Intersection Signal Systems with Intelligent Pedestrian Accommodation: Dynamic Pedestrian Timing

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ABSTRACT:

Perhaps the most critical issue facing urban transportation engineers is the optimization of signalized intersections, with the goal of increasing both safety and efficiency for all modes without additional infrastructure. Furthermore, accommodating pedestrians at high volume intersections is becoming more challenging as increasing vehicular and pedestrian demand requires more green time. To safely accommodate pedestrians, the Highway Capacity Manual prescribes that the parallel vehicular green must be at least equivalent to "WALK" plus the "pedestrian clearance interval (PCI)". A fixed walking speed is used to calculate the PCI. Despite its effectiveness, this practice is not optimal from both and operations and safety perspective since some pedestrians walk more slowly or quickly than the design 4.0 feet/second pedestrian. Variability in the required PCI is not captured in the current design process. A problem also arises when the required PCI length exceeds the parallel vehicular green requirement. Additional green for longer PCI is unnecessary for vehicular flow efficiency and takes green time away from the conflicting phase(s), potentially increasing intersection delay.

In this research, the concept of dynamic PCI timing in traffic signal operations was explored. Two signal systems, the extended NEMA system and a fuzzy logic controller (FLC), were developed and evaluated, with dynamic PCI control, against current signalization methods. Both the extended NEMA and FLC proved to significantly improve operations with most cases evaluated. This research shows that traffic signal control can remove the dependence on a design walking speed and the ongoing debate on what this speed should be. Given there are reportedly 325,000 signalized intersections in the U.S., the potential impact of this research could be significant in traffic safety and operational efficiency.

Key Words:
Signalized Intersection, Pedestrian Safety, PCI, NEMA, Fuzzy Logic Control, Traffic Simulation

1

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BACKGROUND

Traffic congestion has become a problem in urban settings worldwide. Many causal factors can be identified in ad hoc and recurring congestion, but clearly the growing congestion results from the steady increase in motorized vehicle use. Nationally, mobility problems have increased at a relatively consistent rate during the past decade. Congestion is present on more of the transportation system, affecting more daily trips and a greater portion of the average week. A recent report shows the worst congestion levels increased from 12 to 40 percent of peak period travel over the previous 20 years (*1*). Traffic safety, travel time, environmental quality, and quality of life are all adversely affected by the steady congestion growth, which is leading the transportation engineering community to considerable change in philosophy and methodology. Gradually, the transportation engineering practice has transitioned from basic infrastructure improvements to the development and deployment of intelligent transportation systems (ITS) – the utilization of sophisticated technologies to extract more efficiency and safety from existing transportation infrastructure systems. Furthermore, the demand for traffic operations research considering all transportation facility users is increasingly necessary to better understand the steps to a more *intelligent* and *user friendly* transportation system.

Perhaps the most critical issue facing urban transportation engineers is the optimization of signalized intersections to maximize the capacity of the existing infrastructure. It is recognized that the improvement in intersection signal control is one of the most useful and cost-effective methods to reduce congestion and improve public safety for all modes (*2*). A considerable amount of research has been completed in traffic signal control, focused on methodologies for maximizing roadway capacity and minimizing vehicle delay. Intelligent control of signalized intersections could make the roadway systems operate more efficiently without the immediate need to build new roadways or widen existing roadways which is often impossible due to scarce land availability and public opposition. Current research focuses on using technologies and internal control algorithms, aimed to maximize available green time, and "reading" the intersection such that the controller logic can be set to optimally apportion the fixed amount of available green to the movements with the highest demand. Many theories have led to vehicular flow efficiencies at signalized intersections.

United States safety data shows that a pedestrian is killed every 110 minutes and injured every 9 minutes (*3*). Crosswalks are especially perilous for elderly pedestrians. Among people 70 and older, 36 percent of pedestrian deaths in 2006 occurred at intersections, compared with 21 percent of those younger than 70 (*4*). In 2006, 471 pedestrians nationwide were killed in crosswalks (*5*). Cities and authorities alarmed by pedestrian casualties are employing new techniques to make crosswalks safer (*3,6*). However, few engineers and researchers have integrated *all users*, especially pedestrians, into the signal optimization methodologies. Specifically, the impact of crossing pedestrians and their variability in crossing speeds on intersection operations is not fully considered. No research has considered the operations and safety effects of dynamic pedestrian flows on the signalization optimization in terms of ITS-oriented signal system design and development.

PROBLEM STATEMENT

At a signalized intersection, pedestrians are accommodated through various phasing and timing schemes. In a pedestrian phase, after the "WALK" interval, the "Flashing DONT WALK (FDW)", used as the pedestrian clearance interval (PCI), is held for a predetermined duration, and is then followed by a "Steady DONT WALK (SDW)" interval to stop pedestrian movements. The Highway Capacity Manual (HCM) prescribes that the parallel vehicular green must be at least equivalent to "WALK" plus "PCI". Obviously, the walking speed is the critical factor in determining how much crossing time is actually provided. One inherent problem is rooted in the difficulty incorporating varied walking speeds into the

timing design. Consequently, the use of normative values has remained common: the Manual on Uniform Traffic Control Devices (MUTCD) designates a fixed walking speed (4.0 feet/second) to time the PCI. Although this practice has been effective, its use is unsustainable since the growing population of seniors and increasing mobility of children add significant variability to walking speeds at most intersections. Additionally, national debate has taken place regarding the appropaite value for the design walking speed. Past research revealed that walking speeds vary considerably and range from 1.0 to 8.0 ft/sec, so varied design speeds were suggested for different populations (*7,8,9,10,11,12*). Therefore, it seems unreasonable to provide the same PCI for a young runner, an elderly cane user, or a wheel chair user. Yet this is how current intersection signal systems operate.

Certain countermeasures are taken to alleviate this problem. The MUTCD includes a caveat that a walking speed of less than 4.0 ft/sec can be considered for slower pedestrians (*13*). No specific value is provided. The National Committee on Uniform Traffic Control Devices has recommended a lower walking speed, lowering the design standard from 4.0 to 3.5 ft/sec. This countermeasure is believed to better accommodate our aging population and provide more safety for mobility-impaired pedestrians. However, this speed change still implements a fixed time period and may increase the amount of "PCI" time by as much as 15 percent (*3*). It is notable that, other measures, such as pedestrian countdown signal (PCS), are designed for better signal protect. Seemingly being dynamic control, PCS can not provide complete safety to all pedestrians since fixed walking speed is still used for "PCI" timing. The only difference it made is to alert pedestrians to the remaining available time for safe walking on the crosswalk.

A problem arises when the PCI requirement exceeds the parallel vehicular green requirement. It is highly likely that to provide a fixed PCI time to satisfy walking needs incurs more delays, since the additional green is also required for the parallel vehicular phase but it is not needed for vehicular flow efficiency. The additional green time required takes green away from one or more conflicting phases, inflicting more delay on the whole intersection. Therefore, to provide a longer PCI in such a *simplistic* way exerts a negative impact upon vehicular flow efficiency, leaving the operations sub-optimal. This inefficiency becomes more significant when lower pedestrian design speeds are used – once pedestrians walk faster, the additional crossing time is wasted. To improve operational efficiency for all users, there is a need to develop a novel strategy that accommodates, in an *intelligent* way, the variability in walking speed.

