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Operational and Emission Analyses of Roundabouts under Varied Vehicle and Pedestrian Demands

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INTRODUCTION

Roundabouts are becoming more and more common as an alternative to signalized intersections throughout the United States. The primary reason for an increased interest in roundabout construction has been their safety advantages compared to signalized intersections due to the reduced number of conflict points and lower vehicle speeds (*1*). As a result of the increasing popularity of roundabouts, several research efforts have evaluated their performance in terms of operations and safety. However, only a few recent studies have focused on the environmental performance of roundabouts and those have not resulted in consistent conclusions. In addition, most of the studies have focused on the effect of car demand on emissions and there has been less attention to the pedestrian crossing impacts on vehicles' stops and emissions. The goal of the proposed research is to conduct a comparative evaluation of the impact of vehicle and pedestrian demand on the operational and environmental performance at roundabouts and signalized intersections.

METHODOLOGY

In order to assess the operational and environmental performance of roundabouts against signalized intersections, two types of models were developed:

1. Microsimulation models for roundabouts using AIMSUN that were intended to provide some initial guidance on the impact of vehicle and pedestrian demand on the environmental performance of roundabouts.
2. Cellular automata (CA) models for roundabouts and signalized intersections validated against their corresponding AIMSUN microsimulation models and used for a comparative analysis of the impact of vehicle and pedestrian demand patterns on the operations and emissions of those two types of intersections.

Test Site

The roundabout on the campus of the University of Massachusetts (UMass) Amherst (intersection of N. Pleasant St. and Governor's Dr.) was used as the test site (Figure 1). Given its location on campus this roundabout is characterized by high traffic and pedestrian demand volumes. Prior to being converted to a roundabout, this intersection was signalized with permissive left turns, a cycle length of 75 sec and 36 sec of green for the east-west approaches and 31 sec of green for the north-south ones.

Figure 1. Test Site Roundabout at the intersection of N. Pleasant St. and Governor's Dr., Amherst, MA (Source: Google Maps)

Data on traffic and pedestrian demand was collected using cameras on the afternoon peak hour (3:30-5:30 PM) of Tuesday October 11, 2016 and the morning peak hour (8:30-9:30 AM) of Tuesday October 25, 2016. The collected through the cameras data were used to measure traffic flow and pedestrian volume for different approaches. The first set of data was used for the microsimulation model study and the second for the CA model study.

AIMSUN Microsimulation

Integration of AIMSUN traffic microsimulation tool (*2*) with Comprehensive Modal Emission Model (CMEM) (*3*) was used to model operations on a roundabout and the corresponding signalized intersection and assess their environmental performance under various vehicle and pedestrian demand scenarios. The traffic microsimulation tool generates trajectories of individual vehicles (i.e. second by second vehicle velocity and acceleration) for both motorized vehicles and pedestrians. Then, the output of traffic simulation is fed into the CMEM to calculate average gram of pollutants per mile for each vehicle trajectory. CMEM, which is a microscopic modal-based (i.e., it accounts for the time spent in various driving modes) emission model produces emissions using second by second vehicle velocity as well as other vehicle, road, and weather characteristics as inputs. CMEM has been chosen as the emission model because it estimates second by second emissions through the Vehicle Specific power (VSP) approach, which is one of the most acceptable methods of emission estimation. The primary benefit of this approach is that it combines into a single parameter numerous physical factors influential to vehicle fuel consumption and emissions: vehicle speed, acceleration, road grade, and road load parameters such as aerodynamic drag and rolling resistance.

The AIMSUN microsimulation model was calibrated based on queue lengths observed in the field for the test site chosen. The acceleration and deceleration rates used were the default values within AIMSUN, which are 3 m/sec^2 and 4 m/sec^2, respectively.

Cellular Automata Model

The CA model was used in this study for the following reasons:

1. it requires few parameters to be calibrated
2. it reproduces individual vehicle's trajectories, which is important for emission estimation,
3. it can account for different moving objects with different lengths by considering an appropriate cell length and number of cells for each object, and
4. ideally, it can account for different cruising speed of vehicles (depending on the simulation step).

In general, the model consists of cells with equal size that form a one or multi-dimensional array and interact with their neighboring cells. The cells can be in a state, which is updated in discrete time intervals, i.e., time steps based on some predefined rules (*4*):

1. Acceleration: If the gap in front of a vehicle (i.e. the number of empty cells between a vehicle and the preceding vehicle) is greater than the current speed and the current speed is less than the maximum speed then the speed of the vehicle will be increased by one unit.

2. Deceleration (due to other vehicles): if the gap in front of a vehicle is less than its current speed, then the speed will be decreased to match available gap such that the vehicle stops behind the preceding vehicle.
3. Randomization: if the velocity of a vehicle is greater than zero, it will be decreased by one with probability p.
4. Movement: Each vehicle moves u cells forward, where u is the current speed.

The randomization step is essential in simulating traffic to account for fluctuations due to human behavior or varying external conditions such as road's geometry. It is worth noting that in the CA model when a queue of vehicles is dissipating, each vehicle has a reaction time of one simulation step to move forward since it should see an empty cell in front at the previous simulation step to be able to move forward at the current simulation step. For example, when there is a queue at a roundabout and there is enough gap in the circular section, vehicles enter the roundabout at a headway of two simulation steps as shown in Figure 2.

