

# **Analysis of Fuel Consumption and Emissions at Roundabout with Slip Lane, Using SIDRA and Validation by MOVES Simulation**

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## **ABSTRACT**

SIDRA tool enables researchers and practitioners to model vehicle emissions at a project level. Vehicular fuel consumption and emissions performance (CO<sub>2</sub> and CO) are simulated within single-lane roundabouts, with a one approach slip lane, under yield and free-flow exit control scenarios. Results are then compared to a roundabout with no slip lane, as a base, and all-way stop-controlled (AWSC) intersection within this experimental assessment. The MOVES (Motor Vehicle Emission Simulator) from EPA used to validate no slip lane roundabout as a base scenario. Results show that with a free-flow slip lane exit type, overall average total roundabout fuel consumption was reduced by 26%, CO<sub>2</sub> emissions were reduced 27%, and CO emissions were reduced 17%, compared to an AWSC intersection. As expected, results indicate that a roundabout with and without slip lane shows a more significant reduction (improvement) of fuel consumption and pollutant emissions values than an AWSC intersection. Hence, the most effective roundabout performance in reducing delay, fuel consumption, and pollutant emissions generally is obtained from a free-flow slip lane.

**Key words:** Roundabout, slip lane, average delay, MOVES 2010b.

## **INTRODUCTION**

A slip lane, a separate lane that relieves right-turning traffic flow, reduces approach delay by allowing right-turning movements to bypass the roundabout, thereby reducing vehicle conflicts, delays, and stops, Al-Ghandour et al. (2011).

This paper examines vehicle fuel consumption and pollutant emissions improvements when a slip lane is arbitrarily assumed to be placed at the northbound entry to the roundabout, with different configurations, and compared to an all-way stop-controlled (AWSC) intersection. Vehicle delays increase acceleration/deceleration cycles, stops, and time spent idling at the intersection and increase the vehicular fuel consumption and emissions. Operational performance of roundabouts, measured as roundabout capacity and delays explained by (TRB, 2000) and NCHRP Reports 572 and 672 (NCHRP, 2007 and 2010).

MOBILE (2011) vehicle emission factor model, a software tool for predicting gram per mile emissions of hydrocarbons (HC), carbon monoxide (CO), oxides of nitrogen (NO<sub>x</sub>), carbon dioxide (CO<sub>2</sub>), particulate matter (PM), and air toxics from cars, trucks, and motorcycles under various conditions, has been used and recently replaced by Motor Vehicle Emission Simulator (MOVES 2010) as the EPA's official model for estimating emissions from cars, trucks and motorcycles. The MOVES emission modeling system estimates emissions for mobile sources covering a broad range of pollutants and allows multiple scale analysis. MOVES (2010b, latest

version used) estimates emissions from cars, trucks, and motorcycles for project-level analyses and has tools to post-process output for project-level analyses of intersections and roundabouts.

Hallmark et al. (2008) noted that roundabouts reduce vehicle delay and the number and duration of stops that would occur in traditional signalized or all-way stop-controlled intersections. Also, several previous studies show that implementation of roundabouts significantly reduces vehicle fuel consumption and pollutant emissions.

Mandavilli et al. (2003) studied and collected actual data before and after three stop-controlled intersections in Kansas were replaced by roundabouts. Mandeville and his team found a 45% reduction in carbon monoxide (CO), a 61% reduction in carbon dioxide (CO<sub>2</sub>), a 51% reduction in nitrogen oxides (NO<sub>x</sub>), and a 68% reduction in hydrocarbons (HC).

Hyden and Varhelyi (2000) evaluated speeds and emissions before and after installation of roundabouts in Sweden. They found at a previously unsignalized intersection that CO emissions increased by 6% and NO<sub>x</sub> by 4%; at a previously signalized intersection, however, CO decreased by 29% and NO<sub>x</sub> decreased by 21%.

Using SIDRA software (Signalized and Unsignalized Design and Research Aid, SIDRA 2007) to quantify the impact of roundabouts on emissions and energy consumption, Ariniello and Przybyl (2010) studied several sustainable performance measures for 15 roundabouts in the City of Boulder, Colorado. They found that at high volume, these 15 roundabouts can reduce CO<sub>2</sub> emissions by up to 400 metric tons per year and energy consumption by up to 45,000 gallons of gasoline per year.