OBJECTIVES

The primary objective of this research is to develop and evaluate an intersection signal system capable of a dynamic PCI display intelligently adaptive to variable walking speeds. The second objective is to quantify the potential efficiency and safety benefits produced by the new system. Currently, radar is commonly used as an ITS technology to detect approaching vehicles at an intersection or pedestrians *only* at a mid-block crosswalk for "user friendly" purpose (*14,15*). This research hypothesizes that the radar (or similar) technology can be applied to effectively capture real-time pedestrian walking speed and location data to accommodate the data input need in an intersection signal control. Therefore, the PCI can be dynamically adjusted to reflect the pedestrian crossing time instantaneously needed, potentially reducing the efficiency impact upon vehicular traffic.

Study Intersection

With two east-westbound and north-southbound arterials, a typical isolated intersection was used in this analysis. Figure 5 shows the approach geometry. Each approach was posted at 40 mph and had through (TH), right-turn (RT), and left turn (LT) movements. The east-westbound and north-southbound

approaches have two and three lanes, respectively. Four LT bays are provided for protected LT phases (*13,16*).

The Extended NEMA Scheme

Traffic signal control is a process of optimally allocating green time among conflicting movements. A critical issue, given vehicular and pedestrian demands, is when to terminate the current phase. In principle, a signal controller, at regular intervals (Δt), gathers information and evaluates ongoing traffic conditions. Once decision criteria are satisfied, it terminates the current phase and makes the most appropriate adjustments within the designated signal timing plan. The conventional NEMA (conNEMA) system works within these principles. The addition of dynamic PCI requires a change to the conNEMA, based on the decision-making mechanism supported by following parameters.

Basic Parameters

With the conNEMA phase numbering, timing constants and control variables (in seconds) are defined as follows.

$G_{LT_i}^{Min} / G_{LT_i}^{Max}$: <u>Min</u>imum/<u>Max</u>imum <u>G</u>reen for <u>LT</u> phase *i*;

$G_{TH_j}^{Min} / G_{TH_j}^{Max}$: <u>Min</u>imum/<u>Max</u>imum <u>G</u>reen for <u>TH</u> phase *j*;

U_{LT_i} / U_{TH_j}: <u>U</u>nit extension for <u>LT</u> phase *i*/ <u>TH</u> phase *j*;

$W_{TH_j} / PCI_{TH_j}^{Max}$: "<u>W</u>ALK" /<u>Max</u>imum <u>PCI</u> parallel to <u>TH</u> phase *j*;

$T_{LT_i}^{G}(t+\Delta t) / T_{TH_j}^{G}(t+\Delta t)$: <u>G</u>reen <u>T</u>ime length displayed at $(t+\Delta t)$ for <u>LT</u> phase *i*/<u>TH</u> phase *j*;

$H_{LT_i}(t+\Delta t) / H_{TH_j}(t+\Delta t)$: Current <u>H</u>eadway detected at $(t+\Delta t)$ for <u>LT</u> phase *i*/<u>TH</u> phase *j*;

And: $W_{TH_j} < G_{TH_j}^{Min}$; *i* = 1, 3, 5, 7; *j* = 2, 4, 6, 8.

The system is controlled by identifying the basic statuses at $(t+\Delta t)$, in terms of basic parameters, as follows.

"Vehicle Min-over": $T_{LT_i}^{G}(t+\Delta t) \geq G_{LT_i}^{Min}$ for LT phases; $T_{TH_j}^{G}(t+\Delta t) \geq G_{TH_j}^{Min}$ for TH phases;

"Vehicle Gap-out": $H_{LT_i}(t+\Delta t) \geq U_{LT_i}$ for LT phases; $H_{TH_j}(t+\Delta t) \geq U_{TH_j}$ for TH phases;

"Vehicle Max-out": $T_{LT_i}^{G}(t+\Delta t) \geq G_{LT_i}^{Max}$ for LT phases; $T_{TH_j}^{G}(t+\Delta t) \geq G_{TH_j}^{Max}$ for TH phases;

"PCI Max-out": $T_{TH_j}^{G}(t+\Delta t) \geq W_{TH_j} + PCI_{TH_j}^{Max}$ for TH phases.

New Control Logic

The extended NEMA (extNEMA) resembles the conNEMA except for the PCI display. When a TH phase starts, the extNEMA operates in one of two ways. First, in the absence of pedestrian demand, the extNEMA deals solely with vehicles, exactly as how the conNEMA operates (*17*). Second, with pedestrian demand, the extNEMA detects pedestrians within the crosswalks. After sufficient "*Vehicle Min-over*" and "*Gap-out*" (or "*Max-out*") statuses occurs,, the PCI can be dynamically extended to

4

accommodate an unusually slow pedestrian(s) and concurrently extend the vehicular green. Similarly, fast moving pedestrians can be detected, and once cleared, can reduce the PCI timing such that the vehicular green time is returned to optimal values.

With PCI extensions, the vehicular green is terminated if all pedestrians are clear *before* the "*PCI Max-out*" occurs, or the "*PCI Max-out*" occurs regardless of pedestrian movements. Fast pedestrians are accommodated before the signal transfer, posing no delay to conflicting vehicular movements. For slower pedestrians, the PCI is dynamically adjusted to offer additional crossing time. The $PCI_{TH_j}^{Max}$ has significant influence on the vehicular flow efficiency: if the pedestrian demand is short enough, vehicular green can be brought back sooner; otherwise, even the slowest pedestrians are protected while vehicles wait. Figure 1 illustrates the control logic flowchart.
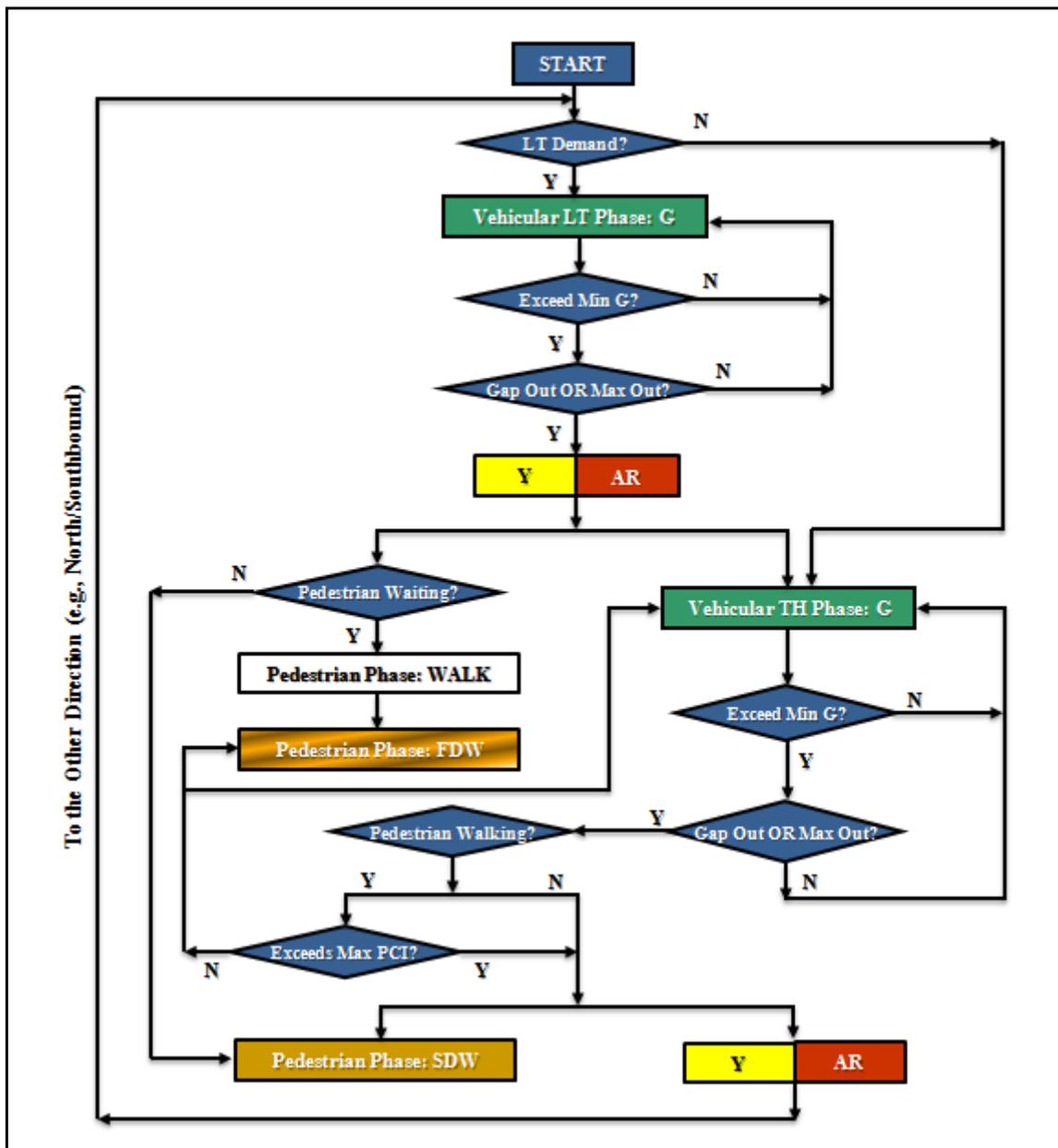
Figure 1 Pedestrian Detection Based NEMA System – Control Logic Flowchart

