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Vehicle and Pedestrian Delay Estimation at Unsignalized Crosswalks Considering Adjacent Traffic Signals

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The vehicle arrival pattern at un-signalized crosswalks is affected by the upstream traffic signals in urban areas. The traffic flow splits into platoons and random arrivals downstream of a traffic signal. Moreover, literature suggests that the vehicle platoons do not normally yield to the pedestrians. Vehicle and pedestrian delays act as an important measure of level of service for crosswalks. However, existing delay models do not consider the simultaneous impact of both bunched and random arrivals, and the yielding behavior on vehicle and pedestrian delays. In this study, simulation approach is adopted to assess the impact of both these factors on delays. A sensitivity analysis with respect to vehicle volume, pedestrian volume and yield rate is also presented. Overall, pulsed vehicle arrivals showed less vehicle and pedestrian delays as compared to those occurred due to random arrivals.

Key Words : *pulsed arrival, random arrival, pedestrians, queueing, delays, simulation, yield rate, un-signalized crosswalks, traffic signals, midblock crosswalks, platoons*

1. INTRODUCTION

The portion of the road designated for pedestrians to cross the street is known as crosswalk[1)]. Midblock crossings are the crossing points for pedestrians present at locations other than intersections[2)]. They are usually installed in areas having high pedestrian demand. Based on control strategy, they can be of two types: signalized and unsignalized. In this study, the focus is on unsignalized crosswalks where the interaction between pedestrians and vehicles is not as simple as in the case of signalized crosswalks. The arrival patterns, pedestrian gap acceptance and vehicle yielding behavior describe the interaction between vehicles and pedestrians at unsignalized crosswalks. Vehicular and pedestrian delays act as an important measure of level of service for unsignalized crosswalks. Several models exist that can be used to evaluate delays for uncontrolled randomly distributed vehicular streams subject to certain assumptions. Adams' delay model[3)] was one of the earliest model to tackle this kind of problem by considering a major and a minor stream. Many other models were then proposed to accurately determine the delays.

The midblock crosswalk should generally be located far away from the nearest signalized intersection. High pedestrian demand nevertheless dictates its location. As the road network is denser and many intersections are controlled by traffic signals in urban areas, the vehicle arrival pattern is strongly influenced by the upstream traffic signals. Also it is observed that when vehicles move in platoons, it is very unlikely that they yield to the pedestrians[4)]. Hence, the vehicle arrival pattern and the driver yielding behavior will impact the vehicle and pedestrian delays.

This research is aimed at simulating abovementioned scenario in order to evaluate vehicle and pedestrian delays. Furthermore, reviewing existing relevant vehicle and pedestrian delay models and comparing them with the simulation results.

Section 1 presents the introduction and background. Literature review and the research gap are presented in Section 2. The next section explains the simulation developed to evaluate the delays. Section 4 comprises the simulation output and discussion. Finally, section 5 covers the conclusions.

2. LITERATURE REVIEW

A brief overview and limitations of the earlier pedestrian and vehicle delay models are presented in this section.

(1) Factors Influencing Delays

One of the major factors that influence delays at unsignalized crosswalks is the arrival pattern of the vehicles and pedestrians. Literature indicates that the assumption about the arrival pattern of the vehicles and pedestrians will yield different values of delay. Yielding behavior of the vehicles also affect the delays of both pedestrians and vehicles[5]. Though vehicles are legally required to yield to the pedestrians at unsignalized crosswalks in most part of the world, yet yield rate varies with many factors. Few studies have evaluated yield rates with respect to some of these factors such as crosswalk treatment type and geometric features etc.[6]. Highway Capacity Manual's pedestrian delay model includes the delay reduction occurring due to the yield rate[7]. A vehicle delay model incorporating yield rates shows that vehicle delays increase with increase in yield rate[5]. Gap acceptance behavior of pedestrians is also considered as an important factor in determining delays. It varies with many factors including pedestrian characteristics for example age, gender etc.[8]. However, for the sake of simplicity, pedestrian gap acceptance behavior is considered as homogeneous in most of the existing models in order to keep the critical gap constant. Vehicle queueing may also occur when a vehicle yields to pedestrians. Although there are many factors that can influence delays, the impact of vehicle and pedestrian arrival patterns, yielding behavior and vehicle queueing due to yielding behavior will be mainly discussed in the following sections.

(1) Pedestrian Delay

Average delay for a pedestrian to find an adequate gap in the (negative exponentially distributed) vehicle headways can be evaluated by using Adams' delay model[3].

$$D = {}^{1}\!/_{N} \cdot e^{-Nt} - {}^{1}\!/_{N} - t \qquad (1)$$

Where,
N = traffic volume
t = minimum gap in traffic required for safe pedestrian crossing
D = total delay sustained by all pedestrians

As vehicles maintain a minimum headway when they travel in a single lane, therefore, shifted exponential distribution can also be used to represent vehicle headways. HCM 2010 presents a method to estimate the reduction in pedestrian delays due to the yielding behavior of the vehicles[7].

$$d_p = \sum_{i=1}^{n} h(i-0.5)P(Y_i) + \left(P_d - \sum_{i=1}^{n} P(Y_i)\right) d_{gd} \qquad (2)$$

Where,
d_p = average pedestrian delay (s)
i = crossing event (i=1 to n)
h = average headway for each through lane
$P(Y_i)$ = probability that motorists yield to pedestrian on crossing event I, and
$n = Int(d_{gd}/h)$ = average number of crossing events before an adequate gap is available.

Here the first term represents the average delay occurring due to the yielding behavior of vehicles and the second term represents the expected waiting time to find an adequate gap. As this model is a modification of Adams' delay model, therefore, it will be applicable to the situations where vehicular headways have a negative exponential distribution. The vehicle flow in urban areas comprises bunched and random flow due to the presence of traffic signals. Such scenario violates the basic assumption of Adams' model. Some models consider mixed distributions for vehicle headways i.e. there are some vehicles that exhibit following/tracking behavior while others move freely[9, 10]. But in such models the correlation between headways is ignored, therefore, a more appropriate model considering vehicle bunching caused by traffic signals was proposed by Guo et al.[11].