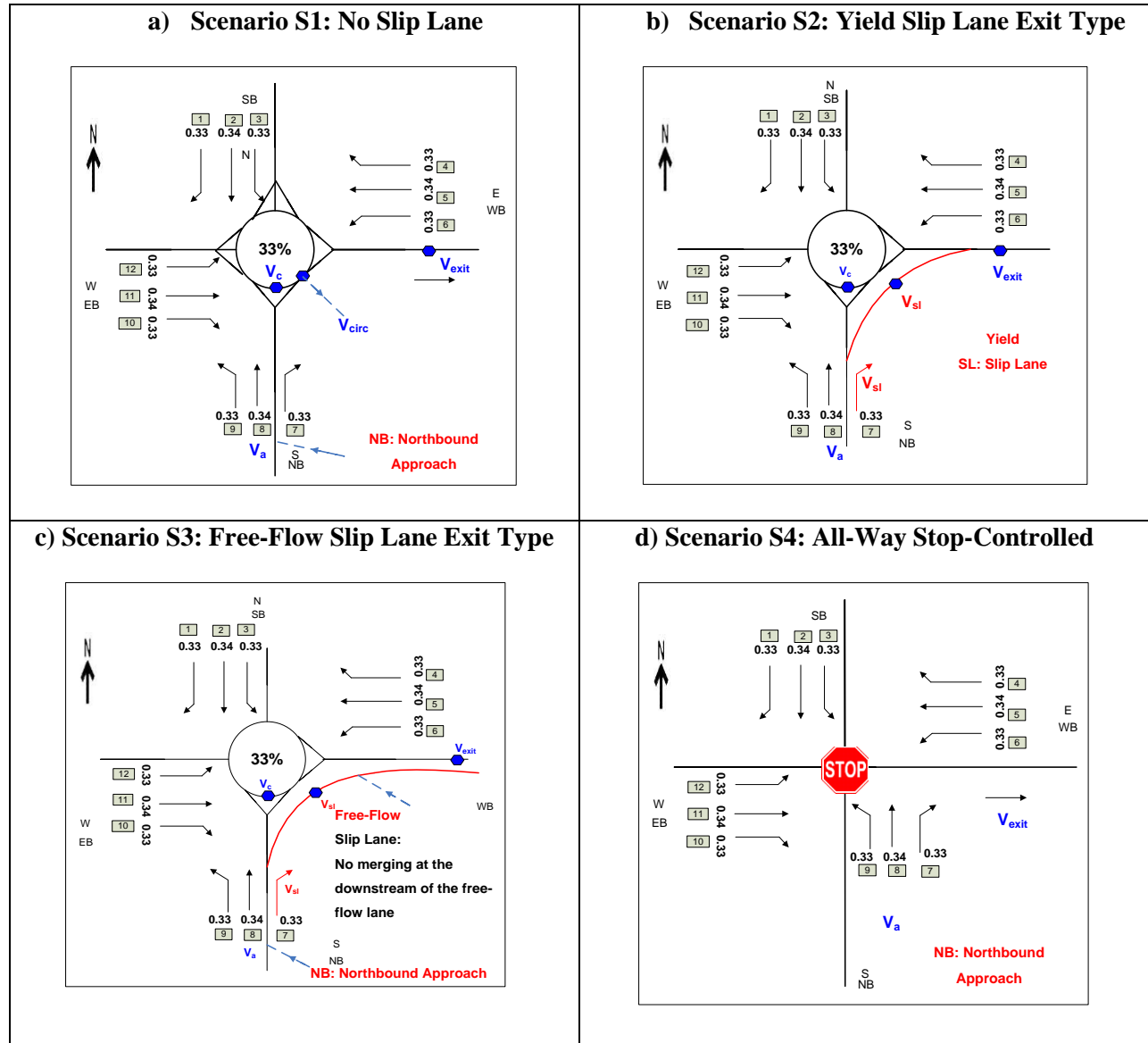
Neither vehicle fuel consumption nor pollutant emissions evaluations were found in the literature for roundabouts where slip lanes were installed. Nothing was found specifically focused on air quality related to roundabout slip lane performance. The purpose of this paper is to estimate vehicular fuel consumption and emissions performance within single-lane roundabouts with a slip lane, under yield and free-flow exit control scenarios and then compared to a roundabout with no slip lane and an AWSC intersection. MOVES2010b is only used for the roundabout with no slip lane, as a base, to validate results of the fuel consumption and emission estimates from SIDRA.

