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Vehicle Actuated Control for Heterogeneous Traffic Using Stop Line Detection

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Abstract

Increasing road traffic congestion in major cities significantly undermines the mobility of urban areas around the globe. Since the space is constraint for construction of new roads for such urban areas, many efforts towards congestion relief are focused on better utilization of existing transportation facilities through the use of electronics and communication technologies. Advanced Transportation Management Systems (ATMS), a key component of the Intelligent Transportation Systems deals with such problems of urban traffic control.

Traditional methods of signal control such as pre-timed or signal coordination works well when there is no fluctuations in the traffic i.e., saturated or over-saturated conditions. However, vehicle actuated (VA) controllers offer better signal time management especially when the traffic has fluctuations. VA controllers were implemented using upstream detectors in most of the developed countries, however their implementations in heterogeneous traffic poses greater challenges. These heterogeneous vehicles have diverse static and dynamic characteristics such as dimensions, acceleration and decelerations respectively. In addition, suchtraffic is characterized by heavy pedestrian movements, no lane discipline, and occasional violation of signals. Modelling such traffic, present in several developing countries, is quite a difficult task. Therefore, developing a vehicle actuated control model to handle highly heterogeneous traffic is a challenging task. The challenge arises because of the difficulty in estimating the demand associated with each turning movement for computing signal timings. Such complex situations can be addressed by placing a detector at stop line rather than in-advance as in homogeneous traffic conditions.

Therefore, the objective of this paper is to implement and evaluate proposed vehicle actuated control algorithm using stop line detector. To test the performance of the model atypical four-way four phase intersection with variable flow is simulated using a traffic simulator (VISSIM) and interfaced with the proposed model. The performance is compared with a traditional pre-timed control. The results using this approach shows significant improvement over traditional control, for both medium and high traffic.

*Keywords:*Signal control, vehicle actuated, and traffic responsive control.

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1. Introduction

The primary purpose of a traffic signal is to assign the right-of-way to intersecting trafficstreams, so that all the streams are served safely and no stream is experienced

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excessivedelay. A properly designed signalized intersection will minimize fuel consumption, delay, and stops without affecting safety. When the traffic signal is properly designed and well timed, one or more of the following benefits are achieved: (1) Increase in the traffic-carrying capacity of the intersection; (2) Reduction in the frequency and severity of certain types of crashes (e.g., right-angle crashes); and (3) Interruption of heavy traffic flow to provide safe opportunities for minor movements or pedestrians to cross. Achieving these benefits requires a signal plan that accommodates fluctuations in volume over the course of the day, week, and year. Periodic re-timing of traffic signals has been shown to yield road-user benefits that typically exceed the cost of the re-timing by as much as a 40 to 1 ratio (Pearson 2012).

Traffic signal systems can be broadly classified into isolated and coordinated systems. Inisolated control, all of the control parameters such as cycle length, phase splits, and phase sequence are fixed and pre-set off-line according to historical flow pattern. The design is done by well-known methods such as equalizing degree of saturation, minimizing total delay, or by balancing LOS (Reilly 1997). For instance, in equalizing degree of saturation, optimal cycle length is usually calculated by finding flow ratios of critical lane groups. Once cycle length has been determined, allocation of green time to each phase is done by equalizing degree of saturation over all critical lane groups. A signal timing plan is typically obtained for the morning peak, evening peak, and off-peak periods. The operational performance of an isolated intersection usually assessed by means of finding average control delay per vehicle. SIDRA 5.1 is a well-known tool for design and evaluation of variety of intersections including roundabouts.

Although design of pre-timed isolated signal control was well established, where there is a predominant traffic along an arterial, additional measures such as signal coordination improves efficiency of the total traffic system. The primary objective when designing a signal coordination is to provide a smooth movement of vehicles along a given corridor such that travel time is minimized i.e., minimizing number of stops. Further, effective signal coordination would improve the throughput of the vehicles from the total system. However, a fundamental question that arises when defining a coordinated system is, when the signal coordination is beneficial? The answer to this question depends on a variety of considerations related to traffic volume, link length, speed, activity around the intersections, and cycle length. However, coupling index is the most determining parameter which is defined as the ratio of traffic volume (veh/hr) to link length (ft). It is desirable to coordinate signals when the link has a coupling index of 0.5 or more (Bonneson et al. 2009). Further, coordination is achieved by operating all the intersections at a common cycle. A typical coordination settings include cycle length, offset, transition mode, and phase splits.

Signal coordination studies can be broadly classified into two categories such as delay minimization or band width maximization models. Traffic Network Study Tool (TRANSYT) is one of the most widely used signal coordination programs, which was originally developed by Transportation and Road Research Laboratory in England in 1968. TRANSYT is a macroscopic, deterministic simulation and optimization model which minimizes delay and no of stops for determining optimal values of the model (Robertson 1969). Another model SYNCHRO optimizes cycle lengths, splits and offsets using a performance index which takesinto account signal delay, queue length, and vehicle stops (Husch and Albeck 2003). MAXBAND is a band width maximization program which determines signal timing plan for an arterial and triangular networks (Cohen and Little 1982). MAXBAND computes cycle lengths, offsets, speeds, and phase sequences to achieve maximum progression band widths. PASSER (Progression Analysis and Signal System Evaluation Routine) was developed by the Texas Transportation Institute in 1990. PASSER maximizes bandwidth efficiency by finding the highest value of through green band divided by twice the cycle length (Chaudhary and Messer 1993). The basic limitation of bandwidth based models is that their progression design criteria do not consider the variable capacities of different links along the corridor.

