Toward Smart Intersections for Urban Travelers on Sustainable Modes: Better Service via Real-Time Sensing

By

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ABSTRACT:

Sustainability has emerged as a social goal for transportation to pursue by making a change, and transportation engineering should be aimed to increase the level of walking and pedalcycling travels to advocate "New Urbanism and Smart Growth". More walkable communities are believed more beneficial to the moving public and the sustainability of multimodal transportation systems. Walking and pedalcycling modes promote healthy living style and possess sustainable advantages over the motorized modes in manifold aspects. Moreover, the increase in walking and pedalcycling travels fosters the ridership level of public transportation systems. Hence, to boost advancements in pedestrian-/pedalcycle-related infrastructure is essential to bettering transportation sustainability in real-world practice.

This research innovatively realized a system prototype which improves non-motorized traveler service at typical urban intersections, in order to resolve the problem that the existing signal timing standard cannot offer friendly accommodation and adequate safety for waiting and crossing pedestrians and/or pedalcyclists. The new system resorts to the real-time sensing concept to smartly adjust signal displays to ensure that waiting pedestrians and/or pedalcyclists are released in a responsive manner and crossing ones are safely protected by signals. In simulation tests, this research quantified the benefits from the new system in comparison with its original counterpart. Simulation experiments unveiled a current pedestrian safety countermeasure in signal timing is operationally deficient for mobility efficiency. In contrast, the new system smartly serves for all non-motorized travelers with friendly accommodation and adequate safety, while maintaining good mobility efficiency for motorized travelers.

Sustainability has emerged as a major social goal for transportation (*1*). To achieve this goal, transportation must change (*2*). A critical objective in transportation engineering studies aimed to advocate "New Urbanism and Smart Growth" is to enhance the level of travels on sustainable modes which mainly include walking and pedalcycling (*3*). It is widely believed more walkable cities will be more beneficial to the wellness of the public and the betterment of multimodal transportation sustainability. Not only do the walking and pedalcycling modes play a significant role in promoting healthy living style but also they provide sustainable alternatives to the motorized travel modes which are notorious for posing negative environmental impacts, producing inefficient energy consumption, and incurring unhealthy societal costs. In addition, the growth in walking and pedalcycling travels will reinforce the urban ridership level of public transportation systems which underlie another sustainable mode choice, because most public transit travels necessitate a short walking or pedalcycling trip at both terminals of an intended route. Hence, to boost technical advancements in improving pedestrian-/pedalcycle-related transportation infrastructure is instrumental for maximizing urban mobility, sustainability, and livability in real-world practice.

Roadway intersection comprises one of the most fundamental elements in urban transportation infrastructure systems which a large number of motorized travelers and non-motorized ones unceasingly make use of every day. In traffic engineering, the intersection control is mostly aimed at realizing twofold objectives: "(a) Ensure safety for all intersection users; (b) Promote efficient movement of all users through the intersection (*4*)". Alternatively speaking, the key considerations in the operation of an isolated intersection are essentially related to user safety, traffic movement, vehicle delay, and facility capacity (*5*). The United States safety data indicate that in 2009 a pedestrian was killed or injured in a traffic accident every 128 or 9 minutes respectively, and one-fifth of the children between the ages of 5 and 9 killed in traffic crashes were pedestrians (*6*). Among pedestrians killed, 25.27 percent of them were sixty years or older. For pedestrians injured, the figure was 11.86 percent. Additionally, 628 pedalcyclists were killed in traffic crashes, which accounted for two percent of all motor vehicle traffic fatalities (*7*). In 2010, seventy-three percent of pedestrian deaths occurred in urban areas, up from 59 percent in 1975 (*8*). The urban intersections pose particular hazards to seniors on foot. In 2010, 37 percent of pedestrian deaths among people 70 and older occurred at intersections, compared with 19 percent for those younger than 60 (*8*). Similar to the rest of the world, the United States is an increasingly aging society. In 2010, almost 40 million people aged 65 and older account for almost 13% of the population in the United States (*9*). There are now more Americans aged 65 and older than at any previous time in history. By 2012, America's 50 and older population will reach 100 million. By 2030 there will be more than 72 million older persons making up 19% of the population (*9*).

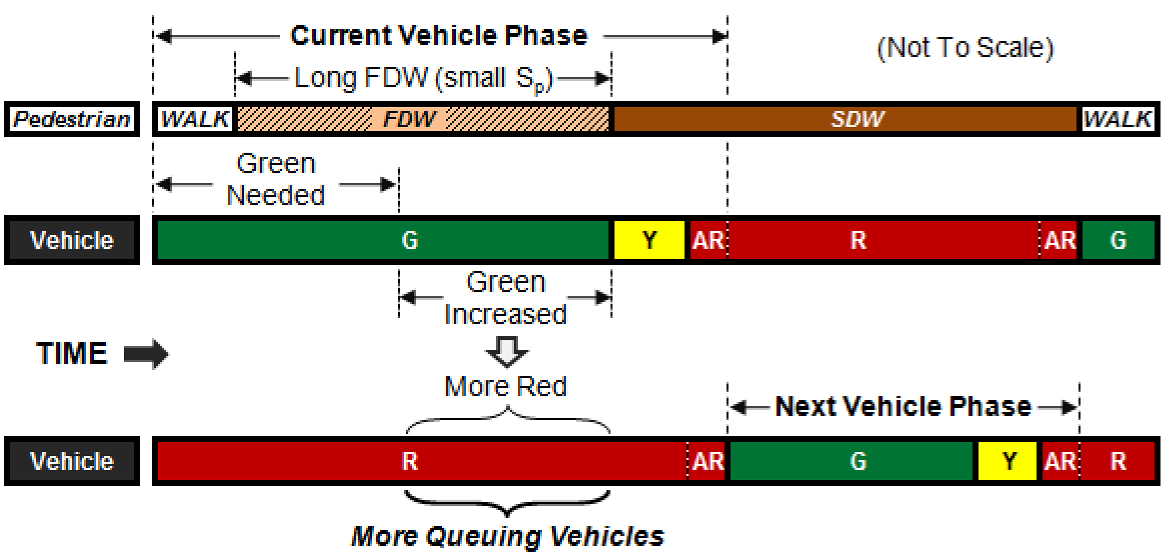
The alarming traveler casualties and irreversible population tendency have urged nationwide cities and municipalities to reinforce their endeavors for rendering walking facilities safer via innovative strategies (*10*). Although past research work has contributed much to more efficient mobility for motorized travelers, the effect of non-motorized travelers upon safety and operations of urban intersections remains inadequately studied and relevant traffic management issues should be well addressed in order to make walking-/pedalcycling-related infrastructure more friendly and safer for increasing, and aging, travelers worldwide on foot or on a pedalcycle.

PROBLEM STATEMENT

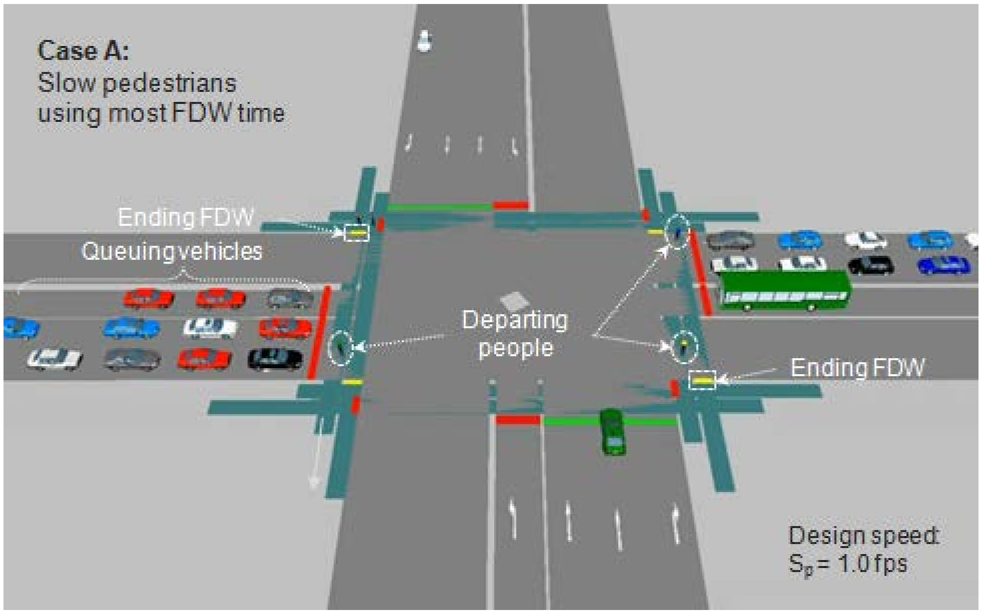
Usually the user population of an urban intersection is composed of both motorized vehicles and travelers on foot and/or on a pedalcycle. The latter, namely pedestrians and/or pedalcyclists, are often served by a traffic signal phase which consists of three intervals specified for distinct functions: (i) the WALK for releasing pedestrians and/or pedalcyclists; (ii) the Flashing DONT WALK (FDW) for clearing crossing pedestrians and/or pedalcyclists; (iii) the Steady DONT WALK (SDW) for prohibiting crossing movements (*11*). For the safety sake, one important timing regulation in the Highway Capacity Manual (HCM) rigorously requires that the parallel vehicle green interval must equal or exceed the WALK plus the FDW in length, and the FDW duration is determined through dividing the street width by a design walking speed (S_p) (*12*). The MUTCD designates 3.5 feet per second (fps) as the S_p for timing the FDW (*11*). However, some historical studies (*13,14,15*) unveiled that the walking speeds of different populations fluctuate between 1.0 and 8.0 fps, and this implies the walking or pedalcycling travelers slower than 3.5 fps are exposed to the tangible hazard posed by the conflicting vehicles which is released by green lights. Therefore, it is precarious indeed to preset a uniform FDW duration for a wheelchair user and a young jogger.

