Traffic Flow Characteristics Comparison between Modern Roundabouts and Intersections

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INTRODUCTION

There has been a strong interest expressed in modern roundabouts in the United States, Europe, and Australia in recent years. While their space requirements are higher, modern roundabouts if properly designed, are expected to provide better operating condition compared to conventional intersections for certain traffic flow conditions. A number of cities in the US, including those in the Detroit metro area, have converted traditional intersections to roundabouts. Because of increased interest in roundabouts, there is continuing research effort at the U.S. Department of Transportation (USDOT) and many state Departments of Transportation (DOT) on exploring appropriate physical locations, design parameters, and their performance relative to alternative control schemes [1].

The design and operation of modern roundabout are different from rotaries and traffic circles. Modern roundabouts are distinguished from traffic circles: yield-at entry, deflection, and flare [2]. Yield-at entry provides priority to circulatory vehicles expected to increase the capacity up to 10% and to reduce delays up to 40%. Deflection in roundabouts helps in accommodating slow entering vehicles and removes possible conflicts at merging points. Design of flare depends on capacity requirements and should be considered in addition to lane width. Flare increases the capacity of entry lane and thereby decreases the critical gap of approaching traffic [3, 4]. Though modern roundabout is a popular concept in most states, the assessment of traffic operation is in development stage [5]. Recent practices and performances of roundabouts in the U.S. are documented in the National Cooperative Highway Research Program (NCHRP) report on “Roundabouts in the United States” and Federal Highway Administration (FHWA) report on “Roundabout: An Informational Guide”[1, 6]. Based on limited data available, traffic operation characteristics such as capacity, delay, saturation flow, queue length estimation are briefly updated in the chapter 17 of Highway Capacity Manual (HCM) [7]. Empirical models for roundabouts in the United States are currently in the development stage considering driver behavior and traffic flow.

MOTIVATION

There is not sufficient literature available for comparing the performance of roundabouts with those of signalized intersections from low to high volume conditions. Roundabouts are expected to provide better operating conditions than intersections for certain conditions of traffic flow and roadway geometry [3]. In this paper, traffic flow operations at roundabouts are assessed by considering a set of intersections and scenarios are created for possible conversion of existing intersections to roundabouts. Candidate intersections are selected in the Detroit metro region. Intersection types vary from one-lane to three-lane approaches. The performance of existing intersections are analyzed and compared to that of corresponding counterpart of roundabouts. Control delay, Volume to capacity (V/C) ratio, and queue length are considered as the Measures of Effectiveness (MOE) for comparison. Estimation of these MOEs is explained below.

Guidelines developed by HCM and FHWA recommend the use of control delay to determine the level of service (LOS) of roundabouts [8]. Control delay is the time that a driver spends queuing and then waiting for an acceptable gap in the circulating flow while at the front of the queue. Control delay consists of stopped time delay, approach delay, travel time delay, and time in queue delay.

HCM defines capacity as the maximum sustainable flow rate that can be achieved during a specified time period under prevailing traffic and control conditions [7]. Roundabout capacity is determined as the cumulative capacity of a series of "T" intersections that are interconnected in a circle. Each intersection operates under YIELD control for the entry approach. The capacity of the entry approach is determined by the availability of gaps on the circulating roadway. The geometric elements that affect capacity are the width of the entry, circulatory roadways, the number of lanes at the entry, and flared sections [8, 9].

Average queue length for an approach is the vehicle-hours of delay for a specific time period for an intersection or roundabout. It is used as one of the measures to compare the performance of roundabouts with that of intersections. Queue lengths can be plotted in a cumulative distribution curve for each approach (or average for an intersection / roundabout). The 95th percentile queue length is generally considered for performance measure. HCM provides empirical formulae to estimate the 95th percentile queue length [8].

METHODOLOGY

The Signalized and Unsignalized Intersection Design and Research Aid (SIDRA) developed by the Australian Road Research Board (ARRB) and Akcelik Associates is used for analyzing performance of roundabouts and intersections. SIDRA has an option to use US HCM and FHWA models. SIDRA can produce consistency of capacity and performance analysis methods for roundabouts, sign- controlled, and signalized intersections through the use of an integrated modeling framework [10]. The signalized intersections and roundabouts considered for performance measure comparison in this paper are discussed below.

