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Real-time Traffic Signal Control for Isolated Intersection, using Car-following Logic under Connected Vehicle Environment

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Abstract

In modern transportation systems, Connected Vehicle (CV) technology has shown its potential as a valuable traffic data source in providing real-time accurate traffic information. Connected vehicles transmit information wirelessly among vehicles and exchange the same with the traffic signal controller. This paper proposes a connected vehicle signal control (CVSC) strategy for an isolated intersection, which utilizes detailed information, including speeds and positions of GPS equipped vehicles on each approach at every second. The proposed strategy first aims at dispersing any queue that was built up during the red interval, and then starts minimizing the difference between cumulative arrival flow and cumulative departure flow on all approaches of the intersection. The proposed algorithm is well responsive to different traffic demand and fluctuations in arrival flows. The performance of the proposed strategy is compared with an adaptive signal control solution developed by PTV EPICS, which optimizes signal timings using the data collected from fixed detectors. Various traffic scenarios with 100% GPS market penetration rate were tested in the VISSIM 8 microscopic simulation tool. Results have shown that the proposed CVSC strategy showed outstanding performance in reducing travel time delays and average number of stops per vehicle when compared to the EPICS adaptive control.

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Keywords: Connected vehicles; GPS; Real-time traffic signal control; Car-following model; Adaptive control; Micro-simulation; VISSIM; EPICS;

1. Introduction

Signalized intersections are an important part of the road transportation system that regulates the traffic flow in urban areas. Correct installation of traffic signals along with proper signal control strategy will minimize delays, stops, fuel consumption and emissions.

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Traffic signals usually operate in one of the three modes: fixed-time, actuated and adaptive. Fixed-time signal control uses historical traffic data and develops cycle lengths that are fixed in duration, assuming that the traffic demand remains similar throughout the time period. However, traffic demand fluctuates in reality.

Actuated signal control, which is usually applied for isolated intersection, collects traffic data in real-time through infrastructure-based sensors like inductive loop detectors (ILD's), video detectors or radars, and develops varied cycle lengths whose intervals are extended in response to vehicle detector's actuation. MOVA, which is a UK based vehicle actuated signal control system, uses ILD's upstream of the stop-line to provide traffic data to the control logic (DfT, 1997). In the USA, various departments of transportation (DOT's) adopt actuated signal control based on the signal control guidelines recommended by the Federal Highway Administration (FHWA) (Koonce, 2008).

Adaptive signal control, which is applied for an arterial or network, utilizes real-time traffic information to predict future traffic conditions and optimizes the signal timing parameters like split, offset and cycle length based on a defined objective function. Several adaptive signal control systems include SCATS (Sims and Dobinson, 1980), SCOOT (Hunt et al., 1982), UTOPIA (Mauro and Di Taranto, 1989), PRODYN (Henry et al., 1983), OPAC (Gartner, 1983), RHODES (Mirchandani and Head, 2001), ACS-Lite (Stevanovic, 2010), BALANCE (Braun et al., 2008). All these adaptive control systems rely mostly on infrastructure based sensors like ILD's or video based detectors. The main limitation of loop based detectors is that they are point detectors that only provide instantaneous vehicle information when the vehicle is passing over the detector and cannot directly provide the vehicle's location, speed, and acceleration data in a geographically continuous way. Moreover, the installation and maintenance cost of such detection systems is considered high. Malfunctioning of one or more loop detectors might degrade the performance of the adaptive signal control system (Feng et al., 2015).

Global positioning system (GPS) technology has opened the doors for a number of new intelligent transportation system (ITS) applications in which *Connected Vehicles* (CV) are one of the most promising technological advances that introduce wireless communications among smart vehicles and roadside infrastructure (FHWA, 2015). Instead of relying on a loop or a video detection system that sense vehicle presence only at fixed locations, signal systems under CV environment can use high speed information transactions between the vehicles (V2V), vehicles and the infrastructure (V2I and I2V), and vehicles and handheld devices (V2D) thus enabling the access to detailed vehicle information such as vehicle's speed, position, and acceleration (ITSJPO, 2016; ITE, 2015).

The current main drawback of this technology is that its low penetration in the population makes it less beneficial to exchange information between V2I and I2V. However, in the era of mobile internet services, and with decreasing costs, and increased accuracy of GPS, mobile sensing industries have started working in the field of probe based traffic monitoring (Herrera et al., 2010). Previous research referred that after federal mandatory installation of on-board equipment (OBE's) in new light vehicles in U.S, connected vehicles might reach 95% penetration rate over 25-30 years (John, 2008). Further, the National Highway Traffic Safety Administration (NHTSA, 2014) plans to mandate the implementation of V2V technology in U.S by 2016. It is, thus, very likely that the penetration rate of the technology will not be an issue for long.

