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PRIORITY METERING CONTROL FOR AN URBAN CIRCULAR INTERSECTION

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ABSTRACT

Circular intersections have been used in transportation systems since the 1900s. Three types of circular intersections have been used in the United States: traffic circles, rotaries and roundabouts. While the use of traffic circles and rotaries in recent decades was found to have resulted in high crash rates, safety issues have been mitigated for roundabouts through the use of improved geometric designs.

Nevertheless, all three types of circular intersections face capacity problems during periods of high traffic volume, resulting in long queues and delays. Signal metering was introduced to reduce long queues and delays on the dominant approaches to circular intersections by stopping the flow of traffic from other approaches. This methodology was found to ease congestion for circular intersections with historically high traffic volumes. However, most signal metering at those intersections employ fixed signal timing, in which the metering rate is not responsive to changes in traffic condition. This study investigates the performance of an adaptive metering system for circular intersections. The system was implemented on a real traffic circle having high and unbalanced volumes. The model was calibrated, and a case study was simulated for peak-hour traffic conditions. Using the PTV VISSIM application programming interface, the algorithm was tested and the performance of the system was compared to the current intersection operation. The results showed that adaptive metering can significantly reduce delays and queues at a traffic circle. This preliminary study can be a useful reference for the development of priority-controlled circular intersections.

KEYWORDS

Metering control, Circular intersection, Simulation, Adaptive control.

INTRODUCTION

Circular intersections are intersections with a circulating roadway where multiple roads intersect, allowing all vehicles to travel in one direction around a central island. Three types of circular intersections are used in the United States: traffic circles, rotaries, and roundabouts. Traffic circles and rotaries were the first circular intersections to be developed, and they were designed with large diameters to enable high-speed merging and weaving of vehicles.

Roundabouts were developed in order to help overcome the safety issues associated with circles and rotaries [1,2]. Roundabouts were first developed in the United Kingdom in 1966 with a priority rule that required approaching vehicles to yield to the circulating traffic [3]. This new rule brought significant improvement in intersection safety, when compared with rotaries and traffic circles [4]. As a result, some traffic circles and rotaries were retrofitted with the same priority rule, while others were modified into roundabouts; however, many circles and rotaries are still in use today due to geometric or budget constraints.

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Regardless of the type of circular intersection in use, all have safety issues, and drivers will experience longer delays and queues when traffic flows are high and unbalanced. As a result, signalization came into use to help reduce long queues and delays during peak periods [5,6,7]. Commonly used signal control for circular intersection signalization is based on fixed time control, where a historical flow profile is used to determine a fixed cycle time at fixed locations, either activated by a detector or scheduled according to the time of day. However, these control modes are beneficial only at locations where traffic conditions are predictable [8,9,10,11,12]. When traffic conditions are unpredictable, a more flexible type of traffic control is desirable.

To reduce the impact of high and unbalanced flows, an adaptive metering system for the priority control of circular intersections is explored in this study. This research implements a method for metering an upstream flow when a queue is detected at a downstream approach to the intersection. Unlike fixed signal timing used only at the selected approach, in adaptive metering, all approaches may be metered and controlled. When more than two approaches have high flows, vehicle arrival and waiting time are used as constraints for the selection of the approach to be serviced first. When a metered signal is activated, the queues and arriving demand on that approach is monitored in real time, and the metering may be switched off to avoid excessively long delays based on the updated priority order for service.

In order to investigate the performance of the adaptive metering system at a priority controlled circular intersection, we used the PTV VISSIM application program interphase (API) to build an algorithm to use in the implementation of the system. A traffic circle located in Tallmadge, Ohio, was selected for the analysis, as this intersection has suffered from long queues and delays due to unbalanced flows during rush hour. Peak-hour video data for the intersection was obtained, and the corresponding VISSIM model was built and calibrated to the prevailing traffic conditions observed in the video footage. The adaptive metering system was implemented for peak hour conditions, and the results showed that the delay and queue lengths were reduced significantly.