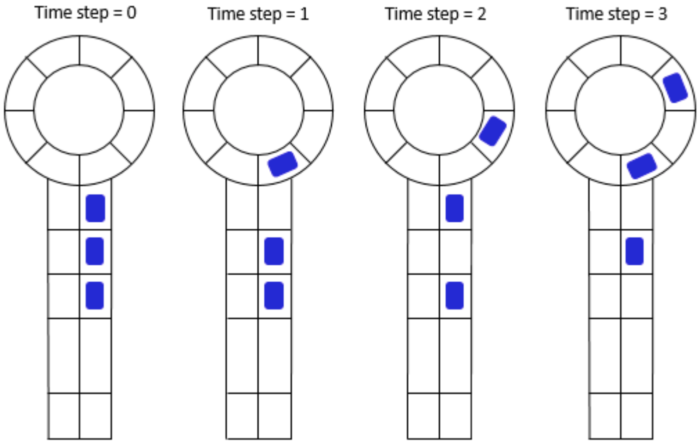
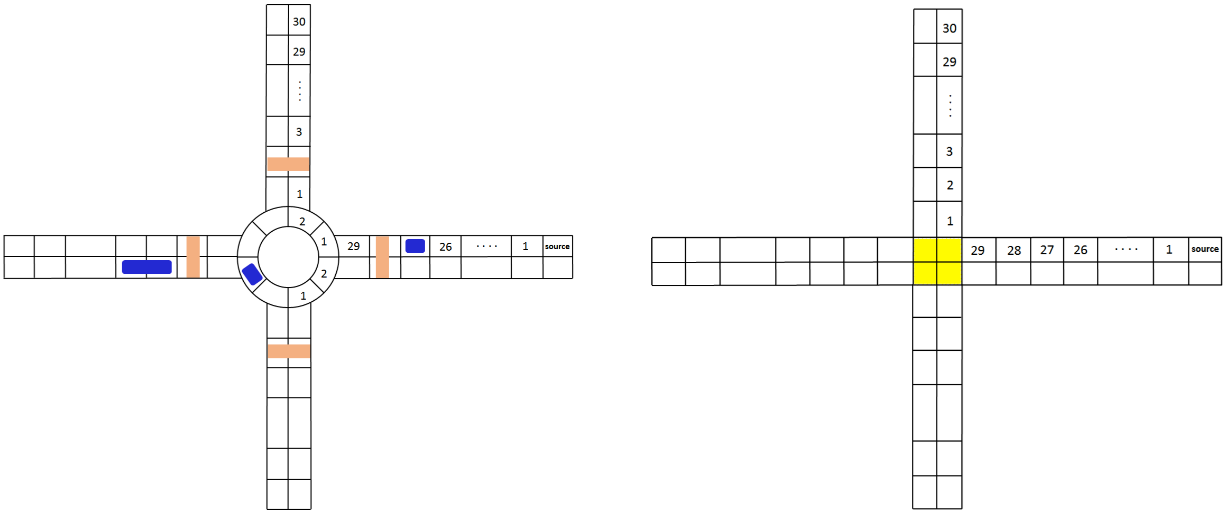


Figure 2. The state of the roundabout at consecutive simulation steps when there is a queue at the entry

Additional considerations specific to roundabout modeling using a CA model are as follows:

1. Vehicles slow down while approaching the roundabout in order to reach a safe speed to enter the roundabout,
2. Vehicles stop at the entry of the roundabout if there is not sufficient gap (i.e. enough empty cells) in the circulating area,
3. Vehicles need to yield before crosswalks if a pedestrian is present at the crosswalk. Thus, if there is any pedestrian at one of the crosswalks, that corresponding cell is assumed to be occupied until the pedestrian crosses the street.

Two CA models were developed, one for a single-lane single-lane roundabout and one for a signalized intersection with single lane approaches. The cell structure for both models is illustrated in Figure 3. The models were developed using a simulation step of 1 sec to match the simulation step of the AIMSUN microsimulation models against which they were validated for a variety of vehicle demand levels. Both CA and AIMSUN models were calibrated for vehicle and pedestrian demands of the morning peak hour for the UMass Amherst campus roundabout.



(a) single-lane roundabout

(b) signalized intersection with single lane approaches

Figure 3. Cell structure of intersection models

The CA model for the roundabout was built assuming a 7.5 m cell length based on the average car length of 4.5 m and a 1.5 m empty space at the beginning and end of a cell. Pedestrian crossing speeds were calibrated to match the ones observed from the real-world video data. Speeds limits were determined based on real-world observations for the upstream and downstream segments as well as for within the circular part of the roundabout. Other parameters that were calibrated included the critical gap, which was set to 3 sec based on previous studies performed at the same roundabout, and the follow-up headway, which was 2 secs since it takes 2 simulation steps for the second vehicle in queue to enter the roundabout as shown in Figure 2.

The CA model for the signalized intersection was built based on the same assumptions as the roundabout one regarding cell length, speed limits, and critical gap for permissive left turns. In addition, the assumption behind pedestrian crossing times was altered to account for the fact that when in a signalized intersection, pedestrians tend to travel in groups once the corresponding pedestrian phase is active, and as a result, their crossing time increases from 4 simulation steps to seven.

Once the two CA models were validated against the AIMSUN microsimulation models, emission rates in gr/sec were estimated for the acceleration, deceleration, idling, and cruising modes using the Vehicle Specific Power (VSP) model and second-by-second rates for gasoline cars from Frey et al. (*5*).

RESULTS

AIMSUN Microsimulation Study

Three sets of scenarios were performed to study the sensitivity of roundabout emissions:

1. varying conflicting vehicle demand for the entry link,
2. varying pedestrian demand on the entry link under study, and
3. varying pedestrian demand on the exit link (i.e., other three links).