CV data can be collected from a single infrastructure device (radio) and is significantly less expensive when compared to installation and maintenance of a series of detectors (ILD's or video). During communication failures, if one or more connected vehicles cannot transact the information to the intersection, it will only decrease the penetration rate slightly which should tend to have a small impact on the system performance. If the infrastructure based device fails the intersection returns to the traditional actuated or fixed-time control (Feng et al., 2015). It should be said, however, that some sorts of data accessibility, and privacy issues might still remain for a while. In time these issues should be adequately solved. The ITS Joint Program Office (ITSJPO, 2015) of U.S Department of Transportation (USDoT) has an ongoing research on identifying solutions to the policy issues, in providing a robust security system that establishes a trust network among the connected vehicle users, in preserving personal privacy.

The objective of this paper is to present a real-time adaptive traffic signal control algorithm for an isolated intersection, utilizing connected vehicle data. The algorithm assumes 100% GPS penetration rate and uses individual vehicle's position and speed information and develop traffic signal timings that enable improved performance over a traditional optimized adaptive signal control.

2. Traffic signal control using technological advancements

In recent years, many authors have used wireless communication technologies in the form of vehicle probes, in the processes of estimation of vehicle travel times, travel speeds using different GPS market penetrations.

Gradinescu et al. (2007) used short-range wireless communication between vehicles to determine demand to optimize the cycle length and green splits of a traffic signal once every cycle. The total average delay, fuel consumption and pollutant emissions, were significantly reduced by their algorithm. Ahmane et al. (2013) has proposed a simple control strategy, which uses wireless vehicle information from an on-board equipment (OBE) and minimizes the sum of queue lengths. As a result of this strategy, each car receives a green signal at the intersection in a given sequence.

He et al. (2012) proposed a unified platoon-based formulation called PAMSCOD that optimizes arterial (network) traffic signals for multiple travel modes, assuming advanced communication systems between vehicles and traffic controllers. The algorithm used mixed integer linear programming (MILP) to determine stage timings every 30 seconds for four cycles in the future, based on platoon sizes and vehicle positions. PAMSCOD has reduced the average vehicle delay by about 8%, when compared to SYNCHROS's optimized actuated signal timings.

Premier and Friedrich (2009) proposed a novel concept for decentralized adaptive signal control using V2I communications based on the IEEE 802.11 standard. The algorithm utilizes the vehicle's position and speed data and forecasts the future queue lengths by optimizing stages in 5-second intervals over a 20-second horizon using the techniques of dynamic programming and complete enumeration. At 100% market penetration, the algorithm outperformed the fixed timing plan, reducing delay by 23% and improving speed by 5%.

Using connected vehicle data, Lee et al. (2013) proposed a real-time cumulative travel-time responsive (CTR) algorithm. The algorithm used 100% market penetration rate to measure cumulative travel time (CTT) and minimizes the cumulative travel time for all approaches of an intersection calculated at 5-second intervals by considering different combinations of stages. The algorithm sums the travel times for each combination of movements of respective stages. The stage with highest CTT was set to be the next stage.

Goodall (2013) has proposed an adaptive signal control algorithm called Predictive Microscopic Simulation Algorithm (PMSA) that uses CV information of the vehicle's position, heading, and speed. The algorithm uses a rolling-horizon strategy to choose a stage by optimizing an objective function over a 15-second horizon period. The algorithm also estimates the locations of unequipped vehicles on an arterial with a reasonable degree of accuracy, and these estimations were used to improve the performance of a connected vehicle mobility application. The authors found that the developed algorithm performed well for low demands, but for near saturated, or over saturated conditions the performance decreased. As pointed out by Feng et al. (2015), the algorithm cannot be applied in real life intersections due to high computational requirements with parallel simulations to predict the future traffic conditions.

Guler et al. (2014) developed an intersection traffic control algorithm for a two one-way streets, which minimizes total delay or total number of stops using the information from CV's. Their algorithm decides to discharge each car from a queue based on how the decision would affect the objective function for all equipped cars and predicted unequipped cars within the radius of interest.