Signalized intersections

Four types of signalized intersections are considered for comparison purpose. These are: four leg intersections with one-lane approach, four leg intersections with two-lane approach, four leg intersections with three-lane approach, and five leg intersections with three-lane approach. Data collected for this study include: traffic volume for ten hours of the day, existing geometry, signal timing, and phasing. All the signalized intersections considered were operating in two phase signal with cycle length ranging from 50 seconds to 90 seconds. The intersections analyzed are the candidate locations identified in an earlier study titled "Safety Improvements for Urban Arterials" conducted at Wayne State University and supported by Michigan Department of Transportation (MDOT) [11].

Roundabouts

For the purpose of this study a set of 'virtual' roundabouts (or scenarios) were created by combining different factors reflected by the following:

- Lane width for flare: FHWA recommends minimum lane width of flare to be 13ft (4m), for the approaches with lane width of 12ft (3.6m). SIDRA guidelines suggest incremental changes of lane width of 3ft (1m), up to maximum roundabout lane width of 20ft (6m) [6, 10]. Two separate cases of roundabouts of lane width of flare of 13ft (4m) and 17ft (5m) are considered in this study.
- Central island diameter: Inscribed circle diameter and minimum circulatory lane width determines the central island diameter. FHWA recommends a minimum central island diameter be 59ft (18m) to 82ft (25m) for one lane roundabouts, and up to 82ft (25m) for

two and three lane roundabouts [6]. In this study, central island diameters of 59ft (18m) and 82ft (25m) are considered for two and three lane roundabouts respectively.

- Circulating lane width: FHWA recommends a range of 29ft (8.7m) – 32ft (9.8m) circulating lane width for two-lane roundabouts [6]. Circulating lane widths of 23ft (7m), 28ft (8.5m), and 33ft (10m) are considered for one lane, two lane and three lane roundabouts in this study.

The performance of intersections and corresponding roundabouts are compared on three MOEs: control delay, V/C ratio, and 95th percentile queue length. Simulated values for roundabouts are obtained from SIDRA. A nonparametric hypothesis test is proposed to investigate the performance of candidate intersections and roundabouts for different MOEs. The Kruskal-Wallis test is sensitive to small samples and provides ranks for comparison of explanatory factors [12]. SPSS software is used for conducting the Kruskal-Wallis test [13]. The MOEs for roundabouts and intersections are assessed at the 95 percent level of confidence.

RESULTS

A measure of effectiveness and comparison tree is presented in Figure 1. Each MOE (Control delay, V/C ratio and 95th percentile queue length) consists of four sets (types of intersections). These are: one-lane approach four legged intersection, two-lane approach four legged intersection, three-lane approach four legged intersection and three-lane approach five legged intersection. For each intersection, two scenarios of roundabouts of entry lane width of 13ft (4m) and 17ft (5m) are proposed, for a total of three comparison groups, one existing intersection, and two scenarios of roundabouts.

Control delay for intersections and roundabouts are presented in Figure 2. Roundabouts appear to provide better level of service (lower control delay) than one-lane approach four legged intersections. Roundabout with 17ft (5m) of flare lane width produce better results among all (Figure 2(a)). In Figure 2(b) control delay for one-lane approach four legged intersections is presented. Roundabouts produce better LOS while the signalized intersection produced lowest LOS. Control delay for three-lane approach four legged intersection is presented in Figure 2(c). Under low traffic conditions, roundabouts provide moderate performance, but under high traffic condition roundabouts do not appear to provide significant improvement in LOS. Figure 2 (d) shows moderate performance of roundabouts of three lane approach (five leg) compared to signalized intersections. Under heavy traffic conditions, intersections produce better LOS than roundabouts.

The performance of intersections and roundabouts cannot be judged only through control delay. V/C ratio is another independent measure that can be considered to evaluate the overall operation of a facility. Results of V/C ratio comparison are presented in Figure 3. Because of increased space availability, roundabouts are expected to provide lower V/C ratios. For one lane approach, roundabouts produced better performance in V/C ratio. On the other hand, roundabouts with two-lane and three-lane (both four and five legged) approaches show lower V/C ratio (better performance). The 95^{th} percentile queue length is the third comparative measure considered (Figure 4). Roundabouts with one, two lane approach show lower back up queue lengths compared to intersections. For three lane approaches (both four and five legged), roundabouts do not show significant improvement in terms of queue length.

