Energy and Environmental Assessment of High-Speed Roundabouts

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Recently, an increased number of roundabouts have been implemented across the United States to improve intersection efficiency and safety. However, few studies have evaluated their energy and environmental impacts. Consequently, this study quantifies the energy and environmental impact of an isolated roundabout on a high-speed road by using second-by-second speed profiles derived from traffic simulation models in conjunction with microscopic energy and emission models. The study demonstrates that, at the intersection of a high-speed road with a low-speed road, an isolated roundabout does not necessarily reduce vehicle fuel consumption and emissions compared with other forms of intersection control (stop sign and traffic signal control). This case study found that the roundabout reduces the delay and queue lengths on the intersection approaches. However, the roundabout results in a significant increase in vehicle fuel consumption and emission levels compared with a two-way stop. The study demonstrates, for this case study, that the roundabout provides efficient movement of vehicles when the approach traffic volumes are relatively low. However, as demand increases, traffic at the roundabout experiences substantial increases in unnecessary delay in comparison with a strategy that uses signalized intersection control.

Recently, an increased number of roundabouts have been implemented across the United States in an effort to improve intersection efficiency and safety. Although the precise number of roundabouts is unknown, approximately 2,000 have been built in the United States, while there are approximately 20,000 in France, 15,000 in Australia, and 10,000 in the United Kingdom (*1*). However, relatively few studies have evaluated the energy and environmental impacts of these roundabouts. Consequently, this study investigates the energy and environmental impacts of an isolated roundabout on a high-speed road by using second-by-second speed profiles derived from traffic simulation models in conjunction with microscopic energy and emission models.

A roundabout is a type of circular intersection that uses yield control to regulate entering vehicles (*2*). While roundabouts emerged as new traffic control approaches in the United States in recent years, the modern roundabout was developed in the United Kingdom to correct problems associated with traffic circles in the 1960s. The new form of junction adopted a right-of-way rule to vehicles at circular intersections, which requires entering traffic to yield to circulating traffic, the addition of a splitter island, and no crosswalks in the circulating path. Moreover, modern roundabouts also involve low speeds for entering and circulating traffic to improve the safety of these facilities. A recent study found that roundabouts are statistically safer than traditional intersection controls because they eliminate or alter conflict types, reduce speed differentials at intersections, and force drivers to decrease speeds as they proceed into and through the intersection (*3*). Furthermore, low speeds associated with roundabouts allow drivers more time to react to potential conflicts.

While traditional intersections force vehicular traffic to slow down and stop, modern roundabouts improve traffic flow and reduce vehicle idling times at intersections. As a result, roundabouts are considered one of the most efficient forms of intersection control for improving fuel economy and vehicle emissions. Furthermore, even when traffic volumes are high, vehicles continue to advance slowly rather than coming to a complete stop, which may improve air quality and produce energy savings by reducing acceleration–deceleration and idling maneuvers (*2*, *4*).

Roundabouts on high-speed approaches (72 km/h or greater) have increased with the development of suburban areas. Traffic control devices in sprawling suburban and rural areas are predominantly connected by higher-speed roadways, and more and more intersections have been replaced by modern roundabouts at these intersections (*5*). While roundabouts may have positive effects on air quality by eliminating longer stops and improving mobility, they also involve operational changes on driver deceleration and acceleration events from and to initial speeds. Thus, there are concerns about possible emission increases due to excessive speed changes for approaching vehicles and the occurrence of partial stops (*6*).

The objectives of this study are twofold. First, the study presents a case study evaluation of the energy and environmental effects of roundabout operations with high-speed approaches. Specifically, the study investigates whether modern roundabouts are appropriate at intersections with high-speed approaches from an environmental perspective. A case study site that currently operates as a two-way stop-control intersection was selected. Second, the study compares the operational efficiency of a two-way stop control, a roundabout, a fixed-time traffic signal at an isolated intersection in relation to travel time, fuel consumption, and emissions. This study compares the feasibility of a roundabout and a strategy for fixed-time traffic signal control at the study site from an environmental perspective.

OVERVIEW OF ENVIRONMENTAL IMPACTS OF ROUNDABOUTS

Very few studies have investigated the energy and environmental effects of roundabouts. *Roundabouts: An Information Guide* (*2*) by the FHWA and the *Status Report* on roundabouts by the Insur-

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ance Institute for Highway Safety (*7*) briefly mention that roundabouts might cut vehicle pollution and fuel consumption compared with alternatives by reducing vehicle delay and idling times at intersections. Specifically, the reports claim that traffic through roundabouts produce fewer vehicle emissions and consume less fuel than traffic at fixed-time signalized intersections. Redington concluded that roundabouts provide a significant potential for conserving energy, reducing air pollutants, and addressing global warming (*8*). That study investigated multiple case studies and concluded that newly installed roundabouts could provide considerable environmental benefits. For example, a Clearwater, Florida, study found that roundabouts could produce savings in vehicle emissions by up to 68% compared with intersections controlled by traffic signals (*8*).

Alternatively, studies conducted in Sweden showed that roundabouts increased CO (carbon monoxide) and NO_x (nitrogen oxide) emissions by 4% to 6% relative to yield-regulated intersections and reduced emissions by 20% to 29% relative to intersections controlled by traffic signals (*9, 10*). However, a similar study using floating cars in a before–after study found that converting a signalized intersection into a roundabout produced savings in CO, NO_x, and fuel consumption by 29%, 21% and 28%, respectively (*11*). Swiss researchers also evaluated the environmental and energy impacts of roundabouts by using a portable emission measurement system or mobile exhaust gas measurement apparatus on a single vehicle. The study concluded that roundabouts resulted in increases in vehicle fuel consumption and emissions relative to traffic signal control. In addition, increased deceleration and acceleration maneuvers at roundabouts resulted in higher fuel consumption and emission levels (*12*).

Coelho et al. (*6*) estimated emissions using a vehicle-specific power method with congestion-specific speed profiles on roundabout approaches in urban corridors in Lisbon, Portugal, and Raleigh, North Carolina. The study concluded that roundabouts increase vehicle emissions. When conflicting traffic is low, emissions are increased because the acceleration levels to cruise speeds appear to be high. The study concluded that, as the difference between the approaching speeds and circulating speeds became larger, emissions substantially increased due to the increased acceleration rates. Researchers from Kansas State University investigated the environmental impacts of modern roundabouts with SIDRA software (*4*). The study found that roundabouts could save HC (hydrocarbons), CO, NO_x, and CO_2 (carbon dioxide) emissions by as much as 65%, 42%, 48%, and 59%, respectively, relative to stop-controlled intersections.

In summary, the literature presents mixed results on the environmental impacts of roundabouts. These differences could be a result of differences in data collection methods, road characteristics, vehicle demands, and emission estimation methods. Previous studies did not consider roundabouts with high-speed approaches. Furthermore, most studies used aggregate characteristics without considering driving patterns of individual vehicles and their associated impact on vehicle energy consumption and emission levels. In an attempt to overcome the limitations of previous studies, this study employs two widely used microscopic traffic simulation models, INTEGRATION and VISSIM, to replicate realistic driving behavior and mimic deceleration and acceleration events at a roundabout, stop sign, and signalized intersection. The proposed study investigates the energy and environmental effects of a roundabout through use of microscopic emission models together with second-by-second speed profiles from the traffic simulation models.

