Simulation Study of Access Management at Modern Roundabouts

Treatments of Pedestrian Crosswalks

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The widespread emergence of modern roundabouts in North America has kindled a controversy about pedestrian access. Almost uninterrupted traffic streams, ambient noises, and urban settings make it difficult for the visually impaired to perceive safe crossing gaps when only auditory cues are used. In 2005, the U.S. Access Board released a revised draft guideline calling for the provision of a "pedestrian-activated traffic signal . . . for each segment of the crosswalk" to ensure access for vision-impaired pedestrians. The *Access Management Manual* prescribes major transportation actions encompassing multimodal streets with sidewalks and adequate pedestrian refuges, but the manual does not address the issue of pedestrian access at roundabouts. In North America few roundabouts have been outfitted with pedestrian signals. Little research has explored signalizing roundabouts for pedestrian access improvements. This simulation study quantitatively assessed the performance of four pedestrian signals placed at roundabouts with a wide spectrum of test scenarios resulting from varied crosswalk layouts, installation schemes, and operational conditions. A two-stage installation scheme was found more operationally efficient than a one-stage scheme; with the two-stage scheme, no significant differences existed between three layouts. When a one-stage scheme operated, a distant layout reduced vehicle delay and queue length because of enlarged storage space. High-intensity activated crosswalk signals induced minimum vehicle delay, and pedestrian user-friendly interface signals minimized pedestrian delay while fully protecting pedestrians. The findings provide an objective basis for identifying crosswalk treatments to improve roundabout accessibility and are informative for transportation policy makers, planners, and practitioners in the access management community who work at enhancing roundabout accessibility for pedestrians.

Since the 1990s, there has been a burgeoning growth in the number of modern roundabouts in many states and municipalities of the United States. The keen interest in roundabouts is mostly attributable to their great success in some European and Oceanian countries. A modern roundabout is an unsignalized intersection that includes a central island encircled by a single- or multiple-lane roadway. Vehicles entering the roundabout must yield cautiously to ones already navigating the circulatory lane(s). The far-reaching appeal of roundabouts can be specifically ascribed to their substantiated safety benefits, strengthened circulation efficiency, decreased maintenance costs, and improved aesthetic effects (*1*). France, leading the world with roughly 15,000 modern roundabouts, has been constructing this type of traffic facility at a rate of 1,000 or so per year (*2*). The inventory in the United States, although rapidly expanding in recent years, remains relatively limited. As of 2010, an online database records over 1,000 modern roundabouts in active operation nationwide, in sharp contrast to over 40,000 in the rest of the world (*3*). Currently, a large number of roundabouts are under construction or in the planning phase in North America. The flourishing emergence of roundabouts has kindled a widespread debate in response to relevant roundabout studies over the pedestrian access issue (*4*). Ashmead et al. found that roundabouts create serious difficulties to the visually impaired, and Harkey and Carter revealed that crossing becomes increasingly difficult as the conflicting vehicle volume rises and that ensuring pedestrian-friendly accessibility is more challenging with multilane than single-lane facilities (*5, 6*). Guth et al. showed that the crosswalk segment on outbound lanes is more hazardous than that on inbound lanes (*7*).

Williams and Levinson have pointed out that "safety, capacity, continuity and connectivity of the roadway network are key" in access management (*8*). Safety research shows a clear link between access design and crash rates, and access management has major concerns for the safety and mobility of a roadway system (*9–12*). The *Access Management Manual* prescribes major transportation actions that include multimodal streets with sidewalks and adequate pedestrian refuges, but it does not address the pedestrian access issue at roundabouts (*13*). In 2002, the U.S. Access Board published *Draft Guidelines for Accessible Public Rights-of-Way, Roundabout,* which proposes pedestrian signals at all roundabout crosswalks. In 2005, the Access Board released a revised draft to call for the provision of a "pedestrian-activated traffic signal . . . for each segment of the crosswalk" at multilane roundabouts to ensure safe access for vision-impaired pedestrians (*14*). Operationally, this provision interrupts the vehicular flow continuity that is intended in roundabout design. Another critical issue is the enhanced likelihood that the yielding queue will spill back into the circulatory lane(s), a problem identified by Inman and Davis for some signalized roundabouts (*15*).

Although signals are in use at roundabout crosswalks in Europe, Australia, and South Africa, few roundabouts have been signalized for pedestrians in North America (*16, 17*). Two single-lane roundabouts were signalized at university campuses (the University of Utah in Salt Lake City and the University of North Carolina in Charlotte), and one double-lane roundabout was signalized (and then

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unsignalized) in Lake Worth, Florida (*15, 16*). In Quebec, Canada, a double-lane roundabout at Gatineau possesses a staggered offset crossing with a pedestrian signal installed on one approach. Currently, very little literature documents the practice of signalizing roundabouts to improve pedestrian access. Rouphail et al. found the introduction of a pedestrian-actuated (PA) signal adds delay to visually impaired pedestrians compared with sighted pedestrians who cross at unsignalized splitter islands (*18*). Schroeder et al. investigated two signal alternatives at single- and double-lane roundabouts to make these facilities accessible to the visually impaired (*19*). Simulation results show the impact of signalization was maximized under oversaturated conditions, but vehicle delay and the queuing effect can be alleviated through an innovative signal. Lu et al. developed an artificially intelligent signal system to improve roundabout accessibility, and simulation results show the new system outperforms an existing one in manifold aspects (*20*). Although roundabouts are rarely signalized for pedestrian access in the United States, the call from the Access Board and the absence of roundabouts in the *Access Management Manual* make it imperative for the access management community to have more practice-oriented research regarding roundabout accessibility for pedestrians.

STUDY OBJECTIVES

Intuitively, the introduction of a pedestrian signal would pose additional delays to vehicles at a roundabout. However, it is not easy to quantify the projected impact of a roundabout signalization. This study quantitatively evaluates the performance of four pedestrian signals experimentally installed at typical single- or double-lane modern roundabouts with varied crosswalk geometric layouts and signal installation schemes under a range of traffic conditions. The objective was to provide the access management community with an objective basis for identifying potential crosswalk treatments to improve roundabout accessibility, especially for children, seniors, and the visually impaired or disabled, while maintaining adequate multimodal traffic mobility. Several key hypotheses were established. First, the operational effect of a pedestrian signal is significantly related to multimodal traffic flow intensities. More pedestrians increase the number of pedestrian signal activations. With more vehicular arrivals, each pedestrian signal activation produces a more powerful impact on vehicle delays and increases the possibility that yielding queues at entry points will spill back into the circulatory lane(s) (*19, 20*). Second, the likelihood of queue spillback can be diminished by shifting the crosswalk segment on the outbound lane(s) farther away from the circulatory lane(s) (*19, 20*). Since vehicle delay is directly proportional to the display length of the red interval, it was hypothesized that signalization with a shortened red display would reduce vehicle delay. Finally, since the pedestrian clearance interval [i.e., flashing don't walk (FDW)] is timed according to the crossing distance and a design walking speed, the reduction of FDW (and thus red) can be achieved by using an installation scheme based on separate segments rather than one based on the entire crosswalk.

STUDY METHODOLOGY

From an operational perspective, this study investigated how specific crosswalk treatments resulting from variations in signalization options, geometric layouts, and installation schemes affect multimodal performance measures under varied traffic conditions. It is nearly impossible to scrutinize the performance of these treatments in a real-world context because of the potential disruptions and hazards posed to smooth and safe traffic circulation if traffic control strategies change on site. However, a controllable in-lab platform provides a valid surrogate means by which treatments can be implemented and quantifiably evaluated.

Study Environment

Traffic simulation is characterized by cost-effectiveness, unobtrusiveness, a risk-free nature, and high-speed computation, qualities that make it indispensable in the repertoire of transportation researchers. It exports various performance measures, some of which are intractable in the field. Most importantly, by giving researchers an exhaustive control over a myriad of operational and geometric factors of interest, traffic simulation offers the unique opportunity to evaluate the effectiveness of different study scenarios before field deployment. VISSIM, a microsimulation program, is applied worldwide to model diverse transportation facilities because of its multimodal modeling capability, adequate detector function, self-customizable traffic control algorithm via vehicle-actuated programming, and convenient run-time control interface for external object-oriented programs (*21*). VISSIM models have been found effective, valid, and credible for traffic studies regarding roundabouts, freeways, urban networks, crosswalks, intersections, and arterials (*18–20, 22–25*). It can mimic vehicle-yielding behaviors at roundabout entries, and its link–connector structure is flexible in modeling unique geometrics. VISSIM was used as a controllable and quantifiable study platform for the present research.