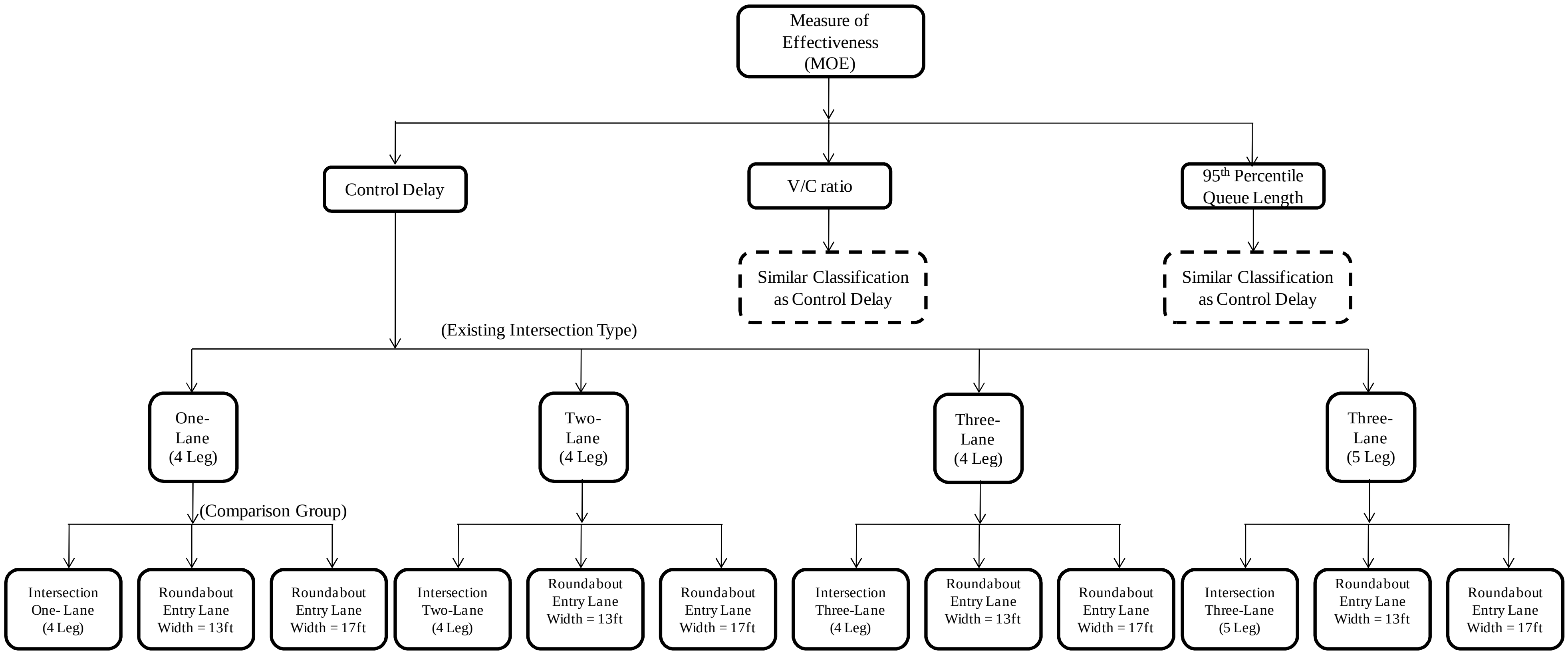

Figure 1: Measure of Effectiveness and Comparison Tree

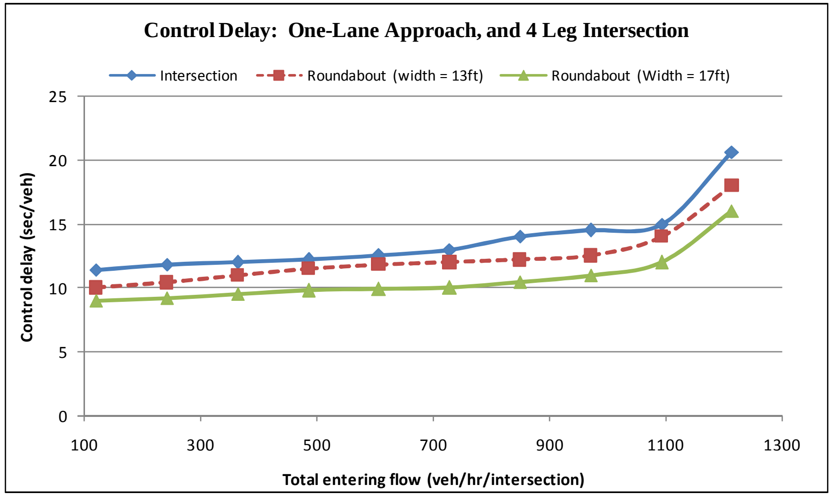

Figure 2 (a): Control Delay for One-Lane Approach Intersection and Roundabout

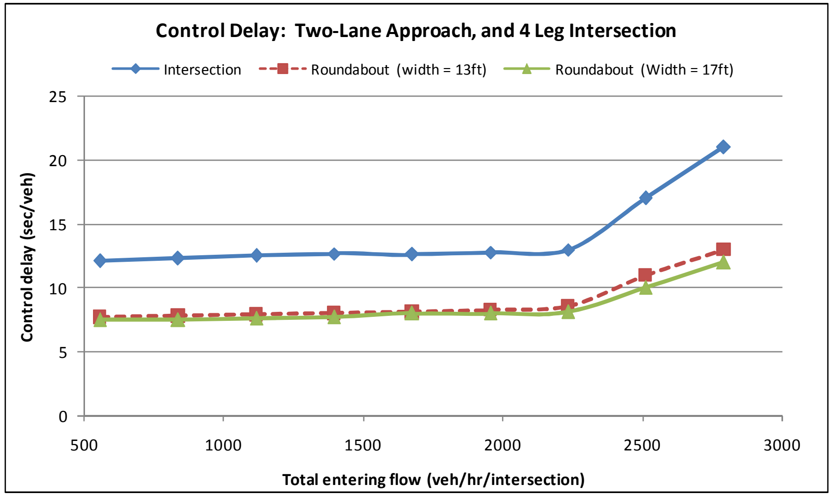