METHODOLOGY

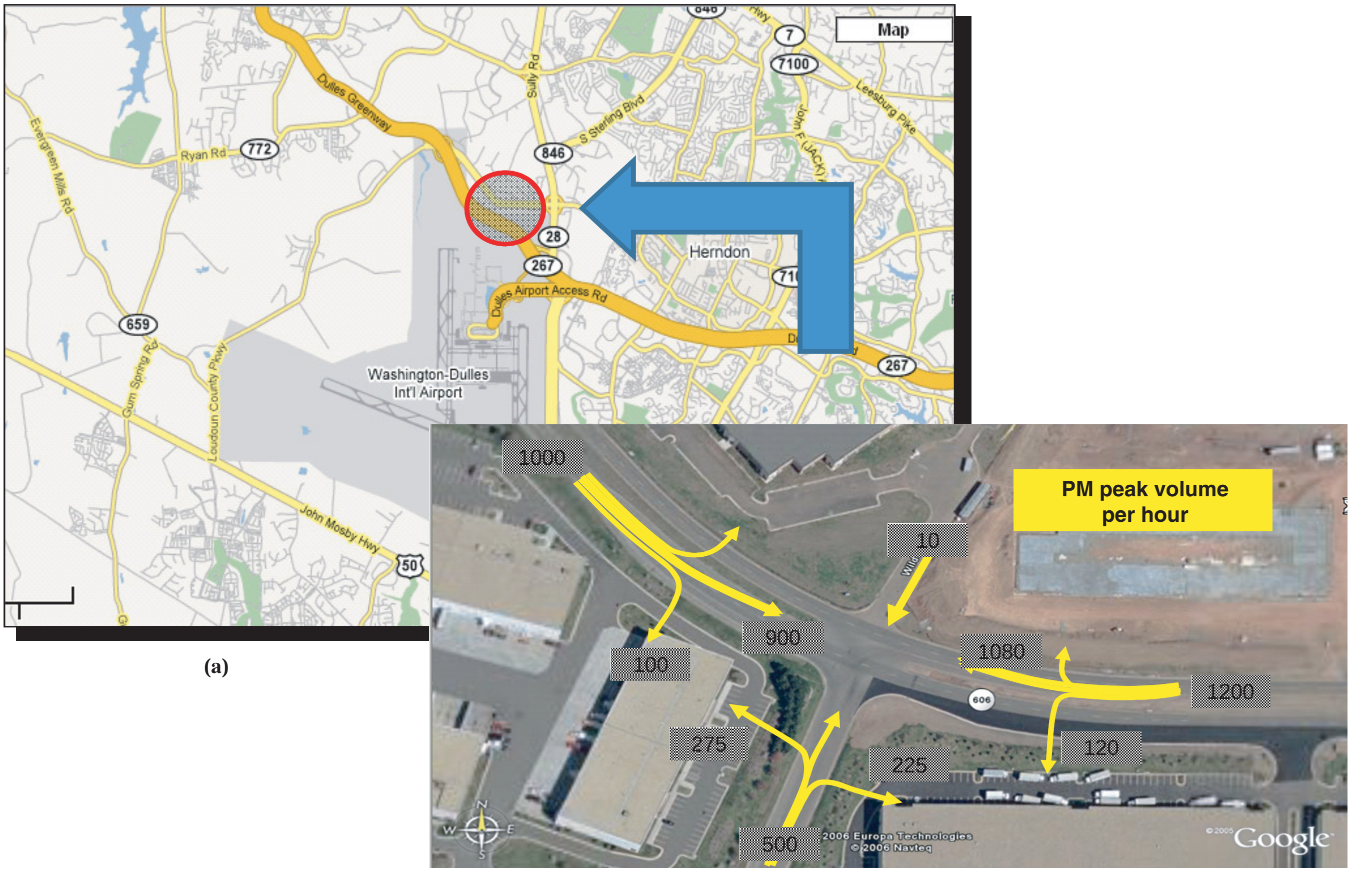
Various methods and techniques can be employed to evaluate the energy and environmental impacts of roundabouts. The main components of the study are twofold. First, there must be understanding of driving patterns of vehicles for different intersection control strategies, including stop signs, traffic signals, and roundabouts. Second, measurements or estimates of vehicle fuel consumption and emissions are required. The information on driving patterns includes speed, acceleration and deceleration levels, travel times, and vehicle delays (or stopping time). The general methodologies to measure or estimate driving patterns include field measurements and simulations that use computer-based microsimulation methods. In addition, to capture the changes in driving behavior during different traffic controls, it is essential to represent individual vehicles realistically. However, it is almost impossible to collect speed profiles of all approaching vehicles for various intersection control strategies. Consequently, microscopic traffic simulation was used: the INTEGRATION and VISSIM software were employed to simulate driving patterns at the study site. Both simulation packages have not only been validated against standard traffic flow theory but have been used for evaluation of real-life applications.

To quantify the energy and environmental impact of various traffic control strategies, vehicle fuel consumption and emission levels should be measured or predicted. Dynamometer testing or on-road emission measurement (OEM) equipment is widely used to measure real-time emissions from vehicles. Though both methods are relatively accurate in measuring vehicle emissions in laboratories and in the field, emission measurements from dynamometers and OEMs are limited to only a few test vehicles. Without the use of sufficient test vehicles, fuel consumption and emission data collected by means of these techniques are limited. Thus, fuel consumption and emission models that can represent general vehicle fleets are considered in this study.

Several methods and techniques can be used to predict accurate fuel consumption and emission levels. The state of the practice is to use simple methodologies such as average speed methods to estimate fuel consumption and emission rates. However, this approach does not consider transient changes in a vehicle's speed and acceleration as it travels on a road, which produce significant contributions to fuel consumption and emission levels. Specifically, a roundabout involves significant speed changes with various deceleration and acceleration events. Consequently, the usage of traditional average speed models cannot capture these effects on vehicle emissions. Therefore, this study employs microscopic fuel consumption and emission models that can estimate instantaneous vehicle emissions. The use of microscopic energy and emission models with second-by-second vehicle speed profiles may result in unreasonable energy and emission estimates at high speed and acceleration levels. Thus, to overcome this possible weakness, the study plan ensured that speed and acceleration levels were within the confines of the models.

