# Multimodal Accessibility of Modern Roundabouts

## Intelligent Management System Versus Common Signalization Scheme

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**Modern roundabouts have become popular in North America during the past decade. This popularity can be attributed to their great success in Europe and Australia. There has been significant debate, however, over their accessibility for pedestrians. With almost uninterrupted traffic flows, roundabouts make it difficult for the visually impaired to determine safe gaps, as they rely on auditory cues alone. Such crossing is particularly complicated by ambient noises and circulating vehicles on busy urban roundabouts. Various pedestrian signals have been installed at roundabouts overseas. The United States Access Board published a draft guideline proposing pedestrian signals at all roundabout crossings to ensure access for the visually impaired. Roundabout operations can be a complex process of transporting multimodal travelers. There is increased interest in harnessing artificial intelligence to address issues to improve transportation systems. This research developed a crosswalk signal and introduced fuzzy logic control (FLC) into the signal timing to accommodate roundabout users. The system was assessed against the Pedestrian User-Friendly Intelligent (PUFFIN) crossings under varied geometries under different traffic conditions. The objective was to identify potential treatments for improving roundabout accessibility, safety, and efficiency. The results reveal that "distant" layout reduces vehicle delays and queue lengths when the FLC signal is applied, especially under saturated traffic conditions. From safety and operational perspectives, the FLC signal outperforms PUFFIN. The FLC signal implements the signal timing effectively, decreases pedestrian delay, and maintains adequate vehicle circulation. Multimodal traveler needs at a modern roundabout are satisfied in manifold ways.**

During the past decade, modern roundabouts have become more popular in many states and municipalities throughout North America. Their popularity can be attributed to their great success in Europe and Australia. Their attractiveness comes from proven safety benefits, enhanced operational efficiency, reduced maintenance cost, and strengthened aesthetic appeals (*1*). In geometry, a modern roundabout is an unsignalized intersection with a round island encircled by a roadway. In operations, vehicles entering the roundabout yield to vehicles simultaneously moving on the circulatory path.

The increasing prevalence of roundabouts generated significant debate over the multimodal accessibility. Past studies identified that roundabouts pose serious difficulties to visually impaired pedestrians (*2, 3*). Pedestrian crossing becomes increasingly difficult as vehicles increase, and multilane roundabouts are more challenging than single-lane facilities to ensure safe pedestrian access (*4*). Another study further verified that crossing segments on exit lanes is more difficult than that on entry lanes (*5*). In 2002, the United States Access Board published the "Draft Guideline for Accessible Public Rights of Way, Roundabout" to propose pedestrian signals at all roundabout crosswalks. Later, the revised draft was released to call for the provision of "A pedestrian-activated traffic signal . . . for each segment of the crosswalk . . ." (*6*) at multilane roundabouts to ensure access for the visually impaired. From an operational perspective, the trade-off for this provision is interruption of motorized vehicle flows. The enhanced likelihood that a yielding queue spills back into the circulatory roadway is also a critical issue that has been identified worldwide at roundabouts with existing signalization (*7*). Until 2009, only three roundabouts were outfitted with pedestrian signals in the United States: two single-lane roundabouts on university campuses (University of Utah, Salt Lake City, and University of North Carolina, Charlotte) and one double-lane roundabout in Lake Worth, Florida. In Gatineau, Canada, a double-lane roundabout shows a staggered offset crossing with a pedestrian signal on one approach. In contrast, varied signal systems have been installed at roundabouts in Europe, Australia (*3*), and South Africa (*8*). There is minimal literature relevant to signalizing roundabouts, but a study by Rouphail et al. (*9*) indicated that addition of a pedestrian-actuated signal to a roundabout incurred delays to visually impaired pedestrians compared with sighted pedestrians who cross at unsignalized splitter islands. Another study [Schroeder et al. (*10*)] explored signalization options to make single- and double-lane roundabouts accessible to the visually impaired. The signalization impact was found to be greatest as the vehicular volume approaches capacity, but vehicle delay and queue can be mitigated through innovative signal control logic.

While few roundabouts have pedestrian signals in North America, the call from the Access Board for pedestrian access implies that more research is expected in the transportation engineering community. Contemporary transportation professionals face increased challenges in offering safe, efficient, and reliable transportation systems. Adding to these challenges is the fact that transportation system operations

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are an inherently complex process consisting of manifold, often competing, or even conflicting objectives in a dynamic setting. "As the complexity of a system increases, our ability to make precise and yet significant statements about its behaviors diminishes, and significance and complexity become almost mutually exclusive characteristics," said Kosko (*11*), which implies some transportation problems are difficult to resolve using traditional methodologies. Gradually, there has been increased interest in employing artificial intelligence (AI) to address complex issues to improve safety, operations, and other aspects of transportation systems (*12, 13*).

## OBJECTIVES AND HYPOTHESES

Inspired by the methodological tendency toward the AI domain, this research developed a new signal system in which fuzzy logic control (FLC) was introduced into the signal timing for vehicles and pedestrians at modern roundabouts. The installation of a pedestrian signal is intuitively associated with additional delays to motorized vehicles, but it is difficult to quantify this effect. This research was intended to quantitatively assess the performance of the new system against a signalization scheme that is commonly used in Europe and Australia for midblock or roundabout crosswalks. The analysis includes evaluating different crosswalk geometries and signalization schemes given a spectrum of pedestrian and vehicle volumes at single- and double-lane roundabouts. The goal is to identify potential treatments that improve the roundabout accessibility especially for the visually impaired, seniors, and children, while maintaining a good service quality for vehicles. It is hypothesized: (*a*) The operational impact of adding a pedestrian signal is a function of vehicle and pedestrian flows. (Increasing pedestrians enhance the frequency of signal actuations. Given more vehicles, each actuation poses a more drastic impact to vehicle delays and increases the likelihood that yielding queues spill back into the circulatory path); (*b*) The risk of queue spillback can be lessened by shifting the crosswalk segment on outbound lane(s) further away from the round island; and (*c*) FLC is more effective, flexible, and adaptable than traditional controls in tackling a dynamic environment.

## STUDY METHODOLOGY

From an all-roundabout-user perspective, this research explored how the change of control affects certain performance measures in three dimensions: signalization strategy, crosswalk layout, and multimodal traffic intensity. It is infeasible to examine the performances of two signal systems in a real-world context due to disruptions and detriments to traffic safety and operations. Instead, a reliable in-lab test bed should be established as a surrogate means by which signal systems can be implemented and evaluated under a controllable condition.

### Study Environment

Traffic simulation is an indispensable tool for contemporary transportation professionals and researchers because of its cost-effectiveness, unobtrusiveness, risk-free nature, and computational efficiency. It yields extensive performance measures that fully reflect the operations. More importantly, it offers the unique opportunity to implement different traffic management strategies and evaluate their effectiveness under various traffic conditions prior to field deployment. VISSIM, a microsimulation program, is widely employed to model various facilities due to some technical advantages over other counterparts (e.g., traveler behavior modeling, detector functionality, control logic flexibility, and run time control) (*14*). VISSIM models have been used or calibrated to mimic real-world situations at freeways (*15*), urban networks (*16*), crosswalks or intersections (*17–19*), arterials, and roundabouts (*9, 10*). Its link-connector structure can flexibly model unique roundabout geometries. It can implement user-defined control strategies and emulate yielding behaviors by vehicles. Therefore, a VISSIM-based framework was established as a reliable and controllable platform for study.

### Crosswalk Geometry

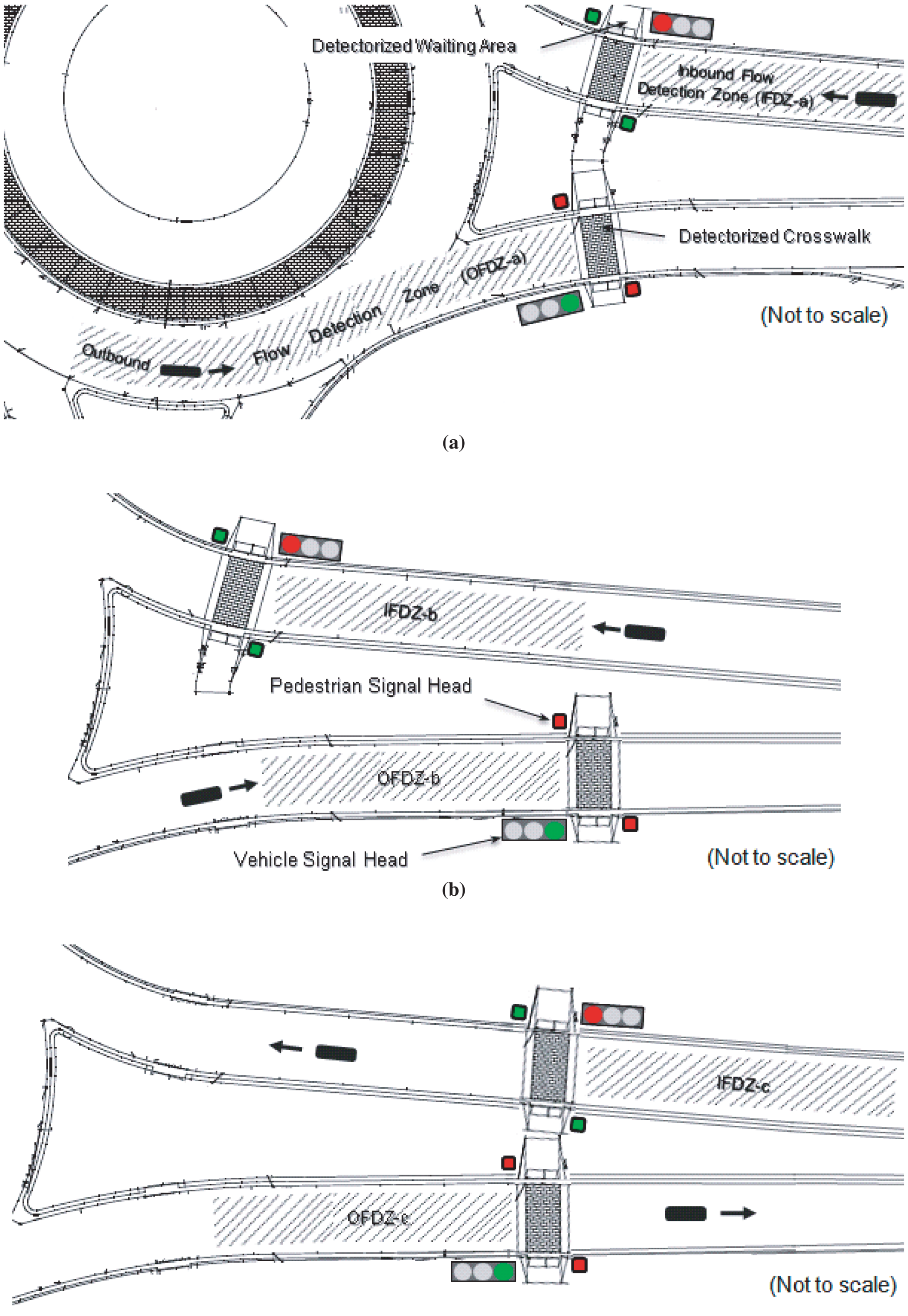
In North America, the most common crosswalk layout for a roundabout runs across the splitter island, about one vehicle length (20 ft) upstream of the yield line, which can be termed conventional layout (Figure 1*a*). Two other layouts were analyzed considering the key issue that vehicle queues may spill back into the circulatory path. One, offset layout, is to spatially shift the crosswalk segment on the exit leg further away from the circle: the exit-leg segment is "offset" by a distance of 80 ft from the circulatory lane(s), and approximately this distance accommodates four vehicles per lane before vehicles intrude into the circulatory path (Figure 1*b*). The other, distant layout, moves the entire crosswalk a distance of 120 ft away outward, which yields roughly six-vehicle queue storage per lane (Figure 1*c*).

