

Pedestrian Crossings at Mid-Block Locations: A Fuzzy Logic Solution for Existing Signal Operations

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ABSTRACT:

The increasing number of mid-block vehicle-pedestrian crashes has led traffic engineers to consider treatments to make crosswalks safer, especially for children and seniors. One common method to resolve this problem is the installation of signalized mid-block pedestrian crossings. However, a wide variety of signalization schemes have been employed, few of which are supported by the Manual on Uniform Traffic Control Devices. Utilizing a microsimulation approach, this paper presents several common alternatives for signalizing a typical mid-block crosswalk (MBC) with varied geometries, aimed to explore how changing signalization schemes and geometries affects various measures of effectiveness from both vehicle and pedestrian perspectives. The results indicate that two-phase timing and the innovative HAWK_(High intensity Activated crossWalk) treatment significantly improve vehicle operations over the one-phase timing and other options.

Compared with these alternatives, PUFFIN (Pedestrian User-Friendly Interface) system is “user friendly” due to its dynamic pedestrian clearance interval, but it still does not encompass more safety and human factors in control logic, so it lacks in the adaptive ability in fulfilling opposing objectives. Fuzzy logic control (FLC) has proven effective for a complex optimization problem with multiple objectives, uncertain information, and vague decision criteria. Traffic signal timing lies in this category. To model the range of variables employed in mid-block pedestrian crossings, a “user friendly” FLC signal is developed and evaluated against PUFFIN to quantify the potential safety and efficiency benefits. The result shows the FLC not only effectively controls the signal timing but also offers equal or better performance than PUFFIN from safety and operational perspectives. With straightforward logic and tractable parameters, the FLC finds a compromise among enhancing safety, ameliorating operations, and then lessening social cost from crashes and delays at a MBC.

Key words:

Pedestrian Crossing, Mid-block, Microscopic Simulation, Signals, Fuzzy Logic Control

INTRODUCTION

United States safety data indicates that a pedestrian is killed in a traffic crash every 110 minutes and injured every 9 minutes (1). Pedestrian crosswalks can be especially perilous for the elderly. In 2006, 471 pedestrians nationwide were killed in crosswalks (2). Among people 70 and older, 36 percent of pedestrian deaths occurred at intersections, compared with 21 percent of those younger than 70 (3). Given the increasing number of pedestrian fatalities and injuries, transportation professionals are striving to make roadway crossing points safer, especially for senior citizens and children who need *more* time to cross streets (1,4). Recent efforts have focused on treatment methods for controlling pedestrian flows at locations away from intersections, specifically mid-block crossings.

Pedestrian crossing at mid-block locations is a critical factor to efficient traffic operations and pedestrian safety. Various traffic control devices are employed at a typical mid-block crosswalk (MBC), including crosswalk pavement markings, advance warnings, and traffic and pedestrian signals. Although a traffic/pedestrian signal is not the sole solution to facilitating pedestrian access to street crossings, it is often a necessary solution at multi-lane facilities having heavy vehicular flows since it offers accessibility and, if installed with accessible pedestrian signals (APS), equal access to vision-impaired pedestrians. Most MBC traffic signal strategies were designed and implemented to operate in an independent fashion, with little consideration to timing and coordination strategies. A need exists to explore these mid-block traffic signal alternatives in a holistic operations and safety framework.

This paper explores several alternatives for traffic signal operations at MBC with varied geometries using microsimulation concepts. The primary objective of this research was to investigate how changing signalization schemes and roadway geometries affects various measures of effectiveness (MOEs) from both vehicle and pedestrian perspectives, ultimately providing traffic engineers with more effective guidance for traffic signal schemes at MBCs.

The challenge faced with many existing traffic signal systems is the complex nature in which they must operate. Traffic signal controls must consider many, often mutually conflicting, objectives. Furthermore, “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” (5). Because of this complexity, analysis and control methods must be adaptable to dynamic environments.

One such method proven to be effective under the conditions is described in Fuzzy Logic Control (FLC). By creating “approximate reasoning” concept based on fuzzy set theory and fuzzy logic, researchers have shown that vague logical statements in FLC enable the algorithm formations that can use vague data to derive vague inferences (6,7). In other words, the variability and complexity common to traffic signal control can be effectively modeled. FLC has proven more effective than traditional control for tackling complex systems involving human perception, imprecise information, ambiguous rules, and conflicting objectives (8,9,10,11). Therefore, this study evaluates a newly developed FLC-based traffic signal control against conventional MBC signal strategies to quantify the potential efficiency and safety benefits produced.

STUDY APPROACH

A traffic microsimulation framework was selected as the best method to the FLC and other traffic signal operations in a controlled multi-iterative environment. Recent studies found VISSIM, a microscopic simulation program, to be advantageous in specific requirements (e.g., pedestrian modeling, detector functions, signal control logic, etc.) (12,13,14,15,16,17). Therefore, VISSIM was used as the primary

research tool. Three dimensions were explored to assess each signal alternative, namely crosswalk geometry, signal scheme, and traffic flow intensity.

Crosswalk Geometry

A typical MBC is located between two signalized intersections, with spacing at least 600 feet per Section 4C.05 of the latest Manual on Uniform Traffic Control Devices (MUTCD) (18,19). MBC used in this research were implemented at multi-lane arterials with near capacity traffic volumes. The selected geometry was consistent with many existing MBC pedestrian signal timing installations (20,21,22). As presented in Figure 1, two crosswalk methods were considered: the most common layout of a single crosswalk across the full street width, and a “dual-crosswalk” dividing the crosswalk into two segments with the ability to store pedestrians in the median. Roadway lanes were set at 12 feet, and crosswalk width at 10 feet (20,21,22,23,24). A 20 foot spacing was placed between the STOP line and the closest crosswalk edge. Varied minimum median widths at different locations were considered to separate traffic and provide pedestrian refuge, making pedestrians more visible to motorists (19,23,24,25,26). This research looked at each of these geometric alternatives.

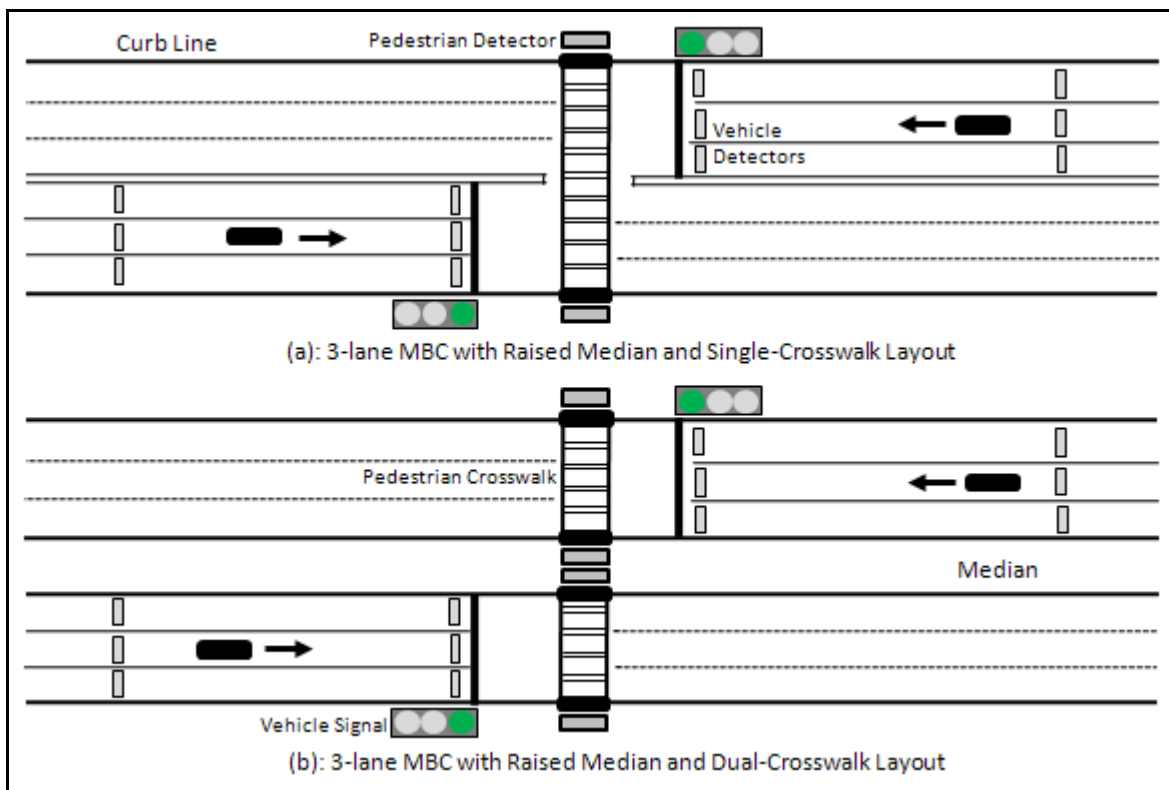


Figure 1 3-Lane MBC Layouts and Detectorization (Not to Scale)

