# Analysis of Single-Lane Roundabout Slip Lanes Using SIDRA

Majed Al-Ghandour P.E.[1]; William Rasdorf Ph.D., P.E.[2]; Billy Williams Ph.D., P.E.[3]; and Bastian Schroeder Ph.D.[4]

[1]Assistant Branch Manager, Program Development Branch, North Carolina Department of Transportation, Raleigh, NC 27699-1534, PH (919) 395-8859; Fax: (919) 733-3585; email: malghandour@ncdot.gov
[2]Professor, Department of Civil, Construction, and Environmental Engineering, North Carolina State University, Raleigh, NC 27606-7908, PH (919) 515-7637 Fax: (919) 515-7908; email: rasdorf@.ncsu.edu
[3]Associate Professor, Department of Civil, Construction, and Environmental Engineering, North Carolina State University, Raleigh, NC 27606-7908, PH (919) 515-7813 Fax: (919) 515-7908; email: billy_williams@ncsu.edu
[4]Senior Research Associate, Institute for Transportation Research & Education, North Carolina State University, Centennial Campus Box 8601, Raleigh, NC 27695-8601, PH (919) 515-8565 Fax: (919) 515-8898; email: bastian_schroeder@ncsu.edu

## ABSTRACT

Roundabout intersections, increasingly used in the U.S., sometimes incorporate slip lanes to facilitate right-turning traffic flow and reduce delay, thereby increasing capacity and safety. Performance of a single-lane roundabout with an adjacent slip lane is modeled with the SIDRA Intersection analysis tool for three types of slip lane: free-flow, yield, and stop, and is compared to having no slip lane. The gap acceptance-based assessment considers four experimental traffic percentage distribution matrices representing flow scenarios. SIDRA results confirm that average delay and circulating conflict volumes in a roundabout with a slip lane are related exponentially to slip lane volumes. A free-flow slip lane exit type helps to reduce total average delay in the roundabout and the slip lane approach. Both yield and stop slip lane exit types also reduce roundabout total average delay but to a lesser degree than a free-flow slip lane. Finally, theoretical capacity threshold values for slip lane volumes are estimated to range from 150 to 350 vehicles per hour for traffic volume distribution scenarios.

**Author keywords**: Roundabout**,** slip lane, gap acceptance, SIDRA, traffic delay, exit type, experimental traffic percentage distribution matrices.

## INTRODUCTION

As modern roundabouts gain popularity in the U.S., consideration of the safety and performance effects of slip lanes also gains importance. A slip lane, a separate lane that facilitates right-turning traffic flow, reduces approach delay by allowing right-turning movements to bypass the roundabout, thereby reducing vehicle conflicts. Though roundabouts are an increasingly common form of intersection control in the U.S., research has yet to quantify slip lane contributions to operational and safety improvements when slip lanes are installed.

NCHRP Report 572 (NCHRP 2007) defines the types of slip lane: a non-yield slip lane, merging with the roundabout exit leg and forming a new acceleration (free-flow) lane adjacent to exiting traffic; and a yield slip lane, terminating at a sharp angle with the roundabout exit approach so that right-turning traffic is yielding.

Operational performance of roundabouts, measured as roundabout capacity, typically is based on one of three capacity methods: gap acceptance; empirical regression; or a hybrid of gap and empirical methods. TRB (2000) and NCHRP Report 572 (NCHRP 2007) provided roundabout capacity models as a function of the circulating flow in the roundabout, follow-up headway, and critical gap. They estimated the capacity of a roundabout's approach (entry lanes) via input parameters such as circulating conflicting traffic volume, follow-up time, and critical gap. U.K. and German linear (empirical) regression methods used roundabout geometry parameters without consideration of driver behaviors (NCHRP 2007). In Australia, Akcelik (2007) derived the gap acceptance capacity model as an exponential relationship between capacity and opposing flow rate in a roundabout.

Neither capacity nor safety evaluations were found in the literature for roundabouts where slip lanes were installed. Nothing was found specifically focused on roundabout slip lanes.

SIDRA software (Signalized and Unsignalized Design and Research Aid, SIDRA 2007) is commonly used to analyze traffic operations at roundabouts. Akcelik and Besley (2004) also observed that both the AUSTROADS Roundabout Guide and the SIDRA software use gap acceptance techniques for roundabout capacity and performance analysis based on empirical models to estimate gap-acceptance parameters.