Pedestrian Delay Model with Pulsed Vehicular Flow

Guo et al. proposed a model which can evaluate pedestrian delays downstream of an intersection, dealing with pulsed arrival patterns[11]. It considers the pedestrians crossing the road section at random points downstream of an intersection. It was inferred based on the field observations that Adams' delay model underestimated the delays by 30% while this model accurately represented the delays to such pedestrians.

Two separate expressions were developed for delays to the pedestrians arriving during the bunch and for those arriving during the random flow period. The overall average delay to a pedestrian downstream of an intersection is given as below;

$$OD = \frac{t_b + \alpha}{c}\left[E(D_b) + \frac{1}{2}\alpha\right] + \frac{t_r}{c}E(D_r) \qquad (3)$$

Where,
OD = overall average delay
t_b = duration of bunched period

t_r = duration of random period
$E(D_b)$ = expected delay to vehicles arriving during bunched period
$E(D_r)$ = expected delay to vehicles arriving during random period
α = critical gap
c = cycle length

As this model does not assume the priority of pedestrians over vehicles, therefore, it does not incorporate the yielding behavior. The application of this model to a crosswalk may not be appropriate owing to the fact that yielding behavior is likely to occur at marked crosswalks. This model is considered as reference pedestrian delay model in this paper against which the simulated pedestrian delays will be compared.

(2) Vehicle Delay

On the one hand the yielding phenomenon impacts pedestrian delays, but on the other hand it also impacts the vehicle delays. Highway Capacity Manual 2010 presents yield rates for different crosswalk treatments. However, it does not provide any methodology to evaluate vehicle delays occurring due to yielding behavior. The literature does not contain much about vehicle delay estimation considering the yielding behavior. However, a recent research tackled this problem and proposed a model to evaluate vehicle delays considering yielding behavior.

Vehicle Delay Model Considering Yielding Behavior

To overcome the limitation of HCM, a model was proposed by Wei et al. which evaluates the delay incurred by the yielding vehicles. The authors provided a model which can be used to compute delays for both conservative and aggressive scenarios considering both yield rate and vehicle queues.

$$d = \frac{q_v t_{qf}\left[t_{qf} + t_m\left(2 - t_m q_v\right)\right] / \left[2\left(1 - t_m q_v\right)\right] + t_{qf}}{q_v\left(t_{qd} + t_{qf}\right) + 1/P_y} \tag{4}$$

Where,
d = expected average vehicular delay
t_{qf} = the length of the queue formation period
t_{qd} = the length of the queue dispersion period
t_m = minimum headway of vehicular flow
q_v = average flow rate
P_y = probability of a yielding event

This model fairly incorporate the yielding behavior of the vehicles in the delay evaluation. However, it assumes that the vehicle headways have a negative exponential distribution which renders it inapplicable to the flow consisting of bunches and free vehicles. Therefore, this model cannot be directly applied to the crosswalk located near an intersection. Hence, the impact of the adjacent traffic signal along with yielding behavior should be taken into account.

(3) Assumptions of Existing Delay Models and the Simulation

This section summarizes the assumptions of the existing vehicle and pedestrian delay models. **Table 1** summarizes the major assumptions of Adams' delay model[3], HCM 2010 pedestrian delay model[7] that includes yielding behavior, vehicle delay model[5] that incorporates the yielding behavior and the pedestrian delay model[11] that includes the impact of upstream traffic signal.

All the existing models, whether pedestrian delay model or vehicle delay model, are based on certain assumptions. They do not include all the necessary factors such as arrival pattern and yielding rate simultaneously.

Simulation approach is used in this paper for delay evaluation. The details of the model are explained in the next section.

3. SIMULATION

Pedestrian and vehicle interaction at unsignalized crosswalks is a complex process. It involves arrival flow patterns of both vehicles and pedestrians, probabilistic yielding behavior and the critical gaps. To deal with all these factors analytically is a quite complicated task. Therefore, it was considered adequate to utilize existing simulation packages for modelling pedestrian and vehicle delays at unsignalized crosswalks considering pulsed vehicle flow as well as yielding behavior. PTV VISSIM[12], a micro-simulation package, was used for this purpose. Pulsed vehicular flow was generated by installing signalized intersection upstream of an unsignalized crosswalk. However, it was later realized that it does not offer much flexibility in terms of defining varying yielding behavior of vehicles. Whereas it has been confirmed empirically that vehicles' yielding behavior vary under different situations. Therefore, it was decided to write down a program by ourselves and run a point queue based simulation for the desired scenarios.

(1) Description

Suppose a stream of vehicles is released from a signalized intersection as soon as the signal indication turns green. Once all the upstream queued vehicles depart as a platoon, rest of the vehicles will arrive as a random process during the leftover green

Table 1 Assumptions of Vehicle and Pedestrian Delay Models

Assumption	Adams' Model[3]	HCM Ped Delay Model[7]	Vehicle Model with Yielding Behaviorl[5]	Reference Pedestrian Model[11]	Simulation
Vehicle Arrivals	Random	Random	Random	Pulsed + Random	Pulsed + Random
Pedestrian Arrivals	N.A.	N.A.	Random	Uniform	Random
Pedestrians Homogeneous & Consistent	✓	✓	✓	✓	✓
Constant Critical Gap for both Pedestrians and Vehicles	✓	✓	✓	✓	✓
Vehicle Yielding Behavior	✓	✓	✓	✘	✓
Vehicles Arriving at Crosswalk with Minimum Headway Don't Yield	N.A.	N.A.	✘	✓	✓
Vehicle Queue Formation During Yielding	✘	✘	✓	✘	✓
Vehicles Don't Yield During Queue Dispersion	N.A.	N.A.	✓	N.A.	✓
Vehicle Arrival During Red Interval	N.A.	N.A.	N.A.	✓	✘
Vehicle Platoons Dispersion	N.A.	N.A.	N.A.	✓	✘
Consideration of Pedestrian Incremental Delay to Next Cycle	N.A.	N.A.	N.A.	✘	✓

