Journal of the Eastern Asia Society for Transportation Studies, Vol. 6, pp. 3309 - 3324, 2005

SAFETY ANALYSIS OF TRAFFIC ROUNDABOUT: CONVENTIONAL VERSUS ALBERTA-TYPE MARKINGS

Jing BIE
Postgraduate Student
Department of Civil Engineering
The Hong Kong University of Science and Technology
Clear Water Bay, Hong Kong
E-mail: jbie@ust.hk

Hong K. LO
Associate Professor
Department of Civil Engineering
The Hong Kong University of Science and Technology
Clear Water Bay, Hong Kong
E-mail: cehklo@ust.hk

S. C. WONG
Associate Professor
Department of Civil Engineering
The University of Hong Kong
Hong Kong

W. T. HUNG
Associate Professor
Department of Civil and Structural Eng.
The Hong Kong Polytechnic University
Hong Kong

Becky P.Y. LOO
Associate Professor
Department of Geography
The University of Hong Kong
Hong Kong

Abstract: This paper analyzes safety at traffic roundabouts with a comparison between conventional lane marking and Alberta-type marking. A cell-based model is developed where the spatial and temporal dimensions are discretized into cells and time intervals. Based on the assumption of independent vehicular movements, a potential conflict is alleged to evolve when two or more vehicles are projected to collide into the same cell at the same time interval. Such potential conflict counts are subsequently used as a measure for quantitatively assessing the safety level of the roundabout. Our results show no significant difference between the safety level for conventional marking and for Alberta-type marking. However, the conflicts of Alberta-type marking tend to centralize at a few black spots.

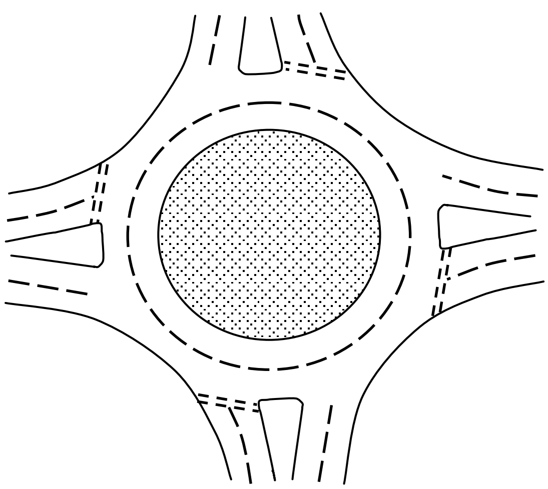
Key Words: roundabout safety, Alberta-type marking, potential conflict

1. INTRODUCTION

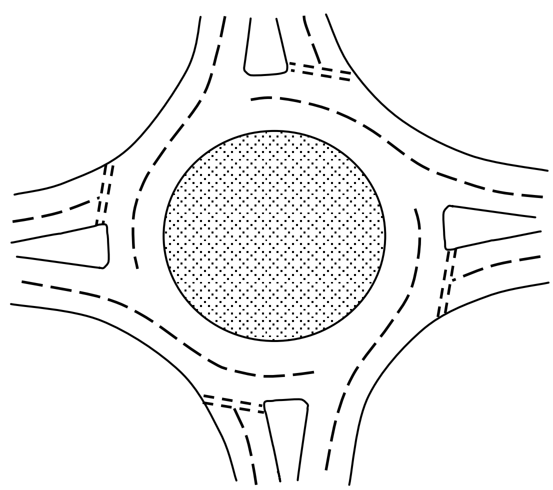
A traffic roundabout is an unsignalized intersection wherein all the vehicles travel in the same direction, i.e. clockwise (counterclockwise for right-hand side traffic), around a central traffic island. Modern roundabouts, with relatively smaller central islands and flared entries, date back to early 1960s in England and are now extensively used throughout Europe and the rest of the world. Roundabouts are introduced as substitutes for signalized intersections on safety grounds. Roundabouts are believed to harbor the advantage of reducing the severity of traffic accidents causing deaths and severe injuries. Cedersund (1988) found that, although the accident rates at signalized intersections and at roundabouts are much the same, the injury consequences at roundabouts are much lower because the types of accidents with the highest injury consequences in signalized intersections, such as right-turn collision (left-turn collision for right-hand side traffic), no longer exist. Furthermore, Al-Masaeid (1999) contended that, at roundabouts, approaching vehicles are slowed to ‘a suitable speed’ and decisions are simple and separated. Statistics show that roundabouts have reduced accidents with fatal and severe injuries by as much as 76% in the U.S., 75% in Australia, and 86% in Great Britain (Baranowski, 2004).

Higher safety level at roundabouts can also be expected because they involve a smaller number of vehicle-to-vehicle conflict points. A four-approach intersection has 32 conflict points, of which 16 are crossing conflicts, 8 are merging conflicts, and the remaining 8 are diverging conflicts. In contrast, the number of conflict points in a roundabout decreases to 8 for vehicle-to-vehicle conflicts, with 4 merging conflicts and 4 diverging conflicts. No crossing conflict is evolved because all the vehicles are regulated to circulate on the same direction along the central island.

Separation is the basic means in traffic management to counteract traffic conflicts. Conflicts are eliminated by either spatially or temporally separating opposing traffic streams. Traffic interchanges manage to separate them by space with grade separation and special design ramps, while signalized intersections try to do so by scheduled or dynamic timing. Unsignalized intersections, including roundabouts, endeavor to achieve this by both space and time but with pre-established rules, such as priority assignment (right-of-way) rules. For roundabouts, common traffic regulations declare that circulating traffic has priority over entering traffic, such as the Australian Road Rules (ARR, 1999). This is enacted with the double dotted ‘give way’ lines at entry (see Figure 1) as suggested by the Transport Planning and Design Manual (TPDM, 1995) of Hong Kong. As a result, vehicles entering the roundabout must give way to the vehicles already in the roundabout and wait for an acceptable gap to enter. The approach rules for multi-lane roundabouts in ARR also spatially separate traffic streams of different prospective exits on different approach lanes.