## **METHODOLOGY**

Al-Ghandour et al. (2011) studied roundabout slip lane operational performance (average delay) by conducting both experimental balanced (total traffic flow into and out of each roundabout approach is the same) and more realistic unbalanced flow scenarios (traffic flow into and out of different roundabout approaches is different) for a range of volume levels using SIDRA. A balanced experimental traffic percentage turning volume distribution (33%) was focused to demonstrate four scenarios S1—no slip lane; S2—slip lane with a yield sign; S3—slip lane with free-flow lane; and S4—all-way stop-controlled (AWSC) intersection (Figure 1). These scenarios were studied under the assumption that total traffic flow into and out of each intersection approach is the same and a slip lane was arbitrarily assumed to be placed at the northbound entry to the roundabout. Scenarios S1 to S4 were initialized, analyzed, and then volumes were controlled through several iterations.

Slip lane right-turning traffic volume as the dominant turn ranged from 50 vehicles per hour to 500 vehicles per hour, in increments of 50—representing low, moderate, and high volumes.

Three volume distributions were sampled: 50, 250, and 500 vehicles per hour (Table 1), and total approach volumes ( $V_a$ ), conflicting volumes ( $V_c$ ), and slip lane right-turn volumes ( $V_{sl}$ ) for all scenarios (S1-S4) are summarized. Volumes for each roundabout approach ( $V_a$ ), or intersection, are assumed to be the same as for each exit approach ( $V_{exit}$ ). Fuel consumption, emissions ( $CO_2$  and  $CO$ ), and average delay (in seconds) for all vehicles entering the intersection approaches are used as the Measure of Effectiveness (MOE).



$V_a$  : Approach volumes.  $V_{exit}$ : Exit approach volumes.  $V_c$ : Conflicting circulating volumes.  $V_{sl}$ : Slip lane volumes as dominant right turn, vehicles per hour, for S2-S3.  $V_{circ}$ : Circulating volumes for S1-S3. Movement Turn No. 7 represents northbound right turn, vehicles per hour, for S1 and S4.

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

**Table 1. Total Approach and Conflicting Volumes.**

<b><math>V_{sl}</math>: Slip Lane Volume, Right-Turn Volume (Vehicle/hour) at Northbound (NB) Approach</b>	<b>Volumes (Vehicle/hour)</b>	<b>S1 (33%)</b>	<b>S2-S3 (33%)</b>	<b>S4 (33%)</b>
<b><math>V_{sl} = 50</math> (Low)</b>	<b><math>V_a</math></b>	150	150	150
	<b><math>V_c</math></b>	0	150	0
<b><math>V_{sl} = 250</math> (Moderate)</b>	<b><math>V_a</math></b>	757	757	757
	<b><math>V_c</math></b>	0	757	0
<b><math>V_{sl} = 500</math> (High)</b>	<b><math>V_a</math></b>	1,515	1,515	1,515
	<b><math>V_c</math></b>	0	1,515	0

$V_a$  : Approach volumes.  $V_c$ : Conflicting circulating volumes.  $V_{sl}$ : Slip lane volumes as dominant right turn, vehicles per hour, for S2-S3. Northbound right turns, vehicles per hour, for S1 and S4.

In this experiment, MOVES2010b is used only to validate the base scenario S1 (roundabout with no slip lane). The MOVES2010b inputs for project level, scenario S1 are shown in Table 2.

**Table 2. Inputs Used for Estimating CO in MOVES2010b for Scenario S1 (No Slip Lane).**

<b>Parameter</b>	<b>Value</b>
<b>Analysis Year</b>	2010
<b>Time Spans: Months/Days/Hours</b>	January /Weekdays/5-6 pm
<b>Geographic Bounds</b>	North Carolina- Wake County
<b>On Road Vehicle Equipment</b>	Gasoline - Passenger Car Gasoline - Passenger Truck Gasoline - School Bus
<b>Road Types</b>	Rural Unrestricted Access
<b>Pollutants And Processes:</b>	Running Exhaust Carbon Monoxide (CO) Extended Idle Exhaust Carbon Monoxide (CO)
<b>Registration (age)</b>	EPA national default
<b>Vehicle Volume</b>	Shown (Figure 1), slip lane right-turning traffic volumes range from 50 to 500 vehicles per hour.

To simplify MOVES2010b coding used for a project level analysis, the four activity modes are assumed for a vehicle entering the roundabout, decelerating to the yield line, and accelerating out entering the circulating lane then accelerating leaving the roundabout. The average speed is assumed as 18 miles per hour for all roundabout links. MOVES2010b specifications were completed for an input database that included required spreadsheet inputs such as links, road type, link source types, and age distribution. MOVES2010b was executed and MySQL database output was extracted to estimate emissions.