A popular countermeasure is implemented in terms of reducing the S_p to stretch the FDW length. MUTCD's Section 4E.06 prescribes "*Where ... pedestrians who use wheelchairs, routinely use the cross-walk, a walking speed of less than 3.5 fps should be considered ...*(*11*)", but no explicit values are pin-pointed yet. However, this remedy induces a concomitant mobility-related deficiency which is anato-mized in a previous study by Lu et al. (*16*). As Figure 1*a* shows, when the longer FDW exceeds the paral-lel green really needed for efficient vehicular mobility, additional green time derived from this prolonga-tion is operationally surplus. The additional right-of-way for vehicles is offered at the unreasonable sacri-fice of a certain amount of green time which would otherwise be available for next vehicle phase (*16*). As the consequence, longer red lights inflict the *whole* intersection with more queuing delays.

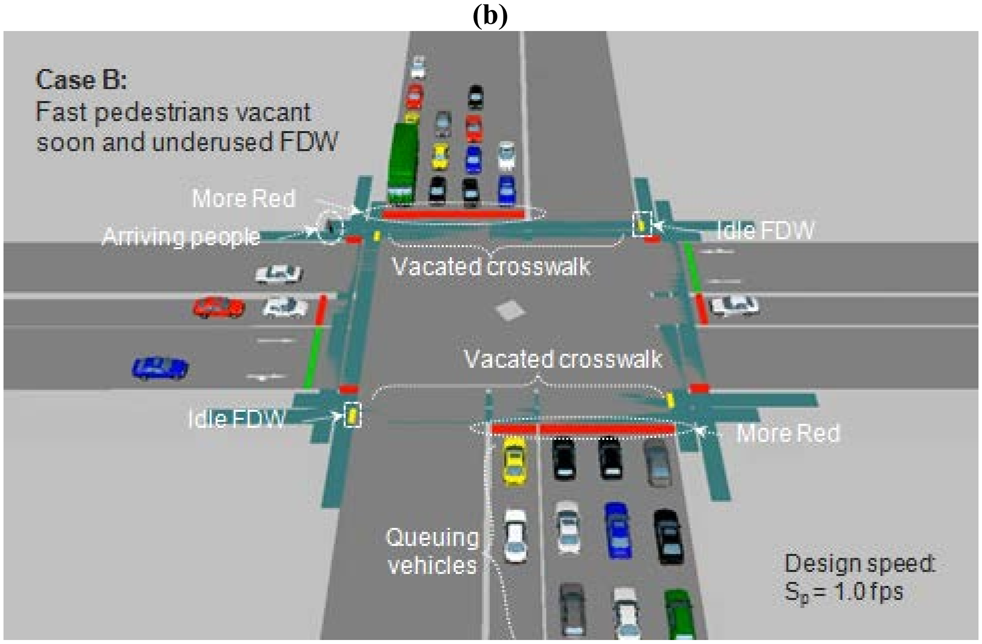
Figure 1*b* and Figure 1*c* exhibit the simulation animations for the queuing vehicles given a small S_p is employed for the safety sake. In one case where pedestrians and/or pedalcyclists are departing as slowly as 1.0 fps, the FDW is terminating soon too. In the other case, however, when the fast pedestrians and/or pedalcyclists entirely vacate the crosswalks soon after the WALK ceases, the FDW rigidly remains in idle state and forces the green to serve for sparsely approaching vehicles; simultaneously, conflicting vehicles are increasingly piling up due to overly prolonged red lights. Therefore, it is expected that inter-section-wide queuing delays will be aggravated to a considerable extent, and it is plausible that the sim-plistic adoption of a small S_p is adequate to better the service for intersection users (*16*). This problem realistically reflects a fact that it is a difficult task to fully achieve the coupled objectives in intersection control since generally safety and mobility efficiency are mutually competing (or even conflicting), in-stead of reinforcing or complementary, issues (*4*).



(a)



(b)



(c)

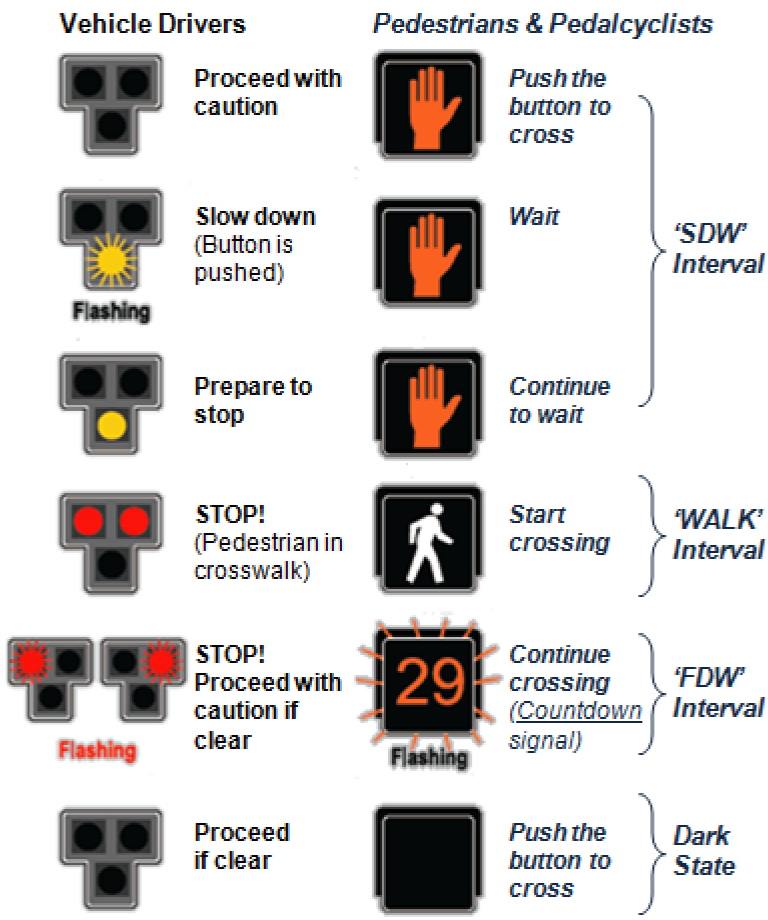
Figure 1 Problem illustration and simulation animations: (*a*) "safety versus efficiency" dilemma in signal phase timing, (*b*) vehicle queuing with slow non-motorized travelers, and (*c*) vehicle queuing with fast non-motorized travelers.

Over past decades, a variety of techniques or devices were developed to assist pedestrians and/or pedalcyclists waiting and crossing at intersections or mid-block crosswalks. One typical example is the countdown timer which has been widely deployed to offer a means for non-motorized travelers to better interpret the signal indications (Figure 2*a,b*). A countdown timer is usually attached to a conventional pedestrian-actuated (PA) signal or a Pedestrian Hybrid Beacon (PHB) signal, which displays either the amount of remaining FDW time or the total crossing time available (in seconds) (*11,17*). The philosophy underpinning this invention is to instantaneously inform travelers on foot or a pedalcycle of how much time is now available for safely getting across a street. However, the foregoing problem still remains unresolved due to the unchanged FDW timing method. Psychologically, the mobility-weakened travelers (e.g., seniors, cane or wheelchair users, etc.) are prone to suffer from an inadequate sense of security when they proceed during the FDW display.

It should be also noted the MUTCD (Section 4E.06) prescribes "*If pedestrian volumes and characteristics do not require a 7-second walk interval, walk intervals as short as 4 seconds may be used*." Otherwise, "*the walk interval should be at least 7 seconds in length so that pedestrians will have adequate opportunity to leave the curb or shoulder before the pedestrian clearance time begins* (*11*)." However, the arrivals of pedestrians characterized by Poisson distributions would make the number of waiting travelers vary phase by phase. Therefore, a static WALK could be frequently insufficient to dissipate all waiting travelers in one phase, thus compromising the quality of service offered by intersections. Similar to the foregoing countermeasure, if a very long WALK interval is predetermined for the sake of discharging waiting travelers as many as possible in a single phase, a certain amount of WALK time will be underused during those phases in which few travelers arrive and wait to cross. In such a case, the squandered WALK time could have been allotted, more reasonably, to the FDW for clearance purpose.

Hence, a smart solution is expected to eradicate the stated problems from technical perspectives of traffic management and control system.

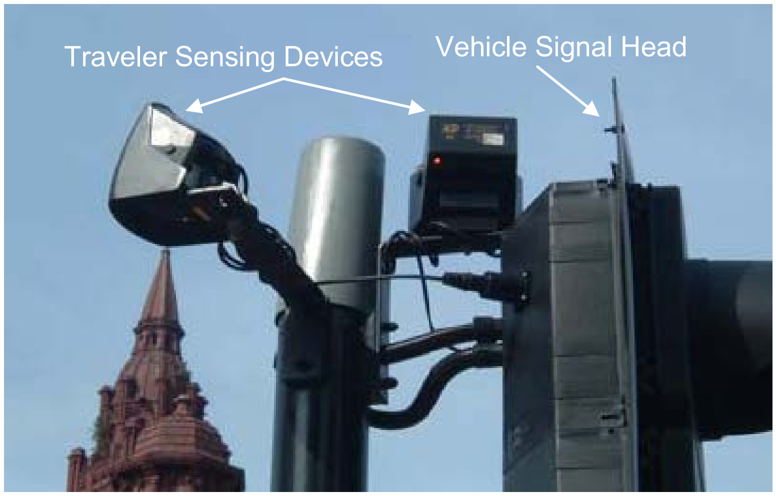
(a)


Vehicle Drivers
Pedestrians & Pedalcyclists
Proceed with caution
Push the button to cross
Slow down (Button is pushed)
Flashing
Wait
'SDW' Interval
Prepare to stop
Continue to wait
STOP! (Pedestrian in crosswalk)
Start crossing
'WALK' Interval
STOP! Proceed with caution if clear
Flashing
29
Flashing
Continue crossing (Countdown signal)
'FDW' Interval
Proceed if clear
Push the button to cross
Dark State

(b)


Combined Pushbutton
Push button
Wait for signal

(c)



(d)

Figure 2 Two pedestrian safety enhancement techniques: (*a*) countdown timer in pedestrian-actuated signal head, (*b*) countdown timer in pedestrian hybrid beacon signal (*11*), (*c*) pedestrian user-friendly interface system's pedestrian demand unit (foreground) and approaching vehicles (background) (*22*), and (*d*) mounted pedestrian and pedalcyclist sensing devices (*22*).