### Signalization Alternatives

Some pedestrian signals installed in Europe include PEdestrian LIght CONtrol (PELICAN), Two CAN (TOUCAN), and Pedestrian User-Friendly Intelligent (PUFFIN) (*20, 21*). In the United States, a few local traffic management authorities provide the guidelines for considering these options to control mid-block crosswalks, which signifies the rising number of applications in North America (*22*). Conventionally, the pedestrian-actuated (PA) signal is used for crosswalks per the *Manual on Uniform Traffic Control Devices* (MUTCD) (*23*), while High-Intensity Activated CrossWalK (HAWK) is experimented at mid-block crosswalks in Tucson, Arizona; Portland, Oregon; and several other cities (*24, 25*).

#### *PUFFIN*

PA, PELICAN, TOUCAN, and HAWK statically time "Flashing DON'T WALK" (FDW) using the crossing distance and a design walking speed. From a safety perspective, this practice is questionable due to the variability in walking speeds among the visually impaired, the aging population, and the growing child mobility. Past studies in North America revealed that walking speeds vary considerably for different populations (*26–28*). Current pedestrian signals lack adequate "pedestrian friendliness" since their static FDW timing does not provide full signal protection for all pedestrians. Pedestrians can be exposed to yielding vehicles if insufficient FDW time is provided.



(a)

(b)

(c)

FIGURE 1 Crosswalk layouts and detection zones for input data collection: (*a*) conventional layout, (*b*) offset layout, and (*c*) distant layout.

In contrast, PUFFIN is adequate in "pedestrian friendliness" because in-crosswalk sensors adjust the pedestrian clearance time to offer the crossing time needed. This dynamic timing provides full protection to the visually impaired, seniors, and children (Figure 2*a*, Tables 1 and 2). However, PUFFIN omits safety elements or human factors in its control logic, without pursuing additional operational and safety objectives in dynamic operations.

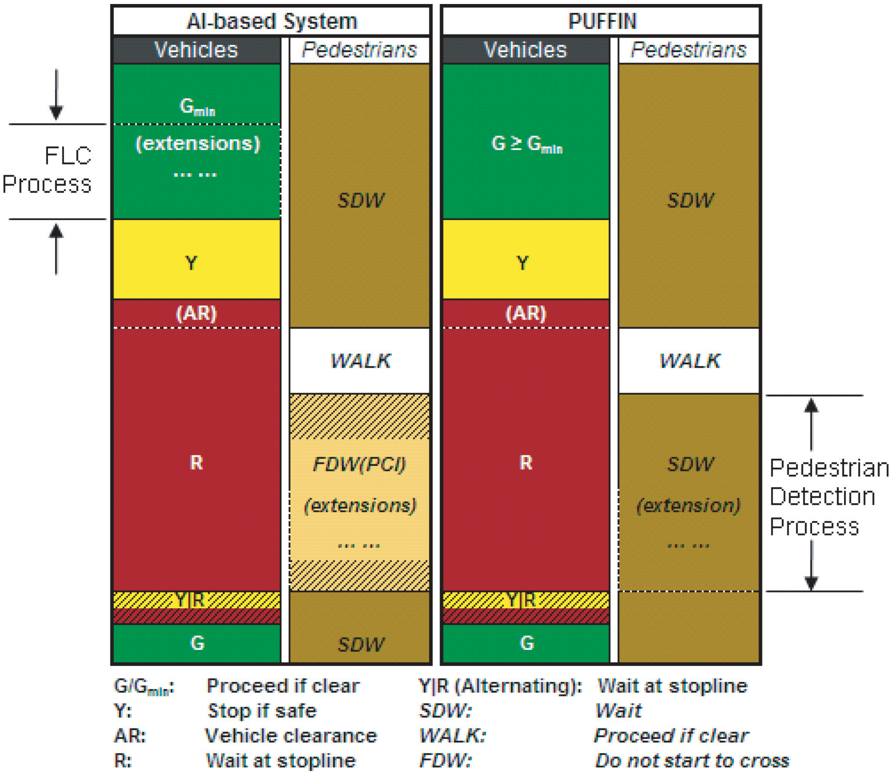
### *An AI-Based System*

An AI-based system signalizes a roundabout means to determine the optimal time for switching the right-of-way between vehicles and pedestrians. Any traffic signal control is a process of apportioning green time to conflicting facility users. The signal system evaluates ongoing traffic conditions with decision-making criteria to conduct appropriate adjustments in timing plans. In principle, signal control is a process of determining, at regular time intervals ($\Delta t$), whether to extend or terminate the current vehicle green.

In reality, a crossing guard is sometimes deployed at a facility (e.g., crosswalk near a school) for traffic management. The guard subjectively processes intuitive rules by evaluating ongoing and desired operations. For example, if he or she feels a pedestrian has been waiting for a "frustratingly long" time and upcoming vehicles are "sparsely" present, he or she "terminates" the right-of-way for vehicles and switches it to pedestrians. This manual control is effective, safe, adaptive, and robust for tackling dynamic traffic operations, because the human intelligence has unlimited flexibility in data processing, logical reasoning, and decision making. In this research, an FLC-based signal system was developed to artificially emulate the human intelligence of the guard. Following the signal control principle, the system compares traffic conditions during current and next phases to realize some competing objectives. It is different from existing systems that do not examine prevailing traffic conditions for all travelers.

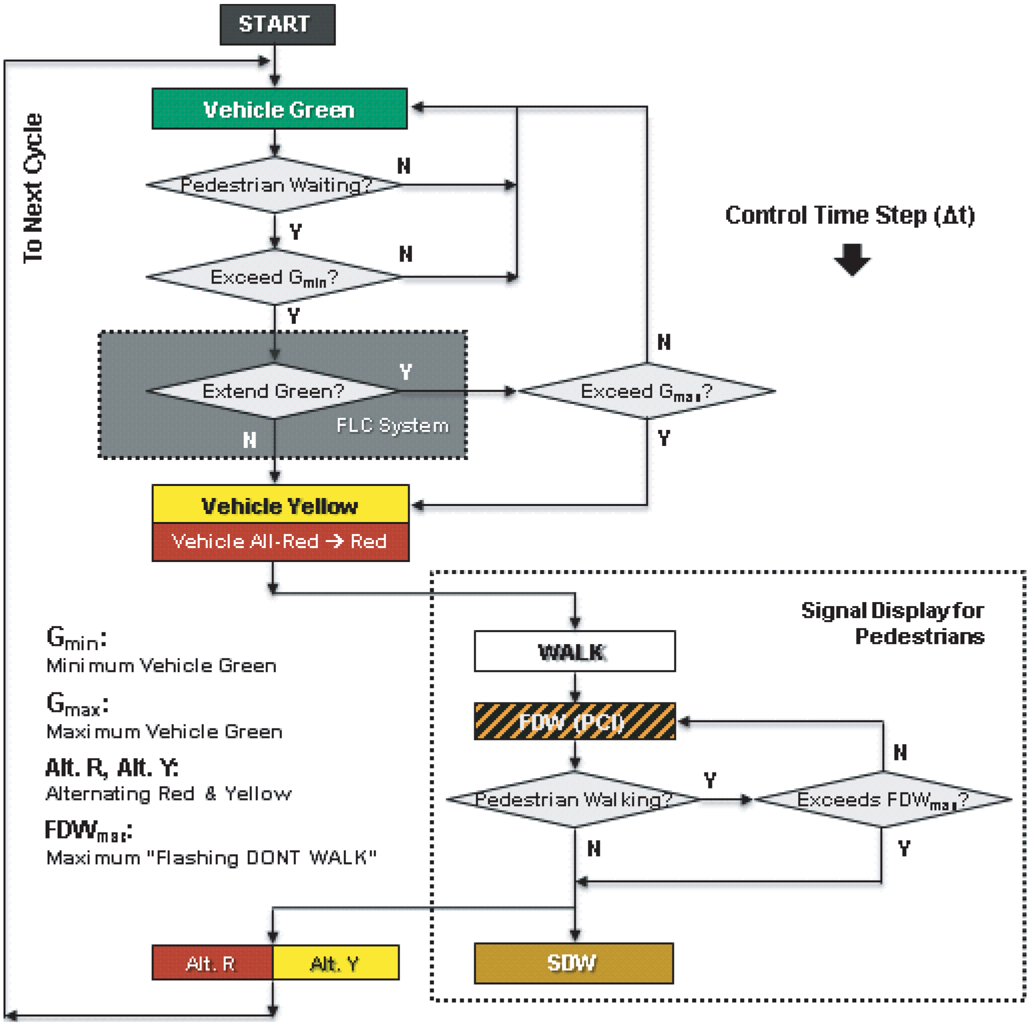
Figures 2*a* and *b* depict the phasing scheme and the control logic of the system. With pedestrians absent, the system displays the "idle phase" (vehicle green). With pedestrians present, it examines whether the minimum green is exceeded by the green already displayed. If so, it evaluates ongoing operations for all roundabout users and executes the fuzzy inference for control action. Once specified, decision-making criteria are triggered and the current green is either terminated or extended. This process is reiterated at time intervals until the right-of-way is switched or the maximum green is reached. When the green is terminated, "WALK" starts, then "FDW" follows. To offer the "pedestrian friendliness," the system displays dynamic "FDW" via on-crosswalk sensors and extends it up to its maximum for the slowest pedestrians. One second of "Alternating Red/Yellow," alerting drivers to possible pedestrians, is displayed before the vehicle green for the sake of the consistence with PUFFIN.