Therefore, to account for actual traffic volumes and flow capacities on each link a variable bandwidth progression was proposed (Gartner et al. 1991). Although design and evaluation of pre-timed isolated and coordinated signal controls were well established, they suffer from the following limitations: (1) Their inability to respond to traffic fluctuations during off-peak period; and (2) Failure to respond to non-historical flow pattern. Therefore, to overcome above limitations vehicle actuated control can be considered as a good alternative. Vehicle actuated (VA) signal controller by virtue of its name responds to random fluctuations in the traffic, which in turn improves the capacity of signalized intersection. It works based on the real time traffic information which forms the input to the signal controller and implements signal timings based on internally computed optimum values.

Actuated control consists of a pre-determined phase sequence or not, wherein the activation of each phase is subject to whether the associated traffic movement has requested a service through a detector or not. The required green time is estimated by the traffic demand information obtained from the detector, subject to pre-determined minimum and maximum limits. The operation of an actuated controller can be classified as fully-actuated and semi-actuated. Fully-actuated control implies that all phases are actuated and all intersection traffic movements are detected. However, the sequence and duration of each phase is determined by real time vehicle arrivals. On the other hand, semi-actuated control uses actuated phases to serve the minor movements at an intersection. Only the minor movements have detection. The phases associated with the major-road through movements are operated as non-actuated. The controller is programmed to dwell with the non-actuated phases displaying green for at least a specified minimum duration.

Vehicle actuated controllers were implemented using advance detectors in most of the developed countries, however they are not efficient when the traffic has heterogeneous vehicle composition and non-lane based movement. These vehicles have diverse static (dimensions) and dynamic characteristics (acceleration and decelerations). In addition, such traffic is characterized by heavy pedestrian movements, limited lane discipline, and occasional signal violations. Modelling such traffic, present in several developing countries, is a challenging task. The challenge arises because of the difficulty in estimating the demand from upstream detectors by respective phases for computing signal timings. Therefore, properly designing an actuated controller to handle highly heterogeneous traffic is a complex task. Such complex situations can be addressed by placing a detector at the stop line rather than in-advance as in homogeneous traffic conditions (Ravikumar and Mathew 2011).

Therefore, the objectives of this study are: (1) Propose a vehicle actuated control algorithm for a traffic with heterogeneous vehicle composition and limited lane discipline; and (2) Evaluate a vehicle actuated control for a typical four phase isolated intersection.

2. Methodology

2.1 Terminology

The following are the definitions associated with vehicle actuated control which are required to be familiar with the reader.

Gap (h):In signal control vehicle arrivals are modelled by means of headway or gap between vehicles. At a given section (stop line), the gap is defined as the time lapse between the instance of crossing of the rear bumper of the leading vehicle to the instance of crossing ofthe front bumper of the following vehicle.

Threshold gap (h_{th}):When the signal turns from red to green, the queue is discharged at saturation rate with minimum gap between vehicles. However, when the queue is discharged completely, the gap between vehicles follows their arrival rate. Hence, threshold gap is defined as the maximum allowable gap between two successive vehicles that will cause the active phase to terminate. This is typically set in the range of 3 to 4 s.

Minimum green (g_{min}):To achieve safe and efficient control, traffic signal requires each phase must be executed certain minimum green time. Hence, this value normally depends on driver’s expectancy, operational performance, and pedestrian’s crossing requirement on the conflicting phases.

Maximum green (g_{max}): To have efficient operational performance traffic signal must be operated between certain minimum and maximum cycle times. Hence, maximum green time of each phase depends on the cycle time, flow pattern on each phase, and the number of phases.

Unit extension (e_0):When the elapsed green time is equal to minimum or initial green time and the vehicle has detected on the current time step, the green time is extended by a small amount known as unit extension. This is typically fixed at 3 s. Every time when the phase is about to terminate and vehicle is detected simultaneously, the green time can be extended if the elapsed green time is less than the maximum green time.

2.2 Vehicle Detection

Detection loops laid at the stop line are scanned by the traffic signal controller at definite intervals for occupied or not. Since the purpose of detection loop is only to identify the gap in the traffic flow, its distance from the stop-line is not very critical. Certain systems consider detection up to about 20 m in advance of the stop-line as stop-line detection. Generally for vehicle actuated controllers the loops are placed at 1 m before the stop line. The vehicle detectors generate digital signal whenever the vehicle is on the sensor loop. The sensor loops are normally configured in presence mode, i.e. the detector gives a high level signal as long as the vehicle occupies the sensor loop. The scan pulses are returned for the period the vehicle occupies the loop; a low level is returned when the loops are not occupied. A comparison between advance detection and stop line detection is illustrated in Figure 1. When a traffic is homogeneous and has good lane discipline, required green time is estimated using advancedetection technique (Reilly 1997). However, when the traffic is heterogeneous and limited or no lane discipline, stop line detection is best suited. In this study sensors are placed at the stop line and vehicles are detected instantaneously as they cross the sensors by means of electric pulses. Each phase begins with pre-set minimum green and this green time will be extended up to the pre-set maximum green time, provided the gap between the vehicles is less than the threshold gap. Otherwise, the phase will be terminated in between minimum and maximum green values when the gap is greater or equal to threshold gap i.e., each phase is executed at least a pre-set minimum green time.

