effect (EE) method was conducted to test which modeling parameters will affect simulation outputs significantly [18]. EE method has been successfully applied in sensitivity analysis of simulation models with large numbers of inputs [19]. Traffic characteristics that were found to be significant are maximum velocity of vehicles (85th), maximum acceleration/deceleration rates of vehicles (85th), maximum velocity of pedestrians (85th), and random deceleration rates of vehicles. Significant inputs were then computed using observed data from both GMCD and non-GMCD pedestrian crosswalks sites, as introduced in Section 2.1. For vehicle movements, maximum velocity (85th) during peak hours is 52.8 km/h; maximum acceleration/deceleration rates are 3.6 m/s^2 and −4.5 m/s^2. In CA models, velocity is represented as integers. For example, to represent 2.4 cells/s, when a vehicle's target speed is 3 cells/s, there is a 40% probability that vehicles will move at a velocity of 3 cells/s and the rest 60% probability that they will move at a velocity of 2 cells/s. Maximum velocity (85th) of pedestrians for both GMCD and non-GMCD pedestrian crosswalks is 1.6 m/s (4 cells/s).

The performance of the CA model was evaluated by a comparison of simulated pedestrian trajectories against field data at both GMCD and non-GMCD crosswalks. Observed arrival distribution and initial density were used to generate vehicles and pedestrians in the simulation. As shown in Table 6, errors on statistics such as average crossing velocity and average velocity during last 10 s of green-man signal of pedestrians are relatively small (<5%) thereby providing evidence that the CA model can well describe traffic dynamics at the microscopic level [14].

2.3. Safety Assessment of Pedestrian-Vehicle Conflicts

2.3.1. Classification of Conflict Types. In this study, conflicts between pedestrian and vehicle at pedestrian crosswalk were

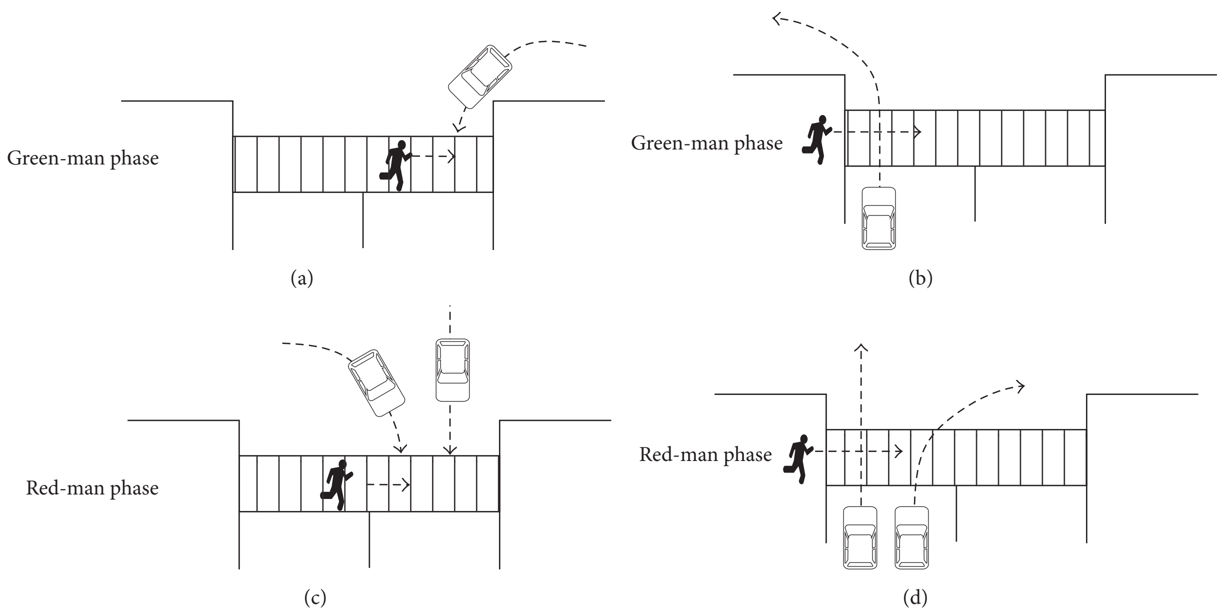


Figure 5: Conflict areas at pedestrian crosswalk.

