JOURNAL OF ADVANCED TRANSPORTATION
J. Adv. Transp. 2016; **50**:988–1007
Published online 11 May 2016 in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/atr.1385

Multi-level traffic control at large four-leg roundabouts

Hongfeng Xu*, Kun Zhang and Dong Zhang

School of Transportation and Logistics, Dalian University of Technology, Dalian, China, 116024

SUMMARY

Yield control and full signalization are typical traffic control solutions that can be used at large roundabouts. In the face of increasing congestion issues, it is preferred to use yield control during off-peak periods and full signalization during peak periods. To automatically accommodate time-varying vehicular demands, a multi-level traffic control (MTC) is developed to implement hybrid yield control and fully actuated control at large four-leg roundabouts. With new application of traffic control devices and traffic detection system, the right-of-way can be assigned to entering and circulating vehicles in three modes. The 'all entering' mode is equivalent to a yield control. The 'no entering' and 'concurrent entering' modes are equivalent to a fully actuated control. On the basis of time headways and occupancy times that are detected on the entry and circulatory roadways, the mode of right-of-way assignment can be changed in response to actual traffic conditions. For a specific mode of right-of-way assignment, traffic signal operation is managed by some detectable traffic events that are happening. The results of the simulation experiments conducted by VISSIM indicated that: (i) MTC was stabilized at the 'all entering' mode during off-peak periods and at the 'concurrent entering' mode during peak periods; (ii) MTC would typically change the mode of right-of-way assignment according to actual traffic conditions as vehicular demands increased from off-peak to peak or decreased from peak to off-peak; and (iii) statistically speaking, MTC inherited the operational advantages of yield control and fully actuated control, and could be effective in improving the operational performance of large four-leg roundabouts for all hours of the day, regardless of the level of left-turn ratios. Copyright © 2016 John Wiley & Sons, Ltd.

KEY WORDS: roundabout; yield control; fully actuated control; traffic event; microscopic traffic simulation

INTRODUCTION

Roundabouts are a landmarked roadway facility that can be found in many cities around the world. In past decades, mini-roundabouts, single-lane roundabouts, and double-lane roundabouts have become popular because of their multiple advantages to aesthetics, safety, and operations [1–3]. A large roundabout is one with more than two entry lanes on every approach. Attraction of central island landscaping and surrounding buildings and pursuit of higher roadway capacity account for the existence of large roundabouts in urban area. Unfortunately, congestion issues are gradually leading to large roundabouts falling out of favor. *There exists a need to substantially improve the operational performance of large roundabouts*.

Previous studies on roundabouts are mainly based on single-lane and double-lane roundabouts. There is much literature concerning safety [4–13], operational analysis [14–21] and environmental impacts [22–25]. By contrast, very few publications are devoted to developing new-style traffic control solutions. This might be the consequence of public opinion on modern roundabouts. In any case, signalizing roundabouts is recommended to be considered only when other feasible alternatives cannot achieve the safety and operational objectives of vehicular and pedestrian movements. Just for this reason, *signalization should be regarded as a last resort to prevent roundabouts from being converted to*

*Correspondence to: Associate Professor Hongfeng Xu, School of Transportation and Logistics, Dalian University of Technology, Dalian, 116024 China. E-mail: xu_hong_feng@126.com

conventional signalized intersections. It does make much sense to innovate the exercise of traffic control at roundabouts.

Basically, there are three traffic control solutions that can be used at a roundabout: (i) yield control, (ii) metering signalization, and (iii) full signalization [1, 2, 26]. At a yield-controlled roundabout, yield lines and yield signs require entering vehicles to give way to circulating vehicles when sufficient gaps do not exist in the circulating stream. Vehicle delay and stops can be minimized during off-peak periods, but will rapidly deteriorate as vehicular demands increase on all approaches. Circulatory roadway locking-up is anticipated once yield rule violations occur frequently. Metering signalization is essentially a signal-aided yield control [27–32]. Still, conflicts between entering and circulating vehicles are managed by yield rule. Red-yellow vehicular signals are installed on a selected approach, 15 to 25 m in advance of the yield line, to stop entering movement when a long standing queue is detected on the next downstream approach. The possibility of excessive queuing and circulatory roadway locking-up cannot be eliminated if multiple unsignalized approaches are heavy load. Full signalization is the most mandatory measure to manage conflicts [33–35]. Yield lines and yield signs are removed from the roundabout area. Red-yellow-green vehicular signals are installed on all approaches and circulatory roadway to alternately stop entering and circulating movements. Elaborate design of signs, lane markings, and signal timings is needed to avoid circulatory roadway locking-up and maximize the use of roundabout area. Full signalization can lead to better operational performance for roundabouts operating near or beyond the capacity. But interrupted vehicular movements caused by signalization will result in unnecessary vehicle delay and stops during off-peak periods. *On the whole, considering time-varying vehicular demands, none of the typical traffic control solutions is effective for all hours of the day, but there is a distinct difference in their respective periods of maximum effectiveness*.

Large four-leg roundabouts require wider circulatory and exit roadways to accommodate more vehicles traveling side by side. The task of managing the increased number of conflicts gets more complicated when the magnitude of conflicting flows increases. *It is preferred to use yield control during off-peak periods and full signalization during peak periods*. The need is great for guidance on how to install traffic control devices and operate them safely throughout the day. Drivers must clearly know what they are supposed to do when approaching entry and circulatory roadways. Although the change between yield control and full signalization can be made manually or on a time-of-day basis, *it is appealing to let that happen in response to actual traffic conditions*. Given the operational advantage of fully actuated control at conventional signalized intersections [36, 37], *it is also of great interest and very challenging to make traffic signals within the roundabout area operate in a fully actuated mode rather than a pretimed mode*.

Based on the idea of *'implementing hybrid yield control and fully actuated control to automatically accommodate time-varying vehicular demands'*, a multi-level traffic control (MTC) is developed for large four-leg roundabouts. Technically, MTC differs from the existing traffic control solutions in three aspects. First, new application of traffic control devices and traffic detection system enables yield control and full actuated control to be safely used. Second, newly proposed right-of-way assignment and traffic signal operation guarantee that yield control and fully actuated control can be conditionally used, depending on traffic flow data that is detected on entry and circulatory roadways. Third, it requires a minimum amount of effort to manage traffic signal operation provided traffic detection system works well. *Admittedly, large roundabouts even with an advanced traffic control solution can hardly outperform conventional signalized intersections in terms of operational performance during peak periods. The comparison of MTC-enabled roundabouts versus conventional signalized intersections is out of the scope of this research*.

The remainder of this paper is organized as follows. Section 2 introduces the assumptions of this research. Section 3 illustrates the traffic control devices used to implement hybrid yield control and fully actuated control. Sections 4 and 5 present the right-of-way assignment and traffic signal operation of MTC-enabled roundabout. Simulation experiments are conducted in Section 6. Conclusions and future studies are provided in Section 7.

ASSUMPTIONS

(1) No pedestrian crosswalks are present at the roundabout area;
(2) Drivers follow lane-use signs and markings to select entry lanes;

DOI: 10.1002/atr

(3) Signal indications are updated every one second; and
(4) Traffic detection system works well.

TRAFFIC CONTROL DEVICES

Figure 1 illustrates the traffic control devices on an approach of MTC-enabled roundabout. Yield lines and yield signs are placed on the approach, downstream of the entrance line. A lane-use sign and a changeable message sign (CMS) showing ‘CAUTION RED AHEAD’ are installed at the start of the entry roadway. Lane-use markings are painted on the entry, circulating, and exit lanes. Lane changes on the entry lanes are discouraged by solid lane lines. Stop lines on the left-turn and through entry lanes are located 15 to 25 m in advance of the entrance line. Stop lines on the circulatory lanes are located 1 to 3 m in advance of the left edge of the innermost entry lane. Red-yellow-green vehicular signals and ‘STOP HERE ON RED’ signs are installed near the entry and circulatory stop lines. The signal indications that are used include flashing circular yellow, steady circular green, steady circular yellow, and steady circular red. Right-turns are permitted all the time.

RIGHT-OF-WAY ASSIGNMENT

Figure 2 shows the signal phase numbering of MTC-enabled roundabout. There are two entering vehicle phases (i.e., Phases K1 and K2) and two circulating vehicle phases (i.e., Phases C1 and C2). The N-S entering movements are controlled by Phase K1 and the E-W entering movements by Phase K2. Phases C1 and C2 conflict with Phases K1 and K2, respectively.

With these phases, the right-of-way can be assigned to entering and circulating vehicles in three modes: (i) all entering mode; (ii) no entering mode; and (iii) concurrent entering mode, as shown in Figure 3.

In the ‘all entering’ mode, all the signals display flashing yellow. Entering vehicles on each approach are allowed to proceed but required to give way to circulating vehicles when sufficient gaps do not exist in the circulating stream. *Each time the ‘all entering’ mode is in operation, the minimum all-flashing-yellow time should be assured*.

In the ‘no entering’ mode, all the entering signals display steady red and all the circulating signals display flashing yellow. Left-turn and through vehicles on all the approaches are stopped from passing through the entry stop lines. Circulating vehicles are protected by yield rule and can clear the circulatory roadway. *The all-red time of the entering vehicle phases can be extended, subject to the minimum, and maximum all-red times*.

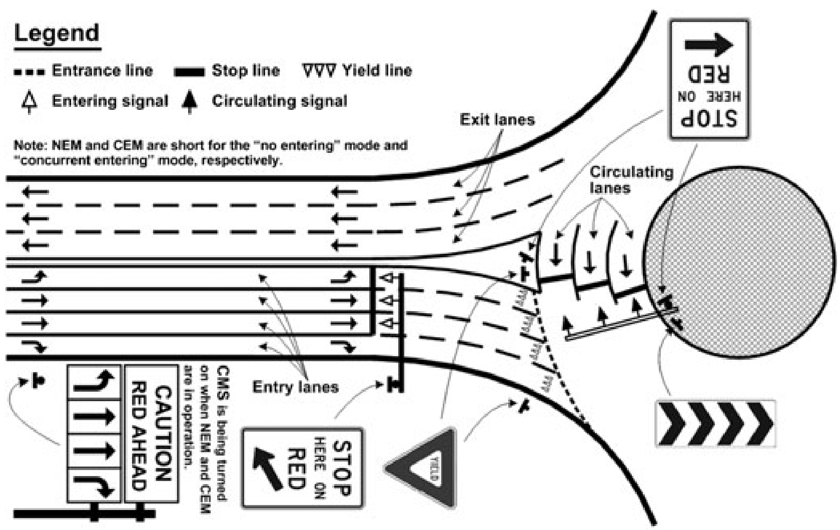

Figure 1. Traffic control devices illustrated. CMS, changeable message sign; NEM, ‘no entering’ mode; CEM, ‘concurrent entering’ mode.