FLC has the ability to handle multiple objectives (*13*). Several objectives were set: (*a*) minimum delay to pedestrians—the wait time should be decreased as much as possible, (*b*) minimum delay to vehicles—vehicles should traverse a roundabout with the least possible delay, (*c*) maximum safety for all users, which is twofold embodied: first, to offer full signal protection for the visually impaired, seniors, and children who walk slowly, and second, to dissipate



(a)

**FIGURE 2 AI-based pedestrian signals at roundabouts: (*a*) signal phasing schemes comparison.** *(continued)*



(b)

FIGURE 2 *(continued)* AI-based pedestrian signals at roundabouts: (*b*) fuzzy logic signal control flowchart.

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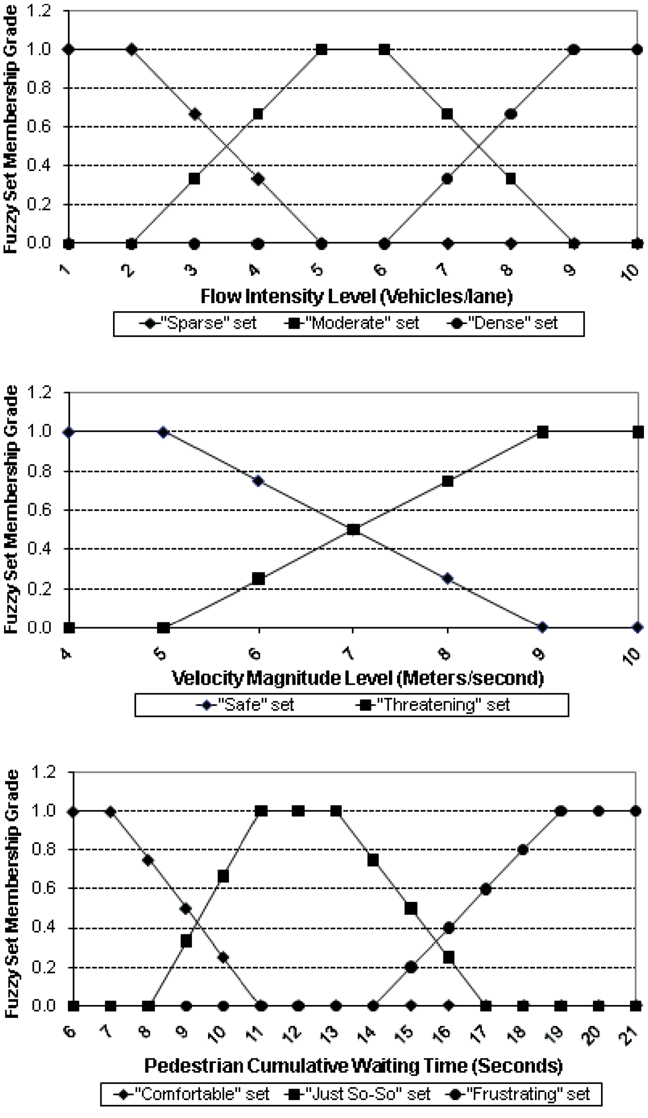
vehicles promptly, when they approach the crosswalk in a large volume and at a high speed, for safety consideration: to diminish the likelihood of rear-end collisions if green terminates abruptly.

A portion in Figure 3*d* illustrates key components of the FLC system: fuzzifier, inference engine, and defuzzifier.

**Fuzzifier** The membership function plays a key role in a fuzzifier, which transforms the following crisp input variables into these fuzzy sets to be processed by the inference engine:

- $CWT_{In}(t+\Delta t)$, $CWT_{Out}(t+\Delta t)$, $CWT_{Cir}(t+\Delta t)$. Definition: Maximum roadside-based Cumulative Waiting Time (seconds) already consumed by pedestrians, at time point $(t+\Delta t)$, who are waiting to cross Inbound, distant Outbound lane(s), or lane(s) near a Circulatory path. This input variable represents how long pedestrians have been waiting since the last change from "WALK" to "FDW," which reflects human factors in accommodating pedestrians. Pedestrian delays have operations- and safety-related implications. The longer a pedestrian has been delayed, the more likely he or she is to cross without an appropriate signal display.
- $FIL_{In}(t+\Delta t)$, $FIL_{Out}(t+\Delta t)$, $FIL_{Cir}(t+\Delta t)$. Definition: Average lane-based Flow Intensity Level (vehicles/lane) within $\Delta t$ for vehicles approaching or passing Inbound, Outbound, or Circulating lane(s). This input variable measures the number of vehicles within detection zones for signalized approach lanes and the circulatory roadway, which reflects ongoing vehicle flow intensity. Vehicle delays have both efficiency- and safety-related impacts. The more intense the flow intensity is, the more strongly the vehicles demand for green. Psychologically, the longer a motorist is delayed, the more likely he or she will become impatient or aggressive.
- $VML_{In}(t+\Delta t)$, $VML_{Out}(t+\Delta t)$, $VML_{Cir}(t+\Delta t)$. Definition: Maximum lane-based Velocity Magnitude Level (meters per second) within $\Delta t$ for vehicles approaching or passing Inbound, Outbound, or Circulating lane(s). This input variable reflects the threatening vehicle when it approaches the crosswalk. The vehicle speed addresses the safety issue: the faster the vehicles are moving, the more likely it is that an abrupt green termination incurs rear-end collisions.
- $SCA(t+\Delta t)$. Definition: Signal Control Action taken at the time point $(t+\Delta t)$. This output variable denotes the control actions on vehicle green: Extension or Termination.



**(c)**

FIGURE 2 *(continued)* AI-based pedestrian signals at roundabouts: (*c*) membership functions used in Rule Base A (Tables 1 and 2) of fuzzy logic signal system.

TABLE 1 Fuzzy Logic Inference Engines for Roundabout FLC Signals: Generic Format of Fuzzy Logic Rules

| Fuzzy Rule | Premises (crisp inputs: $X = a$, $Y = b$, $Z = c$) | Consequences |
|---|---|---|
| Rule 1 | If $\{X\ is\ a_1\}$ and $\{Y\ is\ b_1\}$ and $\{Z\ is\ c_1\}$ | Then $\{E^a$ or $T^b\}$ |
|  | . . . . . . . . . . . . . . . . . . |  |
| Rule i | If $\{X\ is\ a_i\}$ and $\{Y\ is\ b_i\}$ and $\{Z\ is\ c_i\}$ | Then $\{E$ or $T\}$ |
|  | . . . . . . . . . . . . . . . . . . |  |
| Rule n | If $\{X\ is\ a_n\}$ and $\{Y\ is\ b_n\}$ and $\{Z\ is\ c_n\}$ | Then $\{E$ or $T\}$ |
| Crisp output | {E or T} |  |
| Where | $X, Y, Z$ = input (state) variables related to traffic conditions,<br>$a, b, c$ = values of input variables, and<br>$a_i, b_i, c_i$ = natural language expressions for traffic conditions |  |

[a] Terminate current vehicle green.
[b] Extend current vehicle green.

Hypothetically, $CWT_{In,Out,Cir}(t+\Delta t)$ was collected per near-crosswalk pushbuttons and waiting area sensors, while vehicle data were collected in six detection zones that cover inbound–outbound–circulating lane(s) (Figure 1): OFDZ-*a* collects $FIL_{Cir}(t + \Delta t)$ and $VML_{Cir}(t + \Delta t)$; OFDZ-*b* and OFDZ-*c* collect $FIL_{Out}(t + \Delta t)$ and $VML_{Out}(t + \Delta t)$; other three zones (IFDZ-*a,* IFDZ-*b,* and IFDZ-*c*) collect $FIL_{In}(t + \Delta t)$ and $VML_{In}(t + \Delta t)$. Some fuzzy sets were defined for each input variable (Tables 1 and 2). Trapezoid membership function was harnessed to avoid complicating the problem, which needs four parameters of trapezium breakpoints: Trapezoid $(x;m,n,p,q) = \max\{\min((x-m)/(n-m),1,(q-x)/(q-p),0)\}$. For different layouts, membership functions for $CWT(t + \Delta t)$ are segregated into "motorist friendly" and "pedestrian friendly" types, which emphasize the respective convenience to motorists and pedestrians. To capture the quantifiable feeling of all fuzzy sets that represent operational conditions, this research conducted field observations, quantitative recordings, and basic statistical analyses for subject roundabouts, as well as literature review (*12*). To approximate the function shapes that produce near-optimal simulation performances, trial-and-error methods were applied to a number of scenarios. As an example, Figure 2*c* delineates the membership functions in a rule base.