Signalization Alternatives

MBC signals are prevalently used in the Europe, Australia, with a growing number in the U.S. (21,23,27). Among them, conventional PA (Pedestrian Actuated), PUFFIN (Pedestrian User-Friendly Interface), PELICAN (Pedestrian Light CONTrolled), and HAWK (High Intensity Activated CrossWalK) signals were evaluated in this research, in addition to the FLC system newly developed. Figure 2 depicts the phasing sequences for all signals.

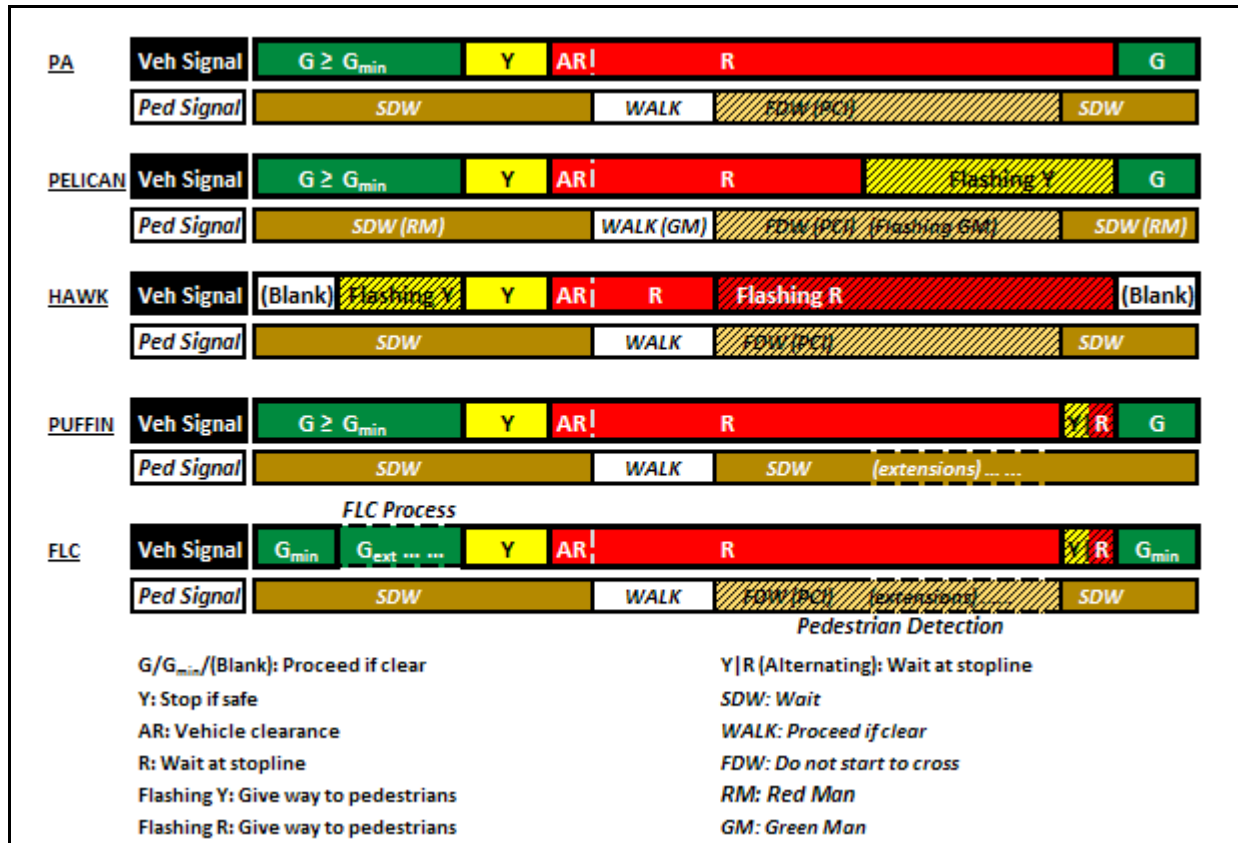


Figure 2 Phasing Sequences for MBC Signals under Study

Some Existing Signals

With standard vehicle signal indications (i.e., “Red”, “Green”, “Yellow”), PA sequentially displays “WALK”, “Flashing DONT WALK (FDW)”, and “Steady DONT WALK (SDW)”, with fixed timing parameters. PELICAN uses “Red”, “Yellow”, “Flashing Yellow”, and “Green”. “Flashing Yellow” permits motorists to proceed if all pedestrians have cleared the conflict areas. Pedestrians must make sure all traffic has stopped before crossing and cross only when the “Green Man” indication is illuminated. Near the end of the interval, the “Green Man” indication changes from a steady to flashing clearance interval during which pedestrians should not start to cross, although there is still enough time for those on the crosswalk to finish their crossing safely. A “Red Man” indication is illuminated as the “SDW”.

HAWK uses traditional signal displays in a different configuration. Vehicle signal remains dark until a pushbutton press occurs. The signal then becomes active, displaying a “Flashing Yellow” and then “Steady Yellow” for several seconds, alerting drivers to a pedestrian. The signal then changes to a “Circular Red” requiring motorist to stop and wait at the STOP line. At this time, the “WALK” begins, followed by the “FDW”. Motorists see an “Alternating Flashing Red” display during which they are required to remain stopped until pedestrians have left conflicting areas. Once pedestrians cleared, motorists may proceed cautiously. Then, the “SDW” comes and the signal goes dark. HAWK has been used in Tucson, Arizona at several MBCs (28). In 2007, the National Committee on Uniform Traffic Control Devices recommended that it be added to the MUTCD as an approved traffic control device.

It should be noted that each signal times the “FDW” clearance interval based on the crossing distance and a design walking speed, as described in the MUTCD (18). Once timed, the “FDW” is fixed. Despite its

effectiveness, this practice is unsustainable from safety perspective since the growing population of older pedestrians and increasing mobility of children add substantial variability to walking speeds. Past studies revealed that walking speeds vary considerably, suggesting varied design speeds for different populations (40,41,42,43,44,45). Therefore, these signals lack effective all-user accommodations due to their static “FDW” timing method. A research effort is currently underway to explore variable pedestrian timing. PUFFIN is “user friendly” in this aspect: equipped with pedestrian sensors, it varies the pedestrian clearance time dynamically to give the crossing time instantaneously needed, which provides much enhanced sense of protection particularly to seniors and children. However, it still does not consider more safety elements (i.e., vehicle flow status) and human factors (i.e., pedestrian waiting time) in its control logic to realize more operational and safety objectives.

A FLC Signal

A critical issue in MBC, given vehicular and pedestrian demands, is when to terminate the current phase. An experienced person processes intuitive rules in linguistic terms and executes the effective control through evaluating ongoing and target conditions. For example, if a pedestrian has been waiting for a long time and approaching vehicles are sparse, the right-of-way should be transferred to the pedestrian signal. To artificially emulate the human intelligence in decision making, a FLC system was developed for MBC signal control.

Essentially, any traffic signal control is a process of allocating green time among conflicting movements at a facility. Alternatively, technology driven signal systems evaluate ongoing traffic condition continuously and make the appropriate adjustments within the designated signal timing plan. In principle, the traffic signal control is a decision-making process of determining, with time passing, whether to extend or terminate the current green. The FLC system works with identical logic. However, it is different from existing signals systems which do not examine the conditions on conflicting movements for safety or operational purposes. Instead, the fuzzy rules compare the traffic conditions during the current and the next candidate phase.