TALLMADGE CIRCLE

Tallmadge Circle, located in Tallmadge, Ohio, was selected for this study due to its high traffic volumes during peak periods with long queues and delays. Tallmadge Circle is a traffic circle with eight intersecting legs and a one-lane circulating roadway. The approaches are named according to the compass direction of travel away from the circle, as shown in Figure 1. All eight legs of the traffic circle have one-lane entries and one-lane exits. The island inside the circle is occupied by a historic church and low trees that do not block the view of drivers. This intersection is otherwise not connected to any other roads and there are no nearby parking facilities or gas stations. Currently, traffic controlled is made through yield signs, where arriving vehicles on each approach yield to the circulating traffic.

Fig. 1 – Arial image of Tallmadge Circle

The traffic circle in Tallmadge operates without much delay during non-rush periods, when traffic volumes are low. However, as traffic volumes in the approaches increase, the delays increase. Long queues of more than 20 vehicles have been observed on one or more approaches during evening rush hour, when the volumes on the approaches reach the daily maximum. The levels of service (LOS) of the circle during morning and evening rush hours were found to be “C” and “F”, respectively, in a study conducted in 2014 by DMZ Ohio, Inc., for the Akron Metropolitan Area Transportation Studies (AMATS) that was performed to investigate congestion problems at the circle. Data collection for this study was conducted using a video camera mounted at the bottom of a hot air balloon.

The data collected on Tallmadge Circle as part of the AMATS study was converted to hourly volumes, as shown in Table 1. From an operational analysis and crash investigation, it was determined that when gaps in traffic are insufficient to allow vehicles to enter into the circle, rear-end collisions often occur at the intersection. This problem was attributed to drivers’ anxiety/impatience to enter the traffic circle following a long delay. As a result, improving the performance of the circle and reducing delays was recommended as the primary solution.

Tab. 1- Volumes during morning and evening peak hours

AM SCENARIO									
FROM	TO								Total
	North	North-west	West	South-west	South	South-east	East	North-east	
North	0	4	34	55	59	42	25	2	221
Northwest	2	0	4	19	38	38	61	6	168
West	13	4	0	8	34	32	50	13	154
Southwest	53	21	4	0	21	21	32	40	192
South	124	101	57	13	0	32	40	29	396
Southeast	99	84	120	36	8	2	4	13	366
East	27	109	122	32	19	4	0	11	324
Northeast	11	15	80	50	25	6	0	0	187
Total	329	338	421	213	204	177	212	114	2008
PM SCENARIO									
FROM	TO								Total
	North	North-west	West	South-west	South	South-east	East	North-east	
North	0	8	38	36	131	59	33	7	312
Northwest	6	1	16	18	101	75	81	12	310
West	26	4	1	2	72	66	127	39	337
Southwest	63	9	17	0	74	68	122	69	422
South	155	114	108	13	1	23	67	87	568
Southeast	74	66	56	14	18	1	14	35	278
East	62	90	125	39	48	8	2	21	395

Northeast	11	21	91	39	55	18	16	2	253
Total	397	313	452	161	500	318	462	272	2875

MODEL DEVELOPMENT

The VISSIM simulation tool [13] was used as the platform for the analysis in this study. VISSIM is a microscopic simulation tool that can simulate individual driver behaviour and traffic characteristics. VISSIM uses a link-connector to define any type of intersection in its interface, and it provides a high level of detail. Various parameters, including reduced speed areas and conflict areas, are estimated in the model calibration process. The model was first built using Google images to obtain the geometric features of the traffic circle and the approaches, and the traffic volumes associated with the circle and its approaches were used as inputs. The data collection videos cover the peak volumes in both the morning (from 7:00–7:30 AM) and the afternoon (4:00–6:00 PM). Both the morning (AM) and afternoon (PM) conditions were studied.