Ten replications were performed for each scenario to account for the randomness in traffic or pedestrian arrivals and each simulation run lasted one hour in addition to a warm up period of 10 minutes.

Conflicting Vehicle Demand

The sensitivity of NO_x emissions to conflicting vehicle demand was assessed by scenarios where the demand of one approach was kept constant (i.e., the approach whose NO_x emissions are assessed), while the vehicle demand on the rest of them varies from zero to 100% of the respective existing vehicle demand for each approach. Figure 4 presents the sensitivity of average NO_x emissions to conflicting traffic demand expressed per vehicle and distance traveled. As shown in the figure a significant increase in NO_x emissions is observed as conflicting vehicle demand increases. When conflicting traffic is added to the scenarios, approaching vehicles on the entry link have to yield to cars that are already in the roundabout so they may experience complete acceleration and deceleration events, which result in higher emission levels. In particular, there is a 56% increase in NO_x emissions in the entry approach of interest when conflicting demand is present. In addition, the average NO_x emission for through vehicles is 0.58 gram per vehicle per mile when the conflicting traffic demand is doubled, which implies more than a 38% increase in emissions compared to existing conflicting traffic demand.

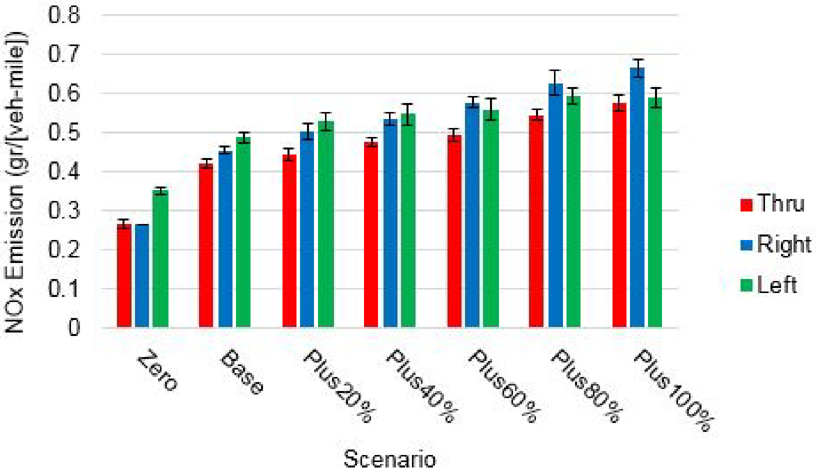


Figure 4. Sensitivity of NO_x emissions to conflicting vehicle demand

The results presented in Figure 4 show similar patterns for all movements (i.e. through, right turning, and left turning movements) as conflicting demand increases, which is anticipated. However, the emission rates corresponding to left turning vehicles are higher compared to other movements and emission rates of right turning vehicles are higher compared to through movements. Investigating trajectories of vehicles for different movements show that in the scenario with zero conflicting demand, left turning vehicles experience two deceleration/ acceleration events, one before entering the roundabout and one before exiting the roundabout, and during the period traveling in the roundabout they have enough time to accelerate and reach their cruising travel speed (i.e. their cruising speed when they enter the simulated network). However, trajectories of through and right turning vehicles show only one deceleration/acceleration event, which occurs before entering the roundabout. This can explain the fact that left turning vehicles result in higher emission rates as shown in Figure 4.

Through and right turning vehicle trajectories present a similar pattern in the sense that both have only one deceleration/acceleration event. However, in most cases right turning vehicles do not have enough time to reach their cruising speed after entering the roundabout section so they spend some time on the exit link in acceleration mode and travel the rest of distance at their cruising speed; on the other hand, through vehicles have enough time to accelerate after entering the roundabout section and most of the times they are able to reach the cruising speed before exiting the roundabout. Thus, they can travel on the exit link at their cruising speed, which is close to free flow speed. It should be noted that the average emissions released when traveling at a constant speed are lower than the average emissions released in the acceleration mode required to reach that speed. Also, considering the travel pattern of through and right turning vehicles, we conclude that the ratio of time spent in acceleration to the time spent at free flow speed is higher for right turning movements compared to through movements. Therefore, for normalized emission rates with respect to distance, it is anticipated that the right turning movements will have higher emission rates than through movements, which is consistent with the findings of these simulation tests as shown in Figure 4.

Although significant differences are observed between emission rates of right, left, and through movements for scenarios with low conflicting traffic demands, as conflicting traffic demand increases the emission rates converge. A potential reason is the high impact of stop-and-go cycles caused by the presence of conflicting traffic in the roundabout and the potential of queues forming on the entry link, which can substantially affect trajectory patterns and consequently emission rates.

Pedestrian Demand

To study the impact of pedestrian volume on emissions, conflicting traffic demand was set to zero and pedestrian demand was defined on either the entry or exit links but not on both. This was done so that vehicle stops and related emissions could be attribute only to pedestrian crossings.

In the first set of scenarios, pedestrian demand was defined only on the entry link. Figure 5 presents the sensitivity of normalized by distance NOx emission rates to the pedestrian volume on the entry link. As shown in the figure, the average emission rate for the through movement corresponding to the zero pedestrian demand scenario is 0.22 grams per vehicle per mile and this rate increases to 0.28 grams per vehicle per mile when the existing pedestrian volume is present on the entry link. This implies a 27% increase in emission rates. In addition, when pedestrian volume increases by more than 40%, there are significant increases in emission rates compared to the scenario with existing traffic demand.