RESEARCH OBJECTIVE

Practically, a problem originates from the technical difficulty in integrating a smart S_p, which is adaptive to ongoing walking speeds, into the FDW timing of an existing traffic signal control system (*16*). Improved traffic management and control systems are widely reported to be cost-effective investments and provide significant benefits in manifold aspects (*23*). Some new technologies provide possibilities for such improvements, including ubiquitous computing and sensing which provides an opportunity for major changes in the efficiency of traffic management (*2*). Automated pedestrian sensors are believed to provide operational and safety benefits if outfitted with pedestrian pushbuttons at actuated traffic signals (*18*). Previous studies have evaluated a spectrum of human-sensing techniques including piezoelectric, ultrasonic, microwave (*18,19*), active- or passive-infrared (*18,19,20*), and video-imaging sensors. Figure 2*c,d* show a typical example, a mid-block signal system, which rely on "smart" sensors to "feel" people waiting to cross, "watch" the crossing activity, and hold the vehicle signals so that people have enough time to cross in safety (*21,22*).

This research is based on the philosophy that the existing sensing technologies can capture pedestrians and/or pedalcyclists to fulfill input data needs in traffic signal control process, then the FDW duration can be implemented in a *dynamic* manner to satisfy instantaneous crossing time demand. In this philosophy, Lu et al. (*16*) invented an artificially intelligent signal system to resolve the stated problem, and it should be imperative to conduct more state-of-the-practice oriented research with regard to bettering the service for urban travelers on foot or on a pedalcycle. Similarly, the WALK can display in a *responsive* fashion by adjusting the start-up time length instantly based on the on-site quantification of waiting travelers. Accordingly, this research extended the functionality of an existing traffic management system to realize a smart service for waiting and crossing pedestrians and/or pedalcyclists. The research quantified the benefits from the new system in comparison with the original counterpart, with the intention of providing the traffic engineering community with a smart system prototype which maximizes intersection safety and friendliness for seniors, the visually impaired or disabled, and children while maintaining adequate traffic mobility and quality of service.

SMART TRAVELER SERVICE

In logic, traffic signal control process is a decision-making mechanism in which green time resource should be apportioned reasonably among conflicting vehicle movements and non-motorized travelers must be accommodated simultaneously in safety. In principle, the signal system determines, at regular time intervals, whether it is the right time to either (a) extend the current vehicle green or (b) terminate it and implement the reasonable changes within the preset phasing scheme. The standard "Dual-Ring 8-Phase" vehicle-actuated signal control system operates in strict compliance with the principle, which is conventionally cited as "NEMA (National Electrical Manufacturers Association) control" (*4*). The NEMA control has been extensively deployed in North America. This research was intended to resolve the stated problems in terms of supplementing the NEMA control with two smart functions.

Standard NEMA System

Figure 3*a* illustrates the phase numbering scheme of the NEMA control: each of odd numbers (1, 3, 5, 7) represents a protected phase which serves for left-turn (LT) vehicles in exclusive LT bays, and each of even numbers (2, 4, 6, 8) denotes a protective phase which serves for a through (TH) movement. This signal control offers the full flexibility in both the phase sequence and the timing of each phase (*4*). Each street may start its green phases in one of three ways, depending upon traffic demand: (a) An exclusive LT phase in both directions if LT demand is present in both directions; (b) A leading green phase (in the appropriate direction) if only one LT demand is present; (c) A combined TH (and right-turn) phase in both directions if LT demand is absent in either direction (*4*). If the first option is selected, the next phase may be a leading green if one direction still has LT demand when the other has none, or a combined TH/RT phase if both LT demands are simultaneously satisfied during the exclusive LT phase. The partial phase boundaries are delineated as four dashed lines in the ring diagram, as their relative position may switch from cycle to cycle depending on which LT demand flow is more intense. If the entire sequence is needed, there are four phase transitions in either ring, making this (as a maximum) a four-phase signal plan (*4*).

In timing logic, minimum and maximum greens delimit the in-between period during which the NEMA control determines the time point to "continue" or "terminate" the current green. Figure 3*b* depicts the logic flowchart. A discrete-time representation of variables with discrete-time index k=0, 1, 2, …, K and the time step Δt is adopted for the sake of explicit formulation and elaboration. The signal control operates by identifying the presence of a specific operational state at a time point ($T_k+\Delta t$) to navigate its logic flow and T_k denotes the amount of time already elapsed before the Δt starts. All specific operational states are defined, in terms of discrete-time variables for green duration and constant timing parameters for limiting green lengths, as follows.

(1). "LT Min-Over" state occurs, when $t_m(T_k+\Delta t)\ge G_m^{Min}$ for LT phase m;

(2). "LT Gap-Out" state occurs, when $h_m(T_k+\Delta t)\ge U_m$ for LT phase m;

(3). "LT Max-Out" state occurs, when $t_m(T_k+\Delta t)\ge G_m^{Max}$ for LT phase m;

(4). "TH Min-Over" state occurs, when $t_n(T_k+\Delta t)\ge G_n^{Min}$ for TH phase n.

(5). "TH Gap-Out" state occurs, when $h_n(T_k+\Delta t)\ge U_n$ for TH phase n.

(6). "TH Max-Out" state occurs, when $t_n(T_k+\Delta t)\ge G_n^{Max}$ for TH phase n.

(7). "FDW Max-Out" state occurs, when $t_n(T_k+\Delta t)\ge W_n+FDW_n^{Max}$ for TH phase n.

Where: $t_m(T_k+\Delta t)$ – Green length displayed for LT phase m at the time point ($T_k+\Delta t$);

$h_m(T_k+\Delta t)$ – Headway detected for LT phase m at the time point ($T_k+\Delta t$);

$t_n(T_k+\Delta t)$ – Green length displayed for TH phase n at the time point ($T_k+\Delta t$);

$h_n(T_k+\Delta t)$ – Headway detected for TH phase n at the time point ($T_k+\Delta t$);

G_m^{Min}, G_m^{Max} – Lower, upper bound of green for LT phase m;

G_n^{Min}, G_n^{Max} – Lower, upper bound of green for TH phase n;

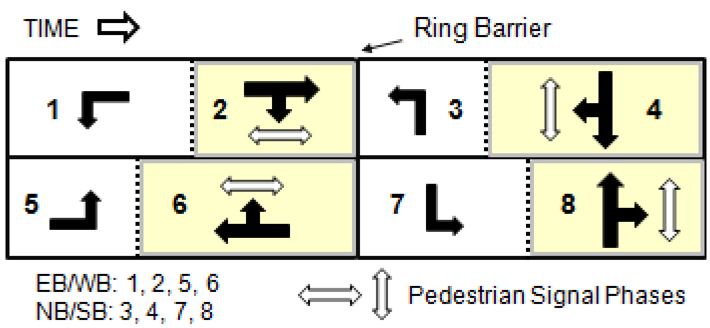
U_m, U_n – unit extension for LT phase m, TH phase n;

W_n – WALK parallel to TH phase n, and $W_n < G_n^{Min}$;