**Inference Engine** It "thinks" as a "human brain" through a set of rules that describe, in natural language, ongoing traffic conditions for current and next phases. Tables 1 and 2 show the generic structure of a rule base. The facts following "IF" and "THEN" are termed "premise" and "consequence," respectively, while "AND" is an "operator." The traditional inference draws a conclusion when a rule is an exact match between the input ($a$, $b$, $c$) and a premise ($a_i$, $b_i$, $c_i$). So, many rules are necessary to cover all possibilities. The output is singular and the decision-making process is characterized by its rigidness. PUFFIN lies in this realm; its timing mechanism performs in an inflexible way, due to the rigidity in maintaining specific parameters. Differently, the fuzzy inference makes a conclusion based on the similarity between the input ($a$, $b$, $c$) and premises ($a_1$, $b_1$, $c_1$; . . . ; $a_i$, $b_i$, $c_i$; . . . ; $a_n$, $b_n$, $c_n$). A one-to-one match is unnecessary and the extent of similarity dominates the degree of truth in consequence. With this paradigm, a specific input triggers multiple rules because the input and premises in triggered rules are represented by fuzzy sets and fuzzy relationships produced by set operations. Hence, different consequences from all activated rules are valid and they are aggregated for a final output space consisting of fuzzy control actions. To be defuzzified, the final output space is a compromise among these conclusions from all triggered rules. Essentially, all rules and conclusions are implicitly associated with procuring manifold, perhaps conflicting, objectives given numerous possibilities of ongoing traffic conditions. The decision-making mechanism is characterized by its flexibleness, which exhibits the robust and adaptive feature in pursuing multiple goals because the membership functions implicitly enclose an extensive scope of possibilities. Typically, the number of rules depends on the combination of fuzzy sets defined. Three layout-specific rule bases were established through "assimilating" the human intelligence of a crossing guard (Tables 1 and 2). Mamdani's method adopted herein is the most common approach for the aggregation process. It was from Zadeh's work on fuzzy algorithms for complex systems and decision processes (*29*), which was among the first control system built using fuzzy set theory by synthesizing a set of linguistic control rules obtained from experienced human operators (*30*).

**TABLE 2 Three Inference Rule Bases Established on Basis of Crosswalk Layouts**

| | If | | | Then |
|---|---|---|---|---|
| Rule Base A | Input (state) Variables | | | Output (control) Variable |
| | $CWT_{In}(t+\Delta t)$ | $FIL_{In}(t+\Delta t)$ | $VML_{In}(t+\Delta t)$ | $SCA(t+\Delta t)$ |
| 1 | Comfortable | Sparse | Safe | T[a] |
| 2 | Comfortable | Sparse | Threatening | T |
| 3 | Comfortable | Moderate | Safe | E[b] |
| 4 | Comfortable | Moderate | Threatening | E |
| 5 | Comfortable | Dense | Safe | E |
| 6 | Comfortable | Dense | Threatening | E |
| 7 | Just so-so | Sparse | Safe | T |
| 8 | Just so-so | Sparse | Threatening | T |
| 9 | Just so-so | Moderate | Safe | T |
| 10 | Just so-so | Moderate | Threatening | E |
| 11 | Just so-so | Dense | Safe | E |
| 12 | Just so-so | Dense | Threatening | E |
| 13 | Frustrating | Sparse | Safe | T |
| 14 | Frustrating | Sparse | Threatening | T |
| 15 | Frustrating | Moderate | Safe | T |
| 16 | Frustrating | Moderate | Threatening | T |
| 17 | Frustrating | Dense | Safe | T |
| 18 | Frustrating | Dense | Threatening | E |
| Rule Base B | Input (state) Variables | | | Output (control) Variable |
| | $CWT_{Out}(t+\Delta t)$ | $FIL_{Out}(t+\Delta t)$ | $VML_{Out}(t+\Delta t)$ | $SCA(t+\Delta t)$ |
| 1 | Comfortable | Sparse | Slow | T |
| 2 | Comfortable | Sparse | Fast | T |
| 3 | Comfortable | Moderate | Slow | E |
| 4 | Comfortable | Moderate | Fast | E |
| 5 | Comfortable | Dense | Slow | E |
| 6 | Comfortable | Dense | Fast | E |
| 7 | Just so-so | Sparse | Slow | T |
| 8 | Just so-so | Sparse | Fast | T |
| 9 | Just so-so | Moderate | Slow | E |
| 10 | Just so-so | Moderate | Fast | E |
| 11 | Just so-so | Dense | Slow | E |
| 12 | Just so-so | Dense | Fast | E |
| 13 | Frustrating | Sparse | Slow | T |
| 14 | Frustrating | Sparse | Fast | T |
| 15 | Frustrating | Moderate | Slow | T |
| 16 | Frustrating | Moderate | Fast | T |
| 17 | Frustrating | Dense | Slow | T |
| 18 | Frustrating | Dense | Fast | E |

*(continued on next page)*

**TABLE 2** *(continued)* **Three Inference Rule Bases Established on Basis of Crosswalk Layouts**

| | If | | | Then |
|---|---|---|---|---|
| Rule Base C | $CWT_{Cir}(t+\Delta t)$ | $FIL_{Cir}(t+\Delta t)$ | $VML_{Cir}(t+\Delta t)$ | $SCA(t+\Delta t)$ |
| 1 | Comfortable | Sparse | Slow | T |
| 2 | Comfortable | Sparse | Fast | T |
| 3 | Comfortable | Moderate | Slow | E |
| 4 | Comfortable | Moderate | Fast | E |
| 5 | Comfortable | Dense | Slow | E |
| 6 | Comfortable | Dense | Fast | E |
| 7 | Just so-so | Sparse | Slow | T |
| 8 | Just so-so | Sparse | Fast | T |
| 9 | Just so-so | Moderate | Slow | E |
| 10 | Just so-so | Moderate | Fast | E |
| 11 | Just so-so | Dense | Slow | E |
| 12 | Just so-so | Dense | Fast | E |
| 13 | Frustrating | Sparse | Slow | T |
| 14 | Frustrating | Sparse | Fast | T |
| 15 | Frustrating | Moderate | Slow | T |
| 16 | Frustrating | Moderate | Fast | T |
| 17 | Frustrating | Dense | Slow | E |
| 18 | Frustrating | Dense | Fast | E |

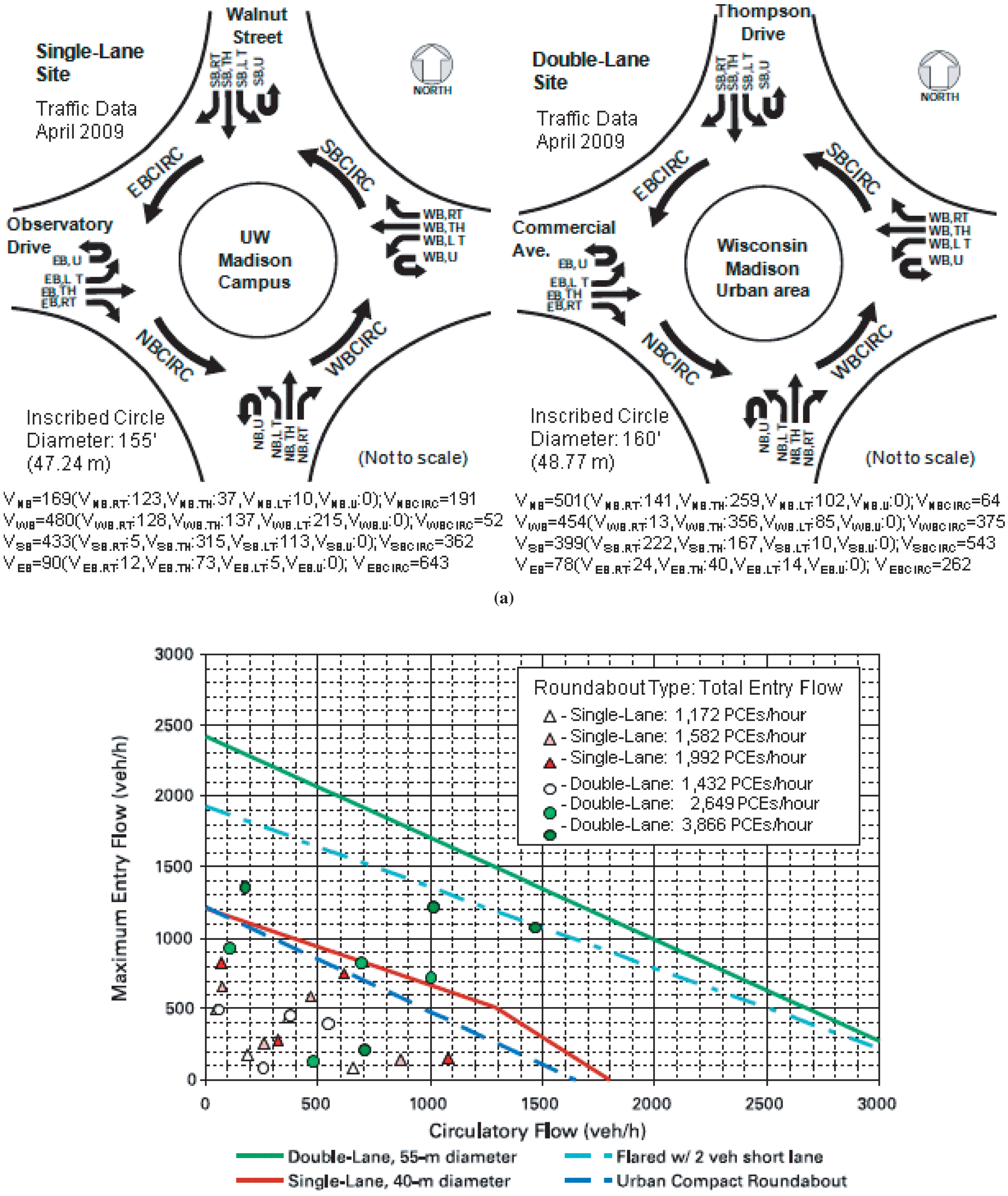
**Defuzzifier** It realizes a mapping from the output space of fuzzy control actions into a final output variable. Some defuzzifiers were developed to finalize the output. The most frequently employed mappings include "maximum criterion," "mean of maximum," and "center of gravity." Each has its own unique features suitable for different control problems (*31*). Traffic signal control has a binary characteristic: extension or termination. This means that the final output variable is in crisp form, so "maximum criterion" is the most appropriate herein in contrast to other defuzzifiers that transform the output space into a continuous variable.