period. It is assumed that there are no turning movements at upstream intersection and thus no vehicles during the red interval. Such vehicle flow consists of bunches and randomly flowing vehicles. These vehicles when arrive at a crosswalk located downstream of an intersection, exhibit different yielding behavior based on their arrival pattern. The vehicles moving in platoons do not normally yield to the pedestrians. Therefore, the bunched flow duration is considered as a block period for pedestrians where they cannot cross. They will look for safe gaps in the random flow period where there is also a possibility of vehicles yielding to the pedestrians. When a randomly arriving vehicle yields to a pedestrian, a queue may start to form until the yielding vehicle finds a suitable gap in the pedestrian stream. Upon finding a suitable gap, the yielding vehicle crosses the road and so do the vehicles queueing behind the yielding vehicle. As these vehicles are departing as a platoon at saturation flow rate, therefore, it is assumed that they do not yield to the pedestrians. **Table 1** summarizes the major assumptions of the simulation. **Fig.1** illustrates the simulation scenario.

Each simulation was run for 3600 seconds and the simulation resolution was set as 1 second. Each average delay value was obtained by taking an average of ten simulation runs.The results obtained are presented in the next section followed by discussion.

4. RESULTS AND DISCUSSION

(1) Comparison with Pedestrian Reference Model[11]

Initially, data set 3 in the reference paper[11] was input in the simulation program to compare simulated delays with those observed in the field and those obtained from reference model. The pedestrian

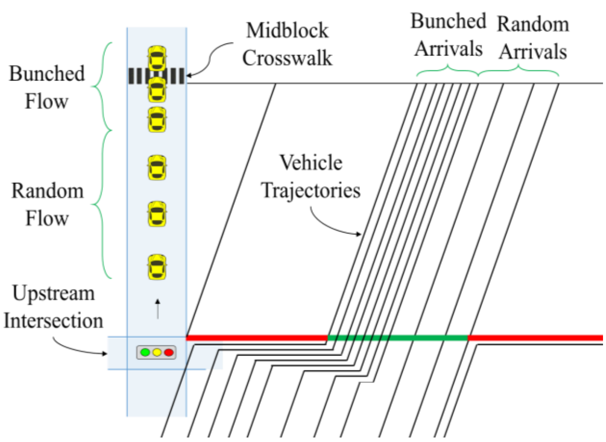

Fig.1 Illustration of Simulation Scenario

delay thus obtained from simulation is shown in **Fig.2** along with delays obtained from analytical model and observed in the field.

The simulation slightly overestimated the pedestrian delays. This is due to the fact that the reference model does not consider the queues of the vehicles formed due to yielding behavior. Whereas the simulation was based on the assumption that when queuing vehicles depart they do not yield to the pedestrians. This assumption might have led to slightly higher delay values. Secondly, the reference model takes bunch size as an input, whereas, bunches were created automatically by upstream signal settings in the simulation. It was assumed that platoon dispersion does not occur, while it might have occurred in case of the dataset 3 in reference paper. Which may have increased the number of randomly arriving vehicles and thus the possibility for the pedestrians to find a safe gap or a yielding event.

Further, simulations were carried out for vehicle yield rates of 0.4 and 0.8 to see its impact on the pedestrian delays. The results of the simulations are presented in **Fig.3.** The yield rates showed very slight decrease in delays. This may be due to the fact that conditions at the upstream signal were almost saturated. Therefore, most of the vehicles will be arriving as a part of bunch leaving less vehicles that arrive randomly. As bunched vehicles do not yield to the vehicles and there are very less random vehicles, therefore, yield rates had a very small role to play in this case.

(2) Simulation with Random Arrivals

Simulations were carried out for random and pulsed vehicle arrivals under the assumptions mentioned in **Table 1**. The simulation parameters are shown in **Table 2**. Initially, the vehicle arrival pattern at midblock crosswalk was assumed as random (Poisson distribution).

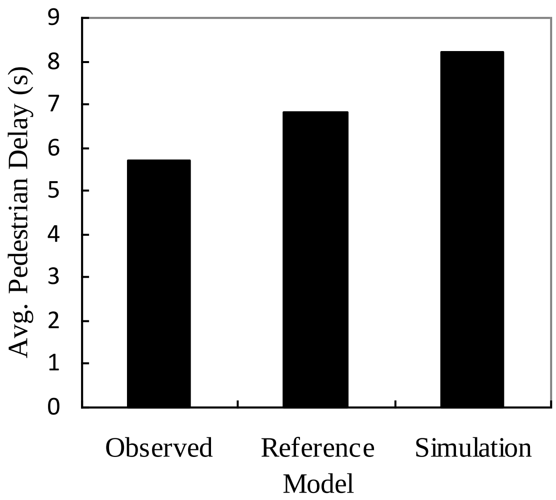

Fig.2 Avg. Pedestrian Delays Obtained from Field Obersvations, Reference Model and Simulation

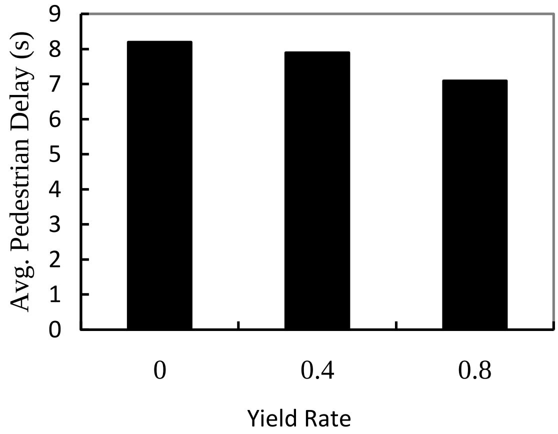

Fig.3 Avg. Pedestrian Delays Obtained from Simulation by Varying Yield Rates

The cumulative curves for one simulation run for vehicles and pedestrians are plotted in **Fig.4** and **Fig.5** respectively. At 600 seconds (the section mentioned with dashed line in **Fig.4**), queued vehicles start to depart at saturation flow rate and they do not yield to pedestrians. The dashed line in cumulative curve for pedestrians (**Fig.5**) at the same time i.e. 600 seconds shows that when vehicle queue was departing at saturation flow rate, the pedestrians could not cross and they finally crossed after the vehicle queue dispersed and they found a gap in subsequent random flow.