SIDRA was used in this study to explore experimental traffic flows in a single-lane roundabout with a slip lane. The work reported in this paper used SIDRA to test two hypotheses:

1. All slip lane types should reduce average delay in a single-lane roundabout, thereby improving its operational performance (its capacity as indicated by average delay), compared to a base single-lane roundabout without a slip lane. A free-flow slip lane exit type is expected to reduce delay more than a yield exit type and a yield exit type more than a stop exit type.

2. Slip lane theoretical threshold capacity volumes increase with increased roundabout right-turn traffic volumes. A threshold value is the limit in volumes where the roundabout operates with a capacity as transition to level of service F (traffic congestion is the result of more traffic flow demand than capacity).

## METHODOLOGY

Gap acceptance theory is used to determine the capacity of each approach and of the entire roundabout (including slip lanes). SIDRA software quantifies parameter values for available operations and geometric data (SIDRA 2007). SIDRA automatically sets gap acceptance parameters for the roundabout and slip lane as a function of geometry, circulating flow rate, entry flow rate, and other factors; it limits other parameters such as critical gap headway ($t_c$) to range from 2 to 8 seconds, and follow-up headway ($t_f$) to range from 1 to 5 seconds. Inputs to SIDRA include vehicle volumes and movement paths, yield and stop slip lane exit configurations, gap acceptance and follow-up headway attributes for selected movements, and roundabout geometry attributes (inscribed diameter, number of entry lanes, and average entry lane width). Average roundabout delay, the average vehicle delay in seconds for all vehicles entering the roundabout, is the Measure of Effectiveness (MOE).

In this study, for a single-lane roundabout with a slip lane, four experimental traffic percentage turning volume distributions (scenarios) were assumed for balanced scenarios (traffic flow into and out of every roundabout approach is the same). The scenarios (S1, S2, S3, and S4) were initialized, analyzed, and then controlled through several iterations. A slip lane was assumed to be placed at the northbound (NB) entry to the roundabout as shown in Figure 1.

Several variables were tested across the four traffic percentage distribution scenarios as follows:

1. Slip lane exit type (free flow lane, yield sign, and stop sign) compared to having no slip lane (base case).
2. Slip lane right-turning traffic volume as the dominant turn (in increments of 50 vehicles per hour and ranging from 50 vehicles per hour to 500 vehicles per hour—representing low, moderate, and high volumes).
3. Approach entry volume.
4. Traffic percentage distribution flow patterns.

A range of traffic conditions intended to imitate real-world traffic flow patterns was represented in these traffic percentage distribution scenarios. In the four flow scenarios, shown in Figure 1, roundabout entry and exit flows for each approach are the same, although the dominant right-turning traffic percentages in the slip lane are different (33%, 45%, 60%, and 75%).

Volume distributions for the roundabout were developed from the traffic percentage distribution matrices and are summarized as shown in a sample of three volumes: 50 vehicles per hour, 250 vehicles per hour, and 500 vehicles per hour (Table 1). Volumes for each roundabout approach ($V_a$) are the same as for exit approach ($V_{exit}$) volumes, based on the assumption of experimental balanced roundabout scenarios. For example, scenario S1, dominant right turn flow percent (33%), sustains more traffic volumes on both approach entry ($V_a$) and exit approaches ($V_{exit}$) and circulating flow ($V_c$), compared to S2 (45%), S3 (60%), and S4 (75%) dominant turn levels. At a slip lane (right turn) volume $V_{sl}$=500 vehicles per hour for S4, a 75% dominant level (high right-turn flow) shows a volume at each approach ($V_a$) of 667 vehicles per hour, (highlighted in yellow, Table 1), smaller values than S1 (1515 vehicles per hour), S2 (1110 vehicles per hour), and S3 (834 vehicles per hour) dominant levels. The conflicting circulating volumes ($V_c$) for S4 (467 vehicles per hour) are also smaller values than S1 (1515 vehicles per hour), S2 (1110 vehicles per hour), and S3 (709 vehicles per hour). All traffic volume distributions scenarios (S1, S2, S3, and S4) were coded into SIDRA for different scenarios to evaluate the performance of a slip lane in terms of average delay and SIDRA sensitivity.

