Evaluation of Roundabout Performance Using SIDRA

By Virginia P. Sisiopiku[1] and Heung-Un Oh[2]

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Abstract: This paper compares the performance of roundabouts with four leg intersections under yield control, two- and four-way stop control, and signal control for various traffic conditions using the SIDRA package. Such conditions include variations in volume levels, turning volume splits, number of approach lanes, and lane widths. The results from the analysis indicate that roundabouts are the best alternative designs for intersections with two-lane approaches that carry heavy through and/or left traffic turning volumes. The performance of roundabouts compares well to the performance of signalized intersections with one-lane approaches and heavy traffic volumes. Roundabout capacities are found higher than capacities of signal controlled intersections with two- and three-lane approaches for any proportion of left-turning traffic volume. This study provides recommendations to traffic engineers on the conditions under which roundabouts perform better than controlled intersections and, thus, should be considered as design alternatives.

INTRODUCTION

The history of traffic circles is almost as long as that of signalized intersections. The first traffic circle concept was introduced in 1877 by French architect Eugene Henard (DeArgao 1992). In 1903 he suggested that the traffic circle is a convenient form of traffic control when many roads converged. The first engineering based design guide was published by the United Kingdom Ministry of Transport in 1929 and design formulas were introduced in 1957 (Troutbeck 1984). The concept of modern roundabouts was introduced in 1963 when the British government employed the off-side rule based on which the priority was given to the circulating vehicles on the traffic circles. The introduction of flare and deflection concepts further assisted roundabouts to prevail as one of the most popular, safe, and convenient traffic-control options in Europe and Australia.

In the United States, traffic circles have had a long but controversial history. Although the Columbus Circle in New York was constructed before 1910 as one of the world's earliest traffic circles, the public opinion about their performance has not been always favorable. In New Jersey, traffic circles were removed after the state government claimed that they were high-accident locations causing long delay (Myers 1994). However, the flourishing modern roundabouts in other countries were intriguing enough to generate a recent interest. Based on literature review, some of the advantages of roundabouts, compared to other controlled intersection types, include safety, increased capacity, reduced delay, lower capital cost, improved aesthetics, U-turn opportunities, and traffic calming (Myers 1994).

Description

The roundabout has evolved in its operation and design. Modern roundabouts are distinguished from traffic circles (conventional roundabouts) by three main characteristics, i.e., yield-at-entry, deflection, and flare (Redington 1997).

The yield-at-entry rule assigns priority to circulating vehicles. Under the rule, it is assumed that the roundabout is a set of T-junctions. Blackmore suggested that the yield-at-entry rule can increase the capacity of roundabouts by 10% and decrease delays by approximately 40% (Blackmore 1963).

The use of deflection in the design of roundabout helps to slow entering vehicles and improves safety at merging points. Design guidelines for deflection, including size and position of central island, introduction of staggered or non-parallel alignment between entrance and exit, and position of approach island are offered in the literature (Country Roads Board 1979).

The flare effect depends on the number of lanes, and is associated with capacity. Akçelik (1997) indicated that, in addition to the number of lanes, flare should also take into account lane widths.

Literature Review

The research on delays at roundabouts began with the introduction of the yield-at-entry element. Tanner studied the delays at the minor stream on the basis of gap acceptance models and the analogy of traffic flow to the Poisson distribution (Tanner 1962). Kimber and Hollis (1979) simplified the variables and suggested an equation for the delay to minor traffic. McDonald and Noon (1978) studied the impact of geometric factors to delay. Mean speed and turning angle were found to be the main contributing factors and an equation to estimate delays was suggested.

In Akçelik's (1997) work, Signalized and Unsignalized Intersection Design and Research Aid (SIDRA) was employed for roundabout capacity and performance analysis as an extension of traditional gap acceptance and queuing theory. The *Florida Roundabout Design Guide* (FDOT 1995) and the *Roundabout Design Guide* recommend SIDRA for the study of roundabouts (MDOT 1995).

The *Florida Roundabout Design Guide* also compared one- or two-lane roundabouts to signalized intersections with one- or two-lane approaches and one exclusive left turn lane. It concluded that the performance of signalized intersections is superior under heavy entering volume, while the roundabout works better under light entering volume in terms of delay. Akçelik (1997) reported that this study failed to consider flare effects correctly as it took under consideration only the number of lanes and not the lane width.

Old versions of the U.S. Highway Capacity Manual (U.S. HCM) and Highway Capacity Software (HCS) are limited in their ability to provide detailed analysis of roundabouts (NRC 2000). The HCM 2000 version (NRC 2000) tries to bridge this

[1]Asst. Prof., Civ. and Envir. Engrg., Michigan State Univ., East Lansing, MI 48824. E-mail: sisiopik@egr.msu.edu

[2]Sr. Res., Korea Highway Corp., 293-1 Kumto-dong, Seongnam-si, Kyonggi 461-380, South Korea. E-mail: ohheung@freeway.co.kr

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gap by introducing the procedures for the study of roundabouts.

Although several other empirical delay studies and procedures exist for delay analysis, SIDRA offers a unique advantage in delay studies. While the empirical studies are limited within the study of the stopped delay (or stopped and queuing delay), SIDRA can conveniently calculate total delay by summing geometric delay, queuing delay, the acceleration and deceleration delay, and stopped delay.