Signalization Options

The conventional PA crosswalk signal is widely used in the United States. The high-intensity activated crosswalk (HAWK) signal, also known as the pedestrian hybrid beacon, had been experimentally installed at midblock locations in Tucson, Arizona; Portland, Oregon; and other cities before it was recently approved by FHWA as an official traffic control device (*26, 27*). HAWK has been added to the *Manual on Uniform Traffic Control Devices* (MUTCD), Chapter 4F, which prescribes its application, design, and operation (*28*). Pedestrian light-controlled (PELICAN) and pedestrian user-friendly interface (PUFFIN) signals have been widely deployed in Europe and Oceania to manage midblock crosswalks and, sometimes, roundabouts (*17, 29, 30*). In the United States, several transportation agencies have published local guidelines for field deployments of PELICAN and PUFFIN signals, which suggests their increasing use on the North American continent (*31*). Figure 1 illustrates the phasing sequences for the four signals. Crossing pedestrians press a push button mounted on a roadside post to activate each signal.

PA Signals

PA signals ramify into two types, one of which is integrated into other signal phases (usually at intersections), and another that operates independently. Both types comply with relevant MUTCD design standards (*28*). Usually installed at midblock points with busy vehicle traffic, the latter type can be timed to respond soon after (or after a preset time) the push button is pressed. All timing parameters are statically preset. PA has a standard set of vehicle signal displays

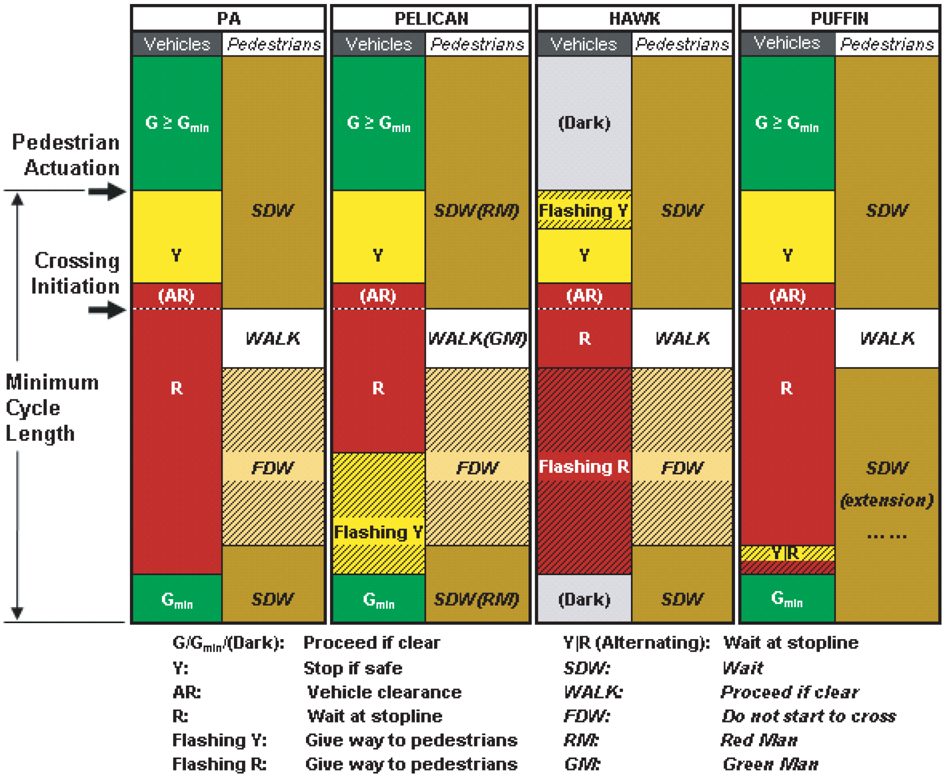


FIGURE 1 Comparison of phasing schemes in four pedestrian signal systems.

composed of red, green, and yellow, while the pedestrian signal intervals encompass walk, FDW, and steady don't walk (SDW).

PELICAN

A substantial number of PELICAN installations remain in operation in Europe and Oceania (*29*). PELICAN's four intervals (red, flashing yellow, green, and yellow) are displayed in sequence for vehicle movements. Flashing yellow permits drivers to proceed if all pedestrians vacate the crosswalk. Frequently, its pedestrian indications use images of a walking green man and a stationary red man. Pedestrians can start crossing only when the steady green man is illuminated. After this interval the flashing green man appears, which means no crossing should be started despite there being enough time for pedestrians already in the crosswalk to continue safely. Finally, the red man is illuminated, which means no pedestrians should be in the crosswalk.

HAWK

HAWK includes an overhead sign labeled pedestrians and a sign instructing drivers to stop on red. Another sign informs pedestrians on how to cross the street safely. Traditional signal displays operate in a different configuration. The vehicle signal remains dark for drivers unless a pedestrian activates it by pressing the push button. After activation, the vehicle signal flashes yellow and then changes to steady yellow for a few seconds, alerting drivers to stop. It then displays a solid red that requires drivers to wait at the stop line. At this time, pedestrians receive a walk indication. After this, pedestrians see an FDW sign and a countdown timer indicating the time left for crossing, and drivers see an alternating flashing red display. During this period, drivers are required to stop or remain stopped until pedestrians have finished crossing the roadway, and then they may proceed cautiously when it is safe. SDW follows for pedestrians, and finally the vehicle signal reverts to dark. HAWK has been found to be associated with a statistically significant reduction in total crashes (*32*). HAWK has appeared at intersections without a standard traffic signal or in the middle of long roadway stretches in cities in Arizona, Georgia, Illinois, Minnesota, Virginia, and Delaware. Its popularity could increase as a result of a recent change in federal guidelines that allows HAWK installation without getting FHWA permission (*28*). Each HAWK system costs roughly $120,000 to install (*33*).

PUFFIN

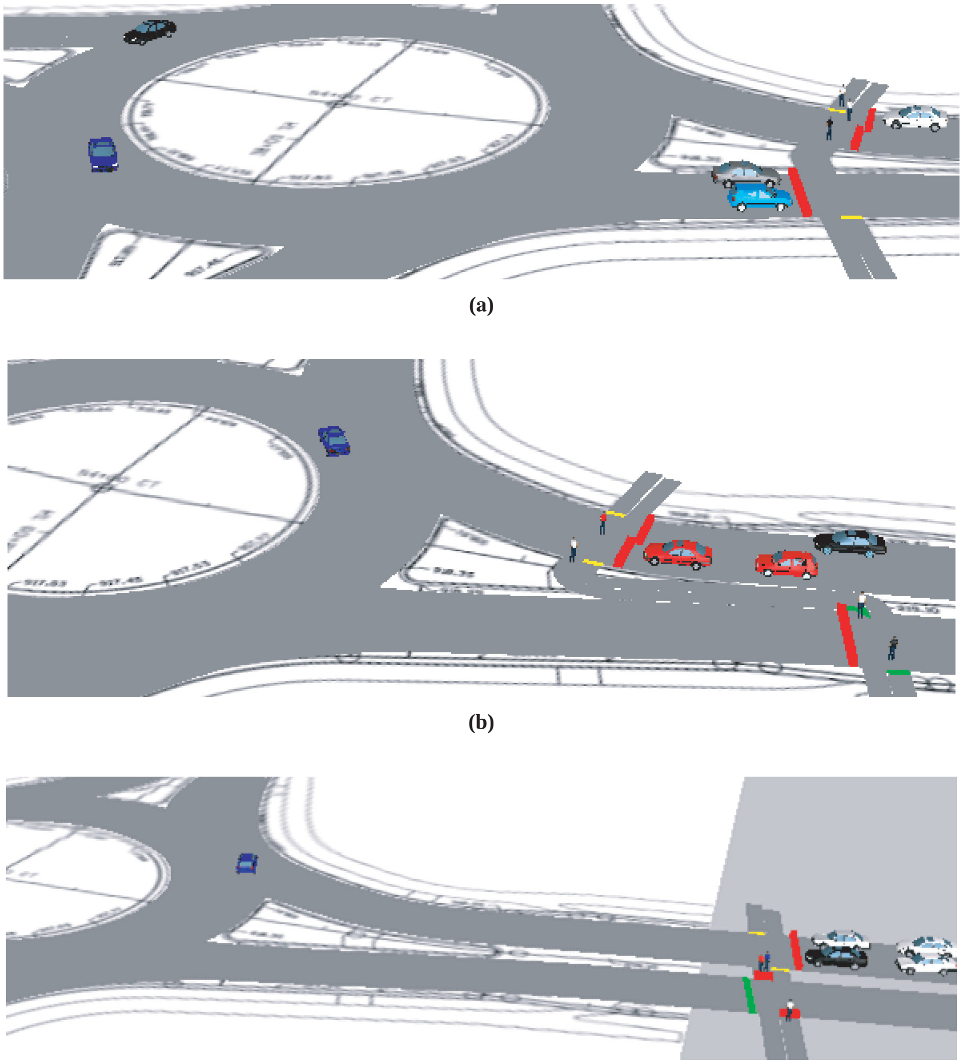
PUFFIN was viewed as an updated version of PELICAN in Europe. PUFFIN has four vehicle signal intervals that iterate from red to alternating red and yellow, and then to green and yellow. The flashing yellow and flashing green man intervals used in PELICAN are omitted. This omission eradicates sources of pedestrians' confusion and harassment sensed from aggressive drivers (*30*). The three signals introduced above time FDW statically by using the crosswalk length and a design speed. From a safety perspective, this timing practice is unsustainable because seniors, children, and vision-impaired or disabled people introduce considerable variability into the walking speed (*34–37*). Thus, a static FDW duration cannot offer all pedestrians full signal protection. In contrast, PUFFIN uses on-crosswalk sensors to track pedestrians, and SDW (partially as FDW) is dynamically adjusted to provide the pedestrian time to traverse the crosswalk safely. In this way PUFFIN offers all pedestrians full signal protection. The installation cost for PELICAN and PUFFIN systems ranges from $50,000 to $75,000, depending on street width, the length of mast arms, and the presence of center islands and ambient landscaping attributes (*38*).