classified into 4 types as shown in Figure 5. During green-man phase, pedestrians come into conflict with left-turn vehicles, as shown in (a), and (b) if Left Turn on Red (LTOR) signal control is permitted. For large intersections with slip roads, such conflicts occur along slip road. During red-man phase, conflicts occur between pedestrians (violators) and straight-through or right-turn vehicles, as shown in (c) and (d). For conflicts between pedestrians and vehicles, the same conflict types are applicable.

2.3.2. Estimation of Conflict Occurrences. Safety performance was modeled in terms of occurrence of conflict between hybrid objects (pedestrian versus vehicle) which was recorded as the occurrence of deceleration caused by the other vehicles/pedestrians. According to defined movement rules of the CA model, when there is a conflict between vehicle and pedestrian, both party will decelerate as necessary. Therefore, a new parameter, Deceleration Occurrence caused by Conflict (DOC), was defined to record the occurrence of conflicts [20]. As only vehicle-pedestrian conflicts were studied, DOC will only be recorded if deceleration of a vehicle is caused by a pedestrian or if a pedestrian's deceleration is caused by a vehicle. Moreover, if the conflicted vehicle and pedestrian both decelerate at the same time step, only 1 DOC will be recorded. For each recorded DOC, moving velocity, position, and deceleration rate of the conflicted vehicle and pedestrian were recorded for estimation of conflict severity.

2.3.3. Estimation of Conflict Severity. A safety indicator, namely, time to collision (TCC), was applied to estimate severity of pedestrian-vehicle conflicts. TTC is defined as the gap distance between a subject vehicle/pedestrian and front vehicle/pedestrian divided by their velocity difference [21]. A lower TCC value means it has a very short time for vehicles to avoid collision. For each recorded DOC, TTC was calculated as

$$t_{\mathrm{TTC}} = \frac{d_n^t}{\left(v_n^{t+1} - v_{n+1}^t\right)}, \tag{6}$$

where d_n^t represents the distance between two hybrid objects at time t; v_n^{t+1} and v_{n+1}^t represent the velocity of vehicle/pedestrian.

3. Results and Discussions

3.1. Simulation Experiments. To produce generalized safety impact of GMCD, various simulation scenarios were designed to provide vehicle movements and conflicts at pedestrian crosswalks without and those with GMCD using MATLAB. Geometric layout and signal timings of simulated crosswalk are shown as Figures 6 and 7. Cycle length of case intersection is 100 s, with 26 s for vehicular straight-through green phase with permissive right-turn and 18 s of exclusive right-turn phase for each approach as shown in Figure 7. Four scenarios with different pedestrian-vehicle volumes are created for pedestrian crosswalks both non-GMCD and GMCD, as shown in Table 7. The simulation ran for 1 hour (36 signal cycles). Outputs were calculated according to average results of 5 runs to reduce errors due to stochastic variables in the proposed CA model as suggested by Zheng et al. [22].

3.2. Results. Simulation outputs for each simulation scenario include average moving velocity, number of pedestrians that cross during the last 10 s, and DOC with different TTC values during green-man signal phase with more than 10 s left or during the last 10 s, as summarized in Table 7. Impact of GMCD is computed as follows: [output at GMCD

Table 7: Simulation outputs.