MODEL CALIBRATION

The VISSIM model was calibrated to ensure that it can accurately reproduce local traffic conditions and vehicle merging behaviour. For this, the travel time for each vehicle at each approach was measured in the video from a fixed starting point to a fixed endpoint. The same starting point and endpoint were selected in the model so that the travel times in each segment would match as closely as possible. Adjustments were made for various parameters in the conflict areas, including front gap, rear gap, visibility and safety distance factor (SFD). Our model included a total of eight conflict areas, one at each approach. Only SFD has a major influence on travel times, as it can reflect the local roadway and environment conditions that influence driver behaviour. Thus, the default SFD value was increased if an approach was found to have longer travel times, and it was decreased if the travel times for an approach were lower than those indicated from the videos. Numerous trials were performed; for each trial, a Student’s t-test was conducted to determine if the difference between the actual travel time and the simulated travel time was significant. The AM and PM models were calibrated separately, and the final parameters selected are shown in Table 2.

Tab. 2- Calibrated parameters and t-test results

AM SCENARIO				
Route	Safety Distance Factor	t-test for model and video		Travel time different after calibration?
		t-statistics	P-value	95% confidence level
North – South	2.5	0.66	0.51	No
Northeast – Southwest	1	−0.97	0.337	No
East – West	1.5	0.14	0.889	No
Southeast – West	1.5	0.51	0.613	No
South – North	1.5	−0.57	0.571	No
Southwest – Northeast	1.5	1.06	0.304	No
West – East	1.5	0.58	0.57	No
Northwest – East	1.5	−0.82	0.42	No

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PM SCENARIO				
Route	Safety Distance Factor	t-test for model and video		Travel time different after calibration?
		t-statistics	P-value	95% confidence level
North – South	1.6	1.2	0.23	No
Northeast – West	1.3	0.34	0.737	No
East – West	0.9	−0.31	0.755	No
Southeast – North	0.9	−0.63	0.53	No
South – North	0.7	−0.27	0.788	No
Southwest – East	0.5	0.69	0.489	No
West – East	2.1	0.38	0.702	No
Northwest – South	1.2	−1.23	0.24	No

ADAPTIVE METERING CONTROL

Adaptive metering control has been developed to make the metering system more efficient by controlling all approaches and determining the appropriate metering rate (signal durations) based on real-time arrival data. The goal of this method is to improve the performance of the intersection by balancing queues when high flows are present in more than one approach. To achieve this, a C++ program with the required control logic has been developed using detector functions deployed through the API. Two adaptive metering methods with different timing strategies have been implemented for comparison purposes. Both methods control all signals, but the first method adaptively switches off the signal from a metered approach if desired, while the second method uses a fixed red time whenever a metered approach is activated. The methods are discussed in greater detail in the following sections.

Adaptive metering signals based on the average gap

For the method that uses adaptive metering signals based on the average gap (AMS-AG), four detectors are used for each approach to determine available gaps, entry flow rates, and upstream arrival flow rates as well as to detect queues. Table 3 describes the detectors used, and Figure 2 presents a diagram showing three of the eight approaches to Tallmadge Circle, including the locations of detectors on each approach. The small red lines before the entry detectors (E_1, E_2, and E_3) represent traffic signal heads, which are placed at a distance of 50 feet from the entry point to the circular road. The queue detectors for each approach were placed at a distance of 175 feet from the entry point, and the demand detectors were placed at a distance of 400 feet from the entry point.

Tab. 3- Description of detectors

Detector. No.	Detector extension	Purpose
1	E_i	To determine entry flow rate
2	Q_i	To detect queues
3	C_i	To determine gaps in circulating flow
4	D_i	To determine arrival flow rate