DOI: 10.1002/atr

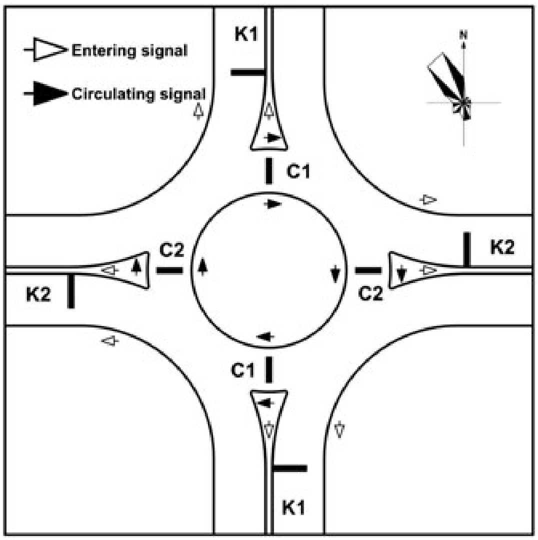

Figure 2. Signal phase numbering.

In the ‘concurrent entering’ mode, all the signals display steady indications with the sequence of ‘Red to Green to Yellow to Red’. *Although yield rule is still in use, conflicts between entering and circulating vehicles are separated by the signals with appropriate yellow change and red clearance intervals*. When an entering vehicle phase starts, through vehicles may proceed without stopping, while left-turn vehicles must be stopped by the circulating signals on the opposing approach to protect the entering movement. A circulatory roadway clearance (CRC) stage that starts from all the circulating signals displaying green and ends at the end of green of a circulating vehicle phase is present to clear vehicles on the circulatory roadway before the entering vehicle phase on the other street inherits the right-of-way. There are up to two CRC stages within the signal cycle. The principles of green time management include the following:

(1) *The green time of Phase Ki can be extended, subject to the minimum and maximum green times, i = 1 or 2;*
(2) *When Phase Ki ends, the right-of-way will be inherited by Phase Cj, (i, j) = (1, 1) or (2, 2);*
(3) *The duration of a CRC stage can be extended, subject to the minimum and maximum durations; and*
(4) *When Phase Cj ends, the right-of-way will be inherited by Phase Ki, (j, i) = (1, 1) or (2, 2).*

For the purpose of avoiding excessive queuing and circulatory roadway locking-up, the ‘all entering’ mode can be changed, via the ‘no entering’ mode, to the ‘concurrent entering’ mode as vehicular demands increase from off-peak to peak. The ‘concurrent entering’ mode that starts at the start of green of Phase K1 and ends at the end of a CRC stage is in operation provided a certain degree of queuing exists on multiple approaches. To avoid unnecessary vehicle delay and stops caused by signalization, the ‘all entering’ mode is recalled as vehicular demands decrease from peak to off-peak. Besides, significant short-term variation in vehicular demands might also result in transient change of the mode of right-of-way assignment.

TRAFFIC SIGNAL OPERATION

Traffic signal operation is managed in accordance with the mechanism of right-of-way assignment. A number of detectable traffic events rather than optimization models are programmed into the signal controller. With the input of signal timing data and traffic flow data, the detectable traffic events that are happening will enable specific traffic signals to maintain or change their indications.

DOI: 10.1002/atr

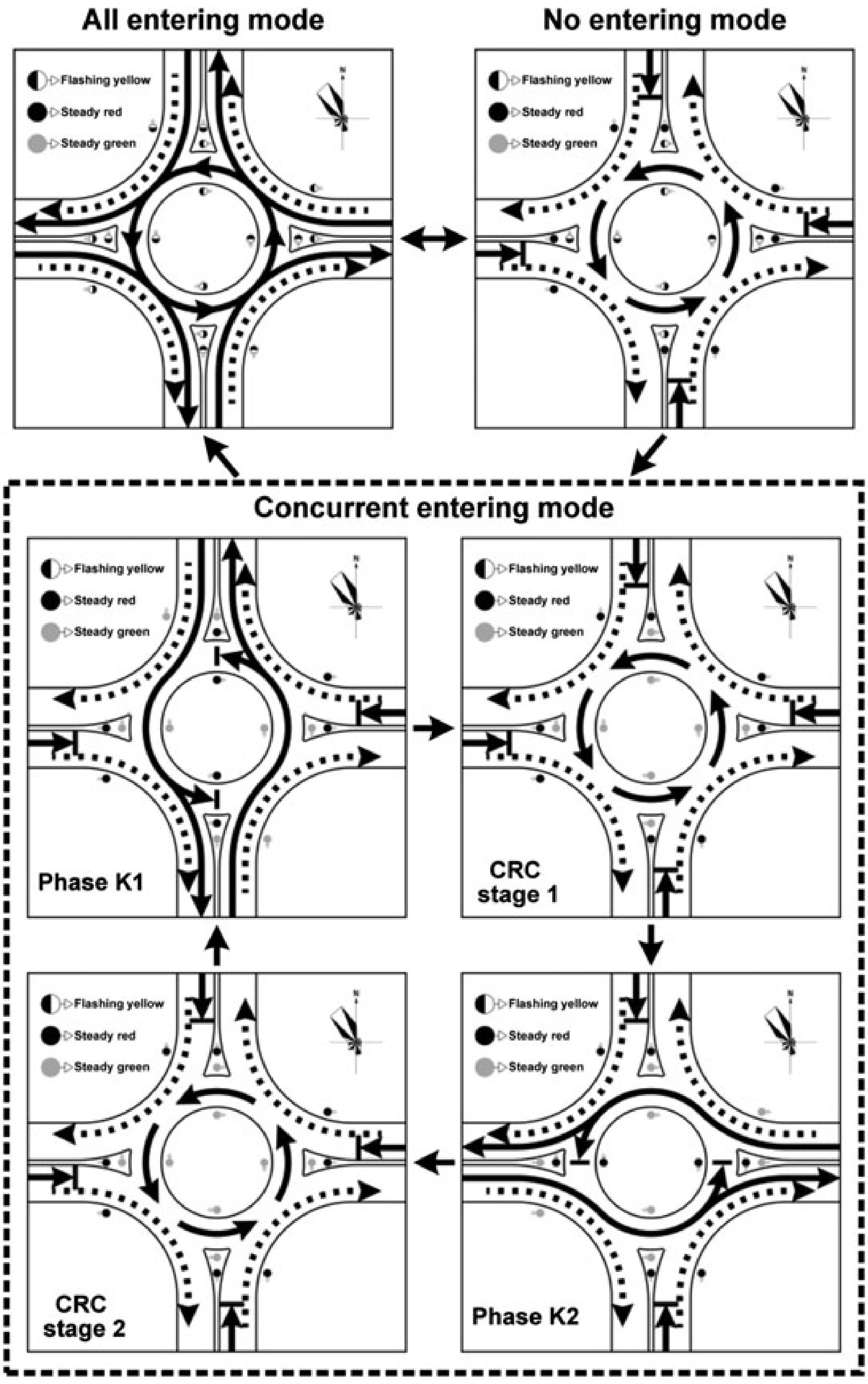

Figure 3. Right-of-way assignment. CRC, circulatory roadway clearance.

Traffic detection

Three types of traffic detectors with different usages are placed on the entry and circulatory roadways, as shown in Table I. Time headways and occupancy times are detected on a lane-by-lane basis [38–40]. The traffic detector placement is illustrated in Figure 8.

All entering mode

In the 'all entering' mode, the traffic flow data required to be detected [TFD_{aem}(no.)] after the expiration of the minimum all-flashing-yellow time includes:

DOI: 10.1002/atr

Table I. Traffic detectors and their usages.

Traffic detector	Location	Usage	Traffic flow data
Upstream detector	On the left-turn and through entry lanes, 40 m upstream of the stop line.	To determine if there is continued demand on the entry lane.	Time headway
		To determine if there is a long standing queue on the entry lane.	Occupancy time
Stop-line detector	On the left-turn and through entry lanes, immediate upstream of the stop line.	To determine if left-turn or through vehicles are continuously entering the circulatory roadway.	Time headway
		To determine if there is a standing queue on the entry lane.	Occupancy time
Circulatory detector	On the outermost circulatory lane, overlapping with the innermost exit lane.	To determine if vehicles are continuously approaching the circulatory stop-line section.	Time headway
		To determine if the exit roadway is blocked. To determine if the circulating stream is stopped at the circulatory stop-line section. To determine if the entering movement on the next upstream approach is stopped.	Occupancy time
	On the circulatory lanes next to the outermost one, immediate downstream of the left edge of the innermost exit lane.	To determine if vehicles are continuously approaching the circulatory stop-line section.	Time headway
		To determine if the circulating stream is stopped at the circulatory stop-line section. To determine if the entering movement on the next upstream approach is stopped.	Occupancy time

$TFD_{aem}(1)$ The occupancy times of all the circulatory detectors; and
$TFD_{aem}(2)$ The occupancy times of all the stop-line detectors.

Once one of the following traffic events [TE_{aem}(no.)] is happening, the 'all entering' mode should be stopped to start the 'no entering' mode by setting all the entering signals to red and maintaining flashing yellow for all the circulating signals.

$TE_{aem}(1)$ There is a standing queue on any entry lane of each of three approaches (i.e., the occupancy time of any stop-line detector on each of three approaches is equal to or larger than the occupancy time for identifying entry queuing in the 'all entering' mode); and
$TE_{aem}(2)$ The circulating stream is stopped at three circulatory stop-line sections (i.e., the occupancy time of any circulatory detector directly behind each of three circulatory stop-line sections is equal to or larger than the occupancy time for identifying circulatory queuing).

The traffic signal operation of the 'all entering' mode is illustrated in Figure 4.

No entering mode

In the 'no entering' mode, the traffic flow data required to be detected [TFD_{nem}(no.)] after the expiration of the minimum all-red time includes:

$TFD_{nem}(1)$ The time headways of all the circulatory detectors; and
$TFD_{nem}(2)$ The occupancy times of all the stop-line detectors and upstream detectors.

