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Roundabout Performance Analysis When Introducing Slip Lanes

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ABSTRACT

A slip lane, an optional separate (exclusive) right-turn lane that lies adjacent to a roundabout, allows right-turning movements to bypass the roundabout itself. A slip lane is not a dedicated right turn lane within a roundabout approach. Slip lanes facilitate right-turning traffic flow, reduce approach delay, and reduce conflict points within a roundabout. In this paper, interest focuses on a single-lane roundabout with and without single-slip-lane options. Performance of a single-lane roundabout with an adjacent slip lane is modeled with the VISSIM microsimulation tool for three slip lane exit types experimental scenarios (free-flow, yield, and stop) and is compared to a roundabout having no slip lane. VISSIM results confirm that average delay in a roundabout with a slip lane is an exponential function of slip lane volumes and is sensitive to slip lane exit type. Results indicate that a free-flow slip lane exit type best helps to reduce total average delay in the roundabout and the slip lane itself. Yield and stop slip lane exit types also reduce roundabout total average delay but to a lesser degree. Finally, having more than one slip lane, at different roundabout approaches, also helps to reduce total roundabout average delay with improvement factors (ratio).

Key words: Roundabout, slip lane, roundabout average delay, roundabout exit type, VISSIM.

INTRODUCTION

Roundabouts can be used as an alternate intersection design to facilitate major traffic turning movements and to enhance operational and safety performance (*1*). 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. NCHRP Report 672 (*1*) defines two types of slip lane: a non-yield or free-flow slip lane (which merges with the roundabout exit leg to form a new acceleration lane adjacent to exiting traffic) and a yield slip lane (which terminates at a sharp an angle with the roundabout exit approach so that traffic exiting the slip lane yields as it joins traffic already in the roundabout exit lane).

Operational performance of roundabouts, expressed as roundabout capacity, typically is measured by one of three capacity methods: gap acceptance; empirical regression; or a hybrid of gap and empirical methods. FHWA (*2*) and NCHRP Report 572 (*3*) described 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 approaches (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 (*3*).

Bared and Edara (*4*) used VISSIM, a microsimulation modeling tool from Germany (*5*), to model roundabouts for various ranges of circulating and entry traffic volumes. Comparing the VISSIM results with the SIDRA analytical model and RODEL empirical model, they found that simulation results from VISSIM (of roundabout capacity in vehicles per hour) were significantly lower than from SIDRA and RODEL models. They also verified that VISSIM capacity results were similar to field measured data (traffic volumes and geometry, speed, and video data) that were collected for NCHRP 572 (*3*) in the U.S. Bared and Afshar (*6*) used VISSIM to predict new planning capacity models by lane for two- and three-lane roundabouts. They introduced capacity models as a function of separate circulatory-lane traffic volume. Trueblood and Dale (*7*) described key VISSIM features for effective simulation of roundabouts, including link and connector, routing decisions, reduced speed zone, and priority rules. In summary, slip lane research results prove to be elusive in the literature.

METHODOLOGY

In this experimental study, using VISSIM, vehicles are modeled using a theory of distribution based on parameters such as driver aggressiveness (used default values, (*5*)), vehicle speeds (used 25 miles per hour), and vehicle types (classified as cars). Inputs to VISSIM include nodes, links and connectors represent the network and center lines, and intersection traffic turning movement volumes. Average roundabout delay, the average vehicle delay in seconds for all vehicles entering the roundabout, is the Measure of Effectiveness (MOE) of the roundabout.

In this study, slip lane-based experimental simulation theory was used to determine the capacity of each approach and of the entire roundabout (including slip lanes). Five experimental scenarios with equal traffic percentage turning volume distributions were assumed for balanced scenarios (traffic flow into and out of each roundabout approach is the same). For each simulation scenario, 20 VISSIM runs were executed using different random number seeds. The scenarios (S1 to S5) were initialized, analyzed, and then controlled through several iterations. Figure 1 shows no slip lane in S1. A slip lane was assumed to be placed at the northbound (NB) entry to the roundabout in S2 (one slip lane), adding additional slip lane at the southbound (SB) entry to the roundabout in S3 (two slip lanes), adding additional slip lane at the westbound (WB) entry to the roundabout in S4 (three slip lanes), and finally adding additional slip lane at the eastbound (EB) entry to the roundabout in S5 (four slip lanes), Figure 1.