Figure 2 (b): Control Delay for Two-Lane Approach Intersection and Roundabout

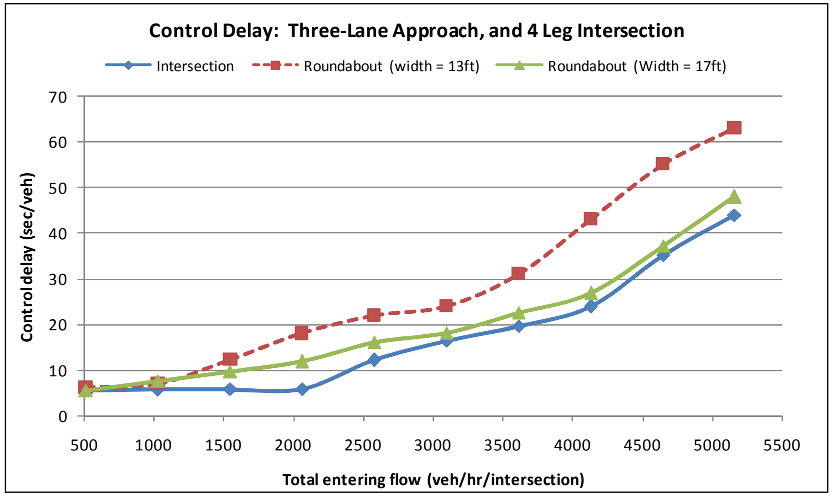

Figure 2 (c): Control Delay for Three-Lane Approach Intersection and Roundabout

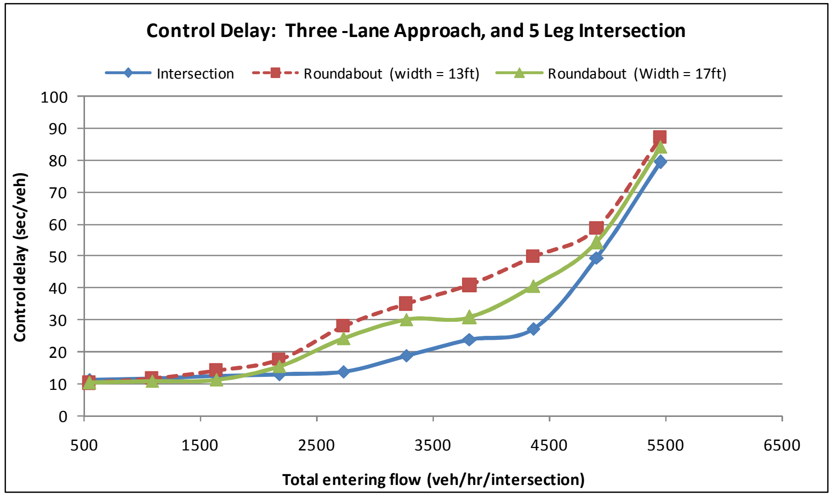

Figure 2 (d): Control Delay for Three-Lane Approach Intersection (5 Leg)and Roundabout