Based on the stated traffic signal control principle, the FLC signal operates as presented in Figure 3. With crossing demand absent, the signal is constantly set to “Idle Phase” - vehicle green. With a pushbutton press, upon completion of the minimum vehicle green, the system evaluates ongoing vehicle density, dissipation status, and pedestrian waiting time and executes the fuzzy inference to determine the control action. Once specified criteria are triggered, the current phase is either terminated or extended. This process is repeated at intervals until the phase change is selected or the maximum vehicle green is used up. Once the current vehicle phase is terminated, the “WALK” is given to pedestrian, followed by the “FDW”. To render “user friendly” for slow pedestrians, this system is also capable of offering dynamic “FDW” display via on-crosswalk detection and extending it up to the maximum for the slowest pedestrians. One second of “Alternating Red-Yellow” interval, warning motorists of possible pedestrians, is inserted before the vehicle green starts to reduce bias in the evaluation against a counterpart.

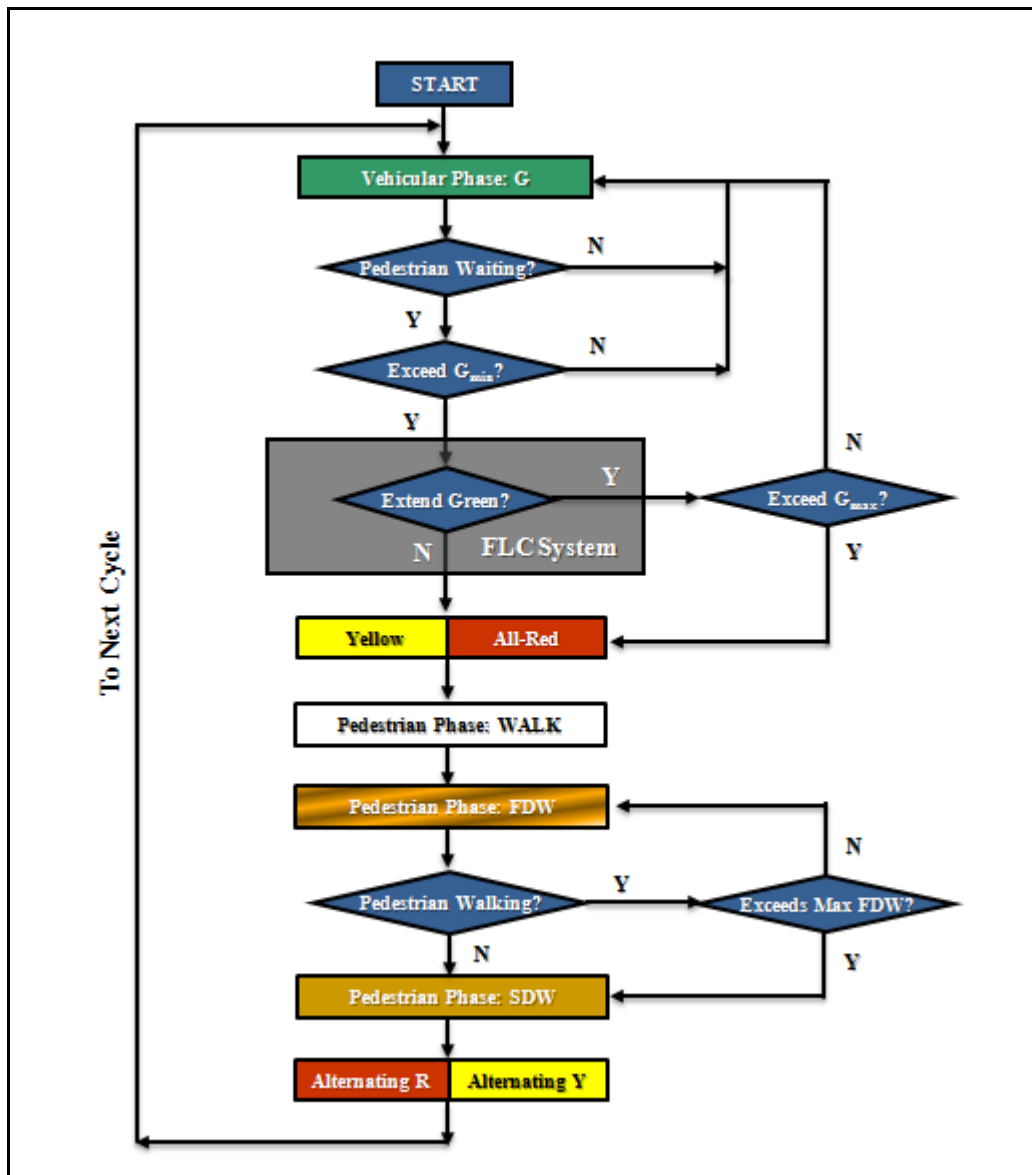


Figure 3 FLC Based Pedestrian Signal Control Logic Flowchart

Given the adaptive ability of FLC to handle multiple objectives, yet keeping the parameter settings in a tractable task, the following objectives were set (29):

- (1). *Minimum Pedestrian Waiting Time* – The waiting pedestrians should be served as soon as possible;
- (2). *Minimum Delay to the Vehicular Movement* – The vehicle delays should be reduced to a minimum;
- (3). *Maximum Safety to Vehicles and Pedestrians* – An approaching vehicle platoon should be preserved and dissipated wholly for two safety purposes: (i). Reduce rear-end collision possibilities resultant from sudden green exterminations; (ii). Create a safer gap for crossing opportunities – packed vehicles trailing the platoon are relatively slow.

Additionally, the FLC system structural components, namely Fuzzifier, Inference Engine, and Defuzzifier, were set (9,30,31,32). Each of them is briefly described below.

(a). Fuzzifier

The key factor in fuzzification is the membership function which transforms the following crisp input variables into fuzzy values to be processed by the inference engine. Mathematically, there is a vast range to choose from, and the Trapezoid membership function in the most common use was selected to avoid complicating the problem. Figure 4 shows all membership functions. Function shapes are consistent with previous research (10,11). The membership functions for “Pedestrian Waiting Time” are segregated into “vehicle friendly” and “pedestrian friendly” types which accentuate respectively the convenience to vehicles and pedestrians.

Approach Flow Level

This variable measures the average number (vehicles/lane) of vehicles between two detectors for all lanes, reflecting the vehicular flow intensity on approaches. It is employed to address the efficiency issue in discharging vehicles, which aims to achieve one operational objective. Obviously, the more intense the flow density is, the more strongly the vehicles demand for green to reduce delay on approaches. Additionally, the longer a motorist has been delayed, the more likely the motorist is psychologically inclined to be aggressive. Reasonably, vehicle delays have both efficiency and safety related meanings. Three fuzzy sets were defined: “Sparse”, “Moderate”, and “Dense”.

Vehicle Discharge Headway

This variable measures the time gap (seconds) between two vehicles being dissipated across the STOP line. It is introduced to embody a safety element in discharging vehicles, which intends to contribute to reaching one safety objective. In operations, the smaller the discharge headway is, the more probably the vehicles are packed (high flow density) while proceeding; the larger it is, the more likely a vehicle platoon is being dissipated. Two fuzzy sets were defined: “Small” and “Large”.

Pedestrian Waiting Time

This variable represents how long (seconds) pedestrians have been waiting from the last change to “FDW”. It is utilized to encompass human factors in meeting the crossing demand, which leads to realizing both safety and operational objectives for pedestrians. Obviously, the longer a pedestrian has been waiting, the more probably the pedestrian is prone to cross without the appropriate signal display. Reasonably, pedestrian delays have both operational and safety related meanings. Three fuzzy sets were defined: “Short”, “Long”, and “Too Long”.

Signal Control Action

This output variable had two fuzzy sets representing control actions taken on current phase for vehicular movements: “Extension” or “Termination”.

Pedestrian data are provided via pushbuttons and detectors at each end of the crosswalk, while some detectors are installed on both approaches to collect vehicular data (Figure 1).