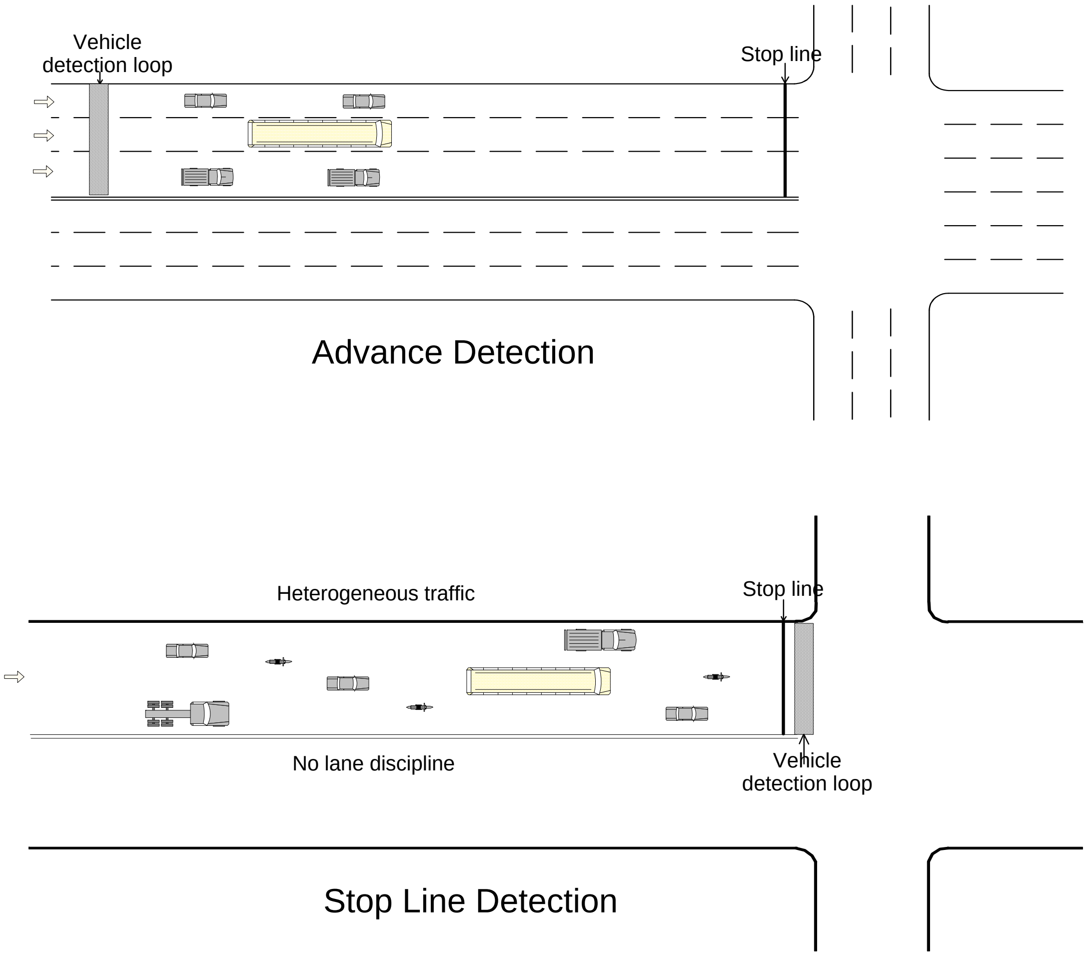


Figure 1: Illustrates types of traffic and their suitable detection techniques

2.3 Gap Identification

The gap detection between vehicles is illustrated in Figure 2. The detector is inactive during red signal, and it is active when the signal turns to green. The phase starts with a minimum green, and the green time is extended for every demand having gap (h) less than the threshold gap (h_{th}) subject to minimum and maximum green time. Demand registered after identification of gap (h) more than the threshold gap (h_{th}) is ignored for further green time extension. The phase would be terminated, and detector become inactive. Further, the phase can assume a maximum of configured maximum green time even if there is continuous demand.