Several variables were tested across the traffic percentage distribution scenarios: 1) slip lane exit type (free-flow lane (no merging at the downstream of the 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 (from 50 vehicles per hour to 500 vehicles per hour, in increments of 50—representing low, moderate, and high volumes), and 3) traffic percentage distribution flow patterns. A sample of traffic distribution is also shown in Figure 1, where roundabout entry and exit flows for each approach are the same (dominant right-turning traffic: 33%).

Volume distributions for the roundabout were developed from the traffic percentage distribution matrices of Figure 1. All traffic volume distributions for S1 to S5 were coded into VISSIM to evaluate the performance of slip lanes in terms of average roundabout delay.

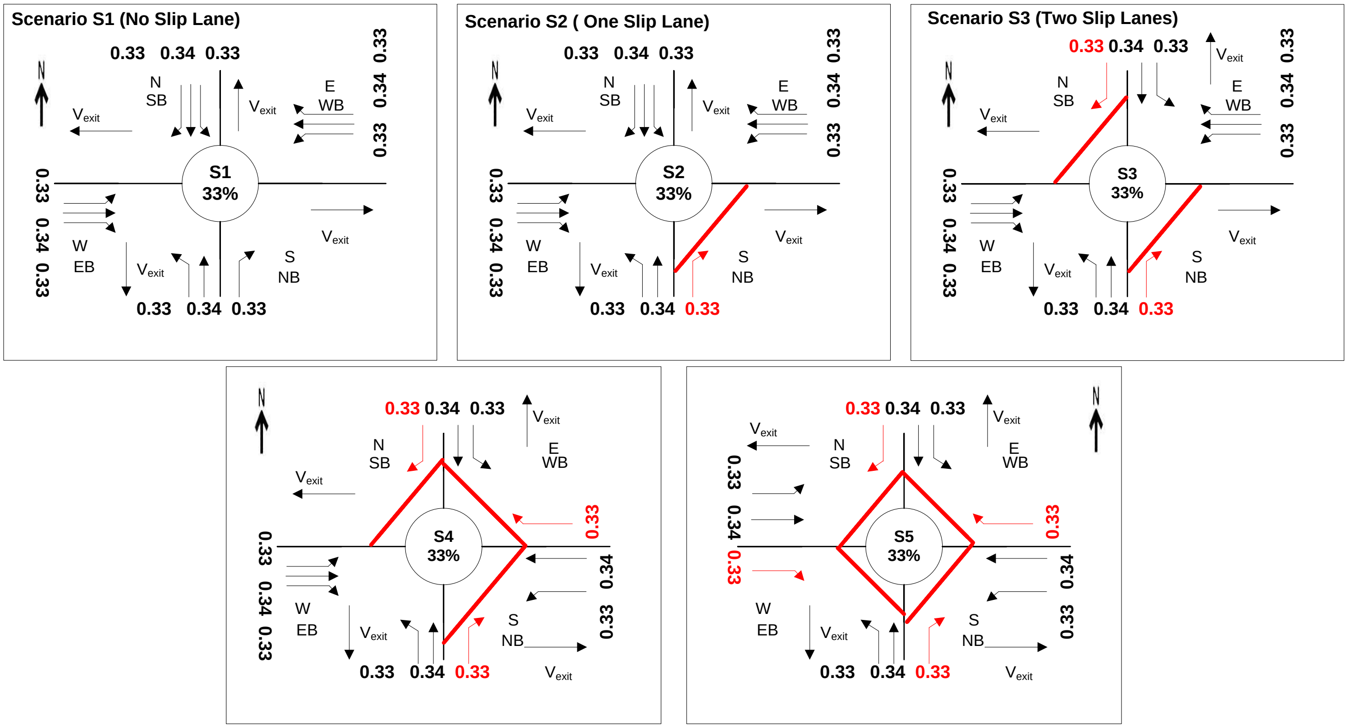

FIGURE 1 Traffic Percentage Distribution Flow Patterns (S1-S5).