The extNEMA effectively eradicates the problem with static design walking speeds as more time is rendered instantaneously for slower pedestrians; or time is given back to the vehicular movements once pedestrian demand is satisfied. Alternatively speaking, if a runner presses the pedestrian pushbutton, receives the "WALK", and travels through the intersection in 3 or 4 seconds, the PCI can then terminate to avoid potential delays to queuing vehicles. The vehicular operation efficiency is balanced with pedestrian safety needs.

A Fuzzy Logic Controller

For complex intersections with heavy traffic demand, traffic signal control must consider many, often mutually conflicting, objectives, in addition to safety for all modes. Thus, traffic signal control deals with a multi-objective problem, which means that "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" (*19*). By creating an "approximate reasoning" concept based on fuzzy set theory and fuzzy logic, Zadeh showed that vague logical statements enable the algorithm formations that can use vague data to derive vague inferences (*20,21,22*). Through applications in areas including transportation engineering, fuzzy logic control (FLC) proved more effective, robust, and adaptive than traditional traffic control for tackling a complex system involving human perception, imprecise information, ambiguous criteria, and conflicting objectives and yet keeping the parameter setting a tractable task (*23,24,25,26*).

A FLC signal system was developed to improve the interaction between walking speeds, crossing safety, and intersection operations. The new system works in the same principle as its counterparts. However, it is different in control logic from the conNEMA, since it compares the traffic conditions during the current phase and the next candidate phase to determine a control action. FLC artificially emulates the decision-making intelligence possessed by a traffic control expert intending to realize multiple objectives: *(a). Minimum Delay and Maximum Safety to Pedestrians* – Pedestrians should be accommodated soon and protected when crossing; *(b). Minimum Delay and Maximum Safety to Vehicles* – Vehicles should not be stopped for an unreasonably long time to avoid driver's incompliance with signal displays, and a vehicular platoon should be preserved and discharged wholly to avoid rear-end collisions.

Phasing Scheme

A four-phase scheme was implemented (Figure 2), which offers the flexibility in skipping LT phases in any cycle when service calls are absent. Each approach may start its green phases in either an exclusive LT phase with LT demand present in either LT bay, or in a combined TH and RT phase.
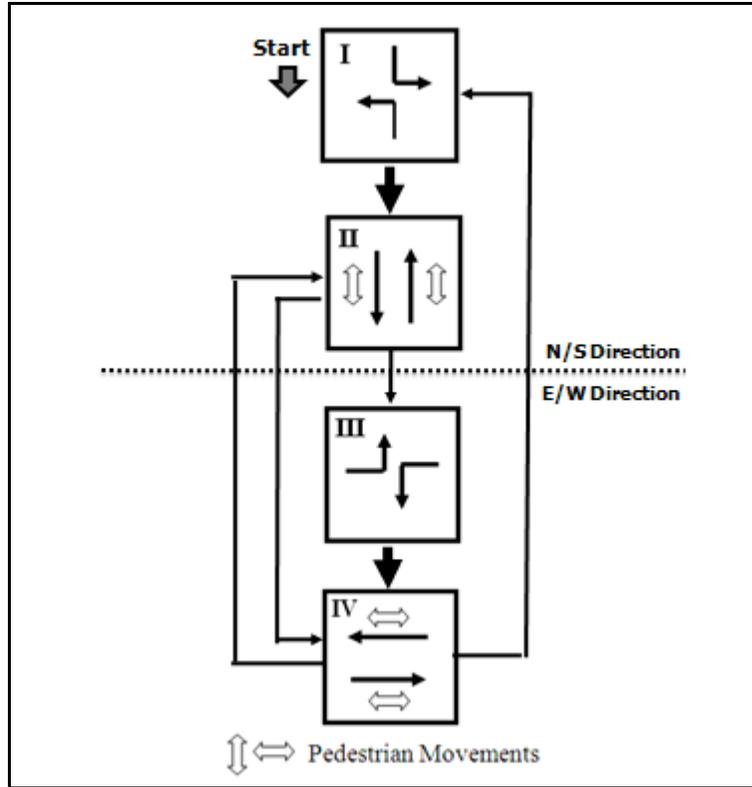
Figure 2 FLC System Phasing Scheme Diagram

Basic Parameters

The system operates via the decision-making mechanism supported by some timing constants and control variables (in seconds) defined as follows:

$G_{LT_p}^F:$ <u>F</u>ixed <u>G</u>reen for <u>LT</u> Phase <u>p</u>;

$G_{TH_q}^{Min}/G_{TH_q}^{Max}:$ <u>Min</u>imum/<u>Max</u>imum <u>G</u>reen for the <u>TH</u> Phase <u>q</u>;

$W_{TH_q}/PCI_{TH_q}^{Max}:$ "<u>W</u>ALK"/<u>Max</u>imum <u>PCI</u> in parallel with <u>TH</u> Phase <u>q</u>;

$T_{LT_p}^G(t+\Delta t)/T_{TH_q}^G(t+\Delta t):$ <u>G</u>reen <u>T</u>ime which has been displayed at $(t+\Delta t)$ for

           <u>LT</u> Phase <u>p</u>/<u>TH</u> Phase <u>q</u>;

And:

$$W_{TH_q} < G_{TH_q}^{Min}, \ G_{TH_q}^{Max} < PCI_{TH_q}^{Max} + W_{TH_q}$$

$p =$ I, III and $q =$ II, IV in the FLC phasing scheme.