Figure 2: Control Delay Comparison for Roundabouts and Intersections

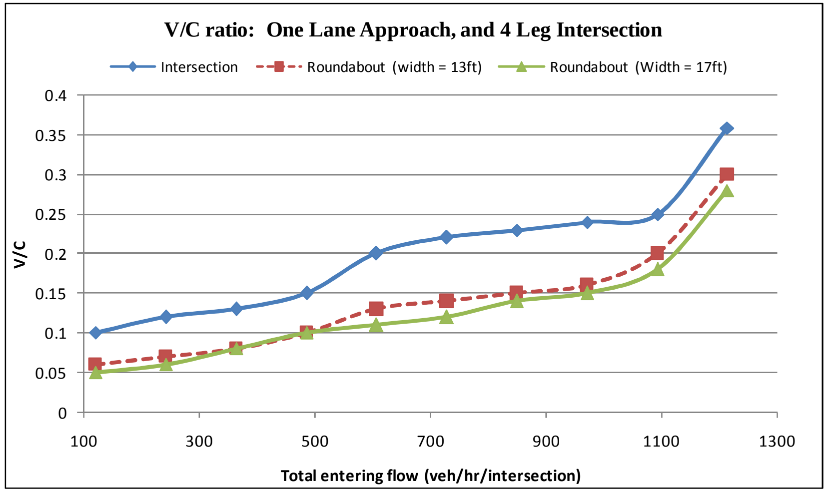

Figure 3 (a): V/C ratio for One-Lane Approach Intersection and Roundabout

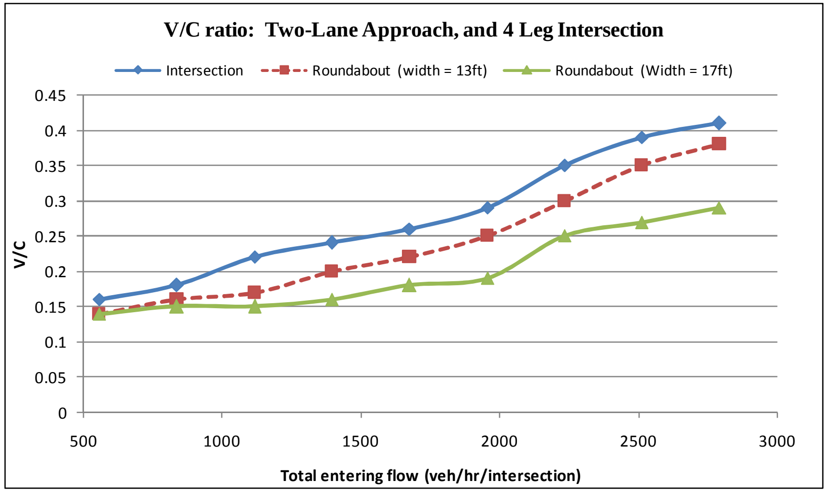

Figure 3 (b): V/C ratio for Two-Lane Approach Intersection and Roundabout