CASE STUDY SITE

A two-way stop-controlled intersection was selected for this study. The site is at the intersection of VA-606 and Ariane Way in Loudoun County, Virginia, and is adjacent to Dulles International Airport, which serves Washington, D.C. (Figure 1). The intersection is frequently used as an alternative access point to Dulles Airport and experiences high traffic volumes during peak hours. The posted speed limit is 88 km/h



(a)

(b)

FIGURE 1 Study site: (*a*) Dulles International Airport and surrounding area and (*b*) intersection with roundabout.

for eastbound and westbound traffic on VA-606. Northbound and southbound traffic on Ariane Way has a 40 km/h speed limit and is controlled by two-way stop signs. Figure 1 also illustrates the traffic volumes at the intersection during an average p.m. peak hour. As shown, very few vehicles enter and exit to the northern side and thus the intersection operates more as a T-intersection. The VA-606 corridor section is a divided four-lane highway (two lanes per direction) with an extra left-turn lane on each approach, while the northbound approach from Ariane Way has only two lanes: a left-turn lane and a right-turn lane.

During nonpeak hours, the traffic volume is fairly low and the two-way stop-controlled intersection is operated without any significant delays. However, as traffic volume increases during peak hours, travel times increase substantially. Specifically, northbound traffic (from Ariane to VA-606) is typically more congested than other portions of the intersection. The northbound left-turn volume is controlled by a stop sign and typical queue lengths at Ariane Way range between 10 and 15 vehicles during p.m. peak hours. In addition, left-turn vehicles from Ariane Way are forced to make aggressive gap acceptance maneuvers, typically accepting gaps ranging from 3 to 5 s in size through the high-speed approaching traffic stream from VA-606. To reduce intersection delay and enhance intersection safety, local transportation professionals explored the feasibility of a modern roundabout. This study investigated the feasibility of alternative intersection control strategies on various measures of effectiveness, including energy and environmental impacts.

TRAFFIC SIMULATION MODELS

Traffic simulation is increasingly being used to assess traffic operations for many types of applications. The INTEGRATION and VISSIM software were employed for this study. Both microscopic traffic simulation software have been used and validated for a number of traffic control applications. They both can provide reasonable assessment of how a proposed intersection or a roundabout may operate. Simulating traffic control applications by using both INTEGRATION and VISSIM can replicate realistic driving behavior and mimic deceleration–acceleration events at a roundabout, stop sign, and signalized intersection.

The simulation models were constructed by means of parameters derived from field data. Only passenger cars were used for both simulation models in this study. The field-collected information included the number of lanes, lane striping, traffic volumes, free-flow speed, saturation flow rate, jam density, and queue length. In particular, all links were coded for a base saturation flow rate of 1,800 veh/h/lane and a jam density of 120 veh/km/lane, with an exception for the northbound approaches, which experience aggressive driving behavior due to excessively long queues. A saturation flow rate of 2,000 veh/h/lane was used for the northbound approach. The speeds at capacity were not measured from the study site. The speeds at capacity were varied from 80% to 100% of the free-flow speed on typical North American roads (*13*). Thus, for INTEGRATION, the speed at capacity was coded at 90% of the free-flow speed of each link to represent the typical speed–flow relationship on U.S. roads (*13, 14*). However, for VISSIM software, which uses Weidemann models, the default value was used for the speed at capacity, which equals the free-flow speed, because there is no parameter to adjust the speed at capacity. The base gap was set between 3 and 4 s for modeling of opposed saturation flow rates. The simulation models were calibrated with field data and validated against side street queue length. Each 60 min simulation run was executed for each scenario with both INTEGRATION and VISSIM.

Figure 2 compares the field-observed side street queue lengths for the northbound left-turn approach to the simulation model estimates. This approach was selected because the movement suffers from excessively long delays as a result of the stop sign control. As Figure 2 shows, the queue sizes generated from the simulation show good agreement with the field-observed queue length data, indicating that the simulation models reasonably replicate the p.m. peak traffic condition for the study corridor. In particular, it was observed that the simulated queue lengths were within the range of the observed queue length, 10 to 15 vehicles. Figure 2 also shows that the simulation results were in good agreement relative to travel time trends and absolute values. Specifically, the eastbound and westbound travel times of both simulation models were similar, with a difference of 4 s, while the travel time difference for the northbound left-turn vehicles was more significant at 2 min.

Figure 3 compares the queue length on the northbound left-turn approach and travel times for major movements for the proposed roundabout and signalized intersection. For both scenarios, the INTEGRATION and VISSIM model inputs were identical to the stop sign alternative. However, the base unopposed saturation flow rate of the northbound approach was reduced to 1,800 veh/h/lane because vehicles would not be as aggressive with the improvement of traffic conditions. The signalized intersection was designed with two-phase movements (eastbound–westbound and northbound–southbound) and a 35-s cycle length, with a 77:23 phase split. The optimum cycle length and green split were estimated on the basis of the level of traffic demand. In the case of the roundabout design, the entry speed of 50 km/h and a diameter of 60 m were used and were based on recommendations from *Roundabouts: An Information Guide* (*2*).

The simulation results demonstrate that the queue lengths on the northbound approach were significantly reduced in the case of a roundabout or a traffic signal, as illustrated in Figure 3. Specifically, the VISSIM results demonstrate that both the roundabout and the signalized intersection reduce the average queue length to 1 and 3 m, respectively, from 118 m in the case of the stop sign. Similarly, the results of the INTEGRATION software show that replacing a two-way stop sign intersection with a roundabout or a signalized intersection can cut the queue length by as much as 84 m or 10 vehicles. The simulation study shows that substituting a two-stop sign control with a roundabout or a traffic signal may increase travel times for the through traffic by less than 6 s per vehicle. However, the figure clearly demonstrates that the alternative traffic controls significantly reduce travel time by as much as 220 s per vehicle on the northbound approach. Figures 2 and 3 illustrate similarities with and discrepancies