Initially, the system must identify some ongoing statuses in terms of basic parameters, to navigate the control logic flow:

"Phase p Green-Over": $T_{LT_p}^G(t+\Delta t) \geq G_{LT_p}^F$ for LT Phase p;

"Phase q Min-Over": $T_{TH_q}^G(t+\Delta t) \geq G_{TH_q}^{Min}$ for TH Phase q;

7

"Phase q Max-Out": $\qquad$ $T^{G}_{TH_q}(t + \Delta t) \geq G^{Max}_{TH_q}$ for TH Phase q;

"Phase q PCI Max-Out": $\qquad$ $T^{G}_{TH_q}(t + \Delta t) \geq W_{TH_q} + PCI^{Max}_{TH_q}$ for TH Phase q.

Secondly, the inference engine evaluates, in linguistic terms, traffic conditions during current and next phases through fuzzifying following state variables (i.e., crisp inputs), to output the action on current phase:

$FL^{c}_{TH_q}(t + \Delta t)$: $\qquad$ Average Approach $\underline{F}$low $\underline{L}$evel (vehicles/lane) on $\underline{TH}$ lanes of

$\qquad$ the $\underline{c}$urrent Phase q within Δt.

This variable reflects the vehicular flow intensity on approaches. It is employed to address the efficiency issue in discharging vehicles. Obviously, the more intense the flow density is, the more strongly the vehicles demand for green to reduce delays on approaches. Each of $FL^{c}_{TH_{II}}(t + \Delta t)$ and $FL^{c}_{TH_{IV}}(t + \Delta t)$ has three fuzzy sets: "Sparse", "Moderate", and "Dense".

$DH^{c}_{TH_q}(t + \Delta t)$: $\qquad$ Average Vehicle $\underline{D}$ischarge $\underline{H}$eadway (vehicles/second/lane) on $\underline{TH}$ lanes of

$\qquad$ the $\underline{c}$urrent Phase q within Δt.

This variable measures the gap between two vehicles being dissipated across the STOP line. It is introduced to embody a safety element in discharging vehicles. 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 probably a vehicle platoon is being dissipated. Each of $DH^{c}_{TH_{II}}(t + \Delta t)$ and $DH^{c}_{TH_{IV}}(t + \Delta t)$ has two sets: "Small" and "Large".

$QL^{n}_{LT_p}(t + \Delta t)$: $\qquad$ Average $\underline{Q}$ueue $\underline{L}$ength (vehicles/lane) on $\underline{LT}$ bays of $\underline{n}$ext Phase $\underline{p}$ within Δt.

$QL^{n}_{TH_q}(t + \Delta t)$: $\qquad$ Average $\underline{Q}$ueue $\underline{L}$ength (vehicles/lane) on all $\underline{TH}$ lanes of $\underline{n}$ext Phase q within Δt.

These variables count the number of vehicles queuing for service. It is utilized to encompass an operational and safety factor in dissipating queued vehicles. The longer a queue is, the more probably drivers feel impatient and commit incompliance with signal displays. Each of these variables (i.e., $QL^{n}_{LT_I}(t + \Delta t), QL^{n}_{TH_{II}}(t + \Delta t), QL^{n}_{LT_{III}}(t + \Delta t), QL^{n}_{TH_{IV}}(t + \Delta t)$) has three sets: "Short", "Long", and "Very Long".

Finally, the control variable $A^{veh}_{TH_q}(t + \Delta t)$ represents $\underline{A}$ctions taken, at the time point $(t + \Delta t)$, on current $\underline{TH}$ Phase q for $\underline{veh}$icular movements: "Termination", and "Extension".

Signal Control Logic

The conNEMA operates on vehicle detection, while the extNEMA attempts a more comprehensive evaluation of all users. The logic rules for green extension are straightforward. However, the FLC system prescribes the green extension or termination not explicitly but implicit in the rule base. As shown in Figure 3, the system was designed to operate as follows:

(a). Constant Phase I to II Transition
Suppose that Phase I is current. After "*Phase I Green-Over*", the system activates Phase II.

(b). Selective Phase II Control Process
After Phase II green starts, if pedestrian crossing demand exists, provide "WALK". First, $G_{TH_{II}}^{Min}$ is satisfied to dissipate the queued vehicles. After the "*Phase II Min-Over*" occurs at $(t + \Delta t)$, one FLC module is activated to determine whether to extend or terminate the current green. To select which module depends on either CASE 1 or CASE 2 is found to be true.

CASE 1: "Present Phase III LT Demand"
At $(t + \Delta t)$, if any vehicles are queuing in LT bays for Phase III, the system goes to the "FLC Module #1" where $FL_{TH_{II}}^c(t + \Delta t)$, $DH_{TH_{II}}^c(t + \Delta t)$, and $QL_{LT_{III}}^n(t + \Delta t)$ are involved. FLC takes actions on the green by determining $A_{TH_{II}}^{veh}(t + \Delta t)$ to be "termination" or "extension":

- If the green is extended, the system forces the PCI to be prolonged as well to accommodate crossing pedestrians. Once the green extensions continue until the "*Phase II Max-out*" occurs, the FLC based on vehicular information is terminated and the control proceeds to "Condition 1" or "Condition 2".
- If the green is terminated, the system detects whether any pedestrians are still walking on crosswalks, and then the control proceeds to "Condition 1" or "Condition 2".

CASE 2: "Absent Phase III LT Demand"
At $(t + \Delta t)$, if no vehicles are queuing in LT bays for Phase III, the system goes to the "FLC Module #2" where $FL_{TH_{II}}^c(t + \Delta t)$, $DH_{TH_{II}}^c(t + \Delta t)$, and $QL_{LT_{IV}}^n(t + \Delta t)$ are involved. Similar to Case I, the system takes actions on the current green:

- If the green is extended, the PCI display is forcedly prolonged equally. Once the green continues until the "*Phase II Max-out*" occurs, the FLC is terminated and the control proceeds to "Condition 1" or "Condition 2".
- If the green is terminated, the system detects any remaining pedestrians, and then the control proceeds to "Condition 1" or "Condition 2".

Condition 1: "Pedestrians Absent on Crosswalks"
If no pedestrians remains on crosswalks at $(t + \Delta t)$, $A_{TH_{II}}^{veh}(t + \Delta t)$ takes "Termination" and the next phase is activated: for CASE 1, Phase III comes; for CASE 2, Phase IV comes.

Condition 2: "Pedestrians Present on Crosswalks"
If some pedestrians are still walking, the PCI is extended, and the adjacent vehicular green is extended equally. Hence, slower pedestrians are accommodated before traffic operations considerations. Therefore, the system is adaptive to the variable walking speeds on crosswalks. Through this novel control logic, pedestrian safety is accommodated in an *intelligent* and *pedestrian friendly* manner.