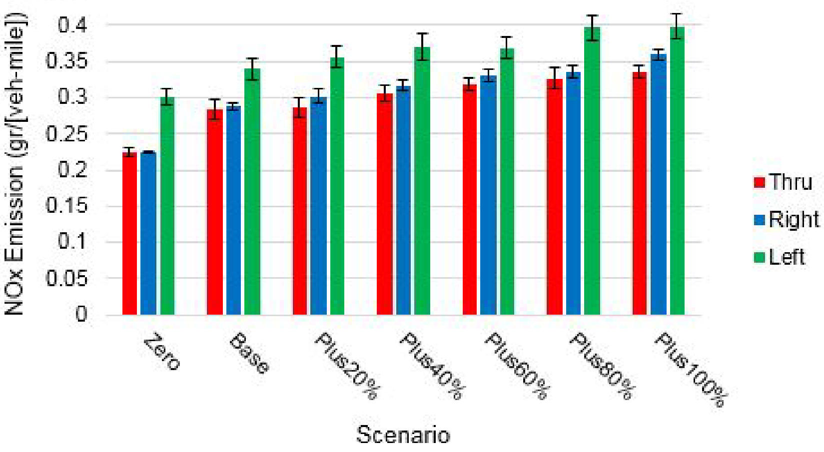


Figure 5. Sensitivity of NOx emissions to pedestrian demand on the entry link

Figure 6 presents the normalized by distance NOx emission rates with respect to distance for scenarios of various pedestrian demand levels on the exit link. As shown in this figure, there is an increase of 18% in the through NOx emission rate when pedestrian demand is present on the exit links. However, no statistically significant changes are observed with higher pedestrian demand volumes on the exit link.

A comparison of the results presented in Figures 5 and 6 reveals higher emission rates for various pedestrian demand scenarios that are higher than the existing demand, when that demand is present on the entry link compared to exit link. This is because cars often have higher speed when entering a roundabout than when exiting a roundabout, which results in higher deceleration rates, and therefore, emissions.

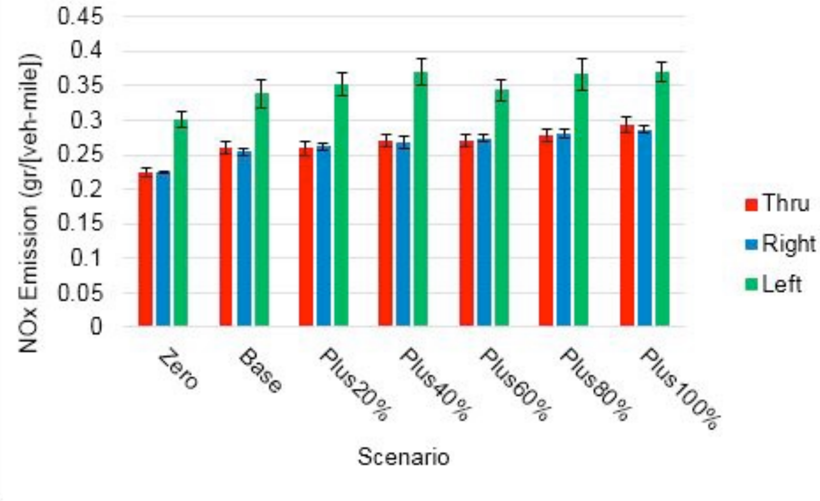


Figure 6. Sensitivity of NOx emissions to pedestrian demand on the exit link

Cellular Automata Model

Three sets of scenarios were performed to study the sensitivity of roundabout emissions:

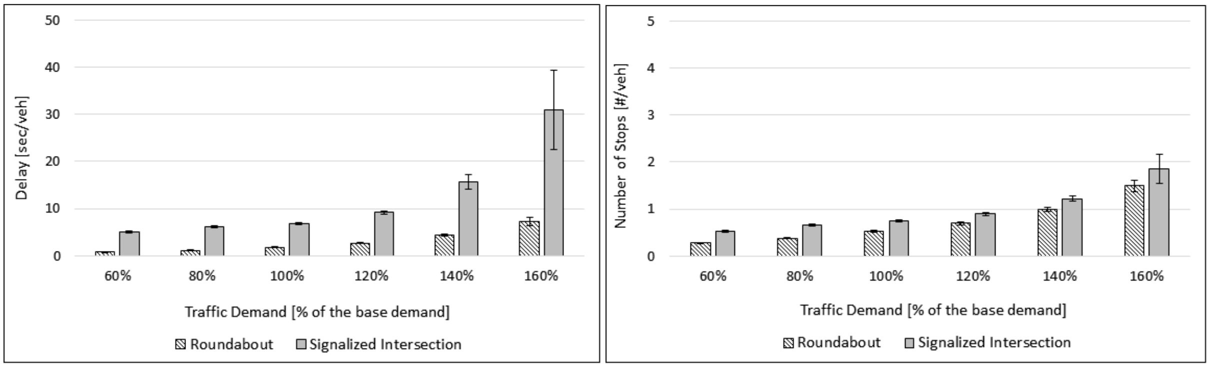
1. varying vehicle demand on all approaches,
2. varying left turn ratio, and

3. varying pedestrian demand on both entry and exit links.