DOI: 10.1002/atr

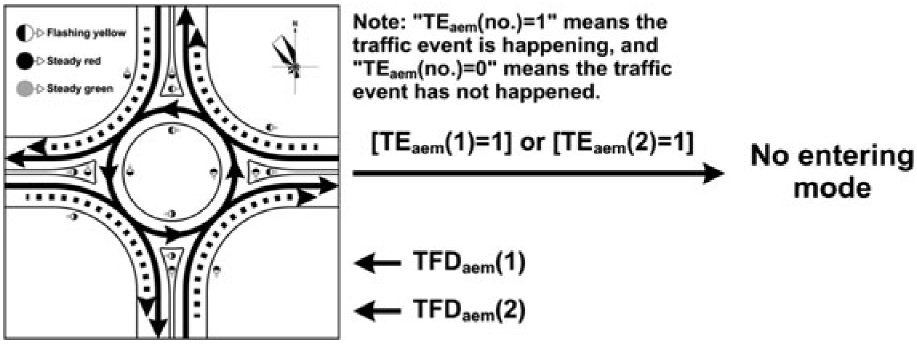

Figure 4. Traffic signal operation of the ‘all entering’ mode.

The ‘no entering’ mode can be stopped because of one of the following traffic events [TE_{nem}(no.)]:

$TE_{nem}(1)$ The maximum all-red time is reached; and

$TE_{nem}(2)$ No vehicles are continuously approaching three circulatory stop-line sections (i.e., the time headways of all the circulatory detectors directly behind each of three circulatory stop-line sections are simultaneously larger than the gap time).

When the decision of stopping the ‘no entering’ mode is made, the ‘concurrent entering’ mode can be started by maintaining red for the signals of Phase K2, setting the signals of Phase C1 to red, and setting the signals of Phases K1 and C2 to green if one of the following traffic events is happening. Otherwise, the ‘all entering’ mode will be started by maintaining flashing yellow for all the circulating signals and setting all the entering signals to flashing yellow.

$TE_{nem}(3)$ There is a standing queue on any entry lane of each of three approaches (i.e., the occupancy time of any stop-line detector on each of three approaches is equal to or larger than the occupancy time for identifying entry queuing in the ‘no entering’ mode); and

$TE_{nem}(4)$ There is a long standing queue on any entry lane of an approach (i.e., the occupancy time of any upstream detector on an approach is equal to or larger than the occupancy time for identifying long entry queuing).

The traffic signal operation of the ‘no entering’ mode is illustrated in Figure 5.

Concurrent entering mode

Entering vehicle phase

When the minimum green time of an entering vehicle phase expires, the traffic flow data required to be detected [TFD_{cem}(no.)] includes:

$TFD_{cem}(1)$ The time headways of the stop-line detectors and upstream detectors of the phase,

$TFD_{cem}(2)$ The occupancy times of the upstream detectors on the other street; and

$TFD_{cem}(3)$ The occupancy times of all the circulatory detectors.

An entering vehicle phase may end due to one of the following traffic events [TE_{cem}(no.)]:

$TE_{cem}(1)$ The maximum green time is reached;

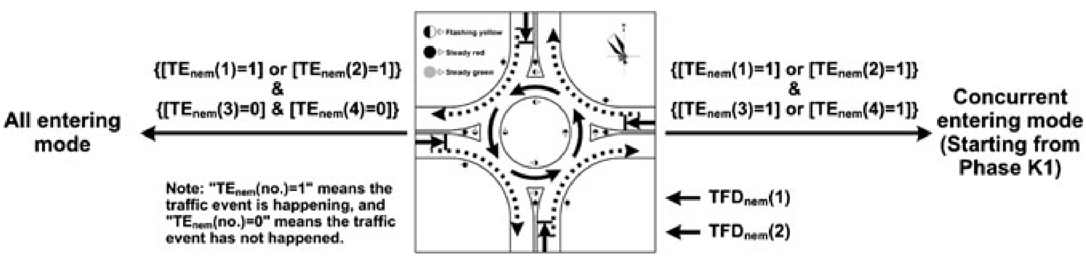

Figure 5. Traffic signal operation of the ‘no entering’ mode.

$TE_{cem}(2)$ The exit roadway of an approach of the phase is blocked (i.e., the occupancy time of the outermost circulatory detector on an approach of the phase is equal to or larger than the occupancy time for identifying circulatory queuing), and meanwhile the though vehicles on the opposing approach are continuously entering the circulatory roadway (i.e., the time headway of any stop-line detector on the through entry lanes of the opposing approach is smaller than or equal to the gap time);

$TE_{cem}(3.1)$ The entering movement on an approach of the phase is stopped (i.e., the occupancy time of any circulatory detector next downstream of an approach of the phase is equal to or larger than the occupancy time for identifying circulatory queuing), and meanwhile the left-turn vehicles on the approach are continuously entering the circulatory roadway (i.e., the time headway of any stop-line detector on the left-turn entry lanes of the approach is smaller than or equal to the gap time);

$TE_{cem}(3.2)$ The entering movement on the opposing approach is stopped, and meanwhile the left-turn vehicles on the opposing approach are continuously entering the circulatory roadway;

$TE_{cem}(4.1)$ There is no continued demand on all the entry lanes of an approach of the phase (i.e., the time headways of all the upstream detectors on an approach of the phase have been larger than the gap time);

$TE_{cem}(4.2)$ There is no continued demand on all the entry lanes of the opposing approach;

$TE_{cem}(5.1)$ There is no continued demand on most of the entry lanes of an approach of the phase (i.e., the time headways of most of the upstream detectors on an approach of the phase have been larger than the gap time), and meanwhile there is a long standing queue on any entry lane of the other street (i.e., the occupancy time of any upstream detector on the other street is equal to or larger than the occupancy time for identifying long entry queuing); and

$TE_{cem}(5.2)$ There is no continued demand on most of the entry lanes of the opposing approach, and meanwhile there is a long standing queue on any entry lane of the other street.

The traffic signal operation of the 'concurrent entering' mode for an entering vehicle phase is illustrated in Figure 6.

Circulatory roadway clearance (CRC) stage

When the minimum duration of a CRC stage expires, the traffic flow data required to be detected includes:

$TFD_{cem}(4)$ The time headways of all the circulatory detectors; and

$TFD_{cem}(5)$ The occupancy times of all the stop-line detectors and upstream detectors.

A CRC stage may end due to one of the following traffic events:

$TE_{cem}(6)$ The maximum duration is reached; and

$TE_{cem}(7)$ No vehicles are continuously approaching the circulatory stop-line sections where the left-turn vehicles of the preceding entering vehicle phase is stopped (i.e., the time headways of all the circulatory detectors of the circulating vehicle phase that conflicts with the preceding entering vehicle phase are simultaneously larger than the gap time).

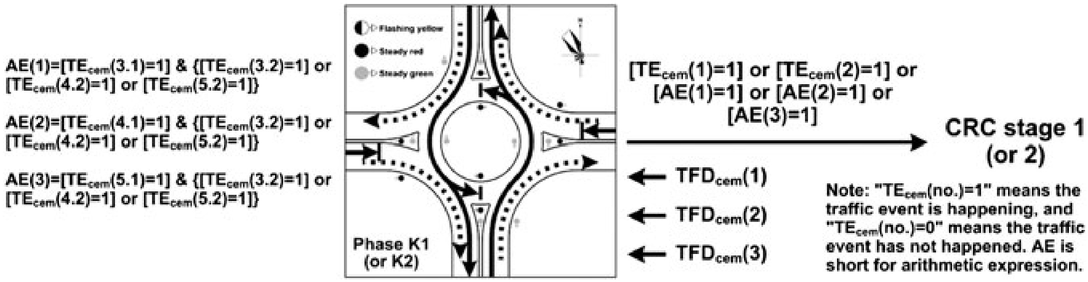

Figure 6. Traffic signal operation of the 'concurrent entering' mode for an entering vehicle phase.

DOI: 10.1002/atr

At the end of a CRC stage, the ‘concurrent entering’ mode can be maintained if one of the following traffic events is happening. Otherwise, the ‘concurrent entering’ mode will be stopped to start the ‘all entering’ mode by setting all the signals to flashing yellow.

$TE_{cem}(8)$ There are standing queues on most of the entry lanes of each of two approaches (i.e., the occupancy times of most of the stop-line detectors on each of two approaches are equal to or larger than the occupancy time for identifying entry queuing in the ‘concurrent entering’ mode); and

$TE_{cem}(9)$ There is a long standing queue on any entry lane of an approach (i.e., the occupancy time of any upstream detector on an approach is equal to or larger than the occupancy time for identifying long entry queuing).

The traffic signal operation of the ‘concurrent entering’ mode for a CRC stage is illustrated in Figure 7.

SIMULATION EXPERIMENTS

In this section, two simulation experiments were conducted based on a hypothetical roundabout. Experiment 1 was to test the effectiveness of MTC. Experiment 2 was to verify the operational advantage of MTC over yield control and fully actuated control.

The test-bed roundabout was modeled by the microscopic traffic simulation tool VISSIM 5.40. The traffic signal operations were programmed by the visual vehicle actuation programming tool VisVAP 2.16. *Specifically, the fully actuated control was derived from MTC by making the ‘concurrent entering’ mode operate all the time.*

Road geometry

Figure 8 shows the test-bed roundabout of two two-way streets with three lanes on each direction. The speed limit of vehicles was 50 km/h and the free-flow speed ranged from 48 to 58 km/h. The central island diameter was 35 m. At the roundabout area, an approach was widened from three lanes to one left-turn entry lane, two through entry lanes, and one right-turn entry lane. The left-turn and through entry lanes were 50 m in length. Traffic detectors of 3 m in length and 2.5 m in width were placed at the sites where they were expected to be (see Traffic Detection).

Traffic demands

For convenience of vehicular demand sampling, the categories of vehicles and the percentages of specific categories of vehicles were not defined. Thus, the vehicular demands were composed of only passenger cars.

A continuous variation of vehicular demands from off-peak to peak and to off-peak was modeled with two levels of left-turn ratios. The sampling populations of the vehicular demands and turning ratios on an approach of the test-bed roundabout were shown as follows.

Vehicular demands:

(1) Low load: 400, 401, … …, 700 (pcu/h);

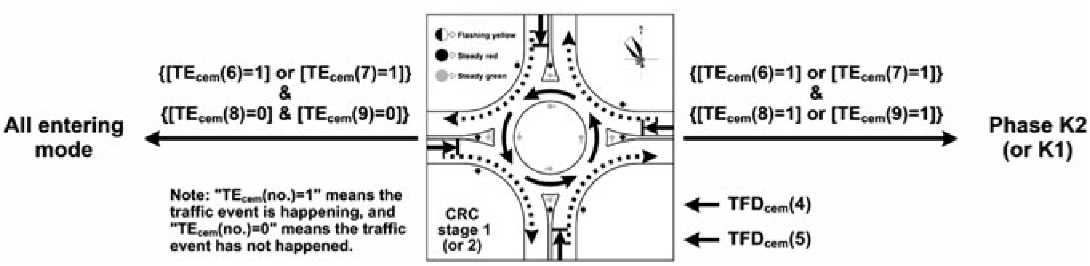

Figure 7. Traffic signal operation of the ‘concurrent entering’ mode for a circulatory roadway clearance (CRC) stage.