ANALYSIS AND RESULTS

A conflict point is any point "where a vehicle path crosses, or merges with another vehicle path" (*2*). The most likely conflict point in a single-lane roundabout is merging, based dynamically on vehicle traffic events in a specific time and space. Conflicts are a function of traffic volumes. Figure 2 illustrates volumes for a single lane roundabout without a slip lane and shows approach volumes (V_a), exit volumes (V_{exit}), conflicting volumes (V_c), and circulating volumes (V_{circ}) for the roundabout, calculated for the northbound approach, for example, as follows:

$V_{a\ NB}$ = volumes at (9) + volumes at (8) + volumes at (7) = 0.33+0.34+0.33=1.0.
$V_{c\ NB}$ = volumes at (3) + volumes at (12) + volumes at (11) = 0.33+0.33+0.34=1.0.
$V_{circ} = V_{c\ NB} + V_{a\ NB}$ = 1.0 + 1.0 =2.0.
V_{exit} = volumes at (3) + volumes at (11) + volumes at (7) = 0.67+0.33=1.0.

Figure 3 illustrates volumes when a slip lane is introduced. Approach volumes (V_a), entry volumes (V_e), exit volumes (V_{exit}), and conflicting circulating volumes (V_c) exist as before. However, the slip lane introduces slip lane right-turn volumes (V_{sl}), and conflicting off-slip lane approach volumes (V_m) calculated for the northbound approach, for example, as follows:

$V_{e\ NB}$ = volumes at (9) + volumes at (8) = 0.33+0.34 =0.67.
$V_{sl\ NB}$ = volumes at (7) = 0.33.
V_m = volumes at (3) + volumes at (11) = 0.33+0.34=0.67 (yield and stop exit type) or V_m = 0 (no merging at the downstream of the free-flow lane).
$V_{circ}= V_{c\ NB} + V_{e\ NB}$= =1.0 + 0.67 = 1.67.

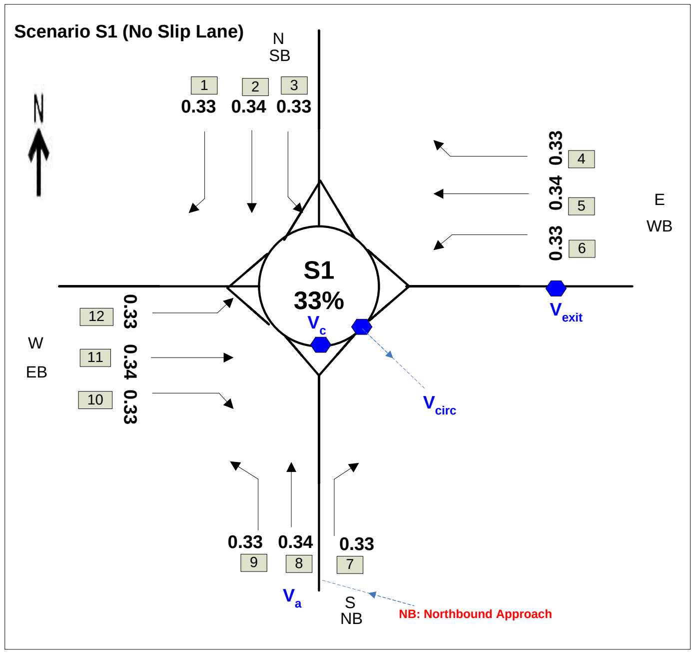

FIGURE 2 Traffic Percentage Distribution Flow Pattern: S1 - No Slip Lane.

As more right-turning traffic is diverted outside the roundabout onto the slip lane, the slip lane will more substantially reduce roundabout entry volumes (V_e) and conflicting off-slip lane approach volumes (V_m). Thus, V_e and V_m are reduced (0.67) in Scenario S2.