If all pedestrians are clear, the system activates the next phase: for CASE 1, Phase III comes; for CASE 2, Phase IV comes. It should be noted that once the PCI extensions continue until the *"Phase II PCI Max-Out"* occurs, Phase II is unconditionally forced to the next appropriate phase.

Cycle by cycle, in Phase IV the control process repeats the same logic as that in Phase II, after the Phase III to IV transition if applicable. In structure, the system has four FLC modules for different cases, as follows.

FLC Module #1 – Phase II vs. Phase III FLC Module #2 – Phase II vs. Phase IV
FLC Module #3 – Phase IV vs. Phase I   FLC Module #4 – Phase IV vs. Phase II

Figure 3 FLC System Signal Control Logic Flowchart

FLC System Configuration

At time intervals (Δt), the FLC system reviews the ongoing situation and executes its logic through three components: Fuzzifier, Inference Engine, and Defuzzifier. The key factor in fuzzification is the membership function transforming input variables into fuzzy values to be processed by the inference engine. Mathematically, there is a range to choose from, and Trapezoid membership function in the most common use was selected to avoid complicating the problem. To determine the function shape for nearly optimal performance, literature reviews, statistics record studies, field observations, and simulation trails were conducted to capture the conceptual feeling of all fuzzy sets under different conditions. Figure 4 show all necessary parameters.

Acting as the "brain", the decision-making process in inference engine is composed of a set of "IF … AND … THEN …" logic rules which assess ongoing traffic condition for current and next phases in natural language. The fact following "IF" is termed as "*premise*" (or "*antecedent*"), and the fact following "THEN" is "*consequence*". The "AND" (or "OR") is called "*operator*", and the connecting operators form the rule base in an inference engine. The generic structure of a rule base could be delineated as follows.

<u>Input</u>: *(x_1 = A)* AND *(x_2 = B)* AND *(x_3 = C)*

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

…… ……

Rule i: IF *{ x_1 is A_i }* AND *{ x_2 is B_i }* AND *{ x_3 is C_i }* THEN *{E or T}*

…… ……

Rule n: IF *{ x_1 is A_n }* AND *{ x_2 is B_n }* AND *{ x_3 is C_n }* THEN *{E or T}*

<u>Conclusion</u>: {E or T}

Where,

x_1, x_2, x_3 = State (input) variables for traffic conditions of the subject;

A, B, C = Values of state variables;

A_i, B_i, C_i = Natural language expressions for traffic conditions of state variables;

E = Extension of current phase;

T = Termination of current phase.

Obviously, "AND" is the appropriate operator here, and the total number of rules depends on the combination of fuzzy sets for state variables: $n = 2 \times 3 \times 3 = 18$ rules for each FLC module (Table 1).

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). Therefore, 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.

Under fuzzy inference embedded in the FLC based signal, the conclusion is drawn based on the similarity between the input (A, B, C) and these premises (A_1, B_1, C_1; …; A_i, B_i, C_i; …; 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 antecedents 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 for the final output, 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.

Table 1 Summary of Fuzzy Control Rules

Vehicle Discharge Headway		Approach Flow Level		
Small		Sparse	Moderate	Dense
Vehicle	Short	T	E	E
Queue	Long	T	T	E
Length	Very Long	T	T	T

Vehicle Discharge Headway		Approach Flow Level		
Large		Sparse	Moderate	Dense
Vehicle	Short	E	E	E
Queue	Long	E	E	E
Length	Very Long	T	T	T
T: Terminate; E: Extend				

Mamdani's method used here is the most common approach employed for the aggregation process. Mamdani's effort was based on Zadeh's work on fuzzy algorithms for complex systems and decision processes (*21*). This method was among the first control systems built using fuzzy set theory, which was proposed as an attempt to control a steam engine and boiler combination by synthesizing a set of linguistic control rules from experienced human operators (*27*).

Defuzzification moves the output space of fuzzy control actions into a control action. Several techniques have been developed to produce a crisp output, and 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 (*28,29*). Due to the "binary" feature in traffic signal control, the "Maximum Criterion" method should be the most appropriate for use.
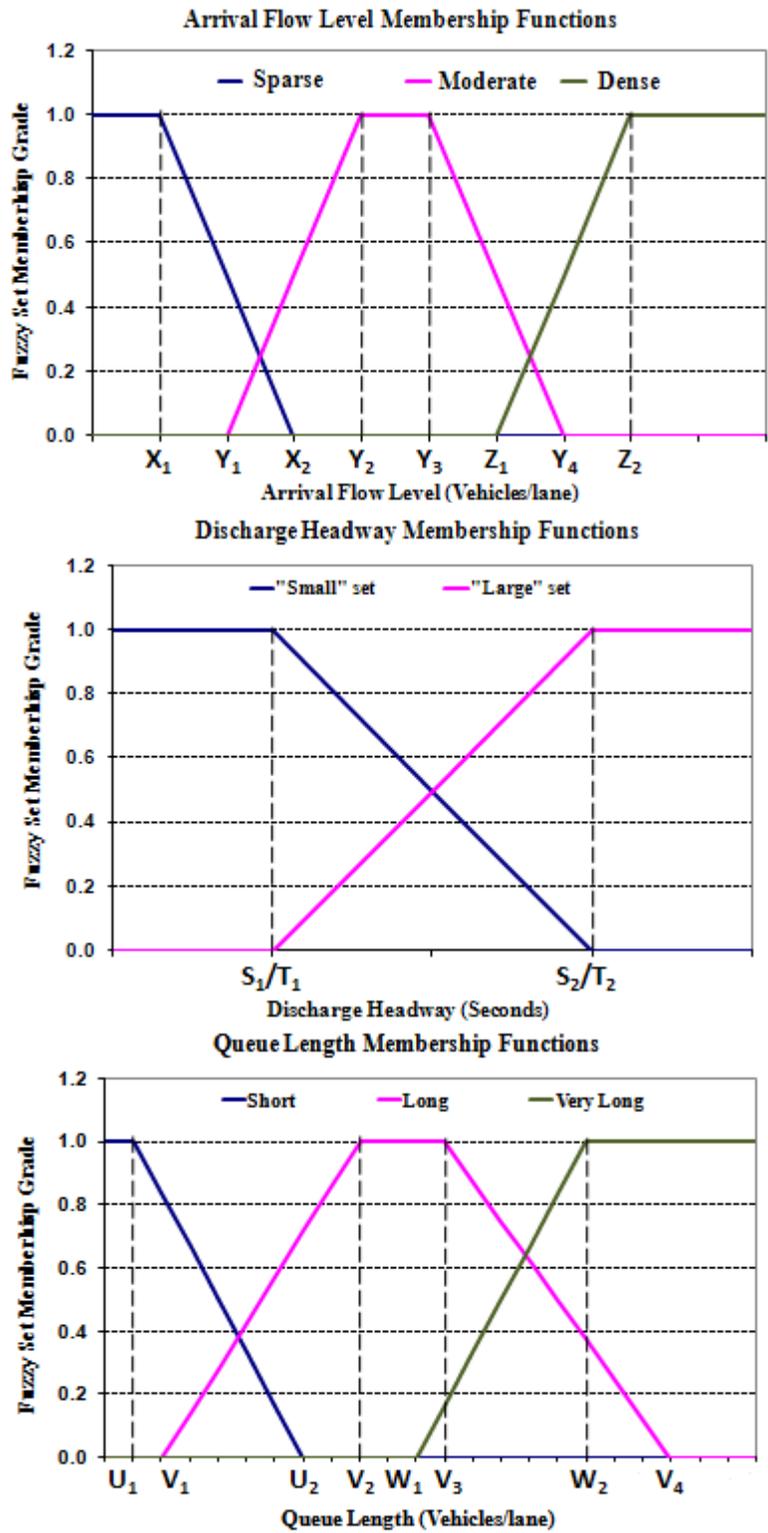
Figure 4 Basic Parameters for Three Membership Functions