DOI: 10.1002/atr

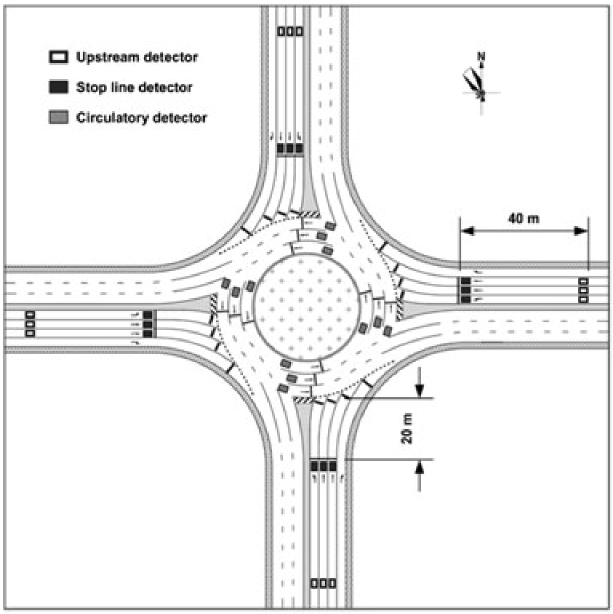

Figure 8. Test-bed roundabout layout.

(2) Medium load: 900, 901, … …, 1200 (pcu/h); and
(3) High load: 1400, 1401, … …, 1700 (pcu/h).

Left-turn ratios:

(1) Low level: 15.0, 15.1, … …, 20.0 (%); and
(2) High level: 20.0, 20.1, … …, 25.0 (%).

Right-turn ratio:

(1) 10.0, 10.1, … …, 15.0 (%).

Table II shows three groups of five-hour vehicular demands that were randomly sampled. The turning ratios were also randomly sampled for each group of vehicular demands, as shown in Table III.

Table II. Vehicular demands sampling (pcu/h).

Time interval (s)	Load scenarios	Demands	SB approach	WB approach	NB approach	EB approach	Total
0–4200	Low	Group 1	508	612	582	561	2263
		Group 2	538	691	514	652	2395
		Group 3	470	545	579	582	2176
4200–7800	Medium	Group 1	1106	1084	1145	950	4285
		Group 2	1147	1006	1112	1194	4459
		Group 3	991	1103	1123	1129	4346
7800–11400	Heavy	Group 1	1595	1680	1619	1484	6378
		Group 2	1534	1421	1646	1616	6217
		Group 3	1637	1589	1535	1689	6450
11400–15000	Medium	Group 1	1143	922	1190	1131	4386
		Group 2	1006	1167	1021	1061	4255
		Group 3	936	1003	1124	1107	4170
15000–18600	Low	Group 1	606	519	498	455	2078
		Group 2	468	584	601	673	2326
		Group 3	569	442	680	510	2201

DOI: 10.1002/atr

Table III. Turning ratios sampling (%).

Demands	Left-turn ratios	SB approach			WB approach			NB approach			EB approach		
		LT	TH	RT	LT	TH	RT	LT	TH	RT	LT	TH	RT
Group 1	Low	15.3	70.5	14.2	19.6	69.8	10.6	16.6	69.4	14.0	17.4	68.4	14.2
	High	20.5	65.6	13.9	22.9	62.3	14.8	24.5	63.5	12.0	21.8	64.7	13.5
Group 2	Low	19.1	69.1	11.8	16.5	69.6	13.9	18.1	71.8	10.1	18.3	69.0	12.7
	High	23.1	65.4	11.5	21.7	65.4	12.9	23.3	63.8	12.9	24.4	65.1	10.5
Group 3	Low	18.6	71.4	10.0	17.3	67.8	14.9	19.3	67.6	13.1	15.6	70.5	13.9
	High	22.8	64.8	12.4	24.6	63.5	11.9	22.9	66.0	11.1	23.8	61.3	14.9

The 'LT', 'TH', and 'RT' were short for left-turn vehicles, through vehicles, and right-turn vehicles, respectively.

Signal timing parameters

The values of the signal timing parameters for MTC and the fully actuated control were presented as follows.

(1) Yellow change interval of an entering vehicle phase or a circulating vehicle phase: 3 s;
(2) Red clearance interval of an entering vehicle phase: 3 s;
(3) Red clearance interval of a circulating vehicle phase: 1 s;
(4) Minimum all-flashing-yellow time (applicable for MTC): 5 s;
(5) Minimum and maximum all-red time of the entering vehicle phases (applicable for MTC): 5 s and 60 s;
(6) Minimum and maximum green time of an entering vehicle phase: 10 s and 60 s;
(7) Minimum and maximum duration of a CRC stage: 5 s and 60 s;
(8) Time gap: 3.0 s;
(9) Occupancy time of the circulatory detectors for identifying circulatory queuing: 5 s;
(10) Occupancy time of the stop-line detectors for identifying entry queuing (applicable for MTC): 10 s in the 'all entering' mode, 5 s in the 'no entering' mode, and 30 s in the 'concurrent entering' mode; and
(11) Occupancy time of the upstream detectors for identifying long entry queuing: 5 s.

Simulation modeling

According to the lane-use signs and markings on the approaches, exclusive links of 50 m in length were created for left-turn vehicles, through vehicles, and right turn vehicles, respectively. It assured that drivers could select the entry lanes properly. To simulate the impact of horizontal curvature of vehicle paths on slowing down entry, circulatory, and exit speeds, the 'Reduced speed area' with the desired speed ranging from 30 to 36 km/h was placed on the roadway space from the entry stop lines to the right edge of the outermost circulatory lane. The giving-way behavior on the circulatory roadway were modeled with the 'Priority rule'.

In the Wiedemann 74 car following model, the 'average standstill distance' was 1.5 m; the 'additive part of desired safety distance' was 2.5 m; and the 'multiplic. part of desired safety distance' was 3.5 m. As a result, the saturation flow rate on the approach was about 1800 pcu per hour per lane, which was normal in real-world situations [41]. The option of the 'Smooth closeup behavior' was checked.

In the lane change model, the 'waiting time before diffusion' was 45 s. The options of the 'Advanced merging' and 'Cooperative lane change' were checked.

The travel time measurement zones started at 200 m upstream of the entry stop lines, covering a distance of 320 m for through vehicles and a distance of 358 m for left-turn vehicles. *Vehicle delay, stops, and space mean speed (SMS) were measured within the travel time measurement zones*.

A simulation test was specific for a traffic control solution, a group of vehicular demands, and a level of left-turn ratios. Seven simulation runs using the random seeds of 9, 19, 29, 39, 49, 59, and 69 were performed in each simulation test. There was a sum total of 18 simulation tests and 126 simulation runs. For each simulation run, the simulation period was 18600 s and the data from 600 to 18600 s was used for subsequent analysis.

DOI: 10.1002/atr

Simulation results

Experiment 1

In this experiment, the measures of effectiveness of MTC for a simulation test were averaged by the outputs of the seven simulation runs.

Table IV shows the means of the frequencies and durations of three modes of right-of-way assignment at the MTC-enabled roundabout. It was found that:

(1) MTC would not frequently change the mode of right-of-way assignment;
(2) Few transient changes of the mode of right-of-way assignment might happen in the heavy load scenarios because of significant short-term variation in the vehicular demands;
(3) The traffic signal operation was dominated by the ‘all entering’ mode in the low and medium load scenarios, and by the ‘concurrent entering’ mode in the heavy load scenarios; and
(4) As the vehicular demands increased from the medium load to the heavy load or decreased from the heavy load to the medium load, it took several minutes for MTC to sense the impact of variation in the vehicular demands on actual traffic conditions and change the mode of right-of-way assignment accordingly.

Tables V and VI show the operational performance of the MTC-enabled roundabout for different levels of left-turn ratios. In the low and medium load scenarios, left-turn and through vehicles had an adequate opportunity to enter the circulatory roadway. Thanks to the operation of the ‘all entering’ mode, MTC could avoid unnecessary vehicle delay and stops and result in higher SMSs of left-turn and through vehicles. As the vehicular demands increased, sufficient gaps did not exist in the circulating stream. MTC had to manage the conflicts between entering and circulating vehicles in the most mandatory manner. The ‘all entering’ mode was changed, via the ‘no entering’ mode, to the ‘concurrent entering’ mode. The consequence of actuating all the signals to alternately stop the entering and circulating movements in the heavy load scenarios was the poor but reasonable measures of effectiveness. As the vehicular demands decreased, the ‘concurrent entering’ mode would continue to be in operation for a few minutes before the ‘all entering’ mode was recalled. Then, the measures of effectiveness returned to favorable conditions again.

Table IV. Means of the frequencies and durations of three modes of right-of-way assignment.

			Mean of the frequencies						Mean of the durations (s)					
			Low left-turn ratios			High left-turn ratios			Low left-turn ratios			High left-turn ratios		
Demands	Time interval (s)	Load scenarios	AEM	NEM	CEM	AEM	NEM	CEM	AEM	NEM	CEM	AEM	NEM	CEM
Group 1	600–4200	Low	1	0	0	1	0	0	3600	0	0	3600	0	0
	4200–7800	Medium	1	0	0	1	0	0	3600	0	0	3600	0	0
	7800–11400	Heavy	1.3	1.1	1	1.3	1.3	1.3	363	37	3200	253	43	3304
	11400–15000	Medium	1	0	0.9	1	0	1	3396	0	204	3417	0	183
	15000–18600	Low	1	0	0	1	0	0	3600	0	0	3600	0	0
Group 2	600–4200	Low	1	0	0	1	0	0	3600	0	0	3600	0	0
	4200–7800	Medium	1	0	0	1	0	0	3600	0	0	3600	0	0
	7800–11400	Heavy	1.4	1.4	1.3	1.3	1.3	1.3	362	39	3199	216	38	3346
	11400–15000	Medium	1	0	1	1	0	1	3352	0	248	3445	0	155
	15000–18600	Low	1	0	0	1	0	0	3600	0	0	3600	0	0
Group 3	600–4200	Low	1	0	0	1	0	0	3600	0	0	3600	0	0
	4200–7800	Medium	1	0	0	1	0	0	3600	0	0	3600	0	0
	7800–11400	Heavy	1.1	1.1	1	1	1	1	283	36	3282	262	43	3295
	11400–15000	Medium	1	0	1	1	0	1	3354	0	246	3445	0	155
	15000–18600	Low	1	0	0	1	0	0	3600	0	0	3600	0	0

The ‘AEM’, ‘NEM’, and ‘CEM’ were short for the ‘all entering’ mode, the ‘no entering’ mode, and the ‘concurrent entering’ mode, respectively.