Geometric Layouts

A key issue is to design the geometric layouts for crosswalk segments on inbound and outbound lane(s). In the United States, the most usual layout (here termed the conventional layout) is to place the entire crosswalk across the splitter island, approximately one vehicle length upstream from the entry yield line (Figure 2*a*). Because of the critical issue regarding the potential queue spillback into the circulatory lane(s), two other layouts were tested. The first, the offset layout, spatially shifts the segment on the outbound lane(s) farther from the circular island; the segment is relocated by an offset of 80.0 ft from the entry yield line (Figure 2*b*). In operation, this can roughly accommodate four vehicles per lane before the rear end of a vehicle infringes on the circulatory lane(s) (*20*). The second alternative, the distant layout, pushes the whole crosswalk away from the circular island by 120 ft, which supplies storage room for nearly six vehicles per lane (Figure 2*c*) (*20*).

Installation Schemes

Since pedestrians cross both inbound and outbound lanes, whether to install signals separately for inbound and outbound lanes is important to roundabout signalization. With the one-stage installation scheme, the same signal indication is valid for the whole crossing distance between roadway curb lines and overrides both inbound and outbound lanes traversing a crosswalk (Figure 2*a*). With the two-stage scheme, inbound and outbound lanes are controlled individually and crossing pedestrians must wait midway either on the splitter island or in the median area (Figures 2*b* and 2*c*). Obviously, it is unreasonable to employ the one-stage scheme in conjunction



(a)

(b)

(c)

FIGURE 2 Tested crosswalk layouts and installation schemes: (*a*) conventional (one-stage scheme), (*b*) offset (two-stage scheme), and (*c*) distant (two-stage scheme) layouts.

with the offset layout because of the long walking coverage, which would definitely cause too much delay to all roundabout users.

Field Sites

Two modern roundabouts newly constructed in Madison, Wisconsin, were identified as field sites for the collection of actual peak hour traffic data for use as the base volumes. This study signalized the crosswalk at the approach where the most intense vehicle volume and highest prevailing speed exist, because such an approach produces the fewest safe crossable gaps for pedestrians (*20*). Field observations revealed serious accessibility issues at the single-lane roundabout (Figure 3*a*). During peak hours on workdays, the heaviest commuter traffic and highest number of pedestrians flow densely on the westbound approach between two bus stops; pedestrians using these stops include vision-impaired or disabled people as well as seniors. Seasonal football events generate even more crowded traffic flows in which many pedestrians are present. The westbound approach of the double-lane roundabout is located between two residential communities and in the proximity of some abutting properties (e.g., a daycare center and stores). The most intense peak hour flows move on the northbound and westbound approaches; vehicles on the westbound approach have the highest prevailing speed, which poses hazards to crossing pedestrians (Figure 3*b*). Future residential growth is expected to the east and will add more traffic to the westbound approach of this roundabout as that growth is realized.

Model Calibration

Simulation models were established with base volumes, turning percentages, and design speeds in compliance with FHWA's *Informational Guide* (*39*). Vehicle-yielding behaviors were modeled consistently or closely with a documented example in which the "values used for minimal gap time, minimal headway and maximum speed have been determined through research. Thus for most applications these serve as a realistic base" (*21*). Vehicle speeds were calibrated using field data; prevailing speeds on approaches, entering speeds near the circulatory lane(s), and circulating speeds around islands were verified to have normal distributions. The model validation in the zero-pedestrian case was implemented by comparing average vehicle delays and average approach queues with counterparts observed from real-world data: these video recordings of field sites were played repeatedly to manually obtain the approximate measurements by means of intensive visual scrutiny, stop watch manipulations, data recording, and simplified calculations. The results shown indicate that vehicle delays and queues match field observations to an acceptable degree (Figure 3*c*). However, it is clearly recognized by the authors that the observation sample size and the measurement method are rather limited; the calibration and validation work can be further refined with massive field data collection and the technical aid of sophisticated image-processing software.

Experiment Design

The observed traffic volumes do not exceed the theoretical capacity for the respective sizes of the roundabouts as cited in FHWA's *Informational Guide* (*39*). To explore additional cases, base volumes were enlarged at a fixed rate to create additional scenarios approaching maximum capacity. FHWA's *Informational Guide* recommends that roundabouts should be designed to operate under 85.0% of their estimated capacity. Through calculations in compliance with this 85.0% threshold, the single-lane roundabout base volumes were augmented by 35.0% and 70.0% to produce 1,582.0 and 1,992.0 passenger car equivalents per hour (pce/h), respectively, and the double-lane roundabout base volumes were increased by 85.0% and 170.0% to obtain 2,649.0 and 3,866.0 pce/h, respectively (*20*). Three vehicle intensity levels were established: existing flow, approaching capacity, and saturated condition. Figure 4*a* depicts both the base and increased volumes of two subject sites superimposed on the *Guide's* capacity figure.

Three pedestrian flow intensities were investigated: 14 pedestrians per hour (pph) (few), 70 pph (some), and 180 pph (many). These designed pedestrian flows do not suffice for the MUTCD Section 4C.05 Warrant 4 because the dominant motivation for outfitting pedestrian signals is not to satisfy a MUTCD design warrant but to ameliorate roundabout accessibility for pedestrians (*28*). Because roughly 15.0% of pedestrians move more slowly than 3.5 ft/s, the mean speed was set to 3.0 ft/s (*40*). A researcher-customized speed distribution with minimum and maximum speeds equal to 1.0 and 8.0 ft/s, respectively, was modeled to embody previous findings (*20*).

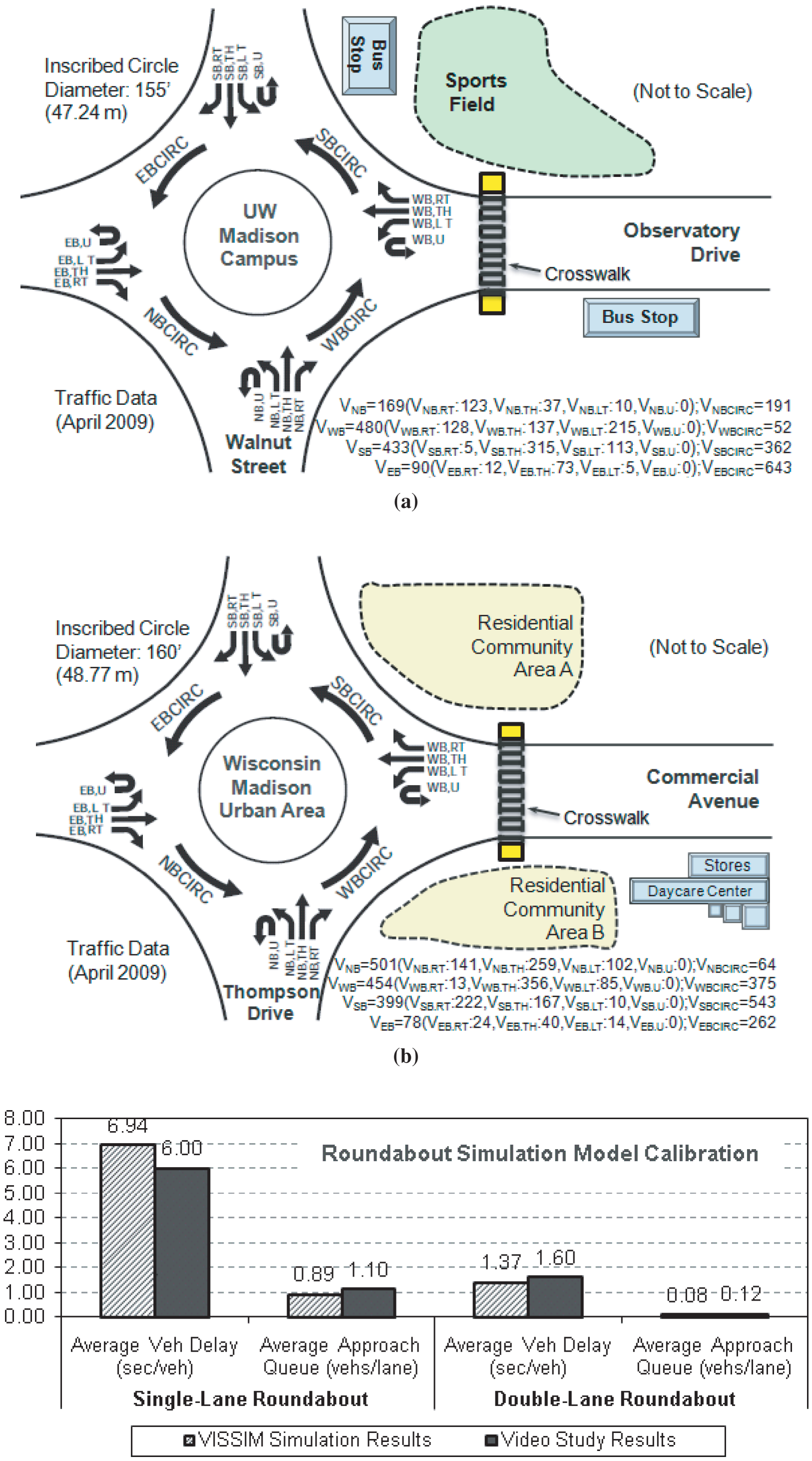
To encompass all possible cases, each geometric layout was combined with one-stage and two-stage installation schemes, except for the offset layout, which can only be combined with the two-stage scheme. Geometric layouts and installation schemes were combined with signalization options to generate 40 pedestrian crosswalk treatments, each of which was modeled with varied traffic conditions to create 360 study scenarios (Figure 4*b*).