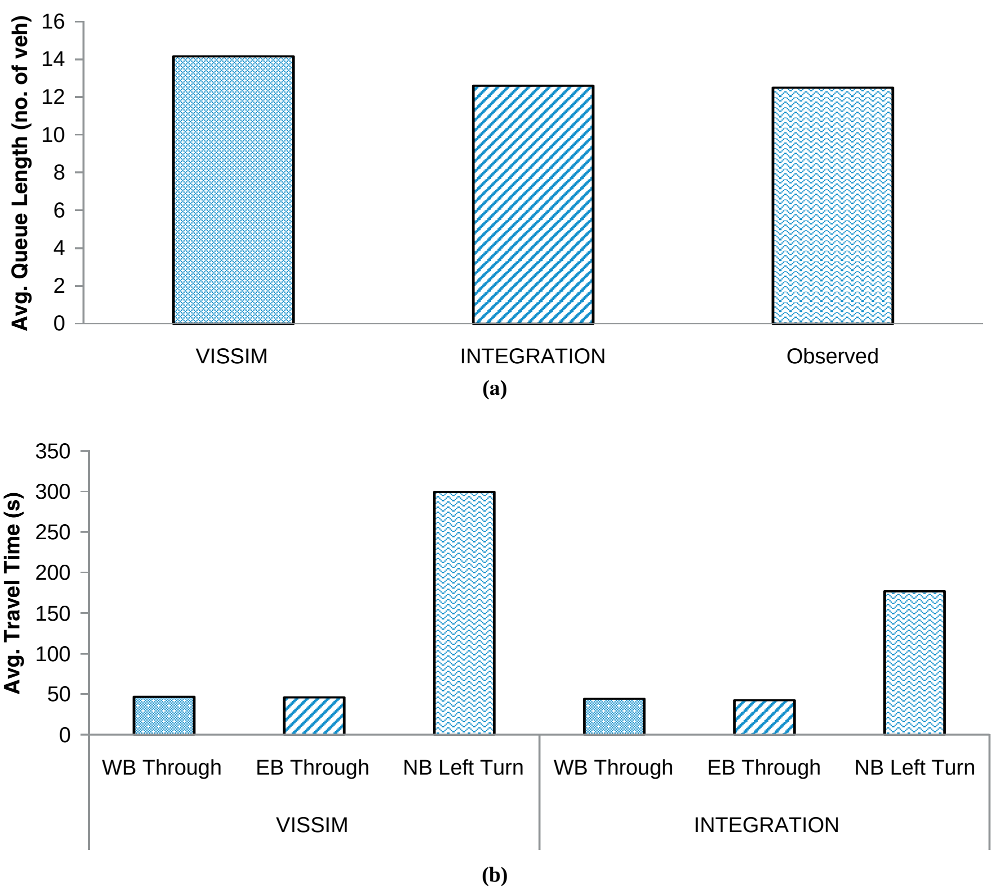
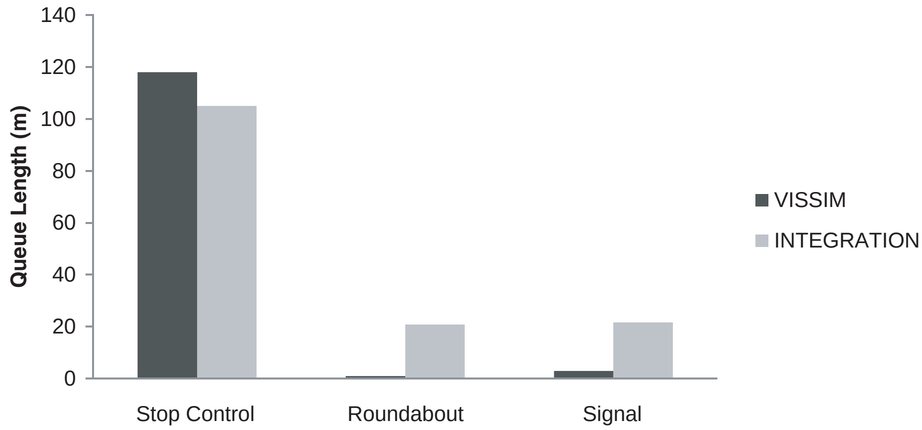


FIGURE 2 Validation of simulation model: (*a*) average queue length and (*b*) average travel time.



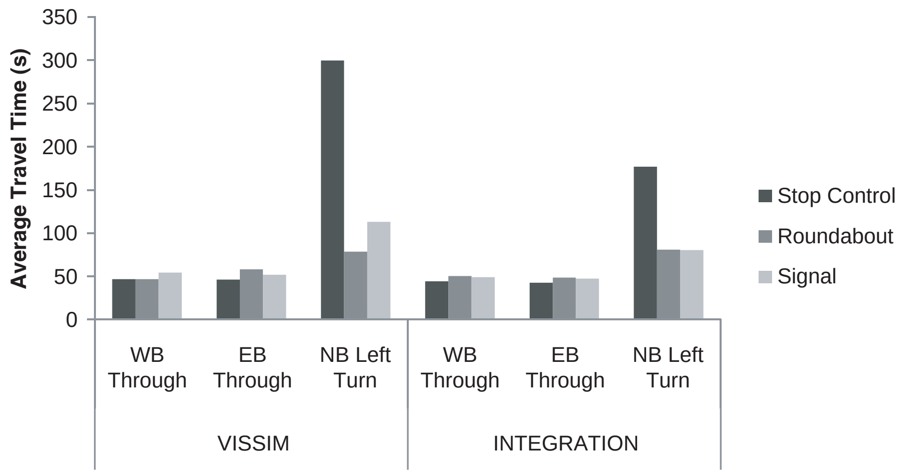


FIGURE 3 Comparison of alternative traffic controls: (*a*) for queue length and (*b*) for average travel time.

between the results of two simulation models. Both the VISSIM and INTEGRATION software incorporate similar psychophysical approaches, which account for vehicle acceleration constraints. However, because each simulation model was developed by means of different car-following models and other underlying logics, each model generates slightly different results. Indeed, a detailed description of the model comparison is beyond the scope of this study but appears in the literature (*13*).

A comparison of different measures of effectiveness, computed by using the INTEGRATION software, including the number of vehicle stops and average intersection delay, is demonstrated in Figure 4. Both the traffic signal and roundabout marginally increased the average number of vehicle stops. The computation of vehicle stops included both complete and partial stops (*15*). The increased number of stops in the case of a roundabout was caused by the partial stops incurred to vehicles approaching the roundabout. However, the increase in vehicle stops did not necessarily increase the total delay, as shown in Figure 4. The simulation results demonstrate that the proposed roundabout reduces the total delay by as much as 64%, from 15.8 to 5.6 s. The roundabout is more effective than the signalized intersection, eliminating 34% of the total delay during the p.m. peak. In summary, a roundabout installation can generate reductions in vehicle delay and enhance the capacity of high-speed intersections.

ENERGY AND EMISSION MODELS

The VT-Micro model and the comprehensive modal emissions model (CMEM) were used to estimate vehicle fuel consumption and emission levels by using second-by-second speed profiles derived from the simulation runs. The VT-Micro mathematical model estimates vehicle fuel consumption and emission levels for individual vehicles, composite vehicles, or both by using instantaneous speed and acceleration as explanatory variables. The VT-Micro model was developed as a regression model from experimentation with numerous polynomial combinations of speed and acceleration levels to construct a dual-regime model of the form. The model was developed by using a number of data sources, including data collected at Oak Ridge National Laboratory (ORNL) (nine vehicles) and

