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Micro-simulation of vehicle conflicts involving right-turn vehicles at signalized intersections based on Cellular Automata

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Abstract:

At intersection, vehicles coming from different directions conflict with each other. Improper geometric design and signal settings at signalized intersection will increase occurrence of conflicts between road users and results in a reduction of the safety level. This study established a Cellular Automata (CA) model to simulate vehicular interactions involving right-turn vehicles (as similar to left-turn vehicles in U.S.). Through various simulation scenarios for four case cross-intersections, the relationships between conflict occurrences involving right-turn vehicles with traffic volume and right-turn movement control strategies are analyzed. Impacts of traffic volume, permissive right-turn compared to Red-Amber-Green (RAG) Arrow, shared straight-through and right-turn lane as well as signal setting are estimated from simulation results. The simulation model is found to be able to provide reasonable assessment of conflicts through comparison of existed simulation approach and observed accidents. Through the proposed approach, prediction models for occurrences and severity of vehicle conflicts can be developed for various geometric layouts and traffic control strategies.

Keywords: vehicle conflicts; signalized intersections; Cellular Automata; permissive turning

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1. Introduction

Intersections are bottlenecks of road capacity and hot spots of safety. Conflicts between road users will reduce road safety as well as add extra travelling time. For an urban environment as Singapore, there are more than 1,400 signalized intersections while noting that motorists drive on the left side of the road as similar to United Kingdom driving convention. In 2009, about one in five (21%) road traffic accidents occurred at the signalized intersections (Hau et al., 2010). Among all vehicle movements, right-turn vehicles are considered to be the most difficult and complex vehicle movements at the signalized intersections, not only because of the turning movement, but also because of the conflict with other road users. Right-turn vehicles colliding with opposing straight-through or along-side straight-through vehicles are severe and very frequent (Wang and Abdel-Aty, 2008). Therefore, the objective of this study is to develop a new approach to estimate vehicle conflicts by microscopic simulation based on Cellular Automata (CA). Through conducting simulation experiments, the impacts of intersection design and traffic factors on conflicts involving right-turn vehicles at signalized intersections are studied.

2. Previous research

2.1 Factors affecting the occurrence of vehicle conflicts

Numerous researchers have found that efficient geometric and signal setting will significantly increase intersection safety level. Based on Poisson regression and

negative binomial regression analyses, it has been found that road environment, lane arrangement at intersection approaches as well as number of signal phases, are significant factors for crash risk (Wong et al., 2007). Kumara and Chin (2005) found that, total traffic flow, right-turn flow as well as number of signal phases significantly affected the occurrence of crashes.

For vehicle conflicts involving right-turn vehicles, a series of study have found factors affecting the occurrence of right-turn crashes (Wang and Abdel-Aty, 2008). Those factors include traffic volume of conflicting flows, the application of shared right-turn lane, and permissive right-turn signal control. It has been found that the application of protected right-turn signal phasing scheme significantly reduced crashes between right-turn vehicles and pedestrians. An 85% reduction in right-turn accidents was found after a permissive right-turn was replaced by a protected signal phase (Zhang and Prevedouros, 2003).

2.2 Conflicts involving right-turn vehicles

Conflicts involving vehicles with right-turn movement that occur most frequently can be classified into 2 types: I) conflicts between right-turn vehicles and straight-through vehicles along the same approach; and II) conflicts between right-turn vehicles and opposing straight-through vehicles.

Type (I) Conflicts between right-turn and straight-through vehicles occur at approaches with shared lanes. Opportunity for this type of vehicle conflict is very common because according to an observation survey of 154 cross-intersections spread over the Singapore island, over 54% of the approaches contain shared straight-through and right-turn lane. A right-turn vehicle can be blocked by a straight-through vehicle ahead of it during right-turn green phase and vice versa. According to study conducted by Fitzpatrick and Schneider IV (2004), number of rear-end crashes along shared lane is 0.04 cases per approach per year from 2001 to 2003 at 8 studied approaches.

Type (II) Conflicts between right-turn vehicles and opposing straight-through vehicles occur under permissive right-turn signal control. At straight-through green phase, the right-turn vehicle needs to wait for appropriate gaps in opposing straight-through traffic stream to make a right-turn (Wang and Abdel-Aty, 2007). There is a risk of collision if the right-turn vehicle moved without enough gap or when the opposing straight-through vehicle travelled too fast. Compared to Type (I) Conflicts, consequences for Type (II) Conflicts are more severe for traffic safety as accidents involving right-turn and opposing straight-through vehicles can lead to a grid-lock of the whole intersection, and such collisions have constituted over 40% of accidents at signalized intersections (Ng et al., 1997), (Wee, 2004).

2.3 Right-turn control methods

Conflicts involving right-turn vehicles are closely related to signal control type for right-turn vehicles. Most commonly used right-turn control methods are right-turn signal phase, lane markings and right-turn waiting area.

In Singapore, the most common right-turn signal phases are straight-through green phase with permissive right-turn followed by a protected right-turn green phase, and straight-through green phase followed by a protected right-turn phase, the so called

Red-Amber-Green (RAG) Arrow control. Under permissive right-turn arrangement, right-turn vehicles are permitted to make a turn during straight-through green phase (Qi et al., 2010). Vehicles making permissive right-turn movements experience shorter delay, but conflicts with other vehicle movements and hence collision risks are higher (Chen et al., 2012). On the other hand, under RAG Arrow control, right-turn vehicles only have an exclusive right-turn green phase and are not allowed to filter through during straight-through green phase. Such kind of signal settings will be able to reduce vehicle conflicts but result in a higher overall delay (Al-Kaisy and Stewart, 2001). Therefore, whether to allow permissive right-turn is a trade-off between intersection capacity and safety (Chen et al., 2012).

Many approaches at intersections in Singapore contain shared right-turn and straight-through lanes. The arrangement of shared lane is usually based on traffic volumes of the two movement streams, especially right-turn traffic volume. Having a shared lane can help to increase right-turn capacity and to balance vehicle flows of diverging movements at an approach (Liu et al., 2008). However, at approaches with a shared lane, blockage may occur and thus results in Type (I) Conflicts. Some large intersections with permissive right-turn also apply right-turn waiting area to give right-turn vehicles a guided waiting area and a better sight line when making right-turn.

2.4 Current safety assessment models

A series of studies estimated road safety performance of signalized intersections for different intersection types (Persaud et al., 2002; Oh et al., 2003; Oh et al., 2010). For example, an ordered Probit model relating crashes at signalized intersections with road attributes was calibrated by Abdel-Aty and Keller (2005). For Singapore's local context, an accident prediction model based on time series analysis has been developed by Kusumawati (2008).