Table 2 Parameters of Simulation

Parameter	**Value**	**Unit**
Vehicle Volume	600 to 1200	Veh/hr
Pedestrian Volume	300 to 900	Ped/hr
Min. Vehicle Headway	2	s
Saturation Flow Rate	1800	Veh/hr
Yield Rate	0.4 & 0.8	
Critical Gap	6	s
Pedestrian End Clearance Time	3	s
Cycle Length (for Pulsed Arrivals Case)	100	s
Green Interval (for Pulsed Arrival Case)	50	s

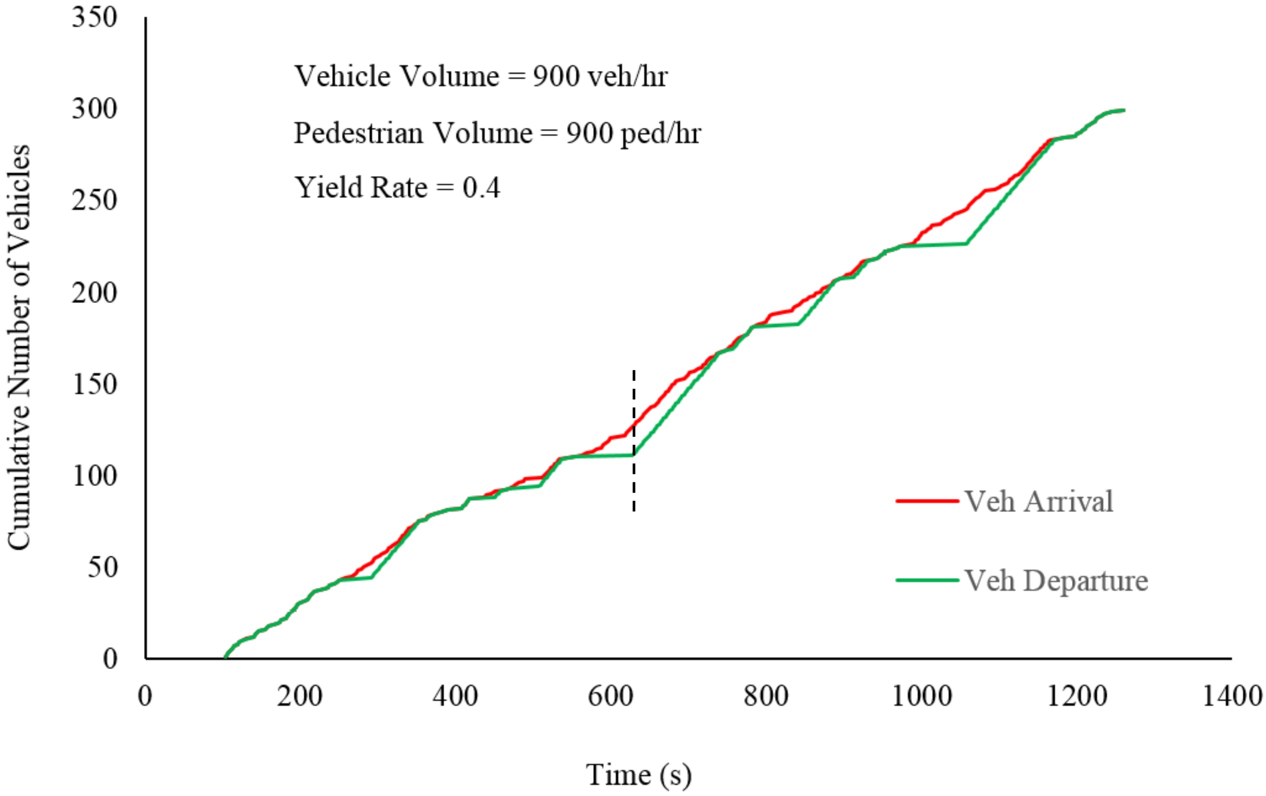

Fig.4 Cumulative Curve for Vehicles (Under Random Vehicle Arrivals Assumption)