## ANALYSIS AND RESULTS

With assumption that approaching traffic stays the same, as slip lane (right-turning) traffic volume ( $V_{sl}$ ) increases, the conflicting circulating volumes ( $V_c$ ), decrease; average delay, fuel consumption, and emissions also decrease, in a non-linear, or exponential, relationship. For roundabouts (S1-S3), the highest roundabout average delay (Figure 2), fuel consumption (Figure 3), and emissions (Figures 4 and 5) observed in Scenario S1 (no slip lane), were a result of the combined highest approach volumes ( $V_a$ ), highest total roundabout volumes, and highest conflicting circulating flow ( $V_c$ ), and also an increased amount of idling (stops). The lowest roundabout average delay, fuel consumption, and emissions observed in Scenario S3 (free-flow slip lane), was a result of the combined lowest approach volumes ( $V_a$ ), lowest total roundabout volumes, lowest conflicting circulating flow ( $V_c$ ), and number of stops.

If Scenario S3 (free-flow slip lane) is compared with Scenario S4 (AWSC intersection) (Figures 2 to 5), Scenario S3 shows significant reduction of total average fuel consumption and pollutant emissions. Therefore, under different scenarios, slip lane performance is most effective under a higher right-turning traffic pattern distribution.

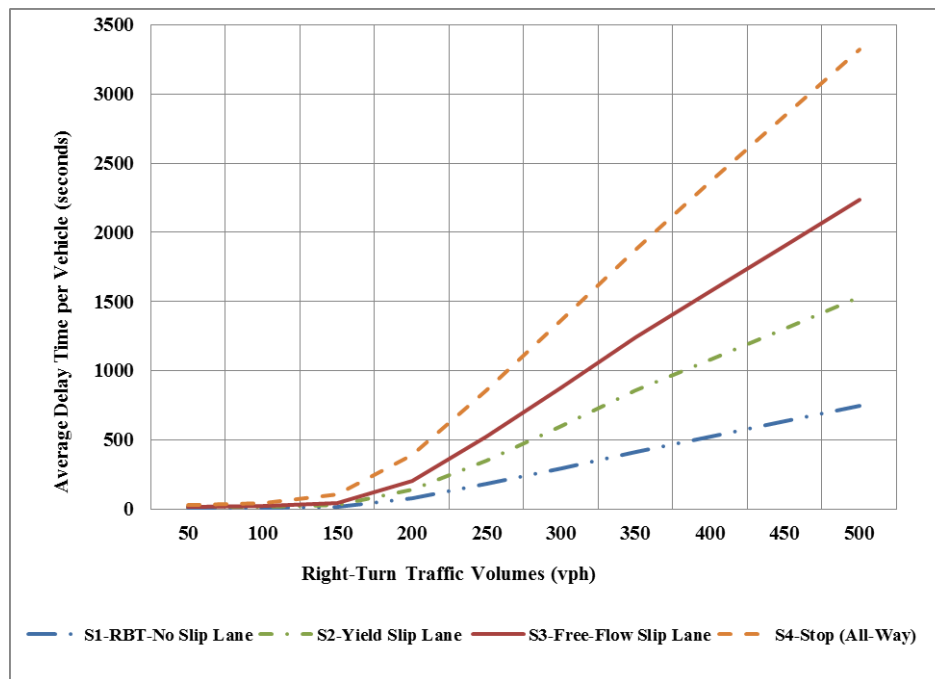
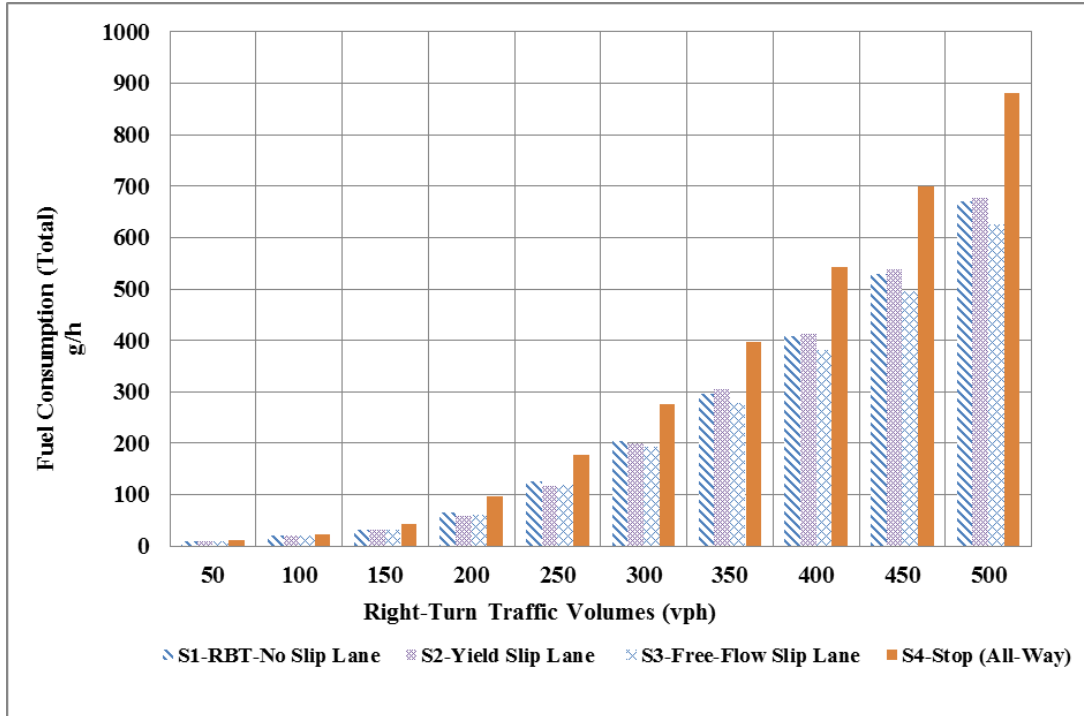
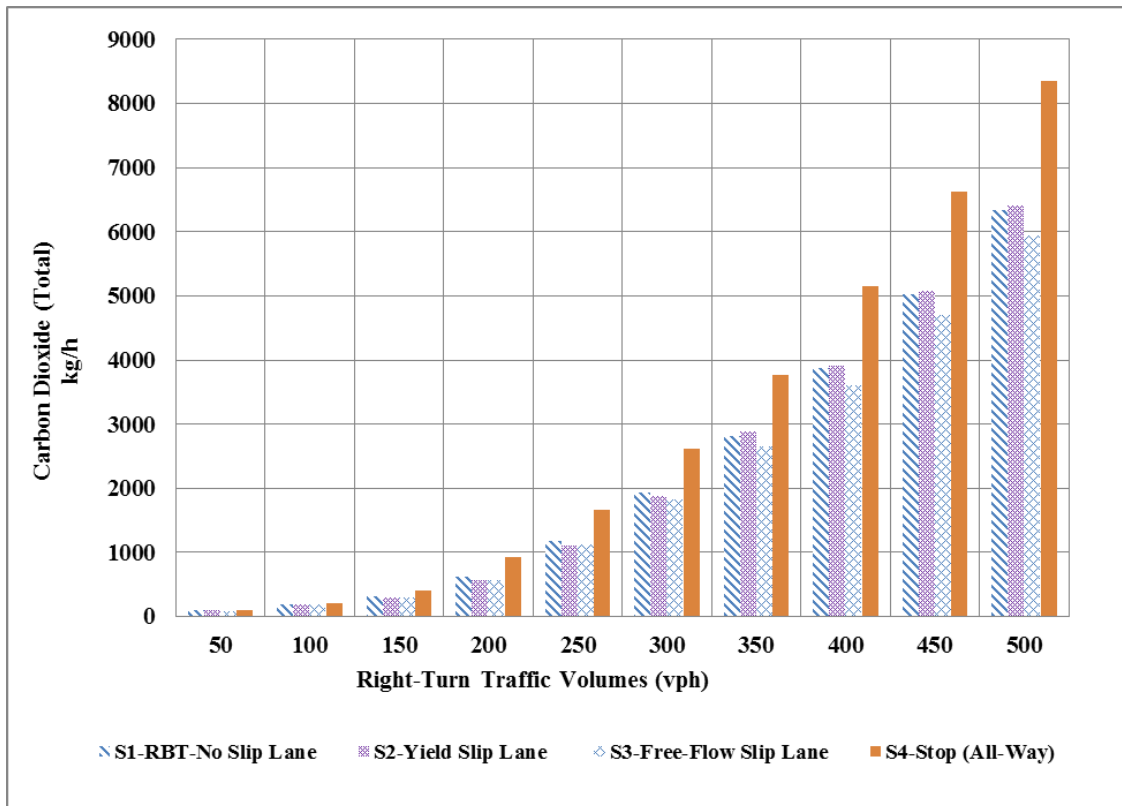