Basic Timings

PUFFIN's dynamic SDW provides full signal protection for all pedestrians, some of whom walk at the minimum walking speed (1.0 ft/s). For other signals, higher design walking speeds for FDW timing would leave slow pedestrians unprotected by signals when FDW terminates and the vehicle signal turns green. Therefore, to protect all pedestrians under study and to maintain strict reasonableness in comparing the four signals so that all study scenarios would have a uniform degree of signal protection for subject pedestrians, the static FDW for the other three signals was timed with the crossing distance and minimum walking speed (1.0 ft/s) to guarantee adequate clearance time for all pedestrians modeled. The walk signal was uniformly 6.0 s based on relevant MUTCD recommendations. Minimum vehicle greens and all-red intervals were universally set to 36.0 s and 1.0 s, respectively. Yellow was set to 2.5 s for HAWK and 4.0 s for the other signals. Flashing yellow and alternating red and yellow were set to 1.5 s for HAWK and 1.0 s for PUFFIN.

Performance Measures

One intention of this study was to quantify the impact of pedestrian crosswalk treatments on roundabout operations. Generic vehicle-based performance measures (e.g., average vehicle delay, average queue length, and average number of stops) were obtained by means of the pedestrian-induced effect, which is defined as the difference between the measures generated at certain pedestrian volumes and their counterparts in the zero-pedestrian case (*19*). Average number of stops was treated as the safety index: its increase implies more

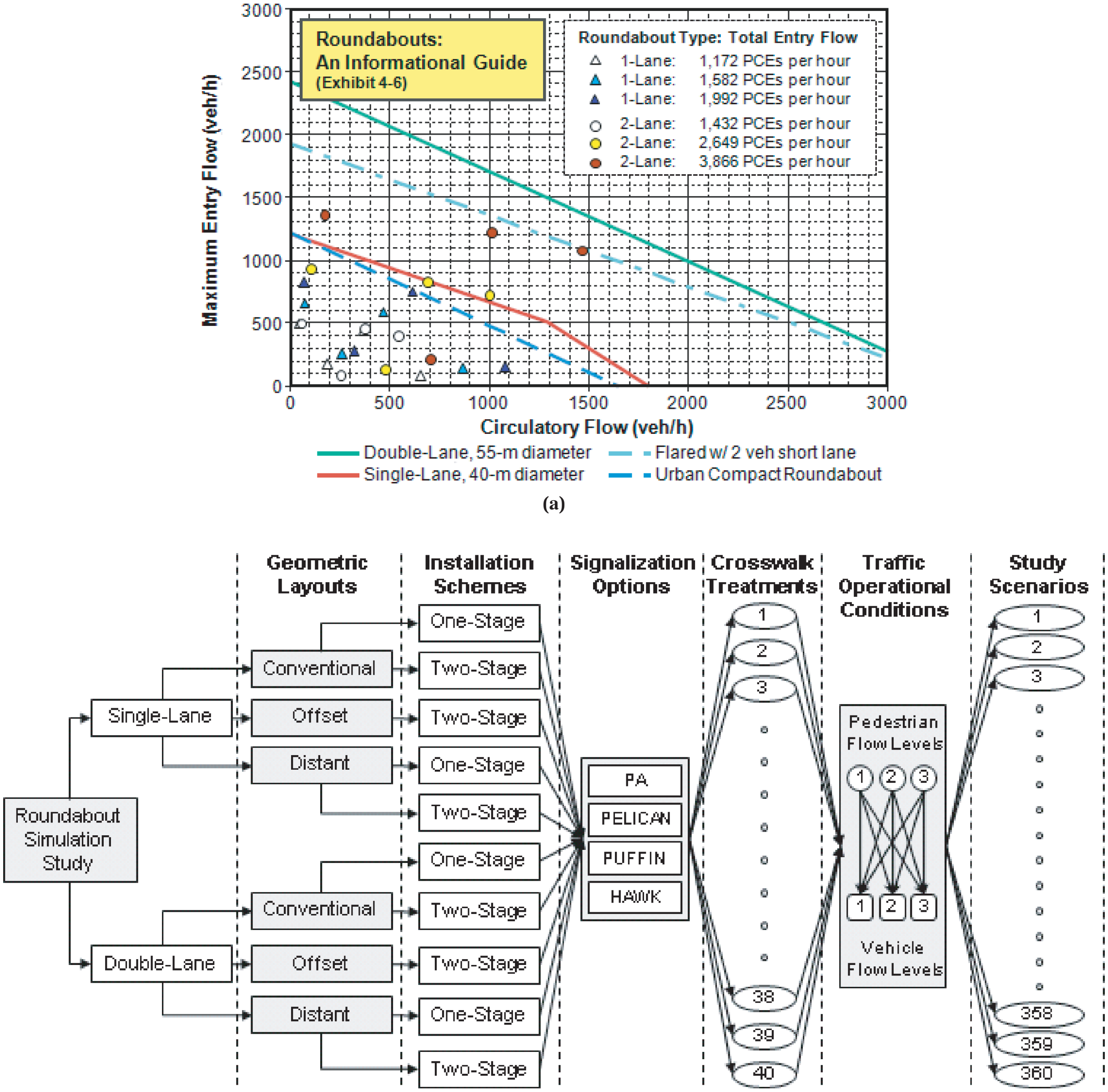


(a)

(b)

(c)

FIGURE 3 Actual peak hour roundabout traffic volumes (V) in passenger car equivalents calculated according to the FHWA *Informational Guide* standard (*39*) for (*a*) single-lane and (*b*) double-lane sites and (*c*) VISSIM model calibration results (*20*) (veh = vehicle).



(a)

(b)

FIGURE 4 Simulation experiment design and implementation: (*a*) entry volumes relative to theoretical capacity in FHWA *Informational Guide* (*39*) and (*b*) simulation experiment design.

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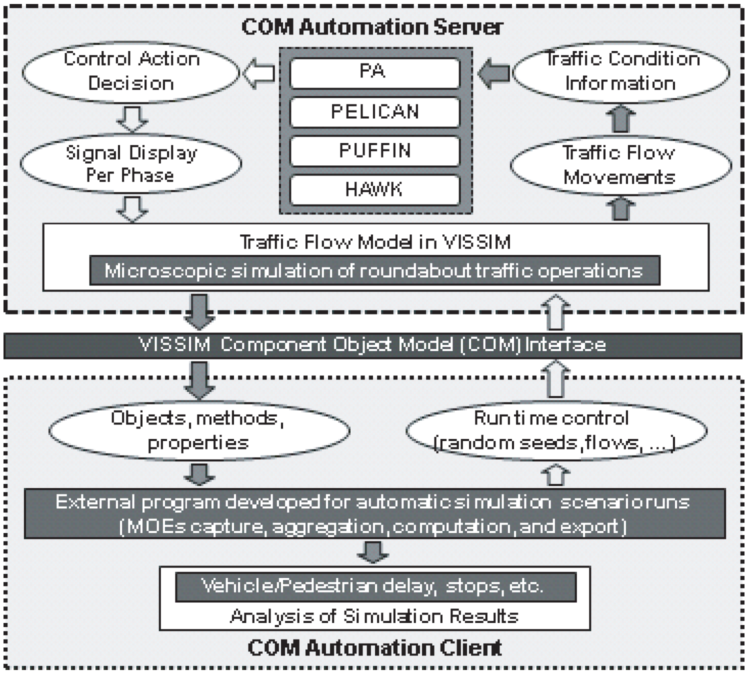
deceleration occurrences, which aggravate the potential for rear-end crashes and, from a human factors perspective, make drivers increasingly prone to incompliance with signals. Average pedestrian delay is defined as the difference between the actual travel time used in crossing a roundabout and the minimum travel time (at a given walking speed without delays) across the pathway of interest.