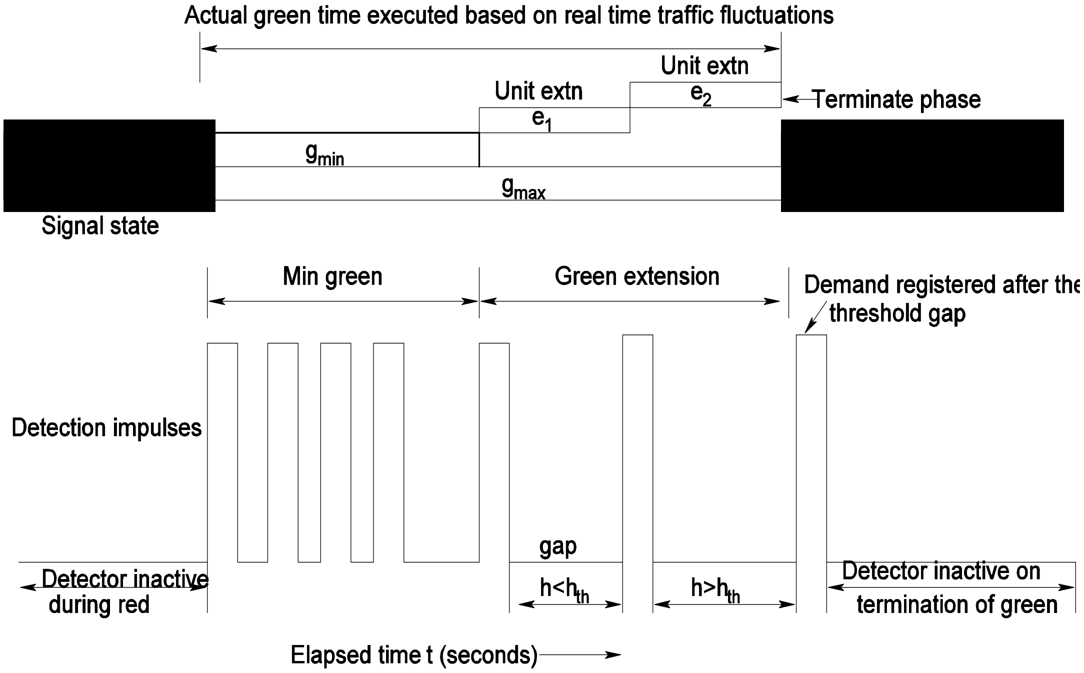
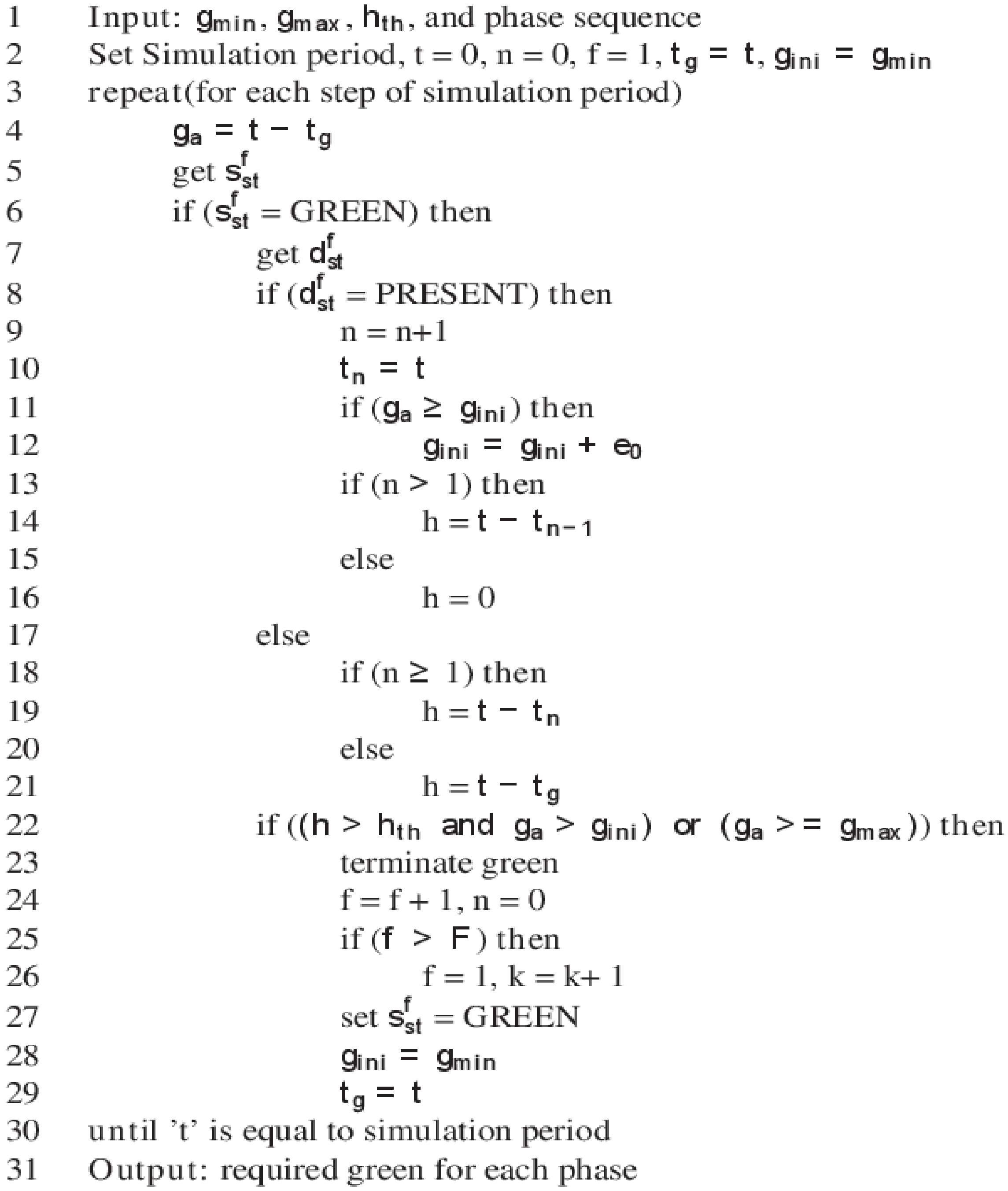