Statistics		Scenarios 1	2	3	4	Overall
Pedestrian volume (ped/h)		100	100	300	300	
Vehicle volume (straight-through) (veh/h/lane)		50	100	50	100	
Vehicle volume (left-turn) (veh/h/lane)		25	50	25	50	
Vehicle volume (right-turn) (veh/h/lane)		25	50	25	50	
Average velocity (m/s)	Non-GMCD	1.49	1.43	1.35	1.24	
	GMCD	1.56	1.54	1.37	1.25	
	Impact of GMCD	5%	8%	1%	1%	4%
Start to cross during last 10 s of green-man signal (%)	Non-GMCD	9.24	12.15	8.01	10.76	
	GMCD	9.12	9.95	8.33	8.21	
	Impact of GMCD	−1%	−18%	4%	−24%	−10%
Average velocity during last 10 s of green-man signal (m/s)	Non-GMCD	1.51	1.46	1.37	1.24	
	GMCD	1.67	1.72	1.52	1.43	
	Impact of GMCD	11%	18%	11%	15%	14%
Average DOC during green-man signal (with more than 10 s left)	Non-GMCD	0.003	0.002	0.006	0.002	
	GMCD	0.003	0.002	0.005	0.002	
	Impact of GMCD	−3%	0%	−12%	0%	−4%
Average TTC during green-man signal (with more than 10 s left)	Non-GMCD	2.33	2.79	3.04	3.28	
	GMCD	2.32	2.7	3.21	3.4	
	Impact of GMCD	0%	−3%	6%	4%	1%
Average DOC during last 10 s of green-man signal	Non-GMCD	0.008	0.003	0.002	0.004	
	GMCD	0.003	0.003	0.001	0.003	
	Impact of GMCD	−63%	−6%	−57%	−27%	−38%
Average TTC during last 10 s of green-man signal	Non-GMCD	2.21	2.57	2.81	2.93	
	GMCD	2.03	2.32	2.73	2.73	
	Impact of GMCD	−8%	−10%	−3%	−7%	−7%

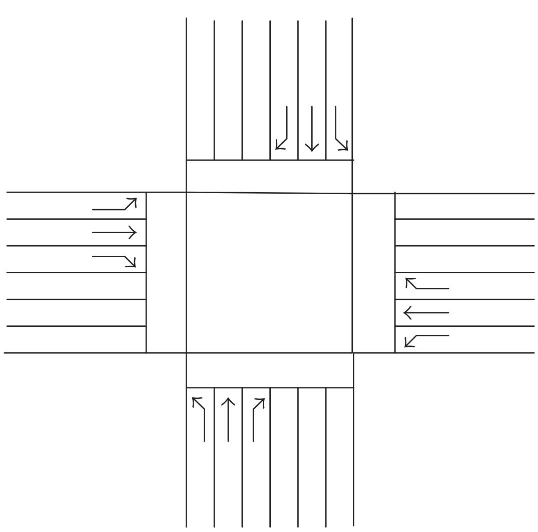


Figure 6: Geometric layouts of simulated pedestrian crosswalk.

<table>
<tr><th colspan="3">Vehicle signal</th><th colspan="2">Pedestrian signal</th></tr>
<tr><td></td><td>26 s</td><td>Green phase for straight through vehicle (filtering allowed)</td><td rowspan="2">29 s</td><td rowspan="2">Green-man</td></tr>
<tr><td></td><td>3 s</td><td>Amber</td></tr>
<tr><td></td><td>1 s</td><td>All-red</td><td rowspan="9">71 s</td><td rowspan="9">Red-man</td></tr>
<tr><td></td><td>18 s</td><td>Green phase for right turn vehicles (last 3 s flashing green arrow)</td></tr>
<tr><td></td><td>2 s</td><td>All-red</td></tr>
<tr><td></td><td>26 s</td><td>Green phase for straight through vehicles (filtering allowed)</td></tr>
<tr><td></td><td>3 s</td><td>Amber</td></tr>
<tr><td></td><td>1 s</td><td>All-red</td></tr>
<tr><td></td><td>18 s</td><td>Green phase for right turn vehicles (last 3 s flashing green arrow)</td></tr>
<tr><td></td><td>2 s</td><td>All-red</td></tr>
</table>

Figure 7: Signal timings of vehicle/pedestrian movements.

crosswalk-output at non-GMCD crosswalk]/output at non-GMCD crosswalk × 100%. The impact of GMCD at different traffic conditions can be summarized in Table 7 and Figure 8. It is found that the safety impact of GMCD is affected by traffic condition as well as different time duration within green-man signal phase.