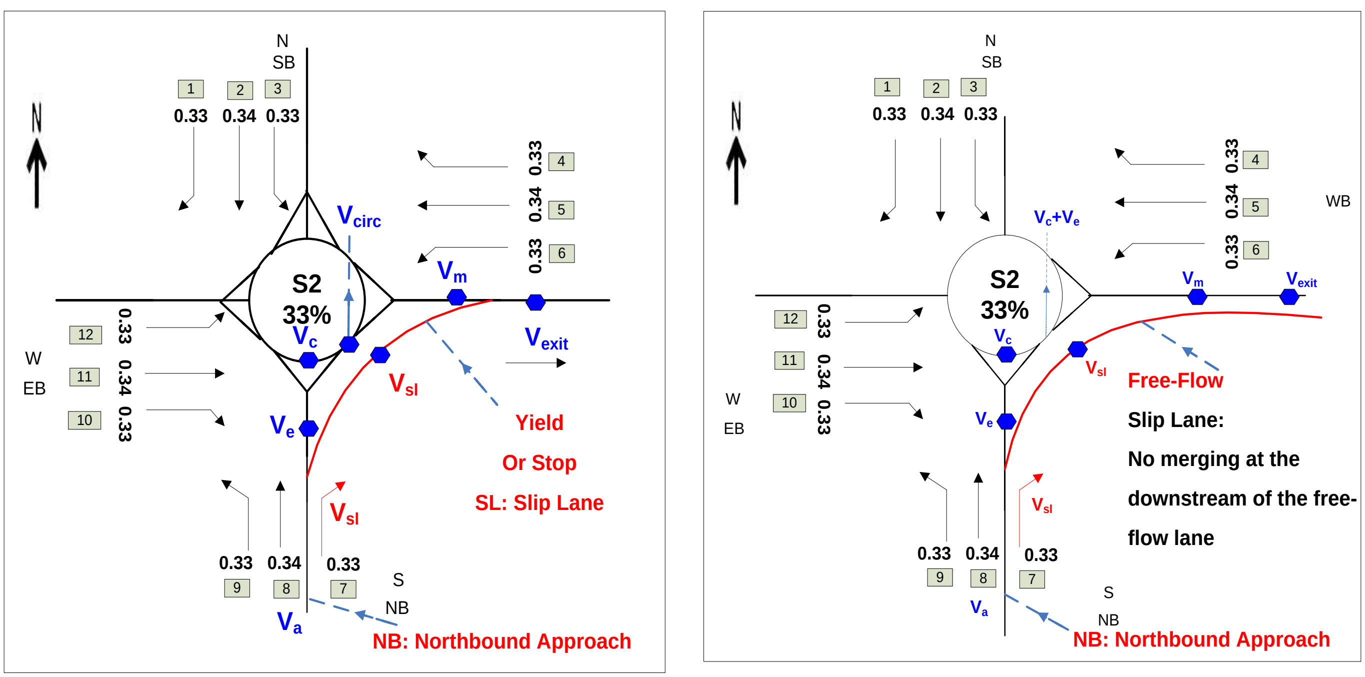

FIGURE 3 Traffic Percentage Distribution Flow Pattern: S2 (One Slip Lane per Exit Types).

Figure 4 illustrates volumes when two slip lanes are introduced. The two slip lane add the northbound slip lane right-turn volumes ($V_{sl\ (NB)}$), the southbound slip lane right-turn volumes ($V_{sl\ (SB)}$), and two conflicting off each slip lane approach volumes (V_m).