Figure 2: Identification of gap between vehicles

2.4 Algorithm

A detailed algorithm of vehicle actuated control operation for heterogeneous traffic conditions with stop line detection is proposed in this paper. Since detectors are placed just after the stop line, the signals are allowed to operate in a definite sequence with initial minimum green and that is extendible up to the maximum green depending on demand. The algorithm is presented in Figure 3. The controller starts with the specification of various control parameters such as g_{min}, g_{max}, h_{th}, phase sequence, and initialization of other parameters (lines 1-2). Then, for every time step the controller calculates elapsed green time $g_a$from the start of the green (lines 3-4). It gets signal state of the current phase f (line 5). If the signal is *green*, then it gets corresponding detector status (lines 6-7). If the detector status is *present*, then it updates vehicle count and stores time of arrival of the vehicle (lines 8-10). Further, if the elapsed green time $g_a$is more than or equal to initial green time g_{ini}, then the initial green time is extended by unit extension e_0 because vehicle is detected in the current time step (lines 11-12). Finally, controller calculates gap between vehicles based on number of vehicles and their time of arrival (lines 13-21). The controller terminates active phase if the gap h is more than threshold gap $h_{th}$and elapsed green $g_a$is more than initial green g_{ini}or if the elapsed green is more than or equal to maximum green g_{max}(lines 22-23). The phase is incremented to next phase and vehicle count is reset to zero (line 24). If all the phases are executed, the controller reset to first phase and updates its cycle count (lines 25-26). Further, new phase is set to *green*, and initialized with minimum green (lines 27-28). The start of the green is also stored in order to calculate elapsed green time at every time step (line 29). The process repeats until time is equal to simulation or control period (line 30).