(a) Conventional Marking

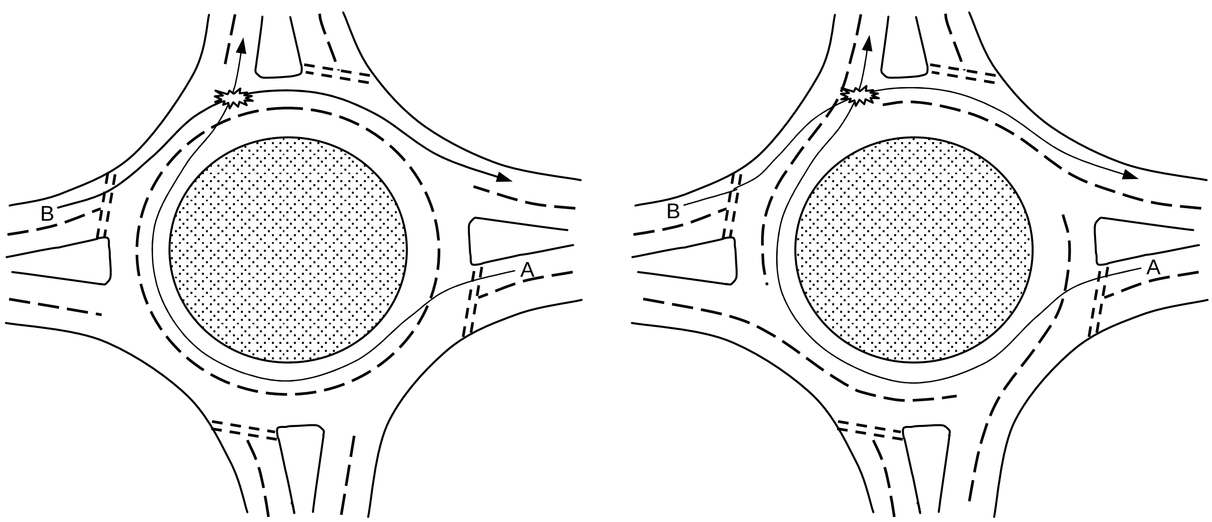


(b) Alberta-type Marking

Figure1. Two Different Marking Systems

Diverging conflicts, however, is not well handled with current rules. For single-lane roundabout, there is no contention on right-of-way at exit whereas the exiting vehicle is requested to signal left to alert the following vehicles of its exiting and probable deceleration (ARR, 1999). For multi-lane roundabout, conflicts arise between vehicles exiting from the inner lane and vehicles continuing on the outer lane. For such instance, lane marking plays an influential role in assigning right-of-way. Figure 1 illustrates two different marking systems: the conventional marking and the so-called Alberta-type marking. The conventional marking, with dotted concentric line around the central island, separates the circle into an inner lane and an outer lane, while the Alberta-type marking manages to provide continuous lanes through the roundabout.

A conventionally marked double-lane roundabout has a concentric circle line around the central island which separates the carriageway into an inner lane and an outer lane. This type of marking at multi-lane roundabouts tends to discourage drivers to use the inner lane due to the well established priority rule. That is, vehicles entering or crossing a lane must give way to vehicles which stay in their original lanes, whereas vehicles without crossing any line-marking will be provided with the priority and right-of-way. Consider the situation demonstrated in Figure 2(a) where the right-turn vehicle A tries to leave the inner lane to exit. Crossing the outer lane, vehicle A has to give way to vehicles circulating in the outer lane such as vehicle B and wait for a gap between the circulating vehicles on the outer lane. This can discourage vehicles from using the inner lane due to this potential problem of exiting from the inner lane.



(a) Conventional Marking (b) Alberta-type Marking

Figure 2. Exiting Conflict

This situation can sometimes become dilemmatic and turn worse, especially under heavy traffic demand. Since vehicle A is not supposed to stop in the circle while waiting for the acceptable gap, as a result it has to circulate around the central island another time to examine its fortune for a second chance. It could happen that certain drivers might get impatient and force their way out despite that the upcoming gap might not be long enough for this endeavor, especially with heavy traffic on the outer lane. On the other hand, if a lot of drivers shift to the outer lane for ease of exiting, the traffic flow on the outer lane becomes denser, leaving the inner lane under-utilized.

In the Alberta-type marking, the circle line is broken and connected with the lane marking on each dissipating arm. This type of marking system has been mainly adopted in New Zealand and Australia, and is currently being field-tested in Hong Kong. In New Zealand, about 50% of double-lane roundabouts have adopted the Alberta-type marking system (LTSA 2000). Australia also uses the Alberta system for multi-lane roundabouts to some extent.

The Alberta-type marking offers exiting vehicles the priority over circulating vehicles. This is upheld by the special layout of the lane marking in the roundabout. For the situation depicted in Figure 2(b), priority switches to the exiting vehicle A, while the circulating vehicle B has to cross a marking line before reaching the conflict point. This priority apportionment requires circulating traffic on the outer lane to yield to traffic exiting from the inner lane. It would increase the utilization of the inner lane and perhaps efficiency of the roundabout could be increased as a result.