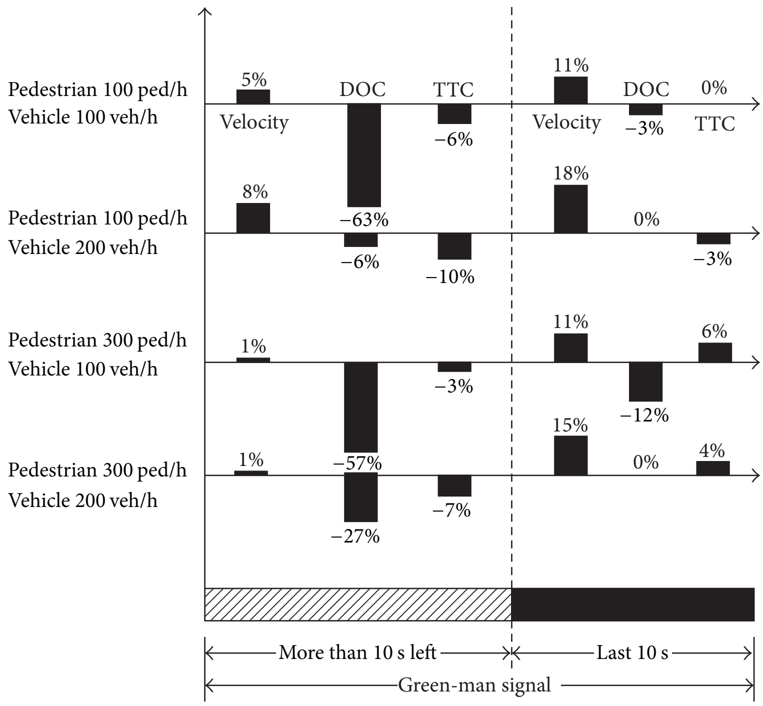


Figure 8: Impact of GMCD for each simulation scenario.

3.3. Findings

3.3.1. Effect of GMCD on Average Walking Velocity. GMCD increases average walking velocity in all the 4 scenarios. This is consistent with previous studies. The impact is more obvious on average velocity at last 10 s of green-man signal. Furthermore, when pedestrian volume is higher (Scenarios 3 and 4), the effect of GMCD is reduced, as walking velocity is also much affected by neighboring pedestrians when density increases.

3.3.2. Effect of GMCD on Pedestrians Starting to Cross within Last 10 s. According to simulation results, in most scenarios, compared with non-GMCD crosswalk, a lower proportion of the crossing pedestrians would cross during the last 10 s at GMCD crosswalk, especially when vehicle volume is higher. However, in scenario 3, when pedestrian volume is high and vehicle volume is low, a higher proportion of pedestrians cross during the last 10 s at GMCD crosswalk.

3.3.3. Effect of GMCD on Conflicts between Vehicles and Pedestrians. The installation of GMCD reduces conflict occurrences between vehicle and pedestrians (represented by average DOC) generally. The reduction of conflict occurrence is more obvious during the last 10 s of green-man signal phase. However, average conflict severity (represented by average TTC) is also increased during the last 10 s of green-man signal phase due to higher crossing velocity. Moreover, it is found that average conflict severity during green-man signal phase with more than 10 s left is not changed or is even reduced when pedestrian volume is low. Overall, GMCD is found to be able to improve safety performance at pedestrian crosswalks, especially for high pedestrian volume.

3.4. Discussions of Simulation Results. Findings from this study have much in common with existing studies about safety impact of GMCD based on other approaches. It is reaffirmed in this study that the installation of GMCD increases both crossing velocity, especially for late starters. Moreover, it is consistent with some existing studies conducted in the US and Serbia that installation of GMCD reduces the proportion of late starters that start to cross during last few seconds of green-man signal [23, 24]. However, the latter finding is contrary to some existing studies conducted in the US and Australia [9, 25].

Concurrently, some new findings are observed from the simulation results based on the proposed microscopic simulation approach. Firstly, according to results from various simulation scenarios, the safety impact of GMCD is more obvious at more crowded pedestrian crosswalks. This suggests that the current practice, which is to install GMCD at more crowded crosswalks or near the school zone, is effective.