Feng et al. (2015) developed a real time stage allocation algorithm under CV environment. The algorithm utilizes vehicle location and speed data and optimizes stage sequence and duration by solving a two-level optimization problem. Under 100% penetration rate, the total delay was reduced by 10.04% and 14.67% and queue length was reduced by 6.37% and 16.33%, under two demand levels respectively.

The aforementioned literature review has demonstrated various ways of addressing the traffic signal control problem, by utilizing CV technology and by replacing traditional point detection methods. However, there is still scope for a simple, computationally effective and easily deployable traffic signal control approaches. This paper proposes a connected vehicle signal control (CVSC) strategy for an isolated intersection, which utilizes detailed traffic information, including speeds and positions of GPS equipped vehicles on each lane at every second. The proposed strategy is a rule-based method that adjusts signal timings by using basic traffic engineering principles. It is capable of responding to different traffic demands and fluctuations in arrival flow patterns. Based on the CV information the signal settings and green splits are adjusted to improve the system-wide measures of effectiveness (travel time delay and average number of stops per vehicle).

3. Modelling approach

3.1. Flow-ratio concept

For any signalized intersection, the goal of designing a signal cycle time should be to serve as many vehicles as possible, taking into account the arrivals, departures and queue lengths of all vehicles on all approaches of the intersection irrespective of green or red intervals. To achieve this goal, a new concept called "Flow-ratio" is proposed. Flow-ratio (Eq. (1)) is defined as the ratio of cumulative departure flow on all approaches to the cumulative arrival flow on all approaches from the beginning of the control period. Note that departure flows are measured at the stop-line on all approaches and arrival flows are measured at 300m before the stop-line on all approaches. Since the cumulative departure flows and cumulative arrival flows are considered from the beginning of the control period, the Flow-ratio will always be less than or equal to 1.0 at any time. The effective range of the connected vehicles to transmit the traffic information through dedicated short range communication (DSRC) system is 300m (Fan et al., 2010). Hence, in this paper the CV data is collected from 300m before the stop-line on all approaches.

$$Flow\ ratio = \frac{\sum_{i=1}^{n}(Cumulative\ departure\ flow\ of\ all\ phases\ at\ any\ time{-}step)_i}{\sum_{i=1}^{n}(Cumulative\ arrival\ flow\ of\ all\ phases\ at\ any\ time{-}step)_i} \quad (1)$$

Where i = approach, and n= total number of approaches.

Note that Flow-ratio includes the cumulative departure and cumulative arrival flows from all the approaches of all stages irrespective of green or amber or red time intervals (or major and minor roads). The conception behind using Flow-ratio is, since it considers the combined effect of vehicle arrivals and departures on all approaches of all stages, if the green time is extended (limiting to the maximum green period) as long as the Flow-ratio is nearer to 1.0, the performance of the entire intersection can be improved without any congestion. The black curve in Fig. 1 represents Flow-ratio values.

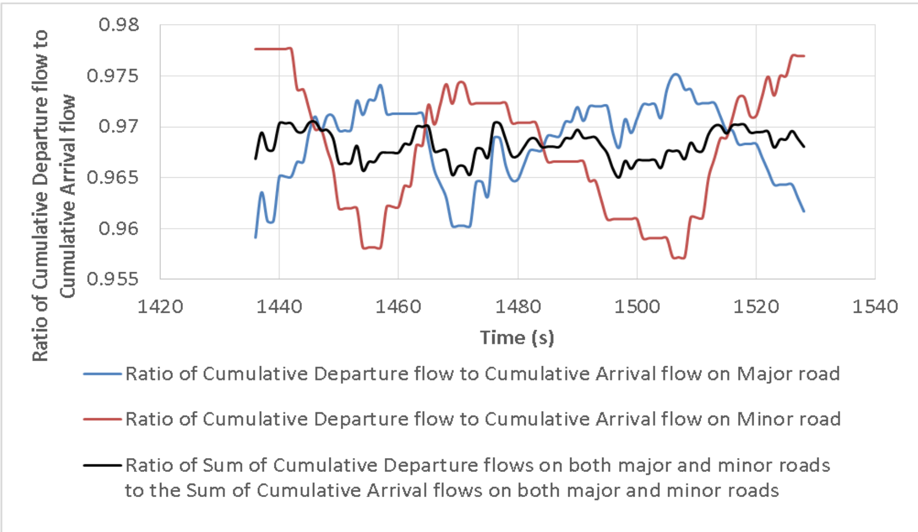

Fig. 1. Flow-ratio curve.