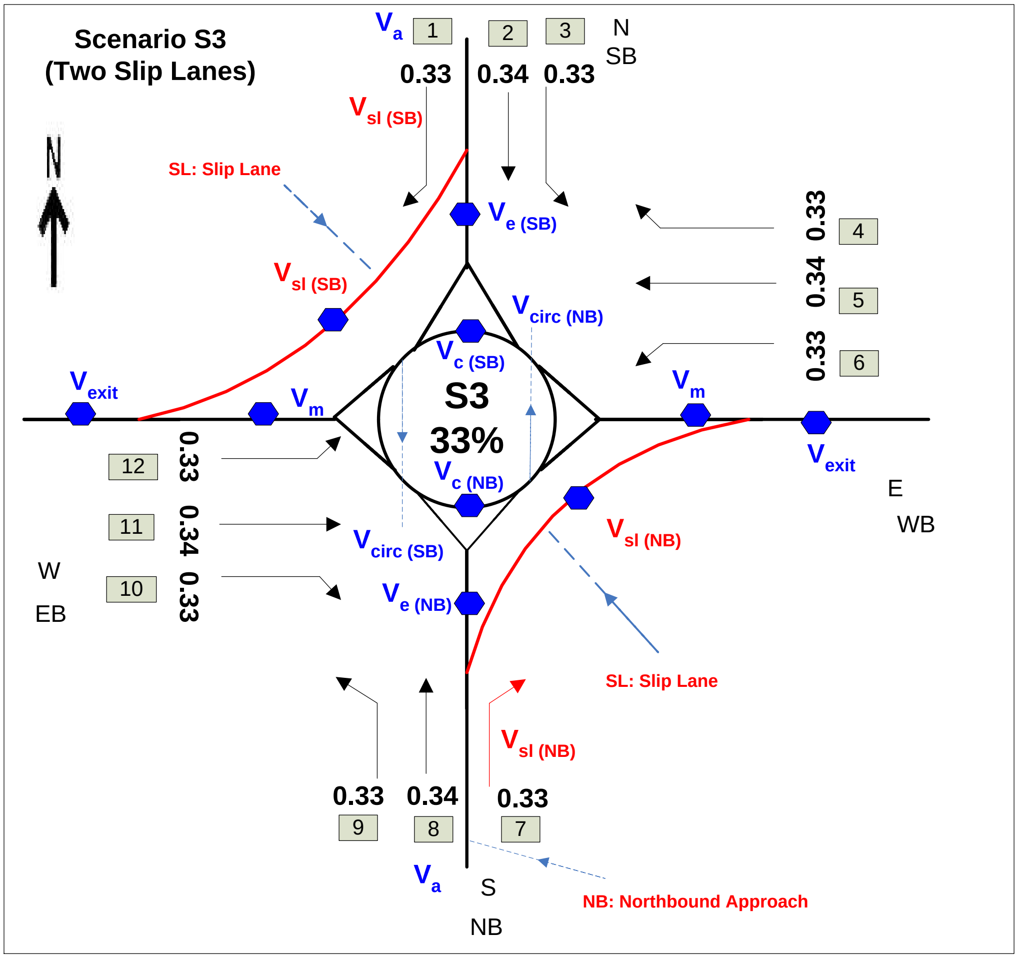

FIGURE 4 Sample of Traffic Percentage Distribution Flow Pattern: S3 (Two Slip Lanes, Yield Exit Type).

Total approach (V_a), circulating (V_{cir}), and conflicting volume (V_c) flows for all scenarios are summarized in Table 1. Scenario S3 shows the lowest roundabout circulating (V_{circ}) volumes (for example, 250 vehicles per hour, 1,264 vehicles per hour, and 2,030 vehicles per hour, shown shaded and bold). At high traffic volumes (V_{sl} = 500 vehicles per hour) with no slip lane (S1), northbound approach volumes (V_a) are 1,515 vehicles per hour, and circulating volumes (V_{circ}) are 3,030 vehicles per hour. With one slip lane (S2), total circulating volumes are 2,530 vehicles per hour; with two slip lanes (S3), 2,030 vehicles per hour (Table 1).