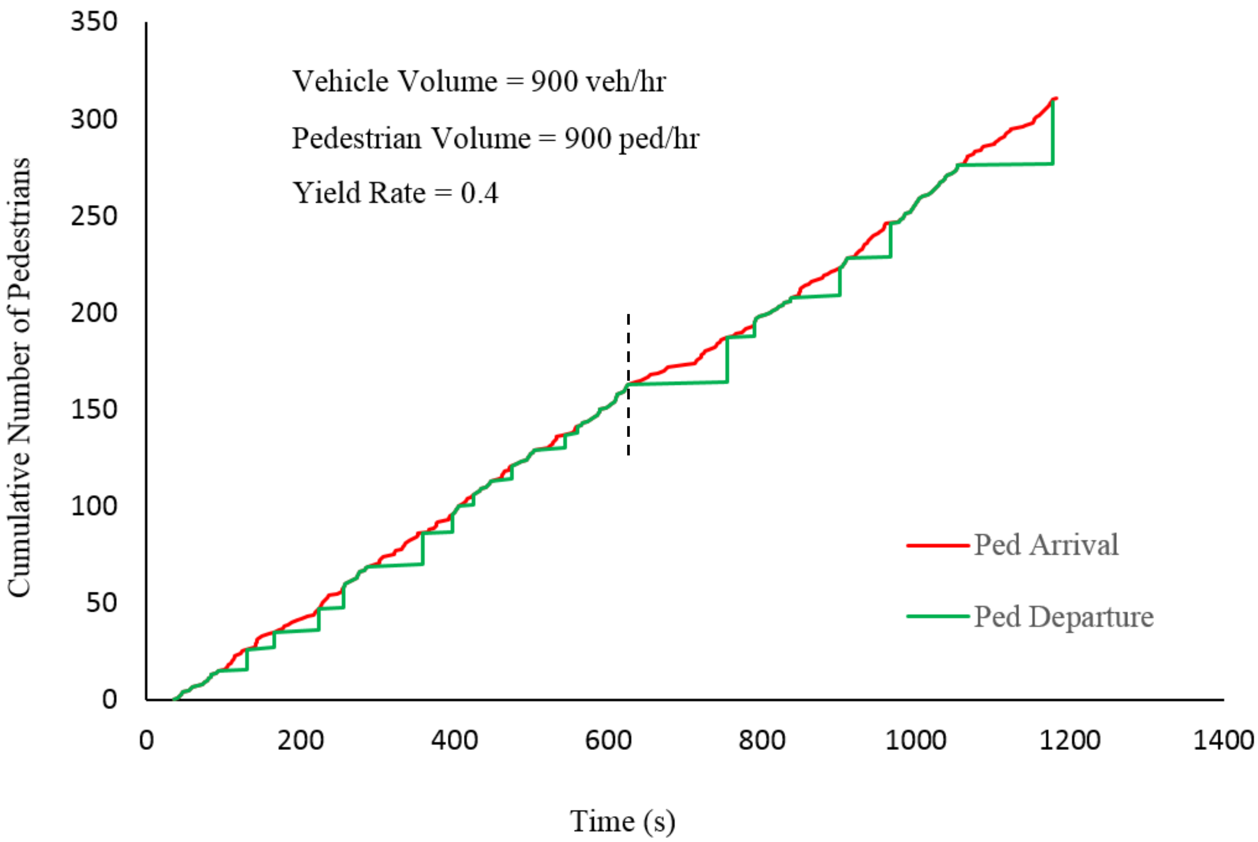

Fig.5 Cumulative Curve for Pedestrians (Under Random Vehicle Arrivals Assumption)

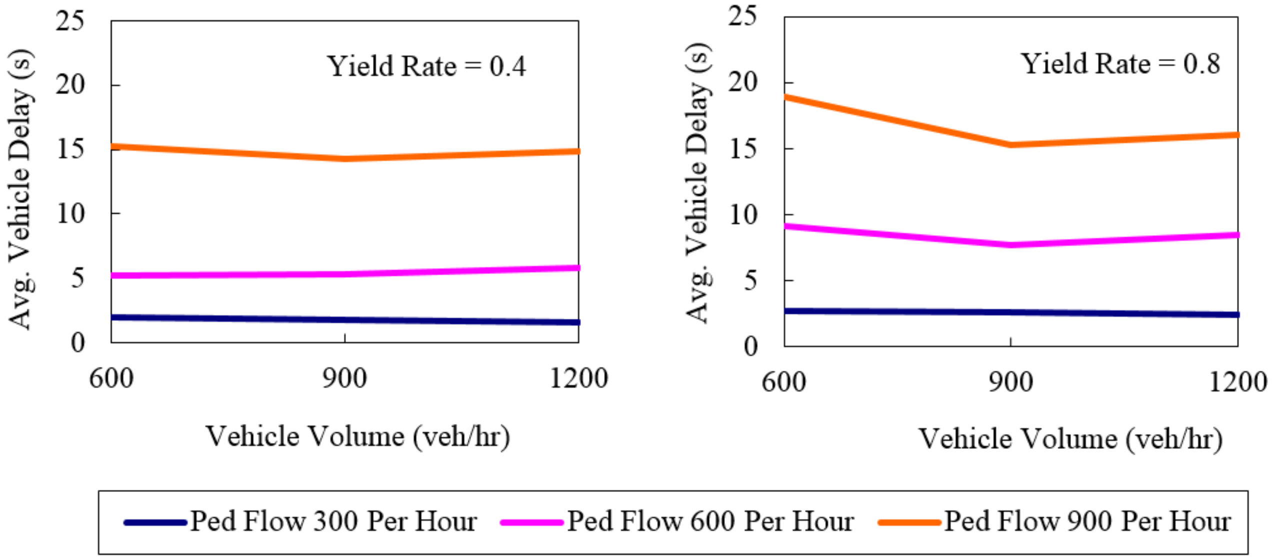

Fig.6 Average Vehicle Delays with Different Vehicle and Pedestrian Volumes for Yield Rates of 0.4 and 0.8 (Under Random Vehicle Arrivals Assumption)

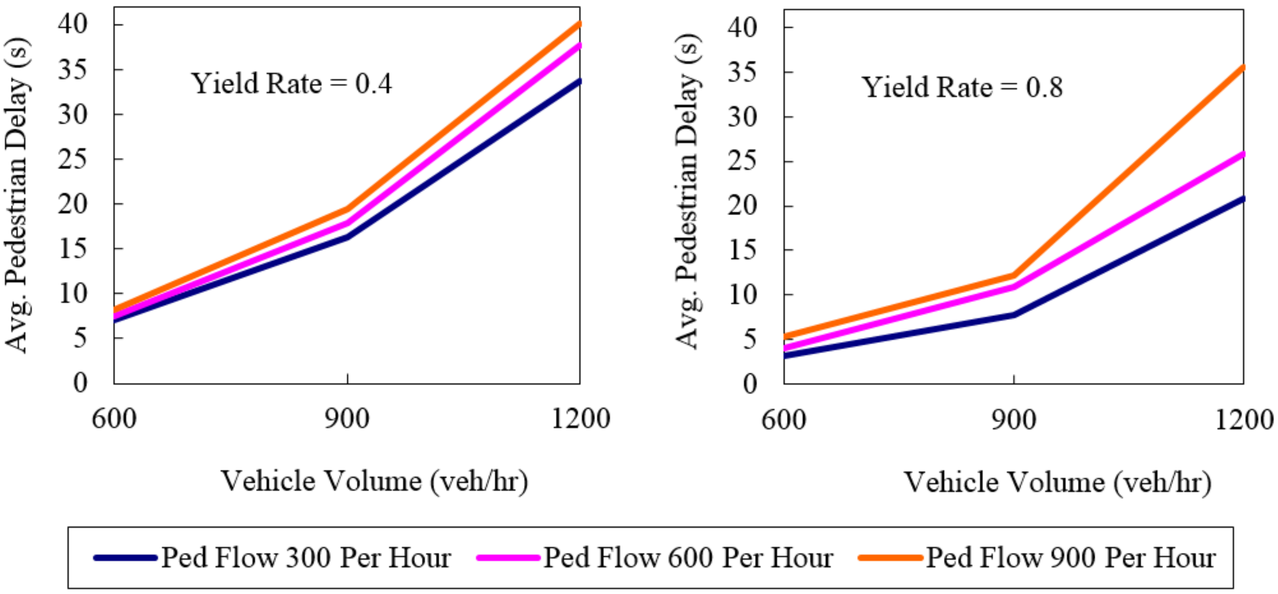

Fig.7 Average Pedestrian Delays with Different Vehicle and Pedestrian Volumes for Yield Rates of 0.4 and 0.8 (Under Random Vehicle Arrivals Assumption)