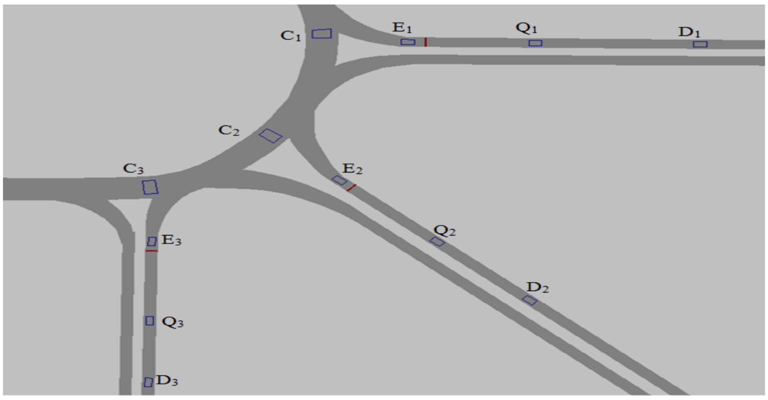

Fig. 2 – Detector setup in the adaptive model

It is difficult to predict the exact number of vehicles that can enter the circulating traffic flow for a given time period. Therefore, vehicle arrival rates, the average gap, and departure rates are used along with queue detectors to prioritize the approaches, decide if an approach should be controlled, and determine when to turn off the signals from metering. In the adaptive metering system, the signals on the metered approaches only use yellow and red lights. No cycle time is used, and the signals become activated or switched off following changes in traffic conditions. A fixed duration of 3 seconds is used for the yellow light, while the duration of the red light depends on the control strategy employed. The stepwise process for this method is explained below:

- A controlling approach is first selected based on the status of the queue detectors on all approaches. If a queue is detected on only one approach, that approach is selected as the controlling one. If a queue is detected in more than one approach, then the one with the highest arrival rate is selected as the controlling approach.
- After selecting the controlling approach, the closest upstream approach (i.e., the one that feeds traffic on the circle to the controlling approach) will be selected as a metered approach, and the signal control will be activated, starting with a yellow light for a duration of 3 seconds, after which it changes to red to prevent any vehicles on that approach from entering the intersection.
- The signal on the metered approach maintains a red light until the queue on the controlling approach is discharged or until a queue is detected on the metered approach. The average gap between vehicles in the circulating flow at the controlling approach is measured. If the gap is found to be less than the safe merging gap obtained from video data at different circulating flow speeds, then the second closest upstream approach to the controlling approach will also be metered. This process continues until no queue is detected on the controlling approach.
- A minimum red time (5~30 seconds) for a signal is used to gradually release vehicles into the intersection from the metered approach if the gaps detected on the circulating flow begin to increase, a strategy that allows limited access. The metering rate increases as conditions continue to improve through shortening the red time on the signal at that approach.
- Once the signal on a metered approach is switched off, a new controlling approach may be selected after 10 seconds. This time lag between each phase allows the system to collect data to aid in selecting the next approach with highest demand.

A flow chart explaining this control logic is shown in Figure 3 below.