TABLE 1 Sample of Total Approach, Circulating, and Conflicting Volumes, Vehicles per Hour, for Scenarios S1-S3

Slip Lane Volume as Dominant Right Turn, (vehicles per hour), V_{sl}	Volumes	Scenarios		
		S1 (No Slip Lane)	S2 (One Yield Slip Lane)	S3 (Two Yield Slip Lanes)
V_{sl} = 50 (Low)	V_a	150	150	150
	$V_{c\ (NB)}$	150	150	150
	$V_{circ\ (NB)} = V_{c\ (NB)} + V_{e\ (NB)}$	300	**250**	250
	$V_{c\ (SB)}$	150	150	150
	$V_{circ\ (SB)} = V_{c\ (SB)} + V_{e\ (SB)}$	300	300	**250**
V_{sl} = 250 (Moderate)	V_a	757	757	757
	$V_{c\ (NB)}$	757	757	757
	$V_{circ\ (NB)} = V_{c\ (NB)} + V_{e\ (NB)}$	1,514	**1,264**	1,264
	$V_{c\ (SB)}$	757	757	757
	$V_{circ\ (SB)} = V_{c\ (SB)} + V_{e\ (SB)}$	1,514	1,514	**1,264**
V_{sl} = 500 (High)	V_a	1,515	1,515	1,515
	$V_{c\ (NB)}$	1,515	1,515	1,515
	$V_{circ\ (NB)} = V_{c\ (NB)} + V_{e\ (NB)}$	3,030	**2,530**	2,530
	$V_{c\ (SB)}$	1,515	1,015	1,015
	$V_{circ\ (SB)} = V_{c\ (SB)} + V_{e\ (SB)}$	3,030	2,530	**2,030**

Average Roundabout Delay

Table 2 provides a sample of the results from VISSIM MOE, the average vehicle delay in seconds for all vehicles in the slip lane (SL), the northbound approach (NB), and the roundabout (RBT), only for a yield exit type. Table 2 also summarizes VISSIM percentage changes of the roundabout average vehicle delay in seconds for all vehicles entering the roundabout, for the three slip lane exit types, and compares these to having no slip lane (S1). Scenario S2, at moderate traffic volumes (V_{sl} =250 vehicles per hour), has a significant reduction (performance improvement) in roundabout average delay from 41 seconds per vehicle (no slip lane) to about 35 seconds per vehicle for all exit type, S2, a 16 percent decrease.

A stop slip lane exit type with high traffic volumes (slip lane right-turn volumes V_{sl} = 500 vehicles per hour) shows less significant average delay reduction (-2%). The delay reduction percentages decrease (i.e., delay increases) because the roundabout average delay reaches oversaturated conditions. Because a free-flow right-turning slip lane exit type has no opposing exiting flow from the roundabout—and therefore a high capacity—it has insignificant delay (25.5 seconds per vehicle in S2, V_{sl} = 500 vehicles per hour). A stop exit type has higher slip lane delay than a yield exit type: 34.7 seconds per vehicle compared to 27.4 seconds per vehicle. Thus, reduction of delay via the use of free-flow slip lanes is shown to be greater than for stop or yield exit types. Furthermore higher traffic volumes leave to oversaturated conditions and the effectiveness of the slip lane is lost.

TABLE 2 Sample of Summary of VISSIM Average Delays for Scenarios S1 and S2

Scenarios	Slip Lane Exit Type	V_{SL}: Slip Lane Volume, Right-Turn Volume (vehicles per hour) at NB Approach	VISSIM Roundabout Average Delay (seconds per vehicle)			VISSIM- Percent Change of Average Delay with Slip Lane		
			SL	NB	RBT	SL	NB	RBT
S1	**No Slip**	50 (Low)	0.9	1.0	1.0	0%	0%	0%
		250 (Med)	40.9	41.2	**41.0**	0%	0%	0%
		500 (High)	44.0	43.5	46.3	0%	0%	0%
S2	**Yield**	50 (Low)	0.4	0.7	0.9	-56%	-30%	-10%
		250 (Med)	10.9	13.2	34.8	-73%	-68%	-15%
		500 (High)	**27.4**	29.6	44	-38%	-32%	-5%
	Stop	50 (Low)	0.9	0.9	0.9	0%	-10%	-5%
		250 (Med)	21.9	18.4	35.9	-46%	-55%	-12%
		500 (High)	**34.7**	34.7	45.2	-21%	-20%	-2%
	Free-Flow	50 (Low)	0.2	0.7	0.9	-78%	-30%	-10%
		250 (Med)	8.9	12.1	**34.5**	-78%	-71%	**-16%**
		500 (High)	**25.5**	28.8	43.7	-42%	-34%	-6%

In Table 2, the northbound (NB) approach and the slip lane itself (SL), also shows significant average delay reduction: 78% (free-flow exit type, V_{sl} = 250 vehicles per hour).