Table 1 compares the lane utilization according to the number of line-crossings. Since priority is given to those vehicles not crossing a line-marking, drivers in this regime prefer to choose a path (i.e. to use the outer lane or the inner lane) with the minimum number of line-crossings. Note that in this case lane changing would increase the number by one and is not encouraged. The analysis on drivers' preferred lane is especially important when traffic demand is high, or when line-crossing (or lane crossing) poses difficulties. For low traffic demand, line-crossing is relatively easy so the impedance is not as high, leaving drivers to use the lanes rather arbitrarily. On the other hand, when traffic demand is high, yielding or giving way means waiting, and in minimizing ones' waiting times, drivers generally prefer the least number of line-crossings. In accordance with the preceding analysis, the lane preference in the Alberta-type marking balances the flows on the two lanes.

Table 1. Priority Assignment at Roundabout

Movement	Conventional marking			Alberta-type marking		
	Line-crossings		Preferred lane	Line-crossings		Preferred lane
	Outer lane	Inner lane		Outer lane	Inner lane	
Left-turn	0	2	Outer	0	1	Outer
Through	0	2	Outer	1	1	Outer/ Inner
Right-turn	0	2	Outer	2	1	Inner
U-turn	0	2	Outer	3	1	Inner

The above inferential analysis leads to concluding the safety advantage of the Alberta-type marking, yet this is not so far supported by quantitative analysis. This paper proposes a cell-based model of traffic simulation for safety analysis. Each lane of the roundabout is divided into a certain amount of cells and each vehicle is simulated to independently move across one cell in one time interval, that is, interactions among circulating vehicles such as deceleration of speed to follow the vehicle in front or checking gap for crossing a lane are not considered. Vehicles are moving from one cell to another independently of each other, and with synchrony, from one time interval to the next. For the integral of many vehicles, we may distinguish the situations when two or more vehicles are occupying the same cell at the same time interval. This multiple occupancy is not realistically possible but forms the concept of potential conflict, the count of which is used as a measurement of safety level for roundabout. Based on potential conflict count, a comparative study between conventional marking and Alberta-type marking proceed with quantitative results.

The paper is organized as follows: Section 2 focuses on the safety model formulation; Section 3 gives the comparison methodology of the two marking systems, together with numerical results; and finally, Section 4 discusses the concluding remarks.

2. POTENTIAL CONFLICT FORMULATION

2.1. Basic Assumptions

In this cell-based demand-oriented model, a basic assumption is the independency of vehicular movements, that is, each vehicle would maintain on its route as if there were no other vehicles in the roundabout. Under this postulation, gap checking is no longer needed as there are no other vehicles present. Moreover, there is no reason for a vehicle to decelerate (so as to yield) or to accelerate (so as to catch a gap). This assumption is reasonable for the purpose of measuring *potential* conflict based on demands, as the potentiality of conflict builds its root in the traffic demand from different origins to different destinations.

A second assumption is the uniformity of circulating velocity, that is, all movement in the circle is normalized to the same speed. This supposition indicates that, firstly, all vehicles circulate in the same speed, and secondly, a vehicle moves around the circle in the same speed (i.e. without change of speed). Furthermore, this uniform velocity is taken as the average speed on the roundabout. For later studies it is possible for this uniform-velocity restriction to be lifted to make the model more comprehensive, in view of the fact that different types of vehicles usually have different circulating speeds.

Another assumption on the potentiality of conflict is based on our one-second scale, i.e. the time interval taken in this model is one second. A potential conflict by definition is evolved when two or more vehicles are to be occupying the same cell at the same one-second time interval. Other scale such as two-second interval can also be implemented with the same methodologies introduced by this model.

2.2. Cell Formulation

All vehicles traveling on the roundabout are simplified as moving along the midline of the lane within the average speed v_a (m/sec). Consider for lane i, the radius of the midline circle is r_i

(m), which makes the perimeter is $L_i = 2\pi r_i$ (m). The time (sec) for a vehicle to circulate around the lane for a whole circle is

$$T_i = \frac{L_i}{v_a} = N_i + (T_i - N_i) \tag{1}$$

Then T_i is rounded to the nearest integer N_i,

$$N_i = [T_i + 0.5] = \text{the integer part of } (T_i + 0.5) \tag{2}$$

The fraction part, $(T_i - N_i)$, ranges between $[-0.5, 0.5)$.

The integer N_i is taken as the number of cells on lane i. Visually, a cell can be defined as a annulus sector with the same width as of the lane. Each cell has the same length of

$$l_i = \frac{L_i}{N_i} = v_a + \frac{(T_i - N_i)}{N_i} v_a \tag{3}$$

The time (sec) a vehicle needs to cross a single cell is

$$t_i = \frac{l_i}{v_a} = 1 + \frac{(T_i - N_i)}{N_i} \tag{4}$$

Simplification is made that a vehicle moves across one cell in exact one second. The bias of approximating t_i as one second is δ_i, which satisfies the inequality below:

$$|\delta_i| = \left| \frac{(T_i - N_i)}{N_i} \right| \le \frac{0.5}{N_i} \tag{5}$$

Consider for a roundabout lane with a mid-radius of 20 meters and an average circulating speed of 6 m/sec (22 km/hr), the number of cells is about 20 and the maximal bias is as little as 0.024 sec. If the radius is 30 meters, this value would reduce to 0.016 sec. Since the magnitude of the error is small, it is accurate enough for our purpose to take t_i as 1 sec. In other words, this means our one-second scale of potential conflict is virtually t_i-second scale. The simplification only affects the time scale by an error δ_i (which is the same to all movements) and indeed does not bring any infraction to the concept of potential conflict.

To sum up, lane i is divided into N_i cells, each with length of l_i. Vehicles are approximated to the same average speed, which precisely covers one cell in one second. The cells are then displayed along the center line of each lane continuously and are numbered in a clockwise order (for left-hand side traffic). A picture is shown in Figure 3 to depict the cell alignment on the roundabout.