Al-Ghamdi (2002) applied the binary logit model to examine the effect of crash characteristics and their causes to study the injury levels of crashes involving right-turn vehicles. Instead of real collisions, some researchers have used vehicle conflicts involving right-turn movement to assess the quantity of risk and safety level of specific intersection design (Zhang and Prevedouros, 2003; Kirk and Stamatiadis, 2012; El-Basyouny and Sayed, 2013).

In essence, there have been numerous studies analyzing conflicts involving right-turn vehicles at signalized intersections. However, most current studies are based on statistical analysis methods of crash occurrences or quantitative approaches to estimate the number of conflicts. Modeling of microscopic vehicle movements and vehicle interactions to study safety performance has seldom been attempted. Essentially, it is very hard to assess safety level and predict conflict occurrences because interaction behavior of vehicles at signalized intersection is a very complex process.

2.5 Micro-simulation based on Cellular Automata (CA)

As many factors such as traffic volume, signal settings and geometric design have to be considered when designing a signalized intersection, micro-simulation is found to have more advantages than traditional quantitative models due to micro-simulation models being more flexible in intersection layout and more accurate for dynamic

traffic demand (Nagel and Schreckenberg, 1992). PTV VISSIM has been calibrated by Genetic Algorithm, to estimate safety performance through micro-simulation (Cunto and Saccomanno, 2008; Huang et al., 2013). A software called Surrogate Safety Assessment Model (SSAM) has been developed by Federal Highway Administration (FHWA) to estimate conflicts by identifying critical safety indicators, such as Time to Collision (TTC) through trajectory files from simulation packages such as VISSIM (Huang et al., 2013). However, as the calibration is conducted in particular traffic conditions, a more flexible and generalized simulation tool is needed.

With increasing computation technology, Cellular Automata (CA) models that require massive computations are becoming popular for modeling and simulating complex scenarios. Based on flexible transition rules, it is becoming easier to use CA models to simulate microscopic traffic behavior accurately while leveraging on parallel CA computation (Clarridge and Salomaa, 2010; Kerner et al., 2011). The developments of CA model have increased the flexibility of modeling road traffic. Currently, it is not widely used for safety assessment because in most conventional CA models, velocity change rules are set to ensure all vehicles are travelling with no collisions and enough gaps.

In this study, an improved model that involves new features for safety assessment is established. With the application of improved CA model, safety performance can be estimated directly by simulation of vehicle interactions and conflicts. Occurrences of vehicle conflicts are estimated by detection and computation of a proxy indicator, namely Declaration Occurrences caused by Conflicts (DOC). Through various simulation scenarios, relationship between safety level and control strategy of right-turn vehicles are analyzed. Simulation results are able to predict the risk of collisions related to right-turn vehicles and thereby identify intersections prone to such collisions.

3. Proposed simulation model based on CA

An improved CA model is established for simulating a typical cross-intersection. Firstly, based on field observation and vehicle tracking technologies, rules of vehicle movements have been improved according to vehicle movements at signalized intersections. Multiple cell sizes are used along intersection approach and in junction-box area to fit geometric layout and vehicle movements. The proposed model is able to simulate flexible intersection layout and signal control under various traffic conditions. Moreover, as different from existing CA models, the improved model involves new features for safety assessment. The output criteria include both capacity and safety aspects.

3.1 Rules of vehicle movements

The model uses multiple cell sizes at intersection approach/ departure lanes and intersection box. Cell sizes are determined according to size and movement of vehicles. Through automatic vehicle tracking technologies (Chai and Wong, 2013), vehicle sizes, headways as well as front and lateral gaps observed from different locations are used to select cell sizes. In this CA model, only cars are simulated while noting that all vehicles operate at relatively low velocity at signalized intersections. Movement characteristics of mixed traffic flow are found to be similar according to observation study. Average space headway is found as 7.0m based on an observation

study of around 300 stand-still cars at four different approaches. Therefore, cell size at approach and departure lane is determined as 7.0m. At intersection-box area, a smaller cell size of 3.5m × 3.5m is chosen to simulate movements at relatively slower velocity. Gap tolerance of vehicles at intersection-box is found as 1 cell within intersection-box area based on tracked path. In this model, small cells at intersection-box are always occupied pair-wise. This means when a particular cell is occupied, rear and alongside cells could not be occupied. Several specific scenarios for simplified lanes within intersection-box area are illustrated in Figures 1a-1c.

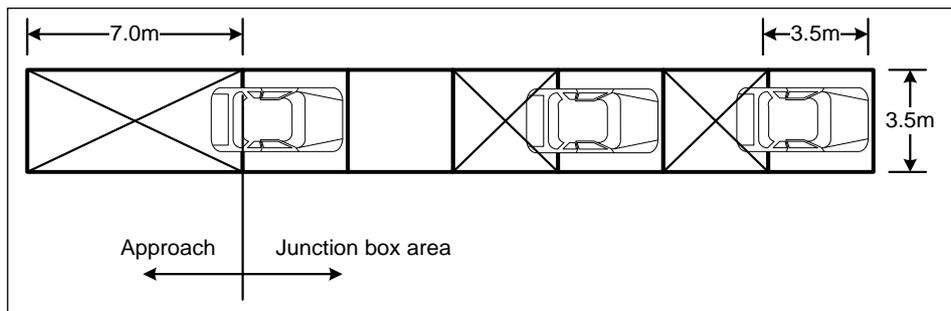


Figure 1a Simplified lanes for straight-through or left-turn

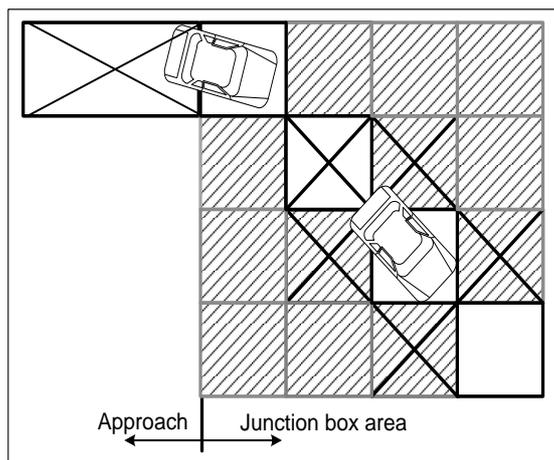


Figure 1b Simplified lanes for right-turn

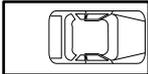
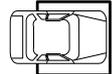
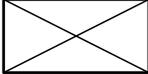
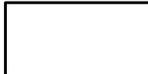
 or 	Occupied
 or 	Cannot be occupied (due to gap tolerance)
 or 	Not occupied
	Neighbourhood lane

Figure 1c Cell states

The gap tolerance rule has been applied in specific condition shown in Figure 2, when vehicle is crossing into intersection-box area, and the target cell cannot be occupied due to gap tolerance. In such situations, the vehicle will occupy the next available cell that could be its present cell. In Figure 2, v stands for current velocity of vehicle; d stands for current front gap.