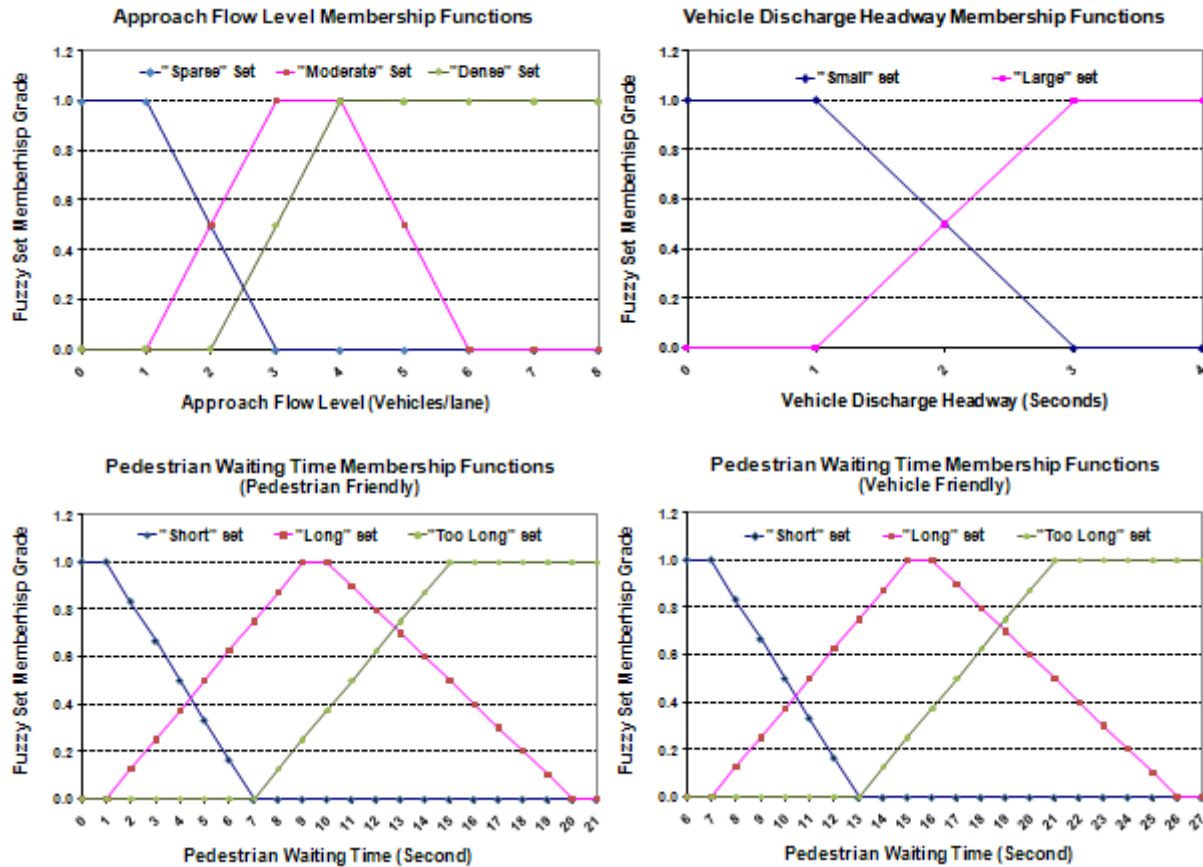


Figure 4 Membership Functions for All FLC Input Variables

(b). Inference Engine

Acting as the “brain” in a FLC system, the decision-making process in inference engine is composed of a set of “IF ... AND ... THEN ...” logic rules which assess ongoing traffic conditions for current and next phases in natural language. The fact following “IF” is termed as “*premise*”, and the fact following “THEN” is “*consequence*”. The “AND” is called “*operator*”, and the connecting operators form the rule base. For the FLC signal system, the generic structure of its rule base could be delineated as follows.

Input: $(x_1 = A)$ AND $(x_2 = B)$ AND $(x_3 = C)$

 Rule 1: IF $\{x_1 \text{ is } A_1\}$ AND $\{x_2 \text{ is } B_1\}$ AND $\{x_3 \text{ is } C_1\}$ THEN $\{E \text{ or } T\}$

.....
 Rule i: IF $\{x_1 \text{ is } A_i\}$ AND $\{x_2 \text{ is } B_i\}$ AND $\{x_3 \text{ is } C_i\}$ THEN $\{E \text{ or } T\}$

.....
 Rule n: IF $\{x_1 \text{ is } A_n\}$ AND $\{x_2 \text{ is } B_n\}$ AND $\{x_3 \text{ is } C_n\}$ THEN $\{E \text{ or } T\}$

Conclusion: $\{E \text{ or } T\}$

Where,

x_1, x_2, x_3 = Input (state) variables related to traffic conditions;

A, B, C = Values of input variables;

A_i, B_i, C_i = Natural language expressions for traffic conditions;
 E = Extend current phase;
 T = Terminate current phase.

Obviously, the total number of rules depends on the combinations of fuzzy sets defined for all input variables: $n=2 \times 3 \times 3=18$ (Table 1).

Table 1 Summary of Inference Rules

Vehicle Discharge Headway		Approach Flow Level		
Small		Sparse	Moderate	Dense
Pedestrian	Short	T	E	E
Waiting	Long	T	T	E
Time	Too Long	T	T	T

Vehicle Discharge Headway		Approach Flow Level		
Large		Sparse	Moderate	Dense
Pedestrian	Short	E	E	E
Waiting	Long	E	E	E
Time	Too Long	T	T	T

T: Terminate; E: Extend

Under traditional inference, a conclusion is drawn from a rule which is an exact match between the input (A, B, C) and a premise (A_i, B_i, C_i) – many rules are necessary to cover all possible inputs. Furthermore, the output, namely a specific consequence, is singular. The whole decision-making mechanism is characterized by its *rigid* process. PA, PELICAN, HAWK, and PUFFIN lie in this domain: their timing mechanisms perform in an *inflexible* fashion, due to their rigidity in maintaining specific parameters.

Under fuzzy inference embedded in the FLC signal, the conclusion is drawn based on the similarity between the input (A, B, C) and these premises ($A_1, B_1, C_1; \dots; A_i, B_i, C_i; \dots; A_n, B_n, C_n$). Essentially, an exact match of only two is unnecessary – the extent of similarity determines the degree of trueness in the consequence. With such a scheme, a given input can activate multiple rules because the input and the premises in activated rules are represented by fuzzy sets and fuzzy relationship resultant from set operations, respectively. Hence, different consequences from all activated rules are strictly valid and then 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 activated rules. In essence, all rules and conclusions are implicitly associated with realizing multiple objectives, perhaps conflicting, given various possibilities of ongoing traffic conditions. Therefore, the whole decision-making mechanism is characterized by its *flexible* process, which exhibits the robustness and adaptive trait in procuring multiple objectives because the membership functions encompass implicitly a vast spectrum of possibilities.

Mamdani's method is used and is the most common approach employed for aggregation process. Mamdani's effort was based on Zadeh's work on fuzzy algorithms for complex systems and decision processes (33). This method was among the first control systems built using fuzzy set theory by synthesizing a set of linguistic control rules obtained from experienced human operators (34).

(c). Defuzzifier

Defuzzification means a mapping from the output space of fuzzy control actions into a control action. Several techniques have been developed to produce an output. The most frequently used methods include “Max Criterion”, “Mean of Maximum”, and “Center of Gravity” each of which has its own features

suitable for different control problems (35,36). Due to the “binary” feature in traffic signal control, the “Maximum Criterion” method was used.

Traffic Flow Parameters

Pedestrian Crosswalk Warrants

The prime function of any crosswalk control device is to channel pedestrians across a roadway safely. Unfortunately, the MUTCD provides little guidance at uncontrolled (i.e., mid-block) locations (18). In developing warrants at the local or state level, various control devices are ranked in a hierarchy from markings to PAs. In practice, a warrant assessment is conducted to determine the appropriate control device. Traditionally, warrants for pedestrian-related control devices are based upon assessing traffic flow intensities in one-hour periods. For example, the criterion developed by Smith and Knoblauch was adopted by the Institute of Transportation Engineers as a recommended guidance for identifying locations where the benefits of markings may outweigh the possible disadvantages (Figure 5) (37,38).