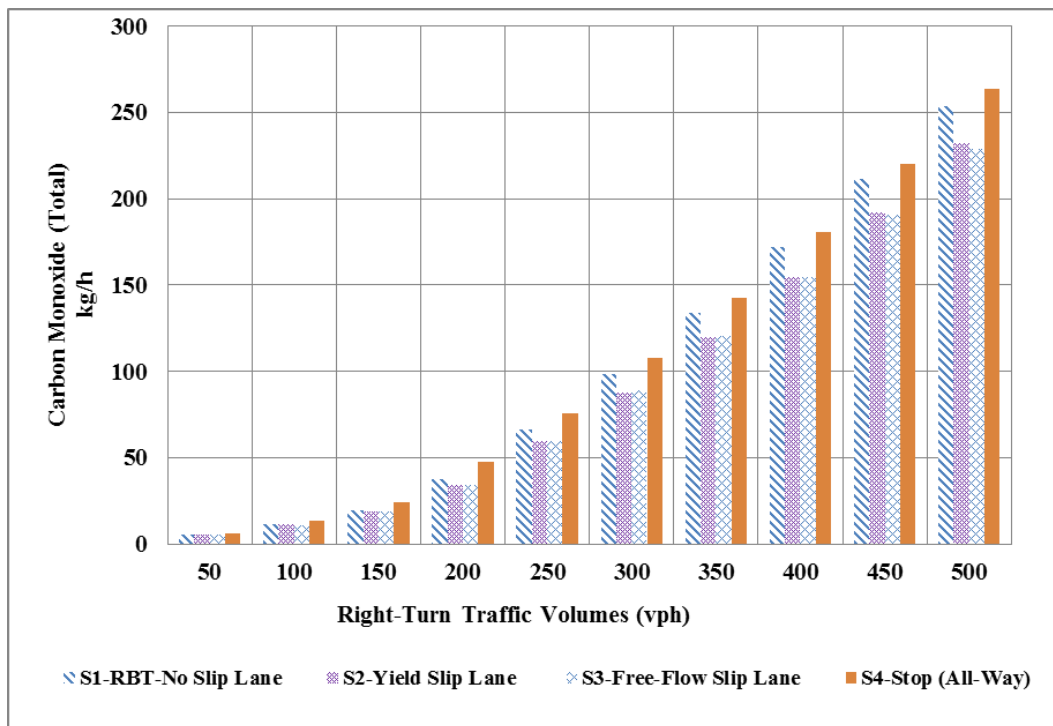
Figure 2. SIDRA: Roundabout (Intersection) Average Delay for Scenarios S1-S4.



**Figure 3. SIDRA: Roundabout (Intersection) Total Fuel Consumption for Scenarios S1-S4.**



**Figure 4. SIDRA: Roundabout (Intersection) Total Carbon Dioxide (CO<sub>2</sub>) Emissions for Scenarios S1-S4.**



**Figure 5. SIDRA: Roundabout (Intersection) Total Carbon Monoxide (CO) Emissions for Scenarios S1-S4.**

As more traffic is diverted outside the roundabout on the slip lane (right-turn movement), more roundabout conflicting circulating volumes are reduced. The average delay in the roundabout is reduced, thereby reducing vehicle conflicts, delays, and stops, and reducing vehicle fuel consumption and pollutant emissions.

Number of stops correlates to both fuel consumption and emissions. For example, with traffic volumes  $V_{sl} = 50$  vehicles per hour, a roundabout with a free-flow slip lane exit type has fewer total effective stops (349 vehicles/hour), and less fuel consumption and emissions, than an AWSC intersection (850 vehicles/hour).

### Impact of Slip Lane on Total Fuel Consumption

A sample of the results from SIDRA is compared, based on total fuel consumption between highest values from Scenario S4 (AWSC intersection), as the before case, and lowest values from Scenario S3 (roundabout with a free-flow slip lane exit type), as the after case (Table 3). Total fuel consumption for all vehicles is shown in Table 3 in gallons per hour.

With high traffic volumes  $V_{sl} = 500$  vehicles per hour, a roundabout with a free-flow slip lane exit type has less total fuel consumption for all vehicles (626.7 gal/hour) than an AWSC intersection (881.9 gal/hour)—a 29% reduction (calculated as  $-28.94\% = ((626.7 - 881.9) / 881.9)$ ). Thus, total fuel consumption via the use of a free-flow slip lane is shown to be less than in an all-way stop-controlled intersection.