Simulation Data

Using different random seeds, 15 replications were simulated for each scenario to dampen stochastic variations resulting from underlying simulation models, which amounted to 5,400 runs. Each run lasted 3,600 simulation seconds. The first replication populated the model, and the last ran as the clear-out period. Data from the remaining 13 replications were collected. The data for performance measures were procured within an evaluation node surrounding roundabouts. Simulation runs for each treatment were implemented automatically. As a client in seamless dialogue with the VISSIM-based server, an external program extracted, aggregated, calculated, and finally output data to Excel spreadsheets during run time (Figure 4*c*).

STUDY RESULTS

Study results for single- or double-lane roundabouts are reported by arithmetic means of 13 replications. Figures 5 and 6 show operational effects of pedestrian volume levels and vehicle flow intensities in



(c)

FIGURE 4 *(continued)* **Simulation experiment design and implementation: (*c*) run-time control and computation via VISSIM-based component object model (COM) automation (MOE = measure of effectiveness).**

conjunction with signalization options and geometric layouts. Figures 5*a* and 5*c* and Figures 6*a* and 6*c* demonstrate one-stage results for eight treatments and 72 scenarios; Figures 5*b* and 5*d* and Figures 6*b* and 6*d* exhibit two-stage results for 12 treatments and 108 scenarios. Each subfigure is plotted at a different scale.

Pedestrian-Induced Vehicle Delay

Figure 5 shows the pedestrian-induced average vehicle delays at single- and double-lane roundabouts.

Single-Lane Roundabout

Figures 5*a* and 5*b* show that when vehicle volume is fixed at a specific level, vehicle delays are ubiquitously enhanced when the level of crossing pedestrians incrementally increases from few to some to many. This operational characteristic can be explained by the fact that more crossing demands pose increased interruptions to vehicular circulation at roundabouts.

As Figure 5*a* demonstrates, when the pedestrian flow level is specifically maintained, a roughly monotonic relationship exists between vehicle volume and vehicle delay for PELICAN, HAWK, and PUFFIN. For these three signals, the saturated condition yields the maximum vehicle delay. HAWK has the lowest vehicle delay compared with the other signals under each operational condition. PA generates the highest vehicle delays in all study scenarios, while PELICAN and PUFFIN have much lower vehicle delays relatively close to each other. Comparatively, the distant layout exhibits potential advantages over the conventional layout since vehicle delays from PA, PELICAN, and PUFFIN are universally reduced when the conventional layout changes to the distant layout.

Figure 5*b* shows that given some or many pedestrians, vehicle delay has an approximately monotonic relationship with vehicle volume for 12 treatments. The saturated condition produces the largest vehicle delay for most of these treatments, excluding the HAWK signal. Under each operational condition, HAWK gives the lowest vehicle delay compared with the other signals regardless of crosswalk layouts. For most scenarios, there are no substantial differences in the average vehicle delays produced by each signal at three layouts.

All one-stage vehicle delays in Figure 5*a* are significantly larger than their two-stage counterparts in Figure 5*b*. The two-stage installation scheme outperforms its one-stage counterpart in operational efficiency because two-stage schemes have shorter FDW intervals, which make vehicles wait for a shorter time to traverse a roundabout.

Double-Lane Roundabout

Figures 5*c* and 5*d* show that under conditions of existing flow and approaching capacity, vehicle delays are universally increased when the level of crossing pedestrians increases from few to some to many. This operational characteristic is mostly attributable to the more frequent interruptions to vehicle circulation caused by denser pedestrian flows. When the pedestrian intensity level is fixed, vehicle delays increase when the vehicle volume condition changes from existing flow to approaching capacity. Interestingly, under the saturated condition, some treatments yield negative pedestrian-induced average vehicle delays. In these scenarios, the presence of pedestrian signals diminishes average vehicle delays. This may be related to the phenomenon observed in simulation that the pedestrian signal metering traffic on the busiest approach facilitates

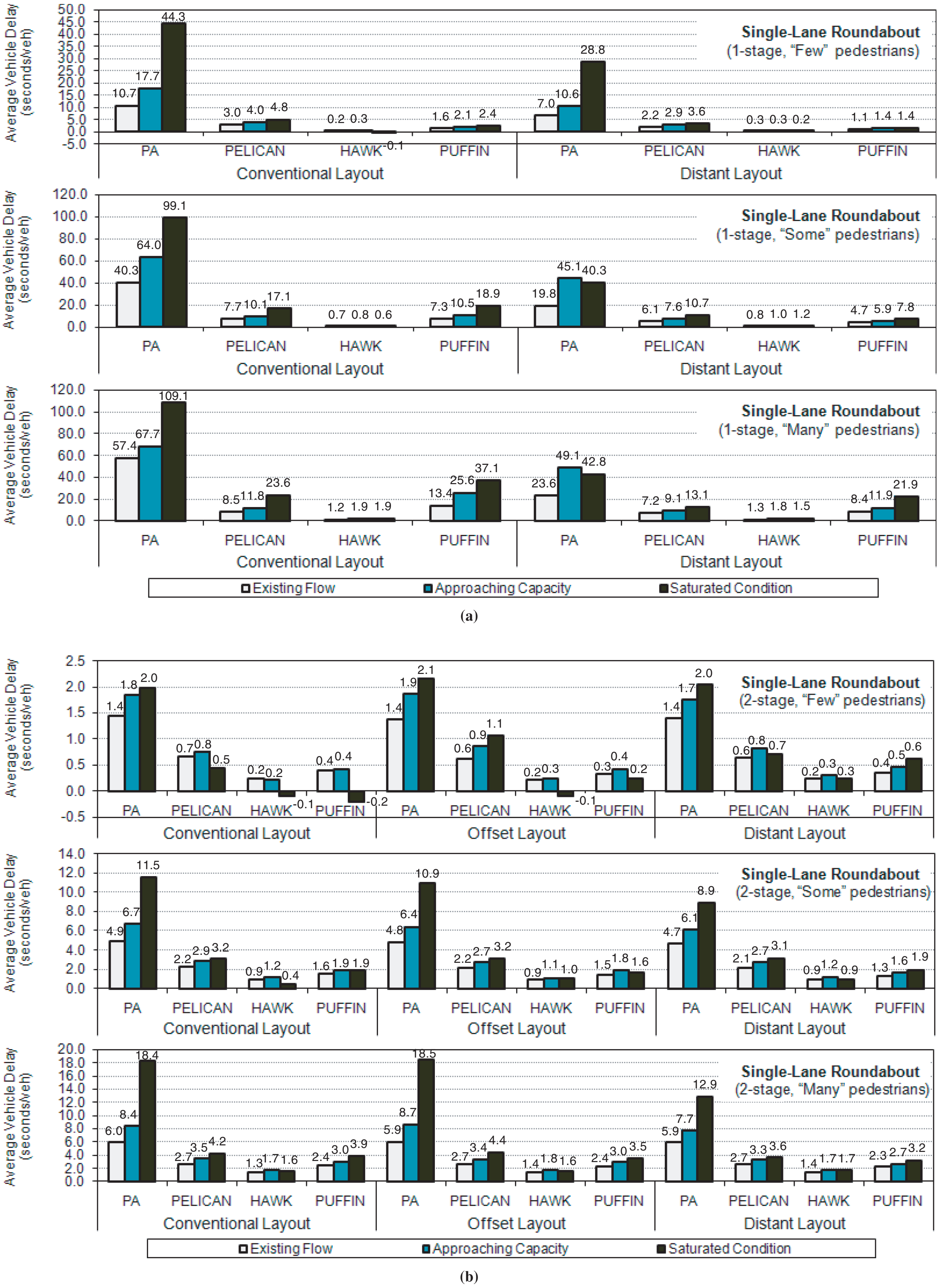


FIGURE 5 Pedestrian-induced vehicle delay with 14, 70, and 180 pph: single-lane roundabout with (*a*) one-stage and (*b*) two-stage schemes.