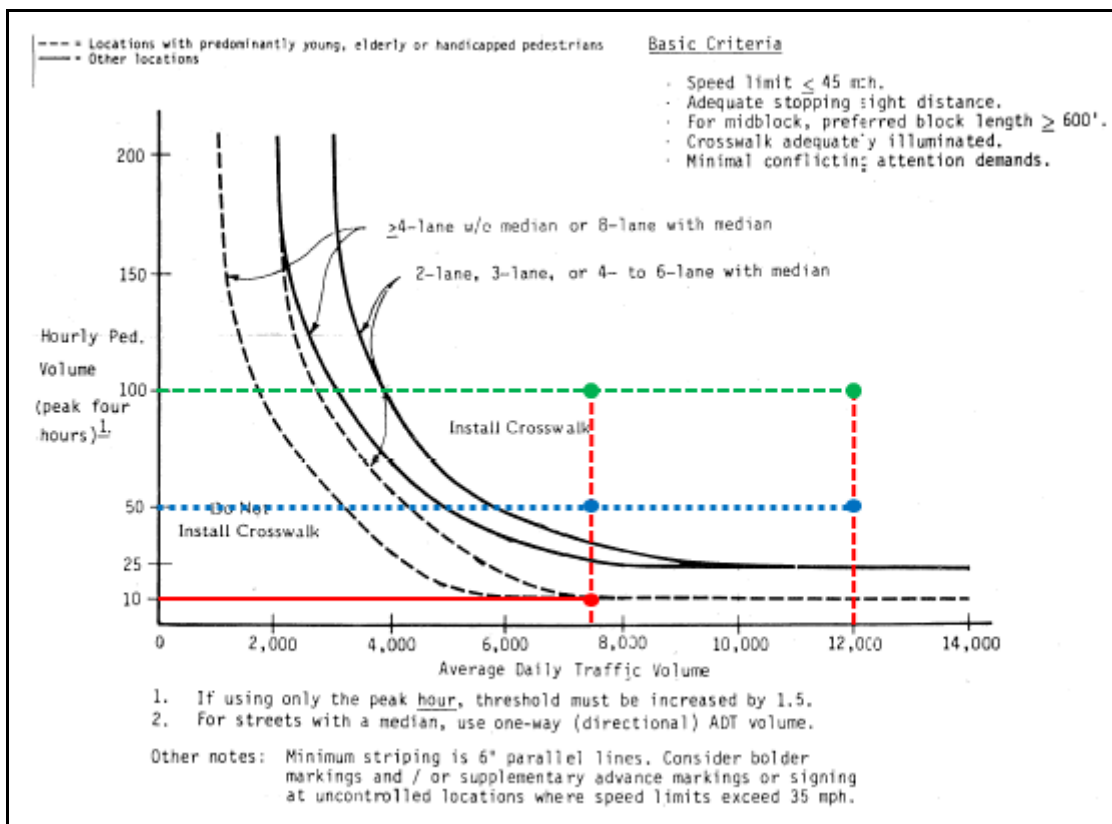


Figure 5 Guidelines for the Installation of Marked Crosswalks at Uncontrolled Crossings (37,38)

The results from a federally sponsored study are nationally adopted to offer recommendations for what conditions are appropriate for marked crosswalks and/or other higher treatment forms (26). Figure 6 from this study provides the warrants for different “Levels” of control devices to enhance marked crosswalks at “intersection and mid-block locations with no traffic signal or stop sign”, where “consider using Level 5 devices if feasible” refers to use “Level 5 Devices: pedestrian actuated traffic signals, grade-separated crossings” (19).

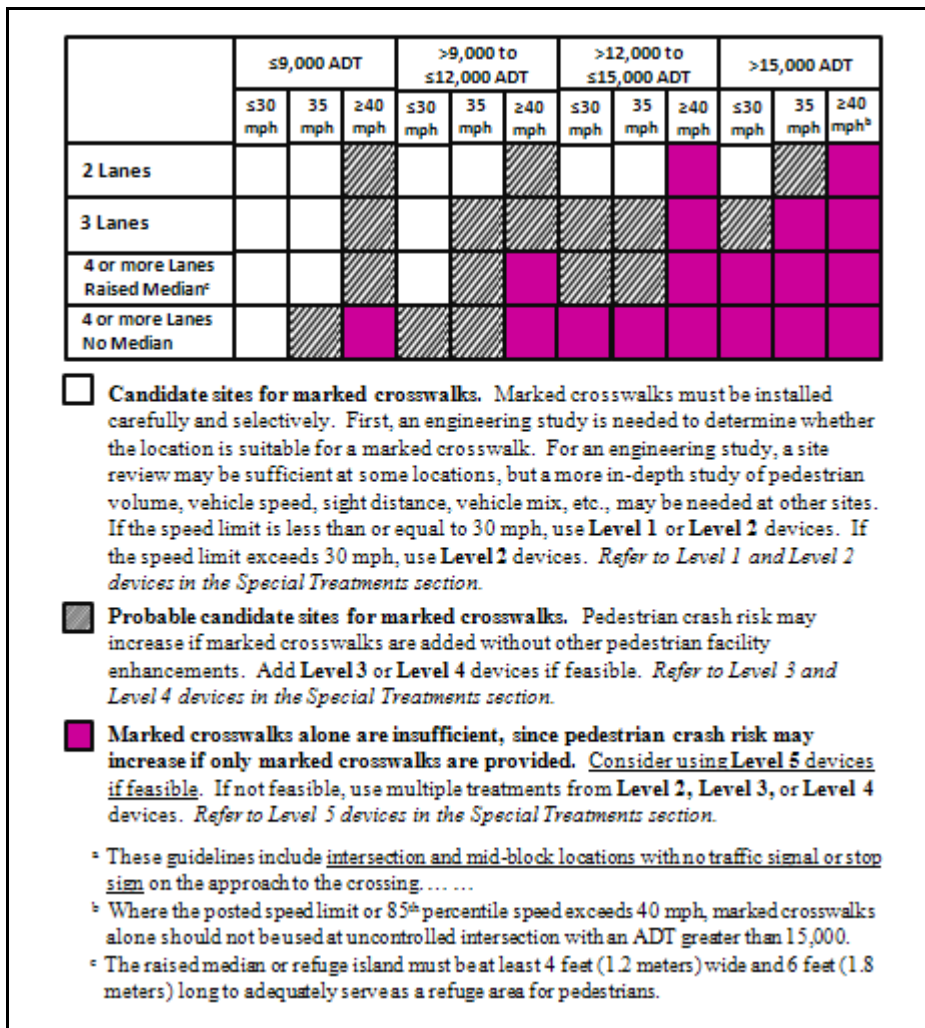


Figure 6 Recommendations for Installing Marked Crosswalks and other Needed Pedestrian Improvements at Uncontrolled Locations^a (19,26)

Traffic Flows and Compositions

Based on Figure 6, the posted approach speed limit was set to 40 mph. Base traffic volume was set to 12,000 ADT (500 vphpl). The volumes for both directions were similar. To investigate the operations at more congested conditions, the base volume was enhanced at fixed growth rates to two additional scenarios: 750 and 1,000 vphpl. So, three vehicular traffic conditions were set: “Under Capacity”, “Approaching Capacity”, and “Oversaturated”. Three pedestrian intensities were set: “Few”, 10 pph; “Some”, 50 pph; “Many”, 100 pph. Four vehicle types and their relative percentages were considered: passenger car (95%), heavy vehicles (4%), and buses (1%) for motorized traffics; pedestrian (100%) for crosswalk traffic. Past research indicated 15 percent of pedestrians walk more slowly than 3.5 ft/s (39). Therefore, the mean walking speed was set to 3.0 ft/s. Based on past walking speed studies, the maximum and minimum walking speeds were set to 8.0 and 1.0 ft/s, respectively. A user-specified walking speed distribution was modeled to reflect the general findings in these past studies.