OBJECTIVES

The major objective of this study is to determine under what conditions roundabouts are viable alternatives to traditionally controlled intersection designs. Different intersection types are compared on the basis of average delay and capacity. These intersection types include roundabouts and four-leg intersections with yield, two-way stop, four-way stop, and signal control. Reasonable assumptions are made about the number of available lanes, lane width, and left turn percentage. The effects of these parameters on the operation of each type of intersection are calculated and compared. The analysis is based on simulated data produced by SIDRA software. Field data are not used due to the difficulties in finding the comparable counterparts and the limited number of roundabouts currently in the United States.

METHODOLOGY

Employment of SIDRA Software

The SIDRA package has been developed by the Australian Road Research Board (ARRB), Transport Research Ltd., as an aid for design and evaluation of intersections such as signalized intersections, roundabouts, two-way stop control, and yield-sign control intersections (Akçelik and Besley 1996). In evaluating and comparing the performance of roundabouts, there are some advantages that the SIDRA model has over any other software model. Akçelik (1997) indicated that the SIDRA method emphasizes the consistency of capacity and performance analysis methods for roundabouts, sign-controlled, and signalized intersection through the use of an integrated modeling framework. This software provides reliable estimates of geometric delays and related slowdown effects for the various intersection types. This property of the software is very important to the evaluation of alternative intersection treatments in a consistent manner. Another strength of SIDRA is that it is based on the U.S. HCM as well as ARRB research results. Therefore, SIDRA provides the same level of service (LOS) criteria for roundabouts and traffic signals under the assumption that the performance of roundabouts is expected to be close to traffic signals for a wide range of flow conditions (Akçelik 1997).

Choice of Measures of Effectiveness

This study considers four intersection alternatives to roundabouts, namely, traffic signal controlled, two-way stop controlled, four-way stop controlled, and yield controlled intersections. Based on the level of service concept, the measures of effectiveness for intersection performance should include volume to capacity (V/C) ratio and delay. The U.S. HCM recommends using delay for all intersection alternatives. For signalized intersection control, it also recommends analyzing the delay and capacity simultaneously to evaluate the overall operation. These two concepts are not as closely correlated in signalized intersections as is the case for all other intersection alternatives (NRC 1994). Therefore, in this study, the average delay is employed to compare the performance between intersection alternatives. V/C ratio is additionally used to compare the performance between signalized intersections and roundabouts.

Delay is estimated based on the path-trace method for measuring delay in SIDRA. This delay value corresponds to the total delay that an average vehicle experiences directly or indirectly due to the intersection. It includes geometric delay, queuing delay, the acceleration and deceleration delay, and stopped delay. For signalized intersections, SIDRA suggests a simple formula that converts the stopped delay to overall delay, based on which overall delay equals 1.3 times the stopped delay.

In SIDRA, capacity is calculated in terms of the intersection capacity that corresponds to summation of capacities from all approaches. If approaching volumes are given, the intersection capacity could be easily transformed to V/C ratio.

ANALYSIS AND RESULTS

Basic Experimental Conditions

Basic experimental conditions are selected for testing and described in detail next. The list of conditions studied is, by no means, exhaustive. Nevertheless, the experimental conditions assumed in the following are believed to be common or representative ones.

Roundabout

- Central island diameter equals to 18 or 24 m.

  Roundabouts require a minimum central island diameter to allow for circulating heavy vehicles. SIDRA suggests 18 m as the default value. This value is used for roundabouts with one and two lanes. However, a small island diameter cannot accommodate well the deflection needs and, thus, 24 m is assumed to be the minimum island diameter for intersections with three lane approaches in this study.
- Circulating lane width of 9 m.

  Wide circulating lanes are needed for accommodating heavy vehicles' turning path. SIDRA suggests 9 m as the default value. This value is used in this study for conducting the experiments.
- Lane width for flare equal to 3.96, 4.96, and 5.96 m.

  Lane width used in the analysis reflects the flare effect and follows recommended guidelines by SIDRA. SIDRA suggests default value of lane width with flare equal to 3.96 m (for approaches with a 3.6 m lane width). For the study of flare effects, SIDRA recommends incremental changes to the lane width of 1 m up to a maximum roundabout lane width of 6 m.
- Volume ratio by approach of 1:1:1:1.
- Left turn percentage of 10%, 20%, and 30%.

  10% left turns reflect prevailing conditions, while 20 and 30% left turns are used to study the effect of heavy left turn volumes on performance.

Two-Way Stop Control

- Volume ratio by approach of 1:1:1:1, 1:99:1:99.

  The latter ratio is assumed to represent the case where there is very low traffic demand on the minor street.
- Left turn percentage of 10%

  This value is assumed to reflect the most prevailing conditions.

Four-Way Stop Control

- Volume ratio by approach of 1:1:1:1.
- Left turn percentage of 10%.

Yield Control

- Volume ratio by approach of 1:1:1:1, 1:99:1:99.
  The latter ratio is assumed to represent the case where there is very low traffic demand on the minor street.
- Left turn percentage of 10%.
  This value is assumed to reflect the most prevailing conditions.