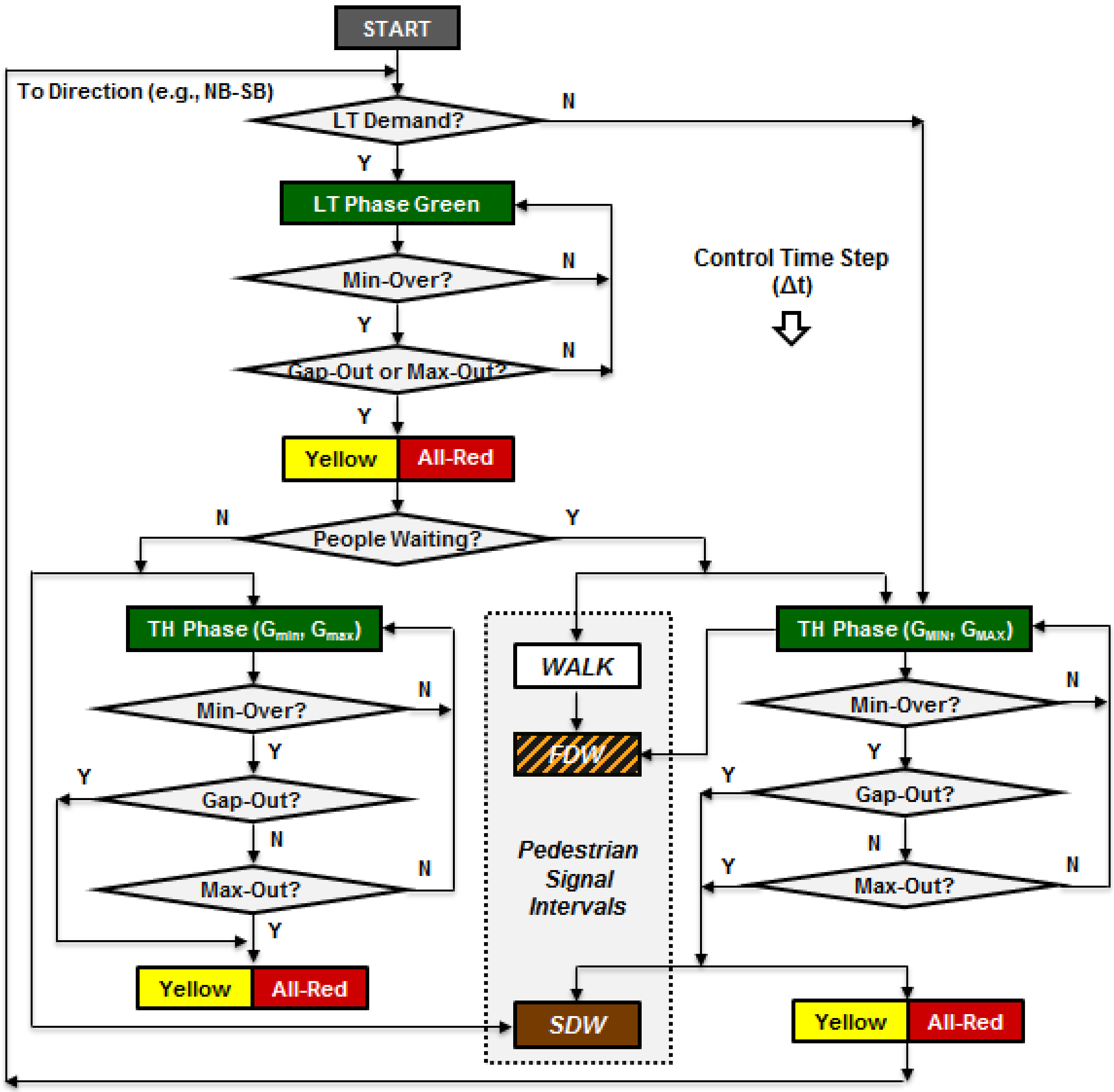
FDW_n^{Max} – upper bound of FDW parallel to TH phase n;

m = 1, 3, 5, 7 (LT phases) and n = 2, 4, 6, 8 (TH phases);
k = 0, 1, 2, …, K; and $T_{k+1}=T_k+\Delta t$, T_K denotes the total time length of control process;
K = an infinite positive integer.

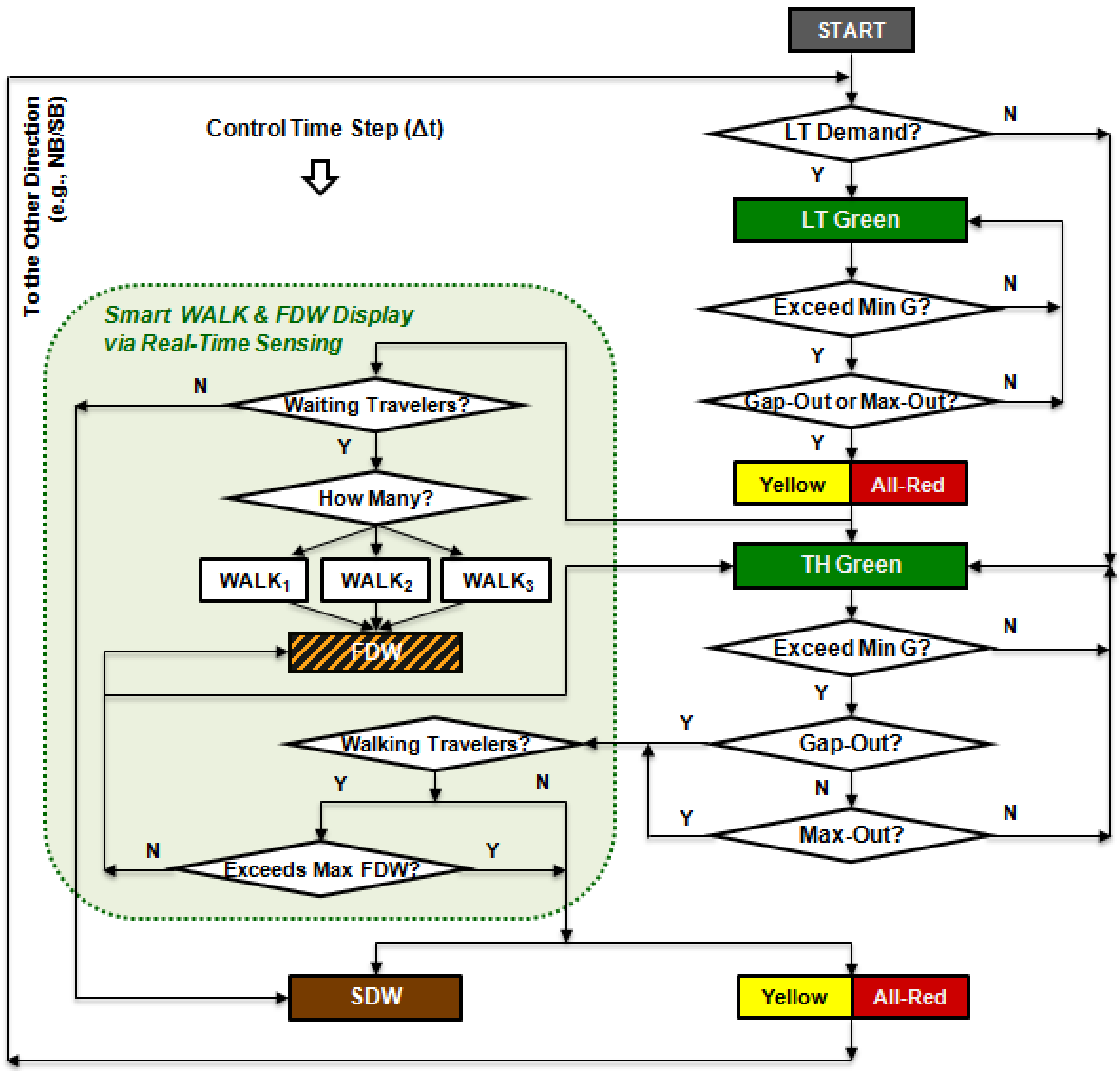
The NEMA control is usually deployed at locations where signalized intersections are relatively isolated from adjacent ones, and it has been proved effective in traffic management. In the existing NEMA control practice, however, the FDW interval is timed by a design speed which is prescribed in the MUTCD (*11*).



(a)


START
To Direction (e.g., NB-SB)
LT Demand?
N
Y
LT Phase Green
Min-Over?
N
Y
Gap-Out or Max-Out?
N
Y
Yellow
All-Red
Control Time Step
(Δt)
N
People Waiting?
Y
TH Phase (Gmin, Gmax)
Min-Over?
N
Y
Y
Gap-Out?
N
N
Max-Out?
Y
Yellow
All-Red
WALK
FDW
Pedestrian
Signal
Intervals
SDW
TH Phase (GMIN, GMAX)
Min-Over?
N
Y
Y
Gap-Out?
N
Y
N
Max-Out?
Yellow
All-Red

(b)



(c)

Figure 3 Two intersection traffic signal systems under study: (*a*) ring diagram of the standard dual-ring 8-phase vehicle-actuated (NEMA) system and (*b*) logic flowchart of the NEMA system, and (*c*) logic flowchart of the S-NEMA system (NB = northbound; SB = southbound; EB = eastbound; WB = westbound; Y = yes; N = no).

Sensing-Based NEMA System

This research innovatively extended the NEMA control to realize *dynamic* FDW and *responsive* WALK. This smart NEMA (S-NEMA) control resembles its original counterpart except for the FDW and WALK timing mechanisms. Figure 3*c* demonstrates the logic flowchart of the S-NEMA system. After a TH phase starts, the S-NEMA system operates in either case: (i) If the crossing demand is absent, it deals merely with motorized vehicles as exactly as how the NEMA system does. (ii) If there are pedestrians and/or pedalcyclists waiting to cross streets, it senses the people on crosswalks after sufficient “Min-Over” and “Gap-Out” (or “Max-Out”) states occur. As to case (ii), firstly the quantitative data of waiting pedestrians and/or pedalcyclists will determine the WALK lengths given to the current pedestrian signal phase.

Therefore, how long the WALK intervals last in each phase depends on how many pedestrians and/or pedalcyclists have been accumulating for the next WALK display.

Later, for the slower pedestrians and/or pedalcyclists on crosswalks, the FDW display is dynamically adjusted to offer the crossing time instantaneously needed (the parallel vehicle green is concurrently turned on). The vehicle green ends when all pedestrians and/or pedalcyclists are clear or when the "FDW Max-Out" state occurs. For fast travelers, their early clearance reduces the FDW duration so that the vehicle green returns to mobility-efficient values, posing no additional delay to conflicting movements. Alternatively, if a young jogger presses the pushbutton, receives the WALK, and jogs across an intersection in 3 or 4 seconds, the FDW terminates timely to avoid potential unreasonable delays to queuing vehicles. Therefore, the S-NEMA system eradicates the problem resulting from static design walking speed: more time is offered for slower pedestrians and/or pedalcyclists; the green is efficiently allocated to vehicular movements once faster travelers are clear. The vehicular mobility efficiency is synthetically balanced with pedestrian and/or pedalcyclist safety needs through a technical innovation in system control logic.