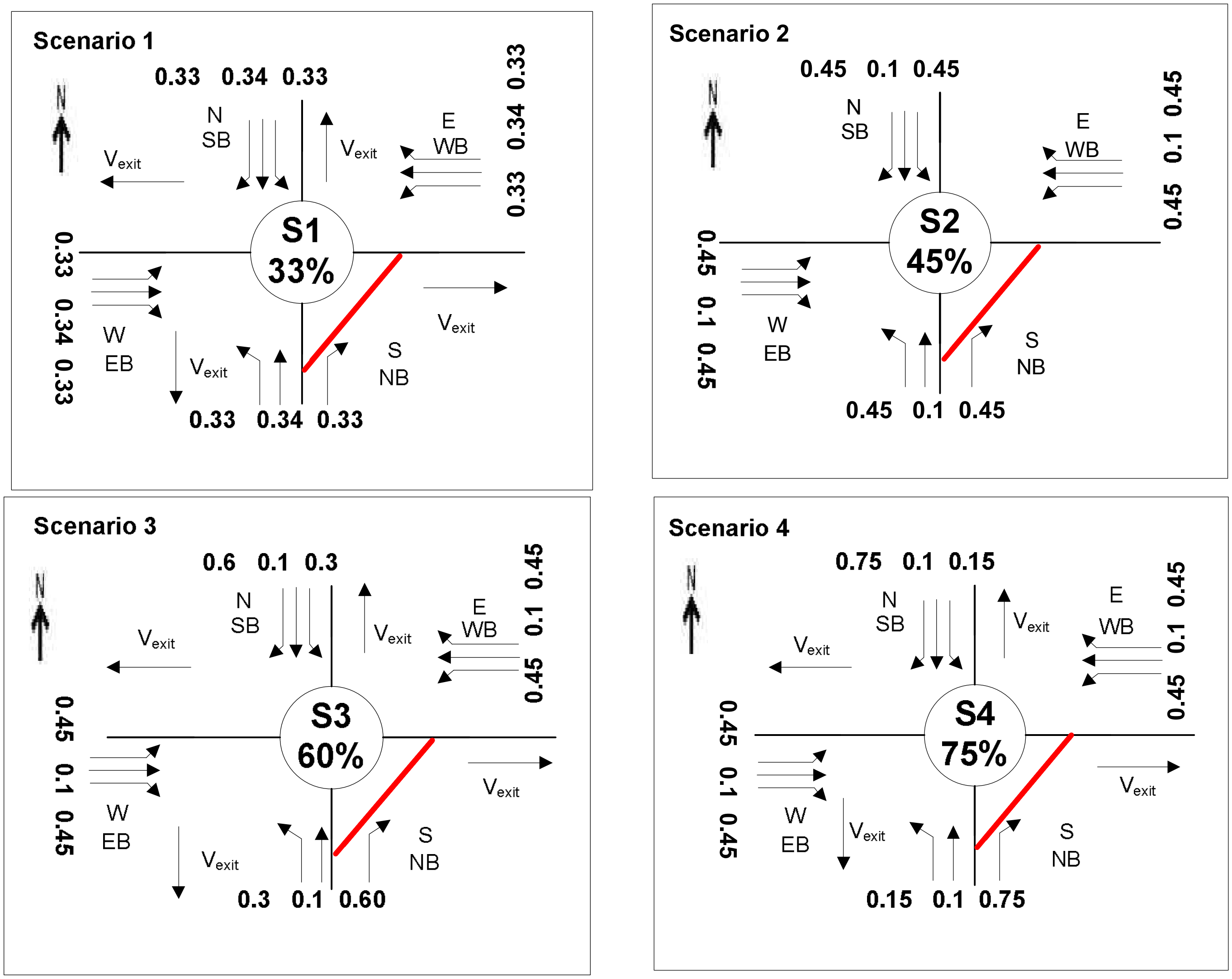


**Figure 1. Traffic Percentage Distribution Flow Pattern Scenarios (S1-S4).**

**Table 1. Total Approach and Conflicting Volumes for Scenarios S1-S4.**

| **Slip Lane Volume as Dominant Right Turn,** (vehicles per hour)**,** $V_{sl}$ | | **Scenarios** | | | |
|---|---|---|---|---|---|
| | | **S1 (33%)** | **S2 (45%)** | **S3 (60%)** | **S4 (75%)** |
| **$V_{sl}$ =50 (Low)** | **$V_a$<br>$V_c$** | **150<br>(150)** | **111<br>(111)** | **83<br>(71)** | **66<br>(46)** |
| **$V_{sl}$ =250 (Moderate)** | **$V_a$<br>$V_c$** | **757<br>(757)** | **555<br>(555)** | **416<br>(354)** | **333<br>(233)** |
| **$V_{SL}$ =500 (High)** | **$V_a$<br>$V_c$** | **1515<br>(1515)** | **1110<br>(1110)** | **834<br>(709)** | **667<br>(467)** |

$V_a$: Approach volumes per approach, vehicles per hour. $V_c$: Conflicting volumes for northbound entry (NB), vehicles per hour. $V_{sl}$: Slip lane volumes as dominant right turn, vehicles per hour.