2.3. Movement Formulation

Any movement in the circle can therefore be expressed as a string of cells. For the roundabout shown in Figure 3, the path of a right-turn vehicle entering from the south, using the inner lane, and exiting to the east, can be represented by the following string of cells:

$$23 \rightarrow 46 \rightarrow 47 \rightarrow 48 \rightarrow 49 \rightarrow 28 \rightarrow 29 \rightarrow 30 \rightarrow 31 \rightarrow 32$$
$$\rightarrow 33 \rightarrow 34 \rightarrow 35 \rightarrow 36 \rightarrow 37 \rightarrow 38 \rightarrow 14$$

Generally, there are a limited number of paths going through a roundabout. Once the roundabout is divided into cells, all these paths can be represented by strings of cells, or path strings, which are then sorted and numbered. Each vehicle drives on one of these paths and is identified with a path number P. With the path number we can retrieve the full details of a path, with N_p as the number of cells in the path string and $P(k)$ as the k-th cell on the path, $k = 1, 2, ..., N_p$.

Since all vehicles move in the same preset average speed, that is, one cell over one second, the path P and the entry time t_e (corresponding to the first cell of the path string) for a vehicle provide the full information needed to portray the vehicular movement in the roundabout. For a vehicle that enters the roundabout at time t_e and uses the path P, at time $t \in \{t_e, t_e + 1, t_e + 2, ..., t_e + N_p - 1\}$ the vehicle will be on the cell

$$C(t) = P(t - t_e + 1), \; t \in \{t_e, t_e + 1, t_e + 2, ..., t_e + N_p - 1\} \tag{6}$$

Take the right-turn vehicle for instance, if the entry time on cell 23 is 18:21:55, then at the second of 18:22:06 the vehicle would be on cell 34, and it will exit from cell 14 at the second of 18:22:11.

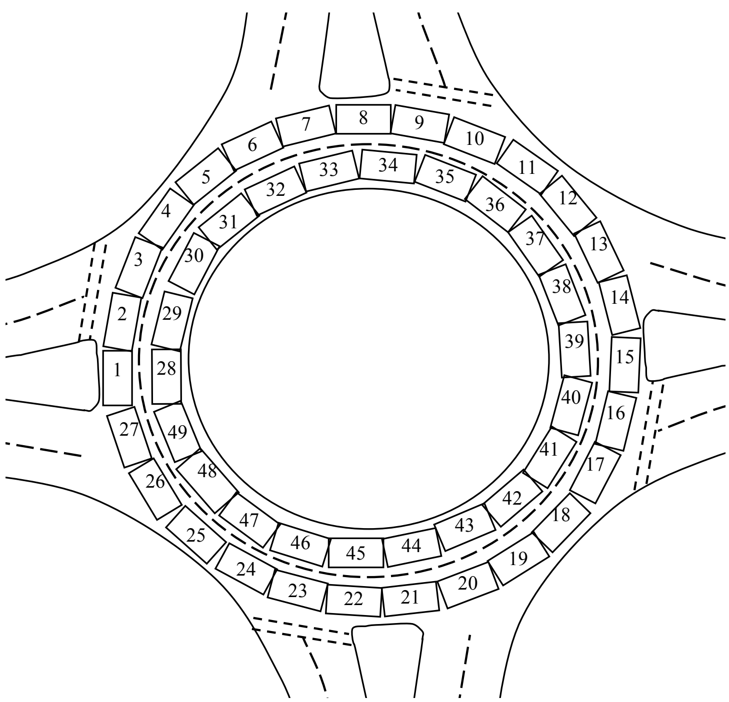


Figure 3. Cells on the Roundabout

2.4. Cell Occupancy Matrix and Potential Conflict

For a roundabout with a number N_c of cells, a volume of V vehicles is recorded over a time span of T_{sp} seconds. A $T_{sp} \times N_c$ cell occupancy (CO) matrix $O_{time,cell}$ presents the vehicular occupancy in cells at time intervals. The value of the element $O_{i,j}$ equals to the number of vehicles occupying the j-th cell in the roundabout at the i-th second of the time span. A potential conflict (PC) occurs when a CO entry $O_{t,c}$ is greater than or equal to 2, i.e. two or more vehicles are occupying the cell c at the time second t.

All elements in the CO matrix $O_{time,cell}$ are initially set as zero. A procedure of vehicular update is implemented to generate the cell occupancy in the CO matrix. For the v-th ($v \in \{1,2,...,V\}$) vehicle with entry time $t_{e,v}$ and path P_v, the vehicle will occupy the cell $P_v(t-t_{e,v}+1)$ at the second $t \in \{t_{e,v}, t_{e,v}+1, t_{e,v}+2, ..., t_{e,v}+N_{P_v}-1\}$ and thus one more series of vehicular occupation is added to CO matrix. This procedure can be described as

$$\begin{aligned} & O[t, P_v(t-t_{e,v}+1)]^{update} = O[t, P_v(t-t_{e,v}+1)]+1 \\ & \forall t \in \{t_{e,v}, t_{e,v}+1, t_{e,v}+2, ..., t_{e,v}+N_{P_v}-1\} \\ & \forall v \in \{1,2,...,V\} \end{aligned} \tag{7}$$

When all the vehicles recorded have one by one been put into the updating procedure, a finalized CO matrix is formed. Any element greater than or equal to 2 corresponds to a potential conflict. The total amount of vehicles-times involved in potential conflict is

$$PCvt = \sum_{c=1}^{N_c} \sum_{t=1}^{T_{sp}} O_{t,c} I[O_{t,c} \geq 2] \tag{8}$$

where the conditional indicator $I[O_{t,c} \geq 2] = \begin{cases} 1, \text{ if } O_{t,c} \geq 2 \\ 0, \text{ otherwise} \end{cases}$.