DOI: 10.1002/atr

Table V. Operational performance of the multi-level traffic control (MTC)-enabled roundabout for high level of left-turn ratios.

		Mean of the average vehicle delay (s)			Mean of the average vehicle stops			Mean of the SMS of through vehicles (km/h)			Mean of the SMS of left-turn vehicles (km/h)		
Time interval (s)		G1	G2	G3	G1	G2	G3	G1	G2	G3	G1	G2	G3
600–4200	*Q1*	2.09	2.14	1.99	0.03	0.03	0.03	41.90	41.91	42.03	40.33	40.21	40.62
	Q2	2.03	2.21	2.00	0.03	0.03	0.03	42.07	41.97	42.04	40.39	40.01	40.32
	Q3	1.97	2.13	1.91	0.02	0.03	0.02	41.96	42.02	42.13	40.52	40.22	40.51
	Q4	2.03	2.21	1.93	0.03	0.03	0.02	41.89	41.92	42.10	40.33	40.07	40.36
4200–7800	*Q1*	4.53	5.11	5.09	0.16	0.19	0.20	38.75	38.18	38.22	35.64	34.66	34.68
	Q2	4.89	5.50	5.37	0.17	0.22	0.22	38.23	37.72	37.79	35.25	33.97	34.33
	Q3	4.70	5.54	5.33	0.17	0.21	0.20	38.55	37.65	37.85	35.37	33.98	34.46
	Q4	4.79	5.43	5.06	0.17	0.21	0.19	38.47	37.79	38.25	35.26	34.19	34.63
7800–11400	*Q1*	32.03	30.29	34.49	1.10	1.03	1.17	20.00	20.67	19.43	17.49	18.10	16.14
	Q2	38.33	38.83	41.81	1.13	1.13	1.17	17.90	17.90	17.04	16.31	16.10	15.57
	Q3	38.60	38.57	46.06	1.13	1.14	1.23	17.78	17.99	16.14	16.03	15.94	14.72
	Q4	43.40	43.09	50.51	1.20	1.19	1.29	16.48	16.76	15.08	15.50	15.10	14.23
11400–15000	*Q1*	14.43	13.76	14.37	0.45	0.44	0.45	28.97	29.78	29.10	26.27	26.86	26.46
	Q2	5.20	5.24	4.96	0.20	0.20	0.18	37.88	37.91	38.24	34.35	34.59	35.07
	Q3	5.14	5.24	5.11	0.20	0.20	0.20	37.98	38.08	38.06	34.40	34.40	34.65
	Q4	4.83	5.03	4.73	0.18	0.18	0.16	38.44	38.33	38.62	34.86	34.80	35.09
15000–18600	*Q1*	2.11	2.40	2.14	0.04	0.05	0.04	41.77	41.53	41.69	40.02	39.35	39.60
	Q2	1.87	2.13	1.93	0.03	0.03	0.03	42.20	41.88	41.97	40.94	39.96	40.30
	Q3	1.77	2.06	1.90	0.03	0.03	0.02	42.40	41.94	41.96	40.82	40.20	40.39
	Q4	1.83	2.13	1.99	0.03	0.03	0.02	42.23	41.88	41.99	40.89	40.09	40.41

The ‘G1’, ‘G2’, and ‘G3’ were short for Groups 1, 2, and 3 of the vehicular demands, respectively.

Table VI. Operational performance of the multi-level traffic control (MTC)-enabled roundabout for low level of left-turn ratios.

		Mean of the average vehicle delay (s)			Mean of the average vehicle stops			Mean of the SMS of through vehicles (km/h)			Mean of the SMS of left-turn vehicles (km/h)		
Time interval (s)		G1	G2	G3	G1	G2	G3	G1	G2	G3	G1	G2	G3
600–4200	*Q1*	1.90	2.04	1.86	0.02	0.03	0.03	41.98	41.98	42.10	36.50	36.26	36.47
	Q2	1.96	2.09	1.89	0.03	0.03	0.02	42.02	41.99	42.14	36.26	36.02	36.30
	Q3	1.86	2.11	1.76	0.03	0.03	0.03	42.14	42.01	42.14	36.30	35.89	36.46
	Q4	1.94	2.11	1.83	0.03	0.03	0.02	42.01	41.83	42.25	36.33	36.12	36.34
4200–7800	*Q1*	4.49	4.83	4.63	0.16	0.17	0.17	38.58	38.33	38.51	32.03	31.02	31.38
	Q2	4.44	5.01	4.69	0.14	0.18	0.16	38.60	37.95	38.36	32.13	31.09	31.31
	Q3	4.37	5.09	4.63	0.15	0.20	0.16	38.72	37.85	38.43	31.99	30.99	31.65
	Q4	4.27	4.91	4.53	0.14	0.18	0.16	38.82	38.03	38.66	32.16	31.17	31.39
7800–11400	*Q1*	28.07	27.19	29.56	1.06	1.05	1.03	21.33	21.79	20.80	16.23	16.82	16.20
	Q2	39.99	39.41	43.09	1.12	1.11	1.19	17.27	17.44	16.23	14.39	14.59	14.56
	Q3	42.41	39.70	47.94	1.15	1.12	1.24	16.57	17.27	15.31	14.28	14.51	13.53
	Q4	45.57	45.31	56.01	1.21	1.19	1.37	15.82	15.92	13.68	13.75	13.87	12.92
11400–15000	*Q1*	16.66	16.51	19.54	0.50	0.50	0.56	27.43	27.58	25.64	22.70	23.16	21.92
	Q2	4.73	4.51	4.29	0.17	0.16	0.14	38.13	38.60	38.84	31.35	31.91	31.91
	Q3	4.79	4.71	4.27	0.17	0.15	0.14	38.17	38.41	38.81	31.28	31.64	32.19
	Q4	4.84	4.57	4.20	0.18	0.16	0.13	38.14	38.41	38.99	31.08	31.92	32.13
15000–18600	*Q1*	2.00	2.17	1.97	0.04	0.04	0.04	41.86	41.68	41.81	36.02	35.41	35.89
	Q2	1.77	1.99	1.90	0.02	0.03	0.02	42.30	41.92	41.96	36.73	36.13	36.07
	Q3	1.60	1.99	1.73	0.02	0.03	0.02	42.34	41.83	42.18	37.09	36.07	36.12
	Q4	1.76	1.91	1.86	0.02	0.02	0.03	42.26	41.88	42.10	36.87	36.29	36.19

The ‘G1’, ‘G2’, and ‘G3’ were short for Groups 1, 2, and 3 of the vehicular demands, respectively. SMS, space mean speed.

Experiment 2

In this experiment, the effectiveness of MTC, yield control, and fully actuated control were compared based on the outputs of all the simulation runs.

Tables VII, VIII, IX, and X show the operational performance of the yield-controlled roundabout

Table VII. Operational performance of the yield-controlled roundabout for high level of left-turn ratios.

Time interval (s)		Mean of the average vehicle delay (s)			Mean of the average vehicle stops			Mean of the SMS of through vehicles (km/h)			Mean of the SMS of left-turn vehicles (km/h)		
		G1	G2	G3	G1	G2	G3	G1	G2	G3	G1	G2	G3
600–4200	*Q1*	2.14	2.23	2.01	0.04	0.03	0.03	41.72	41.83	41.97	40.19	40.10	40.55
	Q2	2.09	2.26	2.10	0.03	0.03	0.03	42.02	41.85	41.99	40.32	40.05	40.19
	Q3	2.04	2.19	1.96	0.02	0.03	0.02	41.91	41.98	42.05	40.40	40.09	40.38
	Q4	2.09	2.27	1.93	0.03	0.04	0.02	41.79	41.84	42.11	40.26	39.98	40.27
4200–7800	*Q1*	4.96	5.64	5.40	0.18	0.22	0.20	38.08	37.61	37.86	35.22	33.91	34.19
	Q2	5.37	5.81	5.59	0.21	0.25	0.21	37.82	37.39	37.51	34.38	33.48	34.13
	Q3	4.97	6.16	5.60	0.18	0.25	0.21	38.21	37.17	37.61	34.88	33.02	33.98
	Q4	4.89	5.99	5.44	0.17	0.25	0.21	38.32	37.23	37.89	35.11	33.05	34.03
7800–11400	*Q1*	47.04	48.21	54.94	2.74	2.88	3.14	17.28	17.55	16.10	9.45	9.09	7.64
	Q2	142.31	133.79	167.34	6.91	6.56	7.46	10.69	10.90	9.53	2.61	3.06	2.37
	Q3	194.00	196.21	209.54	8.94	8.75	9.68	8.80	8.60	7.88	2.21	2.14	2.16
	Q4	196.20	210.54	211.13	9.47	9.89	9.98	7.98	8.09	8.19	2.23	2.20	2.19
11400–15000	*Q1*	209.96	202.23	208.93	9.60	9.54	9.70	8.25	8.35	8.37	1.99	2.12	2.13
	Q2	156.96	153.34	127.69	7.87	7.63	6.47	12.51	14.17	16.71	2.85	2.94	3.72
	Q3	48.90	51.20	20.63	2.76	2.72	1.01	27.56	27.68	34.07	10.60	13.62	26.53
	Q4	5.41	6.01	5.60	0.21	0.25	0.20	37.72	37.68	38.04	34.02	33.03	33.50
15000–18600	*Q1*	2.29	2.39	2.23	0.05	0.05	0.05	41.64	41.52	41.54	39.72	39.42	39.71
	Q2	1.80	2.14	2.07	0.02	0.03	0.03	42.35	41.77	41.87	40.80	40.10	39.97
	Q3	1.79	2.14	2.00	0.02	0.04	0.03	42.25	41.80	41.88	41.05	39.98	40.26
	Q4	1.93	2.20	2.03	0.02	0.04	0.03	42.15	41.87	42.03	40.71	39.77	40.25

The 'G1', 'G2', and 'G3' were short for Groups 1, 2, and 3 of the vehicular demands, respectively. SMS, space mean speed.

Table VIII. Operational performance of the yield-controlled roundabout for low level of left-turn ratios.