Simulation results of this study also suggest that although the installation of GMCD reduces conflict occurrences generally, due to higher velocity of pedestrians, it also increases severity of conflicts during the last few seconds of green signal phase. Engineers should take this into consideration when designing signalized crosswalk as conflicts occur during intersignal (between green-man and red-man) period. Moreover, vehicle may start and cross the stop-line before or immediately at the onset of green signal phase. Such vehicles will conflict with pedestrians who have not yet finished crossing. Therefore, at signalized crosswalks with GMCD, longer all red signal is suggested to improve pedestrian safety during intergreen period.

These new findings show that the proposed CA approach is able to extend existing approaches on safety assessment of traffic devices and control strategies. The CA model serves to provide an alternate solution methodology to complement conventional studies based on crash occurrences. Firstly, compared to analytical models, microscopic simulation models are more flexible for various geometric layouts, signal timings, and traffic characteristics. Moreover, compared to safety assessment approaches based on crash occurrences, safety indicators (DOC and TTC) used in this paper are based on simulation of vehicle interactions. Last but not least, based on user-defined vehicle and pedestrian movements, CA models can be applied to estimate impact of various traffic management strategies.

3.5. Limitations and Further Research. Overall, simulation experiments in this study are able to assess the general impacts of GMCD at typical signalized pedestrian crosswalks. However, the study has several limitations because of the scope of field observation and simulation scenarios. Field observations were conducted at 6 signalized pedestrian crosswalks including 3 GMCD locations during evening peak hours, which was not able to represent all traffic conditions throughout the day. Moreover, as the study is conducted in Singapore City, the effect of GMCD has not been assessed at rural area. Therefore, an observation study at larger scale of signalized crosswalks and longer duration is desired in future research. Furthermore, a before-after study is ideal to estimate the impact of GMCD by minimizing other factors that may affect the behavior of pedestrians, such as surrounding infrastructures of the pedestrian crosswalk. Last but not least, impacts of GMCD to a particular pedestrian group, such as elderly and school children, can be studied in future studies.

4. Conclusions

This study uses a simulation-based approach to estimate quantitative safety impacts of GMCD under various traffic conditions. Pedestrian movements at 6 signalized crosswalks are observed using pedestrian tracking techniques. A CA based simulation model is developed using observed movement characteristics at signalized crosswalks with and without GMCD, including crossing velocity, proportions of pedestrians who start to cross at different time interval during green-man signal phase, and proportions of running pedestrians. The model aims to provide safety assessment from simulated conflicts between vehicles and pedestrians. Traffic performance and safety impacts of crosswalks with GMCD and without GMCD are then compared through simulation experiments with different pedestrian and vehicle volumes.

The relationship among safety performance, GMCD, and traffic conditions is studied from simulation results to help authorities on making decisions about the installation of GMCD to improve safety level of signalized pedestrian crosswalk. It is found that the safety impact of GMCD is affected by traffic condition as well as different time duration within green-man signal phase. According to simulation results, it is found that GMCD is able to improve safety performance at pedestrian crossings with high pedestrian volume. However, as crossing velocity during the last 10 s of green-man signal phase is higher at GMCD locations, conflict severity is also increased. Simulation results are thus useful in helping authorities in making decisions about installation of GMCD to improve safety level of signalized pedestrian crosswalk. Findings from this study suggest that the current practice, which is to install GMCD at more crowded crosswalks or near the school zone, is effective. Moreover, at crosswalks with GMCD, longer all red signal phase is suggested to improve pedestrian safety during intergreen period.

Compared to other simulation approaches, the proposed CA approach has several advantages. Firstly, it is more flexible in creating scenarios and defining movement rules of road users. Moreover, as safety indicators, such as TTC, are computed in the proposed approach, it can be applied in safety assessment. Therefore, the proposed CA based approach has great potential to be applied in various aspects. With proper model calibration based on field observations, it shall help researchers and authorities to estimate traffic performance, in both capacity and safety aspects, of traffic devices and control strategies.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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