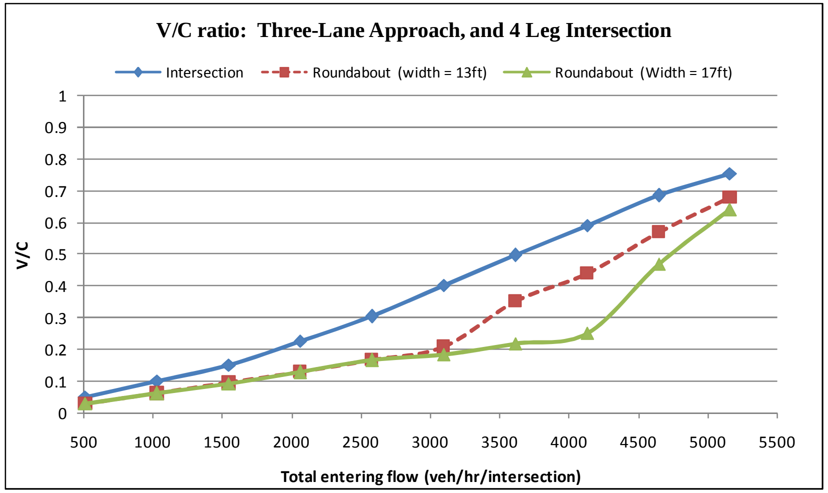

Figure 3 (c): V/C ratio for Three-Lane Approach Intersection and Roundabout

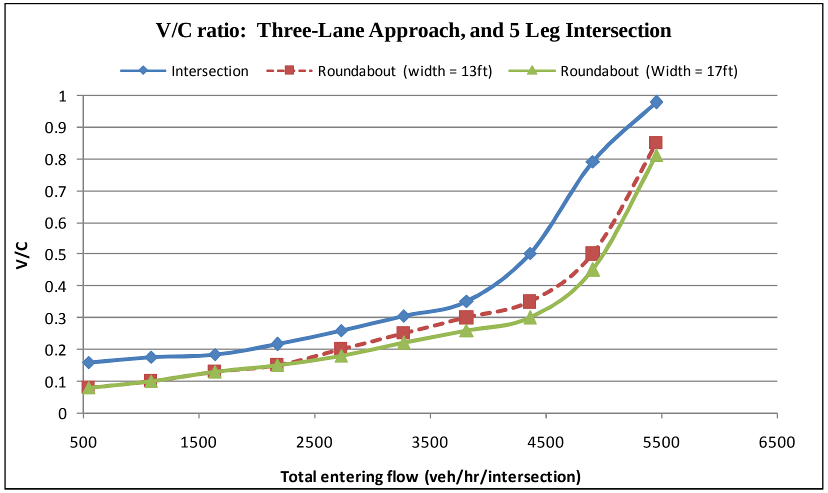

Figure 3 (d): V/C ratio for Three-Lane Approach Intersection (5 Leg) and Roundabout