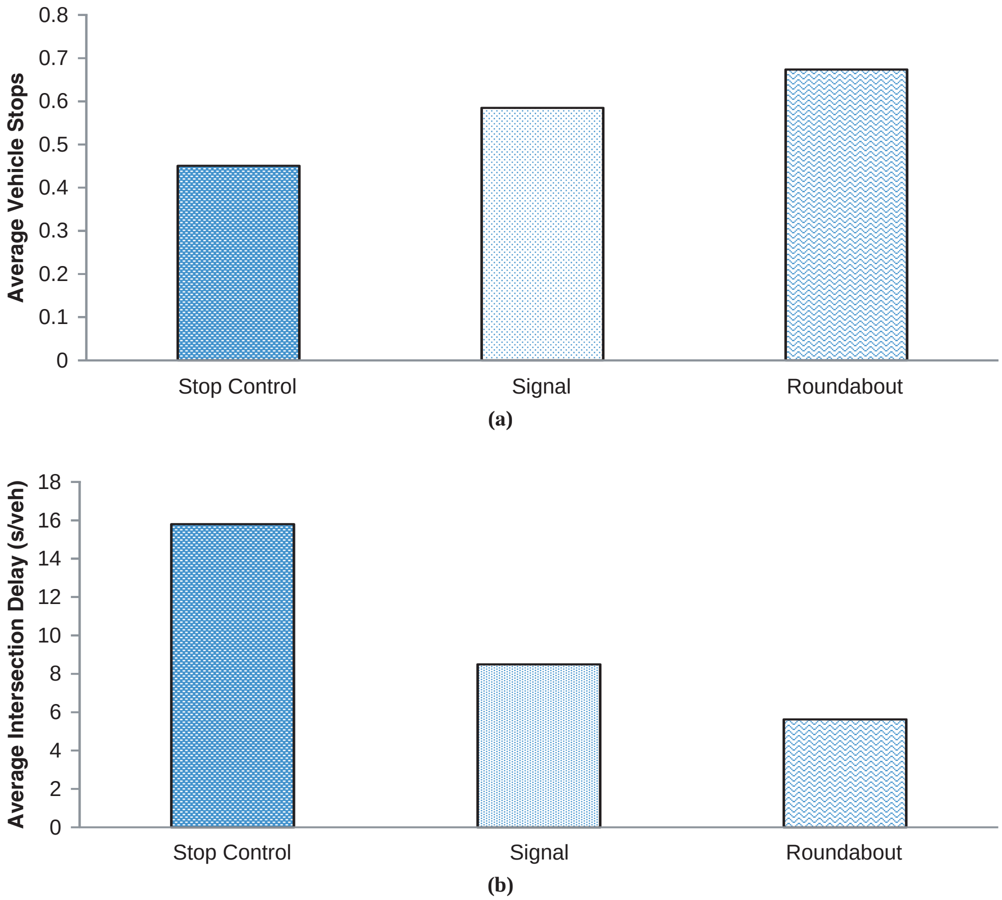


FIGURE 4 Comparison of alternative traffic controls: (*a*) average vehicle stops and (*b*) average intersection delay.

at the U.S. Environmental Protection Agency (101 vehicles). In this study, an average composite vehicle for the nine ORNL vehicles was used. This composite vehicle included six light-duty automobiles and three light-duty trucks (LDTs). These vehicles were selected so as to produce an average vehicle that was consistent with average vehicle sales relative to engine displacement, vehicle curb weight, and vehicle type at the time the data were gathered. The VT-Micro model fuel consumption and emission rates were found to be highly accurate compared with the original data, with coefficients of determination (R^2) ranging from .92 to .99. The model is easy to use for the evaluation of the environmental impacts of operational-level projects, including intelligent transportation systems (*16*, *17*).

The CMEM was developed by researchers at the University of California, Riverside. CMEM estimates light-duty vehicle (LDV) and LDT emissions as a function of the vehicle's operating mode. The term "comprehensive" is used to reflect the ability of the model to predict emissions for a wide variety of LDVs and LDTs in various operating states. CMEM predicts second-by-second tailpipe emissions and fuel-consumption rates for a wide range of vehicle and technology categories. Vehicle operational variables (such as speed, acceleration, and road grade) and model-calibrated parameters (such as cold-start coefficients and engine-friction factor) are used as input data (*18*). To estimate fuel consumption and emissions, CMEM vehicle Category 11 was used. Category 11 represents Tier 1, relatively new low-mileage vehicles that reflect low-emitting passenger cars.

ENVIRONMENTAL IMPACT OF ROUNDABOUT

Because the INTEGRATION software includes the VT-Micro model, the energy and environmental outputs are generated automatically; however, for the VISSIM software, the VT-Micro model was applied as a postprocessor that used individual second-by-second vehicle speed profiles. In addition, fuel consumption and emissions were also estimated by using the CMEM model, which considered the speed profiles generated by the INTEGRATION and VISSIM software.

Figure 5 demonstrates that the fuel consumption increased by 13% and 8% when the intersection with stop sign control is replaced with the proposed roundabout or a signalized intersection, respectively, on the basis of VISSIM speed profiles and the VT-Micro fuel consumption and emission estimates. Similarly, the output of the CMEM model demonstrates that the intersection with stop sign control can reduce fuel consumption by more than 18% relative to a roundabout installation on the basis of both the INTEGRATION and VISSIM software. These trends are consistent across the two software results.

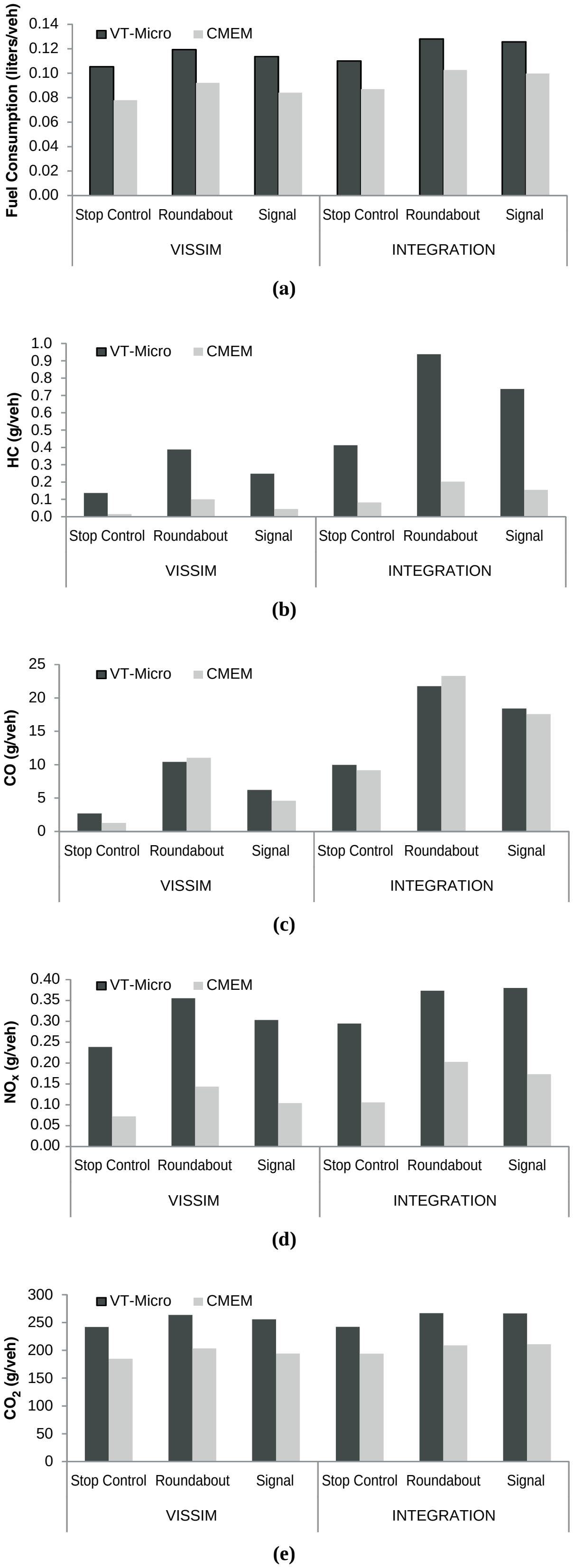


FIGURE 5 Comparison of fuel consumption and emissions variables estimates for VISSIM and INTEGRATION models: (*a*) fuel consumption, (*b*) HC emissions, (*c*) CO emissions, (*d*) NO_x emissions, and (*e*) CO_2 emissions.