SIMULATION TEST

It is obvious that many real-world limitations make it necessary to exploit an in-lab platform on which the new signal control logic can be implemented as designed and apprised quantifiably. A traffic microsimulation tool, VISSIM, is in prevalent use for transportation research and practice worldwide, thanks to its cost-effectiveness, unobtrusiveness, risk-free nature, and high-speed feature. Especially, VISSIM can model actuated signal control in conjunction with an external signal state generator (SSG). This SSG allows users to define their own signal control logic including any type of special features using a C-like programming language named VAP (vehicle actuated programming)(*24*).

Test Intersection

This research made use of the data from Next Generation Simulation (NGSIM) project sponsored by the Federal Highway Administration (FHWA) and the summary report which contains traffic volumes and signal timing information for a signalized intersection located in Atlanta of Georgia (*25*). The intersection has typical roadway geometrics, which is managed by a standard "dual-ring 8-phase" NEMA control system (*16*). It has four multi-lane inbound approaches each of which receives TH, RT, and LT vehicular movements. A crosswalk is placed downstream each of four STOP lines. In simulation test, the vehicle-actuated loop detector placements comply largely with the common layout in real-world practice.

Test Strategy

It has been found that approximately 15% of pedestrian population walks at a speed less than 3.5 fps (*26*). Therefore, the mean walking speed was conservatively set to 3.0 fps. To reflect previous findings, a researcher-customized speed distribution was modeled with maximum and minimum walking speeds set to 8.0 fps and 1.0 fps (*16*). The new FDW function of the S-NEMA system can offer adequate protection for *all* simulated travelers on foot or on a pedalcycle even they walk at the lowest speed (S_p=1.0 fps). To maintain a *uniform* degree of signal protection in one NEMA-based case, the static FDW was timed by adopting S_p=1.0 fps to guarantee adequate FDW – this uncommon adoption follows the philosophy which the countermeasure aforementioned follows (*16*). A higher S_p=2.0 fps was used to construct another case for more information. Furthermore, the current FDW timing paradigm makes it necessary to examine another common case in which S_p=3.5 fps is employed (*11*). For three NEMA-based cases, the minimum vehicular green G_{min} rises to G_{MIN} which is equal to FDW plus WALK, as long as the pushbutton is activated. The in-between time spacing (G_{max}–G_{min}) determines the new maximum green in terms of G_{MAX}= G_{MIN}+(G_{max}–G_{min}). Therefore, there are four comparison cases: the 1.0-fps NEMA, the 2.0-fps NEMA, the 3.5-fps NEMA, and the S-NEMA.

Study Scenarios

The performances of the NEMA and S-NEMA systems were evaluated in varied operational states. Three pedestrian flow densities were examined: "Sparse", 25 pedestrians per hour per 2-way crosswalk (pphpc) (100 pph per intersection); "Moderate", 75 pphpc (300 pph/intersection); "Intense", 150 pphpc (600 pph/intersection).

Simultaneously, two vehicular volume levels of mixed traffic composition were investigated: Existing Traffic Flows, and High Traffic Flows. The 15-min traffic volumes observed (4:00 to 4:15 p.m.) at the test intersection of the 10th Street NE and the Peachtree Street NE lie in in the common range for urban intersections, which gave rise to the one-hour Existing Traffic Flows condition after linearly augmenting them to be on vehicles per hour (vph) unit. The proportions of trucks and buses in the Existing Traffic Flows are very low (*25*).

To explore the performances of two systems in varied traffic conditions, the Existing Traffic Flows were proportionally increased at a fixed rate (45%) to establish the High Traffic Flows condition which approximates the saturation level. Accordingly, six operational states were established, such as: "Sparse (25 pphpc)" and "Existing Traffic Flows (vph) (EB 736, WB 104, NB 452, SB 636)", "Intense (150 pphpc)" and "High Traffic Flows (vph) (EB 1067, WB 151, NB 655, SB 922)", and so forth.

In the end, six operational states were combined with four comparison cases to yield 24 study scenarios.

Timing Parameters

The signal timing data summarized by the NGSIM project were referenced as closely as possible to set timings for the "Existing Traffic Flows" condition, as shown in Table 1. For the "High Traffic Flows" condition, the NEMA green timings for the "Existing Traffic Flows" condition were proportionally augmented to meet more intensified traffic demands. For the NEAM system, different design speeds yield varied FDW durations. The MUTCD Section 4E.06 prescribes that the WALK interval can be set to from 4.0 seconds until more than 7.0 seconds (*11*). Here, 7.0 seconds is used to time the WALK of the standard NEMA.

The WALK in the S-NEMA control is designed as changeable on three scales in the unit of (non-motorized) travelers per phase (tpp) at each of eight signal heads placed at the simulated intersection. Based on the MUTCD prescriptions and some calculations using relevant HCM equations (*12*), they are $WALK_1$ = 4.0 seconds (1 – 3 tpp), $WALK_2$ = 7.0 seconds (4 – 7 tpp), and $WALK_3$ = 10.0 seconds (equal to or more than 8 tpp).

Table 1 Signal Timing Settings for NEMA and S-NEMA Systems

Signal Timings (s)		Existing Traffic Flows								High Traffic Flows							
		LT Phase				TH (& RT) Phase				LT Phase				TH (& RT) Phase			
		Φ1	Φ3	Φ5	Φ7	Φ2	Φ4	Φ6	Φ8	Φ1	Φ3	Φ5	Φ7	Φ2	Φ4	Φ6	Φ8
Green Interval	G_{min}	5.0	8.0	8.0	5.0	15.0	12.0	15.0	16.0	7.0	11.0	11.0	7.0	20.0	16.0	20.0	21.0
(No people)	G_{max}	10.0	15.0	10.0	15.0	45.0	30.0	45.0	30.0	13.0	20.0	13.0	20.0	60.0	40.0	60.0	40.0
Green Interval	G_{MIN}^{a}	5.0	8.0	8.0	5.0	61.0	74.0	61.0	74.0	7.0	11.0	11.0	7.0	61.0	74.0	61.0	74.0
(With people)	G_{MAX}^{a}	10.0	15.0	10.0	15.0	91.0	92.0	91.0	88.0	13.0	20.0	13.0	20.0	101.0	98.0	101.0	93.0
	G_{MIN}^{b}	5.0	8.0	8.0	5.0	34.0	41.0	34.0	41.0	7.0	11.0	11.0	7.0	34.0	41.0	34.0	41.0
	G_{MAX}^{b}	10.0	15.0	10.0	15.0	64.0	59.0	64.0	55.0	13.0	20.0	13.0	20.0	74.0	65.0	74.0	60.0
	G_{MIN}^{c}	5.0	8.0	8.0	5.0	22.0	26.0	22.0	26.0	7.0	11.0	11.0	7.0	22.0	26.0	22.0	26.0
	G_{MAX}^{c}	10.0	15.0	10.0	15.0	52.0	44.0	52.0	40.0	13.0	20.0	13.0	20.0	62.0	50.0	62.0	45.0
Intergreen	Yellow	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
Interval	All-Red	1.0	1.0	1.0	1.0	2.0	2.0	2.0	2.0	1.0	1.0	1.0	1.0	2.0	2.0	2.0	2.0
Pedestrian	WALK*	—	—	—	—	7.0	7.0	7.0	7.0	—	—	—	—	7.0	7.0	7.0	7.0
Interval	WALK^{1}	—	—	—	—	4.0	4.0	4.0	4.0	—	—	—	—	4.0	4.0	4.0	4.0
	WALK^{2}	—	—	—	—	7.0	7.0	7.0	7.0	—	—	—	—	7.0	7.0	7.0	7.0
	WALK^{3}	—	—	—	—	10.0	10.0	10.0	10.0	—	—	—	—	10.0	10.0	10.0	10.0
	FDW^{a}	—	—	—	—	54.0	67.0	54.0	67.0	—	—	—	—	54.0	67.0	54.0	67.0
	FDW^{b}	—	—	—	—	27.0	34.0	27.0	34.0	—	—	—	—	27.0	34.0	27.0	34.0
	FDW^{c}	—	—	—	—	15.0	19.0	15.0	19.0	—	—	—	—	15.0	19.0	15.0	19.0

NOTE: $^{a, b, c}$ S_p = 1.0, 2.0, 3.5 fps for the FDW timing in the standard NEMA system, * The WALK length used for the standard NEMA system
$^{1, 2, 3}$ Three WALK lengths optional for the S-NEMA system
Φ1 and Φ6 – WB (westbound), Φ3 and Φ8 – NB (northbound), Φ2 and Φ5 – EB (eastbound), Φ4 and Φ7 – SB (southbound)
G_{max} and G_{MAX} – Maximum greens, G_{min} and G_{MIN} – Minimum greens, G_{MIN}=WALK+FDW, $G_{MAX}=G_{MIN}+(G_{max}-G_{min})$, FDW=L/$S_p$, L=Street width,
— = not applicable

Performance Measures

The HCM stipulates the levels of service for multimodal travelers at signalized intersections can be quantitatively assessed by average control delay and average pedestrian delay (*12*). Traffic simulation is also used as a standard approach to resolve operational analysis issues which cannot be adequately addressed by the HCM-based or other analytical procedures (*28*). Keeping track of individual travelers, VISSIM measures average total delay as the difference between the real travel time and the theoretical travel time, and the latter is the time which would be consumed if there were no other vehicles, no signal controls or other stops in the subject network (*24*). Hence, total delay includes HCM-defined control delay and delays resulting from congested, car-following, and other conditions (*29*). The objective of minimizing total delay is to maximize the intersection capacity utilization and reduce the potential accident-incurring conflicts. If the speed of a vehicle is slower than 5.0 km/h and remains under 10 km/h, such a state is defined as "being queued"; average and maximum queues can be recorded in simulation during analysis period. Related to this, number of stops reflects the number of all occasions on which a vehicle enters the "being queued" state (*24*). The magnitude of average number of stops is believed implicitly associated with the propensity for rear-end collisions.