Evaluation Strategy

Due to the “FDW” timing strategies differently executed by all signals, it should be more reasonable to take two perspectives to evaluate them in separate groups as follows.

“Perspective I” Group

PA, PELICAN, and HAWK were evaluated in one group due to the *static* way of FDW timing, which lack in the “user friendliness” since they do not provide full signal protection for crossing pedestrians. Pedestrians are either exposed to yielding vehicles or too slow to be protected by signals.

“Perspective II” Group

PUFFIN and the FLC signal were evaluated in the other group due to the *dynamic* way of FDW timing, which feature in the “user friendliness” since they provide full signal protection for crossing pedestrians no matter how slow, if not ridiculously, their walking speeds could be.

Average pedestrian delay and average vehicle delay were used as efficiency and safety related MOEs. The average queue length was also determined, measured just upstream from the crosswalks using the default queue definition. A trade-off exists between the reduction of pedestrian and vehicle delays. The average number of stops was viewed here as a traffic safety indicator: the increasing average number of stops implies more frequently occurring accelerations or decelerations at the MBC, which aggravate the rear-end collision possibility and make motorists increasingly impatient from human factors perspective. All of these factors pose more potential hazards to the safety of vehicular flows.

Timing Implementation

For the 2-lane and 3-lane single-crosswalk MBCs, a one-phase signal was implemented. At a two-phase signal, all lanes in two directions are timed independently and a pedestrian may wait on the median. Minimum green times for vehicular phases varied. “All-Red” was set to 1 second, and yellow change interval to 4 seconds. The MUTCD recommends a “WALK” time of 4 to 7 seconds which were used here (18). For “Perspective I” signals, “FDW” was calculated per the mean walking speed and crossing distance.

Treatments and Data

In developing the treatment matrix, four geometries were combined with all signalization alternatives, which resulted in 12 “Perspective I” and 8 “Perspective II” treatments. Each treatment was modeled with varied traffic intensities to create study cases. Twelve replications, each of which was configured with a different random seed, were performed for each case to encompass the stochastic variations from underlying simulation models. The evaluation node boundaries were user-defined such that no queues extended beyond the edges. During run time, all node-based MOEs were extracted, aggregated, averaged, and outputted automatically.

RESULTS

“Perspective I” Group

Figure 7 shows the results for the “Perspective I” group. Note that each sub-figure is presented at a different scale. The 2-lane results suggest that for each signal the average vehicle delay is highest at the 1,000 vph level. At lower volumes, it is less. At a specific vehicular flow level, the delay impact is the

highest at the 100 pph pedestrian intensity for each signal. At lower pedestrian volumes, the influence is less. This suggests a nearly *linear* relationship between the average vehicle delay and vehicle and pedestrian volumes. This observed trend is found at 3-lane and 4-lane configurations.

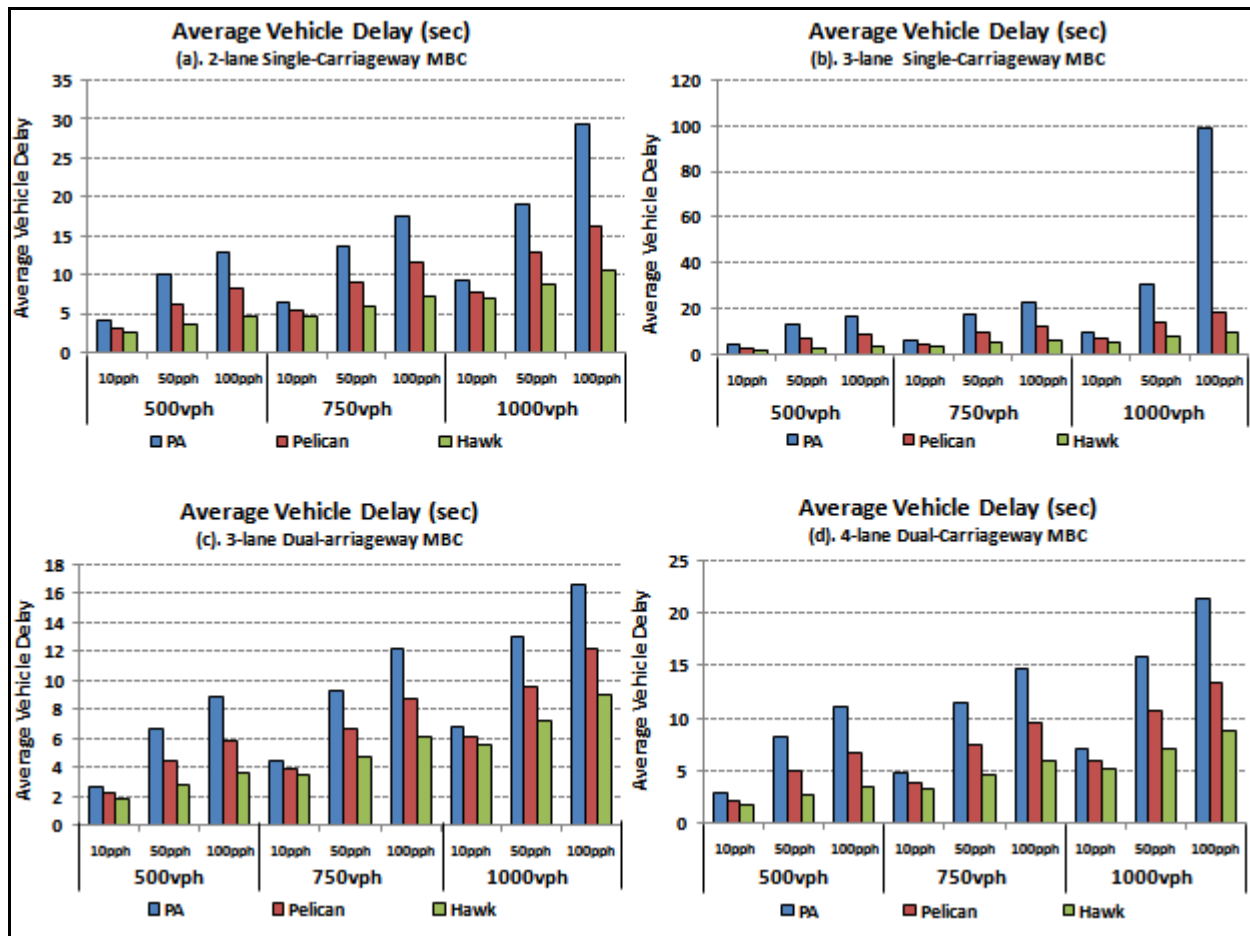


Figure 7 Average Vehicle Delay for “Perspective I” Group

As shown in Figure 7(b), with the highest vehicle and pedestrian volumes, the PA results in the highest average vehicle delay across all other sites. This is explained by the longer crossing distances while the PA holds vehicles. Across all geometries and pedestrian/vehicle volumes, the HAWK option consistently ranks better than all other signal systems, and the PELICAN method performs better than the PA. Again, the benefits are most predominant at the 3-lane single-crosswalk sites, but are evident in all cases. For the dual-crosswalk layout, there is no substantial difference in average vehicle delay for 3-lane and 4-lane MBCs.

The average pedestrian delay is defined as the difference, on average, between actual travel time and theoretical travel time (at a randomly distributed speed with the mean 3.0 ft/sec) through the node. Given that the signal timing is implemented without green extension parameters, it is expected that the average pedestrian delay is almost constant for all volumes. At the 2-lane MBCs, the average pedestrian delays are 8.84, 20.52, and 25.05 seconds for 10, 50, and 100 pph levels, respectively. At the 3-lane single-crosswalk/dual-crosswalk sites, they are 9.73/14.87, 23.07/34.79, and 29.33/43.23 seconds, respectively. At the 4-lane sites, they are 15.68, 36.95, and 47.71 seconds. The 3-lane numbers indicate that the pedestrian delay at the dual-crosswalk layout is higher than that for others, as some pedestrians must wait

for two-phase timed signals. Furthermore, the delays for higher pedestrian intensities are consistently higher than these for lower values, because pedestrians are more likely to arrive during the minimum green constraint. The results for average number of stops and average queue length are very similar to the average vehicle delay.