Figure 5 also illustrates the environmental impact of the proposed roundabout and signalized intersection on HC, CO, NO_x, and CO_2 emissions. The figure demonstrates that both the roundabout and the traffic signal produce significant increases in vehicle emissions. In particular, the roundabout generates 155%, 203%, 38%, and 10% higher HC, CO, NO_x, and CO_2 emissions, respectively, while the signalized intersection is responsible for an extra 80%, 108%, 28%, and 8% of HC, CO, NO_x, and CO_2 emissions, respectively, on the basis of the VT-Micro model. Furthermore, with results similar to those of the VT-Micro model, the CMEM model estimated that HC, CO, NO_x, and CO_2 emissions were increased 344%, 456%, 95%, and 9%, respectively, when the roundabout was operated instead of the stop control. These results demonstrate that the roundabout tends to increase fuel consumption and emission levels relative to a signalized intersection control, as shown in Figure 5, even though the roundabout effectively reduces the long queues and delays on the minor approach.

In this study, the absolute values of fuel consumption and emissions are not of much concern given the potential for differences depending on vehicle characteristics; however, the intent of this paper is not to derive definitive fuel consumption and emission inventories but to demonstrate the relative energy and emission differences associated with various traffic controls. Indeed, because each emission model is based on a different data set, it generates different fuel consumption and emission values. As illustrated in Figure 5, the VT-Micro model estimates significantly higher fuel consumption and emission levels than the CMEM model. In this study, the Category 11 vehicle type of the CMEM model was used and represents relatively low-mileage passenger cars, while the VT-Micro model used both passenger cars and LDTs. However, Figure 5 shows that the trend of the results from the VT-Micro model are consistent with that of the CMEM model because both models are designed to capture second-by-second operational behavior.

Figure 6 illustrates sample speed profiles of vehicles traversing the roundabout. The speed profiles from both the INTEGRATION and VISSIM software involve a deceleration maneuver followed by an acceleration maneuver as the vehicles approach the roundabout and yield to traffic there. The sample vehicles were selected randomly; however, they have a travel time of 47 s, which is nearly identical to the average travel time of the westbound traffic. The figure illustrates the sample vehicles that travel at 88 km/h, reduce their speeds to 50 km/h before entering the roundabout, and then accelerate to 88 km/h after leaving it. Both simulation models demonstrate a reasonable representation of real-world driving patterns.

Figure 6 also illustrates the variations in the instantaneous vehicle fuel consumption and HC emission rates as estimated by the VT-Micro and the CMEM models. The figure shows the peaks and valleys of the instantaneous vehicle fuel consumption and HC emission rates, demonstrating that the measures of effectiveness are sensitive to changes in a vehicle's speed and acceleration profile. While both the INTEGRATION and VISSIM trips have similar driving patterns at the roundabout, the INTEGRATION driving profile generates higher fuel consumption and HC emissions than the VISSIM profile. The higher fuel consumption and emission rates are a result of the slightly higher acceleration levels of the vehicles leaving the roundabout.

Figure 7 illustrates the two sample profiles for vehicles turning left from the northbound approach. The figure demonstrates the driving behavior at the roundabout, where vehicles make a complete stop before entering the roundabout and then accelerate to the free-flow

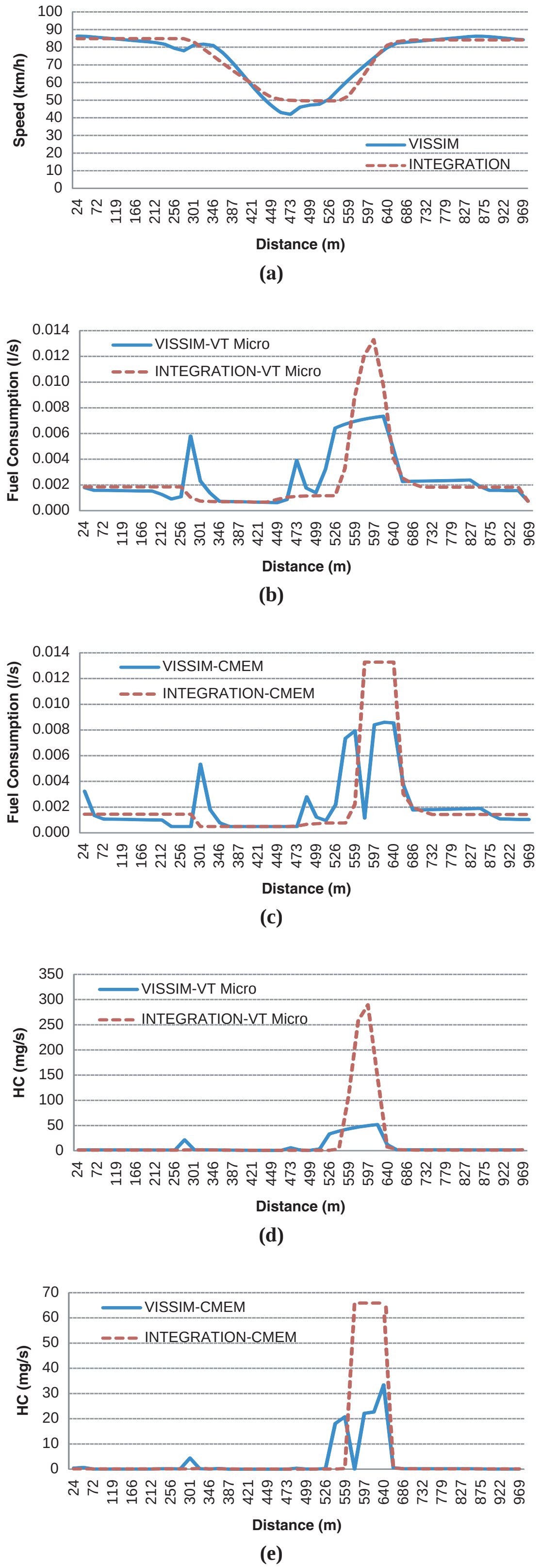


FIGURE 6 Comparison of speed and fuel variables for VISSIM and INTEGRATION models for a sample through-vehicle at roundabout: (*a*) speed, (*b*) fuel consumption for VT-Micro model, (*c*) fuel consumption from CMEM model, (*d*) HC emissions from VT-Micro model, and (*e*) HC emissions from CMEM model.

speed after circling the roundabout. As the figure shows, after the vehicles traverse the roundabout, CO emissions are increased significantly. As much as several hundred times as many CO emissions were observed when the vehicles accelerate, demonstrating that emissions were significantly affected by the various acceleration–deceleration cycles in the vicinity of the roundabout. The figure clearly shows that the vehicle speed profiles generated by the two software programs are quite similar.