Data Collection

It is common in transportation research to evaluate the intersection performance by averaging multiple simulation replications from varied operational conditions (*27*). Here, 15 replications, each of which has unique random seeds on disparate magnitude levels, were conducted for each study scenarios to lessen the stochastic variations resultant from underlying simulation models. Therefore, there were totally 360 simulation runs each of which lasted 3,600 simulation seconds.

TEST RESULTS

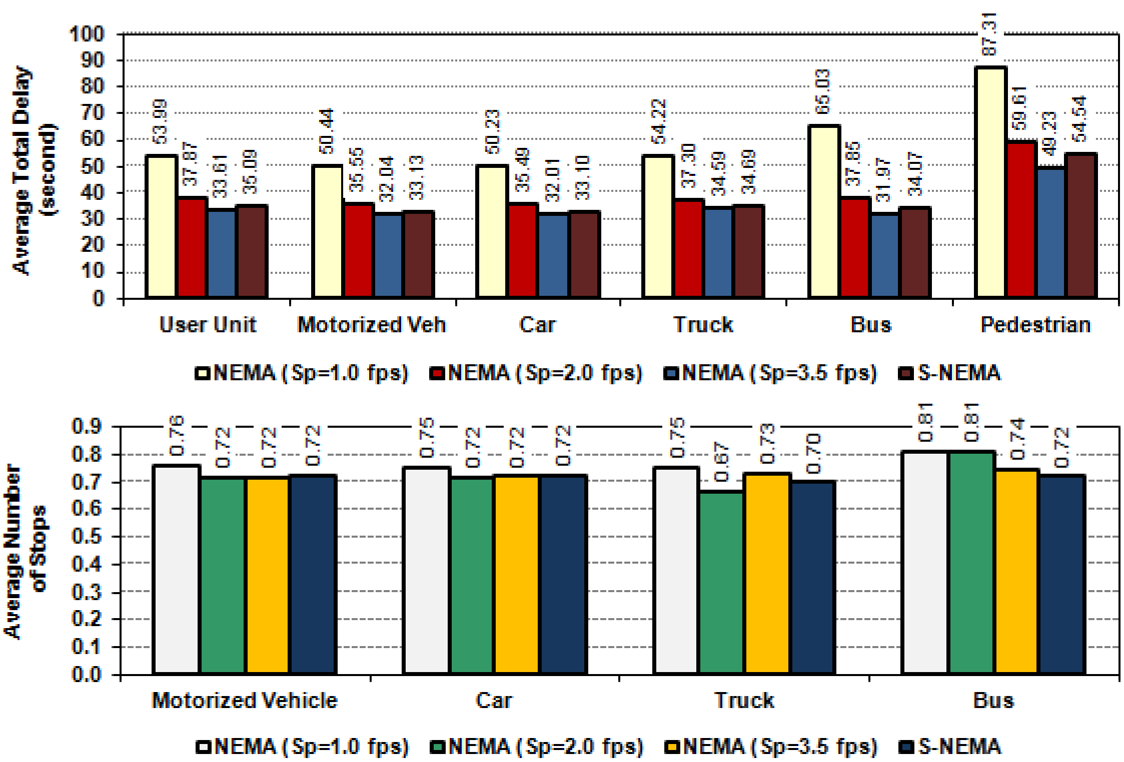
Results for three pedestrian flow levels in the Existing Traffic Flows and High Traffic Flows conditions are shown in Figure 4 and Figure 5, respectively. The results are reported with arithmetic means of 15 replications. The performance measures for a motorized vehicle denote the weighted averages on the basis of cars, trucks, and buses involved in a study scenario, and the proportions of cars relative to trucks and buses are predominantly high (*25*): 98.1% for cars, 1.8% for trucks and buses; the measures for a user unit account for both the motorized intersection users and the pedestrians dominantly representative (in the sense of crossing speed) of the non-motorized intersection users. For three NEMA-based cases, the 1.0-fps one embodies the maximized emphasis on safety for pedestrians and/or pedalcyclists, while the 3.5-fps one reflects the utmost inclination to vehicular mobility efficiency without failing to satisfy basic safety requirements by the MUTCD.

Existing Traffic Flows

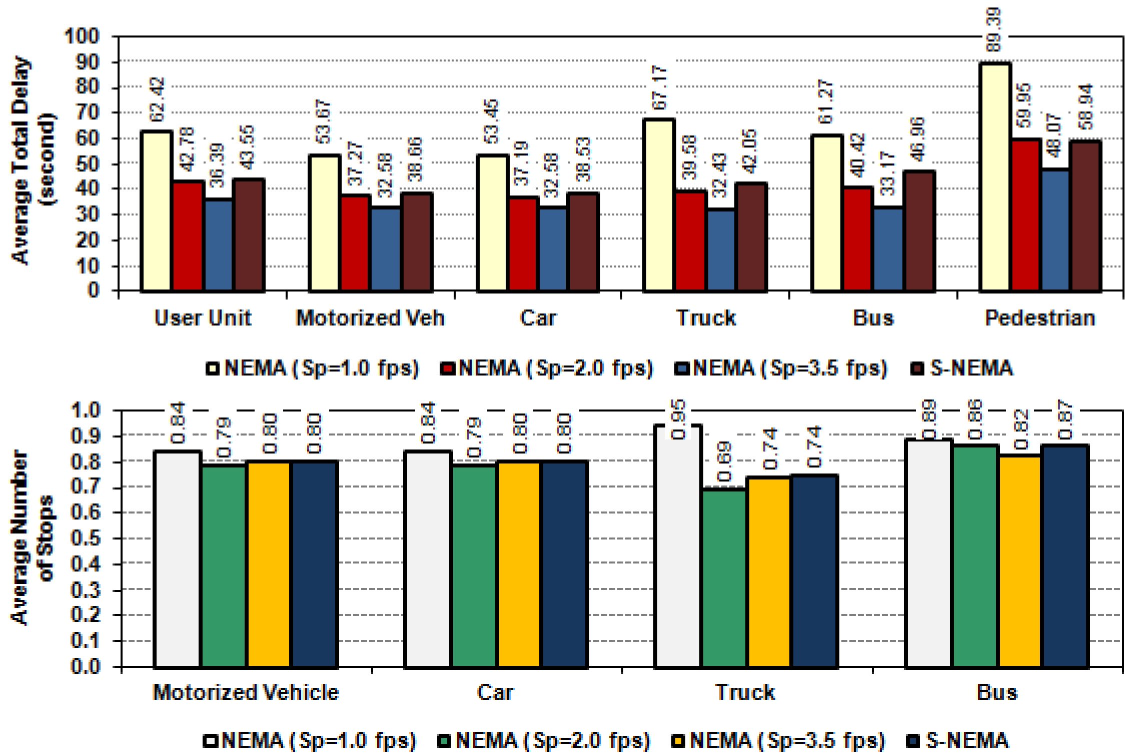
As shown in Figure 4*a,* with sparse pedestrian flows the NEMA 1.0-fps case generates much higher average total delay for each travel mode than does the S-NEMA system. For instance, the S-NEMA system tremendously reduces the average total delay per user unit by 35.01%, from 53.99 s to 35.09 s; per motorized vehicle by 34.32%, from 50.44 s to 33.13 s; and per pedestrian by 37.53%, from 87.31 s to 54.54 s. With the S_p increased from 1.0 fps to 2.0 fps, average total delay is considerably decreased: per user unit by 29.86%, from 53.99 s to 37.87 s; per motorized vehicle by 29.52%, from 50.44 s to 35.55 s; and per pedestrian by 37.53%, from 87.31 s to 54.54 s. This exhibits the significant impact of design walking speeds on the intersection operations. Simultaneously, average total delays generated in the NEMA 3.5-fps case are quantitatively approximate to those in the S-NEMA system. For example, average total delays are 33.61 s and 35.09 s per user unit, 32.04 s and 33.13 s per motorized vehicle, and 49.23 s and 54.54 s per pedestrian for the 3.5-fps case and the S-NEMA system, respectively. Figure 4*a* also demonstrates that in contrast to the NEMA 1.0-fps case, the S-NEMA system obviously decreases the average number of stops for vehicles. For example, it diminishes the average stops per motorized vehicle from

0.76 to 0.72, per truck from 0.75 to 0.70, and per bus from 0.81 to 0.72. In addition, the average number of stops generated in the NEMA 3.5-fps case very closely approximates the counterparts in the S-NEMA case. For example, the average number of stops is 0.72 s per motorized vehicle (or car) for both the 3.5-fps case and the S-NEMA case.