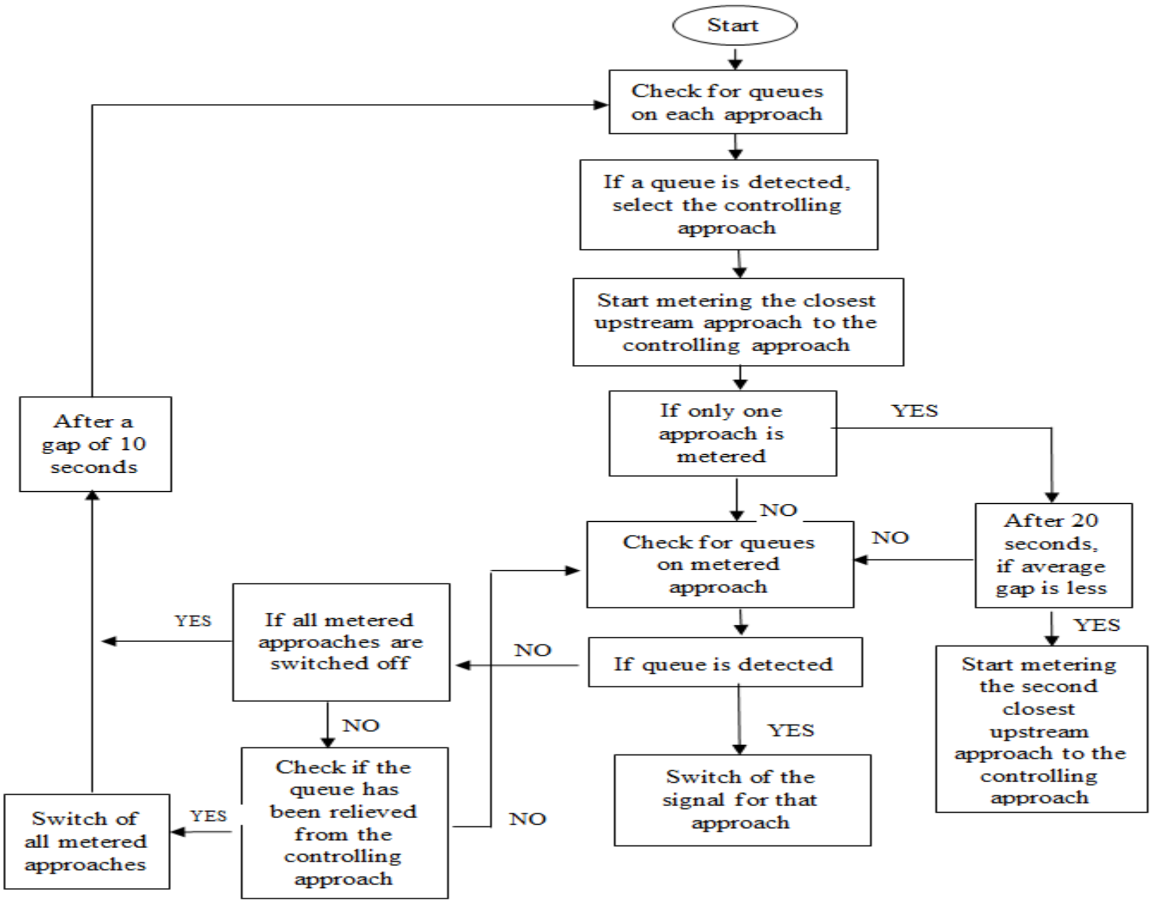

Fig. 3 – Flow chart for AMS-AG method

Adaptive metering signals based on a fixed signal time

A second adaptive metering method, which employs adaptive metering based on a fixed signal time (AMS-FS), has been developed for comparison purposes. This method uses a fixed red light duration for a signal instead of the flexible duration used in the first method. In this method, in order to simplify the implementation, only one approach is used to stop vehicles from entering the circular road, and no gap detectors are used in the circulating flow. The same process is used for selecting a controlling approach as the one used in the AMS-AG method. A yellow light duration of 3 seconds and a red light duration of 25 seconds is used for the signal whenever an approach becomes metered. The 25-second red light duration was selected as the best time interval following an evaluation of all volume conditions. Once the back queue is reduced, the controlling approach is either switched to another approach or is completely eliminated once metering control is no longer needed. A time lag of 25 seconds is used after the completion of a red signal on one controlling approach, before the next controlling approach is selected. Figure 4 shows a flow chart that summarizes the control logic for the AMS-FS method.