PERFORMANCE TESTING STRATEGY

The FLC was compared with the conNEMA and the extNEMA. A uniform degree of pedestrian crossing signal protection was provided throughout. Crossing variables are directly embodied in timing the conNEMA PCI. The conNEMA PCIs are timed for a fixed pedestrian speed. In operations, once the crossing demands paralleling a TH phase is detected, the conNEMA makes the minimum green equal the PCI plus "WALK". Beyond the minimum green, the signal control follows the "unit extension" logic. Two Measures of Effectiveness (MOEs), average pedestrian delay (APD) and average vehicle delay (AVD), were used. In traffic engineering, solutions have long been sought to balance two mutually conflicting objectives: maintaining efficient traffic movements while providing pedestrian efficiency and safety. Typically, a trade-off exists between modes. To evaluate three systems in a comprehensive way, a new MOE was designed as follows:

$$\text{Weighted Average Delay (WAD)} = (1-\alpha) \cdot AVD + \alpha \cdot APD$$

Where:
α - Weight for APD, lying in [0, 1].

The weight (α) makes it possible to adjust evaluative emphasis between old MOEs: when α equals one or zero, the WAD solely equals APD or AVD; otherwise, it reflects a comprehensive consideration of intersection delays to all users.

ANALYSIS

VISSUM traffic microscopic simulation was used to complete this analysis. Recent studies found VISSIM, a microscopic simulation program, advantageous in specific requirements (e.g., pedestrian modeling, detector functions, signal control logic, etc.) and its models effectively represent various field conditions in many real-world urban settings (*29*,31,*32,33,34,35*). Hence, VISSIM was selected as the research tool. In two dimensions (i.e., signal schemes and traffic flow intensity), the analysis sought to explore how the control logic change affects MOEs from the perspective of vehicles and pedestrians.

Geometry and Detectorization

The vehicle travel lanes and pedestrian crosswalk were set to 12 and 10 feet in width (*36,37,38,39,40*). Distance between the STOP line and the crosswalk edge was 5 feet. Figure 5(a) shows the approach detectorization for NEMA systems. Advance point detectors were applied, with the setback equaling the stopping sight distance for 40 mph: $vt_{br}+v^2/2a$=202.07 ft (brake-reaction time t_{br}=1 second, minimum deceleration rate a=12.0 ft/s^2) (*41*). A detector was placed at the STOP line for each TH lane. All LT lanes under NEMA controls must have STOP line detection (*41*). Figure 5(b) shows the approach detectorization for the FLC system. Paired vehicle detectors are installed for TH and LT lanes and their spacing accommodate 12 and 6 vehicles, respectively. A service call detector and a discharge headway detector are placed at the STOP line for each of LT bays and TH lanes. Besides on-crosswalk sensors, pedestrian pushbuttons were provided at each end of a crosswalk.

Flow and Timing Implementation

Past research indicated that 15 percent of pedestrians walk more slowly than 3.5 ft/s (*42*), and a speed less than 3.5 ft/s is used somewhere for the PCI timing (*43*). Due to increasing safety concerns for mobility-impaired populations, the mean speed was set to 3.0 ft/s, and the maximum/minimum speeds were set

14

1.0/5.0 ft/s. Two pedestrian intensities were set: "Few", 15 pph; "Many", 75 pph. The MUTCD recommends 4 to 7 seconds for "WALK", and it lasts 7 seconds in all cases. For all systems, maximum PCIs were computed with intersection widths using the lowest walking speeds.

Three typical vehicular conditions were designed: "Under Capacity", "Approaching Capacity", and "Oversaturated". "Yellow" and "All-Red" last 4 seconds and 1 second for vehicles. Other basic timing parameters were computed with standard methods (*17*). The basic timing structure for common signal systems is identical or similar – the minimum/maximum greens must be established for an in-between period during which the control logic plays its role. Therefore, some FLC timing parameters were determined in a consistent manner. The fixed LT green and minimum/maximum TH greens in the FLC were applied consistently with those for NEMAs.

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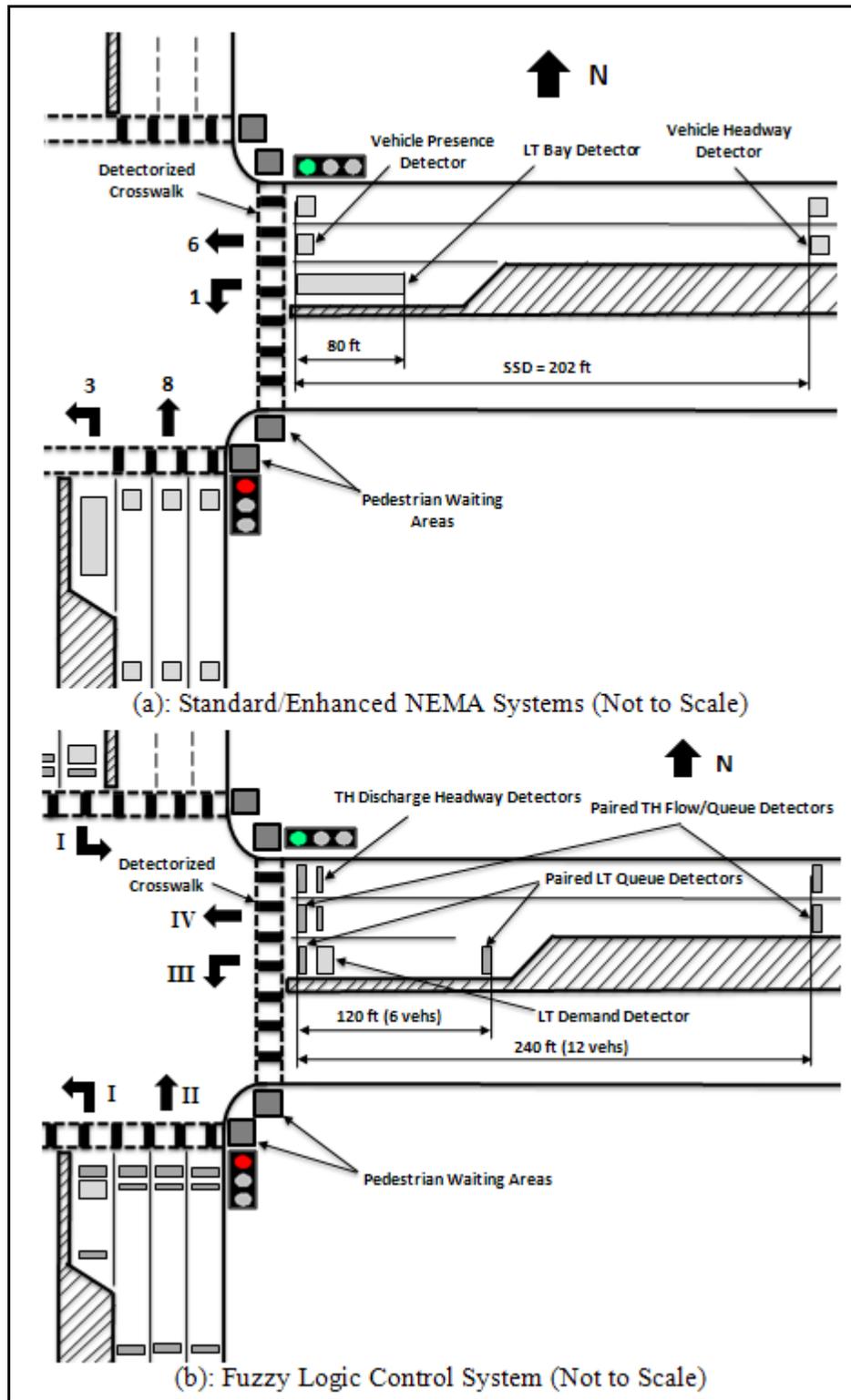
Figure 5 Approach Detectorization for Signal Systems under Study