Signal Control

- Volume ratio by approach of 1:1:1:1.
  Under signal control, the need to provide for the most critical of two or more movements that proceed simultaneously results in effective use of green time by the noncritical movement. The suggested ratio minimizes this ineffectiveness.
- Left turn percentage of 10%.
- Phasing: two-phase signal.
  For the given percentage of left turns, a two-phase signal control resulted in minimum average delay during the study. This is supported by the fact that it maximizes capacity (NRC 1994; Stover and Koepke 1988) and minimizes stopped delays. Permitted left turns and right turns on red are also assumed. This phasing condition may not guarantee the optimum operation for all cases possible. However, for simplification, this study employs this phase type uniformly.
- Cycle length is 60–120 s.
  The short cycle length generally minimizes delays while the long cycle length maximizes capacity (NRC 1994; Stover and Koepke 1988). The SIDRA software gives the optimized cycle length. During the study the optimized cycle length is found to be less than 60 s. Nevertheless, the minimum cycle length was set to 60 s to allow for realistic values.
- Turning lane: the leftmost and the rightmost lane are considered as shared lanes.

For simplification, the analysis is restricted to four-leg intersections. The delay represents the average delay, including queuing delay and geometric delay. Total flow refers to the summation of all vehicle volumes from all approaches.

Delay Comparison of Single-Lane Approaches

Fig. 1 provides a comparison for four-leg intersections with one-lane approach. Signalized intersections are assumed to operate under two-phase, 60-s-cycle length signal control. Roundabouts with 18 m of central island diameter are considered. The lane width for flare varies from 3.96 to 4.96 to 5.96 m.

The results show that roundabouts and signalized intersections provide similar average delays for the entire range of total entering flow values studied. As the flare effect is maximized (5.96 m of lane width), roundabouts give slightly better level of service than signal controlled intersections.

The two-way stop and yield controlled intersections prove to be better intersection alternatives than roundabouts under light traffic, regardless of the volume ratio between major and minor streets. On the other hand, the four-way stop is clearly the worst alternative for the design conditions.

In summary, with respect to four-leg intersections with one-lane approach, roundabouts do not show considerable advantage over signal control intersections in terms of delay. Either of the two intersection alternatives could replace the other without any burden on existing traffic.

Delay Comparison of Two-Lane Approaches

Fig. 2 compares delays among four-leg intersection types with two-lane approaches. With respect to signalized intersections, one lane is assumed to be a shared through and left turn lane and the other a shared through and right turn lane. The central island diameter for roundabouts is 18 m. The conditions of the two-way stop, four-way stop, and yield controlled intersections are assumed similar to those used in the study of intersections with one-lane approaches.

As shown in Fig. 2, two-way stop and yield controlled intersections are still good intersection alternatives under light traffic conditions. However, under heavy traffic condition (total flows higher than 2,800 vehicles/h) roundabouts ensure

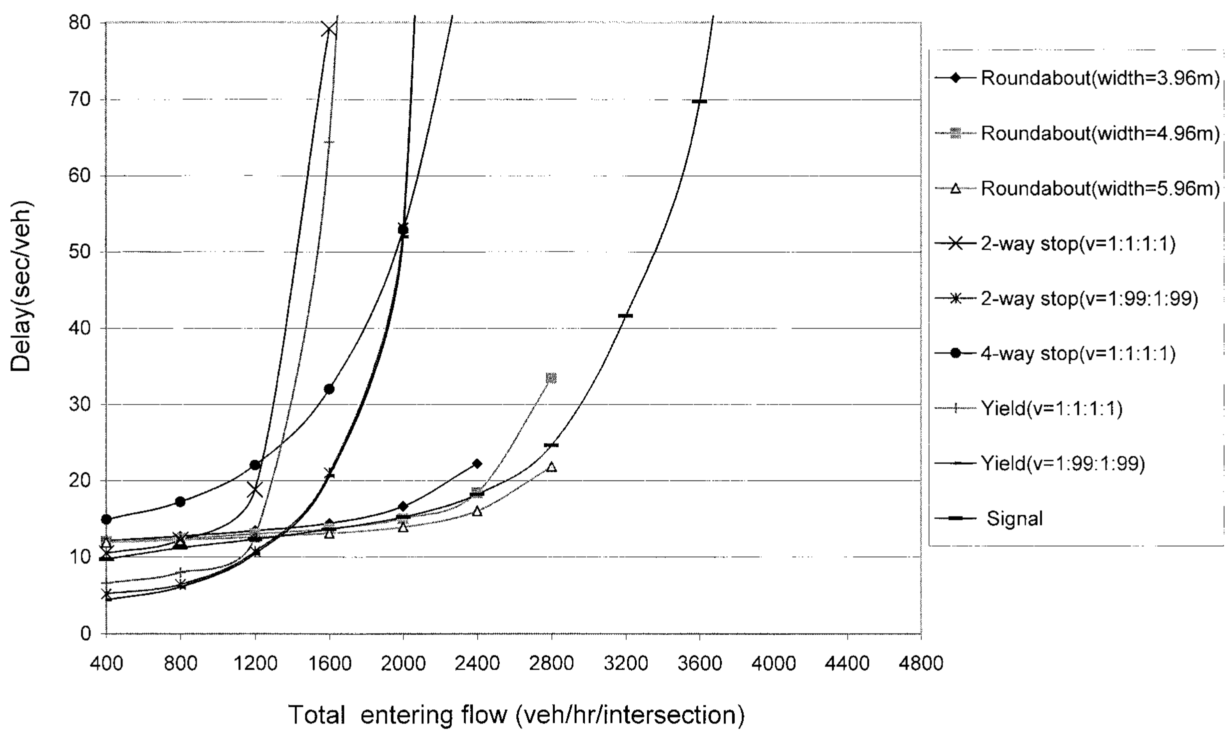

FIG. 1. Comparison of Delays under Various Intersection Types (1-Lane Approaches, 4 Leg, LT = 10%)