Time interval (s)		Mean of the average vehicle delay (s)			Mean of the average vehicle stops			Mean of the SMS of through vehicles (km/h)			Mean of the SMS of left-turn vehicles (km/h)		
		G1	G2	G3	G1	G2	G3	G1	G2	G3	G1	G2	G3
600–4200	*Q1*	1.94	2.06	1.89	0.02	0.02	0.02	41.98	41.90	42.08	36.45	36.27	36.51
	Q2	2.01	2.11	1.93	0.03	0.03	0.03	41.98	41.91	42.14	36.28	36.13	36.14
	Q3	1.91	2.11	1.80	0.02	0.03	0.02	42.02	41.97	42.09	36.20	35.92	36.42
	Q4	1.97	2.19	1.87	0.03	0.04	0.03	42.00	41.76	42.15	36.26	35.92	36.18
4200–7800	*Q1*	4.53	5.06	4.69	0.16	0.18	0.15	38.44	37.97	38.38	31.93	30.84	31.46
	Q2	4.80	5.41	5.00	0.16	0.21	0.17	38.12	37.54	38.01	31.58	30.15	30.96
	Q3	4.76	5.50	4.90	0.17	0.22	0.18	38.19	37.37	38.08	31.51	30.34	31.22
	Q4	4.41	5.04	4.76	0.15	0.18	0.17	38.70	38.05	38.20	31.93	30.98	31.39
7800–11400	*Q1*	41.66	38.89	50.96	2.52	2.38	3.10	18.49	18.47	15.51	9.74	10.74	8.72
	Q2	125.20	124.71	143.27	6.70	6.28	7.11	9.63	10.10	9.09	2.39	2.38	2.10
	Q3	201.13	189.33	207.26	9.21	8.98	9.59	7.91	8.54	7.81	1.59	1.74	1.61
	Q4	211.94	199.30	214.10	9.60	9.39	10.13	7.81	7.97	7.50	1.74	1.67	1.56
11400–15000	*Q1*	211.60	201.46	206.46	9.57	9.39	9.67	8.67	8.94	8.16	1.75	1.77	1.77
	Q2	146.76	131.90	131.53	6.92	6.34	6.07	13.10	15.43	17.56	2.54	2.88	2.87
	Q3	34.77	14.89	16.44	1.72	0.78	0.81	31.93	35.56	36.63	16.35	20.49	21.20
	Q4	4.87	4.76	4.47	0.17	0.16	0.14	38.20	38.27	38.63	30.85	31.59	31.77
15000–18600	*Q1*	2.13	2.23	2.07	0.04	0.05	0.03	41.78	41.61	41.75	35.85	35.60	35.59
	Q2	1.77	2.06	1.91	0.02	0.03	0.03	42.25	41.90	41.95	36.67	36.12	35.98
	Q3	1.80	2.03	1.80	0.02	0.03	0.02	42.37	41.85	42.08	36.49	36.07	36.12
	Q4	1.73	2.04	1.80	0.02	0.03	0.03	42.34	41.87	42.05	36.72	35.94	36.26

The 'G1', 'G2', and 'G3' were short for Groups 1, 2, and 3 of the vehicular demands, respectively. SMS, space mean speed.

Table IX. Operational performance of the fully-actuated-controlled roundabout for high level of left-turn ratios.

Time interval (s)		Mean of the average vehicle delay (s)			Mean of the average vehicle stops			Mean of the SMS of through vehicles (km/h)			Mean of the SMS of left-turn vehicles (km/h)		
		G1	G2	G3	G1	G2	G3	G1	G2	G3	G1	G2	G3
600–4200	*Q1*	17.36	17.93	17.31	0.75	0.75	0.75	25.98	25.89	26.35	24.31	24.01	23.98
	Q2	17.40	18.07	17.70	0.75	0.76	0.75	26.02	25.93	25.96	24.20	23.82	23.94
	Q3	17.14	17.76	17.57	0.73	0.76	0.75	26.14	26.13	25.91	23.81	23.78	24.25
	Q4	17.14	17.51	17.16	0.74	0.76	0.74	26.16	26.16	26.39	23.95	23.99	23.63
4200–7800	*Q1*	20.83	21.84	21.39	0.81	0.84	0.82	24.20	23.95	24.26	21.73	21.35	21.31
	Q2	21.27	22.06	21.87	0.82	0.84	0.84	24.04	23.73	23.96	21.69	21.47	21.21
	Q3	21.03	22.57	21.69	0.83	0.85	0.83	24.19	23.64	23.89	21.72	21.13	21.64
	Q4	21.10	22.14	21.44	0.82	0.83	0.82	23.94	23.81	24.19	21.83	21.20	21.43
7800–11400	*Q1*	32.80	32.23	35.44	1.03	1.04	1.08	19.65	20.06	18.88	17.13	17.26	16.50
	Q2	37.33	39.24	41.96	1.11	1.14	1.19	18.12	17.67	16.93	16.49	16.19	15.78
	Q3	40.70	38.36	45.26	1.16	1.12	1.22	17.25	17.85	16.23	15.53	16.33	15.00
	Q4	45.13	43.40	50.13	1.23	1.21	1.29	16.18	16.63	15.18	15.06	15.41	14.46
11400–15000	*Q1*	26.91	26.49	27.36	0.92	0.91	0.93	21.44	21.78	21.40	19.86	20.10	19.86
	Q2	21.84	21.90	21.30	0.83	0.83	0.82	23.82	23.80	24.21	21.10	21.64	21.48
	Q3	22.90	22.27	21.54	0.85	0.84	0.83	23.20	23.84	24.28	20.98	21.27	21.33
	Q4	22.00	21.70	21.17	0.84	0.83	0.82	23.85	24.09	24.25	21.20	21.55	21.74
15000–18600	*Q1*	18.07	18.54	18.19	0.75	0.77	0.76	25.56	25.61	25.50	23.72	23.18	23.68
	Q2	16.69	18.00	18.04	0.73	0.75	0.76	26.68	25.82	25.72	23.98	23.86	23.61
	Q3	16.96	17.69	17.66	0.74	0.76	0.76	26.25	26.19	25.84	24.04	23.61	23.65
	Q4	16.93	17.67	17.06	0.75	0.76	0.74	26.41	26.25	26.36	24.20	23.50	24.11

The 'G1', 'G2', and 'G3' were short for Groups 1, 2, and 3 of the vehicular demands, respectively. SMS, space mean speed.

Table X. Operational performance of the fully-actuated-controlled roundabout for low level of left-turn ratios.

Time interval (s)		Mean of the average vehicle delay (s)			Mean of the average vehicle stops			Mean of the SMS of through vehicles (km/h)			Mean of the SMS of left-turn vehicles (km/h)		
		G1	G2	G3	G1	G2	G3	G1	G2	G3	G1	G2	G3
600–4200	*Q1*	16.93	17.66	16.94	0.72	0.74	0.72	26.14	25.88	26.31	21.81	21.52	21.39
	Q2	17.74	17.84	16.86	0.74	0.74	0.72	25.81	25.79	26.23	21.15	21.43	21.64
	Q3	17.24	17.66	17.14	0.72	0.74	0.72	25.79	25.79	26.07	21.60	21.80	21.34
	Q4	16.97	17.37	16.96	0.72	0.72	0.71	26.14	25.94	26.03	21.51	21.48	21.64
4200–7800	*Q1*	20.70	21.70	21.41	0.79	0.81	0.81	24.09	23.66	23.63	19.49	19.33	19.47
	Q2	21.56	22.24	21.67	0.80	0.83	0.80	23.61	23.34	23.77	19.27	19.19	18.76
	Q3	21.47	22.21	21.70	0.80	0.82	0.81	23.59	23.47	23.66	19.48	19.14	19.24
	Q4	21.54	22.27	21.23	0.81	0.82	0.80	23.62	23.32	23.79	19.24	19.30	19.56
7800–11400	*Q1*	34.36	32.53	36.46	1.04	1.01	1.05	18.79	19.43	18.20	15.38	15.72	15.03
	Q2	40.34	39.39	42.90	1.14	1.12	1.17	17.11	17.44	16.44	14.61	14.75	14.34
	Q3	49.04	38.66	45.00	1.26	1.10	1.19	15.09	17.67	16.28	13.62	14.61	13.66
	Q4	48.89	43.84	49.79	1.25	1.17	1.28	14.99	16.28	15.06	13.52	14.07	13.33
11400–15000	*Q1*	28.69	26.17	31.17	0.91	0.88	0.97	20.60	21.80	19.71	17.23	17.84	17.33
	Q2	21.56	22.23	21.53	0.80	0.81	0.80	23.57	23.44	23.64	19.33	19.04	19.28
	Q3	22.09	22.14	21.50	0.81	0.82	0.81	23.26	23.64	23.62	19.29	18.95	19.52
	Q4	21.69	21.26	20.86	0.80	0.80	0.80	23.64	23.93	24.01	19.40	19.63	19.81
15000–18600	*Q1*	18.19	18.06	17.99	0.76	0.74	0.74	25.30	25.57	25.26	21.13	20.99	21.38
	Q2	16.93	17.50	17.29	0.72	0.75	0.74	26.36	26.03	25.88	21.15	21.10	21.95
	Q3	16.50	17.07	16.83	0.71	0.72	0.73	26.29	26.10	26.22	21.62	21.71	21.01
	Q4	16.89	17.10	16.99	0.71	0.73	0.73	26.26	26.04	26.27	21.63	21.79	21.29

The 'G1', 'G2', and 'G3' were short for Groups 1, 2, and 3 of the vehicular demands, respectively. SMS, space mean speed.

and fully-actuated-controlled roundabout for different levels of left-turn ratios. The yield control failed to avoid rapid and dramatic deterioration of the operational performance as the vehicular demands increased from off-peak to peak. With the decrease of the vehicular demands from peak to off-peak, it

DOI: 10.1002/atr

Table XI. General linear model (GLM)-repeated measures ANOVA for the average vehicle delay and stops (p-values).