During the green interval of any cycle, if the Flow-ratio values at every time-step are estimated in advance, it will be possible to obtain the growth trend of the Flow-ratio and the green time can be extended till the point of time where the Flow-ratio is nearer to 1.0. Therefore, to estimate the Flow-ratio values in advance, the cumulative arrival and departure vehicle counts are to be known. To estimate the vehicle arrival rates for future time, a vehicle arrival model has to be used. To estimate the vehicle departure counts at the stop-line for future time, individual vehicle positions are needed, which can be predicted from a car-following model. The next section illustrates how to estimate the positions of individual vehicles using a car-following model by utilizing the information provided by the connected vehicles.

3.2. Vehicle location estimation using a Car-following model

In this paper, the Wiedemann’74 car-following model is used to predict the location of individual vehicles. The Wiedemann model is used as the basis for the microscopic simulation software VISSIM (PTV AG, 2015a). The model estimates the thresholds for a driver’s decision to accelerate or decelerate based on driver’s perceptions of changes in the relative velocity. The model uses four states: free driving, following, closing, and emergency, to classify the state of a moving vehicle. A vehicle’s current state is based on its change in headway and relative velocity of the leading vehicle. The Wiedemann model has several calibration parameters to determine a vehicle’s state and the corresponding rate of acceleration (see Table 1), which are derived from empirical freeway data collected by Wiedemann and Reiter (1992). The working procedure to estimate a vehicle’s position, speed and acceleration is inspired by Goodall (2013).

Using the calibration parameters from the Table 1, each vehicle will be classified into one of the four states of Wiedemann model. The decision process to select the correct state is demonstrated in Fig. 2. Once the vehicle’s state is determined, its acceleration(a_n^t), speed (v_n^t), and position (x_n^t) at time *t*, scan-interval (Δt)are determined according to the following equations.

Table 1. Vehicle input flows for different scenarios (Wiedemann and Reiter, 1992; Goodall, 2013)

Parameter	**Description**	**Value used**	**Unit**
Δx	Headway	$x_{n-1} - x_n$	*m*
Δv	Relative velocity	$v_n - v_{n-1}$	*m/s*
Δt	Scan interval	1.0	*s*
l_n, l_{n-1}	Length of vehicle	4.75	*M*
v	Min speed of vehicle and leader	$\min\{v_n, v_{n-1}\}$	*m/s*
AX	Min headway	$l_n + 2.5 = 7.25$	*m*
BX	Calibration factor	$2.5\sqrt{v}$	-
ABX	Desired min headway at low Δv	$AX + BX = 7.25 + 2.5\sqrt{v}$	*m*
CX	Calibration factor	40	-
EX	Calibration factor	1.5	-
a_{max}	Max acceleration	$3.5 - \frac{3.5}{40}v$	*m/s*^{2}
a_{min}	Min acceleration	$-20 + \frac{1.5}{60}v$	*m/s*^{2}
SDX	Maximum following distance	$AX + EX \times BX = 7.25 + 3.75\sqrt{v}$	*m*
SDV	Decreasing speed difference	$\left(\frac{\Delta x - AX}{CX}\right)^2 = \left(\frac{\Delta x - 7.25}{40}\right)^2$	*m/s*
OPDV	Increasing speed difference	$-2.25SDV$	*m/s*

In the **free-state**, the acceleration rate is either the maximum possible acceleration rate, or the acceleration rate needed to reach the desired speed, whichever is lower. The acceleration rate at any time *t* is defined in Eq. (2).

$$a_n^t = min\{a_{max}^{t-\Delta t}, v_{des} - v_n^{t-\Delta t}\} \tag{2}$$

For the **emergency-state**, defined by Eq. (3), the vehicle attempts to slow as quickly as possible to avoid a collision.

$$a_n^t = \frac{1}{2}\left(\frac{(\Delta v)^2}{AX-\Delta x}\right) + a_{n-1}^{t-\Delta t} + a_{min}^{t-\Delta t} \cdot \left(\frac{ABX-\Delta x}{BX}\right) \tag{3}$$