## ANALYSIS AND RESULTS

A conflict point is any point "where a vehicle path crosses, or merges with another vehicle path" (FHWA 2000). The most likely conflict point in a single-lane roundabout is merging, based dynamically on vehicle traffic events in a specific time and space. To illustrate conflict volumes, a sample is shown in Figure 2 showing the northbound details for Scenario S1 (33%). Slip lane right turns volumes ($V_{sl}$), approach volumes ($V_a$), exit approach volumes ($V_{exit}$), entry volumes ($V_e$), conflicting circulating volumes for the roundabout at northbound ($V_c$), and conflicting volumes off slip lane ($V_m$) are assumed and calculated as follows:

$V_a$= volumes at (4) + volumes at (5) + volumes at (6) = 0.33+0.34+0.33=1.0.
$V_e$= volumes at (4) + volumes at (5) = 0.33+0.34 =0.67.
$V_c$= volumes at (1) + volumes at (2) + volumes at (3) = 0.33+0.33+0.34=1.0.
$V_{sl}$= volumes at (6) = 0.33.
$V_m$= volumes at (1) + volumes at (3) = 0.33+0.34=0.67.
$V_{exit}$= (volumes at (1) + volumes at (3)) + volumes at (6) =$V_m$ +$V_{sl}$ = 0.67+0.33=1.0.

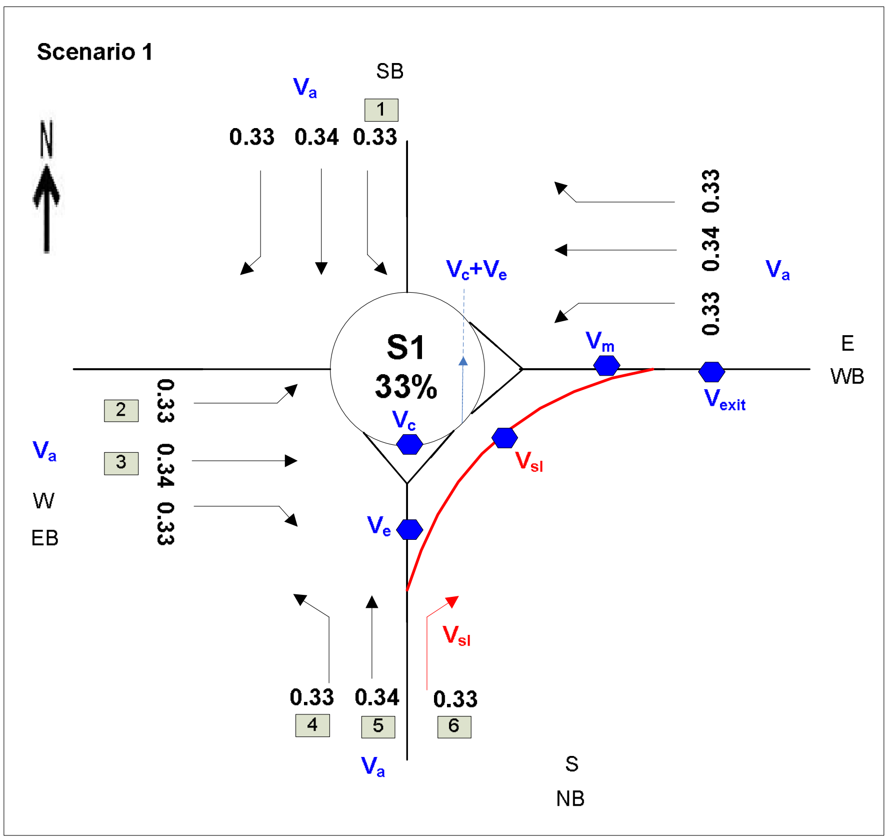


**Figure 2. Sample of Traffic Percentage Distribution Flow Pattern Scenario S1.**

$V_a$: Approach volumes per approach, vehicles per hour. $V_{exit}$: Exit volumes per approach, vehicles per hour. $V_e$: Entry volumes for the specific northbound entry (NB), vehicles per hour. $V_c$: Conflicting volumes for northbound entry (NB), vehicles per hour. Vm: Conflicting volumes off slip lane, vehicles per hour. $V_{sl}$: Slip lane volumes as dominant right turn, vehicles per hour.