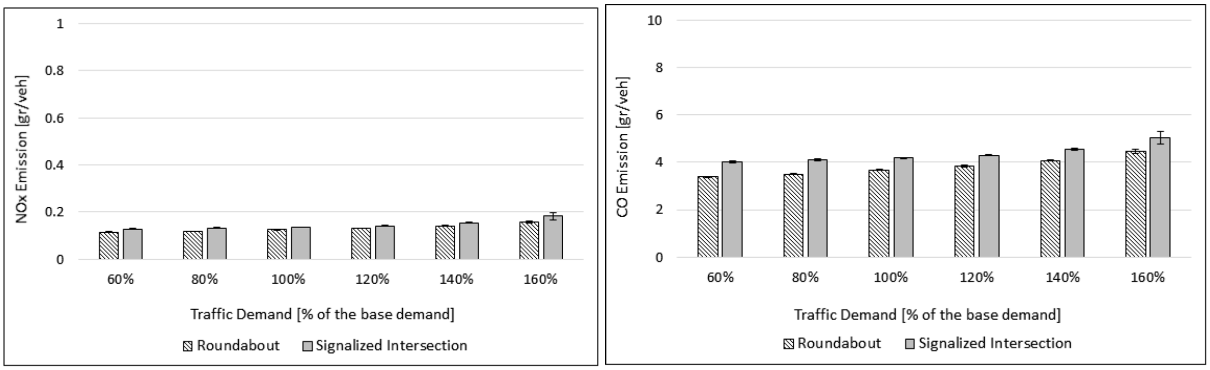
Ten replications were performed for each scenario to account for the randomness in traffic or pedestrian arrivals and each simulation run lasted one hour in addition to a warm up period of 10 minutes. Each scenario was evaluated with regards to several performance measures such as average delay, number of stops, NO_x and CO emissions.

Vehicle Demand

Six vehicle demand scenarios were performed where demand varied from 60% to 160% of the existing demand for all approaches and the results are presented in Figure 7. In particular, Figure 7 presents average delay, number of stops, as well as NO_x and CO emission per vehicle for the entire time of traveling in the network. Figure 7a shows that average delay at the roundabout is considerably improved compared to the signalized intersection. At traffic demand of 60\% of the base demand, average delay at the roundabout is less than 1 sec/veh while average delay at the signalized intersection is 5 sec/veh. The difference between delay at the roundabout and the signalized intersection increases to 23 sec/veh at traffic demand of 160% of the base demand. The reason is that at signalized intersections vehicles may have unnecessary stops and imposed delay due to the red signal.



a) Average Delay b) Average Number of Stops



c) Average NO_x Emissions d) Average CO Emissions

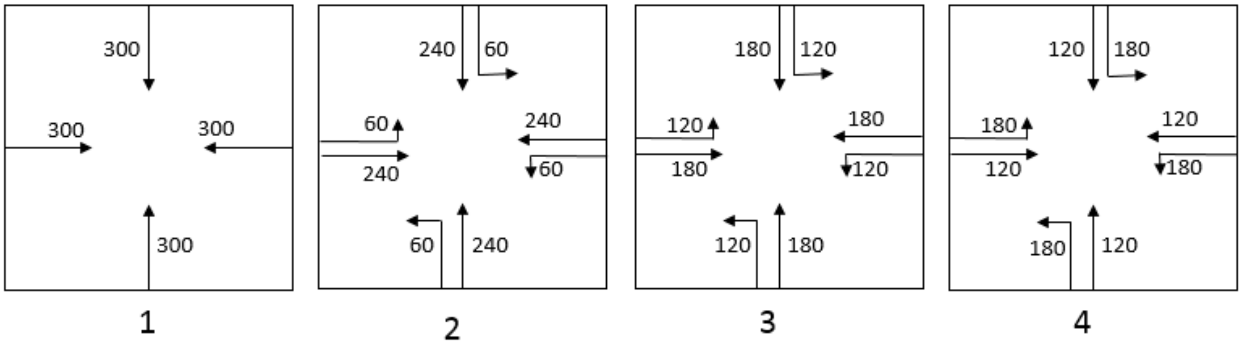
Figure 7. Impact of vehicle demand on performance measures at the roundabout vs signalized intersection

As shown in Figure 7b the number of stops at the roundabout is lower than the signalized intersections for lower traffic demands. As traffic demand increases, the difference between the number of stops at the roundabout and signalized intersection decreases such that there is no statistically significant difference at traffic demand of 160% of the base demand. The reason for this pattern is that at low traffic demands and consequently low conflicting traffic demand traveling within the roundabout, vehicles can travel more smoothly. However, at signalized intersections and low traffic demands, there are always some unnecessary stops due to the red signals even when there is no conflicting traffic. At high traffic demands, the number of stops due to conflicting traffic at roundabouts increases at a high rate.