“Perspective II” Group

Figure 8 shows the MOEs for “Perspective II” group at 2-lane MBCs. With pedestrian volume increased to “Many”, all MOEs are consistently worse than those for the “Few” case, which shows the strong impact of pedestrian intensities upon traffic operations. This finding is expected because the higher pedestrian volumes will increase the occurrence of traffic flow interruption. Other vehicle-based MOEs (i.e., average vehicle/pedestrian delay, average number of stops, average queue length) also tend to increase. For pedestrians, this is explained because they are likely to arrive during the minimum green constraint and must wait before crossing.

With the vehicle flow increased to “oversaturated”, most MOEs consistently tend to be higher than those for the “under capacity” case, which shows the influence of vehicle intensities. However, this tendency is not very clear when pedestrians are “many” – they remains nearly unchanged no matter what signal schemes, which indicates that the effect of vehicles on the pedestrian waiting time diminishes with heavy pedestrian flows present.

Both the “pedestrian friendly (P-F)” and “vehicle friendly (V-F)” membership functions were tested for their effects. First, when the former is assumed with “Many” pedestrians, the average pedestrian delay is clearly lower than that for the latter and PUFFIN, but other vehicle-based MOEs are slightly higher. Secondly, when the latter is assumed with “Few” pedestrians, vehicle-based MOEs are smaller, although the differences are slight. However, although the “pedestrian friendly” signal still clearly reduces the waiting time, the average pedestrian delay for PUFFIN systems is smallest compared with two FLC signals and it tends to be unchanged with the vehicle intensity increased. This finding is expected because with “Few” pedestrians the inference engine implicitly gives more priority and safety concerns to approaching vehicles (relatively more than pedestrians even under “Under Capacity” condition) and then hold “disadvantageous” pedestrians for some time after the minimum green is released. Instead, the PUFFIN activates “WALK” only if the minimum green is satisfied and pedestrians are present – it never “thinks” about the ongoing traffic condition.

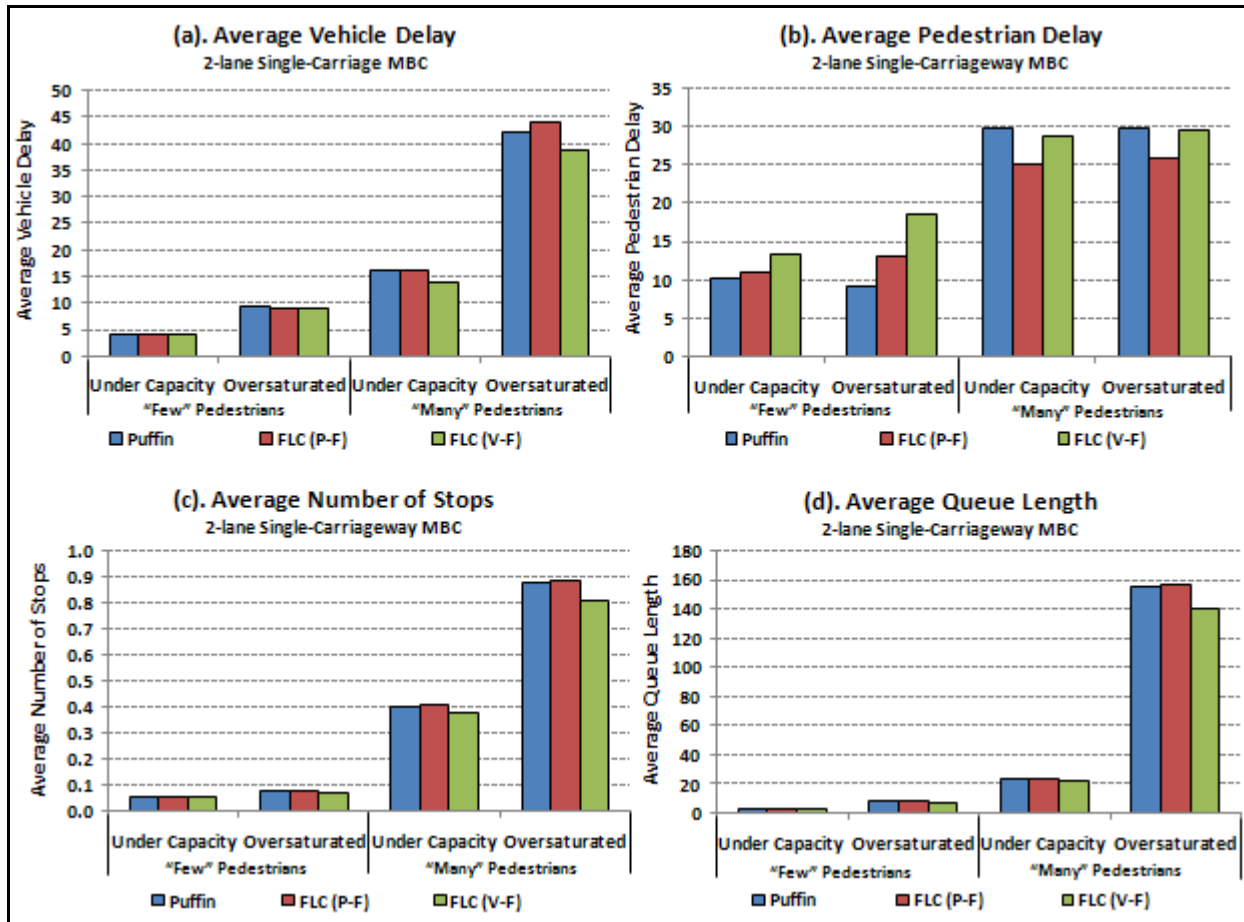


Figure 8 “Perspective II” Group Comparisons – 2-lane MBC (Single-Crosswalk)

Figure 9 and Figure 10 show the results for 3-lane MBCs. Almost all MOEs display a similar result to 2-lane sites, although the considerable difference in these vehicle-based MOEs exists between two layouts. At the single-crosswalk layout, these vehicle-based MOEs are drastically higher than those for the dual-crosswalk layout, because this layout has the longest crossing distance while all traffic signals hold vehicles unless the crosswalks are clear. Therefore, the benefits of the latter layout are significant to vehicular traffic. However, average pedestrian delays at the latter are higher than those at its counterpart, because pedestrians have to wait in the median for two-phase signals.