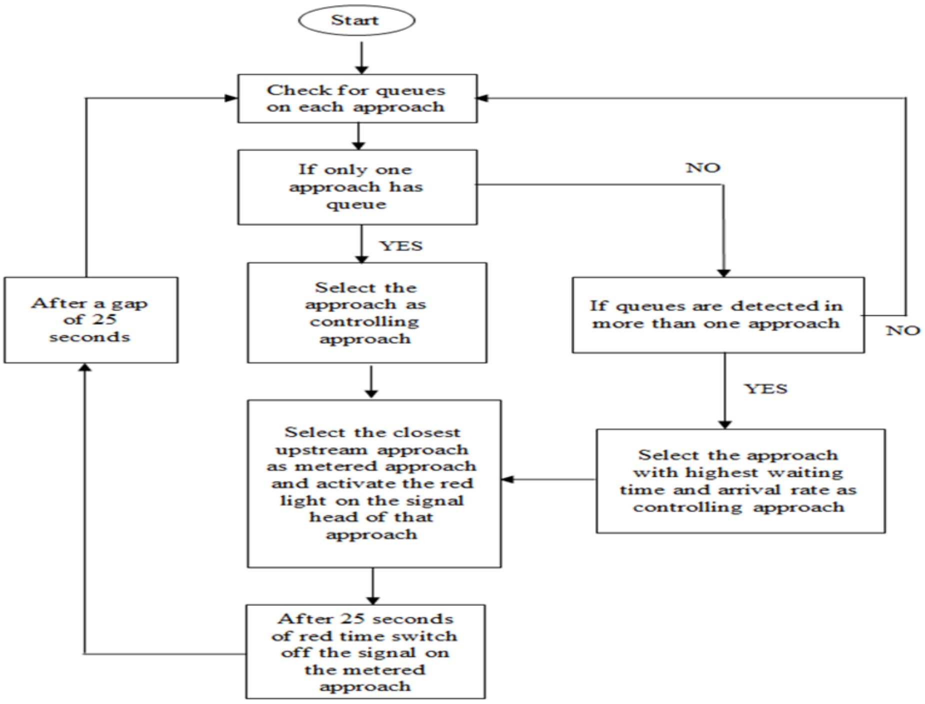

Fig. 4 – Flow chart for AMS-FS method

RESULTS AND ANALYSIS

The results from the two adaptive methods were compared with the current traffic circle operation (i.e., with no signal control). Four scenarios for traffic volume were used in the comparison, including two current AM and PM peak hour conditions and two future traffic conditions that assume a 15% increase over the current peak volumes. The simulations of the future conditions used the same calibration parameters and routing information as the current AM and PM conditions.

In the United States, the Transportation Research Board's *Highway Capacity Manual* [14] recommends comparing the delay for the entire intersection during intersection analysis. In addition, McShane and Roess [15] suggest that the "length of queue at any given time is a useful measure and is critical in determining when a given intersection will begin to impede the discharge from an adjacent upstream intersection". Hence, four measures of effectiveness (MOEs) — the average delay per vehicle, total delay, average queue size, and maximum queue size — were selected in order to compare the performance of the different control scenarios. Six simulation runs were performed for each scenario, and the average for each was used for comparison purposes. A Student's t-test was also conducted to determine if the differences between the adaptive methods and the current (no signal) control are statistically significant. The results for AM, Future AM, PM and Future PM traffic conditions are shown in Tables 4, 5, 6 and 7, respectively.

Tab. 4- Summary of results for AM scenario

Method	AM	% reduction	t-test
	Average delay time per vehicle (s)	Compared with no control	95% significance
AMS-AG	13.59	40.66	YES
AMS-FS	12.5	45.41	YES
No control	22.9	N/A	N/A
Method	Total delay time (h)		95% significance
AMS-AG	7.88	40.71	YES
AMS-FS	7.15	46.20	YES
No control	13.29	N/A	N/A
Method	Average queue length (ft)		95% significance
AMS-AG	10.29	61.02	YES
AMS-FS	8.65	67.23	YES
No control	26.4	N/A	N/A
Method	Maximum queue size (ft)		95% significance
AMS-AG	172.06	38.60	YES
AMS-FS	154.04	40.70	YES
No control	228.73	N/A	N/A

Table 5: Summary of results for Future AM scenario

Method	FUTURE AM	% Reduction	t-test
	Average delay time per vehicle (s)	Compared with no control	95% significance
AMS-AG	38.33	60.98	YES
AMS-FS	35.81	63.55	YES
No control	98.24	N/A	N/A
Method	Total delay time (h)		95% significance
AMS-AG	25.49	60.13	YES
AMS-FS	23.82	62.74	YES
No control	63.93	N/A	N/A

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Method	Average queue length (ft)		95% significance
AMS-AG	60.04	71.28	YES
AMS-FS	56.06	73.18	YES
No control	209.06	N/A	N/A
Method	Maximum queue size(ft)		95% significance
AMS-AG	369.88	51.88	YES
AMS-FS	305.92	51.73	YES
No control	520.10	N/A	N/A

It can be seen from the above results that adaptive metering is able to reduce delay and queue length by a large proportion with statistical significance. The results also show that there is little difference in the effectiveness between the two adaptive metering methods in handling the moderate AM traffic.