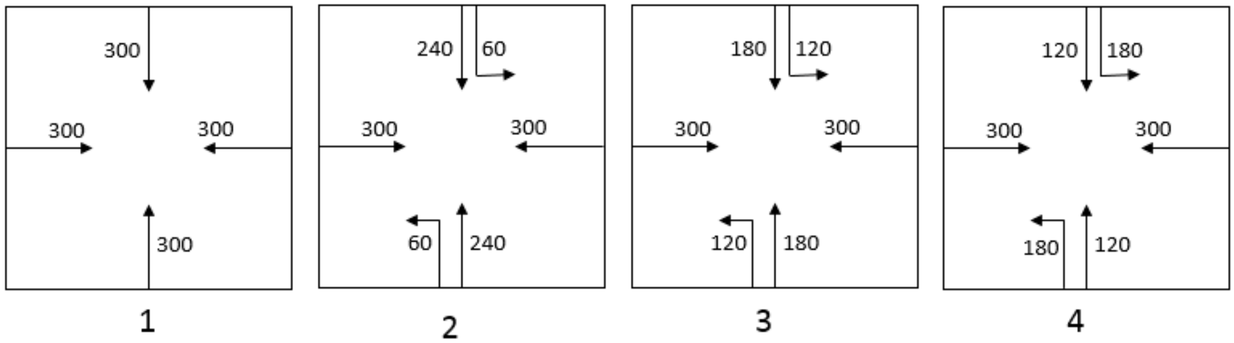
In addition to better operational performance, the roundabout leads to improved NO_x and CO emissions per vehicle at all traffic demands as shown in Figures 7c and 7d. The difference of emissions at roundabouts and signalized intersections is higher for low traffic demands, which is the same pattern as for the number of stops shown in Figure 7b. Both the roundabout and the signalized intersection show small yet statistically significant increases in emissions as the traffic demand increases.

Left Turning Ratio

In order to perform a sensitivity analysis with respect to the left turning ratio, we pursue two types of scenarios: 1) changes in the left turning ratio for only the northbound and southbound approaches and 2) changes in the left turning ratio for all approaches. In the scenario type, the left turning ratio of the northbound and southbound approaches changed as shown in Figure 8a. In the second scenario type, the left turning ratio of all approaches changed as shown in Figure 8b. Note that for all the scenarios the total demand per approach was set equal to 300 vehicles per hour.



a) Varying left turning ratio on northbound and southbound approaches

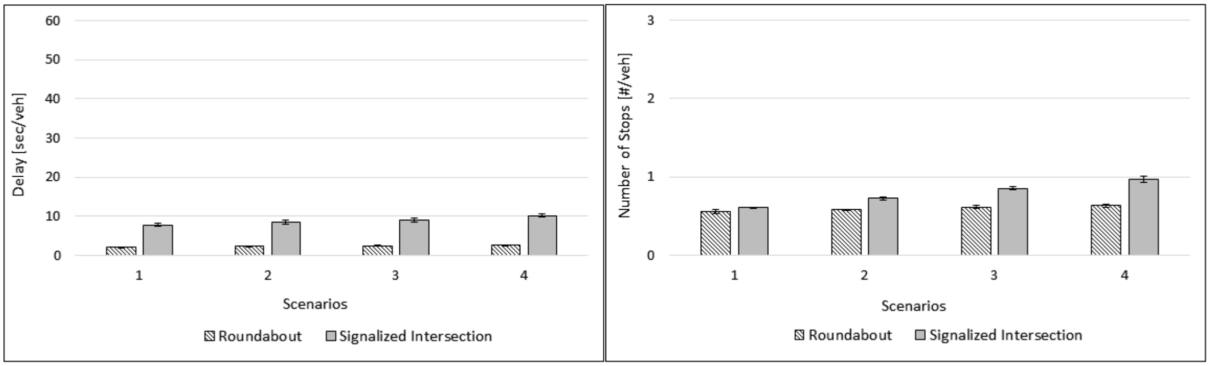


b) Varying left turning ratio on all approaches

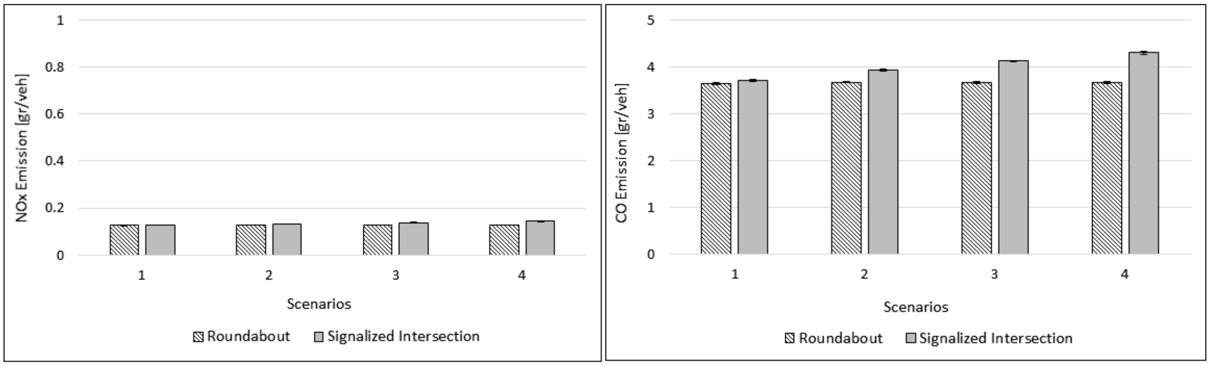
Figure 8. Left turning ratio scenarios

Varying Left Turning Ratio on Northbound and Southbound Approaches

Figure 9 shows that the operational and environmental performance of roundabout does not change with varying left turning ratios for only the northbound and southbound approaches. However, there are small yet statistically significant increases in emissions as well as operational and environmental performance measures at the signalized intersection. Figure 9a shows an increase of 2.3 sec/veh in average delay at the signalized intersection from scenario 1 to 4. Figure 9b also shows that the number of stops at the intersection increases by 0.36 (60%) from scenario 1 to 4. The changes in NO_x emissions are statistically insignificant from scenarios 1 to 4 according to Figure 9c, but Figure 9d shows an increase of 0.6 gr/veh (16%) in CO emissions at the signalized intersection. These results show that roundabouts can better control left turning demand compared to signalized intersections and therefore, they are a promising alternative intersection design at sites with high left turning traffic.