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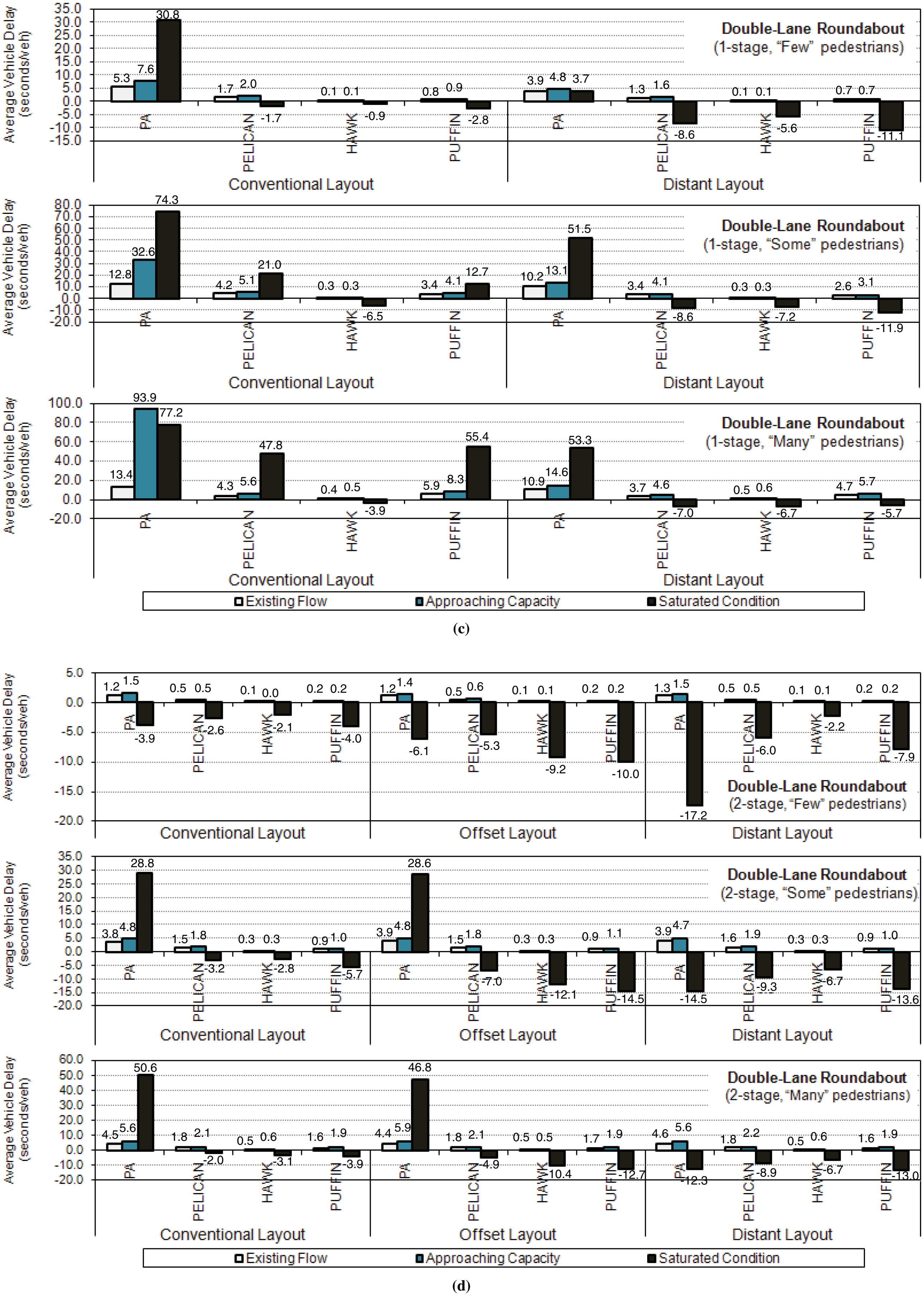
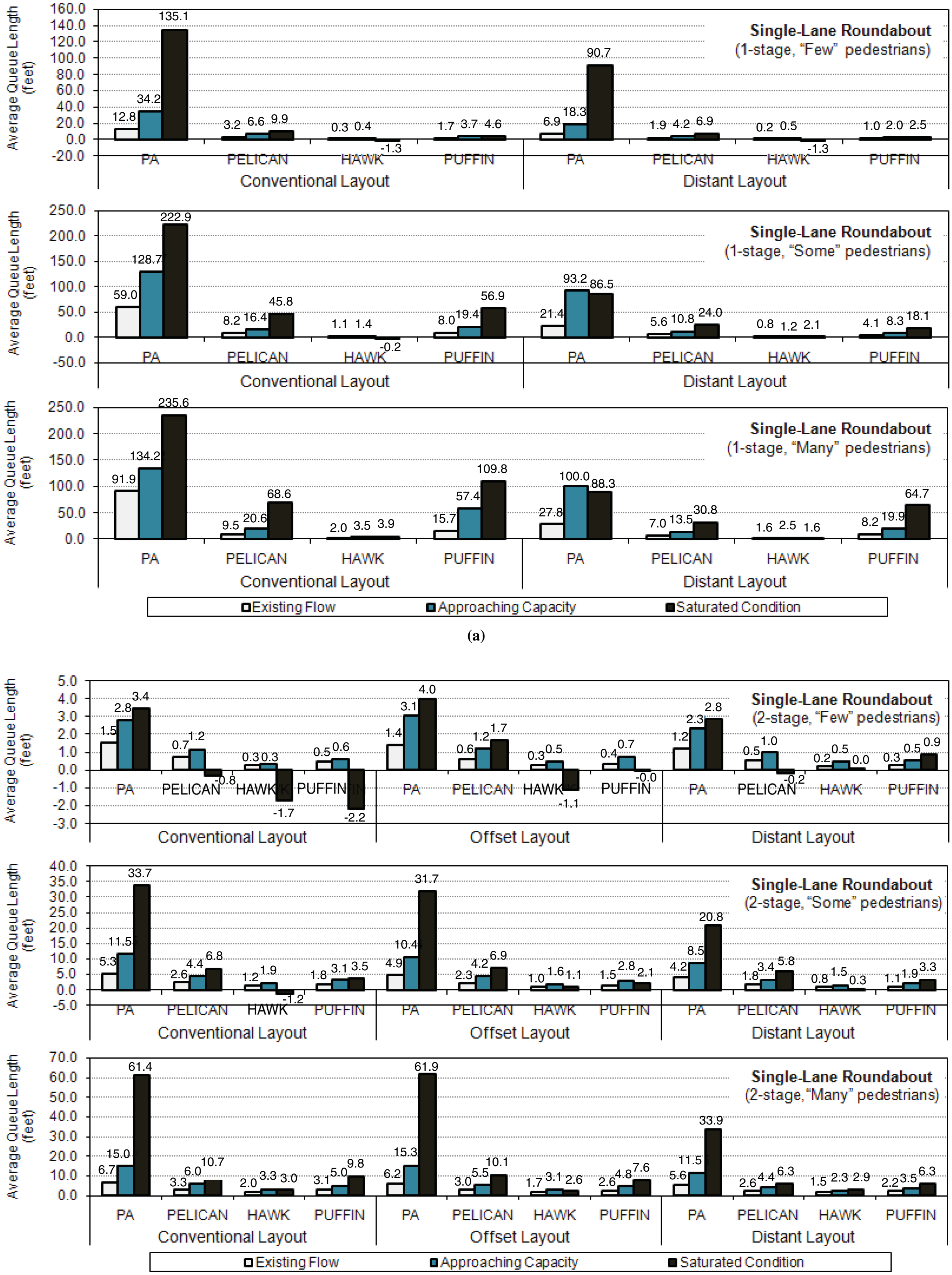


(c)

(d)

FIGURE 5 *(continued)* Pedestrian-induced vehicle delay with 14, 70, and 180 pph: double-lane roundabout with *(c)* one-stage and *(d)* two-stage schemes.



(b)

FIGURE 6 Pedestrian-induced queue length with 14, 70, and 180 pph: single-lane roundabout with (*a*) one-stage and (*b*) two-stage schemes.