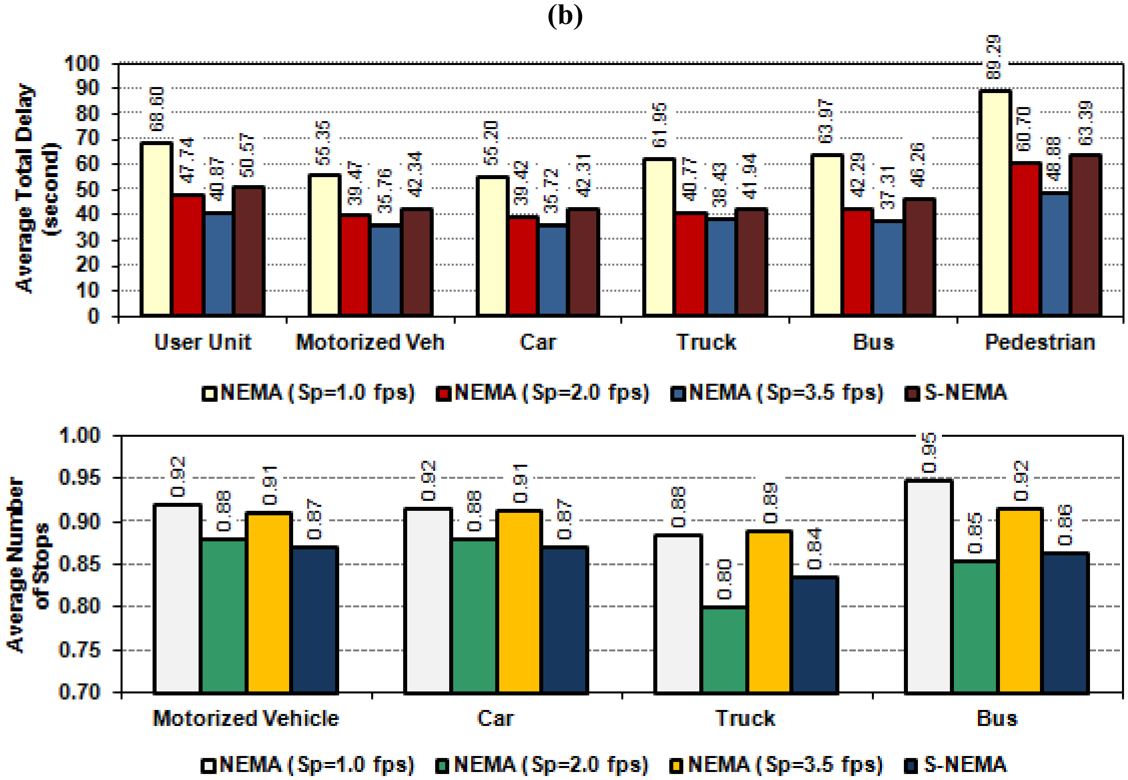
Figure 4*b* shows, with moderate pedestrian density, the performance measures are universally increased, to different extents, from their counterparts in Figure 4*a* and this reveals the operational influence from pedestrian flow volumes. For example, average total delay per car produced in the NEMA 3.5-fps case varies from 32.01 s to 32.58 s, and average stops per bus generated in the S-NEMA case ascends from 0.72 to 0.87. Figure 4*b* shows that, in comparison with the 1.0-fps case, the S-NEMA significantly lessens average total delay per user unit from 62.42 s to 43.55 s, per car from 53.45 s to 38.53 s, per truck from 67.17 s to 42.05 s, per bus from 61.27 s to 46.96 s, and per pedestrian from 89.39 s to 58.94 s. The S-NEMA case also apparently decreases average number of stops per motorized vehicle (or car) from 0.84 to 0.80, per truck from 0.95 to 0.74. Similar to results shown in Figure 4*a,* the performance measures in the S-NEMA case are rather close to those in both 2.0-fps and 3.5-fps cases.



(a)



(b)



(c)

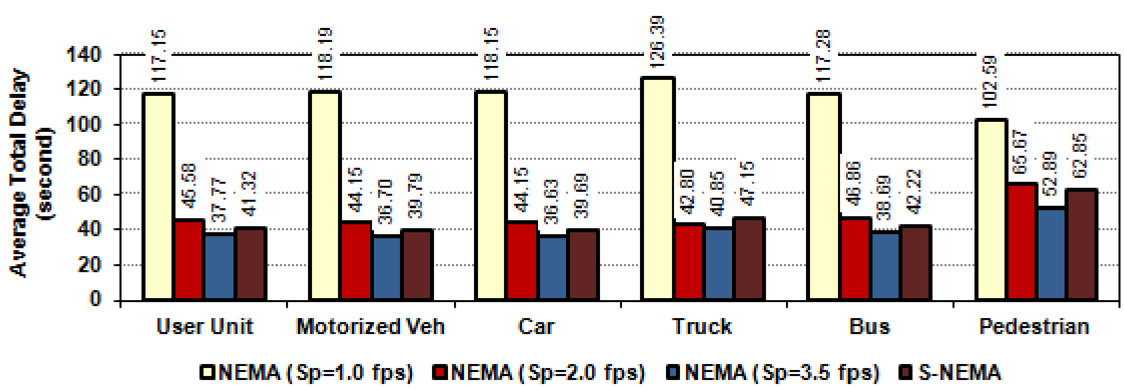
Figure 4 Average total delay and number of stops under existing traffic flows: (*a*) sparse (25 pphpc) pedestrian flow density, (*b*) moderate (75 pphpc) pedestrian flow density and (*c*) intense (150 pphpc) pedestrian flow density.

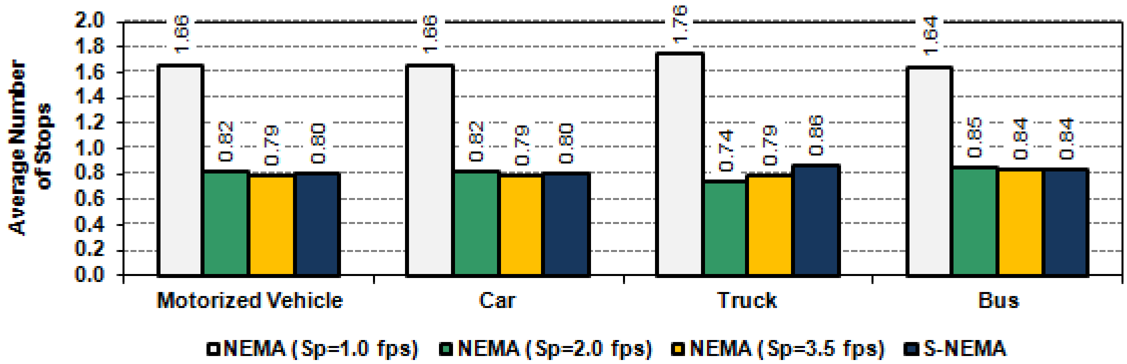
Figure 4*c* indicates, with intense pedestrian flows, the performance measures continue to rise and they exhibit characteristics consistent with their counterparts in Figure 4*a* and Figure 4*b* except for the augmented magnitude. For example, the S-NEMA system is also found to significantly shorten average total delay per user unit and on each travel mode. The relative closeness between the 3.5-fps case and the S-NEMA case still exist.

High Traffic Flows

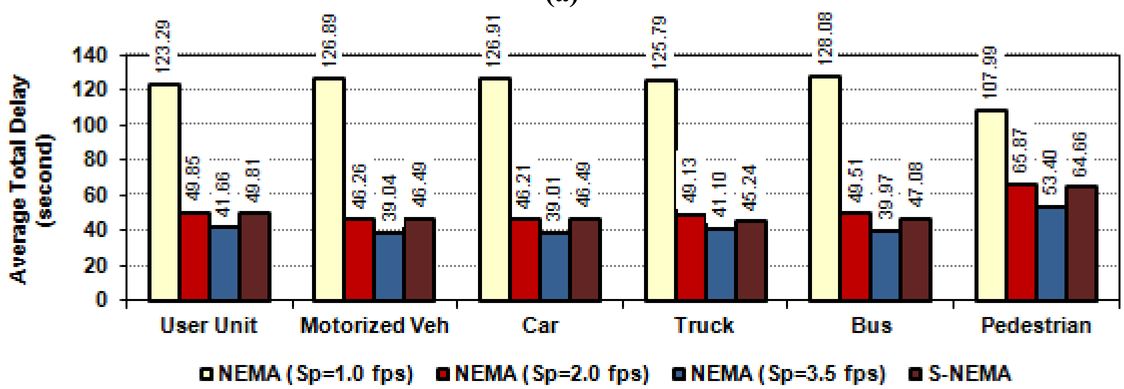
Figure 5*a* shows that, compared with the 1.0-fps case, the S-NEMA system substantially lowers average total delay per user unit from 117.15 s to 41.32 s, per motorized vehicle from 118.19 s to 39.79 s, and per pedestrian from 102.59 s to 62.85 s. For user unit and pedestrian, the average total delay generated in the 3.5-fps case is very close to that in the S-NEMA case; respectively, average total delays are 37.77 s and 41.32 s per user unit, 36.70 s and 39.79 s per motorized vehicle, 102.59 s and 62.85 s per pedestrian for the 3.5-fps case and the S-NEMA system. Note that, when the S_p changes from 1.0 fps to 2.0 fps, average total delay is massively shortened: per user unit by 61.09%, from 117.15 s to 45.58 s; per motorized vehicle by 62.64%, from 118.19 s to 44.15 s; and per pedestrian by 35.99%, from 102.59 s to 65.67 s. Additionally, Figure 5*a* demonstrates that the S-NEMA enormously decreases the average number of stops per motorized vehicle (or per car) from 1.66 to 0.80, per truck from 1.76 to 0.86, per bus from 1.64 to 0.84. For each motorized vehicle (or car), the average number of stops created in the 3.5-fps case almost equals that in the S-NEMA case, which is 0.79 s and 0.80 s, respectively.