higher level of service than any other alternatives, including signal control. Comparing Figs. 1 and 2, the number of lanes prove to be associated with the performance. Additionally, the comparison of roundabout delays for different lane widths at higher flow levels in Fig. 2 shows that lane widths have an effect on delay. Larger flare results in lower delays for similar flow levels.

Delay Comparison of Three-Lane Approaches

Fig. 3 provides results from a comparison of four-leg intersections with three-lane approaches. For practical reasons, two-way stop, four-way stop, and yield controls are not desirable alternatives, and, thus, the experiment is limited to the comparison between signalized intersections and roundabouts.

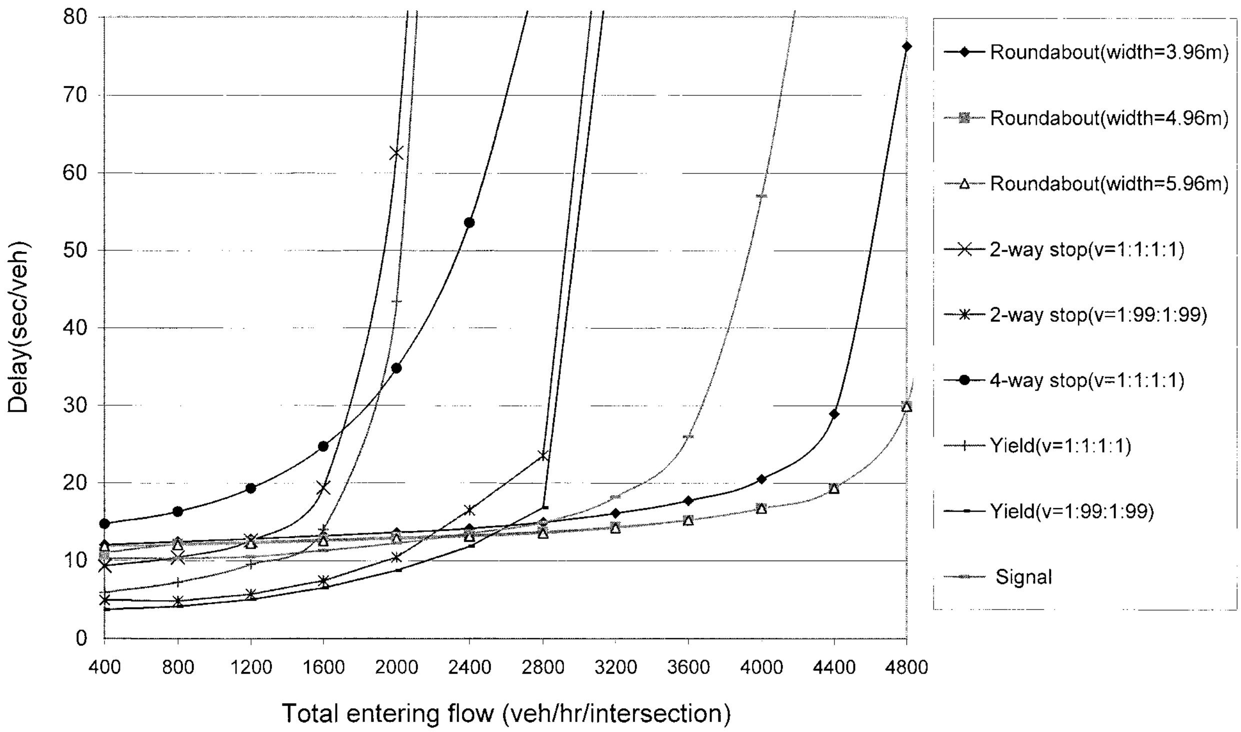

FIG. 2. Comparison of Delays under Various Intersection Types (2-Lane Approaches, 4 Leg, LT = 10%)