a) Average Delay b) Average Number of Stops



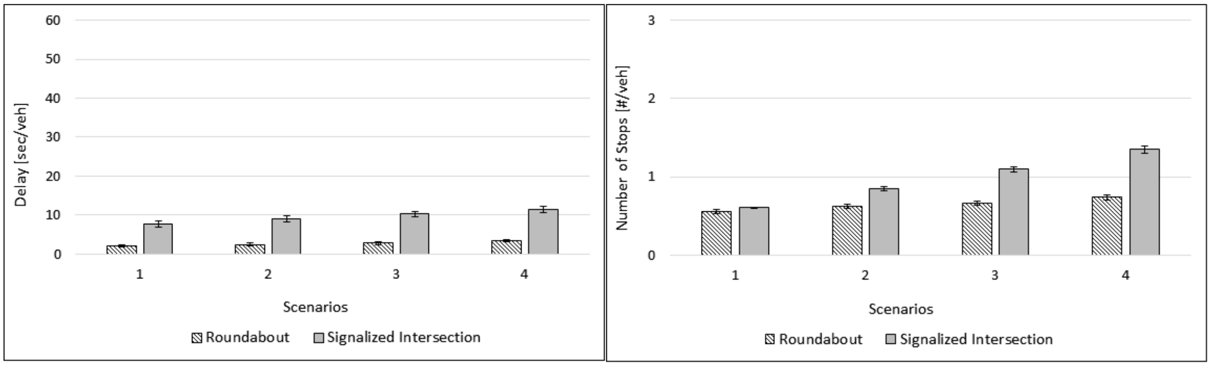
c) Average NO_x Emissions d) Average CO Emissions

Figure 9. Impact of left turning ratio on performance measures at the roundabout vs signalized intersection (when left turning ratio changes on northbound and southbound approaches)

Varying Left Turning Ratio on all Approaches

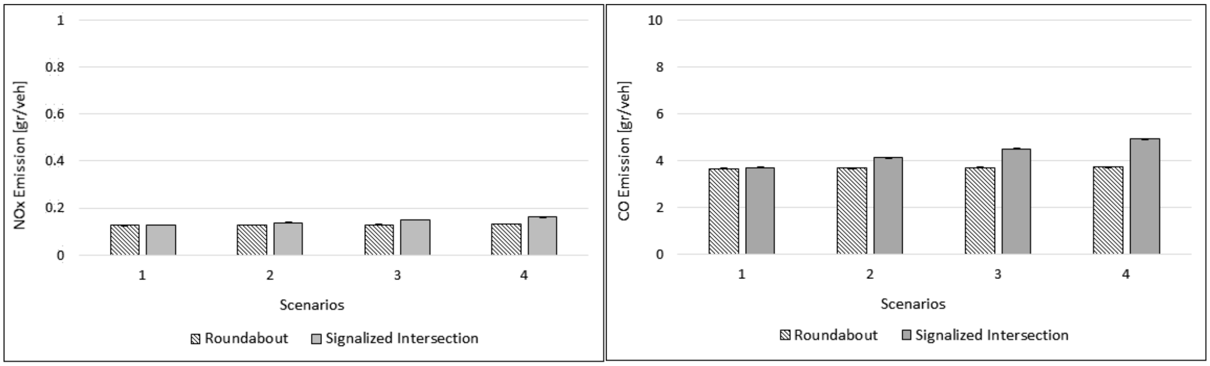
Figures 10a and 10b show that the operational performance of both the roundabout and the signalized intersection is affected by changing left turning ratio on all approaches. Average delay at the roundabout and signalized intersection increases by 1.5 sec/veh and 3.6 sec/veh at the roundabout and signalized intersection, respectively, from scenario 1 to scenario 4. Figure 10b shows that the number of stops increases by 0.2 (34%) at the roundabout and 0.7 (116%) at the signalized intersection. Although average delay, and number of stops increase at both types of intersection designs, the roundabout can better control left turning traffic and results in lower increases in these performance measures.

Furthermore, Figures 10d and 10e show that NO_x and CO emissions at the roundabout are not sensitive to the left turning ratio when overall traffic remains the same. However, NO_x and CO emissions at the signalized intersection increase by 0.04 gr/veh (26%) and 1.2 gr/veh (33%), respectively, from scenario 1 to scenario 4. The reason could be the higher rate of increase in the number of stops at the signalized intersection compared to the roundabout when the left turning ratio increases on all approaches. As before, these tests concluded that roundabouts control left turning traffic more adequately compared to signalized intersections.