## Traffic Flow Modeling

It is reasonable to signalize the crosswalk on the approach with the densest vehicle volumes and highest speeds, since such an approach generates the scarcest safe crossable gaps. Actual peak-hour traffic volumes collected at two modern roundabouts in Wisconsin were used as the base volumes (Figure 3*a*). The single-lane site has significant commuting traffic. Field observations uncovered pedestrian access issues: two bus stops in the vicinity yield a large number of riders, including vision-impaired pedestrians; seasonal football events generate massive pedestrian streams in which many seniors walk. The double-lane site is in proximity to a residential community in Madison. The peak-hour traffic is heavy and prevailing vehicle speeds are fast. The observed volumes are below the theoretical capacity for the respective size as cited in FHWA's roundabout guide (*32*). To investigate more cases, vehicle flow intensities were increased at a fixed growth rate to simulate scenarios closer to maximum capacity. The roundabout guide recommends that roundabouts be designed to operate at less than 85% of the estimated capacity. Through a guide-based calculation toward the 85% threshold, the single-lane volume was increased by 35% and 70% to achieve 1,582 and 1,992 PCEs/h, while 85% and 170% were applied to the double-lane volume to get 2,649 and 3,866 PCEs/h. Conceptually, three intensity levels (existing condition, approaching capacity, and saturated condition) were established. Figure 3*b* illustrates the base and enhanced volumes of two sites superimposed on the guide's capacity figure. Each scenario was analyzed at pedestrian flows of 0 (none), 12 (few), 60 (some), 150 (many) pedestrians/h. These pedestrian flows are less than the MUTCD Section 4C.05 Warrant 4 (*23*), since the primary motivation for installing these signals is not to suffice for a MUTCD warrant but to make roundabouts more accessible. Approximately 15% of pedestrians walk more slowly than 3.5 ft/s (*33*). So, the mean walking speed was set to 3.0 ft/s and a researcher-customized distribution was modeled (maximum/minimum speeds: 8.0/1.0 ft/s) to reflect past study findings.

## Model Calibration

VISSIM models were coded with observed volumes, turning movements, and geometric designs consistent with the FHWA roundabout guide (*32*). Vehicle speeds were calibrated from field data, which include speeds prevailing on inbound approaches, entering circles, and bypassing islands. Speeds are characterized by normal distributions. Minimum gap times, minimum headways, and maximum speeds have been determined through previously documented research results that "serve as a realistic base for most applications" (*14*). The yielding behaviors were modeled in compliance with two examples (*14*). Then, the performance of each model for the "zero-pedestrian" case was validated by contrasting average vehicle delays and approach queues with manual measurements from video recordings. The results demonstrated vehicle delays, and queues match video observations to a large extent (Figure 3*c*), although there was a limited sample of observations and the validation work could be improved with additional data.



$V_{NB}$=169($V_{NB.RT}$:123,$V_{NB.TH}$:37,$V_{NB.LT}$:10,$V_{NB.U}$:0);$V_{NBCIRC}$=191
$V_{WB}$=480($V_{WB.RT}$:128,$V_{WB.TH}$:137,$V_{WB.LT}$:215,$V_{WB.U}$:0);$V_{WBCIRC}$=52
$V_{SB}$=433($V_{SB.RT}$:5,$V_{SB.TH}$:315,$V_{SB.LT}$:113,$V_{SB.U}$:0);$V_{SBCIRC}$=362
$V_{EB}$=90($V_{EB.RT}$:12,$V_{EB.TH}$:73,$V_{EB.LT}$:5,$V_{EB.U}$:0); $V_{EBCIRC}$=643

$V_{NB}$=501($V_{NB.RT}$:141,$V_{NB.TH}$:259,$V_{NB.LT}$:102,$V_{NB.U}$:0);$V_{NBCIRC}$=64
$V_{WB}$=454($V_{WB.RT}$:13,$V_{WB.TH}$:356,$V_{WB.LT}$:85,$V_{WB.U}$:0);$V_{WBCIRC}$=375
$V_{SB}$=399($V_{SB.RT}$:222,$V_{SB.TH}$:167,$V_{SB.LT}$:10,$V_{SB.U}$:0);$V_{SBCIRC}$=543
$V_{EB}$=78($V_{EB.RT}$:24,$V_{EB.TH}$:40,$V_{EB.LT}$:14,$V_{EB.U}$:0); $V_{EBCIRC}$=262

**(a)**

**(b)**

FIGURE 3 Roundabout modeling and simulation experiments: (*a*) actual peak-hour traffic volumes (Vs) in passenger car equivalents (PCEs) calculated by FHWA Roundabout Guide standard (*32*) for both subject sites, (*b*) VISSIM model calibration results.

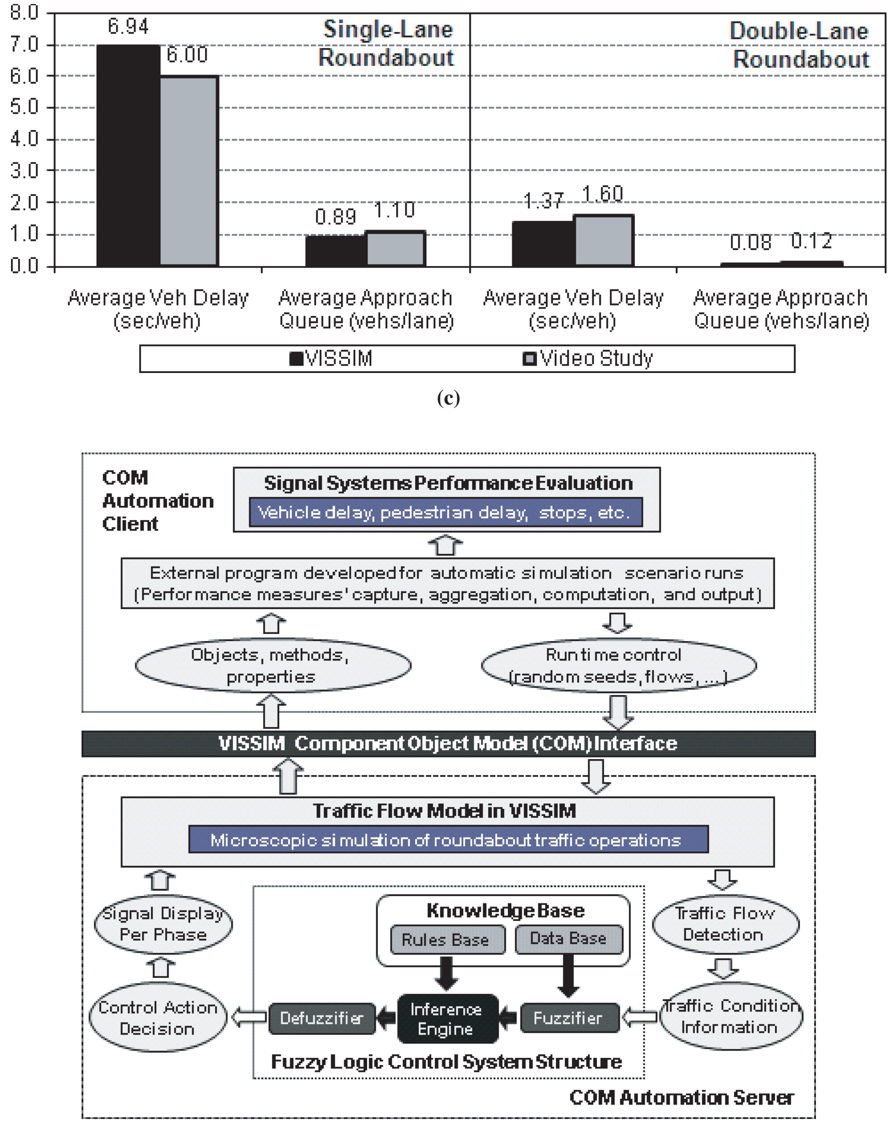
*(continued on next page)*

## Performance Measures

One major objective was to quantify the impact of pedestrians crossing at a signalized approach upon the roundaboutwide operations. These vehicle-related performance measures (i.e., average vehicle delay, average queue length, and average number of stops) were determined in terms of the "pedestrian-induced" effect, which was defined as the discrepancy between measures generated at certain pedestrian volumes and those at the "zero-pedestrian" base case. Average number of stops was viewed as a safety indicator: its increase signifies more frequent acceleration or deceleration occurrences, which intensify the potential for rear-end collisions. Average pedestrian delay was used to evaluate operational efficiency and safety, which is defined as the difference between actual travel time and minimum one (at given walking speed without delays) across the path of interest.

## Basic Timing Parameters

The time interval ($\Delta t$) lasted 1.0 s. With two-phase signals, all lanes in two directions were managed independently and a pedestrian may wait on the median. Minimum vehicle greens varied; "Yellow"



(c)

(d)

FIGURE 3 *(continued)* **Roundabout modeling and simulation experiments: (*c*) entry volumes relative to theoretical capacity in FHWA Informational Guide, and (*d*) FLC system structure and run time control–computation via VISSIM-based COM automation.**

and "All-Red" intervals displayed for 1 and 4 s, respectively. The MUTCD recommends 4 to 7 s for "WALK"; 6 s was used.