As, more traffic is diverted outside the roundabout using the slip lane (right-turn movement), slip lane will have the greatest impact on reducing the roundabout conflicting circulating volumes ($V_c$) and the conflicting off slip lane approach volumes ($V_m$).

## Conflicting Volumes

Conflicting volume ($V_c$) flow pattern ratios for all scenarios are summarized (Table 2). Compared to scenarios S1-S3, S4 shows the lowest slip lane ($V_c$) ratio (0.7, highlighted in yellow). Thus, the highest right-turn slip lane volumes ($V_{sl}$) reduce the conflicting volumes ($V_m$) off slip lane (0.25). A higher dominant right-turning traffic percentage in the slip lane also causes a lower conflicting circulating volume ($V_c$) for the northbound (NB) entry approach and lower entry volumes ($V_e$) into the roundabout.

**Table 2. Conflicting Volume Ratios for Scenarios S1-S4.**

| Type of Volumes | Scenarios | | | |
|---|---|---|---|---|
| | **S1 (33%) Low Right Turn Flow** | **S2 (45%) Moderate Right Turn Flow** | **S3 (60%) Moderate Right Turn Flow** | **S4 (75%) High Right Turn Flow** |
| $V_a$ | **1.0** | **1.0** | **1.0** | **1.0** |
| $V_e$ | **0.67** | **0.55** | **0.40** | **0.25** |
| $V_c$ | **1.0** | **1.0** | **0.85** | **0.7** |
| $V_{sl}$ | **0.33** | **0.45** | **0.60** | **0.75** |
| $V_m$ | **0.67** | **0.55** | **0.40** | **0.25** |
| $V_{exit}$ | **1.0** | **1.0** | **1.0** | **1.0** |

$V_a$: Approach volumes per approach, vehicles per hour. $V_{exit}$: Exit volumes per approach, vehicles per hour. $V_e$: Entry volumes for the specific northbound entry (NB), vehicles per hour. $V_c$: Conflicting volumes for northbound entry (NB), vehicles per hour. $V_m$: Conflicting volumes off slip lane, vehicles per hour. $V_{sl}$: Slip lane volumes as dominant right turn, vehicles per hour.

## Average Roundabout Delay

The SIDRA results for the four scenarios are compared (Table 3). A free-flow slip lane exit type with high traffic volumes (500 vehicles per hour) shows significant reduction (operational improvement) in roundabout average delay, from 42.7 sec/vehicle (no slip lane) to 31.8 sec/vehicle: a 25.5% reduction in S4, as highlighted in yellow. Within a yield slip lane exit type, the reduction of roundabout average delay is 25.48%. Within a stop slip lane exit type, reduction is 24.8%. As expected, the results from SIDRA for the four scenarios show that delay is significantly reduced in a single-lane roundabout with any type of slip lane, before oversaturation occurs, with only marginal differences in delay reduction between the slip lane types (yield and stop). The northbound (NB) approach, the slip lane approach, shows significant average delay reduction—91.68%—when slip lanes are used, regardless of exit types, compared to having no slip lane at high traffic volumes (500 vehicles per hour). The northbound average delay reduction percentage is calculated as (for example, using a yield sign exit type) 91.68% = ((3.8-45.7)/45.7). The slip lane average delay within a stop slip lane exit type (32.1 sec/vehicle in S4, 500 vehicles per hour) is slightly higher than the average delay of a yield exit type(31.8 sec/vehicle). Because a free-flow right-turning slip lane exit type has no opposing exiting flow from the roundabout—and therefore a high capacity—a free-flow slip lane exit type has no delay (zero). Reduction of delay via the use of free-flow slip lanes is shown to be greater than in stop or yield sign slip lanes. Thus, a free-flow slip lane exit type provides significant reductions in total roundabout average delay and to the slip lane approach.

Samples from the SIDRA results are shown in Figures 3 and 4 for all scenarios using a yield slip lane exit type and having no slip lane as the base. Corresponding oversaturated conditions (volume/capacity>1.0) that are expected to occur as roundabout approach volumes and right-turning traffic volumes are increased are also shown. Lower right-turning volumes ($V_{sl}$) showed fast-occurring roundabout oversaturation. For example, Scenario S1 (33%), presenting the greatest delay, oversaturated at a right-turning volume of 200 vehicles per hour, S2 at 300 vehicles per hour, and S3 at 400 vehicles per hour; these oversaturation points are marked by dashed lines in Figure 3. In contrast, as expected, average delay is reduced within a roundabout with a slip lane, within a higher percentage of slip lane volumes as shown by S1 (from 715.7 sec/vehicle with no slip lane to 672.29 sec/vehicle with a yield slip lane) to S4 (from 42.68 sec/vehicle with no slip lane to 31.80 sec/vehicle with a yield slip lane).