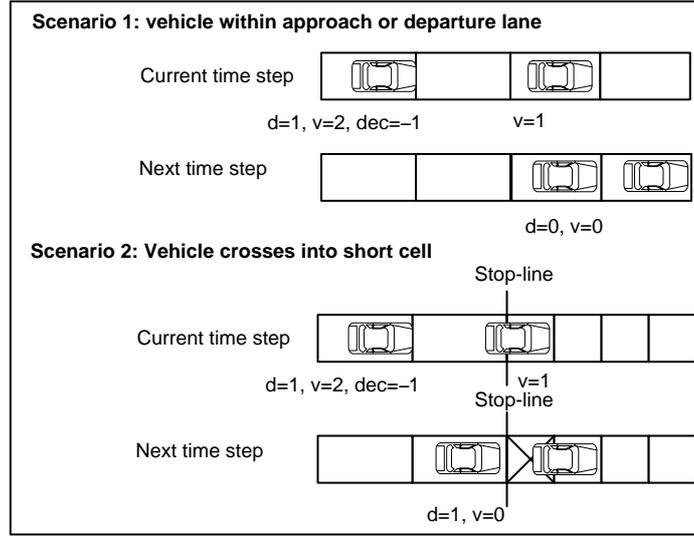


Figure 2 Gap tolerance

Transition rules for vehicle movements are modified from multi-lane Nagel Schreckenberg (NaSch) model with new features such as multiple cell states (occupied, not occupied, cannot be occupied due to gap tolerance) and multiple acceleration and deceleration ratios. The improved transition rules are as follows:

The velocity v of each vehicle can take one of the $v_{\max} + 1$ allowed integer values $= 0, 1, \dots, v_{\max}$. Suppose, x_n and v_n denote the position and velocity, respectively, of the n^{th} vehicle. Then, $d_n = x_{n+1} - x_n$ is the minimum space headway in between the n^{th} vehicle and the $(n+1)^{\text{th}}$ vehicle in front of it or opposite vehicle at time t . At each time step $\rightarrow t+1$, the arrangement of the N vehicles on a finite lattice of length L is updated in parallel according to the following rules:

Rule 1: Acceleration.

If $v_n < v_{\max}$, the velocity of the n^{th} vehicle is increased by $v_n = 1$ cell/s (2 cells/s within intersection-box area), but v_n remains unaltered if $v_n = v_{\max}$, i.e.

$$v_n \rightarrow \min(v_n + v_a, v_{\max})$$

Rule 2: Deceleration (due to other vehicle).

At green or amber phase:

If $d_n/t \leq v_n$, which means if subject vehicle continues moving, it will exceed the front or opposing car at next time step. Therefore, the velocity will be reduced by $v_d = 1$ cell/s (2 cells/s within intersection-box area) to $d_n/t - v_d$;

At red phase: Assume s_n is the distance between vehicle and stop-line.

If $\min(d_n, s_n)/t \leq v_n$, which means if subject vehicle continues moving, it will exceed the front/opposing car or stop-line at next time step, the velocity of the n^{th}

vehicle is reduced to $\min\left(\left(\frac{d_n}{t} - v_d\right), \left(\frac{s_n}{t}\right)\right)$

$$v_n \rightarrow \min(v_n, (d_n/t - v_d), (s_n/t))$$

At intersection-box area, to avoid collision between vehicles in different movement direction, if two vehicles projected to share the same target cell, one of them (with equal probability = 0.5) will decelerate by $v_d = 1$ cell/s.

Rule 3: Randomization.

If $v_n > 0$, the velocity of the n^{th} vehicle is decreased randomly by $v_r = 1$ with probability p but v_n does not change if $v_n = 0$, i.e.,

$$v_n \rightarrow \max((v_n - v_r), 0) \text{ with probability } p$$

Rule 4: Vehicle movement.

Each vehicle is moved forward according to its new velocity determined in Steps 1-3, i.e.,

$$x_n \rightarrow x_n + v_n \times t$$

3.2 Model validation on microscopic level

The performance of the CA model is evaluated by a comparison of simulated vehicle trajectories against field data. A real-world intersection (Jurong Town Hall Road and Jurong East Avenue 1) is selected. Vehicles' position and velocity at each time step are collected by video image processing technologies. In order to generate the same initial headway, observed arrival distribution and initial vehicle density are used to generate vehicles in the simulation. An error assessment is also done for the sample of 114 cars from 5 signal cycles. The summarized results include distribution of velocities, Root Mean Square Error (RMSE) and Mean Percentage Error (MPE). Relatively small and acceptable errors (around 5%) between the simulation and field data present evidence that the CA model can well describe traffic dynamics at the microscopic level.

3.3 Indicator of conflict occurrence

In this study, Declaration Occurrences caused by Conflicts (DOC) is used to represent the occurrence of vehicle conflicts in the above-described CA model. In each run of the simulation, occurrence of vehicle's deceleration is recorded. According to Rule 2 of the vehicle's movement, there are three possible causes of vehicle deceleration as follows:

- 1) To avoid collision with the front vehicle;
- 2) To avoid collision with neighboring vehicles (along-side or opposite); and
- 3) To come to a stop before the stop-line.

Therefore, the frequency of DOC can be used to indicate occurrence of conflicts between vehicles. Higher DOC implies more frequent vehicle conflicts and therefore higher crash risk.

The DOC indicator is generated in accordance to simulated microscopic vehicle movements. The movement characteristics in CA model are calibrated from field observations, and quantitative assessments provide the deceleration rates. Such

approach is different from conventional traffic conflict techniques that tend to be more centric are based on rating and classification instead of rigorous quantitative assessments.