a) Average Delay

b) Average Number of Stops



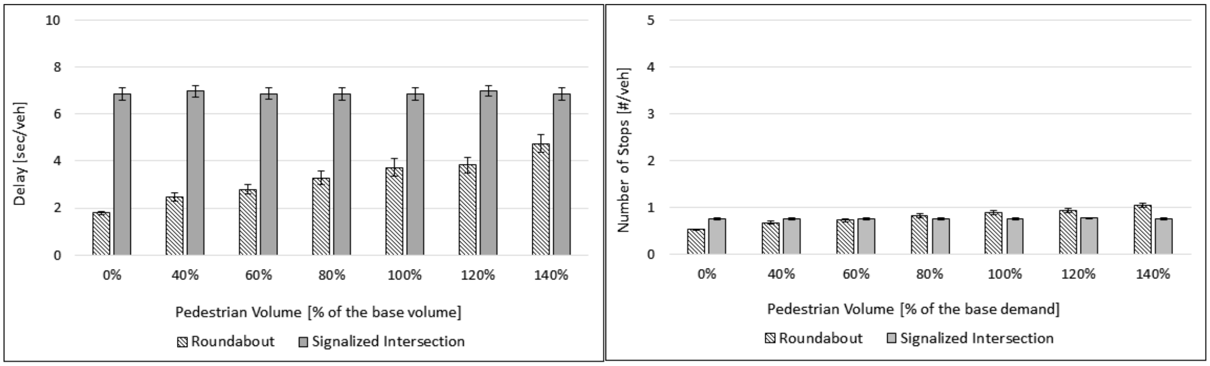
c) Average NO_x Emissions

d) Average CO Emissions

Figure 10. Impact of left turning ratio on performance measures at the roundabout vs signalized intersection (when left turning ratio changes on all approaches)

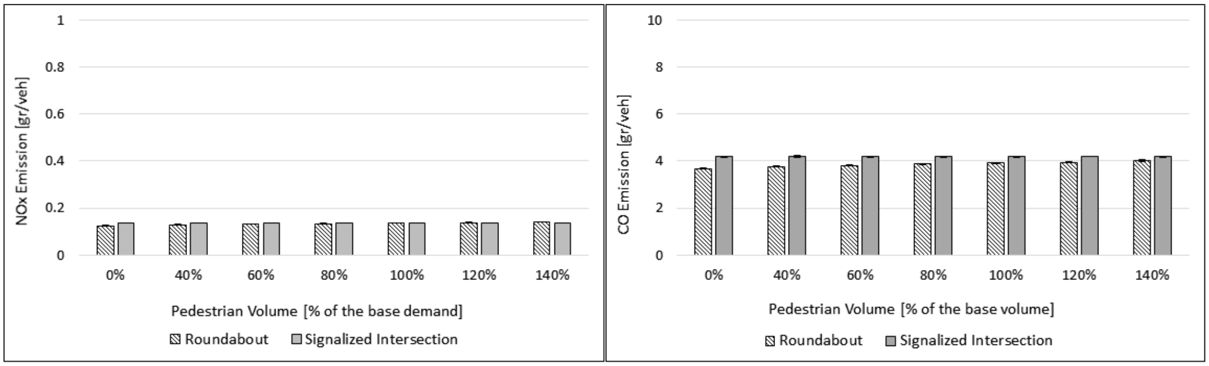
Pedestrian Demand

Various levels of pedestrian volume, 0%, 40%, 60%, 80%, 100%, 120%, and 140% of the base vehicle volume are paired with the base traffic demand in these sensitivity analysis scenarios. Figure 11 shows the sensitivity of performance measures to pedestrian volume at the roundabout and signalized intersection. The performance of the signalized intersection is not affected by increased pedestrian volume across all scenarios. This is because at signalized intersections pedestrians cross the street in the same direction as through traffic on each link. As a result, only right and left turning traffic can be affected by pedestrians, but those impacts are not significant in the current scenarios with the base traffic demand. Unlike signalized intersections, both the operational and the environmental performance of the roundabout is impacted by pedestrian crossings. Increase in pedestrian volume from 0 to 140% of the base volume results in increases in average delay, number of stops, NO_x and CO emissions. Therefore, at sites with high pedestrian volume, the impact of pedestrians on the performance measures should be considered. Despite the sensitivity of the roundabout performance to pedestrian volume, roundabouts have better operational performance in terms of average delay and environmental performance than signalized intersections at the base vehicle traffic demand and for any pedestrian volume.



a) Average Delay

b) Average Number of Stops



e) Average NO_x Emissions

d) Average CO Emissions

Figure 11. Impact of pedestrian volume on performance measures at the roundabout vs signalized intersection

CONCLUSIONS

This study utilized microsimulation and cellular automata models to assess the impact of vehicle and pedestrians demand as well as vehicle demand patterns on the operational and environmental performance of roundabouts vs signalized intersections.

The results of the microsimulation model tests revealed that increases in car or pedestrian demand can have significant impacts on emission rates per vehicle-mile traveled and vary by type of movement. In general, left turning movements result in higher emissions than right or through movements. In addition, in most vehicle demand scenarios, emission rates are more sensitive to increasing pedestrian demand on the entry link than exit one. This could be due to the fact that when vehicles are entering the roundabout have higher speeds than when they are exiting the roundabout.

The CA model tests results revealed that roundabouts are advantageous compared to signalized intersections in terms of both operational and environmental performance for a variety of vehicle and pedestrian demands as well as left turning ratios when operating in undersaturated traffic conditions. In addition, both the roundabout and signalized intersection result in steady increases in the performance measures as total vehicle demand increases. However, a higher rate of change in performance measures is observed at higher traffic demands as the intersection becomes more congested. Furthermore, roundabouts are able to better control left turning traffic compared to signalized intersections. Finally, signalized intersections are not sensitive to the changes in pedestrian volume while delay and number of stops at the roundabout increase significantly as pedestrian volume increases. Despite this fact, the roundabout still has a better performance than the signalized intersection at the base traffic demand and any pedestrian volume in terms of delay and emissions.

The models and results produced by this research project can provide guidance for implementing roundabouts versus signalized intersections based on certain measures of effectiveness such as delay and air pollutant emissions while accounting for the presence of pedestrians.

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