2.5. First-order Potential Conflict and its Approximation

It is noted that in the preceding algorithm vehicle overlap is allowed, which brings about the potential conflicts. If two vehicles use the same paths or the same portions of their paths through the roundabout, after their first "collision", they will move along with each other by occupying the same downstream cells in the next several time intervals. Consider the following example:

$$\text{Vehicle 148: } \begin{cases} t_e = 1996(\text{sec}) \\ P = [2,29,30,31,32,33,34,35,36,37,38,14] \end{cases}$$

$$\text{Vehicle 155: } \begin{cases} t_e = 2002(\text{sec}) \\ P = [9,35,36,37,38,39,40,41,42,43,44,45,46,47,48,26] \end{cases}$$

The two vehicles first collide on cell 35 at time 2003. The collision repeats for the next three seconds respectively on the three following cells: on cell 36/37/38 at time 2004/2005/2006.

The unprecedented first-order potential conflict is the cell-second where and when two vehicles first collide with each other. The second-order potential conflicts take place in the follow-up cells-seconds till the pair disjoins, and goes along with the lasting time of the conflict between the pair. They involve the same pair of vehicles of the same "collision" event. To avoid multiple counting of the same collision event, only the first-order potential conflict should be counted in the measurement.

For the purpose of counting only first-order potential conflict, the first-order CO matrix is built up where two vehicles after their first collision merge into each other as a single entity until they diverge into different destinations. That is, when vehicle A and B collide into the same cell at a certain second, starting from the next second till their departure the two vehicles act exactly as one single vehicle and contribute only a single occupancy into the CO matrix. The update procedure in Equation (7) is modified as

$$\begin{aligned} &O[t, P_v(t-t_{e,v}+1)]^{update} = O[t, P_v(t-t_{e,v}+1)] + I[v,t] \\ &\forall t \in \{t_{e,v}, t_{e,v}+1, t_{e,v}+2, ..., t_{e,v}+N_{P_v}-1\} \\ &\forall v \in \{1, 2, ..., V\} \end{aligned} \tag{9}$$

where the non-second-order indicator is

$$I[v,t] = \begin{cases} 0, \text{ if adding vehicle } v \text{ at time } t \text{ is causing a second-order conflict} \\ 1, \text{ otherwise} \end{cases}.$$

First-order potential conflict involvement amount is then summed up from the finalized CO matrix using Equation (8).

Through this procedure second-order conflicts can be removed, since those second-order co-occupancies are not added into the CO matrix. The CO matrix update procedure for vehicle 155 in the example above will be the same in Equations (7) and (9) except the following steps:

$$O[\begin{cases}2003\\2004\\2005\\2006\end{cases}, \begin{cases}35\\36\\37\\38\end{cases}]^{update} = O[\begin{cases}2003\\2004\\2005\\2006\end{cases}, \begin{cases}35\\36\\37\\38\end{cases}] + (7)\begin{cases}1\\1\\1\\1\end{cases}, (9)\begin{cases}1\\0\\0\\0\end{cases}.$$

As adding entries of vehicle 155 into $O[\begin{cases}2004\\2005\\2006\end{cases}, \begin{cases}36\\37\\38\end{cases}]$ are causing second-order conflicts with previous vehicle 148 and thus no occupancy should be re-added.

To include the inter-vehicular effect in identifying second-order co-occupancy as in Equation (9), vehicle numbers need to be labeled. This will make the matrix into three-dimensional and cost much longer time on computation. The following approximation is reasonable when traffic volume is not too high. For the update procedure of vehicle v, if we consider the previous $(v-1)$ vehicles as an integrated vehicle V, interactions between vehicle v and any vehicle(s) in the previous $(v-1)$ vehicles can be represented by the interaction between vehicle v and the integral vehicle V. The verification for second-order conflicts with any previous individual vehicles is applied to vehicle V instead.

The update procedure as in Equation (9) is approximated as

$$\begin{aligned}
&O[t, P_v(t - t_{e,v} + 1)]^{update} = O[t, P_v(t - t_{e,v} + 1)]^{original} + i(v,t) \\
&\forall t \in \{t_{e,v}, t_{e,v} + 1, t_{e,v} + 2, ..., t_{e,v} + N_{P_v} - 1\} \\
&\forall v \in \{1, 2, ..., V\}
\end{aligned} \tag{10}$$

where, $i(v,t) = \max\{I[\text{non-occupancy}], I[\text{non-second-order}]\}$

$$I[\text{non-occupancy}] = \begin{cases} 1, \text{ if } O[t, P_v(t - t_{e,v} + 1]^{original} \text{ equals } 0 \\ 0, \text{ otherwise} \end{cases}$$

$$I[\text{non-second-order}] = \begin{cases} 1, \text{ for } t = t_{e,v} \\ 1, \text{ if } O[t-1, P_v(t - t_{e,v})]^{original} \text{ equals 0 for } t \geq t_{e,v} + 1. \\ 0, \text{ otherwise} \end{cases}$$

The update procedure described in Equation (10) requires the algorithm to check two criteria before adding occupancy to the current cell-time instance: 1) the current time-cell is not occupied; and 2) this is the entry cell-time or the previous cell-time originally is not occupied. If either of the two conditions holds, one occupation is added for the current cell-time. Through this process, only first-order multi-occupation enters the CO matrix and the same Equation (8) can be used to calculate the approximate first-order PC. For the situation in the example of second-order conflict, the occupations of vehicle 155 on cell 36, 37, and 38 would not be added since vehicle 148 is already there and these occupations can be identified as second-order conflict.