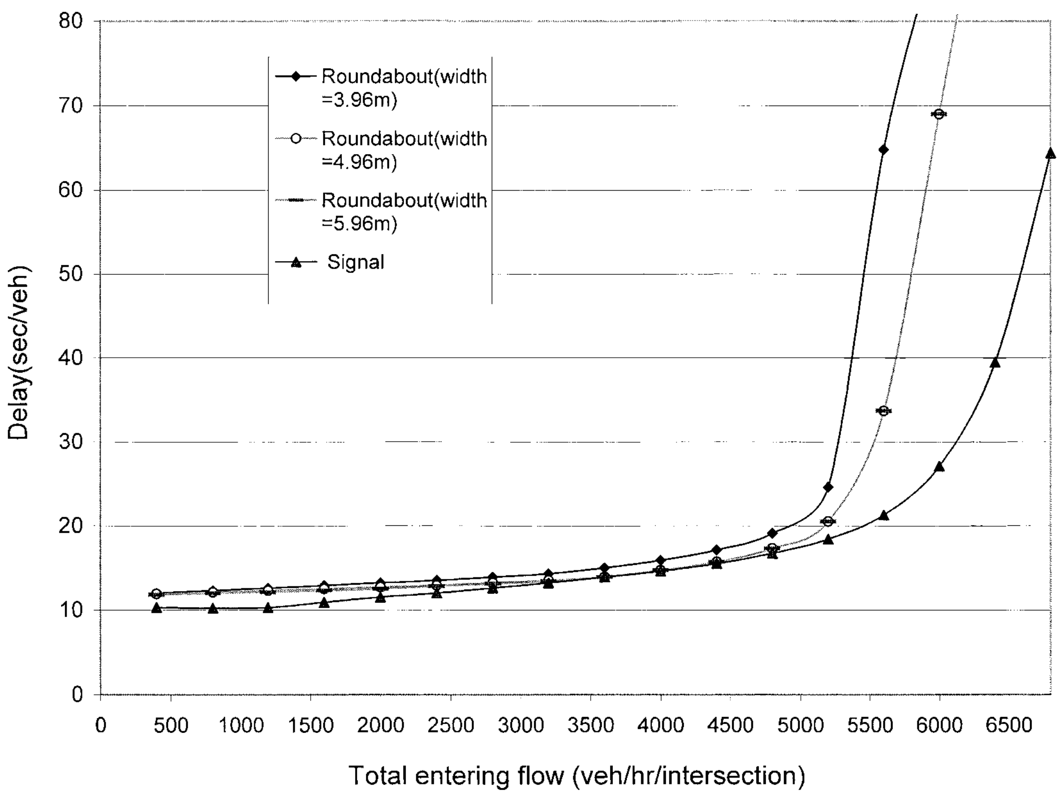

FIG. 3. Comparison of Delays under Various Intersection Types (3-Lane Approaches, 4 Leg, LT = 10%)

In the case of signalized intersections, the left lane is allocated to left-turning vehicles, the middle lane carries through traffic, and the rightmost lane is assumed to be shared by through-moving and right-turning vehicles. The central island diameter for roundabouts is assumed to be 24 m. This value is regarded as the minimum to reflect the deflection effect on roundabouts with three-lane approaches.

In this case, the signal-controlled intersection performs better than the roundabout, in terms of delay savings, especially for total flows in excess of 5,000 vehicles/h. Thus, for heavy traffic demand conditions, three lane roundabouts are not warranted based on delay.

Evaluation of Impact of Left-Turn Volume Percentage

The *Florida Roundabout Guide* (FDOT 1995) and the *Roundabout Design Guidelines* (MDOT 1995) indicated that roundabouts would be beneficial under heavy left-turn volume. This recommendation appears intuitively correct. However, vehicles entering at roundabouts use gaps between circulating vehicles. During circulation, the left-turning vehicles may stay longer on roundabouts than through-moving vehicles, lowering the capacity of the circulating lane. This means that the performance of roundabouts could be more susceptible to the left-turn percentage than that of other intersection types.