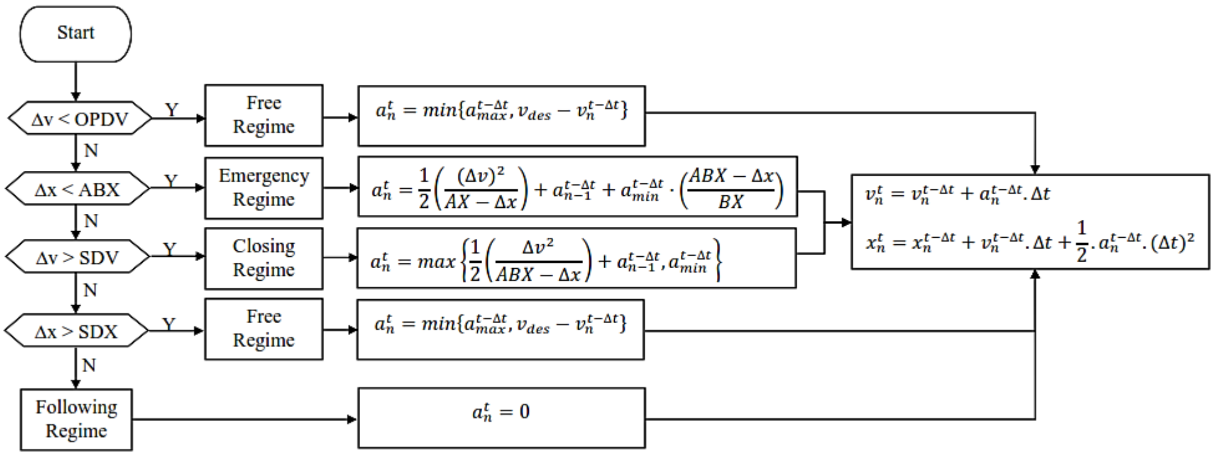

Fig. 2. Decision flowchart to select a vehicle's state and calculate its acceleration, speed and position (Goodall, 2003).

In the **closing-state**, defined by Eq. (4), the vehicle decelerates at a rate designed to start following the lead vehicle.

$$a_n^t = max\left\{\frac{1}{2}\left(\frac{\Delta v^2}{ABX - \Delta x}\right) + a_{n-1}^{t-\Delta t}, a_{min}^{t-\Delta t}\right\} \quad (4)$$

In the **following-state**, given by Eq. (5), the vehicle maintains its speed with an acceleration equal to zero.

$$a_n^t = 0 \quad (5)$$

Based on Newton's laws of motion, the governing equations for vehicle's speed and position were defined as,

$$v_n^t = v_n^{t-\Delta t} + a_n^{t-\Delta t}.\Delta t \quad (6)$$

$$x_n^t = x_n^{t-\Delta t} + v_n^{t-\Delta t}.\Delta t + \frac{1}{2}.a_n^{t-\Delta t}.(\Delta t)^2 \quad (7)$$

3.3. Proposed Connected Vehicle Signal Control (CVSC) strategy

The objective of this strategy is to develop a traffic signal timing algorithm for an isolated intersection, which minimizes the travel time delay and average number of stops per vehicle, taking into account the arrival and departure flows of all vehicles on all the approaches of the intersection at every time-step. This strategy utilizes the CV data assuming that all vehicles (with 100% GPS market penetration with a DSRC range of 300m before the stop-line) would share their information (such as acceleration, speed, and global position coordinates) at every second to the signal controller. The CVSC strategy aims at achieving better measures of effectiveness (MOE's) (travel time delay and number of stops per vehicle) when compared to an actuated signal control solution. The flowchart of CVSC algorithm is shown in Fig 4. The strategy is explained step-wise as below.

Step-1: During the green interval of a cycle, minimum green time is provided (limiting to the maximum green period) until the last-vehicle that was in queue during the red interval, with a speed of 'zero kmph', crosses the stop-line coordinate. This time period is termed as "Zero-speed queue service time". Once this time period is finished, the algorithm moves to next step.

Step-2: This step aims to serve the vehicles that were joining the queue whose speeds are more than zero kmph. In this step, a metric called "Speed-ratio" is defined as follows,

$$Speed\text{-}ratio = \frac{\begin{matrix}(Actual\ \ space\ mean\ speed\ of\ all\ vehicles \\ in\ the\ current\ green\ phase\ at\ the\ current\ time\ step \times 100)\end{matrix}}{\begin{matrix}(Desired\ space\ mean\ speed\ of\ all\ vehicles \\ in\ the\ current\ green\ phase\ at\ the\ current\ time\ step)\end{matrix}} \quad (8)$$

The metric in Eq. (8) indicates if the approaching vehicles are moving close to their free flow speed or desired speed. The green time after step-1 is continued to extend (limiting to the maximum green period) till the speed-ratio is greater than or equal to 90%. In other words, this step ensures that the green time is extended till the average speed of all vehicles in the current green interval reaches 90% of its desired speed.