Further, it can be seen from the vehicle cumulative curve in **Fig.4** that when a vehicle yields to a pedestrian, it waits until a suitable gap occurs in the pedestrian stream. During this period a vehicle queue is formed which departs at the saturation flow rate and it does not yield to the pedestrians. On the other hand, the pedestrian cumulative curve in **Fig.5** shows that the pedestrians, upon finding a suitable gap or a yielding event, depart instantaneously. Because minimum headway for pedestrians was kept zero based on the assumption that pedestrians have enough space that they can cross side by side simultaneously. The vehicle delays were obtained from cumulative curves and are shown in **Fig.6** for yield rates of 0.4 and 0.8, respectively. Similarly, pedestrian delays are shown in **Fig.9.**

Fig.6 shows average vehicle delays under the assumption of random vehicle arrivals at the midblock crosswalk. It indicates that increase in pedestrian volume increases the vehicle delays which is quite expected. If pedestrian volume is high then there will be more chances that a vehicle may encounter a pedestrian. And it may yield to that pedestrian. Once a vehicle yields to pedestrians under high pedestrian

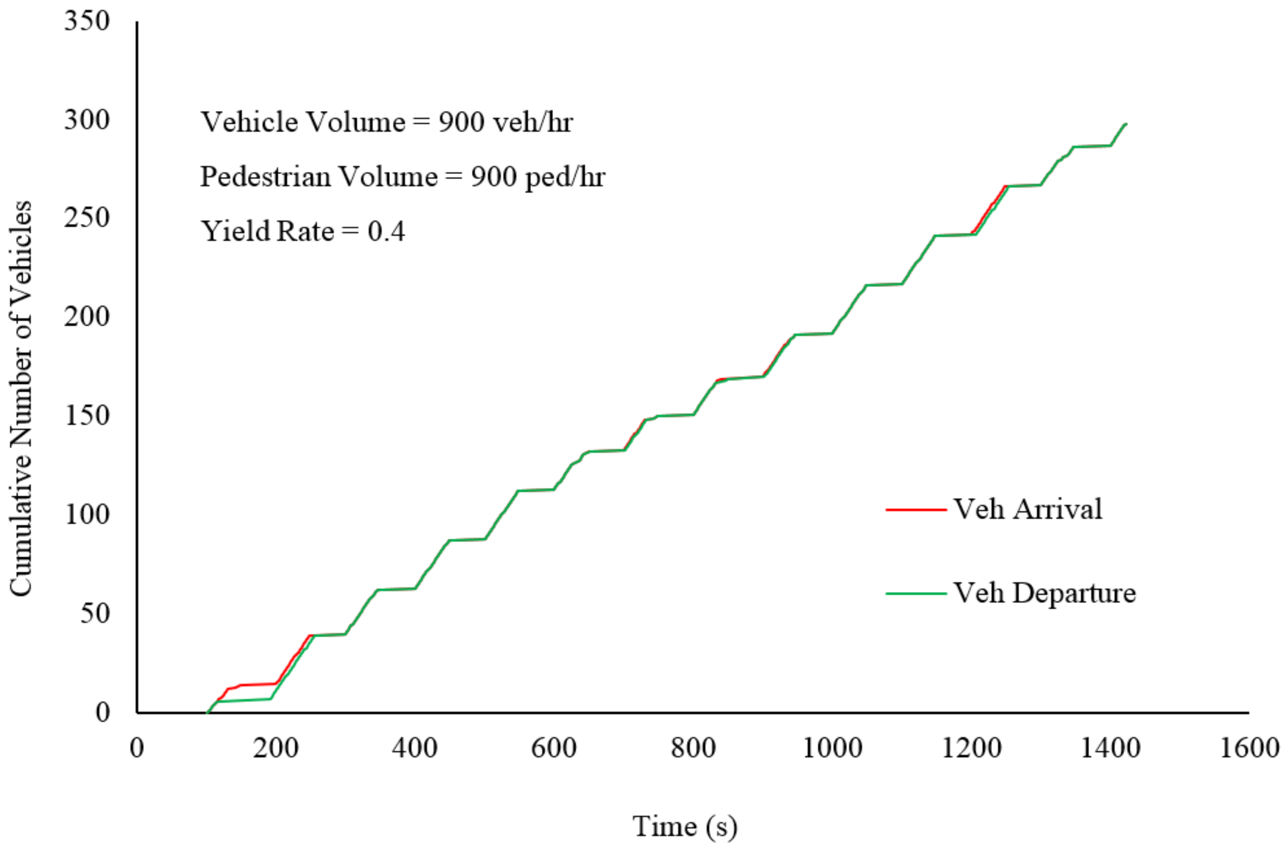

Fig.8 Cumulative Curve for Vehicles (Under Pulsed Vehicle Arrivals Assumption)