Figure 3: V/C ratio Comparison for Roundabouts and Intersections

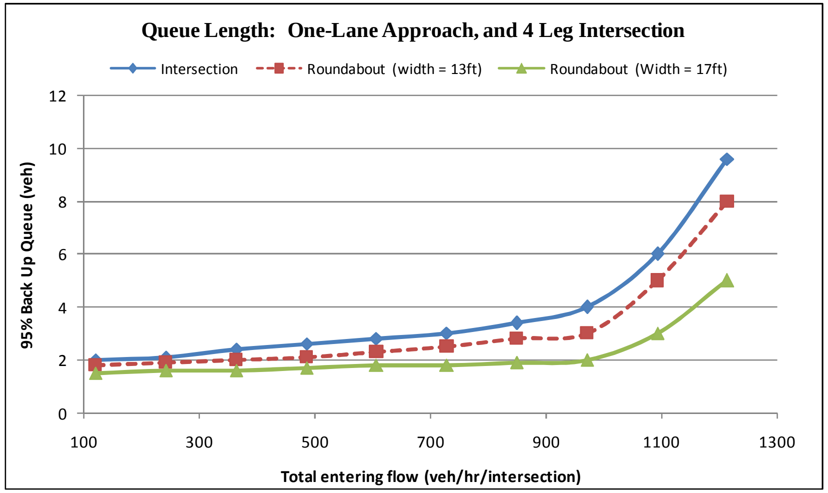

Figure 4 (a): Queue Length for One-Lane Approach Intersection and Roundabout

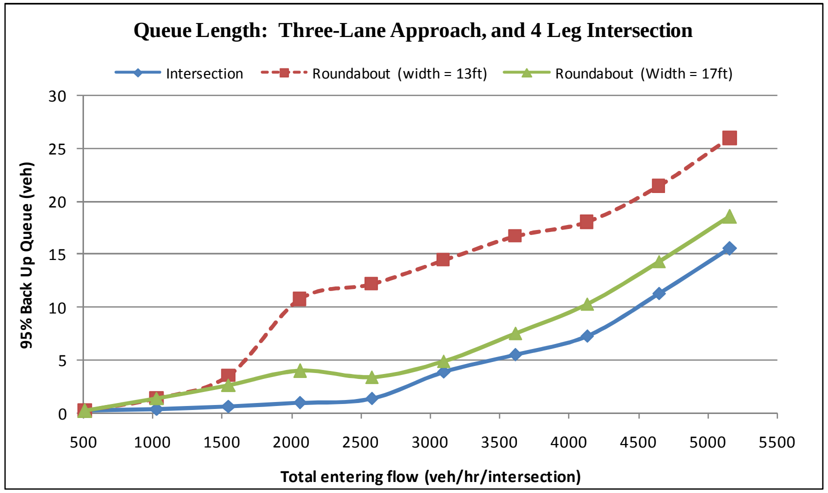

Figure 4 (b): Queue Length for Two-Lane Approach Intersection and Roundabout

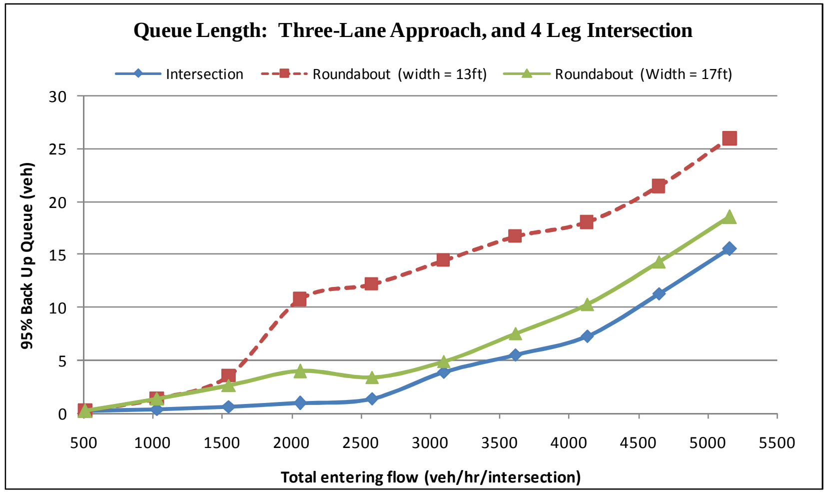

Figure 4 (c): Queue Length for Three-Lane Approach Intersection and Roundabout

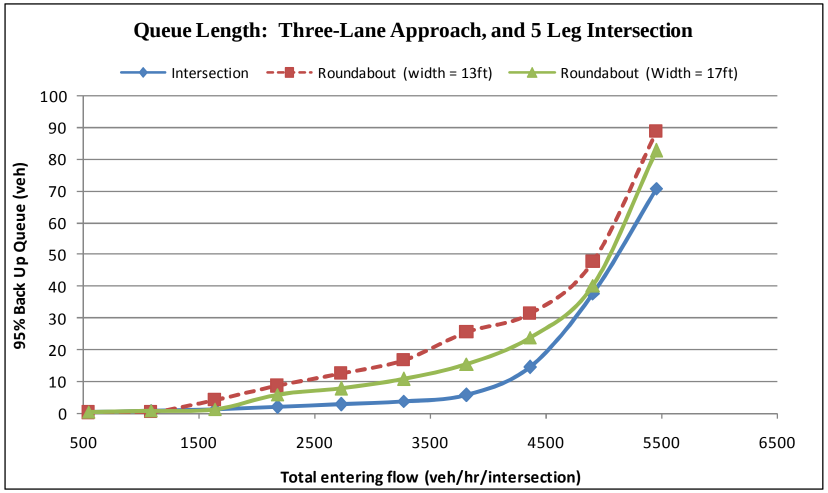

Figure 4 (d): Queue Length for Three-Lane Approach Intersection (5 Leg)and Roundabout