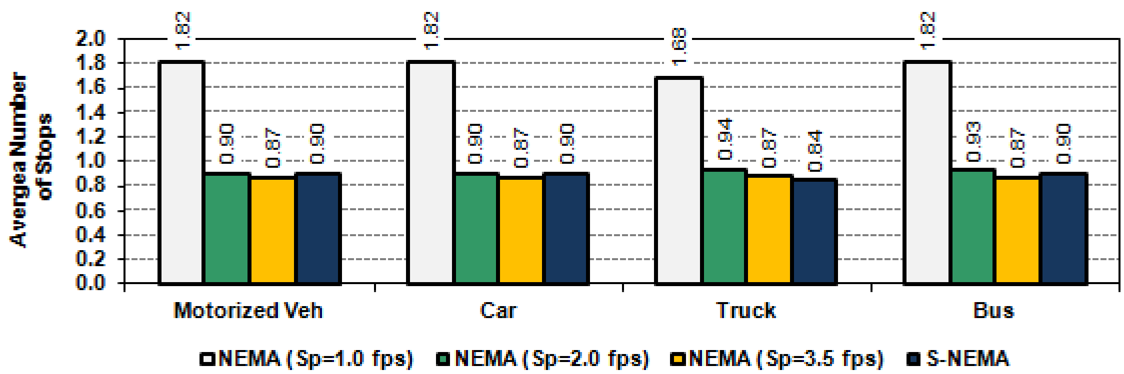
As shown in Figure 5*b,* with moderate pedestrians, all performance measures for each mode are enlarged compared to their counterparts on the sparse level, as shown in Figure 5*a.* For instance, average total delay per car in the 1.0-fps case changes from 118.15 s to 126.91s, and average number of stops per bus by the S-NEMA system rises from 0.84 to 0.90. In contrast with the 1.0-fps case, the S-NEMA system immensely cuts average total delay per user unit from 123.29 s to 49.81 s, per motorized vehicle from 126.89 s to 46.49 s, per pedestrian from 107.99 s to 64.66 s. The differences between average total delays in the 3.5-fps case and the S-NEMA case are relatively inconsiderable: 41.66 s and 49.81 s per user unit, 53.40 s and 64.66 s per pedestrian, respectively. The S-NEMA system substantially alters the average number of stops per motorized vehicle (or car) from 1.82 to 0.90, in comparison with the 1.0-fps case. The difference between average number of stops for the 3.5-fps case and the S-NEMA system are very small for motorized vehicles and cars (0.87 versus 0.90).



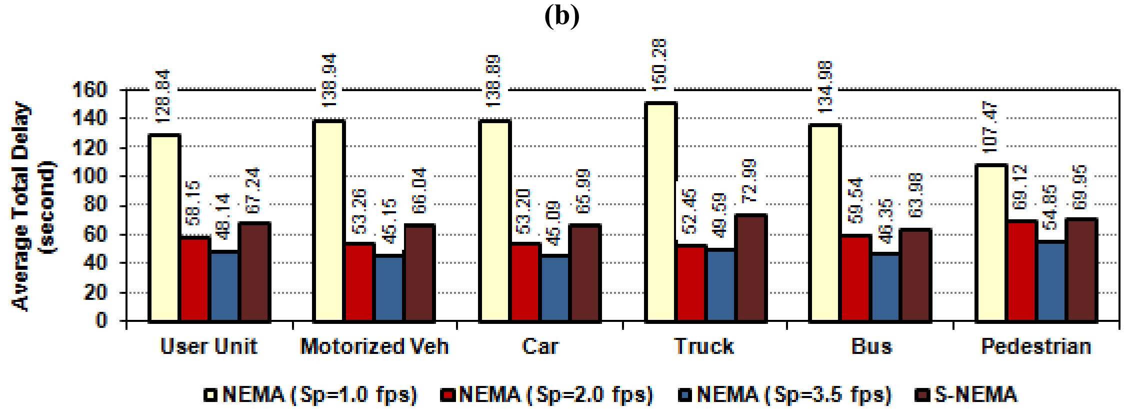

Average Number of Stops
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
1.66
0.82
0.79
0.80
1.66
0.82
0.79
0.80
1.76
0.74
0.79
0.86
1.64
0.85
0.84
0.84
Motorized Vehicle
Car
Truck
Bus
NEMA (Sp=1.0 fps)
NEMA (Sp=2.0 fps)
NEMA (Sp=3.5 fps)
S-NEMA

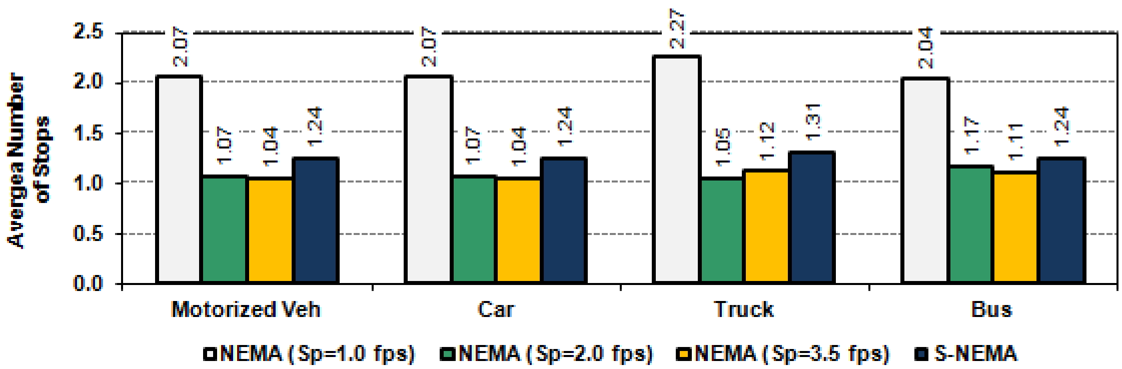
(a)


Average Total Delay (second)
140
120
100
80
60
40
20
0
123.29
49.85
41.66
49.81
126.89
46.26
39.04
46.49
126.91
46.21
39.01
46.49
125.79
49.13
41.10
45.24
128.08
49.51
39.97
47.08
107.99
65.87
53.40
64.66
User Unit
Motorized Veh
Car
Truck
Bus
Pedestrian
NEMA (Sp=1.0 fps)
NEMA (Sp=2.0 fps)
NEMA (Sp=3.5 fps)
S-NEMA


Avergea Number of Stops
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
1.82
0.90
0.87
0.90
1.82
0.90
0.87
0.90
1.68
0.94
0.87
0.84
1.82
0.93
0.87
0.90
Motorized Veh
Car
Truck
Bus
NEMA (Sp=1.0 fps)
NEMA (Sp=2.0 fps)
NEMA (Sp=3.5 fps)
S-NEMA

(b)


Average Total Delay (second)
160
140
120
100
80
60
40
20
0
128.84
58.15
48.14
67.24
138.94
53.26
45.15
66.04
138.89
53.20
45.09
65.99
150.28
52.45
49.59
72.99
134.98
59.54
46.35
63.98
107.47
69.12
54.85
69.95
User Unit
Motorized Veh
Car
Truck
Bus
Pedestrian
NEMA (Sp=1.0 fps)
NEMA (Sp=2.0 fps)
NEMA (Sp=3.5 fps)
S-NEMA



(c)

Figure 5 Average total delay and number of stops under high traffic flows: (*a*) sparse (25 pphpc) pedestrian flow density, (*b*) moderate (75 pphpc) pedestrian flow density and (*c*) intense (150 pphpc) pedestrian flow density.

Figure 5*c* indicates, with intense pedestrian flows, the performance measures continue to rise and they exhibit characteristics generally consistent with their counterparts (Figure 5*a* and *b*). The performance closeness between the 3.5-fps case and the S-NEMA case is found.

CONCLUDING REMARKS

Based on an existing traffic signal system, a smart version was developed for a typical urban intersection where pedestrians and/or pedalcyclists prevail, with an aim to make a fundamental traffic facility safer and friendlier for travelers on sustainable modes. During each signal phase, the responsive WALK and the dynamic FDW offer pedestrians and/or pedalcyclists the startup time and the crossing time in instantaneous needs; mobility efficiency, user safety, and human factors were blended into the vehicle green control.

On microsimulation platform, the performance of the novel system was compared with the standard NEMA signal system which adopted three design walking speeds. The simulation results in NEMA-based 1.0-fps case indicate that, although all pedestrians and/or pedalcyclists are covered by sufficient FDW display, the intersection operation collapses. Therefore, the current countermeasure, which simplistically makes the design walking speed smaller, proved operationally deficient for reaching vehicular mobility efficiency. It was also verified that the change in design walking speed has significant influence on vehicular mobility efficiency. The results from the 3.5-fps case are close to or a little lower than those from the S-NEMA system. However, the 3.5-fps standard cannot offer crossing protection for pedestrians and/or pedalcyclists moving more slowly than 3.5 fps. In contrast, the S-NEMA system guarantees full signal protection and flexible startup time via a real-time sensing mechanism.

The new system disuses a constant walking speed as a signal timing input, closing the controversy on the most appropriate design standard in FDW timing practice. This research first addressed the pressing issue of how to synthesize all intersection users into a systematic framework by means of an innovative traffic management system which smartly serves for non-motorized travelers. With more than 272,000 signalized intersections nationwide (*30*), the prospect of the intellectual merit herein should be promising from perspectives of transportation sustainability, multimodal safety, operational efficiency, and quality of life for the traveling public.

FUTURE DIRECTIONS

To pursue a robust real-world deployment of the signal control logic, modern structure-modeling mechanisms should be utilized to formalize the interactive process among logic design, traffic signal controller software development, and field operations (*31*). A critical step in that process would be to transplant the new logic onto a physical traffic controller and conduct a sufficient number of hardware-in-the-loop simulation tests, in order for more realistically evaluating the system performance (*32,33*). To realize that, potential hardware and software obstacles, expectedly regarding embedded system and controller interface device, would be technically essential to avoid impeding the actual implementation of the traffic management system (*23*). Another major issue for ultimate deployments is relevant to maximizing the efficacy, accuracy, reliability, sensitivity, and robustness of field sensing technologies in a practicable manner. Merely focused on isolated intersections, this research should add impetus to further exploring how such a system plays a role at other fundamental traffic facilities, such as urban T-intersections or highly-railroad crossing, and in an urban multimodal transportation network which countless travelers traverse every day.

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