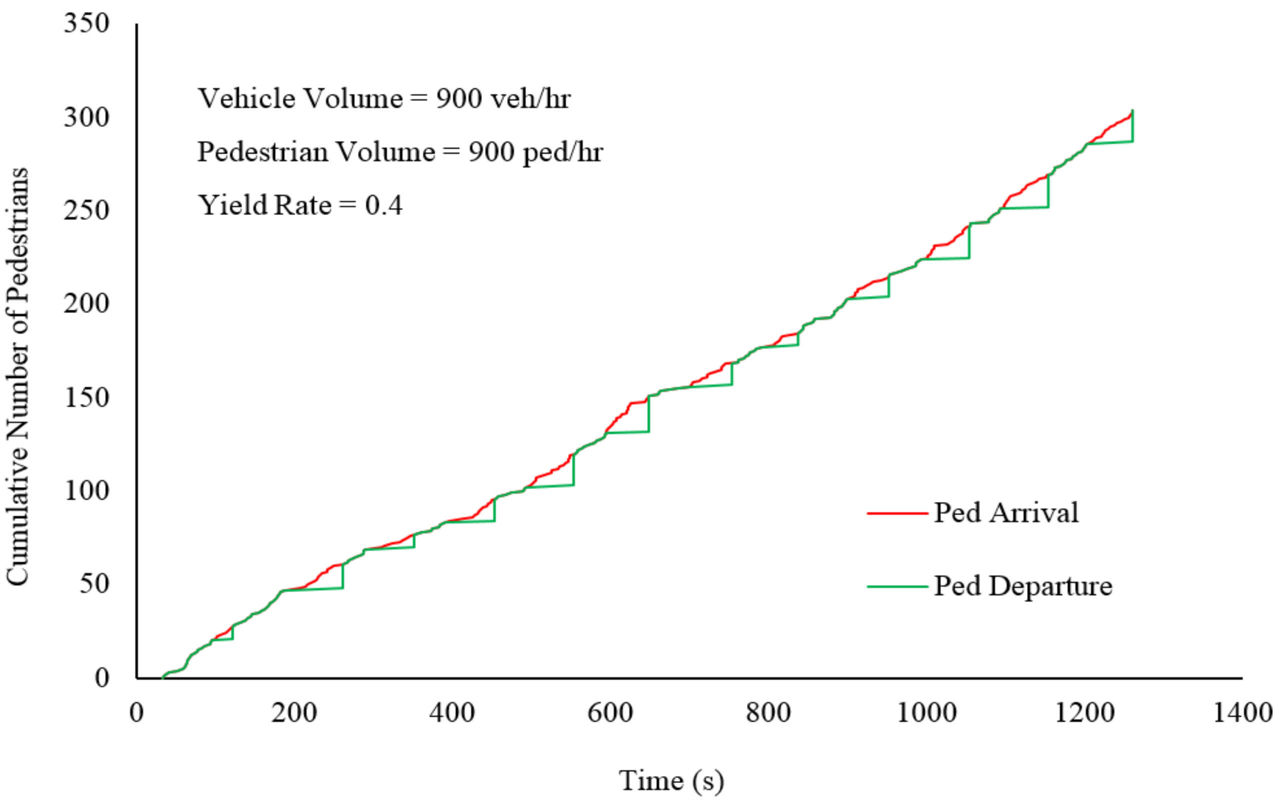

Fig.9 Cumulative Curve for Pedestrians (Under Pulsed Vehicle Arrivals Assumption)

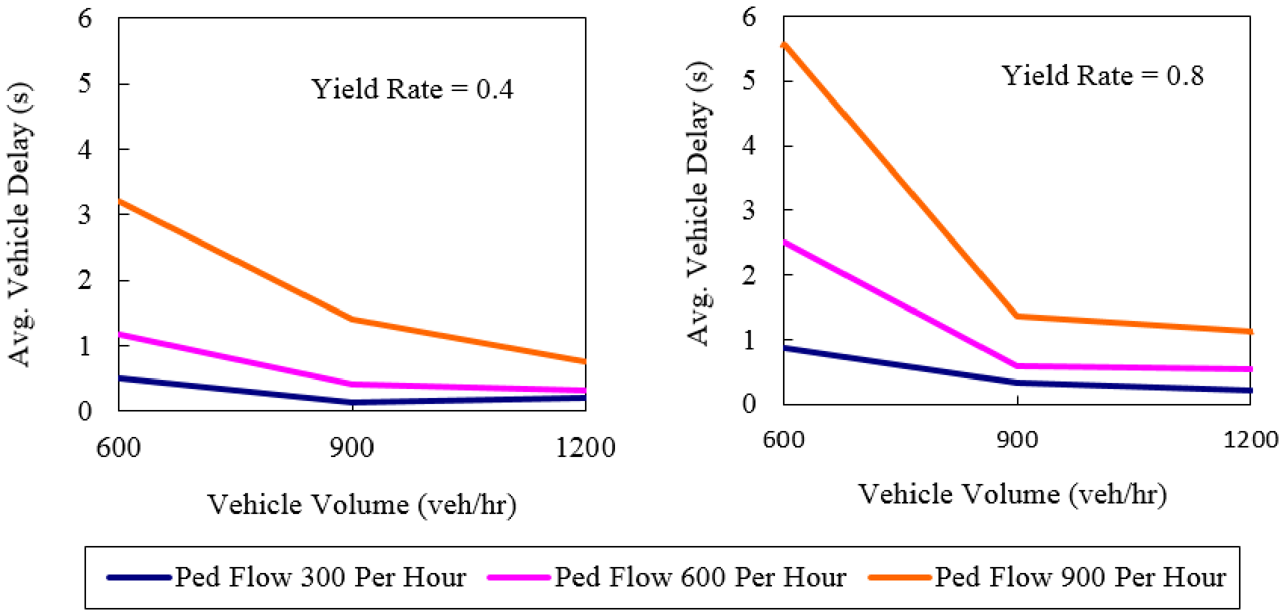

Fig.10 Average Vehicle Delays with Different Vehicle and Pedestrian Volumes for Yield Rates of 0.4 and 0.8 (Under Pulsed Vehicle Arrivals Assumption)