### Run-Time Control and Computation

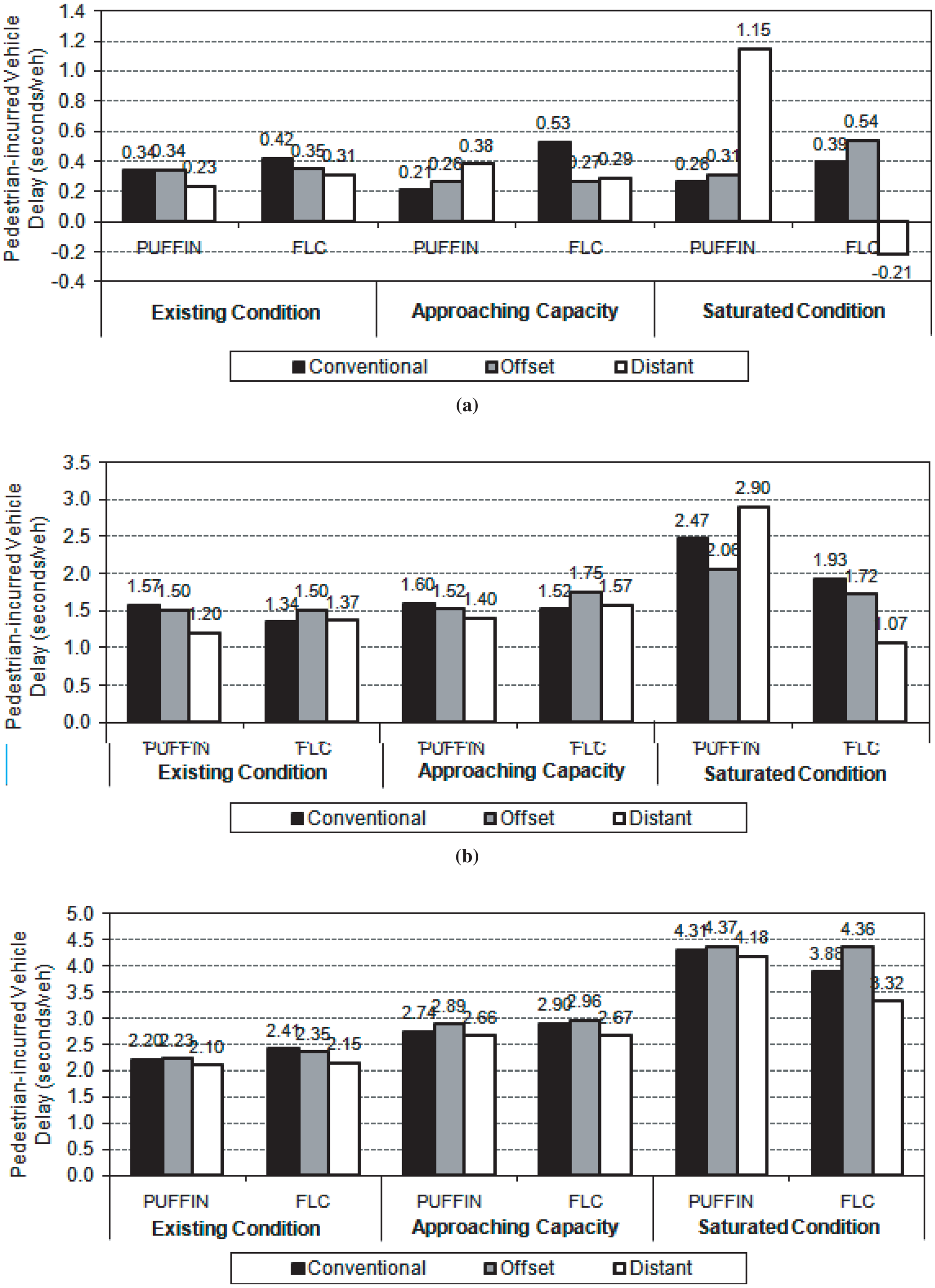
Crosswalk layouts were combined with signal systems to yield six treatments, each of which was modeled with vehicle and pedestrian flow intensities to create 108 scenarios. Twelve simulation replications were implemented for each scenario to overcome stochastic variations from underlying models. There were 1,296 runs; each lasted 3,600 s. The data for performance measures were collected within an evaluation node surrounding roundabout models. During run time, 1,296 runs were carried out automatically and data were captured, aggregated, computed, and exported per an external program that was developed as a Component Object Model client in dialogue with the VISSIM-based server (Figure 3*d*).

## STUDY RESULTS

Figures 4 and 5 show the results regarding single- and double-lane roundabouts in conjunction with signalization schemes, crosswalk layouts, and pedestrian volume levels. Figures also illustrate the effects of vehicle flow intensities: existing condition, approaching capacity, and saturated condition. Results are reported by mean values of 12 replications.

### Pedestrian-Induced Vehicle Delay

The single-lane roundabout results in Figures 4*a–f* suggest, at a specific vehicle flow intensity, pedestrian-induced vehicle delays are consistently enhanced when pedestrians increase from "few" to "some" to "many." This demonstrates the operational effect of crossing pedestrians upon vehicle flow efficiency, which means more pedestrians



(a)

(b)

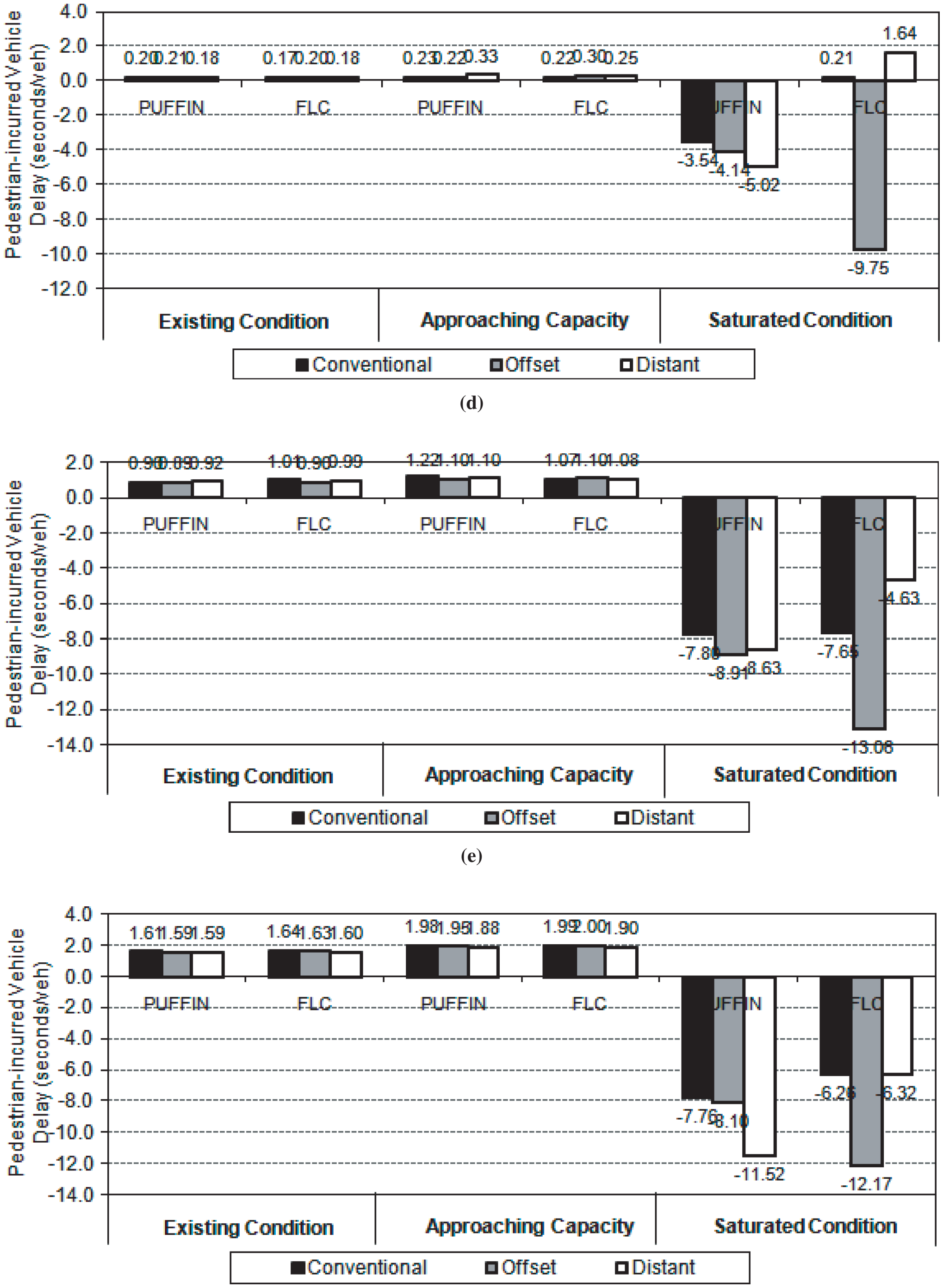
(c)

**FIGURE 4** Pedestrian-induced vehicle delay: (*a*) single-lane roundabout—few pedestrians [12 pedestrians per hour (pph)], (*b*) single-lane roundabout—some pedestrians (60 pph), (*c*) single-lane roundabout—many pedestrians (150 pph).

*(continued on next page)*

make the vehicle flow interruption occur more frequently. When the vehicle volume increases given "some" or "many" pedestrians, the delay impact of PUFFIN on vehicles, regarding each layout, gradually rises up to its maximum under "saturated condition." Given "many" pedestrians, for each signal there exists a roughly monotonic relationship between vehicle volumes and pedestrian-induced vehicle delays.