**Table 3. Summary of SIDRA Average Delays.**

| Slip Lane Exit Type | $V_{SL}$: Slip Lane Volume, Right-Turn Volume (vehicles per hour) at NB Approach | Average Delay (sec/vehicle) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Scenarios | | | | | | | | | | | |
| | | S1 (33%) | | | S2 (45%) | | | S3 (60%) | | | S4 (75%) | | |
| | | SL | North App. (NB) | RBT | SL | North App. (NB) | RBT | SL | North App. (NB) | RBT | SL | North App. (NB) | RBT |
| **Yield** | 50 (Low) | 0.6 | 1.0 | 1.0 | 0.4 | 0.7 | 0.7 | 0.2 | 0.5 | 0.5 | 0.1 | 0.3 | 0.3 |
| | 250 (Med) | 3.1 | 26.7 | 151.1 | 2.2 | 7.1 | 22.1 | 1.2 | 2.7 | 3.9 | 0.6 | 1.6 | 1.8 |
| | 500 (High) | 6.6 | 384.1 | 672.3 | 3.8 | 83.8 | 428.1 | 2.6 | 7.9 | 141.7 | 1.6 | 3.8 | 31.8 |
| **Stop** | 50 (Low) | 0.6 | 1.0 | 1.0 | 0.4 | 0.7 | 0.7 | 0.2 | 0.5 | 0.5 | 0.1 | 0.3 | 0.3 |
| | 250 (Med) | 3.1 | 26.7 | 151.1 | 2.2 | 7.1 | 22.1 | 1.2 | 2.7 | 3.9 | 0.6 | 1.6 | 1.8 |
| | 500 (High) | 6.0 | 384.1 | 672.2 | 3.5 | 83.3 | 428.0 | 2.4 | 7.9 | 141.7 | 1.6 | 3.8 | 32.1 |
| **Free-Flow** | 50 (Low) | 0.0 | 1.0 | 1.0 | 0.0 | 0.7 | 0.7 | 0.0 | 0.5 | 0.4 | 0.0 | 0.3 | 0.2 |
| | 250 (Med) | 0.0 | 26.6 | 150.9 | 0.0 | 7.1 | 21.8 | 0.0 | 2.7 | 3.8 | 0.0 | 1.6 | 1.7 |
| | 500 (High) | 0.1 | 384.1 | 671.8 | 0.1 | 83.5 | 427.6 | 0.1 | 7.9 | 141.3 | 0.0 | 3.8 | 31.8 |
| **No Slip** | 50 (Low) | 1.1 | 1.1 | 1.1 | 0.8 | 0.8 | 0.8 | 0.5 | 0.5 | 0.5 | 0.3 | 0.3 | 0.3 |
| | 250 (Med) | 162.8 | 162.8 | 162.8 | 28.5 | 28.5 | 28.0 | 4.7 | 4.7 | 4.7 | 2.1 | 2.1 | 2.1 |
| | 500 (High) | - | 715.7 | 715.7 | 480.6 | 480.6 | 480.6 | - | 177.2 | 170.3 | - | 45.7 | 42.7 |

$V_{SL}$: Slip lane volumes as dominant right turn, vehicles per hour. RBT: roundabout. NB: Northbound approach, slip lane approach. S1 to S4: Scenarios. SL: Slip lane. Yield: Slip lane with a yield exit type. Stop: Slip lane with a stop exit type. Free-Flow: Free slip lane exit type. No Slip: No slip lane (base).