**Table 3. SIDRA Percent Change in Fuel Consumption – Scenarios (S3 and S4).**

<b>V<sub>sl</sub>: Slip Lane Volume, Right-Turn Volume (Vehicle/hour) at Northbound (NB) Approach</b>	<b>Total Fuel Consumptions (gal/hour)</b>		<b>Percent Change</b>
	<b>S4 (Before)</b>	<b>S3 (After)</b>	
<b>V<sub>sl</sub> = 50 (Low)</b>	10.4	9.6	-7.96%
<b>V<sub>sl</sub> = 250 (Moderate)</b>	176.3	118.3	-32.90%
<b>V<sub>sl</sub> = 500 (High)</b>	881.9	626.7	-28.94%

V<sub>sl</sub>: Slip lane volumes as dominant right turn, vehicles per hour, for S3. Northbound right turn, vehicles per hour, for S4.

### Impact of Slip Lane on Total Emissions

With high traffic volumes V<sub>sl</sub> = 500 vehicles per hour (Table 4), a roundabout with a free-flow slip lane exit type has less total CO<sub>2</sub> emissions for all vehicles (5,935 kg/hour) than AWSC intersection (8,353 kg/hour)—a 29% reduction (Table 4). Similarly, with a free-flow slip lane, there is a 17% reduction of CO emissions, compared to an AWSC intersection. Thus, reduction of total CO<sub>2</sub> and CO emissions via the use of a free-flow slip lane is shown to be greater than in an AWSC intersection.

**Table 4. SIDRA Percent Change in Emissions – Scenarios (S3 and S4).**

<b>V<sub>sl</sub>: Slip Lane Volume, Right-Turn Volume (Vehicle/hour) at Northbound (NB) Approach</b>	<b>Total Carbon Dioxide (CO<sub>2</sub>) (kg/hour)</b>		<b>Percent Change</b>	<b>Total Carbon Monoxide (CO) (kg/hour)</b>		<b>Percent Change</b>
	<b>S4 (Before)</b>	<b>S3(After)</b>		<b>S4 (Before)</b>	<b>S3 (After)</b>	
<b>V<sub>sl</sub> = 50 (Low)</b>	98.60	90.80	-7.91%	6.28	5.34	-14.9%
<b>V<sub>sl</sub> = 250 (Moderate)</b>	1,669.40	1,120.00	-32.90%	75.96	59.53	-21.04%
<b>V<sub>sl</sub> = 500 (High)</b>	8,352.70	5,935.10	-28.94%	263.41	229.13	-13.01%

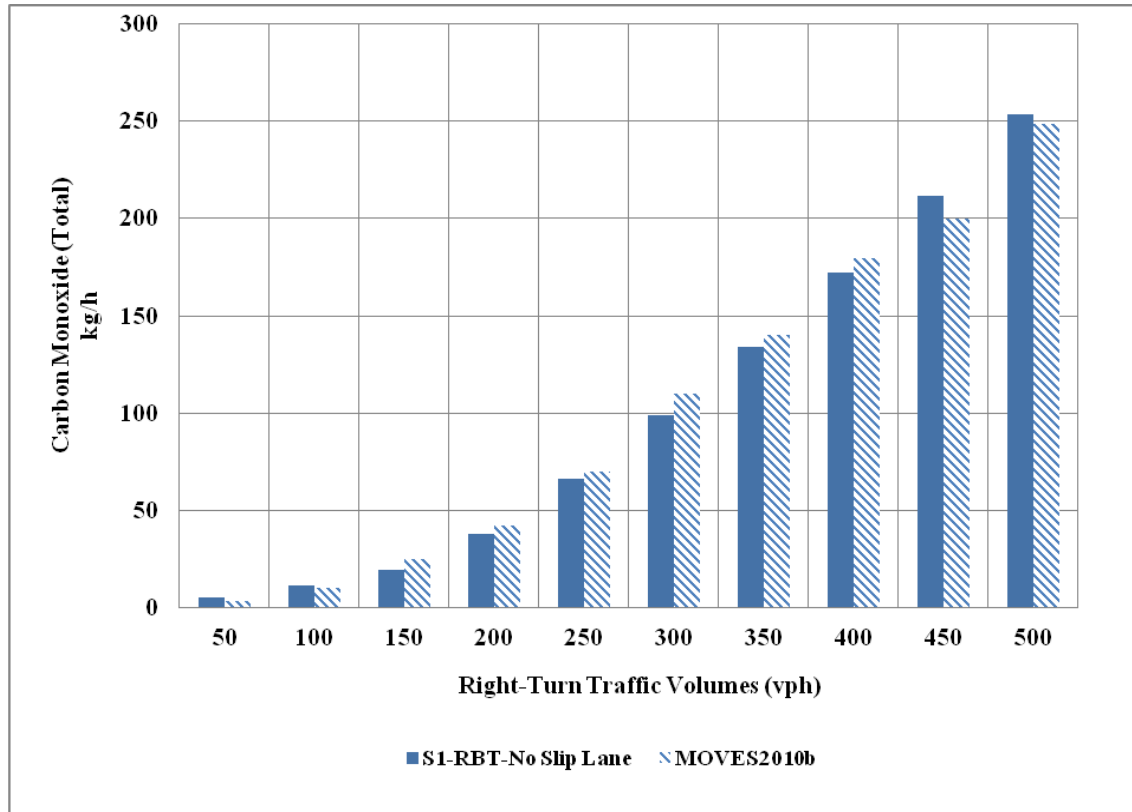
V<sub>sl</sub>: Slip lane volumes as dominant right turn, vehicles per hour, for S3. Northbound right turn, vehicles per hour, for S4.