Figure 5 shows a sample of a comparison between roundabout average delays for no slip lane, one slip lane, and two slip lanes (all using a yield exit type). At V_{sl} = 300 vehicles per hour, without any slip lane, the right-turn delay for a single-lane roundabout is 45.4 seconds per vehicle; with one slip lane, 41.2 seconds per vehicle; and for two slip lanes, 35.7 seconds per vehicle. As slip lane (right-turning) traffic volumes (V_{sl}) increase, conflicting circulating volumes (V_c) decrease and average delay also decreases, in an exponential, relationship. Significant changes in entry flow (V_e) and circulating flow (V_c) cause a higher impact on the total average delay within a roundabout with a slip lane and more with two slip lanes.

In addition to the VISSIM roundabout average delay, standard deviations errors of 20 runs, and percentage change in the reduction of roundabout average delays, Table 3 also shows a sample of the ratio (factor) of improvement for roundabout average delay reductions through implementation of one to two slip lanes. At V_{sl} =250 vehicles per hour, two slip lanes (S3) with a yield exit type show doubling of the reduction percentage of roundabout average delay (ratio of improvements factor), before oversaturation (calculated 2.4 = 36/15). At V_{sl} =500 vehicles per hour, four slip lanes (S5) with a yield exit type show four times of the reduction percentage of roundabout average delay before oversaturation (calculated 4.0 = 20/5).