Step-3: Once the speed-ratio has reached to 90%, calculate the time that is still available to utilize the green interval until the maximum green period is reached. This time is termed as "Reserve-time".

Reserve-time = (Maximum green time of current stage – Zero speed queue service time – Time when the speed-ratio reaches 90%)

The maximum green time is calculated by finding the average actual green times of past five cycles and multiplying it by a factor 1.30. This factor accommodates well, most fluctuations in vehicle arrival rates.

Step-4: At this time-step, the Flow-ratio from Eq. (1) should be determined for every second for the horizon period of Reserve-time. The algorithm to calculate Flow-ratio is presented in Fig. 3. To determine Flow-ratio, the cumulative arrival flows and cumulative departure flows on each approach are needed. Using the CV information, the cumulative arrival flows at each time-step are measured at 300m before the stop-line on all approaches. However, to estimate the future arrival flows for the period of Reserve-time, a vehicle arrival model has to be used. In this paper, Poisson distribution is used to generate vehicle arrivals. The probability density function of the Poisson distribution is defined in Eq. (9).

$$p(x) = \frac{\mu^x e^{-\mu}}{x!} \quad (9)$$

Where $p(x)$ is the probability for x vehicles that will arrive during Reserve-time period, and μ is the arrival flow rate for the interval of Reserve-time.

The value of μ for the period of Reserve-time is calculated as the Reserve-time period multiplied by the cumulative vehicle count (taken at 300m before the stop-line) and divided by the current time-step.

To estimate the vehicle departure counts at the stop-line at every second for the horizon period of Reserve-time, the individual vehicle positions are predicted using the car-following model algorithm which was presented in Fig. 2. The results of car-following algorithm are taken into the Flow-ratio algorithm (see Fig. 3) to plot the Flow-ratio values at every second for the horizon period of Reserve-time. Fig. 4 shows the Flow-ratio plot, pointing the time where the Flow-ratio is nearer to 1.0.

Step-5: The green time after step-2 is continued to extend (limiting to the maximum green period) until the time (T_f), where the estimated Flow-ratio is nearer to 1.0.

Step-6: Once the current green interval is ended, the next green interval is decided for the signal group which has the highest number of vehicles standing in queue with 0kmph speed, which is found during the end of the red interval of each signal group.

Step-7: Switch to the next stage by repeating the procedure from Step-1.