IMPACT OF INCREASED DEMAND

This section quantifies the impact of a roundabout at different levels of congestion. While the proposed roundabout significantly reduces the total delay relative to other traffic control strategies, varying the congestion level could produce different results and possibly identify the range of feasible traffic demands for such a control strategy. In the analysis, through-traffic demands were increased by up to 150% at increments of 25%. The increased demands were assigned to both the eastbound and westbound traffic flows from the western (or eastern) end to the eastern (or western) end. In addition, traffic signal timings were optimized for each traffic demand level. The INTEGRATION software with the VT-Micro model was used for this analysis.

Figure 8 compares the total delay for a roundabout, an intersection controlled by a two-way stop, and a signalized intersection as the through-traffic demand increases. The figure shows that, as the traffic volume increases, the average delay generally increases for all three controls. As the figure shows, a roundabout is most efficient when the demand is increased by up to 50%. However, if the demand is increased further, a signalized intersection effectively minimizes the total delay, while a roundabout produces a substantial increase in unnecessary delay. The figure also illustrates the results for CO emissions for the increased through-traffic demands. In a similar fashion to the base case, a roundabout produces the highest CO emissions, while a stop-controlled intersection generates the least CO emissions. The results demonstrate that the total CO emissions are significantly increased as the traffic demand increases.

The impacts of increased total demands are further illustrated in Figure 9. The total demand was increased in increments of 25% of the original demand up to 100%. In a similar way to the previous results, a roundabout operates effectively only when the traffic demands are relatively low, up to a 25% increase in total demand. Moreover, if the total demand is increased, the signalized intersection becomes the most appropriate control strategy. In the case of CO emissions, the general trends of CO emissions are consistent with the total delay. Similarly, a roundabout generates the highest CO emissions with an increase in traffic demands, while a stop controlled intersection is the most environmentally friendly control strategy.

CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

This study demonstrates that, for the specific example illustration, an isolated roundabout on high-speed approaches does not necessarily produce savings in systemwide vehicle fuel consumption and emission levels relative to other intersection control strategies (stop sign control and traffic signal). In particular, the study site that included

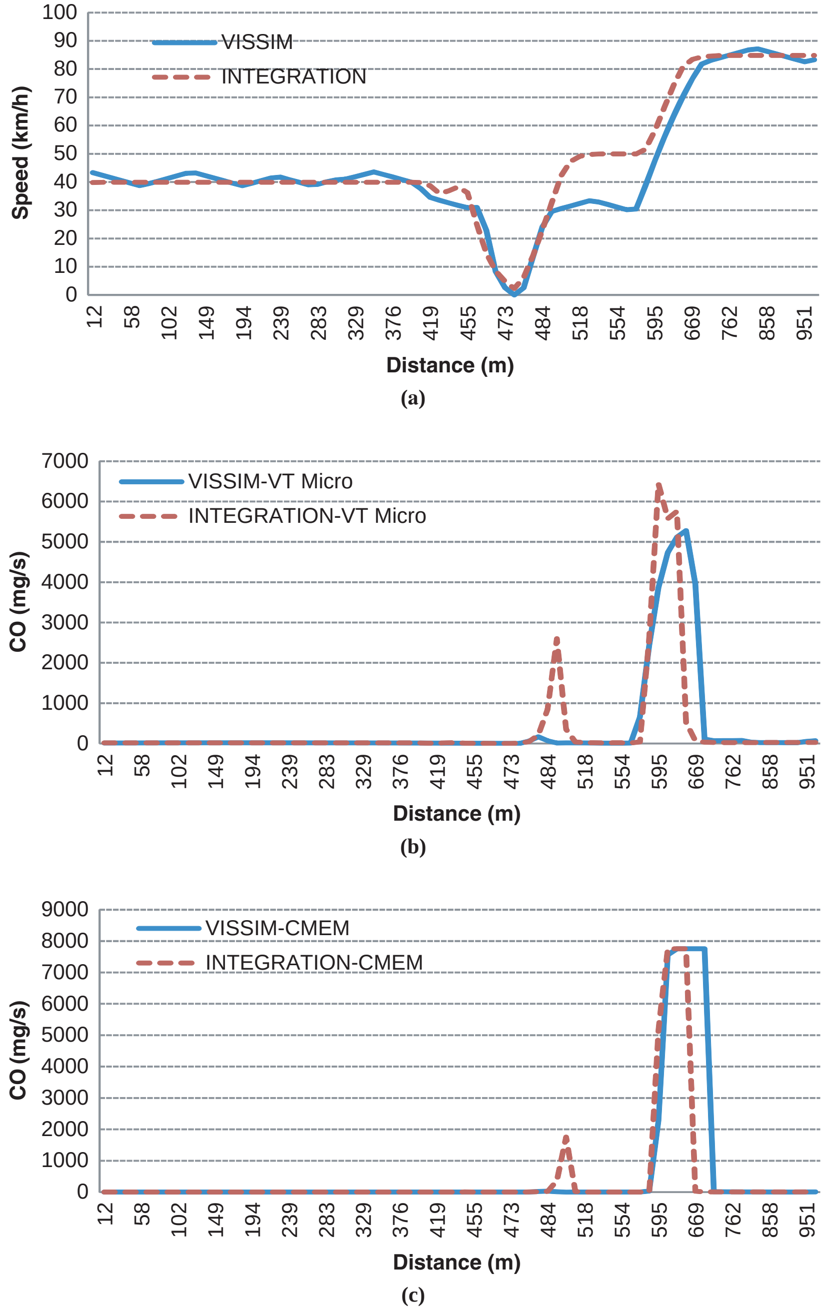
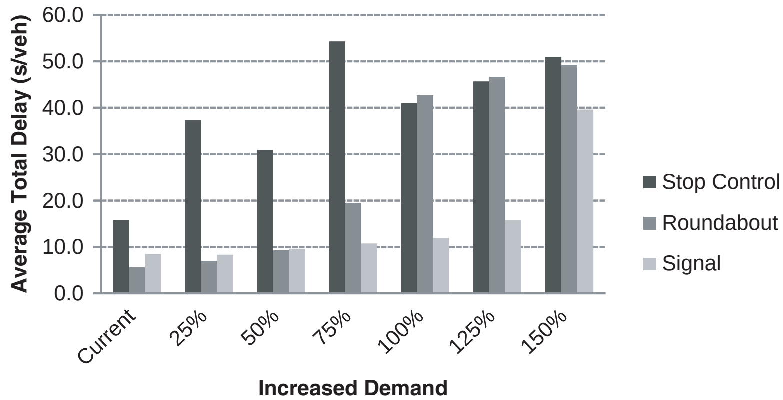


FIGURE 7 Comparison of speed and emissions variables VISSIM and INTEGRATION models for sample left-turning vehicle at roundabout: (*a*) speed, (*b*) CO emissions from VT-Micro model, and (*c*) CO emissions from CMEM model.

high-speed approaches for a main corridor and low-speed approaches for side streets found that the proposed roundabout reduces vehicle delays and the queue lengths in the case of low traffic demand levels. However, it produces significant increases in fuel consumption and emission levels relative to a base scenario with two-way stop control. Specifically, increases of up to 344%, 456%, 95%, and 10% of emissions for HC, CO, NO_x, and CO_2 emissions, respectively, are observed. Moreover, the study demonstrated that the roundabout increases fuel consumption by 18% relative to an intersection with a traditional two-way stop control.