Bias exists in the approximation. The modified algorithm above can avoid all the overlapping follow-up re-count, but also would eliminate some minor occasions such as the example below and thus slightly underestimate the potential conflict rates:

$$\text{Vehicle 021: } \begin{cases} t_e = 200 \\ P = [10,11,12,13,14,15,16,17,18,19] \end{cases}$$

$$\text{Vehicle 022: } \begin{cases} t_e = 200 \\ P = [9,35,36,37,38,39,40,41,42,43,20] \end{cases}$$

$$\text{Vehicle 023: } \begin{cases} t_e = 206 \\ P = [16,41,42,43,44,45,46,47,48,27] \end{cases}$$

In this example, there are actually two first-time conflicts, vehicle 023 with vehicle 021 at second 206 on cell 16, and vehicle 023 with vehicle 022 at second 207 on cell 41. But the algorithm above will only count the first one conflict.

For light traffic, the possibility of those occasions is low and thus the method is acceptable. When the traffic is very heavy, amendment is needed for further implementation. A potential option is to ‘label’ the vehicles in the CO matrix and thus to make it practical to count only and all of these first-time conflicts as PCs. This proposal remains a task for future research.

3. COMPARISON METHODOLOGY

Drivers may choose different routes in roundabouts with different markings. For example, drivers who use the outer lane under the conventional marking may use the inner lane instead under the Alberta-type marking. An ideal approach to compare two different markings is to change the marking of a certain roundabout and compare the lane utilizations for the same group of road users before and after the change. Traffic volume and demand pattern also play an important role for the safety comparison – imagine the extreme condition when all traffic are turning left (turning right for right-hand side traffic). The comparison is fair only when it is made under the same traffic flows, i.e. under the same demand patterns before and after the change. This is not always possible as the demand patterns may have shifted during the change. Instead, in this study, we undertake an approach in which we observe drivers' lane utilizations based on surveys of roundabouts with conventional markings. Subsequently, we gradually "migrate" the lane utilizations of users from conventional marking to the Alberta-type marking and study the sensitivity of this behavioral change.

3.1. Field Survey

In the field survey, we study the roundabout as shown in Figure 4, which has four arms designated as A, B, C, and D in a clockwise order. The average circulating speed is estimated to be 20 km/hr, and the outer lane is divided into 24 cells and the inner lane 17 cells, making a total of 41 cells. Different paths are then expressed as strings of cells.

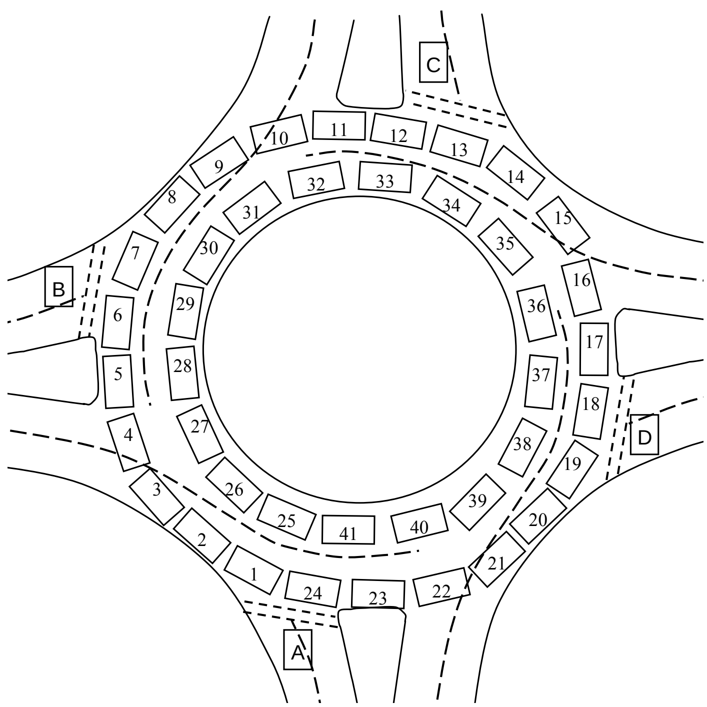


Figure 4. Studied Roundabout

A traffic stream survey is carried out for an off-peak hour and a peak hour. Hourly volumes on different entry/exit arms are shown in Table 2. Each vehicle is recorded with an entry time and a path number. Totally 101 different paths are found in the survey. The diversity of paths results from drivers' arbitrary route choices and lane changing under conventional marking.

Table 2. Volume Distribution on Entry Arms and Turning of Movements

Off-peak Hour					
Entry arm	Left-turn	Through	Right-turn	U-turn	Sum
A	13	12	9	0	34
B	24	30	6	1	61
C	69	9	43	50	171
D	3	64	83	1	151
Sum	109	115	141	52	417
Peak Hour					
Entry arm	Left-turn	Through	Right-turn	U-turn	Sum
A	22	20	7	0	49
B	25	43	10	5	83
C	71	18	62	66	217
D	5	118	75	0	198
Sum	123	199	154	71	547

3.2. Route Choices within Roundabout

While 101 paths are recorded under conventional marking, there are much fewer paths under condition with full compliance to Alberta-type marking. For a four-arm double-lane roundabout, the Alberta rules embedded in the Alberta-type marking suggest drivers to follow these patterns of routes: (i) left-turn traffic uses the left entry and the outer lane; (ii) through traffic uses either the left entry and the outer lane, or the right entry and inner lane until exit; (iii) both right-turn and U-turn vehicles use the right entry and the inner lane until exit. Under this condition, an arm only generates 5 different routes, making a total of 20 for all four arms.