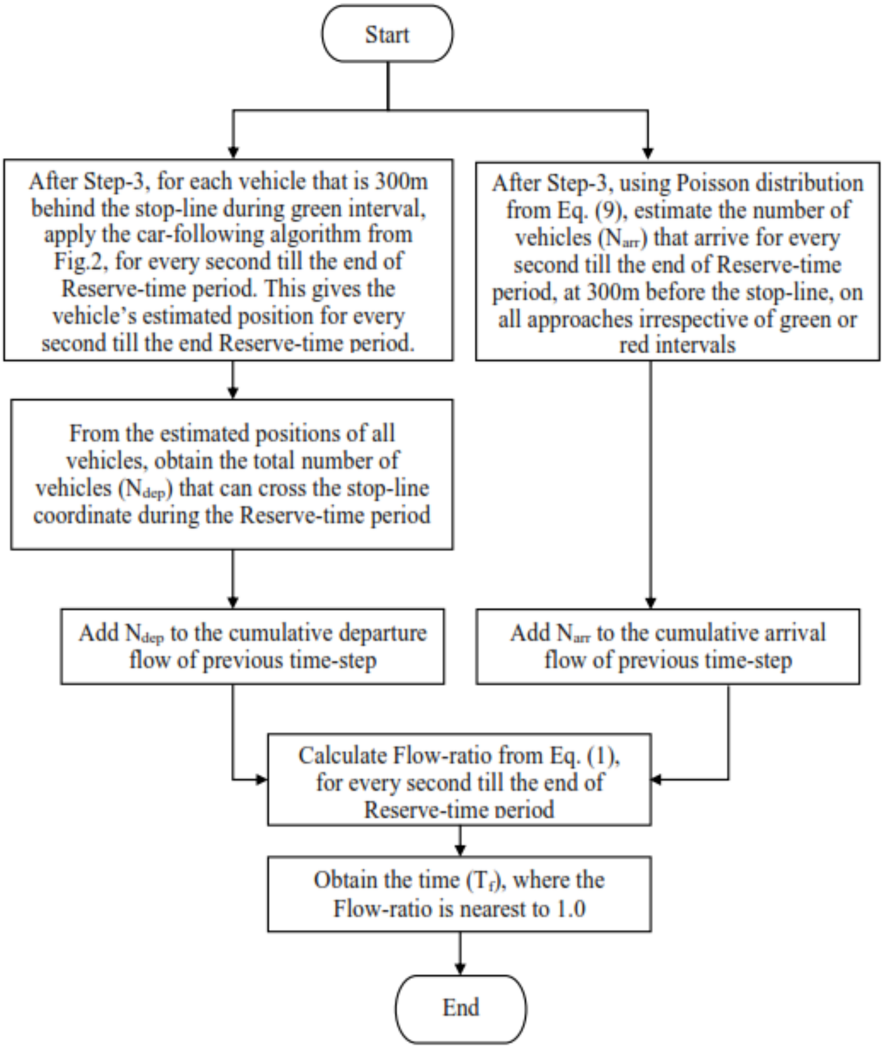

Fig. 3. Flowchart for the estimation of Flow-ratio for the period of Reserve-time.

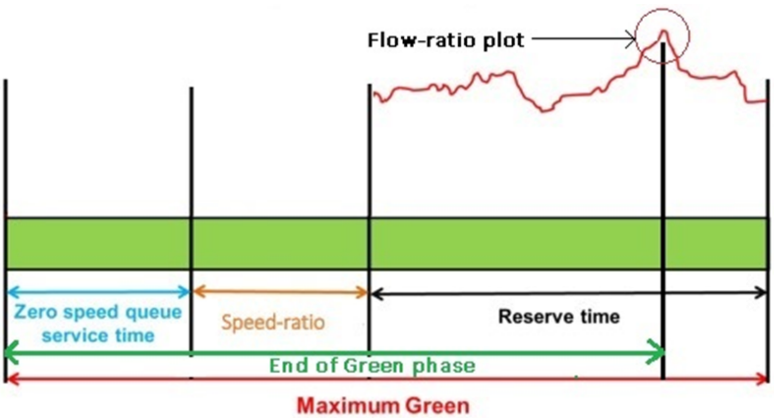

Fig. 4. Different components of a green interval and Flow-ratio plot in CVSC strategy.

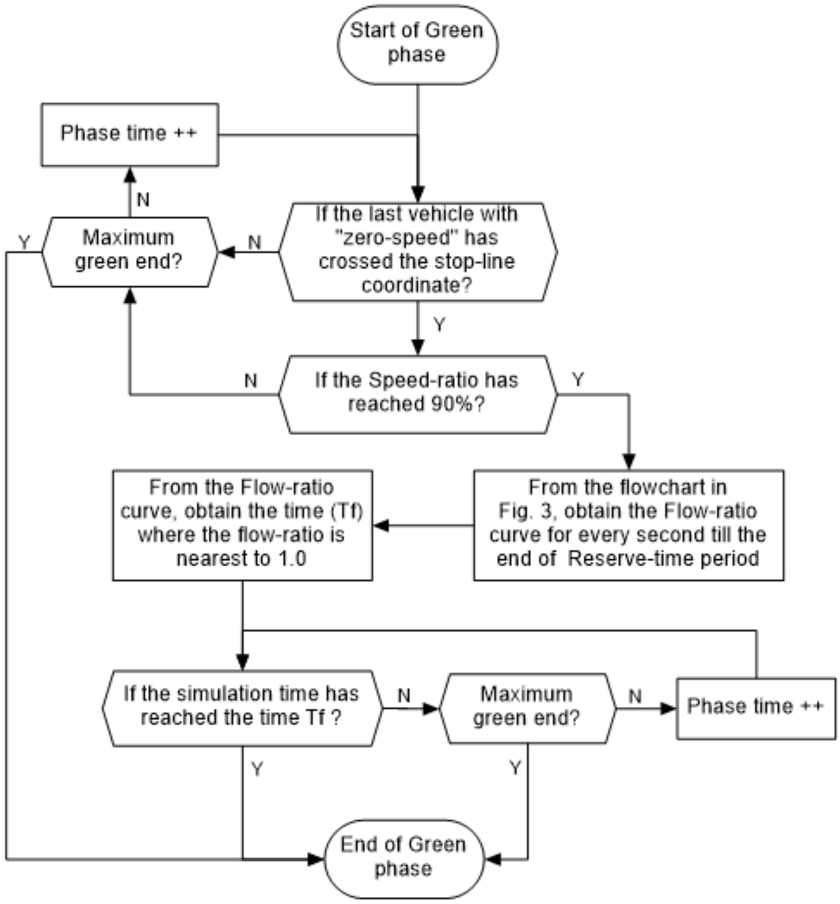

Fig. 5. Flowchart of CVSC algorithm.