Treatments and Data

Six cases were studied through combining vehicular and pedestrian intensities, each of which was combined with three systems to form 18 scenarios. Seventeen replications, each configured with a unique random seed, were conducted for each scenario to encompass the stochastic variations from underlying simulation models. Five nodes were used: four for vehicle delays and one for pedestrian delays. The 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 produced.

RESULTS

Figure 6 presents the results for systems comparison in three cases: (1). "Few" vs. "Under Capacity"; (2). "Few" vs. "Approaching Capacity"; (3). "Few" vs. "Oversaturated". Figure 6(a) shows that for each system, the delay impact on vehicles is strongest in Case (3). At lower vehicular flow levels, the impact is less. This suggests an interesting caveat; there is a nearly *linear* relationship between the AVD and volumes when each system is applied, which is consistent with past operations studies and the intuitive reasoning. At a specific vehicular volume, the delay impact on vehicles is comparatively lowest for the extNEMA.

The APD was defined as the difference between actual travel time and theoretical travel time (at a randomly distributed walking speed around the mean) through the node. Figure 6(b) suggests that, when the conNEMA and the extNEMA are used, the APD tends to increase with the vehicular intensity enhanced from Case (1) to Case (3) and the extNEMA causes less delay to pedestrians than the conNEMA. When the FLC was employed, the APD tends to diminish with vehicular flows being intensified. In Case (3), the FLC poses the least delays to pedestrians compared with others.

Considering the conflicting changes in two single-mode-based MOEs, it should be reasonable to evaluate these systems from a more comprehensive perspective. Therefore, to reflect the emphasis more inclined to the pedestrians, different weights are introduced, based on the relative intensity between pedestrians and vehicles, as follows: Case (1), $\alpha=0.70$; Case (2), $\alpha=0.60$; Case (3), $\alpha=0.50$.

Figure 6(c) shows the WADs for three cases: the extNEMA performs best and the conNEMA worst. For Case (2) and (3), the FLC's performance is close to the extNEMA and obvious better than the conNEMA. For Case (1) in which pedestrians and vehicles are few, the FLC approaches (but still outperforms) the conNEMA and its performance is not much worse than the extNEMA. Considering its intelligent accommodation for dissipating vehicular platoons to avoid rear-ends collisions, the FLC is still advantageous over the conNEMA and competitive enough with the extNEMA in this case.
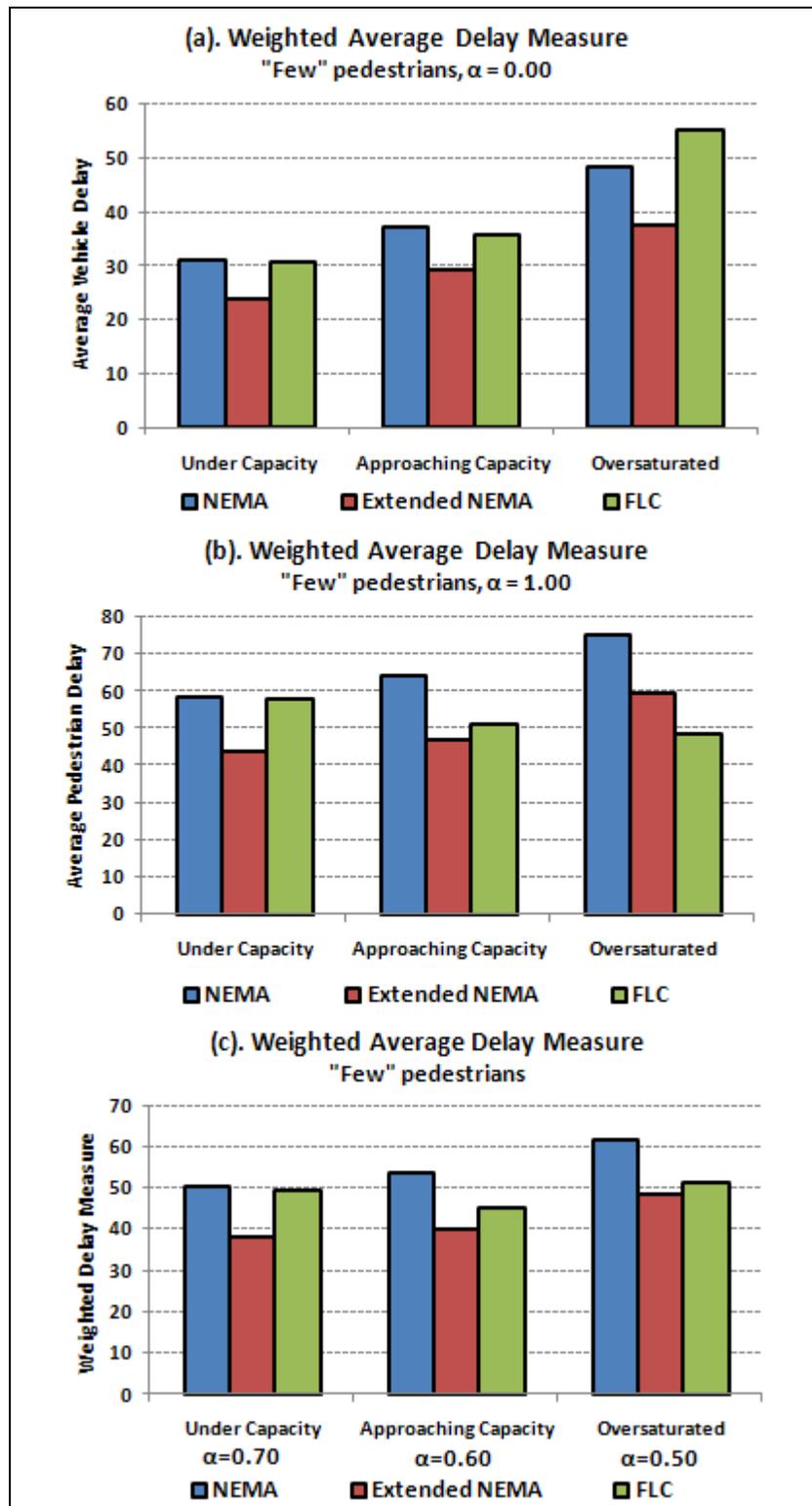
Figure 6 Systems Comparison with "Few" Pedestrian Intensity

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Following the same reporting pattern, Figure 7 shows the results for three other cases: (i). "Many" vs. "Under Capacity"; (ii). "Many" vs. "Approaching Capacity"; (iii). "Many" vs. "Oversaturated". Similarly, some weights are added: Case (i), $\alpha=0.75$; Case (ii), $\alpha=0.65$; Case (iii), $\alpha=0.55$.