Drivers' route choices are recorded and those complying with the Alberta rules as defined above are counted and listed in Table 3. Overall, we have nearly 40% of drivers already driving in compliance with the Alberta rules whereas left-turn traffic contributes to more than half of this volume. The mostly seen deviations from the Alberta rules include route choices of: 1) through traffic taking the inner lane → outer lane → exit; 2) right-turn traffic taking the outer lane → outer lane → outer lane → exit; 3) U-turn traffic taking the inner lane → inner lane → inner lane → outer lane → exit for U-turn traffic. The result supports our analysis of outer lane preference (see Table 1), especially before exiting.

In simulating the route choices in the Alberta-type marking, we gradually convert non-compliant choices to compliant choices. Table 4 illustrates some examples of this conversion from conventional markings to the Alberta-type marking. The cell sequence shown in Table 4 refers to those in Figure 4.

Table 3. Percentage (%) of Original Flow Following the Alberta Rules

Off-peak	Left-turn	Through	Right-turn	U-turn	Sum*
Volume	109	115	141	52	417
Compliant	106	14	35	10	165
Percentage	97%	12%	24%	19%	39%
Peak	Left-turn	Through	Right-turn	U-turn	Sum*
Volume	123	199	154	71	547
Compliant	117	35	46	12	210
Percentage	95%	17%	29%	16%	38%

* The values in the rows of percentage represent average instead of sum.

Table 4. Examples of Route Choice Conversion within a Roundabout

Movement	Original route	Conversion to compliance with the Alberta rules
Left-turn	$\begin{cases} t_e = 2003 \\ P = [1,2,3] \end{cases}$	Unchanged.
Through	$\begin{cases} t_e = 1937 \\ P = [7,30,31,32,33,13,14,15] \end{cases}$	Either $\begin{cases} t_e = 1937 \\ P = [7,8,9,10,11,12,13,14,15] \end{cases}$ or $\begin{cases} t_e = 1937 \\ P = [6,29,30,31,32,33,34,35,16] \end{cases}$
Right-turn	$\begin{cases} t_e = 0585 \\ P = [24,25,26,27,28,29,30, \\ \quad 31,32,33,13,14,15] \end{cases}$	$\begin{cases} t_e = 0585 \\ P = [24,25,26,27,28,29,30, \\ \quad 31,32,33,34,35,16] \end{cases}$
U-turn	$\begin{cases} t_e = 585 \\ P = [19,38,39,40,41,25,26,27,28, \\ \quad 29,30,31,32,33,34,35,15] \end{cases}$	$\begin{cases} t_e = 585 \\ P = [18,37,38,39,40,41,25,26,27,28, \\ \quad 29,30,31,32,33,34,35,16] \end{cases}$

Gradual conversion is a reasonable way to model the different degrees of compliance with the Alberta rules. By systematically and randomly selecting a certain percentage of the traffic to be converted into the Alberta rules, we obtain the results for different degrees of compliance. In the upper bound case, all traffic follows the Alberta rules. We then study the impact on potential conflict between the original traffic via the various levels of compliance being followed to the ultimate stage of 100% compliance.

3.3. Results

Using the procedure described above, we obtain the results on potential conflict as shown in Table 5. With the Alberta conversion, we gradually convert 30%, 60%, 80%, and 100% of Alberta-disobeyed routes into Alberta-obeyed routes according to the Alberta rules.

The results show no appreciable advantage of the Alberta-type marking on potential conflict counts. Along with the gradual conversion, the counts vary depending on the specified traffic flow pattern, showing no significant increase or decrease.

Table 5. Potential conflict with different degrees of compliance to the Alberta rules

Off-peak Hour					
Data	Original	With conversion			
Alberta compliance	39%	58%	76%	88%	100%
Potential conflict	26	24	20	20	28
Peak Hour					
Data	Original	With conversion			
Alberta compliance	38%	57%	75%	88%	100%
Potential conflict	36	34	44	40	32