4. Simulation study of conflicts involving right-turn vehicles

4.1 Design of experiments

Four case intersections with different lane configuration and signal timings for right-turn vehicles along East-West approaches are created, as shown in Figure 3. The geometric layout with two lanes in each approach is very common in most minor signalized intersections Singapore. Another reason for choosing two-lane approach for simulation is that if no exclusive right-turn is given, conflicts along shared lane will be more frequent. For Intersections (1) and (2), permissive right-turn phase followed by protected right-turn phase is applied; for Intersections (3) and (4), RAG Arrow: only protected right-turn phase is applied. Intersections (1) and (3) have shared straight-through and right-turn lanes and Intersections (2) and (4) are using exclusive right-turn lanes.

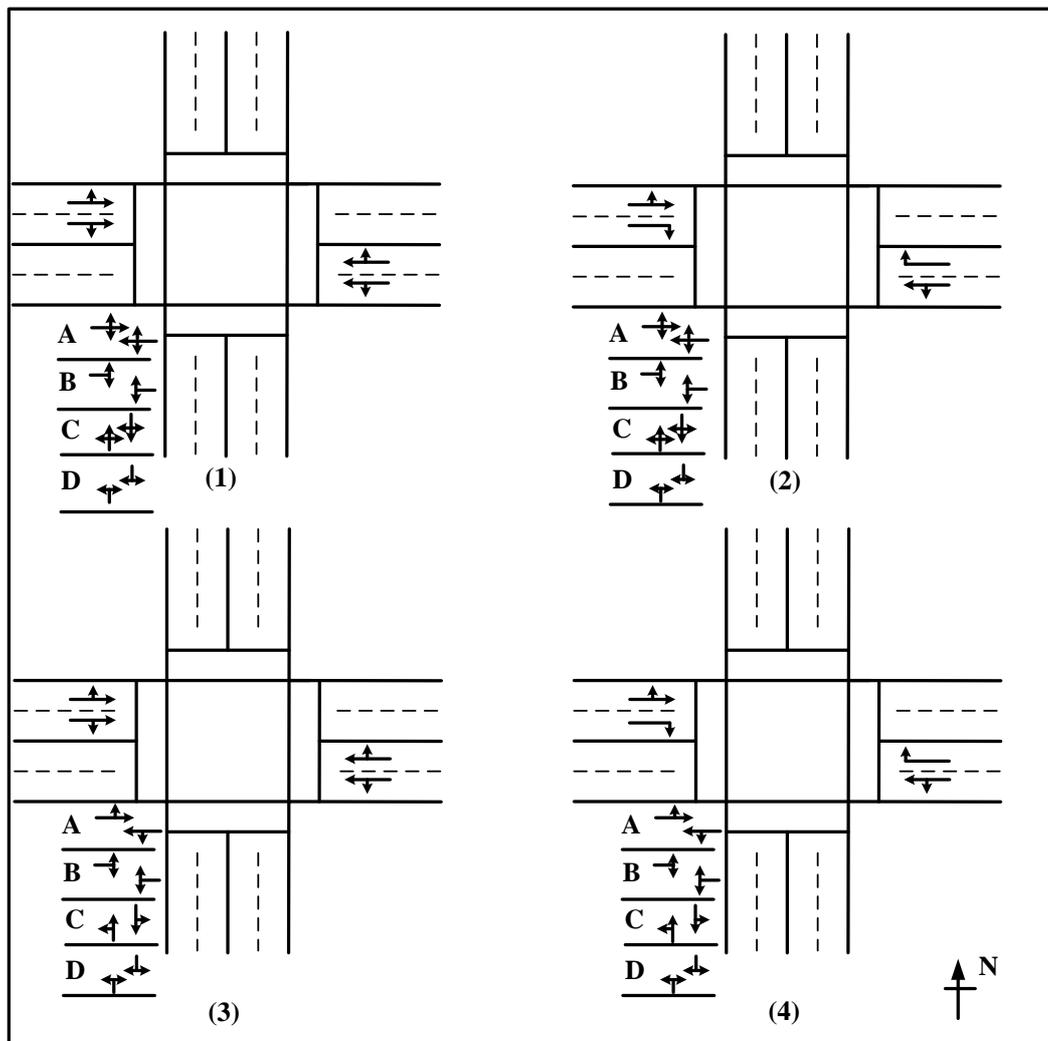


Figure 3 Geometric configuration and signal phasing for case study intersections:
Intersections (1)(2): Permissive right-turn phase followed by right-turn green arrow;

Intersections (3)(4): RAG Arrow; Intersections (1)(3): Shared straight-through and right-turn lane; Intersections (2)(4): Exclusive right-turn lane.

To create various simulation scenarios, two variables, signal settings and traffic volume, are defined in each case intersection. First, two signal settings are applied with fixed cycle length and different green time for straight-through and right-turn green phases, as shown in Figure 4. The two applied signal settings have been observed in different locations with the same geometric layout as Case Intersections. The studied approach is the major approach with larger traffic volume and longer green time. Two simulation experiments are conducted.

	Set (A)	Set (B)	
	40s	30s	Green phase for straight-through vehicles
	3s	3s	Amber
	1s	1s	All-red
	20s	30s	Green phase for right-turn vehicles
	2s	2s	All-red
	20s	20s	Green phase for straight-Through vehicles
	3s	3s	Amber
	1s	1s	All-red
	15s	15s	Green phase for right-turn vehicles
	2s	2s	All-red

Figure 4 Signal settings applied in simulation scenarios

1) For each group of settings (Case Intersection and Signal Set), different traffic volume is applied in each scenario. Straight-through and right-turn vehicles in the approach are simulated at 200 veh/h step interval from 200 veh/h to 1000 veh/h per approach for each vehicle movement independently (approximate saturation degree = 0.2 to 1 for each lane). The simulation runs for 30 signal cycles, approximately 1 hour. Outputs are calculated according to average results of 5 runs as suggested by Zheng et al. (2012).

2) For each group of settings, the average DOC per vehicle of 25 runs in different traffic volumes are averaged. In this way, average DOC of each combination of control strategies is estimated.

To determine the traffic volume of opposing straight-through flow in simulation, a sensitivity test has been conducted over a range of opposing straight-through traffic volume from 200 veh/h/lane to 1200 veh/h/lane. Two layouts with one or two

opposing straight-through lanes have been simulated. Right-turn traffic volume is fixed as 1000 veh/h/lane. Simulation results are summarized in Figure 5.