FLC system performance is better than, close, or roughly equal to PUFFIN across most pedestrian and vehicle flow levels, considering the magnitude of vehicle delays generated by the "zero-pedestrian" case (6.94 s/vehicle for "existing condition" and higher for larger vehicle volumes). Comparatively, the "distant" layouts show potential advantages at the single-lane roundabout, since their additional queue storages produce vehicle delays less than those



(d)

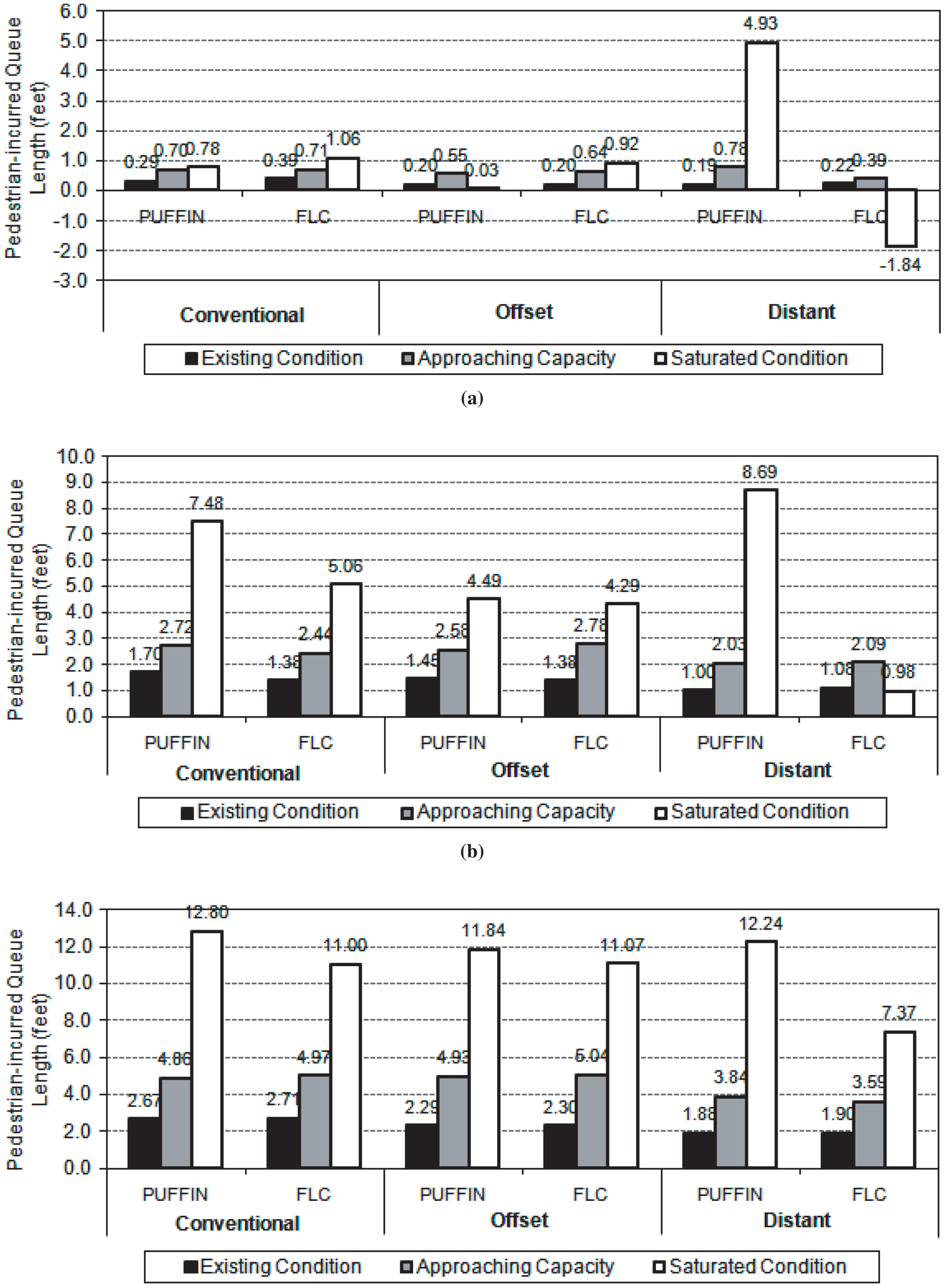
(e)

(f)

**FIGURE 4** *(continued)* Pedestrian-induced vehicle delay: (*d*) double-lane roundabout—few pedestrians (12 pph), (*e*) double-lane roundabout—some pedestrians (60 pph), and (*f*) double-lane roundabout—many pedestrians (150 pph).

at other layouts across most scenarios, especially when the FLC signal operates under "saturated condition." Note that this layout is disadvantageous when PUFFIN works in two situations where pedestrians are "few" or "some" and vehicles are in "saturated condition."

The results at the double-lane roundabout have similar characteristics to those at the single-lane site, except for an interesting observation that some scenarios yield negative vehicle delays under "saturated condition." In these scenarios, the presence of pedestrian actuations substantially decreases pedestrian-induced vehicle delays. This phenomenon could be the consequence of pedestrian signal metering traffic on the busiest approach, thus facilitating the entering vehicle flows at downstream roundabout approaches.



(a)

(b)

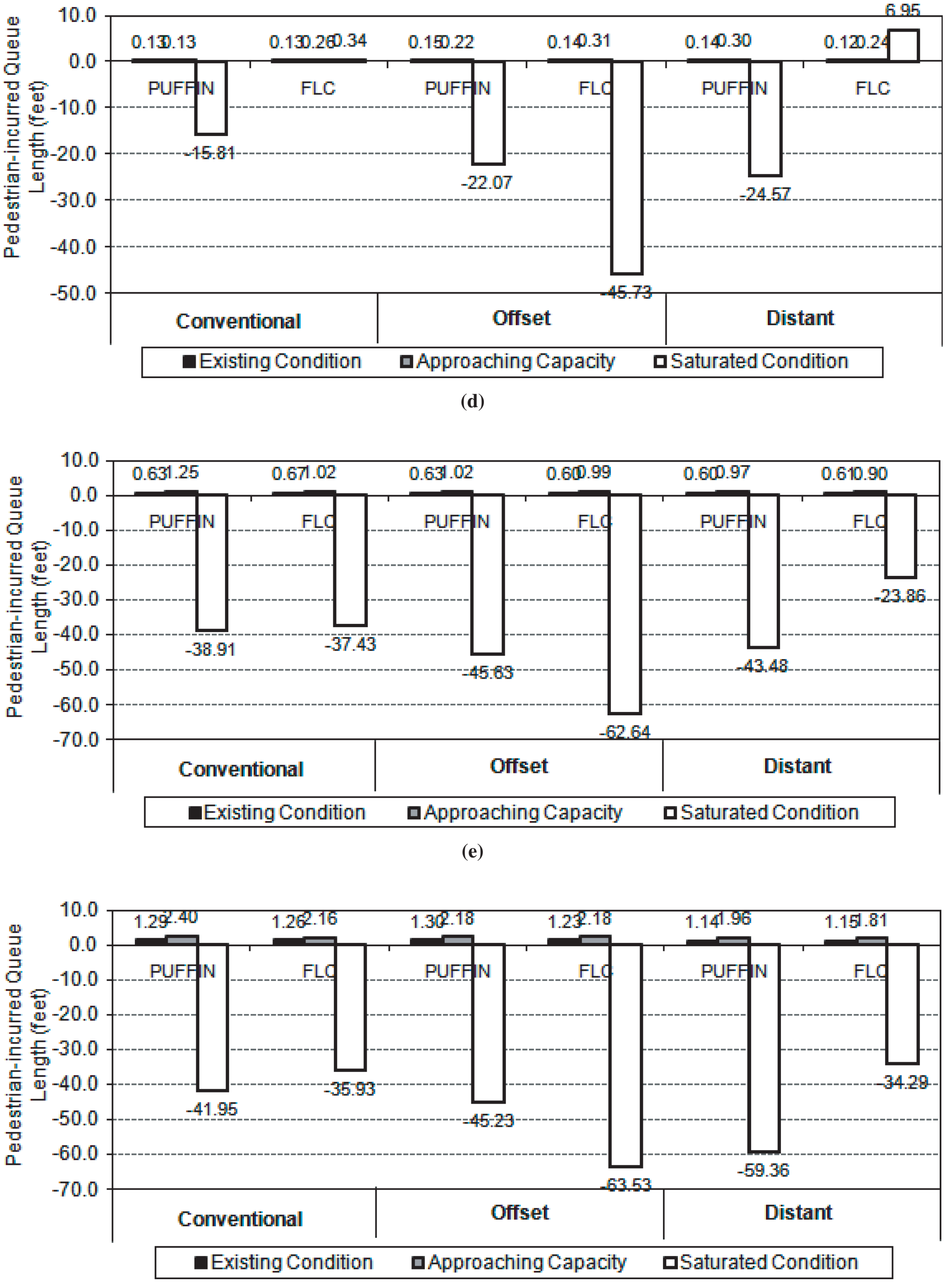
(c)

FIGURE 5 Pedestrian-induced queue length: (*a*) single-lane roundabout—few pedestrians (12 pph), (*b*) single-lane roundabout—some pedestrians (60 pph), (*c*) single-lane roundabout—many pedestrians (150 pph).

*(continued on next page)*

## Pedestrian-Induced Queue Length

The results in Figures 5*a* through *f* give the pedestrian-induced queue lengths. At specific vehicle intensity, queue lengths at the single-lane roundabout are prolonged if pedestrian volume increases. When the vehicle volume increases at a specific pedestrian flow, the influence of a pedestrian signal upon vehicle queues reaches, across most scenarios, its maximum under "saturated condition." There exists a nearly monotonic nexus between vehicle volumes and queue lengths regardless of signals and layouts, especially when there are "many" pedestrians. Given the magnitude of "zero-pedestrian" queue lengths, the FLC signal outperforms or resembles PUFFIN across most scenarios. The "distant" layout exhibits potential advantages at the single-lane roundabout when the FLC



(d)

(e)

(f)

FIGURE 5 *(continued)* Pedestrian-induced queue length: (*d*) double-lane roundabout—few pedestrians (12 pph), (*e*) double-lane roundabout—some pedestrians (60 pph), and (*f*) double-lane roundabout—many pedestrians (150 pph).