Measures of effectiveness	Left-turn ratios	Demands	Solutions	600–4200 s				4200–7800 s				7800–11400 s				11400–15000 s				15000–18600 s			
				Q1	*Q2*	*Q3*	*Q4*	*Q1*	*Q2*	*Q3*	*Q4*	*Q1*	*Q2*	*Q3*	*Q4*	*Q1*	*Q2*	*Q3*	*Q4*	*Q1*	*Q2*	*Q3*	*Q4*
Average vehicle delay	High	G1	YC	**0.82**	**0.76**	**0.67**	**0.72**	**0.14**	**0.08**	**0.39**	**0.60**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.16**	**0.47**	**0.82**	**0.97**	**0.47**
			FAC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.75**	**0.89**	**0.60**	**0.66**	0.02	**0.07**	**0.07**	0.00	0.00	0.00	0.00	0.00
		G2	YC	**0.66**	**0.77**	**0.86**	**0.78**	**0.13**	**0.28**	**0.08**	**0.12**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.14**	**0.96**	**0.94**	**0.66**	**0.72**
			FAC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.32**	**0.94**	**0.97**	**0.95**	**0.06**	**0.14**	**0.23**	0.00	0.00	0.00	0.00	0.00
		G3	YC	**0.93**	**0.60**	**0.83**	**1.00**	**0.25**	**0.44**	**0.40**	**0.08**	0.00	0.00	0.00	0.00	0.00	0.00	**0.15**	**0.20**	**0.73**	**0.42**	**0.60**	**0.80**
			FAC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.65**	**0.98**	**0.91**	**0.95**	**0.05**	**0.10**	**0.13**	0.00	0.00	0.00	0.00	0.00
	Low	G1	YC	**0.88**	**0.77**	**0.66**	**0.88**	**0.80**	**0.28**	**0.27**	**0.55**	0.00	0.00	0.00	0.00	0.00	0.00	0.01	**0.95**	**0.52**	**1.00**	**0.35**	**0.78**
			FAC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.15**	**0.95**	**0.32**	**0.61**	0.03	**0.14**	**0.13**	0.00	0.00	0.00	0.00	0.00
		G2	YC	**0.93**	**0.83**	**1.00**	**0.77**	**0.30**	**0.12**	**0.20**	**0.65**	0.00	0.00	0.00	0.00	0.00	0.00	0.01	**0.53**	**0.84**	**0.57**	**0.70**	**0.52**
			FAC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.07**	**0.99**	**0.90**	**0.79**	**0.11**	**0.15**	0.00	0.00	0.00	0.00	0.00	0.00
		G3	YC	**0.91**	**0.82**	**0.85**	**0.78**	**0.87**	**0.47**	**0.50**	**0.52**	0.00	0.00	0.00	0.00	0.00	0.00	0.02	**0.26**	**0.57**	**0.96**	**0.58**	**0.76**
			FAC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.13**	**0.98**	**0.75**	**0.29**	**0.06**	**0.23**	0.00	0.00	0.00	0.00	0.00	0.00
Average vehicle stops	High	G1	YC	**0.72**	**0.89**	**0.86**	**0.69**	**0.13**	0.02	**0.49**	**0.77**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.12**	**0.69**	**0.54**	**0.80**	**0.90**
			FAC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.47**	**0.92**	**0.83**	**0.87**	0.00	**0.10**	**0.19**	0.00	0.00	0.00	0.00	0.00
		G2	YC	**1.00**	**0.87**	**1.00**	**0.81**	**0.07**	0.03	**0.06**	**0.16**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.13**	**0.89**	**0.72**	**0.49**	**0.68**
			FAC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.92**	**0.95**	**0.93**	**0.92**	**0.14**	**0.15**	**0.37**	0.00	0.00	0.00	0.00	0.00
		G3	YC	**0.58**	**0.91**	**0.87**	**0.54**	**0.85**	**0.66**	**0.21**	**0.24**	0.00	0.00	0.00	0.00	0.00	0.00	**0.12**	**0.20**	**0.34**	**0.58**	**0.50**	**0.43**
			FAC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.38**	**0.89**	**0.95**	**0.99**	0.04	**0.10**	**0.23**	0.00	0.00	0.00	0.00	0.00
	Low	G1	YC	**0.69**	**0.69**	**0.81**	**0.48**	**0.61**	**0.26**	**0.09**	**0.26**	0.00	0.00	0.00	0.00	0.00	0.00	0.01	**0.66**	**1.00**	**0.89**	**0.29**	**1.00**
			FAC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.92**	**0.94**	**0.60**	**0.80**	0.01	**0.05**	**0.25**	0.00	0.00	0.00	0.00	0.00
		G2	YC	**0.75**	**0.88**	**0.90**	**0.90**	**0.18**	0.04	**0.21**	**1.00**	0.00	0.00	0.00	0.00	0.00	0.00	0.01	**0.55**	**0.74**	**0.38**	**0.72**	**0.66**
			FAC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.78**	**0.98**	**0.96**	**0.90**	**0.16**	**0.17**	0.00	0.00	0.00	0.00	0.00	0.00
		G3	YC	**0.80**	**0.86**	**0.68**	**0.73**	**0.39**	**0.58**	**0.17**	**0.65**	0.00	0.00	0.00	0.00	0.00	0.00	0.02	**0.21**	**0.90**	**0.29**	**0.84**	**0.84**
			FAC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.92**	**0.93**	**0.85**	**0.78**	**0.09**	**0.25**	0.02	0.00	0.00	0.00	0.00	0.00

(i) The multi-level traffic control (MTC) was the reference; (ii) the significance level was 0.05; (iii) the 'G1', 'G2', and 'G3' were short for Groups 1, 2, and 3 of the vehicular demands, respectively; and (iv) the 'YC' and 'FAC' were short for the yield control and fully actuated control, respectively.

Table XII. General linear model (GLM)-repeated measures ANOVA for the space mean speed (SMS) (*p*-values).

Measures of effectiveness	Left-turn ratios	Demands	Solutions	600–4200 s				4200–7800 s				7800–11400 s				11400–15000 s				15000–18600 s			
				Q1	*Q2*	*Q3*	*Q4*	*Q1*	*Q2*	*Q3*	*Q4*	*Q1*	*Q2*	*Q3*	*Q4*	*Q1*	*Q2*	*Q3*	*Q4*	*Q1*	*Q2*	*Q3*	*Q4*
SMS of through vehicles	High	G1	YC	**0.50**	**0.73**	**0.67**	**0.36**	0.01	**0.11**	**0.23**	**0.35**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	**0.59**	**0.58**	**0.51**	**0.51**
			FAC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.63**	**0.80**	**0.41**	**0.68**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		G2	YC	**0.65**	**0.44**	**0.84**	**0.61**	0.04	**0.19**	**0.07**	**0.08**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.07**	**0.99**	**0.35**	**0.38**	**0.94**
			FAC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.37**	**0.77**	**0.80**	**0.86**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		G3	YC	**0.82**	**0.80**	**0.52**	**0.98**	**0.14**	**0.35**	**0.40**	**0.11**	0.00	0.00	0.00	0.00	0.00	0.00	**0.15**	0.04	**0.38**	**0.46**	**0.59**	**0.66**
			FAC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.38**	**0.89**	**0.91**	**0.90**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Low	G1	YC	**1.00**	**0.80**	**0.35**	**0.92**	**0.44**	**0.12**	**0.05**	**0.33**	0.02	0.00	0.00	0.00	0.00	0.00	0.02	**0.79**	**0.73**	**0.82**	**0.86**	**0.54**
			FAC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	**0.85**	**0.11**	**0.15**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		G2	YC	**0.61**	**0.65**	**0.79**	**0.70**	**0.06**	**0.09**	**0.06**	**0.94**	0.00	0.00	0.00	0.00	0.00	0.00	0.01	**0.57**	**0.59**	**0.92**	**0.91**	**0.93**
			FAC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	**0.99**	**0.58**	**0.57**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		G3	YC	**0.91**	**0.99**	**0.61**	**0.56**	**0.67**	**0.28**	**0.30**	**0.09**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	**0.58**	**0.96**	**0.55**	**0.75**
			FAC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	**0.76**	**0.29**	**0.09**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SMS of left-turn vehicles	High	G1	YC	**0.70**	**0.81**	**0.62**	**0.74**	**0.29**	**0.10**	**0.20**	**0.59**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.09**	**0.31**	**0.69**	**0.33**	**0.54**
			FAC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.54**	**0.71**	**0.25**	**0.16**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		G2	YC	**0.68**	**0.92**	**0.62**	**0.66**	**0.11**	**0.17**	**0.07**	**0.05**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.17**	**0.84**	**0.61**	**0.40**	**0.27**
			FAC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.09**	**0.83**	**0.32**	**0.21**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		G3	YC	**0.86**	**0.67**	**0.61**	**0.69**	**0.16**	**0.56**	**0.22**	**0.10**	0.00	0.00	0.00	0.00	0.00	0.00	0.04	**0.25**	**0.72**	**0.33**	**0.65**	**0.54**
			FAC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.31**	**0.61**	**0.57**	**0.62**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Low	G1	YC	**0.84**	**0.94**	**0.64**	**0.77**	**0.73**	**0.13**	**0.25**	**0.31**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.53**	**0.57**	**0.82**	0.03	**0.44**
			FAC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.44**	**0.58**	**0.11**	**0.56**	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00
		G2	YC	**0.98**	**0.56**	**0.93**	**0.49**	**0.53**	0.02	0.04	**0.57**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.34**	**0.58**	**0.94**	**0.99**	**0.26**
			FAC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.19**	**0.58**	**0.76**	**0.46**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		G3	YC	**0.89**	**0.55**	**0.90**	**0.51**	**0.80**	**0.28**	**0.34**	**0.99**	0.00	0.00	0.00	0.00	0.00	0.00	0.01	**0.24**	**0.35**	**0.78**	**0.98**	**0.82**
			FAC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.06**	**0.47**	**0.77**	**0.35**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

(i) The multi-level traffic control (MTC) was the reference; (ii) the significance level was 0.05; (iii) the 'G1', 'G2', and 'G3' were short for Groups 1, 2, and 3 of the vehicular demands, respectively; and (iv) the 'YC', and 'FAC' were short for the yield control and fully actuated control, respectively.

took a substantial amount of time for the yield-controlled roundabout to recover from excessive queuing that was formed during peak periods. By contrast, the fully actuated control to relatively stable operational performance throughout the continuous variation of the vehicular demands. However, complaints related to the use of traffic signals would be exacerbated during off-peak periods because of unnecessary vehicle delay and stops that were experienced by all the vehicular movements.

Tables XI and XII show the general linear model (GLM)-repeated measures ANOVA for the average vehicle delay, stops, and SMSs of left-turn and through vehicles that was performed based on the data in Tables V-X. The *p*-values greater than 0.05 were highlighted by bold numbers. From a statistical perspective, it was found that:

(1) In the low and medium load scenarios before the heavy load scenarios (i.e., 600–7800 s), MTC operated as efficiently as the yield control but significantly outperformed the fully actuated control;
(2) In the heavy load scenarios (i.e., 7800–11400 s), MTC operated as efficiently as the fully actuated control but significantly outperformed the yield control;
(3) In the medium load scenarios after the heavy load scenarios (i.e., 11400–15000 s), MTC operated no worse, if no better, than either of the two alternatives; and
(4) In the low load scenarios after the heavy load scenarios (i.e., 15000–18600 s), MTC operated as efficiently as the yield control but significantly outperformed the fully actuated control; and
(5) The above findings were valid regardless of the level of left-turn ratios.