### Validation of the SIDRA Result

For each scenario, the standard deviation and standard error were recorded for roundabout (intersection) fuel consumption that tested statistically significant, using the 95% confidence interval (alpha 0.05). Using the standard error, it was possible to calculate the 95% confidence interval for the roundabout (intersection) total fuel consumption reduction that might be achieved by implementing the free-flow slip lane exit type. The 95% confidence interval is  $\pm 1.96$  standard errors from the total fuel consumption reduction percentage of reduction. Therefore, reduction of total fuel consumption from implementing a free-flow slip lane exit type, compared to an all-way stop-controlled intersection, is estimated between -34% and -19% (Table 3). Reduction of total fuel consumption from implementing a yield-sign slip lane exit type is estimated between -32% and -16%.



The SIDRA results for the S1 scenario were validated and compared to MOVES2010b outputs (Figure 6). At low and medium traffic levels, both SIDRA and MOVES 2010b results are very significantly similar. At higher traffic volume, MOVES2010b results were slightly lower for CO emissions.



**Figure 6. SIDRA and MOVES2010b Comparison: Total Carbon Monoxide (CO) Emissions for Scenario S1.**

A free-flow slip lane exit type with moderate traffic volumes (250 vehicles per hour) shows significant reduction in roundabout average delay (operational improvement), from 182.3 sec/vehicle (no slip lane) to 171.3 sec/vehicle: a 6% reduction in S3, and from 333.1 sec/veh (AWSC): a 46% reduction (Figure 2). Similar results were noticed for CO<sub>2</sub> and CO emissions. A free-flow slip lane exit type shows significant reduction of CO<sub>2</sub> from an average total of 2,982 kg/h (AWSC): a 27% reduction. Finally, for CO emissions, a free-flow slip lane exit type shows significant reduction of CO from an average total of 108 kg/h (AWSC) to 91 kg/h: a 17% reduction.

## CONCLUSIONS

SIDRA and MOVES2010b were used in this study to explore experimental traffic flows in a single-lane roundabout with a slip lane, compared to all-way stop-controlled (AWSC) intersections. Roundabouts with slip lanes were expected to reduce vehicle fuel consumption and emissions as a result of reduced delays and stops. Reasonable estimates were generated for overall CO<sub>2</sub> and CO emissions as well as fuel consumption.

As expected and statistically validated, results indicate that a roundabout with a free-flow slip lane exit type significantly reduces total roundabout (intersection) average fuel consumption and pollutant emissions values, compared to having no slip lane or AWSC intersection. With a free-flow slip lane exit type, overall average roundabout fuel consumption was reduced -26% (the estimated 95% confidence interval of reduction estimated between -19% and -34%) compared to an AWSC intersection. Results are similar for carbon emissions: the overall average CO<sub>2</sub> value was reduced from 2,982 kg/hour (AWSC intersection) to 2,099 kg/hour (roundabout with a free-flow slip lane). A roundabout with and without slip lane shows a more significant reduction (improvement) of fuel consumption and pollutant emissions values than an AWSC intersection. Hence, the most effective roundabout performance in reducing delay, fuel consumption, and pollutant emissions generally is obtained from a free-flow slip lane.

## RECOMMENDATIONS

SIDRA and MOVES2010b can be used to analyze a slip lane's contribution to improving roundabout capacity and delay, and to diminishing fuel consumption and pollutant emissions. Additional analysis should be conducted for other variables: different unbalanced flow scenarios (traffic flow into and out of different roundabout approaches is different); heavy vehicles (trucks and buses), different speeds, and other traffic controls such as a two-way stop sign of a major-minor intersection. To validate results, field data collection is required, and future analysis should be compared with a micro-simulation such as VISSIM, which will be able to estimate emissions based on vehicle mode. Hydrocarbons (HC) and nitrogen oxides (NO<sub>x</sub>) emissions can be included in future studies.

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