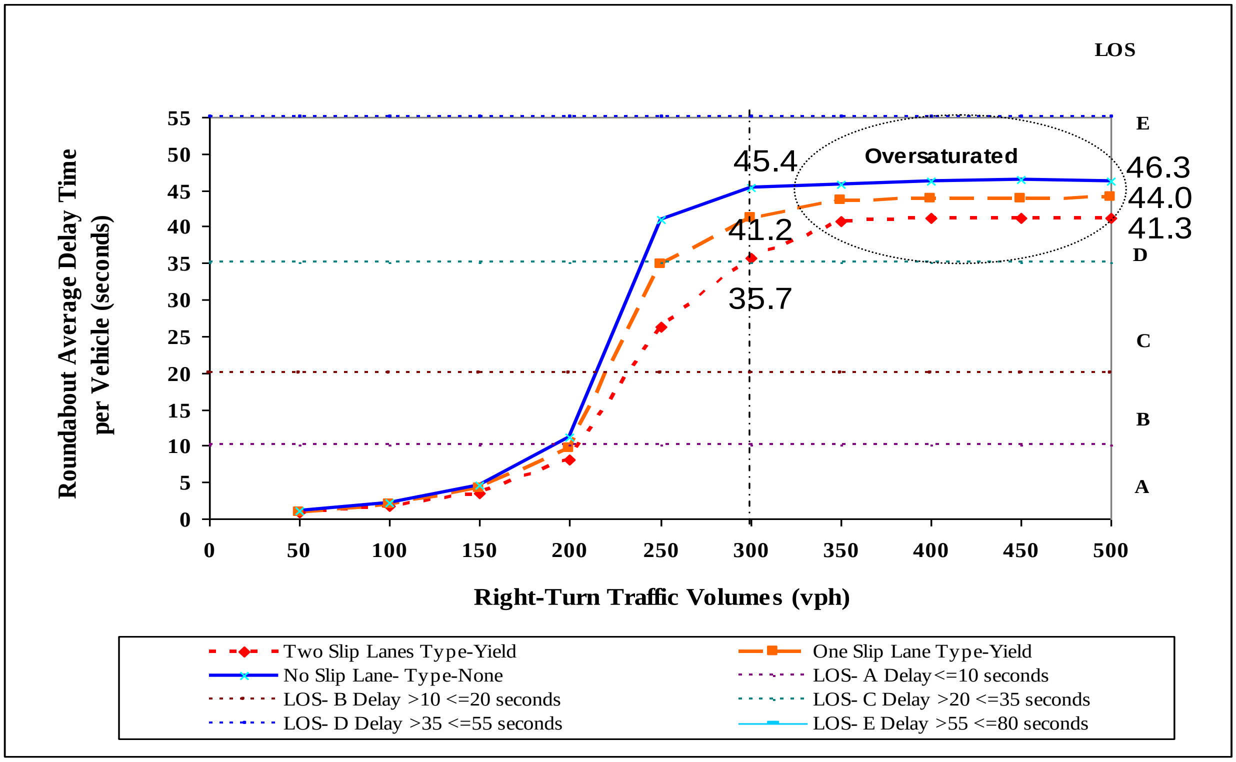

FIGURE 5 Sample of Outputs from VISSIM: Comparison between Roundabout Average Delay, Scenarios S1-S3.

TABLE 3 Sample of VISSIM Percentage Change of Average Delay with One to Four Slip Lanes- for Scenarios S1 – S5, Yield Exit Type

Slip Lane (SL) Exit Type	V_{SL}: Slip Lane Volume, Right-Turn Volume (vehicles per hour)	VISSIM- Roundabout Average Delay (Seconds per Vehicle) (Standard Deviation(s) Errors for 20 Runs)					VISSIM- Percent Change of Average Delay by Adding Slip Lane per Scenario (Base S1)				Ratio of Improvements of Delay Factor per Scenario (Base S2)		
		S1 (No SL)	S2 (One SL)	S3 (Two SL)	S4 (Three SL)	S5 (Four SL)	S2	S3	S4	S5	S3	S4	S5
Yield	50 (Low)		0.9 (1.2)	0.8 (1.2)	1 (1.4)	1 (1.4)	-10%	-20%	0%	0%	2	0	0
	250 (Med)		34.8 (21)	26.4 (20.7)	21 (19.4)	13.9 (12.6)	-15%	-36%	-48%	-66%	2.4	3.2	4.4
	500 (High)		44 (16.9)	41.3 (18.8)	39.9 (17.1)	37.4 (14.1)	-5%	-11%	-14%	-20%	2.2	2.8	4
No Slip	50 (Low)	1 (1.2)					0%	0%	0%	0%			
	250 (Med)	41 (17.3)					0%	0%	0%	0%			
	500 (High)	46.3 (13.8)					0%	0%	0%	0%			

CONCLUSIONS

VISSIM results confirm that average delay and circulating conflict volumes in a roundabout with a slip lane are related exponentially to slip lane volumes up to a saturation point. In this case study the saturation point began at 250 vehicles per hour. Average delay is more effectively reduced in a roundabout with a slip lane than in one without because 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). For example, results showed the overall roundabout delay was reduced by 16% with the use of a free-flow slip lane; 15% with use of a yield slip lane; and 12% with use of a stop slip lane. Hence the most effective roundabout delay performance generally is obtained when using a free-flow slip lane. Having more than one slip lane at different roundabout approach locations also adds further significant reduction of total roundabout average delays by at least a factor of two. Four slip lanes will improve the roundabout average delays by at least a factor of four for moderate and high volumes compared to one slip lane.

RECOMMENDATIONS

VISSIM can be used to analyze a slip lane's contribution to improved roundabout capacity and safety before traffic flow becomes oversaturated. Differences in roundabout configurations, geometric parameters, gap acceptance thresholds, driver behaviors, pedestrians at slip lanes, slip lane length, and operational parameters may differently affect slip lane operational measures in further analysis. 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 of multiple traffic volume distribution matrices with other percentages of dominant right-turning traffic may provide 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. To validate VISSIM sensitivity, future analysis should vary its default values for gap acceptance parameters (priority rules) and compare results to field data.

It also is suggested that further analysis address slip lane exit types such as use of a ramp metering signal, and use of a traffic barrier.

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