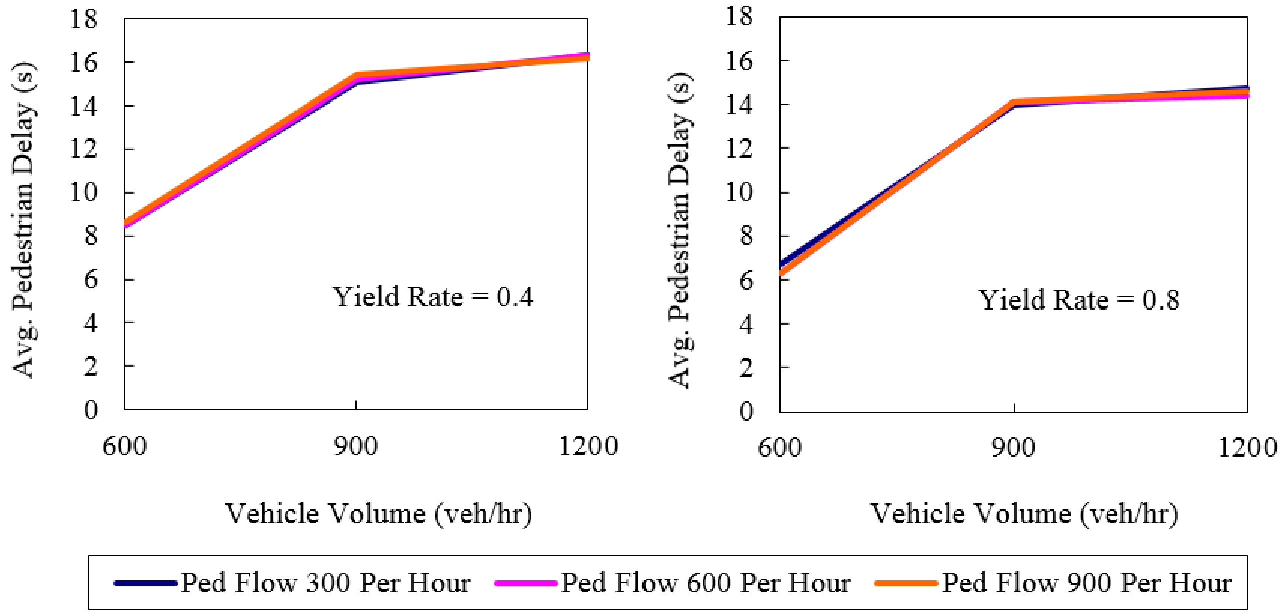

Fig.11 Average Pedestrian Delays with Different Vehicle and Pedestrian Volumes for Yield Rates of 0.4 and 0.8 (Under Pulsed Vehicle Arrivals Assumption)

demand, it becomes difficult for it to find a suitable gap in the pedestrian stream. Vehicle queues also build up during this period which further increase the delays. A higher yield rate increases delays for vehicles. The more number of vehicles yield, the more will be the vehicular delays.

Fig.7 shows pedestrian delays. Increase in pedestrian and vehicle volumes increases pedestrian delays. On the other hand, higher yield rates decrease pedestrian delays.

(3) Simulation with Pulsed Arrivals

Finally, the assumption of pulsed vehicle arrivals was applied to assess its impact. The cumulative curves for one simulation run for certain input parameters are plotted in **Fig.8** and **Fig.9** for vehicles and pedestrians respectively. It is evident from the cumulative curve that most of the vehicles are arriving as platoons from upstream intersection, therefore, they do not yield to the pedestrians and incur very low delays. On the contrary, pedestrians cumulative curve shows that pedestrians, when encountered with vehicle bunches, wait until they find a suitable gap or a yielding event in the random flow period. The vehicle delays obtained from cumulative curves for different vehicle and pedestrian volumes and yield rates are shown in **Fig.10**. Similarly, pedestrian delays are shown in **Fig.11.**

Vehicular delays decrease with increasing vehicle volume shown in **Fig.10**. It is simply because more vehicles arrive as platoons and they do not yield to the pedestrians. Higher pedestrian demand imposes higher delays on vehicles owing to the fact that random vehicles may not easily find a gap in the pedestrian stream. Increasing the yield rate from 0.4 to 0.8 fairly increased the delays for vehicles as shown in **Fig.10**.

Pedestrian delays increased with vehicle volume. Firstly, there is high possibility of finding a safe gap in low vehicle volume decreasing pedestrian delays. Secondly, vehicles at higher volumes are more likely to arrive in platoons resulting in higher pedestrian delays. However, change in pedestrian volume did not show much variance in pedestrian delays. Yield rates, on the other hand, reduced pedestrian delays.

Overall, both vehicle and pedestrian delays were higher in case of random arrivals (**Fig.6** and **Fig.7**). Which means that under the assumption of Poisson vehicle arrivals, the delays are overestimated for such situation where adjacent traffic signals impact the flow pattern. Lower vehicle delays (shown in **Fig.10**) can be attributed to the fact that vehicles are released as bunches during green interval which do not yield to the pedestrians. On the other hand, the reason for lower pedestrian delays (shown in **Fig.11**) is that the pedestrians arriving during a vehicle bunch will have a certain maximum delay after which they are going to find a safe gap either in the random flow during leftover part of green or during the subsequent red interval. Moreover, it was assumed that no vehicle will be released from upstream intersection during red interval. Hence, pedestrians can cross during this interval without getting delayed.

5. CONCLUSIONS

This paper summarized existing delay models and their assumptions. Existing models did not consider all the necessary factors needed to be considered in case of pulsed arrivals generated by an upstream traffic signal. Therefore, a point queue based simulation was conducted to evaluate the impact of pulsed vehicle arrivals, vehicle yielding behavior and vehicle queueing phenomenon occurring due to yielding behavior of vehicles. The delays were obtained against these factors as well as vehicle and pedestrian volumes.

The results obtained for pulsed arrivals were compared with the ones obtained for random arrivals. Simulation results for pulsed arrivals showed overall less delays for both vehicles and pedestrians (**Fig.10** and **Fig.11**). Yield rate also had a significant impact on vehicular delays while a mild impact on pedestrian delays. Sensitivity analysis with respect to vehicle and pedestrian volumes under pulsed vehicle arrival assumption showed that vehicle delays decrease with vehicle volume and increase with pedestrian volume. While pedestrian delays increased with vehicle volume and stayed almost unimpeded with the pedestrian demand.

Hence, based on the results drawn from the simulation analysis, it is concluded that there is a need to develop a model that takes into account both pulsed arrival pattern as well as yielding behavior for unsignalized midblock crosswalks located downstream of a signalized intersection.

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