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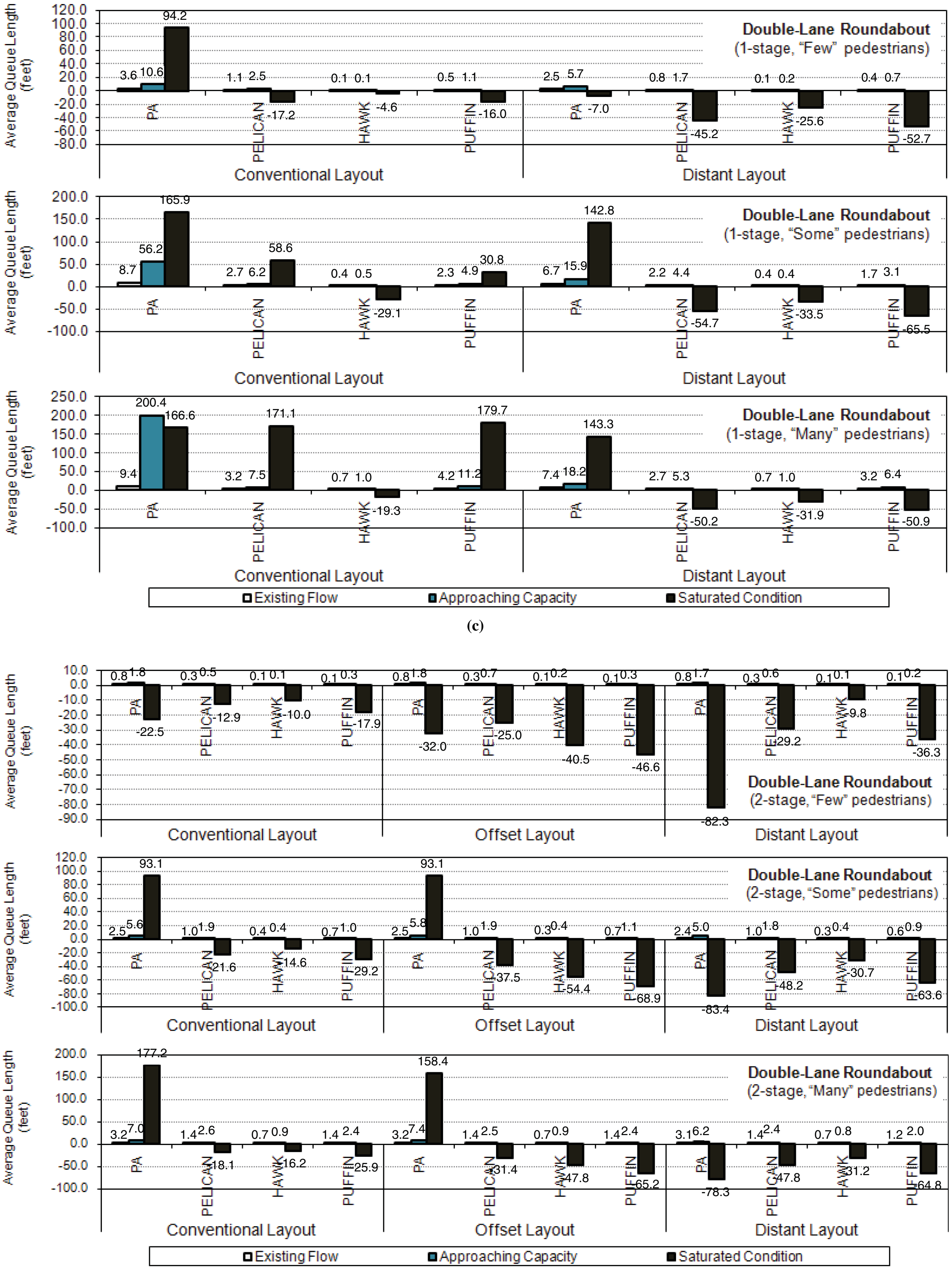

(c)

(d)

FIGURE 6 *(continued)* Pedestrian-induced queue length with 14, 70, and 180 pph: double-lane roundabout with (*c*) one-stage and (*d*) two-stage schemes.

vehicular inflows at counterclockwise downstream roundabout approaches.

Figures 5*c* and 5*d* also reveal that under existing flow and approaching capacity conditions, HAWK generates the lowest vehicle delay compared with other signals, no matter which crosswalk layout is applied. PA generates the highest vehicle delay, while PELICAN and PUFFIN have lower vehicle delays relatively close to each other. Figure 5*c* reveals that PA, PELICAN, and PUFFIN produce more vehicle delays in the conventional layout than in the distant layout. Figure 5*d* shows that no substantial differences are found among average vehicle delays produced at three geometric layouts. For PA, PELICAN, and PUFFIN, the one-stage vehicle delays (Figure 5*c*) are significantly larger than their two-stage counterparts (Figure 5*d*). For HAWK, the discrepancies between vehicle delays of both installation schemes are limited.

Pedestrian-Induced Queue Length

Figure 6 exhibits the pedestrian-induced average queue lengths generated at single- and double-lane roundabouts. The results are similar to the pedestrian-induced average vehicle delays shown in Figure 5.

Single-Lane Roundabout

Figures 6*a* and 6*b* show that at a specific vehicle intensity level, most average queue lengths are prolonged for all treatments when increasing crossing demands pose more disruptions to vehicle movements at roundabouts.

Figure 6*a* shows that when the pedestrian flow intensity level is specifically maintained, there is a roughly monotonic relationship between vehicle volume and queue length for most treatments. The saturated condition yields the maximum queue length for most treatments that involve PA, PELICAN, and PUFFIN. In comparison, average queue lengths from HAWK are the shortest in most cases no matter which crosswalk layout is employed. PA generates the longest queue length in almost all cases; PELICAN and PUFFIN generate much shorter queue lengths. The distant layout is more efficient than its conventional counterpart: average queue lengths from PA, PELICAN, and PUFFIN are shortened when the conventional layout changes to the distant one.

Figure 6*b* shows that queue length has a monotonic relationship with vehicle volume; the saturated condition produces the longest queue for most treatments. Generally, HAWK produces the shortest average queue length, while PA has the longest. In most cases, the differences between the three layouts do not result in significant distinctions in the queue length produced by each signal. Figure 6*a* shows all one-stage queue lengths are significantly longer than their two-stage counterparts (Figure 6*b*), which indicates that the two-stage scheme is more operationally efficient for vehicles than the one-stage alternative.

Double-Lane Roundabout

Figures 6*c* and 6*d* show that under conditions of existing flow and approaching capacity, average queue lengths increase for all treatments when pedestrian flow levels intensify from few to many. HAWK generates the shortest queue length when compared with PA, PELICAN, and PUFFIN.

Figures 6*c* and 6*d* show that if the pedestrian flow intensity is fixed, average queue length increases when the vehicle volume increases from existing flow to approaching capacity. For PA, PELICAN, and PUFFIN, the one-stage queue lengths (Figure 6*c*) are significantly longer than their two-stage counterparts (Figure 6*d*). The discrepancies between one- and two-stage queue lengths for HAWK are small. Many treatments yield rather large negative pedestrian-induced queue lengths under the saturated condition. In these cases, the introduction of the pedestrian signal makes queue lengths shrink, which could be ascribed to the metering effect of the pedestrian signal on the busiest approach. It also shows that under conditions of existing flow and approaching capacity, HAWK has the shortest queue length of any signal. PA generates the largest queue length, and PELICAN and PUFFIN have shorter queue lengths relatively close to each other.

PA, PELICAN, and PUFFIN produce longer queues in the conventional layout than in the distant layout (Figure 6*c*). There are no substantial differences among queue lengths generated at the three layouts (Figure 6*d*).

Average Number of Stops

The results for single- or double-lane roundabouts reveal similar operational features to pedestrian-induced vehicle delays. It could be inferred that the distant layout and the two-stage scheme are safer across most study scenarios and that the introduction of pedestrian signals allows vehicles to move more smoothly under the saturated condition, which diminishes the likelihood of vehicle-to-vehicle crashes. Additionally, HAWK and PUFFIN are believed safer than the other signals for most treatments. The latter should be more advantageous because of its protective on-crosswalk pedestrian sensor.

Average Pedestrian Delay

Since the four signals operate with a fixed length of minimum vehicle green, it is expected that average pedestrian delays will be independent of traffic flow fluctuations. Table 1 indicates that when the pedestrian flow level is specifically maintained at single- and double-lane roundabouts, average pedestrian delay with varying treatments changes very little despite the vehicle volume changes from existing flow to saturated condition. At a specific vehicle flow level, pedestrian delays consistently increase with increases in the number of crossing pedestrians. With more crossing pedestrians, it is more likely for a larger portion of a pedestrian flow to arrive during the minimum green time and then wait for the signal display. In other words, more pedestrians are delayed by minimum green constraints.

PA, PELICAN, and HAWK generate equal average pedestrian delays for a specific combination of geometric layout and installation scheme, which can be explained by their having identically timed FDW lengths. Additionally, paired *t*-tests reveal that each of these three signals has significantly higher average pedestrian delays than PUFFIN, which means it should be confidently believed that the dynamic pedestrian clearance time provided by PUFFIN not only protects pedestrians well but also significantly saves pedestrian waiting time.