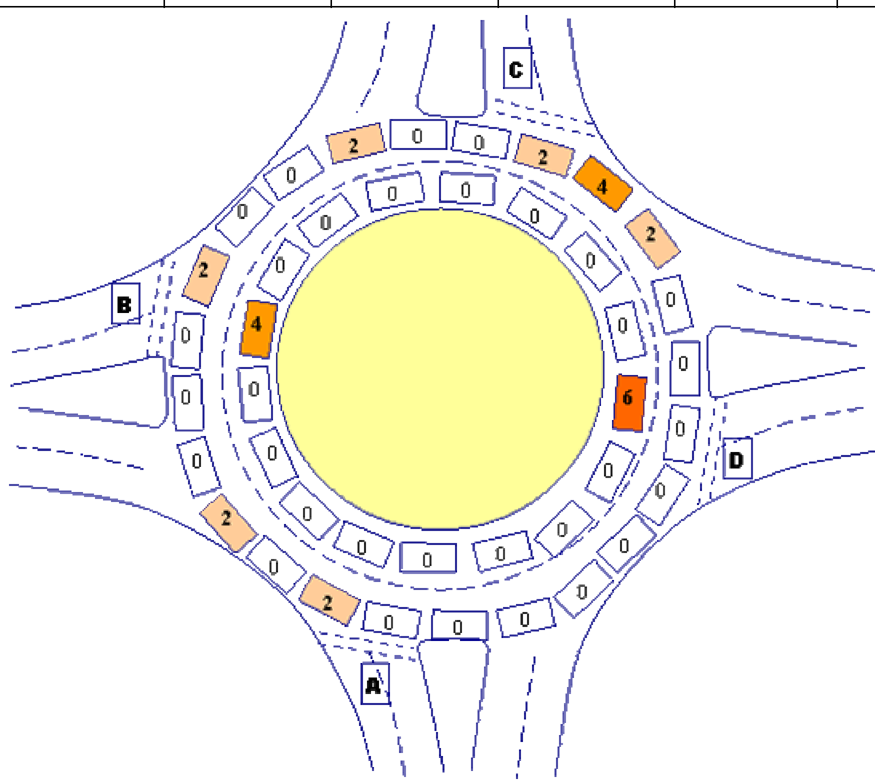


Figure 5. Potential Conflict Count of the Original Flow

Figure 5 and Figure 6 show the potential conflict count of peak hour with occurrences on cells of the original flow and the Alberta converted flow. For the original flow, potential conflict locations are widely distributed. Meanwhile, for the Alberta converted flow, potential conflicts are centralized to certain cells where the entering and the circulating traffic collide into each other. These cells such as cell 34 and 37 can be identified as black spots. This may have safety benefits as conflict points are more predictable, making drivers more aware of the risk of accident when passing these points. On the down side, this concentration of conflict points may have capacity implications, which we will examine in a future study.

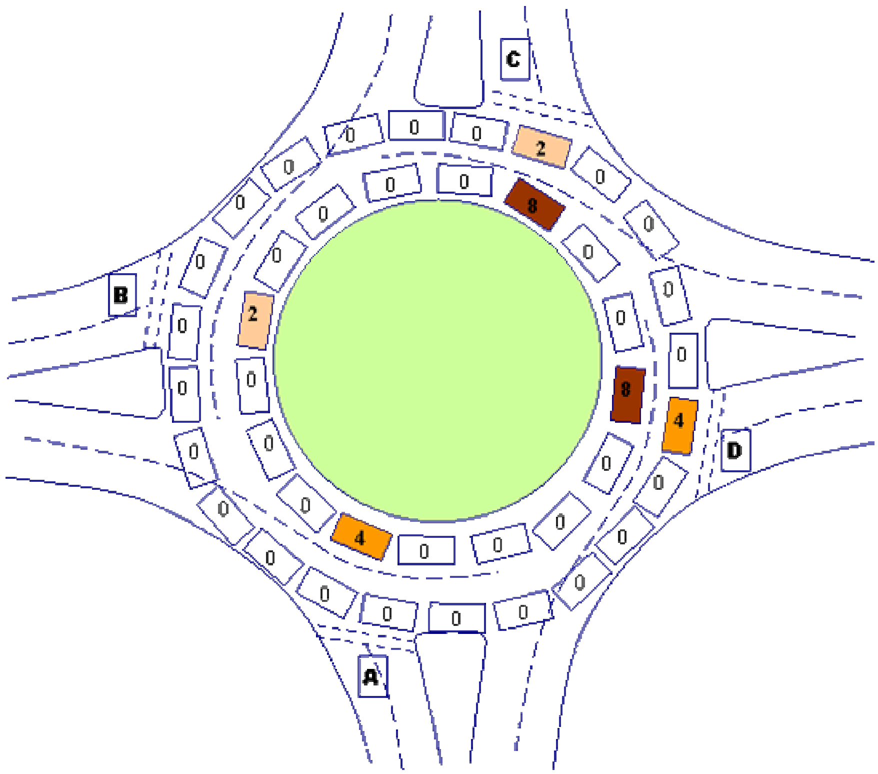


Figure 6. Potential Conflict Count of 100% Alberta Converted Flow

4. DISCUSSIONS AND CONCLUSIONS

This paper provides a cell-based model with potential conflict calculation that can be used to assess safety levels. PC count can be used as an indicator of exposure to risk. The proportionality of traffic accident rates to PC count needs further investigation. Also, improvement is possible for the method to calculate the first order PC counts. The sparse CO matrix in this model is not efficient for computation; other approaches can be developed for this purpose. One probable approach is to count PC based on the spatial-temporal relationship between paths, i.e. the time difference between two vehicles enter on the two paths.

From the results of this study, there is no significant difference in potential conflict count to conclude that the Alberta-type marking generally makes the roundabout safer. However, a distinctive feature of the Alberta-type marking is that the spots of potential conflict are centralized to several merging points.

ACKNOWLEDGEMENTS

The work described in this paper is partially supported by the Competitive Earmarked Research Grants from the Research Grants Council of the Hong Kong Special Administrative Region (Project number: HKU7031/02E).

REFERENCES

Al-Masaeid, H. R. (1999) Capacity and performance of roundabouts, **Canadian Journal of Civil Engineering 26(5)**, 597-605

Baranowski, B. (2004) **History of the Modern Roundabout**. Internet source: http://www.roundaboutsusa.com/history.html (retrieved on 15 Jul. 2004)

Cedersund, H. A. (1988) Traffic safety at roundabouts. In W. Brilon (ed.), **Intersections without Traffic Signals**. Springer-Verlag, Berlin

Land Transport Safety Authority (LTSA), New Zealand (2000) **Road Safety Survey 14: Roundabouts**. Wellington, New Zealand

Land Transport Safety Authority (LTSA), New Zealand (2001) **Traffic Laws for Roundabouts**. Internet source:http://www.ltsa.govt.nz/legislation/road-user/rur-roundabouts.html (retrieved on 20 Dec. 2003)

Roads and Traffic Authority NSW (1999) **Australian Road Rules** (ARR): part 9. National Road Transport Commission, Australia

Transport Department, Hong Kong SAR (1995) **Transport Planning and Design Manual** (TPDM). Hong Kong, China