Tab. 6- Summary of results for PM scenario

Method	PM	% reduction	t-test
	Average delay time per vehicle (s)	Compared with no control	95% significance
AMS-AG	71.9	30.32	YES
AMS-FS	91.17	11.65	NO
No control	103.19	N/A	N/A
Method	Total delay time (h)		95% significance
AMS-AG	58.83	30.69	YES
AMS-FS	74.67	12.03	NO
No control	84.88	N/A	N/A
Method	Average queue length (ft)		95% significance
AMS-AG	159.56	42.17	YES
AMS-FS	182.14	33.99	YES
No control	275.91	N/A	N/A
Method	Maximum queue size (ft)		95% significance
AMS-AG	607.43	37.79	NO
AMS-FS	626.29	27.81	YES
No control	716.27	N/A	N/A

Tab. 7- Summary of results for Future PM scenario

Method	Future PM	% reduction	t-test
	Average delay time per vehicle (s)	Compared with no control	95% significance
AMS-AG	194.01	16.50	YES
AMS-FS	214.8	7.55	NO
No control	232.34	N/A	N/A
Method	Total delay time (h)		95% significance
AMS-AG	176.02	15.38	YES
AMS-FS	193.89	6.79	NO
No control	208.02	N/A	N/A
Method	Average queue length (ft)		95% significance
AMS-AG	560.35	16.19	YES
AMS-FS	549.35	17.84	YES
No control	668.6	N/A	N/A
Method	Maximum queue size (ft)		95% significance
AMS-AG	1132.08	0.62	YES
AMS-FS	1111.58	0.62	YES
No control	1214.10	N/A	N/A

For the PM peak, the results in Tables 6 and 7 show an overall increase in the MOEs due to high traffic volumes and especially in a scenario with a 15% growth over current peak volumes. Nevertheless, a similar cross-the-board reduction in delays and queue lengths is observed after adaptive metering methods are applied. Moreover, the flexible metering rate method is able to outperform the fixed metering rate method due to its policy of allowing metering at multiple intersection approaches at the same time, resulting in a more strict metering control to help maintain smooth traffic circulation within the intersection. During modelling, we also observed that the queue length increased for approaches with a low volume, but the increase in queue length was much smaller when compared to the corresponding decrease in queue length from the high-volume approaches. This indicates that more vehicles were able to enter the intersection when the metering is under adaptive control, demonstrating that the metering is effective in redistributing and reducing the queues for unbalanced flows. The t-tests generally show the difference between adaptive metering (especially the flexible metering rate method) and no metering control is significant; the results would have become significant in all cases if a 90-percent significance level was used.

CONCLUSION

In this study, an adaptive metering system was developed and tested for circular intersections. The method was implemented for a traffic circle with eight legs having an unbalanced flow, where backup queues exceed 600 ft on two or more approaches. The traffic circle simulation was calibrated to the peak hour conditions, and the results of the computer simulation for both adaptive metering methods (flexible metering rate and fixed metering rate) were compared to the data on the current operation of the traffic circle without any signal control.

The modelling results showed that adaptive metering methods can bring significant improvements to the traffic circle in terms of mitigating delays and queues. The decrease in delay is over 30%, and the average queue length is reduced by more than 40% for the highest PM peak hour traffic volume. For the future PM scenario, the gain in delay and queue length control becomes smaller (reduced by approximately 15%). This indicates when traffic volumes are too high, congestion can form on all approaches as a result of queue balancing, thus diminishing the advantage of metering control. Therefore, other traffic management countermeasures, such as arrival demand diversion before reaching the roundabout and geometric improvements at the entrances/exits or addition of a circulation lane, should be used in conjunction with metering control. In summary, for all scenarios tested with existing conditions, the flexible metering rate method is most effective for reducing delays and controlling queues, and it should be further studied and tested in future research efforts. It should be noted that the system and settings of adaptive metering discussed in the paper represents only a basic proposal; if practically implemented in the field, the system would require execution of a multivariable program that is able to address many conditions according to input variables and limitations by technical standards.

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