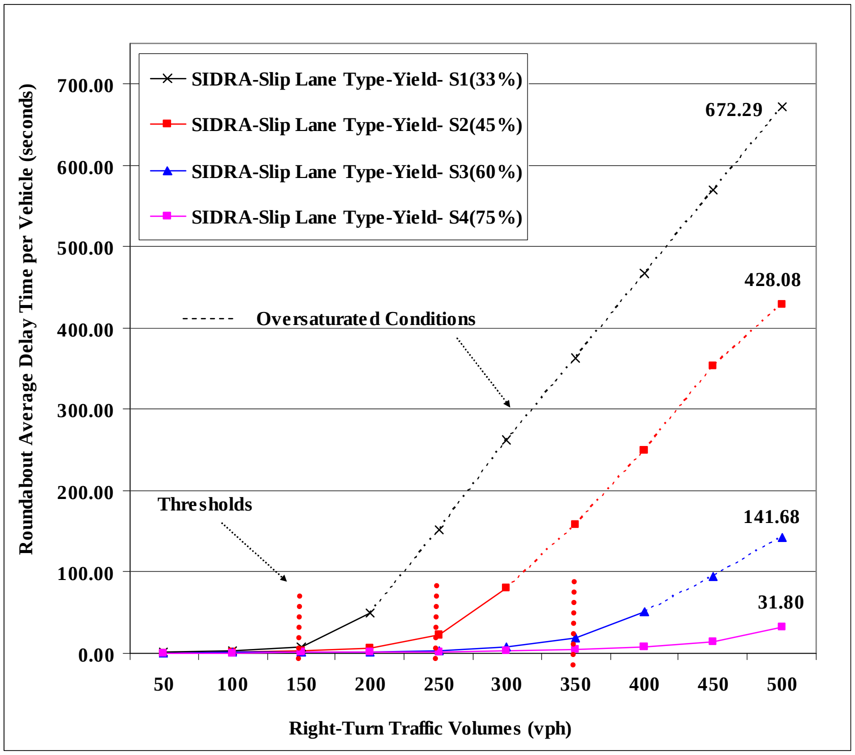


**Figure 3. SIDRA Roundabout Average Delay for Slip Lane Yield Exit Type.**

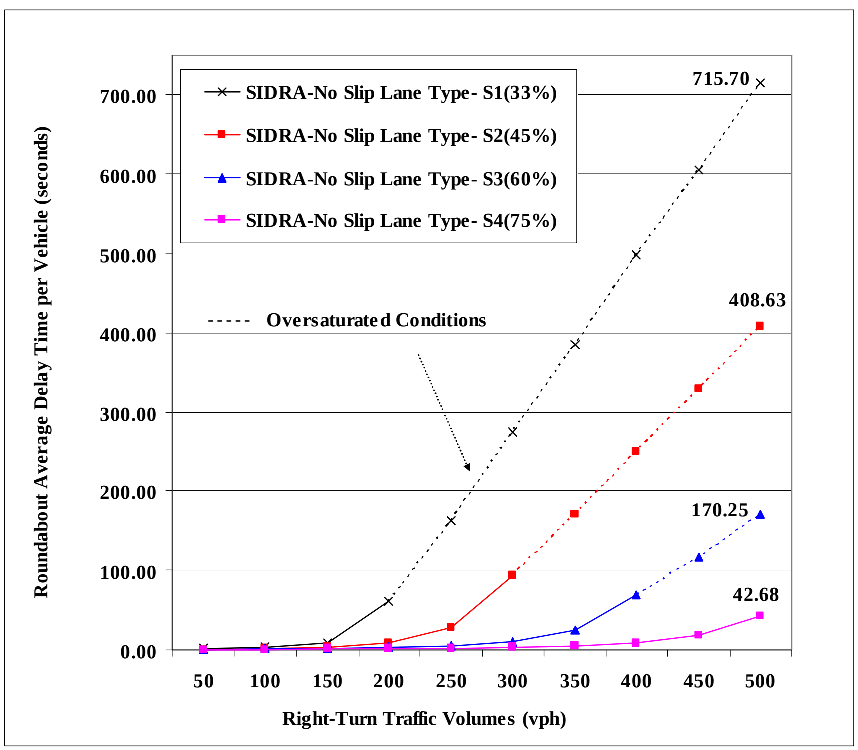


**Figure 4. SIDRA Roundabout Average Delay Having No Slip Lane (base).**

As slip lane (right-turning) traffic volume ($V_{sl}$) increases, the conflicting circulating volumes ($V_c$), decrease and the average delay also decreases, in a non-linear, or exponential, relationship. The highest roundabout average delay, observed in S1, was a result of the combined highest approach volumes ($V_a$), highest total roundabout volumes, and highest conflicting circulating flow ($V_c$). The lowest roundabout average delay, observed in S4, was a result of the combined lowest approach volumes ($V_a$), lowest total roundabout volumes, and lowest conflicting circulating flow ($V_c$). Therefore, under different scenarios, slip lane performance is most effective under a higher right-turning traffic pattern distribution. Slight changes between entry lane flow ($V_e$) and circulating flow ($V_c$) cause less impact on the total average delay within a roundabout with a slip lane