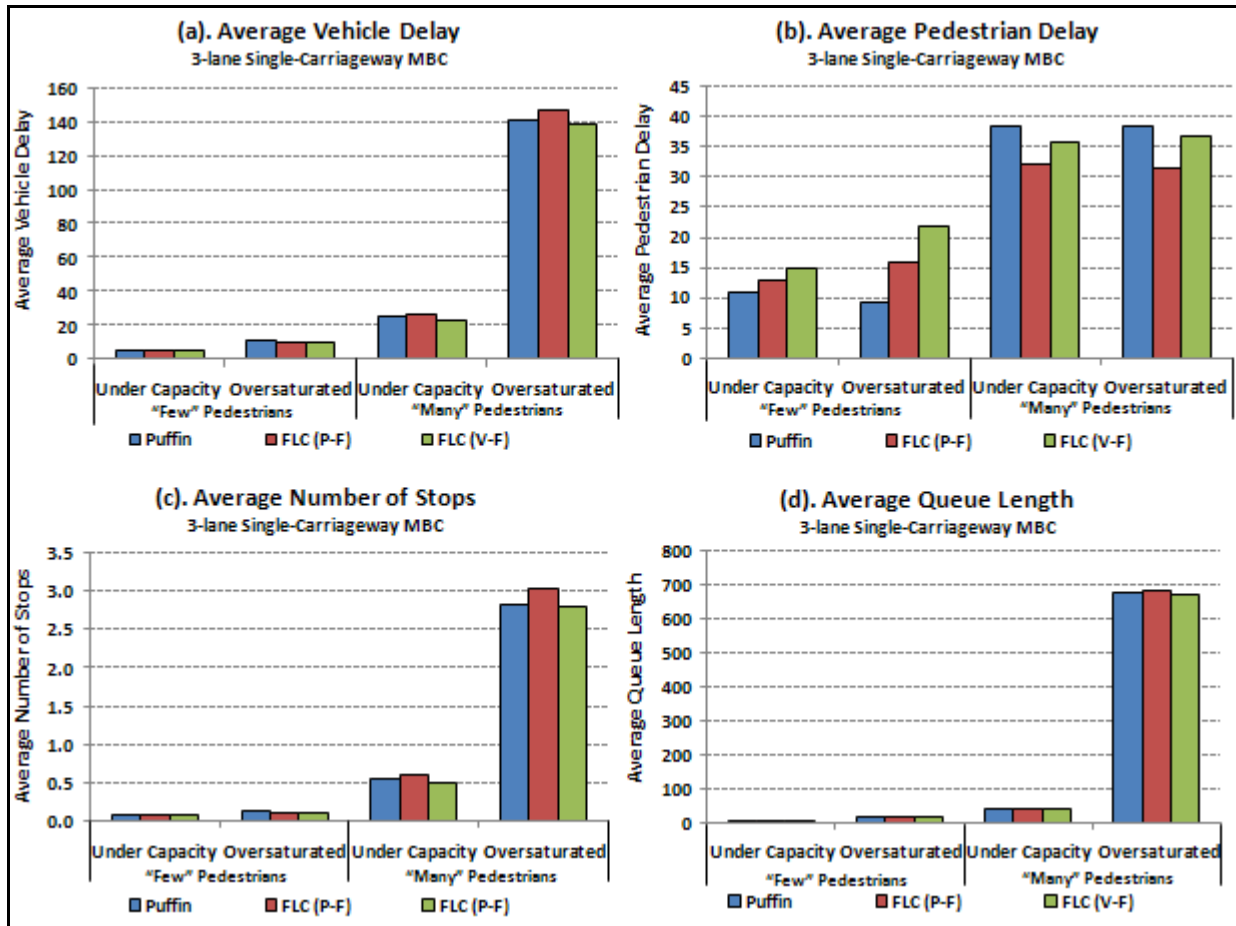


Figure 9 "Perspective II" Group Comparisons – 3-lane MBC (Single-Crosswalk)

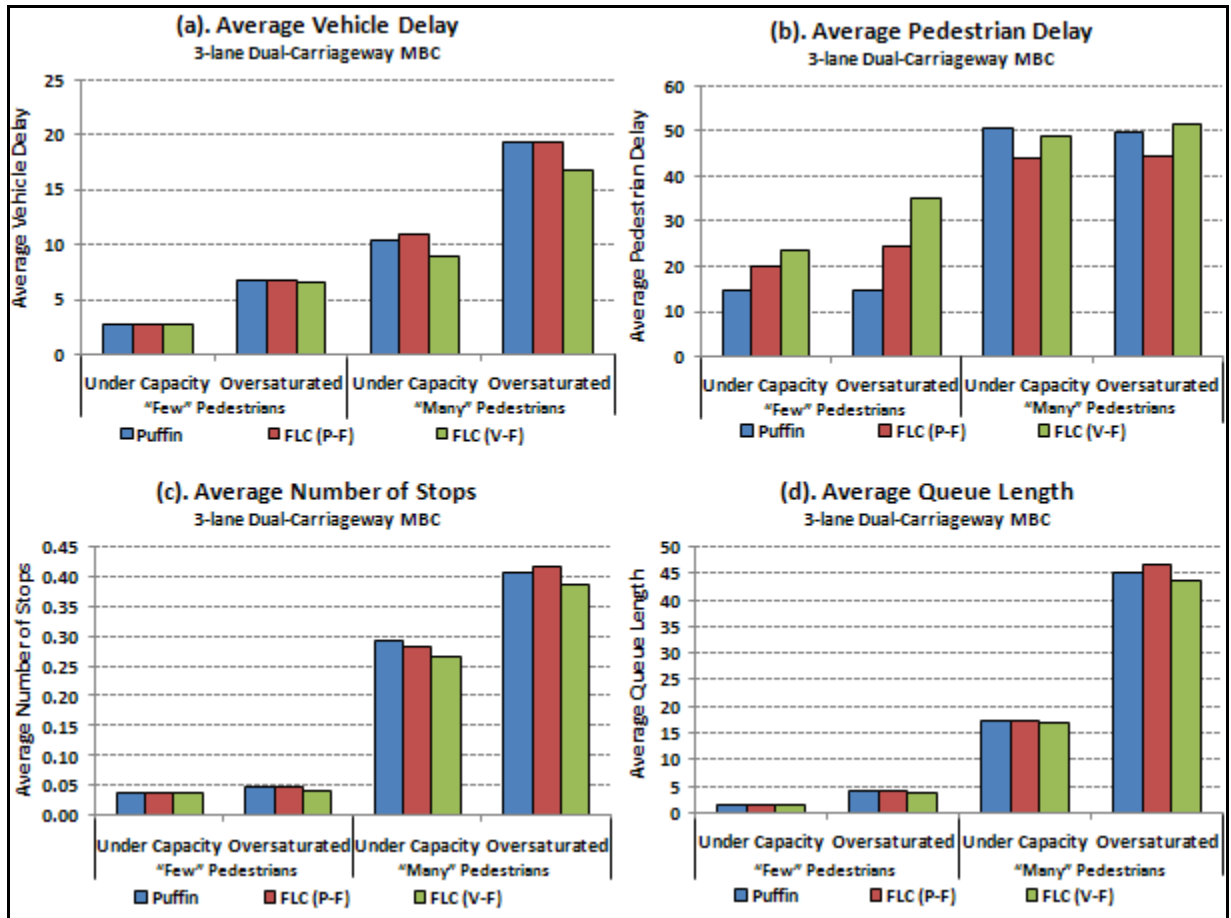


Figure 10 “Perspective II” Group Comparisons – 3-lane MBC (Dual-Crosswalk)

Results for 4-lane cases provide a very similar finding to Figure 10 except for the larger MOEs’ magnitudes.

The FLC provides better pedestrian accommodation and vehicular operations. Although average pedestrian delay increases somewhat when pedestrians are few, the system is still advantageous enough since it intelligently accommodate a safety element in dissipating vehicular platoons and creating downstream crossing gaps. Generally, it provides a compromise between multiple opposing objectives: minimum pedestrian delay, minimum vehicle delay, and maximum safety for all users. Also, such a compromise is executed without specific limits explicitly imposed in the rule base.

Due to their rigidity in timing methods, existing signals are inflexible in adjusting delays: for each condition, all parameters need being preset adequately to reach an operational goal. Comparatively, the FLC can be adaptive to different situations. Dual membership functions for pedestrian waiting time render the dependence scheme on the priority between vehicles and pedestrians.

CONCLUSIONS

This research provides a quantitative comparison between several common options for signaling MBCs at varied geometries. The results indicate consistent findings that two-phase signal timing and the

innovative HAWK significantly improves vehicle operations over the one-phase timing and other signals. The analysis further suggests a nearly linearity between MOEs and vehicle volume levels.

However, these signals lack effective all-user accommodations due to their static “FDW” timing method. Although the PUFFIN system is “user friendly” in this aspect, it still does not encompass more vehicle safety elements and human factors in control logic, so it lacks in the adaptive ability in fulfilling multiple opposing objectives. Hence, this research developed a “user friendly” FLC system for MBC signal timing and evaluated its performance against PUFFIN. The result shows that the FLC system not only effectively controls the signal timing but also offers at least equal or better performance than PUFFIN from both safety and operations perspectives. The logic is straightforward and the numbers of parameters are tractable; yet the performance is found to be strongly adaptive. All pedestrian and traffic needs are satisfied comprehensively in terms of enhanced pedestrian safety, reduced rear-end collision potentials, ameliorated operational efficiency, and then lessened social cost from delays and crashes at a MBC.

The uniqueness in FLC is suitable for tackling complex facilities with heavy traffic movements. The research should add an impetus to developing a FLC intersection system. Given there are numerous MBCs and intersections in the U.S. alone, the potential impact of this research is significant in traffic safety and signal control efficiency.

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