Figure 4: Queue Length Comparison for Roundabouts and Intersections

Table 1: Nonparametric test results for performance of intersections and roundabouts

Intersection Type	Comparison Categories	Control Delay			V/C ratio			95th Percentile Queue Length		
		p-value[1]	Hypothesis[2]	Rank	*p-value*[1]	Hypothesis[2]	Rank	*p-value*[1]	Hypothesis[2]	Rank
One-Lane Approach Four Legged Intersections	Intersection	0.004	Reject	3	0.046	Reject	3	0.01	Reject	3
	Roundabout (Width=13ft)			2			2			2
	Roundabout (Width=17ft)			1			1			1
Two-Lane Approach Four Legged Intersections	Intersection	0.002	Reject	3	0.037	Reject	3	0.002	Reject	3
	Roundabout (Width=13ft)			2			2			1
	Roundabout (Width=17ft)			1			1			2
Three-Lane Approach Four Legged Intersections	Intersection	0.308	Fail to reject	-	0.041	Reject	3	0.099	Fail to Reject	1
	Roundabout (Width=13ft)			-			2			3
	Roundabout (Width=17ft)			-			1			2
Three-Lane Approach Five Legged Intersections	Intersection	0.425	Fail to Reject	-	0.118	Fail to reject	-	0.449	Fail to Reject	-
	Roundabout (Width=13ft)			-			-			-
	Roundabout (Width=17ft)			-			-			-

Note: - Statistical test does not produce significant evidence of improvement.

[2]Significance Level : $\alpha = 0.05$
Rejection Region: Reject Null Hypothesis if *p-value* ≤ 0.05

[2]Hypothesis: Ho: Mean MOE for three comparison categories is equal
Ha: Mean MOE for three comparison categories is not equal
Reject Null Hypothesis: At $\alpha = 0.05$, there exists significant difference in the mean of three comparison categories

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Hypothesis test results are presented in Table 1. The Kruskal-Wallis nonparametric test is conducted for intersections, and corresponding two roundabouts, for a total of three factors. The null hypothesis tested is stated as “There is no significant difference between the means MOEs among comparison groups”. A confidence level of 95% is selected as the critical limit and the null hypothesis is rejected for α lesser than 0.05. If the null hypothesis is rejected, the comparison groups are ranked in the order of performance. For cases of failure to reject null hypothesis, no conclusive judgment were made. For control delay, roundabouts of 17ft width appeared to be the best alternative for corresponding one-lane and two-lane approach intersections. There was no significant difference in control delay performance for three-lane roundabouts and intersections. Roundabouts produced better performance for V/C ratio except five leg intersections with three-lane approach. One-lane and two-lane approach roundabouts produced smaller queue lengths than corresponding intersections. There were no conclusive evidence of improvement on queue length for three-lane roundabouts.

CONCLUSION

The performance of roundabouts is compared to intersections in three measures: control delay, volume to capacity ratio, and 95th percentile queue length. Four types of signalized intersections are considered and corresponding highway geometry is simulated for two types of roundabouts of entry lane width of 13ft (4m) and 17ft (5m). For the first MOE, control delay, one-lane and two-lane approach roundabouts are viable alternatives compared to intersections at both high and low volume conditions. Three lane (both four and five legged) roundabouts show average performance on control delay during light traffic conditions. At heavy traffic conditions, signalized intersections show better performance on control delay.

For the second MOE (V/C ratio), roundabouts show better performance under all conditions. This is because of increased space of roundabouts and the provision of relatively easier traffic movement in the central island. Flared lane width appears to be another factor contributing to lower V/C ratio. For the third MOE, the 95th percentile queue length, one-lane and two-lane approach roundabouts show better performance compared to intersections. For low and high volume conditions, one-lane and two-lane approach roundabouts produced lower queue lengths, irrespective traffic volume. Three lane intersections show better performance on queue length compared to corresponding roundabouts. For heavy traffic conditions, three lane roundabouts do not seem to show better performance on queue lengths. The nonparametric test revealed the significance and rank of improvement among comparison categories.

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