First, with the enhanced pedestrian intensity, all MOEs are consistently higher than their counterparts in Figure 6, which suggests the strong impact of pedestrian flows upon the operations. Figure 7(a) paints a very similar picture to Figure 6(a): the AVD in Case (iii) is consistently higher than those in Case (i) and (ii), which shows the influence of vehicle intensities upon the operations. In Figure 7(b), the similar tendency to Figure 6(b) is also clearly observed for the APD when the conNEMA and the extNEMA are used, although a little less sensitive comparatively. However, this tendency is not very clear when the FLC system is used – they remain nearly unchanged no matter what vehicular intensity is. Compared to Figure 6(b), this indicates that with "Many" pedestrians the APD is very insensitive to vehicular intensity changes if the FLC is used.

Figure 7 (c) reveals that in all cases the FLC and the extNEMA much outperform the conNEMA, and they are very close to each other. Compared with Figure 6(c), the improvements created by two new systems are substantial: the more pedestrians, the more pedestrian friendly characteristics the system exhibits.
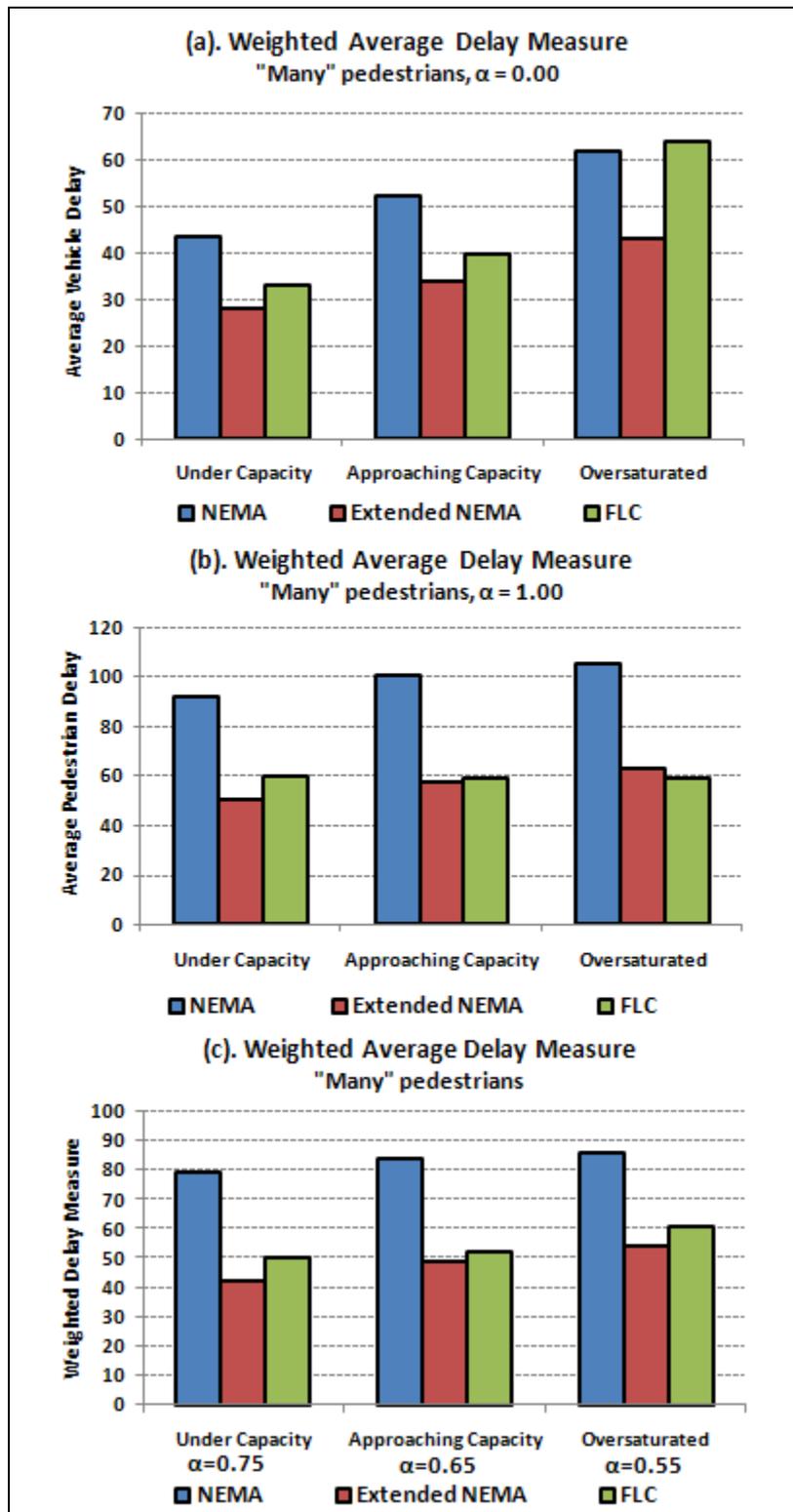
Figure 7 Systems Comparison with "Many" Pedestrian Intensity

CONCLUSIONS

Two new signal systems, the extended NEMA and a FLC system, were developed and evaluated as potential signal systems capable of accommodating dynamic PCIs. A dynamically adjusted real-time PCI timing provided only the crossing time needed by pedestrians during each phase. Their performances were tested against the current NEMA standards, and the results show that for most cases both significantly improves the intersection operations in a comprehensive way - dynamic PCI technology can lead to improved efficiency while improving pedestrian safety.

The FLC provides a compromise between multiple opposing objectives: less delays and more safety to all users. Such a compromise is executed without specific limits explicitly imposed in the rule base. For conventional and extended NEMAs, however, they don't implicitly include safety enhancement elements in their control logic. Due to their rigidness in maintaining specific parameters, both NEMA-based methods lack the flexibility in adjusting timing for delay. Fuzzy control can provide adaptive services for operational improvements, due to the membership functions implicitly encompassing a vast spectrum of possibilities. With FLC, the signal control efficiency is recaptured from operational and safety angles, and all user needs can be satisfied optimally in terms of enhancing pedestrian safety, reducing rear-end collisions, ameliorating operational efficiency, and then lessening social cost from delay and congestion at an intersection.

The primary contribution of this research is a solution to the debate on appropriate walking speed. With dynamic PCIs, a fixed walking speed of 3.5 or 4.0 feet/second is no longer an input variable in calculating PCI times. Walking speeds are evaluated in real-time and the traffic signal operations adjusted accordingly. Given the fact that there are reportedly 325,000 signalized intersections in the U.S. alone, the potential impact of this research is significant from perspectives of both traffic safety and efficiency.

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23

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