CONCLUSIONS AND FUTURE STUDIES

Roundabouts have more functions than just being a roadway facility. Preserving large roundabouts means a lot to a city. This research is motivated by the need for proposing a new-style traffic control solution to substantially improve the operational performance of large four-leg roundabouts.

Technically, MTC is featured as new application of traffic control devices and traffic detection system, changeable modes of right-of-way assignment, and event-driven traffic signal operation. Hybrid yield control and fully actuated control can be safely implemented to automatically accommodate time-varying vehicular demands.

The results of the simulation experiments conducted by VISSIM indicated that:

(1) MTC was stabilized at the ‘all entering’ mode during off-peak periods and at the ‘concurrent entering’ mode during peak periods;
(2) MTC would typically change the mode of right-of-way assignment according to actual traffic conditions as vehicular demands increased from off-peak to peak or decreased from peak to off-peak; and
(3) Statistically speaking, MTC inherited the operational advantages of yield control and fully actuated control, and could be effective in improving the operational performance of large four-leg roundabouts for all hours of the day, regardless of the level of left-turn ratios.

Although the effectiveness of MTC is verified experimentally, it is costly to implement MTC because of great amount of investment on the traffic detection system. Public concern about landscaping damage may also discourage the installation of too many traffic control devices within the roundabout area. Even so, MTC will always be a viable alternative to prevent large four-leg roundabouts from being converted to conventional signalized intersections. The proposed application of traffic control devices can be instructive for traffic engineers to develop new-style traffic control solutions at large roundabouts.

In future studies, an improved version of MTC will be developed for large four-leg roundabouts with pedestrian actuated crosswalks. Based on the concept of entrance metering on all approaches, the possibility of implementing hybrid yield control and fully metering signalization will be investigated.

DOI: 10.1002/atr

ACKNOWLEDGGEMENTS

This research is a part of the project 'Development and Application of an Event-driven Bus Rapid Transit Signal Priority at Arterials', which is sponsored by the National Natural Science Foundation of China (No. 61374193) and the project 'Multi-level Traffic Control at Large Roundabouts', which is sponsored by the Humanities and Social Science Foundation of Ministry of Education of China (No. 13YJCZH213).

REFERENCES

1. Bruce W, Lee R, Wade S, et al. *FHWA-RD-00-067: Roundabouts: An Informational Guide*. Federal Highway Administration: McLean, Virginia, USA, 2000.
2. Lee R, Justin B, Christopher T, *et al*. *NCHRP Report 672: Roundabouts: An Informational Guide* (Second edn). Transportation Research Board: Washington, D.C., USA, 2010.
3. Pochowski A, Myers E. Review of state roundabout programs. Transportation Research Record 2182, Transportation Research Board, Washington, D.C., 2010, 121–128.
4. Ashmead D, Guth D, Wall R, Long R, Ponchillia P. Street crossing by sighted and blind pedestrians at a modern roundabout. *Journal of Transportation Engineering-ASCE* 2005; **131**(11): 812–821.
5. Brabander B, Nuyts E, Vereeck L. Road safety effects of roundabouts in Flanders. *Journal of Safety Research* 2005; **36**(3): 289–296.
6. Brabander B, Vereeck L. Safety effects of roundabouts in Flanders: signal type, speed limits and vulnerable road users. *Accident Analysis & Prevention* 2007; **39**(3): 591–599.
7. Daniels S, Brijs T, Nuyts E, Wets G. Explaining variation in safety performance of roundabouts. *Accident Analysis & Prevention* 2010; **42**(2): 393–402.
8. Daniels S, Nuyts E, Wets G. The effects of roundabouts on traffic safety for bicyclists: an observational study. *Accident Analysis & Prevention* 2008; **40**(2): 518–526.
9. Elvik R. Effects on road safety of converting intersections to roundabouts: Review of evidence from Non-U.S. studies. Transportation Research Record 1847, Transportation Research Board, Washington, D.C., 2003, 1–10.
10. Flannery A. Geometric design and safety aspects of roundabouts. Transportation Research Record 1751, Transportation Research Board, Washington, D.C., 2001, 76–81.
11. Flannery A, Datta T. Modern roundabouts and traffic crash experience in United States. Transportation Research Record 1553, Transportation Research Board, Washington, D.C., 1996, 103–109.
12. Jensen S. Safety effects of converting intersections to roundabouts. Transportation Research Record 2389, Transportation Research Board, Washington, D.C., 2013, 22–29.
13. Persaud B, Retting R, Garder P, Lord D. Safety effect of roundabout conversions in the United States: empirical bayes observational before-after study. Transportation Research Record 1751, Transportation Research Board, Washington, D.C., 2001, 1–8.
14. Al-Madani H. Dynamic vehicular delay comparison between a police-controlled roundabout and a traffic signal. *Transportation Research Part A* 2003; **37**(8): 681–688.
15. Bie J, Lo H, Wong S. Circulatory markings at double-lane traffic roundabout: comparison of two marking schemes. *Journal of Transportation Engineering-ASCE* 2008; **134**(9): 378–388.
16. Bie J, Lo H, Wong S. Capacity evaluation of multi-lane traffic roundabout. *Journal of Advanced Transportation* 2010; **44**(4): 245–255.
17. Hallmark S, Fitzsimmons E, Isebrands H, Giese K. Roundabouts in signalized corridors-Evaluation of traffic flow impacts. Transportation Research Record 2182, Transportation Research Board, Washington, D.C., 2010, 139–147.
18. Polus A, Lazar S, Livneh M. Critical gap as a function of waiting time in determining roundabout capacity. *Journal of Transportation Engineering-ASCE* 2003; **129**(5): 504–509.
19. Qu X, Ren L, Wang S, Oh E. Estimation of entry capacity for single-lane modern roundabouts: case study in Queensland, Australia. *Journal of Transportation Engineering-ASCE* 2014; **140**(7): 05014002.
20. Schroeder B, Rouphail N, Hughes R. Toward roundabout accessibility-Exploring the operational impact of pedestrian signalization options at modern roundabouts. *Journal of Transportation Engineering-ASCE* 2008; **134**(6): 262–271.
21. Sisiopiku V, Oh H. Evaluation of roundabout performance using SIDRA. *Journal of Transportation Engineering-ASCE* 2001; **127**(2): 143–150.
22. Ahn K, Kronprasert N, Rakha H. Energy and environmental assessment of high-speed roundabouts. Transportation Research Record 2123, Transportation Research Board, Washington, D.C., 2009; 54–65.
23. Gastaldi M, Meneguzzer C, Rossi R, Lucia L, Gecchele G (2014). Evaluation of air pollution impacts of a signal control to roundabout conversion using microsimulation. 17th Meeting of the EURO Working Group on Transportation, Sevilla, Spain, **3**: 1031–1040.
24. Mudgal A, Hallmark S, Carriquiry A, Gkritza K. Driving behavior at a roundabout: a hierarchical Bayesian regression analysis. *Transportation Research Part D* 2014; **26**: 20–26.
25. Várhelyi A. The effects of small roundabouts on emissions and fuel consumption: a case study. *Transportation Research Part D* 2002; **7**(1): 65–71.

DOI: 10.1002/atr

26. Azhar A, Svante B. Signal control of roundabouts. 6th International Symposium on Highway Capacity and Quality of Service, Stockholm, Sweden 2011; **16**: 729–738.
27. Akçelik R. Capacity and performance analysis of roundabout metering signals. National Roundabout Conference, Transportation Research Board, Vail, Colorado, USA, 2005.
28. Akçelik R. An investigation of the performance of roundabouts with metering signals. National Roundabout Conference, Transportation Research Board, Kansas City, Missouri, USA, 2008.
29. Akçelik R. Roundabout metering signals capacity performance and timing. 6th International Symposium on Highway Capacity and Quality of Service, Stockholm, Sweden, 2011.
30. Hummer J, Milazzo J, Schroeder B, Salamati K. Potential for metering to help roundabouts manage peak period demands in the United States. Transportation Research Record 2402, Transportation Research Board, Washington, D. C., 2014, 56–66.
31. Natalizio E. Roundabouts with metering signals. ITE Annual Meeting, Melbourne, Victoria, Australia, 2005.
32. Shawaly E, Li C, Ashworth R. Effects of entry signals on the capacity of roundabout entries: a case-study of Moore street roundabout in Sheffield. *Traffic Engineering and Control* 1991; **32**(6): 297–301.
33. Ma W, Liu Y, Head L, Yang X. Integrated optimization of lane markings and timings for signalized roundabouts. *Transportation Research Part C* 2013a; **36**: 307–323.
34. Ma W, Xie H, Bai Y, Zhao J, Yang X. Signal timing optimization model based on dual-ring phase scheme for roundabout. *Journal of Central South University* 2013b; **20**(2): 563–571.
35. Yang X, Li X, Xue K. A new traffic signal control for modern roundabouts: method and application. *IEEE Transaction on Intelligent Transportation System* 2004; **5**(4): 282–287.
36. Koonce P, Rodegerdts L, Lee K, *et al*. *FHWA-HOP-08-024: Traffic signal timing manual*. Federal Highway Administration, Turner-Fairbank Highway Research Center, McLean, Virginia, USA, 2008.
37. Urbanik T, Tanaka A, Lozner B, *et al*. *NCHRP Report 812: Signal Timing Manual* (Second edn). Transportation Research Board: Washington, D.C., USA, 2015.
38. Lee J, Strack E, Park B. *UVA-2008-02: Development and evaluation of lane-by-lane gap-out based actuated traffic signal control*. Virginia Department of Transportation, Charlottesville, Virginia, USA, 2012.
39. Smaglik E, Bullock D, Sturdevant J, Urbanik T. Implementation of lane-by-lane detection at actuated controlled intersections. Transportation Research Record 2035, Transportation Research Board, Washington, D.C., 2007, 81–87.
40. Tian Z, Urbanik T. Green extension and traffic detection schemes at signalized intersections. Transportation Research Record 1978, Transportation Research Board, Washington, D.C., 2006, 16–24.
41. PTV AG. (2012). VISSIM 5.40 - User Manual.

DOI: 10.1002/atr