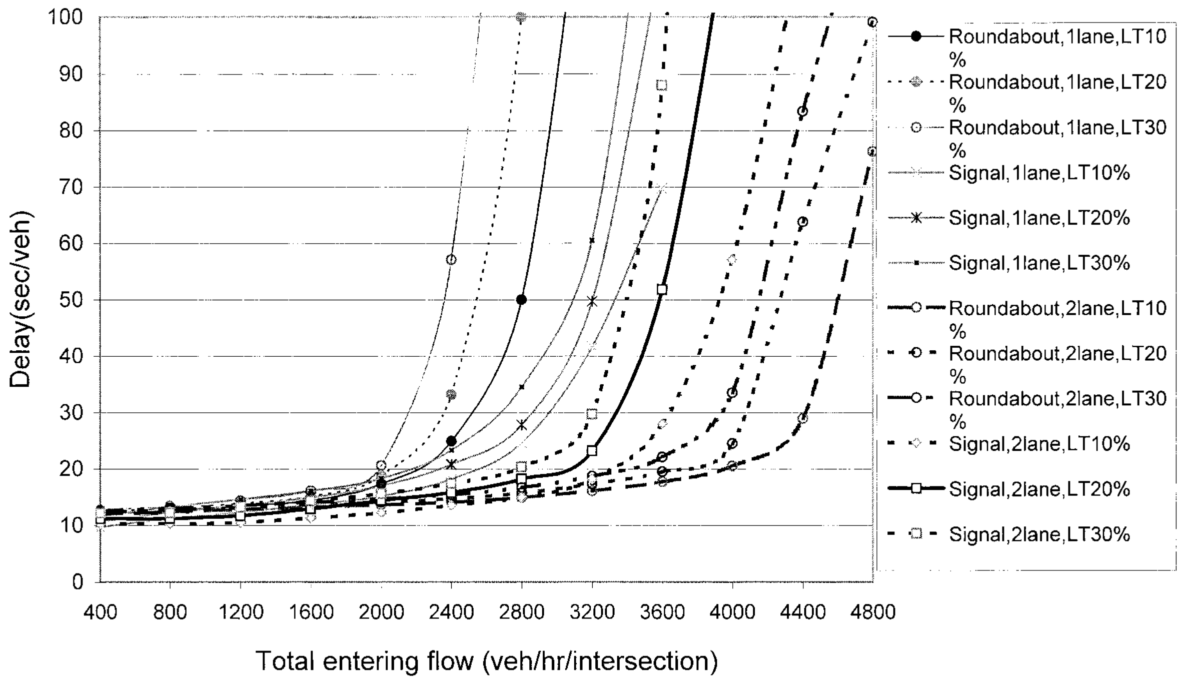

FIG. 4. Effect of Left-Turn Percentage on Delay for Roundabouts and Signalized Intersections

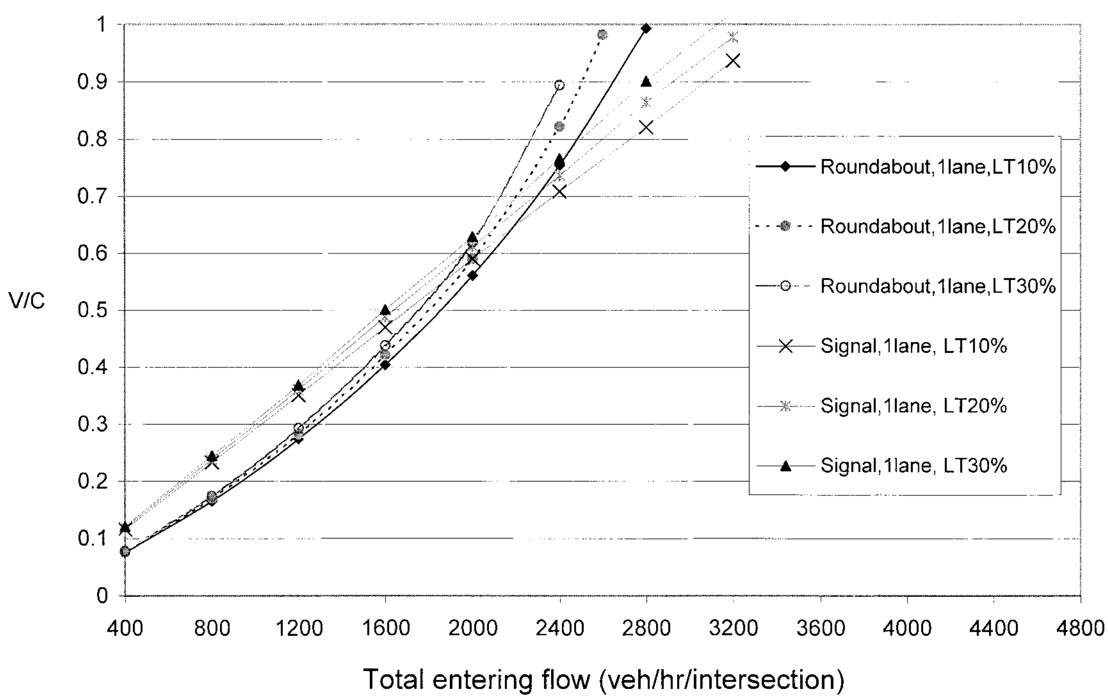

FIG. 5. Comparison of V/C for Roundabouts and Signalized Intersections (1-Lane Approaches, 4 Leg)

Variance of delays occurring under different left-turn percentages considered as a measure of effectiveness for evaluating heavy left-turn-induced delay. On the condition that each leg has a single approaching lane and identical volumes, roundabouts are slightly more affected by the left-turn-percentage variations. On the other hand, signalized intersections seem more affected by the left-turn-percentage variations for intersections with two-lane approaches. These results are demonstrated in Fig. 4.

Considering the performance in terms of delay and sensitivity to the left-turn volumes, roundabouts with two-lane approaches prove to work better than any other alternative for heavy left-turn volume. On the other hand, signalized intersections with one-lane approaches and heavy left-turn volume demonstrate lower total delay values than their roundabout counterparts.

Comparison Based on Capacity and Delay

For signalized intersections, the U.S. HCM recommends analyzing capacity and delay simultaneously to evaluate the overall operation of signalized intersection because these two concepts are not correlated as they are for other facility types (NRC 1994). Therefore, the performance of intersection alter-