**TABLE 3 Pedestrian Delay (seconds): Average of 12 Simulation Replications, Existing Condition**

| | Single-Lane Roundabout (1,172 PCEs/h) | | Double-Lane Roundabout (1,432 PCEs/h) | |
|---|---|---|---|---|
| Crosswalk Layout | PUFFIN | FLC | PUFFIN | FLC |
| | (A-1-1). Few pedestrians (12 pph) | | (A-2-1). Few pedestrians (12 pph) | |
| Conventional | 14.29 (1.89) | 13.51 (1.95) | 14.99 (3.32) | 13.87 (1.91) |
| Offset | 13.64 (2.18) | 12.29 (1.83) | 13.65 (2.43) | 12.37 (1.88) |
| Distant | 14.26 (2.44) | 13.35 (1.60) | 15.37 (2.87) | 13.72 (1.54) |
| | (A-1-2). Some pedestrians (60 pph) | | (A-2-2). Some pedestrians (60 pph) | |
| Conventional | 30.61 (3.17)[a] | 26.83 (2.77)[a] | 31.42 (3.20)[a] | 24.71 (2.59)[a] |
| Offset | 28.59 (2.34)[a] | 24.40 (1.30)[a] | 30.36 (2.18)[a] | 25.30 (2.68)[a] |
| Distant | 30.97 (3.12)[a] | 23.34 (2.61)[a] | 29.33 (2.80)[a] | 24.18 (3.44)[a] |
| | (A-1-3). Many pedestrians (150 pph) | | (A-2-3). Many pedestrians (150 pph) | |
| Conventional | 40.12 (2.76)[a] | 35.29 (3.00)[a] | 43.66 (2.89)[a] | 37.34 (3.23)[a] |
| Offset | 38.76 (3.67)[a] | 33.31 (2.43)[a] | 43.07 (4.05)[a] | 36.60 (2.15)[a] |
| Distant | 41.51 (3.19)[a] | 34.24 (2.79)[a] | 43.76 (3.02)[a] | 38.24 (3.52)[a] |

NOTE: Standard error shown in parentheses.

[a] Delays under PUFFIN and FLC signal controls, which are significantly different at $\alpha = 0.05$ by *t*-test.

signal works, since this combination renders queue lengths shorter than those at other layouts across most scenarios.

There is an interesting observation for the double-lane roundabout: for all scenarios in which there are "some" and "many" pedestrians under "saturated condition," negative pedestrian-induced queue lengths are generated regardless of signals and layouts. The metering effect of pedestrian signal on vehicles could explain this phenomenon. Queue lengths become the shortest when the FLC signal operates at the "offset" layout.

## Number of Stops

The results for single- and double-lane roundabouts disclose similar operational characteristics to pedestrian-induced vehicle delays in basic aspects. It could be interpreted that the "distant" layout is safer across most scenarios, and the addition of pedestrian signals makes vehicles flow more smoothly somewhere under "saturated condition," which reduces the potential for vehicle-to-vehicle collisions.

## Pedestrian Delay

Tables 3–5 list average pedestrian delays. Because PUFFIN timing runs without vehicle green extensions, it is expected that the pedestrian delay is independent of traffic volume change, and this is verified by Tables 3–5. The results suggest that, at specific vehicle intensity, pedestrian delays given denser pedestrian volumes are consistently larger than those given lower pedestrian volumes, because pedestrians in denser volumes are more likely to arrive during the minimum green time. A comparison shows that pedestrian delays from the FLC signal are consistently lower than those from PUFFIN, even though the differences are not statistically significant for low pedestrian volumes. At higher pedestrian flow intensities, pedestrian delay savings from the FLC signal are more obvious, since more pedestrians are affected by "minimum green" constraints. Statistical *t*-tests of the differences confirm that, with relatively high pedestrian volumes, the FLC signal results in significantly lower pedestrian delays than those from PUFFIN. Different crosswalk geometries were expected to produce different pedestrian

**TABLE 4 Pedestrian Delay (seconds): Average of 12 Simulation Replications, Approaching Capacity**

| | Single-Lane Roundabout (1,582 PCEs/h) | | Double-Lane Roundabout (2,649 PCEs/h) | |
|---|---|---|---|---|
| Crosswalk Layout | PUFFIN | FLC | PUFFIN | FLC |
| | (B-1-1). Few pedestrians (12 pph) | | (B-2-1). Few pedestrians (12 pph) | |
| Conventional | 14.29 (1.89) | 13.59 (1.64) | 13.20 (3.59) | 13.90 (1.91) |
| Offset | 13.64 (2.18) | 12.61 (1.71) | 13.65 (2.43) | 12.41 (1.88) |
| Distant | 15.58 (4.75)[a] | 13.70 (1.74)[a] | 15.37 (2.87) | 13.71 (1.54) |
| | (B-1-2). Some pedestrians (60 pph) | | (B-2-2). Some pedestrians (60 pph) | |
| Conventional | 30.61 (3.17)[a] | 25.12 (2.39)[a] | 31.42 (3.20)[a] | 24.73 (2.59)[a] |
| Offset | 28.59 (2.34)[a] | 24.85 (1.34)[a] | 30.36 (2.18)[a] | 25.31 (2.68)[a] |
| Distant | 28.42 (1.55)[a] | 23.28 (2.42)[a] | 29.33 (2.80)[a] | 24.18 (3.44)[a] |
| | (B-1-3). Many pedestrians (150 pph) | | (B-2-3). Many pedestrians (150 pph) | |
| Conventional | 40.12 (2.76)[a] | 35.16 (3.65)[a] | 43.66 (2.89)[a] | 37.13 (3.23)[a] |
| Offset | 38.76 (3.67)[a] | 33.68 (2.56)[a] | 43.07 (4.05)[a] | 36.73 (2.15)[a] |
| Distant | 41.51 (3.19)[a] | 34.24 (2.77)[a] | 43.76 (3.02)[a] | 38.25 (3.52)[a] |

NOTE: Standard error shown in parentheses.

[a] Delays under PUFFIN and FLC signal controls, which are significantly different at $\alpha = 0.05$ by *t*-test.

**TABLE 5 Pedestrian Delay (seconds): Average of 12 Simulation Replications, Saturated Condition**

| | Single-Lane Roundabout (1,992 PCEs/h) | | Double-Lane Roundabout (3,866 PCEs/h) | |
|---|---|---|---|---|
| Crosswalk Layout | PUFFIN | FLC | PUFFIN | FLC |
| | (C-1-1). Few pedestrians (12 pph) | | (C-2-1). Few pedestrians (12 pph) | |
| Conventional | 14.29 (1.89) | 15.06 (2.39) | 15.44 (2.33) | 13.99 (1.86) |
| Offset | 13.64 (2.18) | 13.89 (2.21) | 13.65 (2.43) | 12.41 (1.88) |
| Distant | 15.58 (4.75) | 14.61 (1.87) | 15.37 (2.87) | 13.71 (1.54) |
| | (C-1-2). Some pedestrians (60 pph) | | (C-2-2). Some pedestrians (60 pph) | |
| Conventional | 30.61 (3.17)[a] | 26.10 (2.22)[a] | 31.42 (3.20)[a] | 24.78 (2.53)[a] |
| Offset | 28.59 (2.34)[a] | 24.97 (1.81)[a] | 30.36 (2.18)[a] | 25.39 (2.72)[a] |
| Distant | 28.42 (1.55)[a] | 24.09 (2.39)[a] | 29.33 (2.80)[a] | 24.22 (3.44)[a] |
| | (C-1-3). Many pedestrians (150 pph) | | (C-2-3). Many pedestrians (150 pph) | |
| Conventional | 40.12 (2.76)[a] | 34.90 (3.68)[a] | 43.66 (2.89)[a] | 37.33 (3.23)[a] |
| Offset | 38.76 (3.67)[a] | 33.99 (1.73)[a] | 43.07 (4.05)[a] | 36.58 (2.15)[a] |
| Distant | 41.51 (3.19)[a] | 34.72 (2.89)[a] | 43.76 (3.02)[a] | 37.83 (3.32)[a] |

NOTE: Standard error shown in parentheses.

[a] Delays under PUFFIN and FLC signal controls, which are significantly different at $\alpha = 0.05$ by *t*-test.

crossing times due to varied path deflections, but Tables 3 through 5 do not unveil significant differences among three layouts across most scenarios.

## CONCLUSIONS AND FUTURE DIRECTIONS

This research developed an AI-based roundabout management system, which was quantitatively compared with an existing signal system at varied geometries under different operational conditions. The analysis suggests a nonmonotonic relationship between signalization effects and all levels of vehicle volumes. Pedestrian-induced vehicle delays appear to be the largest as traffic volumes approach the roundabout capacity. Partly due to the vehicle storage space at roundabout exit lanes, the modified crosswalk geometry, “distant” layout, can reduce vehicle delays and queue lengths, especially when the FLC signal works under saturated traffic conditions. An interesting finding is, when vehicle flows are saturated, the addition of pedestrian signals to the double-lane roundabout results in lower vehicle delays than the absence of pedestrian signals, which could be explained by the metering effect of pedestrian signal on vehicles.

The results also reveal that FLC controls the signal timing effectively and outperforms PUFFIN from safety and operational perspectives, especially under saturated traffic conditions. It significantly decreases pedestrian delays and also maintains good vehicle service. Comprehensively, multimodal traveler needs are satisfied through increased pedestrian safety, decreased rear-end hazard, bettered operational efficiency, and diminished social cost; such a compromise is executed by a flexible decision-making mechanism implicitly embedded in the fuzzy logic system. The control algorithm and the parameter setting are straightforward, yet the system performance is adaptive to dynamic roundabout operations. Therefore, the merit in FLC is suitable for resolving complex transportation operation issues.

These findings are important for engineering practitioners faced with the task of improving roundabout accessibilities for pedestrians. The research also adds an impetus to developing AI-based signals for other multimodal transportation facilities. Future direction should include field test, validation, and deployment of FLC-based signal control strategies.

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