Finally, the study demonstrates that, with increased traffic demands, the effectiveness of a roundabout in reducing overall intersection delay diminishes and a signalized intersection becomes a more appealing option. Furthermore, a roundabout produces higher energy consumption and emissions compared with a signalized intersection.

Further research should be pursued to identify the overall impact of a roundabout within an urban network with various vehicle types and different roadway characteristics, including various approach speeds.



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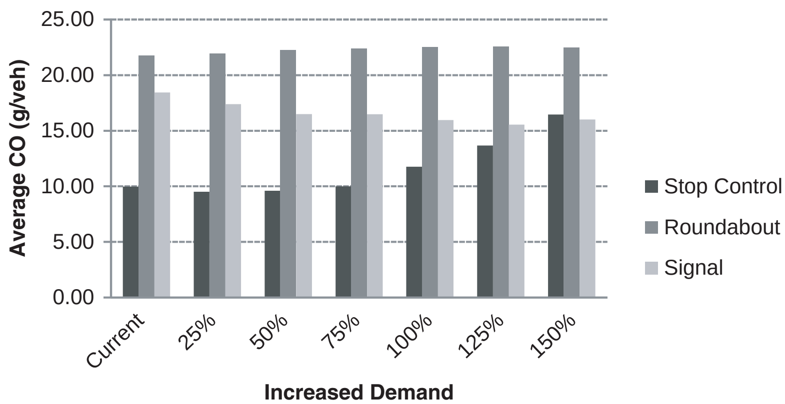

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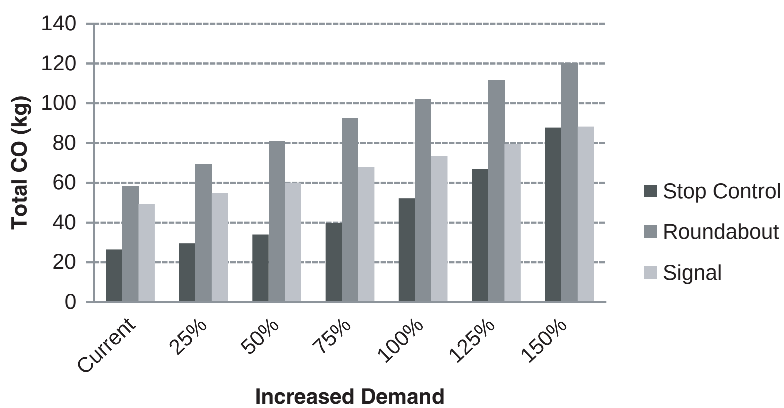

(c)

FIGURE 8 Impacts of increased through-traffic demands: (*a*) average total delay. (*b*) average CO, and (*c*) total CO.

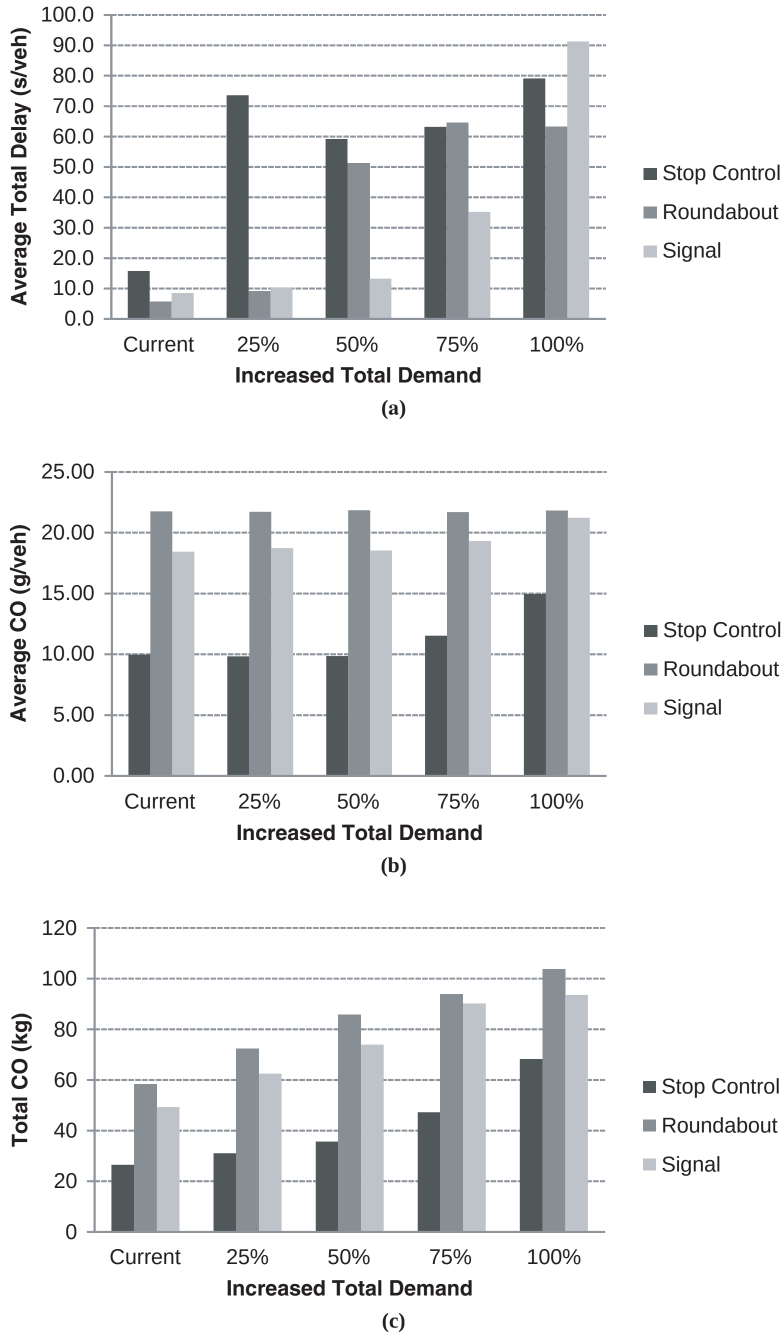

FIGURE 9 Impacts of increased total traffic demands: (*a*) average total delay, (*b*) average CO, and (*c*) total CO.

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