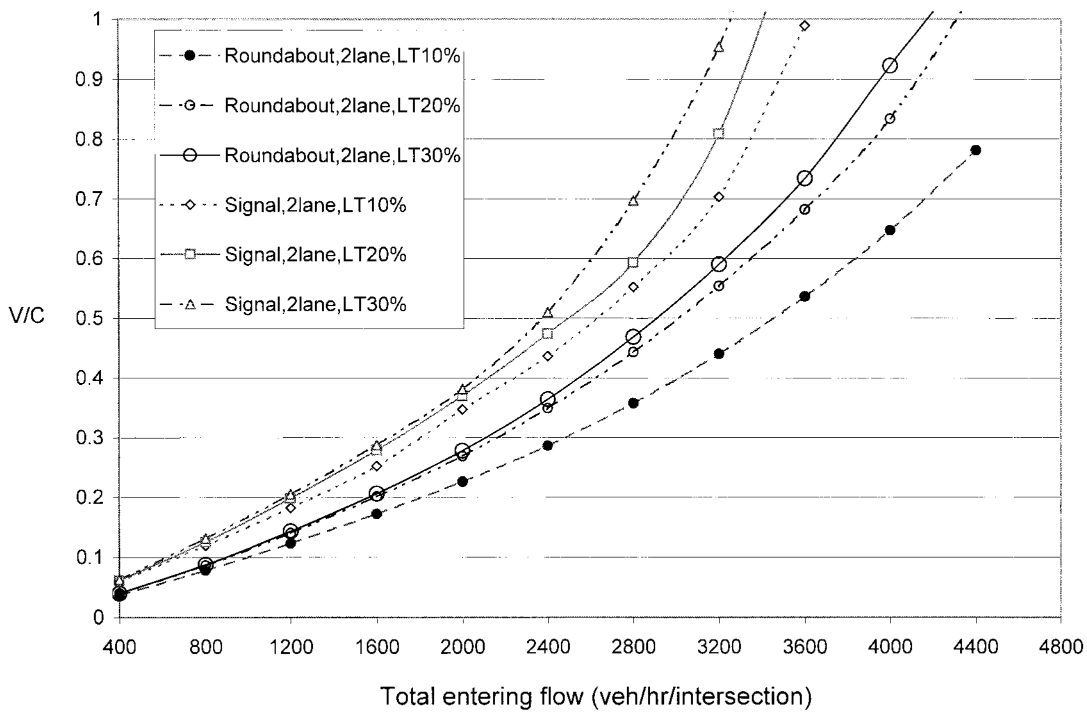

FIG. 6. Comparison of V/C for Roundabouts and Signalized Intersections (2-Lane Approaches, 4 Leg)

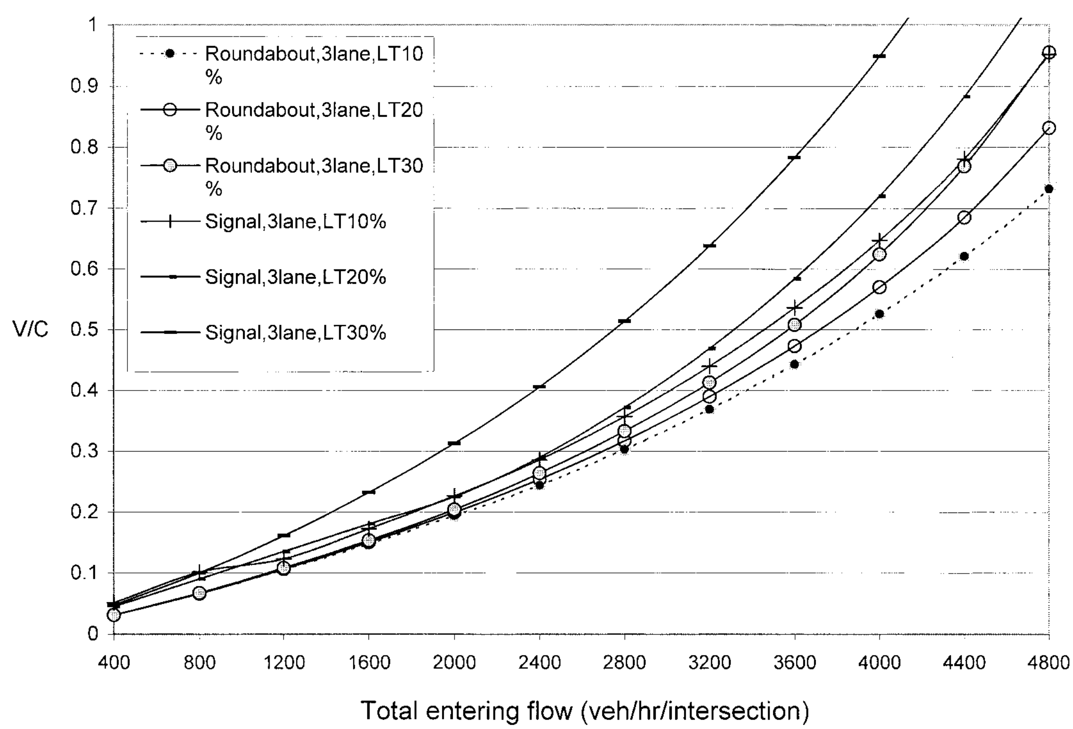

FIG. 7. Comparison of V/C for Roundabouts and Signalized Intersections (3-Lane Approaches, 4 Leg)

TABLE 1. Comparison of Performance of Intersection Alternatives with Respect to Delay and V/C

Intersection type (1)	Number of lanes (2)	Demand Level (Delay-Based Comparison) Low (3)	Demand Level (Delay-Based Comparison) High (4)	LT Percentage (Delay-Based Comparison) Low (10%) (5)	LT Percentage (Delay-Based Comparison) High (30%) (6)	Intersection V/C Low (7)	Intersection V/C High (8)
Roundabout	1	Average	Average	Average	Average	Average	Average
Roundabout	2	Average	Superior	Superior	Superior	Superior	Superior
Roundabout	3	Average	Average	—	—	Superior	Superior
Signal	1	Average	Average	Superior	Superior	Average	Average
Signal	2	Average	Average	Average	Average	Average	Average
Signal	3	Average	Superior	—	—	Average	Average
4-way stop	1	Inferior	Inferior	—	—	—	—
4-way stop	2	Inferior	Inferior	—	—	—	—
2-way stop and yield	1	Superior	Inferior	—	—	—	—
2-way stop and yield	2	Superior	Inferior	—	—	—	—

Note: — = not available or not applicable.

natives is also assessed based on capacity consideration through comparisons of V/C ratios.