### Threshold Capacity Values

Slip lane theoretical threshold volumes were determined when the roundabout operates with a volume/capacity ratio greater than 1.00 as transition to Level of Service F (traffic congestion is the result of more traffic flow demand than capacity). The threshold capacity volumes are based on SIDRA average delay results (Figure 3: threshold limits are shown by vertical dotted lines). At oversaturated conditions, all delay values greater than 50 seconds also are shown by dashed lines, representing the proposed LOS F threshold for U.S. roundabouts (NCHRP 2007). As roundabout approach volumes ($V_a$) and right-turning volume ($V_{sl}$) increase, threshold capacity occurs at higher volumes: whereas S1 shows a threshold of around 150 vehicles per hour to be oversaturated, the S2 threshold occurs at 250 vehicles per hour, and the S3 threshold occurs at 350 vehicles per hour, for a slip lane yield exit type. An interesting point is that for all slip lane types in these scenarios, threshold values are the same per same scenario. SIDRA analysis shows therefore that the single-lane roundabout operates with a volume/capacity ratio greater than 1.00 regardless of slip lane type. Hence, the slip lane theoretical capacity operational thresholds volumes increase with greater right-turn volumes ($V_{sl}$).

## CONCLUSIONS

SIDRA results confirm that average delay and circulating conflict volumes in a roundabout with a slip lane are related exponentially to slip lane volumes. Higher right-turn traffic volumes (percentages) in the slip lane reduce roundabout conflicting circulating volume ($V_c$) and conflicting volumes off slip lane ($V_m$). Results also showed overall roundabout delay was reduced 25.51% with use of a free-flow slip lane; 25.48% with use of a yield slip lane; and 24.80% with use of a stop slip lane. Hence the most effective roundabout delay performance generally is obtained from a free-flow slip lane.

Average delay is more effectively reduced within a roundabout with a slip lane than in one without. The most striking example from this study is a 91.68% delay in reduction from use of a slip lane in the northbound (NB) slip lane approach (scenario S4 at 500 vehicles per hour) regardless of the slip lane exit types.

When roundabout traffic becomes oversaturated, any reduction of delay obtained is similar for both yield or stop slip lane exit types. Theoretical capacity thresholds values (limits) for right-turning slip lane volumes ($V_{sl}$) are estimated to be within a range of 150 to 350 vehicles per hour for traffic distribution volumes.

## RECOMMENDATIONS

SIDRA can be used to analyze a slip lane's contribution to improved roundabout capacity and safety before traffic flow becomes oversaturated. Determining theoretical threshold value ranges can be helpful to practitioners who are considering the use of a slip lane in a roundabout design. Fully testing multiple traffic volume distribution matrices with other percentages of dominant right-turning traffic provides insight to different roundabout pattern flows. Therefore, understanding the effect of traffic demand and distribution patterns of traffic on roundabout delay will help in assessing a slip lane's impact on improving operational performance. Additional analysis should be conducted for other variables: different unbalanced flow scenarios (traffic flow into and out of different roundabout approach is different); number of lanes within a slip lane (one or two); slip lane widths (10 ft or 12 ft) and lengths; distance of slip lane exit/merge from the roundabout; number of pedestrian crosswalks (one or two); and other geometric configurations. To validate SIDRA sensitivity, future analysis should vary its default values for gap acceptance parameters (critical gap and follow-up headway per lane) and compare results to field data.

## REFERENCES

Akcelik, R. (2007). "A review of gap-acceptance capacity models." Paper presented at the 29th Conference of Australian Institutes of Transport Research (CAITR 2007), Adelaide, December 2007.

Akcelik, R. A., and Besley, M. (2004). "Differences between the AUSTROADS roundabout guide and aaSIDRA roundabout analysis methods." Presented at 26th Conference of Australian Institutes of Transport Research (CAITR 2004), Clayton, Melbourne, 8-10 December 2004.

Federal Highway Administration (FHWA) (2000). "Roundabouts: An Informational Guide." Publication No. FHWA-RD-00-067, Washington, D.C.

National Cooperative Highway Research Program (NCHRP) (2007). "Roundabouts in the United State." National Research Council, Transportation Research Board, National Cooperative Highway Research Program; NCHRP Report 572, Washington, D.C.

SIDRA (2007). SIDRA User's Manual. P.O. Box 1075G, Greythorn, Vic 3104, Australia.

Transportation Research Board (TRB) (2000). *Highway Capacity Manual.* 4$^{th}$ edition. National Research Council, Transportation Research Board, Washington, D.C.