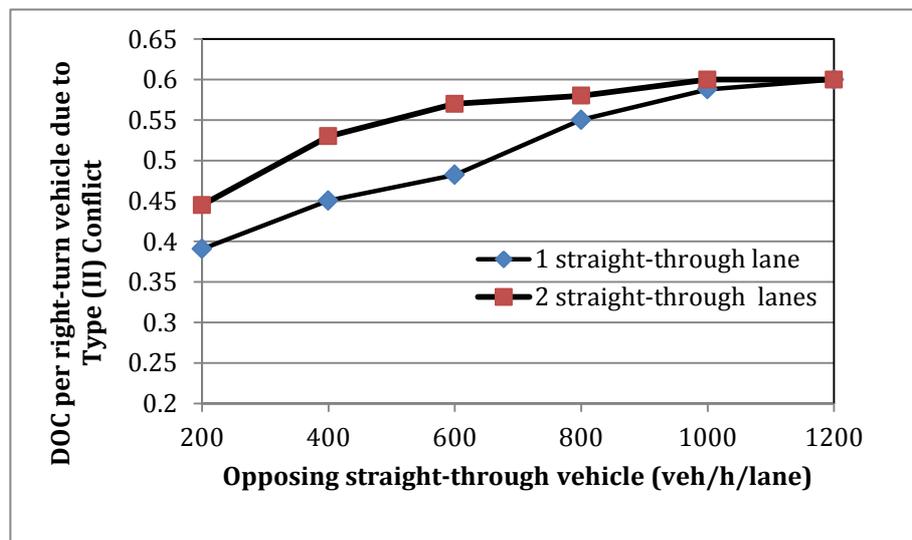


Figure 5 DOC per right-turn vehicle for different opposing straight-through traffic volume

As shown in Figure 5, Type (II) Conflicts increases gradually with increasing traffic volume of opposing straight-through vehicles. The frequency of DOC per vehicle for 2 opposing straight-through lanes is larger than for 1 lane. In both layouts, DOC per right-turn vehicle tends to a maximum value (0.6) when opposing straight-through flow exceeds 1000 veh/h/lane. In essence, when opposing straight-through flow is saturated, there will not be sufficient gap for right-turn vehicles. In practice, permissive right-turn signal phase will not be considered in such saturated situations. Therefore, in this study, opposing straight-through traffic volume is fixed at 800veh/h/lane within two limiting regimes: at over 1000 veh/h/lane, opposing straight-through flow will not be able to provide sufficient gaps for right-turn vehicles to filter through; less than 600 veh/h/lane is too small to generate enough vehicle conflicts.

4.2 Simulation results

In all simulation scenarios, average number of DOC per vehicle is calculated to indicate the degree of occurrence of vehicle conflicts. The simulation results show how input factors, including permissive right-turn or RAG Arrow, signal setting, shared lane and traffic volume, affect the occurrence of vehicle conflicts. The effect of permissive right-turn, shared right-turn lane and signal setting on vehicle conflicts at intersection approach was thus evaluated over a range of traffic volume for both traffic movements.

Severity of Types (I) & (II) Conflicts

As velocity and position of each vehicle is recorded as well as conflict occurrence (DOC), safety indicator to measure the severity of conflicts by way of Time-To-Collision (TTC) can be computed. Figure 6 shows the cumulative

distributions of DOC for a range TTC values computed for Types (I) & (II) Conflicts at 800 veh/h per vehicle movement in Intersection (1) and Signal Set (A). As velocity and position of vehicles are discrete numbers in CA model, hence the simulated TTC values are also discrete.

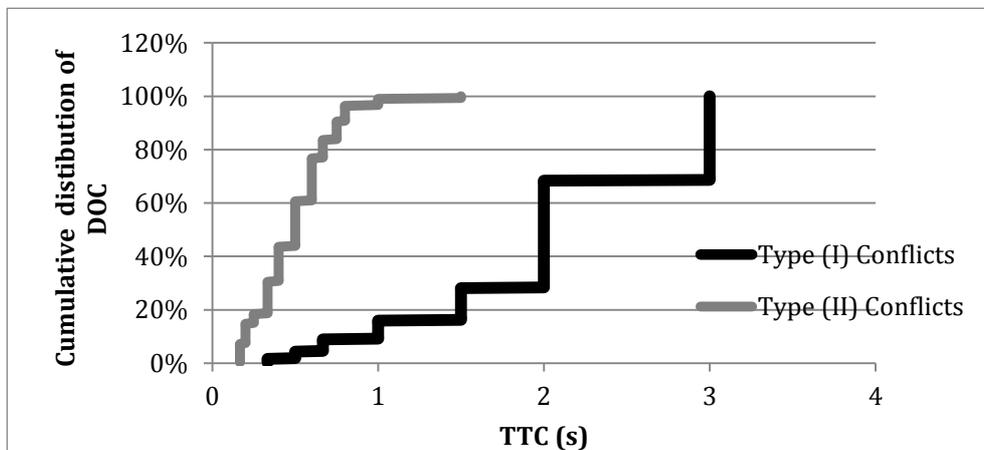


Figure 6 Cumulative distribution of DOC for Types (I) & (II) Conflicts

More conflicts are generated from the simulation for Type (I) than Type (II) Conflicts, with Type (I) Conflicts spanning over a much larger range of TTC values. This is because a Type (I) Conflict involves a pair of vehicles moving in the same direction with small velocity differential and TTC can become quite large. On the other hand, a Type (II) Conflict involves a pair of vehicles coming together from opposite directions and velocity differential tends to be large leading to a narrow range of small TTC values. From Figure 6, suppose a TTC threshold of 1.5 s is set to identify the more severe conflicts. About 15% of Type (I) Conflicts and 99% of Type (II) Conflicts would be selected. This is consistent with the pattern of traffic accident occurrences; for example in 2011, there were 593 rear-end, 63 lane-changing and over-taking collisions and 1571 right-turn-against collisions at signalized intersections in Singapore (Singapore Police Force, 2012).

Experiment 1: Relationship between conflict occurrences (DOC) and traffic volumes

Traffic volume is found to have significant effect on Type (I) Conflicts at intersection approach. Figure 7 shows the trend of DOC with input traffic volumes of Intersection (1) and Signal setting (A). For the other intersections and signal settings, trends of DOC change with traffic volumes are the same as Figure 7. X and Y axes represent traffic volumes of straight-through and right-turn vehicles in the approach with a 200 veh/h/lane step interval from 200 veh/h to 1000 veh/h (approximately 20-100% of total capacity). Average DOC values are calculated for all straight-through and for right-turn vehicles. Larger DOC indicates more frequent occurrences of vehicle conflicts. The dots represent average simulation outputs of 5 runs in the same simulation scenario. Lowess method (locally weighted smoothing linear regression) was used to generate the surface (minimum R-square= 0.9684).