Fig. 5 shows that there is no considerable difference in V/C ratios between roundabouts and signalized intersections when one-lane approaches are considered. On the other hand, Figs. 6 and 7 clearly show that roundabouts with two- or three-lane approaches outperform the signal-controlled intersections with identical number of approach lanes. Thus, roundabouts with two- or three-lane approaches are warranted based on capacity, regardless of the level of the total entering flow.

CONCLUSIONS

The performance of roundabouts was evaluated in terms of delay and capacity in comparison to the performance of intersections with various types of control. Table 1 provides the results from performance comparison. In summary, the following conclusions can be drawn from this study.

1. On the basis of average delay, the analysis confirmed that two-way stop and yield sign control can be effective design options when serving light traffic demand.
2. The four-way stop control results in greater delays under either light or heavy traffic demand compared to roundabout and signalized intersection designs.
3. For intersections with one-lane approaches and heavy traffic volumes, both roundabouts and signal-controlled intersections are viable alternatives when maximizing flare effect.
4. For intersections with two-lane approaches and heavy traffic volumes, roundabouts show a better performance over any other intersection type.
5. Intersections with three-lane approaches are best served by signal control, especially under heavy traffic volumes. Roundabouts are no longer good alternatives under such conditions.
6. For heavy left-turn demand, the roundabout with two-lane approaches shows superior performance in terms of capacity and delay.
7. Roundabouts with two- or three-lane approaches provide increased capacities compared to signal controlled intersections.

In summary, throughout the experiments performed in the analysis, roundabouts are rated as the most competitive alternative for heavy traffic intersections with two-lane approaches in terms of capacity and delay. For intersections with one-lane approaches, the performance of roundabouts is similar to that of signalized intersections as the flare effect is maximized. Although roundabouts with three-lane approaches provide higher capacities than three-lane signalized intersections, they show inferior performance in terms of delay.

LIMITATIONS AND RECOMMENDATIONS

The findings from this study are based on a variety of conditions, which are clearly stated in the previous paragraphs. For conditions other than specified, additional testing is recommended.

The basis for the study was the number of lanes by approaches (including left-turn and/or right-turn lanes). Alternatively, the number of lanes at the midblock can be considered. Moreover, at signalized intersections, consideration of exclusive left-turn lanes and protected phasing may provide more-realistic design conditions under high flows.

In the subject research, two-phase signal control with permitted left turn and right turn on red was used. The two-phase signal control minimizes average delay in that it maximizes capacity (NRC 1994) and minimizes stopped delays. The assumed condition for signal controls may not be the absolutely optimal, although the condition is the best for the phase during the study. This is because for different ratio of volume over saturation flow, different signal control settings may be optimal.

This study is based on SIDRA software. One should keep in mind that SIDRA is a very appropriate tool to use for the type of analysis performed in this research. However, being a simulation model, SIDRA has some limitations and internal assumptions. It is recommended that further testing be performed with the use of field data. Also, consideration of the 2000 version of HCS as an alternative simulation software is recommended in future studies.

The results from the present study can be also compared with those of other similar studies. It should be noted, however, that each study explores unique conditions. This makes the equivalent delay comparison between studies difficult. Aside from the size of roundabouts and traffic flow rates, inclusion of geometric delay can be a main factor affecting the comparisons. The geometric delay value can be significant for vehicles that negotiate speeds for relatively long turning paths. Based on the SIDRA 5 Manual (Akçelik and Besley 1996), the geometric delay for a negotiation radius of 15 m is calculated as 10.8 s.

Due to the difference in delay definitions between this and other studies direct delay comparisons are not advisable. For example, the *Florida Roundabout Guide* shows that the lower bound of the delay range is near to zero, when there is no traffic (FDOT 1995). The figures in the present paper show this value to be around 10 s due to the existence of geometric delay. In their study, Flannery et al. (1997) showed that the roundabout delay ranged from 0.97 to 9.04 s. However, it was clearly stated that these values represent the ideal delay, which excludes the geometric delay. Therefore, consideration of geometric delay should be taken into account when comparing delays at roundabouts among various studies. Given such consideration, the present delay values in this paper are in accordance with field and calculated results reported by other researchers.

Finally, this study does not consider the safety and operation effect of roundabouts. Although this intersection alternative is becoming popular in its use, the safety issue, especially related to pedestrians and stopped vehicles, is still unresolved. Additionally, the operational effect of high vehicular volume from one direction only and that of small central island are unclear and leave room for a detailed study in the future.

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