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Input: $g_{min}$, $g_{max}$, $h_{th}$, and phase sequence
Set Simulation period, t = 0, n = 0, f = 1, $t_g = t$, $g_{ini} = g_{min}$
repeat(for each step of simulation period)
        $g_a = t - t_g$
        get $s^f_{st}$
        if ($s^f_{st}$ = GREEN) then
                get $d^f_{st}$
                if ($d^f_{st}$ = PRESENT) then
                        n = n+1
                        $t_n = t$
                        if ($g_a \geq g_{ini}$) then
                                $g_{ini} = g_{ini} + e_0$
                        if (n > 1) then
                                h = $t - t_{n-1}$
                        else
                                h = 0
                else
                        if (n ≥ 1) then
                                h = $t - t_n$
                        else
                                h = $t - t_g$
                if (($h > h_{th}$ and $g_a > g_{ini}$) or ($g_a >= g_{max}$)) then
                        terminate green
                        f = f + 1, n = 0
                        if (f > F) then
                                f = 1, k = k+ 1
                        set $s^f_{st}$ = GREEN
                        $g_{ini} = g_{min}$
                        $t_g = t$
until 't' is equal to simulation period
Output: required green for each phase
```

Figure 3: Stop line based vehicle actuated control algorithm

2.5 Implementation

The proposed vehicle actuated control algorithm is tested using a scalable, high performance microscopic simulation package, Vissim 5.10. It is being widely used in the testing of various algorithms in traffic engineering studies because of its microscopic behavioural models. The users can access the core models to modify and extend many features of the underlying simulation model such as signal control through its application programming interface (API) tool. The vehicle actuated (VA) model is developed as a Vissim plug-in through API using c++ programming language.

The interaction between vehicle actuated model and Vissim simulator is designed in such a way that the model receives detector status from simulator, and in turn instruct the simulator to change the signal state as shown in Figure 4. The instructions are broadly divided into following 3 steps.

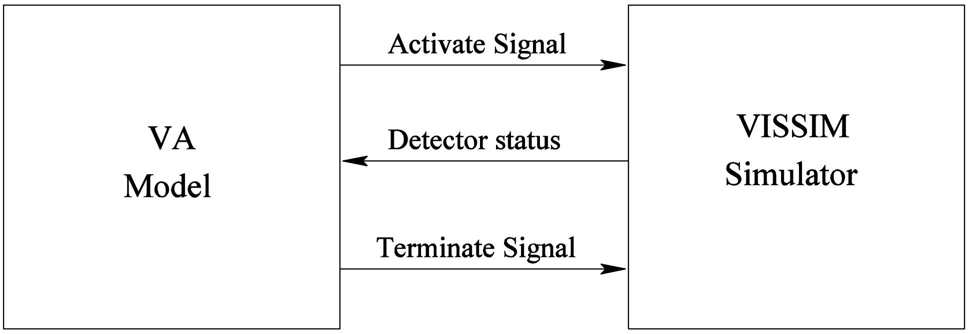

Figure 4: Interaction between vehicle actuated model and the simulator

1. The VA model starts the simulator and generates traffic according to the given input flow.
2. It instructs the simulator to activate signal as per given phase sequence and gets detector status at every time step.
3. Accordingly, it calculates gap between vehicles and checks termination criteria (step 22 of Figure 3). If the criteria satisfies, it instructs the simulator to terminate active phase and start the next phase.

Following are the com interface commands used to interact with the Vissim simulator by assigning its instance IVissimPtr to the spVissim.

1. Loading of the intersection is done by using *LoadNet* command as follows:
    - spVissim → LoadNet(filename)
2. The state of the detector is scanned for *Presence* or *Absence* of the vehicles as follows:
    - spVissim → GetNet() → GetSignalControllers() → GetSignalControllerByNumber() →GetDetectors() → GetDetectorByNumber(phase) →GetAttValue('Impulse')
3. Setting of the signal as *Green* or *Red* is done by assigning signal heads attribute value to 2 or 3 respectively as follows:
    - spVissim→GetNet() →GetSignalControllers() → GetSignalControllerByNumber() →GetSignalGroups() → GetSignalGroupByNumber(phase) →PutAttValue('Type',2)

3. Evaluation

In order to evaluate, a typical four-phase isolated intersection as shown in Figure 5 is selected. The intersection has 3 lanes each in West and East bound directions and 2 lanes each in South and North bound directions. The detectors supplies vehicles information to VA model which in turn suggests signal state through controller. The traffic is represented by left bound direction typically observed in developing countries. To account for the effect of heterogeneity and limited lane discipline, the VISSIM model is developed following an earlier study (Mathew and Radhakrishnan 2010). The traffic composition consists of a mixed vehicle types such as buses (9%), trucks (5%), LCV (6%), cars (18%), three-wheelers (26%), and two-wheelers (35%). The driving behaviour is set by allowing a vehicle to place anywhere on the lane, permitting vehicle to overtake along left or right of a slower vehicle, and allowing a diamond shaped queuing at intersection stop line. The performance of the widely used pre-timed control is used as a bench mark and is compared to the proposed model. The efficiency of a proposed vehicle actuated control is evaluated by means of following measures such as average intersection delay, average queue length, and total throughput.