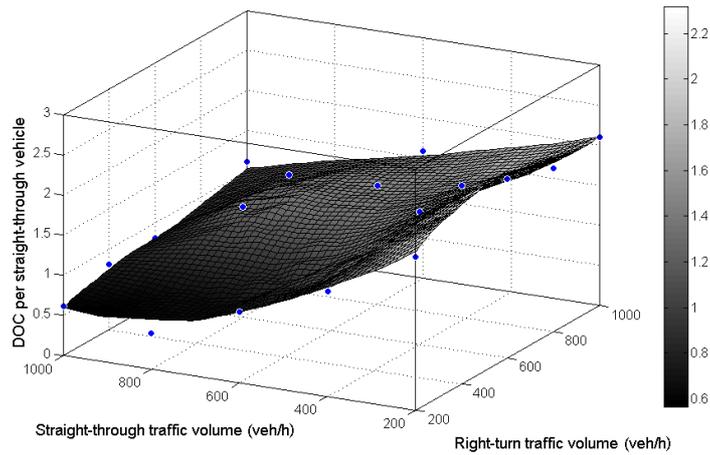


Figure 7 DOC per straight-through vehicle
(Type (I) Conflicts, Intersection (1), Signal setting (A))

From Figure 7, as higher DOC implies more frequent vehicle conflicts, conflicts for each straight-through vehicle decrease when straight-through traffic volume increases, and increase when right-through traffic volume increases. The results can be easily explained that conflicts per straight-turn vehicle will be reduced when the total number of straight-through vehicle increases. Moreover, as conflicts for straight-through vehicles along intersection approach are caused by right-turn vehicles, average conflicts per each straight-through vehicle will increase when “block” vehicle volume is increasing.

Figure 8 shows the trend of DOC per right-turn vehicle with input traffic volumes. For the other intersections and signal settings, trends of DOC change with traffic volumes are the same as Figure 8.

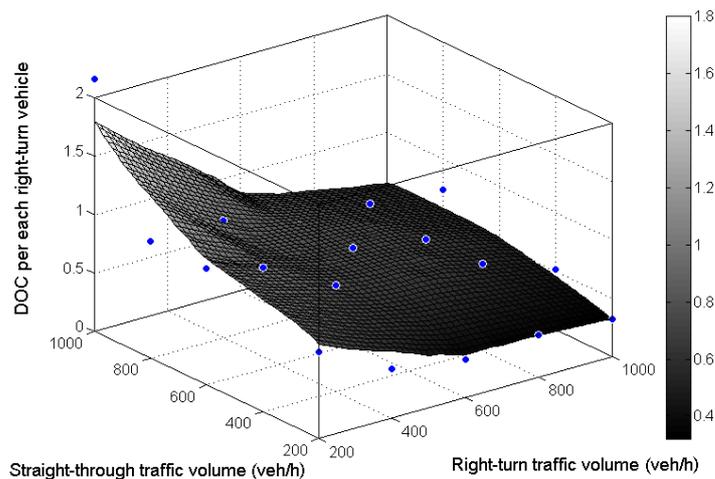


Figure 8 DOC per right-turn vehicle
(Type (I) Conflicts, Intersection (1), Signal setting (A))

Trends for right-turn vehicles are very similar to straight-through vehicles in all the selected scenarios (both permitted and RAG Arrow, both long and short green times for right-turn green phase). Conflicts frequency for each right-turn vehicle decreases when right-turn traffic volume increases, and increases when straight-through traffic volume increases.

On the other hand, according to a linear regression analysis for all scenarios ($R^2= 0.39$, $F= 7.05$), influence of traffic volume is not found to be statistically significant ($p= 0.05$) for Type (II) Conflicts.

Experiment 2: Relationship between conflict occurrences (DOC) and intersection control

For all the intersections, average DOC per vehicle with different traffic volume and signal setting has been calculated. Tables 1 and 2 respectively summarize the average DOC results for Types (I) & (II) Conflicts. DOC per vehicle with TTC smaller than 1.5s is also computed to reflect the more severe conflicts. In Table 1, as Type (I) Conflicts between right-turn vehicles and straight-through vehicles along the same approach occur mainly at shared lanes before stop-line, Intersections (1) and (3) are selected for comparison. In Table 2, Intersections (1) and (2) are selected for comparison as they both have permissive right-turn signal phases, which are associated with Type (II) Conflicts.

Table 1 Comparison of average DOC of Type (I) Conflicts

DOC per straight-through vehicle				DOC per right-turn vehicle		
Signal settings	Intersection(3) RAG Arrow	Intersection(1) Permissive	Difference	Intersection(3) RAG Arrow	Intersection(1) Permissive	Difference
Set (A)	1.54 (0.23*)	1.31 (0.20*)	- 6.55%	1.23 (0.18*)	0.85 (0.13*)	- 30.89%
Set (B)	1.62 (0.24*)	1.44 (0.22*)	- 12.69%	1.05 (0.16*)	0.75 (0.11*)	- 28.57%
Difference	4.8%	9.2%		- 17.10%	- 13.3%	

*: DOC per vehicle with TTC smaller than 1.5s

Table 2 Comparison of average DOC of Type (II) Conflicts

DOC per right-turn vehicle			
	Intersection (1) shared lane	Intersection (2) exclusive lane	Difference
Set (A)	0.50 (0.49*)	0.35 (0.35*)	- 30.00%
Set (B)	0.37 (0.37*)	0.29 (0.29*)	- 27.59%
Difference	- 35.14%	- 10.34%	

*: DOC per vehicle with TTC smaller than 1.5s

As shown in Table 1, permissive right-turn can reduce Type (I) Conflicts at intersection approach in all simulated scenarios, which is because right-turn vehicles are less likely to block following straight-through vehicles during full-green signal phase. The reduction for right-turn vehicles is more substantial because during

straight-through green phase, right-turn vehicles are allowed to queue beyond the stop line. However, during right-turn green phase, straight-through vehicles cannot cross the stop line resulting in more opportunities for vehicle conflicts. Signal settings are found to have significant affect on Type (I) Conflicts along the approach. Longer right-turn green arrow phase and shorter straight-through green phase increases vehicle conflicts for straight-through vehicles and reduces conflicts for right-turn vehicles.