It was originally expected that different geometric layouts would produce variable average pedestrian delays as a result of distinct pathway deflections. When the two-stage scheme is applied to single- and

TABLE 1 Mean of 13 Simulation Replications of Average Pedestrian Delay in Seconds

	Conventional Layout		Offset Layout	Distant Layout	
Crosswalk Treatment	IS-1	IS-2	IS-2	IS-1	IS-2
Existing Flow					
Single-lane roundabout site (1,172 PCEs per hour)					
Few pedestrians (14 pph)					
PA	22.05	18.04	19.58	17.37	17.46
HAWK	22.05	18.04	19.58	17.37	17.46
PELICAN	22.05	18.04	19.58	17.37	17.46
PUFFIN	9.81[a]	15.09[a]	15.50[a]	9.05[a]	14.67[a]
Some pedestrians (70 pph)					
PA	48.61	44.23	41.95	41.75	43.77
HAWK	48.61	44.23	41.95	41.75	43.77
PELICAN	48.61	44.23	41.95	41.75	43.77
PUFFIN	24.34[a]	30.12[a]	32.04[a]	22.45[a]	29.62[a]
Many pedestrians (180 pph)					
PA	49.41	51.14	51.82	43.66	52.47
HAWK	49.41	51.14	51.82	43.66	52.47
PELICAN	49.41	51.14	51.82	43.66	52.47
PUFFIN	34.52[a]	42.15[a]	41.89[a]	30.13[a]	42.85[a]
Double-lane roundabout site (1,432 PCEs per hour)					
Few pedestrians (14 pph)					
PA	22.82	20.32	22.95	17.52	20.00
HAWK	22.25	20.32	22.95	17.52	20.00
PELICAN	22.25	20.32	22.95	17.52	20.00
PUFFIN	9.19[a]	15.81[a]	15.39[a]	8.62[a]	15.30[a]
Some pedestrians (70 pph)					
PA	50.19	52.65	53.43	43.80	52.34
HAWK	50.08	52.65	53.43	43.80	52.34
PELICAN	50.08	52.65	53.43	43.80	52.34
PUFFIN	24.38[a]	33.97[a]	33.17[a]	23.35[a]	31.81[a]
Many pedestrians (180 pph)					
PA	51.38	60.80	59.32	44.46	60.51
HAWK	51.88	60.80	59.32	44.46	60.51
PELICAN	51.88	60.80	59.32	44.46	60.51
PUFFIN	34.87[a]	45.31[a]	45.23[a]	31.23[a]	44.74[a]
Approaching Capacity					
Single-lane roundabout site (1,582 PCEs per hour)					
Few pedestrians (14 pph)					
PA	19.69	17.91	18.23	16.21	18.34
HAWK	19.69	17.91	18.23	16.21	18.34
PELICAN	19.69	17.91	19.61	16.21	18.34
PUFFIN	8.95[a]	15.49[a]	14.81[a]	8.25[a]	15.69[a]
Some pedestrians (70 pph)					
PA	48.61	44.23	41.95	41.75	43.77
HAWK	48.61	44.23	41.95	41.75	43.77
PELICAN	48.61	44.23	41.50	41.75	43.77
PUFFIN	24.34[a]	30.12[a]	32.04[a]	22.45[a]	29.62[a]
Many pedestrians (180 pph)					
PA	49.41	51.14	51.82	43.66	52.47
HAWK	49.41	51.14	51.82	43.66	52.47
PELICAN	49.41	51.14	51.82	43.66	52.47
PUFFIN	34.52[a]	42.15[a]	41.89[a]	30.13[a]	42.85[a]

(continued)

TABLE 1 *(continued)* **Mean of 13 Simulation Replications of Average Pedestrian Delay in Seconds**

	Conventional Layout			Distant Layout	
Crosswalk Treatment	IS-1	IS-2	Offset Layout IS-2	IS-1	IS-2
Double-lane roundabout site (2,649 PCEs per hour)					
Few pedestrians (14 pph)					
PA	22.82	20.87	20.31	16.51	21.22
HAWK	21.02	20.87	20.31	16.51	21.22
PELICAN	21.02	20.87	20.31	16.51	21.22
PUFFIN	8.83[a]	16.18[a]	14.35[a]	8.42[a]	16.28[a]
Some pedestrians (70 pph)					
PA	50.19	52.65	53.43	43.80	52.34
HAWK	50.08	52.65	53.43	43.80	52.34
PELICAN	50.08	52.65	53.43	43.80	52.34
PUFFIN	24.38[a]	33.99[a]	33.1[a]	23.35[a]	31.81[a]
Many pedestrians (180 pph)					
PA	51.88	60.80	59.32	44.46	60.51
HAWK	51.88	60.80	59.32	44.46	60.51
PELICAN	51.88	60.80	59.32	44.46	60.51
PUFFIN	34.87[a]	45.31[a]	45.23[a]	31.23[a]	44.74[a]
Saturated Condition					
Single-lane roundabout site (1,992 PCEs per hour)					
Few pedestrians (14 pph)					
PA	19.69	17.91	18.23	16.21	18.34
HAWK	19.69	17.91	18.23	16.21	18.34
PELICAN	19.69	17.91	19.61	16.21	18.34
PUFFIN	8.95[a]	15.49[a]	14.81[a]	8.25[a]	15.69[a]
Some pedestrians (70 pph)					
PA	48.61	44.23	41.95	41.75	43.77
HAWK	48.61	44.23	41.95	41.75	43.77
PELICAN	48.61	44.23	41.50	41.75	43.77
PUFFIN	24.34[a]	30.12[a]	32.04[a]	22.45[a]	29.62[a]
Many pedestrians (180 pph)					
PA	49.41	51.14	51.82	43.66	52.47
HAWK	49.41	51.14	51.82	43.66	52.47
PELICAN	49.41	51.14	51.82	43.66	52.47
PUFFIN	34.52[a]	42.15[a]	41.89[a]	30.13[a]	42.85[a]
Double-lane roundabout site (3,866 PCEs per hour)					
Few pedestrians (14 pph)					
PA	22.82	20.87	20.31	16.51	21.22
HAWK	21.02	20.87	20.31	16.51	21.22
PELICAN	21.02	20.87	20.31	16.51	21.22
PUFFIN	8.83[a]	16.18[a]	14.35[a]	8.42[a]	16.28[a]
Some pedestrians (70 pph)					
PA	50.19	52.65	53.43	43.80	52.34
HAWK	50.08	52.65	53.43	43.80	52.34
PELICAN	50.08	52.65	53.43	43.80	52.34
PUFFIN	24.38[a]	33.99[a]	33.17[a]	23.35[a]	31.81[a]
Many pedestrians (180 pph)					
PA	51.88	60.80	59.32	44.46	60.51
HAWK	51.88	60.80	59.32	44.46	60.51
PELICAN	51.88	60.80	59.32	44.46	60.51
PUFFIN	34.87[a]	45.31[a]	45.22[a]	31.23[a]	44.74[a]

NOTE: IS-1 = “one-stage” installation scheme; IS-2 = “two-stage” installation scheme.

[a] Pedestrian delay from PUFFIN is significantly different from that of PA, PELICAN, or HAWK at $\alpha = 0.05$ by paired *t*-test, given a specific combination of geometric layout and installation scheme.

double-lane roundabouts, pedestrian delays from a specific signal fluctuate to a limited degree among three layouts given each of the three pedestrian flow levels. When the one-stage scheme is applied to single- and double-lane roundabouts and there are some or many pedestrians, the average pedestrian delays generated by a specific signal in a conventional layout are longer than those in a distant layout.

CONCLUDING REMARKS

This simulation study assessed four pedestrian signals hypothetically installed at typical single- or double-lane modern roundabouts. Crosswalk layouts and installation schemes were varied under a typical array of multimodal operational conditions to enable the quantification of interactions among pedestrian crossing behaviors and traffic circulation. The intention was to objectively identify potential crosswalk treatments to improve roundabout accessibility, especially for seniors, children, and visually impaired and disabled pedestrians, while maintaining acceptable multimodal mobility and quality of service.

The study results suggest a nonmonotonic relationship between signalization effects and all levels of vehicle volume. Vehicle delays appear to be the largest as traffic volumes approach the roundabout's capacity. It could be concluded that (*a*) the two-stage installation scheme is much more operationally efficient than its one-stage counterpart; (*b*) there are no significant differences among the three geometric layouts if they are used in conjunction with the two-stage scheme. When the one-stage scheme is employed, the distant layout, compared with the conventional layout, can reduce vehicle delays and queue lengths because of the enlarged vehicle storage space at the exit lanes; (*c*) HAWK poses the least delay to vehicles for most study scenarios, and PUFFIN generates minimum pedestrian delay for all scenarios. These two signals are both promising for roundabout signalization, but PUFFIN is believed to provide a better balance between pedestrian crossing safety and traffic movement efficiency; and (*d*) the addition of pedestrian signals to double-lane roundabouts is operationally beneficial for roundabout vehicle circulation when vehicular inflows are in a saturated state.

The study findings should be informative to transportation policy makers, planners, and practitioners in the access management community who face the challenge of improving roundabout accessibility to pedestrians, especially those with impaired vision or mobility.

FUTURE DIRECTIONS

This study focused on two specific roundabouts, each of which has a very busy approach and frequent crossing pedestrians, and thus only single signalization was applied to each site. For roundabouts with heavy multimodal inflows on two or more approaches, the effect of multiple signalizations on traffic operations should be explored. Simultaneously, the authors believe that an all-approach signalization might be questionable since it would resemble a hybrid between a modern roundabout and a signalized intersection. Random pedestrian arrivals, however, make it difficult to weave four independent pedestrian signals into a coordinated operation. It is highly likely that an all-approach signalization would incur additional disturbances or queuing delays to the entire roundabout circulation. For the sake of wide practical use, a sufficient number of real-world experiments under various conditions will be essential to procuring the latest knowledge, expertise, and experience for boosting advances in state-of-the-practice roundabout access management and integrating them into established planning, policy, and design processes and relevant documents.

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