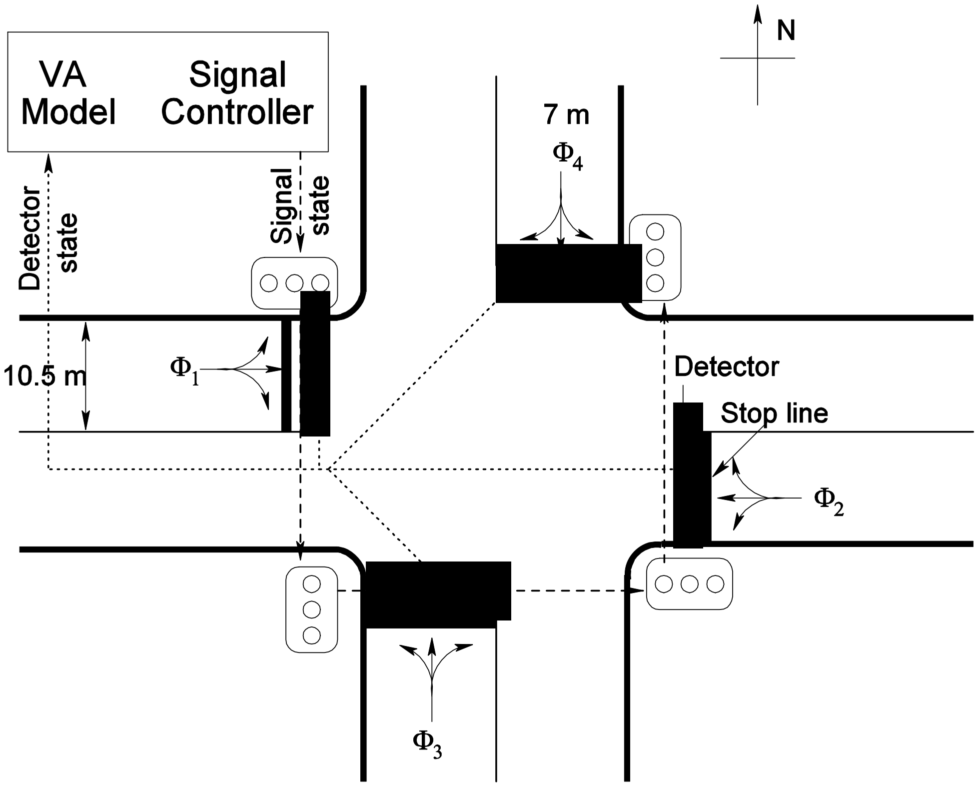

Figure 5: Illustrates intersection geometry, phasing scheme, detector, and signal state communication

To demonstrate robustness of the model, three traffic flows such as low (v/c = 0.35), medium (v/c = 0.70), and high (v/c = 1.2) flow cases are considered. Each case is characterised by varying traffic with multiple peaks and off-peaks. For instance, a flow pattern inhigh volume case is shown in Figure 6. Similar pattern is given for low and medium flow cases. It may be noted that the required green time under pre-timed control is estimated according to HCM 2000 guide lines (Reilly 1997). Accordingly, for low flow case a minimum green time of 10 s is estimated for each of all the four phases. Hence, it is observed that there is no difference in performance between pre-timed and vehicle actuated control for low flow scenario. The delay, queue, and discharge for a total of 16 hrs period for both pre-timed and VA control is estimated as 12 s/veh, 5 m, and 30371 veh.

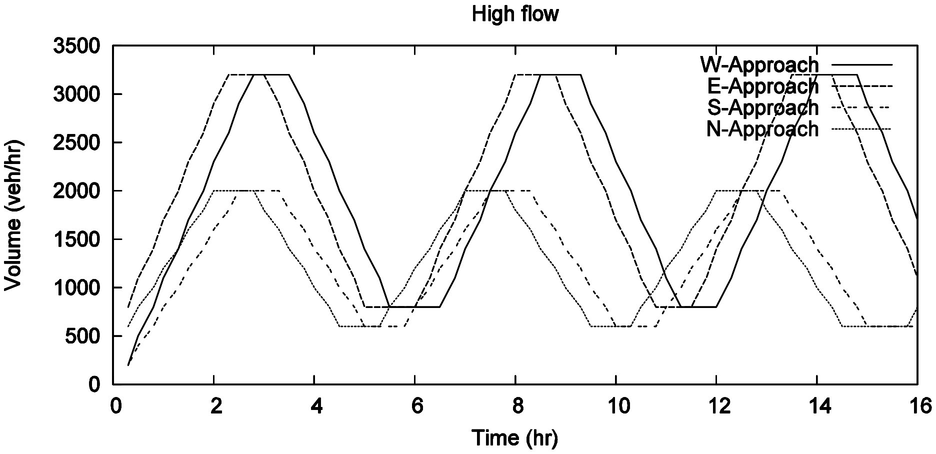

Figure 6: Flow pattern on various approaches of the study intersection in high volume case

A truly vehicle actuated control will propose green time in response to the current demand. In order to examine whether the proposed model is able to respond to changes in the traffic pattern, the allotted green time and the corresponding volume are measured. The measured volume of vehicles and the allotted green times on a minor and a major approach using the VA model and pre-timed control for the medium flow case is shown in Figure 7. The comparison demonstrates that though pre-timed control decreased the green time during off-peak time (selecting plan based on the time of the day), there is a gap between actual off-peak and pre-timed off-peak on the both approaches due to the natural fluctuations in the vehicle arrivals. On the other hand, actuated control responds on real time to the fluctuations in the traffic which led to decreased delay, queue, and increased discharge as discussed below.

The evaluation results for the medium and high flow cases are summarized in Table 1. The operational performance measures such as delay, queue, and discharge are computed separately for total, peak, and off-peak periods for each case. These measures obtained from VA control is compared with pre-timed control (time of the day plans) for each approach (phase) and also for the whole intersection. It can be observed that almost all the approaches and the whole intersection experienced reduction in delay for all the cases such as total, peak, and off-peak periods. A maximum of 66.23 % decrease is found on South approach for medium traffic during its off-peak period. However, delay increased on certain occasions. For instance, a maximum of 72.73 % increase is found on the North approach for high traffic during its off-peak period. Nevertheless, such increase is observed only 4 out of 30 instances (Table 1). Further, the increase is observed on the minor approach (North). This is actually expected from VA algorithm because the objective is to improve overall intersection performance for the total period and not the particular period or approach.

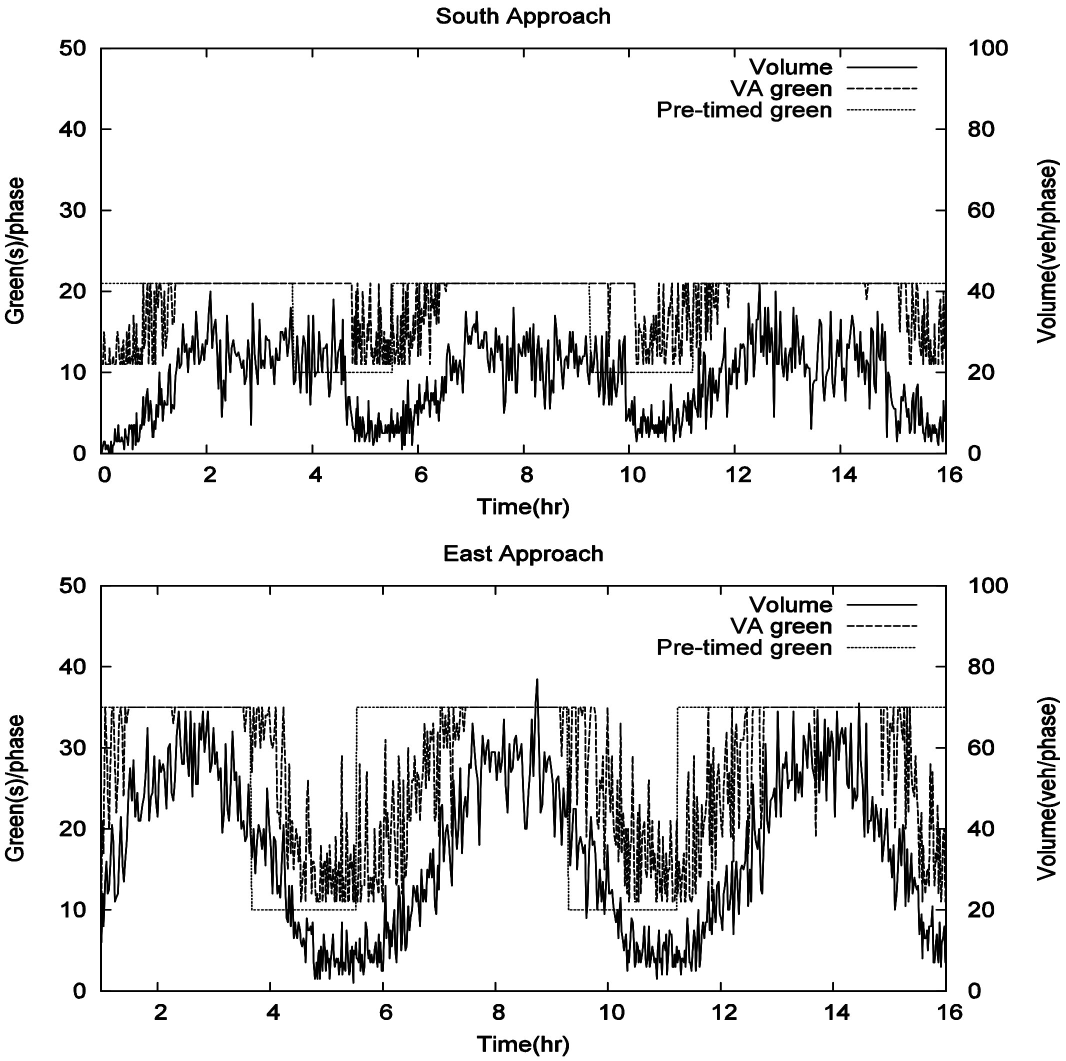

Figure 7: Comparison of volume, actuated and pre-timed green times on the South and East approaches

In accordance with delay results, queue is also decreased for most of the instances. A maximum of 80.39 % decrease is observed on the South approach for medium traffic during its off-peak period. However, queue is also increased on certain occasions, 3 out of 30 instances. For instance, a maximum of 47.3 % increase is found on North approach for high traffic condition during its off-peak period. Of course, this is again on same minor approach (North), and can be ignored when the benefit attained on remaining instances is compared.