From Table 2, the usage of shared straight-through and right-turn lane is found to have significant negative effect on Type (II) Conflicts. For signalized settings, longer right-turn green arrow phase and shorter straight-through green phase (Set (B)) will reduce vehicle Type (II) Conflicts between straight-through vehicles and right-turn vehicles.

4.4 Comparison of CA Model with VISSIM and SSAM

As cross-validation, all the simulation scenarios are also run on PTV VISSIM. Simulation programs run for 30 signal cycles (about 1 hour) to get converged outputs. Average travel times (from the beginning of intersection approach to end of departure, around 200 m) of each lane or each movement direction are compared with results from CA model. From very good agreement shown in simulation results, the CA model as developed is confirmed to be able to replicate signalized intersection traffic on macroscopic level as well as PTV VISSIM. Table 3 shows the travel time differences of straight-through and right-turn vehicles at intersection approach for all 4 case intersections with signal setting (A).

Table 3 Average travel time (s) per vehicle

Intersections	Straight-through vehicles			Right-turn vehicles		
	PTV VISSIM	CA model	Difference	PTV VISSIM	CA model	Difference
Intersection (1)	203.6	197.78	- 2.9%	119.31	122.65	2.8%
Intersection (2)	185.88	190.53	2.5%	180.54	185.35	2.7%
Intersection (3)	205.88	216.44	5.1%	122.3	125.95	3.0%
Intersection (4)	242.12	249.16	2.9%	196.01	204.22	4.2%

Furthermore, DOC statistics from CA model are compared with outputs from Surrogate Safety Assessment Model Software (SSAM). Trajectory files recorded in simulation by VISSIM is analyzed in SSAM. Vehicle conflicts with TTC smaller than 1.5 s are recorded according to a sensitivity test conducted. It is noted that for some conflicts recorded in SSAM, some TTC values are equal to 0 which indicates that the simulation has generated some unrealistic conflicts (Huang et al., 2008). Table 4 summarizes DOC with TTC less than 1.5s compared with number of conflicts recorded in SSAM. Traffic volume used in simulation is 800 veh/h for each vehicle movement.

Table 4 Comparison of recorded conflicts (TTC smaller than 1.5s) in CA and SSAM

	Signal Set (A)				Signal Set (B)			
	Type (I)		Type (II)		Type (I)		Type (II)	
	CA	SSAM	CA	SSAM	CA	SSAM	CA	SSAM
Intersection (1) Permissive, shared lane	97	32	300	13	98	31	222	9
Intersection (2) Permissive, exclusive lane	59	28	210	5	60	20	174	3
Intersection (3) Restricted, shared lane	124	37	0*	0	120	39	0	0
Intersection (4) Restricted, exclusive lane	71	28	0	0	64	24	0	0

* Type (II) Conflicts are not allowed under restricted right-turn (Intersections (3) and (4))

As shown in Table 4, even though more conflicts are recorded in CA than SSAM because of the usage of different indicators, those recorded by SSAM have the same trend as DOC recorded in the CA model. It is noted that SSAM is unable to differentiate the Type (I) Conflicts by movement stream (straight-through or right-turn vehicles). This is because SSAM is based on estimating TTC values between two vehicles while CA model is based on behavior of each vehicle.

Another observation is that the ratio between Type (I) Conflicts to Type (II) Conflicts is 1: 3.3 from CA model and 1: 0.3 from SSAM. Compared to the corresponding ratio in the accident data (at about 1:2.4), SSAM is found to be over estimating Type (I) Conflicts. It is noted that the difference is caused by a number of lane-changing conflicts near the stop line related to following lane-markings for each movement direction in SSAM. Among all the recorded conflicts at intersection approaches by SSAM, over 60% are lane-changing conflicts rather than rear-end conflicts. However, in CA, the proportion of lane-changing among Type (I) Conflicts is about 12%. The observed proportions of lane-changing accidents (about 10%) is much closer to simulation results from CA model rather than SSAM. The route-decision module in VISSIM, upon which SSAM relies in this study, may cause the over-estimation of lane-changing conflicts at intersection approaches. In VISSIM, route decisions are made at a certain user-defined point. However, in CA model, drivers can dynamically make route decision at any time step. This shows that the CA model is more flexible in simulating vehicle movements and interactions.

5. Discussion of simulation results

With a safety indicator of average DOC per vehicle that is obtained from microscopic simulation, the influence of permissive right-turn, shared straight-through and right-turn lane, signal settings and traffic volume are analyzed. It is found that conflict occurrences involving right-turn vehicles (with both alongside and opposing

straight-through vehicles) are affected by lane configuration and signal settings (as summarized in Table 5). DOC per vehicle with TTC smaller than 1.5 are selected for comparison. Through microscopic simulation, impacts of several factors can be analyzed quantitatively. In Table 5, increase of frequency of conflicts are represented by the symbol “+” and reduction of conflicts by “-”. Effect of each input factor is estimated by averaging simulation results over a range of other factors.

Table 5 Summary of average DOC (TTC<1.5s) influenced by several factors

Factors	Type (I) Conflicts at intersection approach		Type(II) Conflicts at intersection-box
	Straight-through	Right-turn	Right-turn
Permissive right-turn	- 9.62%	- 29.73%	+ 58.80%
Shared right-turn lane	+22.45%	+39.27%	+28.80%
Straight-through traffic volume along studied approach (200-1000 veh/h/lane)	Significant (-)	Significant (+)	Not significant
Right-turn traffic volume along studied approach (200-1000 veh/h/lane)	Significant (+)	Significant (-)	Not significant
Longer right-turn arrow phase (30s instead of 20s)	+ 7.01%	- 15.25%	- 22.74%

5.1 Impact of permissive right-turn phase

According to simulation results summarized in Table 5, the incidence of conflicts involving right-turn vehicles, both Types (I) & (II) Conflicts, are very sensitive to the usage of permissive right-turn and shared-movement. Permissive right-turn significantly reduced the occurrence of Type (I) Conflicts both for straight-through and right-turn vehicles along intersection approach (9.62% for straight-through vehicles, 29.73% for right-turn vehicles). However, the usage of permissive right-turn results in additional Type (II) Conflicts between right-turn vehicles and opposing straight-through vehicles. In conventional intersection design guidelines, permissive right-turn phase is considered to improve intersection capacity by saving travel time for right-turn vehicles but tends to decrease intersection safety due to more Type (II) Conflicts. However, simulation results in this study show that permissive right-turn is able to reduce vehicle conflicts along shared lane at intersection approaches such as to reduce the risk of Type (I) Conflicts.

It is also noted that in scenarios with permissive right-turn, the amount of DOC per right-turn vehicle being reduced at approach area is less than DOC per vehicle added at intersection-box area in most simulation scenarios thus the negative effect is much more severe. Thus, for traffic engineers, when applying permissive right-turn control, management of Type (II) Conflicts should be first taken into consideration. For example, there should be situations that opposing straight-through traffic is not too

heavy so that enough gaps can be provided for right-turn vehicles to filter through and complete the turn. Geometric layout of intersection approach should also be taken into consideration as permissive right-turn can help to reduce vehicle conflicts along approach with shared lane.

5.2 Impact of shared straight-through/ right-turn lane

Usage of shared lane can increase the flexibility of assigning lane grouping to accommodate variable traffic volume by direction. However, a shared lane is not always beneficial as it can at time results in blockage which leads to both capacity and safety constraints. Simulation results indicate the usage of shared lane increases both Types (I) & (II) Conflicts by a large amount. The increase of Type (I) Conflicts within shared lane is very obvious. However, according to simulation results, the occurrence of Type (II) Conflicts will also be increased from shared lane usage. This phenomenon can be explained by car following behavior. When right-turn vehicles are queued at an exclusive lane, they pass the stop-line and move to intersection-box area continuously. Therefore, if sufficient gap is provided by opposing straight-through vehicles, it is likely right-turn vehicles tend to move in a platoon. However, for right-turn vehicle coming from a shared lane, as they queue between straight-through vehicles, they enter conflicts zone independently which could increase the frequency of conflicts with opposing straight-through vehicles.

On the other hand, according to simulation results, both shared lane and RAG Arrow will increase the occurrence of Type (I) Conflicts. Therefore, if RAG Arrow is selected to reduce Type (II) Conflicts, an exclusive lane could be provided in lieu of shared lane to reduce Type (I) Conflicts.

In summary, shared lane should be applied very carefully due to high conflicts occurrence involving right-turn vehicles. In practice, Land Transport Authority (LTA) of Singapore is also generally cautious in arranging shared lanes. Most shared lanes in Singapore are arranged to save land usage while accommodating vehicles for both movements (straight-through and right-turn at same approach). Among the intersection improvement projects from 2010 to 2011, over 90% newly added lanes are exclusive and two shared lanes have been changed to exclusive lanes.

5.3 Impact of traffic volumes

As occurrence of conflicts is calculated as DOC per vehicle in this study, the impact of total traffic volume is also analyzed. Traffic volume at studied approach is found to have significant influence on Type (I) Conflicts only. That is, higher straight-through traffic volume will reduce conflicts per straight-through vehicle and increase conflicts per right-turn vehicle. On the contrary, higher right-turn traffic volume will increase conflicts per straight-through vehicle and reduce conflicts per right-turn vehicle. These results have demonstrated that when one of the two traffic

movements is the majority at a shared lane, each vehicle of the other movement will have a higher conflict frequency.

On the other hand, for the case that the opposing straight-through volume is fixed, right-turn volume is found not to have significant influence on Type (II) Conflicts. This is the case even when total conflicts increase with traffic volume, but the average conflicts per vehicle remains unchanged.

5.4 Impact of signal timing

In this study, two sets of signal timing are simulated. With the total green time fixed, 10s extra green arrow signal time is added in signal Set (B) at the expense of 10s reduction in straight-through green phase. Relatively longer right-turn green arrow time reduces conflicts per right-turn vehicle (both Types (I) & (II) Conflicts) and increase conflicts per straight-through vehicle significantly.

Therefore, in practice, safety level for right-turn vehicles at intersections with permissive right-turn phase and shared straight-through right-turn lane can be improved by giving longer green time for the right-turn green arrow phase.

6. Conclusions

The study evaluates occurrence of conflicts involving right-turn vehicles at signalized intersection through microscopic simulation based on Cellular Automata (CA). A safety indicator by way of Declaration Occurrences caused by Conflicts (DOC) is estimated through vehicle interactions at conflict area. To estimate the impact of factors on conflicts involving right-turn vehicles, a study is conducted for four case intersections, with different lane configuration and signal control strategy, two different signal splits, and varied traffic volume.

Simulation results indicate that 4 factors, traffic volume, permissive right-turn signal phase, shared right-turn and straight-through lane and signal timing, affect conflicts involving right-turn vehicles significantly. However, their impact on the two types of conflicts is different. Permissive right-turn phase is found to reduce Type (I) Conflicts that occur along intersection approach and increase Type (II) Conflicts at the intersection-box. Shared right-turn and straight-through lane is found to increase both Types (I) & (II) Conflicts. Longer right-turn arrow will reduce both Types (I) & (II) Conflicts for right-turn vehicles. It is also found that even though Type (I) Conflicts are more frequent, Type (II) Conflicts tend to be much more severe.

Compared to existing safety assessment methods, the contribution of the proposed micro-simulation model can be summarized as follows:

- 1) The proposed micro-simulation model is developed based on CA with several advantages. CA models allow local calibration on several aspects including car-following, lane-changing, and interaction between vehicles. Especially, for

signalized intersections, queuing behavior and amber running behavior can also be simulated and adjusted. With user-defined traffic characteristics, the proposed CA model can be more flexible and accurate compared to analytical models.

2) Although CA model is widely used in simulating road traffic, the application has mostly been on traffic capacity assessment. In this study, CA model is applied to assess safety performance by involving a proxy indicator from microscopic vehicle interactions. Simulation results of case intersections demonstrated that this simple approach is successful in applying CA models to estimate safety performance.

3) Compared to conventional conflict techniques that rely on observation and rating, the proxy indicator (DOC) used in this paper is based on simulation of vehicle interactions. Compared to SSAM, which is based on trajectory from VISSIM, the CA model is better able to simulate microscopic vehicle movements and dynamic decision-making of drivers.

3) From the case study, impacts of intersection design and traffic factors on the occurrence of vehicle conflicts are estimated accurately. Apart from the proposed intersection layout, the CA model can also be applied to estimate safety performance in various intersection layouts, signal sequences and traffic conditions.

The proposed model would be able to help authorities to make decisions on whether to involve shared lane and permissive right-turn signal phase. As the design of signalized intersection entails combination of control strategies under dynamic traffic demand, micro-simulation model provides a user-friendly tool to estimate conflict occurrences. Through the proposed approach, prediction models of traffic conflicts can be developed for various geometric layouts and traffic control strategies.

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