Similar results are found with respect to the discharge. As expected highest increase in discharge is noticed under high flow condition. For instance, a maximum of 8.16 % increase is observed on the South approach during its off-peak period. However,

Table 1: Comparison of delay, queue, and discharges obtained from vehicle actuated model with pre-timed control

	Medium Traffic (v/c = 0.7)						High Traffic (v/c = 1.2)					
	VA			% Change			VA			% Change		
Del(s/veh)	Total[1]	Peak[2]	Offpeak[3]	Total[1]	Peak[2]	Offpeak[3]	Total[1]	Peak[4]	Offpeak[3]	Total[1]	Peak[4]	Offpeak[3]
Phase 1	42	71	18	-10.64	-10.13	-5.26	119	160	78	-3.25	-0.62	-22.00
Phase 2	41	49	19	-4.65	-3.92	0.00	121	158	52	-6.20	-5.39	-5.45
Phase 3	181	287	26	-16.97	-7.72	-66.23	267	307	183	-7.93	-1.29	-35.11
Phase 4	158	269	21	-16.40	-8.19	-34.38	271	320	152	2.26	13.88	72.73
Intersection	88	132	21	-13.25	-7.16	-43.41	168	203	114	-3.37	0.45	-9.44
Queue (m)	Total[1]	Peak[2]	Offpeak[3]	Total[1]	Peak[2]	Offpeak[3]	Total[1]	Peak[4]	Offpeak[3]	Total[1]	Peak[4]	Offpeak[3]
Phase 1	35	72	8	-7.89	-11.11	0.00	118	167	70	-4.07	-1.18	-29.29
Phase 2	35	42	8	-2.78	-6.67	0.00	121	160	32	-4.72	-5.88	-25.58
Phase 3	115	180	10	-12.88	-6.25	-80.39	172	191	133	-6.01	-1.55	-32.14
Phase 4	103	179	10	-13.45	-4.79	-44.44	173	191	109	4.85	11.05	47.30
Intersection	62	97	9	-9.68	-6.57	-57.67	137	171	85	-2.75	-1.1	-15.44
Disch (veh)	Total[1]	Peak[2]	Offpeak[3]	Total[1]	Peak[2]	Offpeak[3]	Total[1]	Peak[4]	Offpeak[3]	Total[1]	Peak[4]	Offpeak[3]
Phase 1	18802	4311	921	0.18	2.35	-1.29	26221	6585	2057	-0.58	0.52	-1.72
Phase 2	19095	4371	896	0.05	1.20	-1.86	26801	6135	1642	0.01	-3.43	-3.70
Phase 3	10759	2094	739	2.87	4.13	-19.85	12591	2502	1630	3.15	-0.28	8.16
Phase 4	11073	2171	989	3.86	3.48	2.17	12892	2504	1690	1.65	-7.16	7.85
Intersection	59729	12947	3545	1.28	2.43	-5.11	78505	17726	7019	0.57	-2.12	2.14

Note: [1]Total indicates 16 hrs period of study, [2]Peak period (6.8 to 9.5 hrs), [3]Offpeak period (4.8 to 6.4 hrs), and[4]Peak period (7.4 to 10.7 hrs) discharge is decreased on certain occasions, and there is very little increase is noticed in medium traffic, possibly due to lack of demand. Overall, the discharge improved in 19 out of 30 instances. Therefore, it can be concluded from the above results that the proposed VA algorithm is truly responsive to the traffic fluctuations. This has resulted in overall decreased intersection delay, queue lengths and increased intersection discharge when compared to the traditional pre-timed control.

4. Conclusion

This study is an attempt to propose and evaluate vehicle actuated control algorithm using stop line detection information, increasingly used in heterogeneous traffic characterized by non-lane based movement and presence of mixed vehicle types. Placing detector at the stop line addresses inaccurate estimation of demand associated with the heterogeneous traffic. Thus the contribution of this study is the development of a control algorithm for a vehicle actuated system using stop line detection; and use of algorithm in evaluation framework. The performance of the proposed algorithm is evaluated by obtaining various measures-of-effectiveness from a typical four-phase signalized intersection for low, medium, and high traffic scenarios. The results indicate that the proposed algorithm is able to provide green time responding to real time vehicle arrivals as opposed to historical information in pre-timed control. Results are also obtained using traditional pre-timed control and comparison indicates that model performed much better for medium and high traffic flows. It is also found that a pre-determined minimum green time with pre-timed control is advisable for low traffic conditions.

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Notation

The notations used in the model are described below.

g_{min} : minimum green
g_{ini} : initial green
t_g : green start
g_{max} : maximum green
g_a : actual green
f : phase
n : vehicle count
t_n : arrival time of nth vehicle
e_0 : unit extension
h : time gap between vehicles
h_{th} : threshold gap between vehicles
k : cycle count
s^f_{st} : signal state {GREEN or RED} of the given phase f
d^f_{st} : detector state {PRESENT of ABSENT} of the given phase f
F : number of phases