It should be noted that the Flow-ratio concept is applied only once, during the start of the Reserve-time period and not from the start of the green interval. The flowchart of the car-following algorithm in Fig. 2 is the sub algorithm that runs in Flow-ratio estimation algorithm in Fig.3 and the flowchart of Flow-ratio estimation algorithm (Fig. 3) is the sub-algorithm that runs in the CVSC algorithm presented in Fig. 5.

3.4. Adaptive traffic signal control by PTV EPICS

The proposed CVSC strategy is compared with a real-time traffic adaptive system which is developed by PTV EPICS, exclusively for isolated intersections (PTV AG, 2015b). EPICS's microscopic optimization model optimizes a target function consisting of total delay as the Performance Index (PI) (see Eq. (10)), on the basis of the picture of the current situation that it has from status changes of detectors and of the various signal groups.

$$PI(sp) = \sum_{sg \in SG} \alpha_{sg} D_{sg}(sp) + \beta \Delta(ref, sp) \quad (10)$$

Where,

SG - set of signal groups.
sp - signal plan to be valued.
ref - reference signal plan, given by the user.
α_{sg} - weighting of the signal group sg.
D_{sg} - sum of the delay at signal group sg over time horizon (100s) considered.

Δ - deviation of control alternative sp from ref.
β - weighting of deviation from ref.

Table 2. EPICS stage parameters for the reference signal plan (PTV AG, 2015b)

Parameter	Description
Stage Nr.	Defined stage number
Earliest start	Cycle second (s) defining the earliest possible start of the cycle for the corresponding stage
Latest End	Cycle second (s) defining the latest possible end of the cycle for corresponding stage
Minimum length	The minimum green interval for the corresponding stage
Maximum length	The maximum green interval for the corresponding stage
Preferred start/end	Preferred start and end time of the reference fixed time signal plan
Cost/sec Preferred/Non-Preferred	The objective function of PTV EPICS considers the active traffic demands and potential additional costs to activate any stage. Inside the interval defined by Preferred start/end, Cost/sec Preferred is applied. Outside the interval defined by Preferred start/end, Cost/sec Non-Preferred is applied

The optimization model in EPICS works on a stage-based control strategy, which means it calculates a stage sequence that minimizes the performance index for the given time horizon of 100 seconds (PTV AG, 2015b). To measure the traffic situation, EPICS uses detectors that are ideally placed 50 to 80m upstream of the stop-line corresponding to about 4 to 6 seconds, so that the traffic light system can react to an approaching group of vehicles. If a detector is occupied for more than 4 seconds, EPICS assumes that the queue ranges beyond the detector and applies the queue length estimator algorithm according to the method of Liu et al. (2009). This technique identifies the queue length beyond the detector during green, and predicts this value for the next cycle. In this paper, detectors of 3m size are placed 80m before the stop-line.

EPICS requires the provision of a reference signal plan (Eq. (10)) and stage dependent parameters that define parameters and boundaries for the optimization. The stage dependent parameters with their definitions are presented in Table 2. The values considered for different parameters are presented in the next section.

4. Simulation tests and results

4.1. Simulation framework

The testing and evaluation of the proposed CVSC strategy are done by comparison with the EPICS's adaptive signal control and Webster's fixed-time signal control, in the microscopic simulation software VISSIM 8 (PTV AG, 2015a), which has PTV EPICS adaptive signal control module embedded in it. Thus VISSIM 8 provides same platform for the comparison of CVSC strategy and EPICS actuated solution. The entire CVSC algorithm is coded in C++ language and was integrated with VISSIM COM Application Programming Interface (API). Note that VISSIM provides the vehicle information (position, speed, and acceleration) through its IVissim object of COM API. This information is used at every time-step in CVSC strategy.

The test network is a four-legged isolated intersection along Castle Downs Road and 97 Street, Edmonton, Canada (see Fig. 6). Vehicle volumes and turning movements were taken from Edmonton (2015), which were collected in 2012, between 4:40PM and 5:40PM on weekdays. Pedestrian movements which were very low at the intersection, were not considered in the analysis. Volumes for each movement are listed in Table 3.

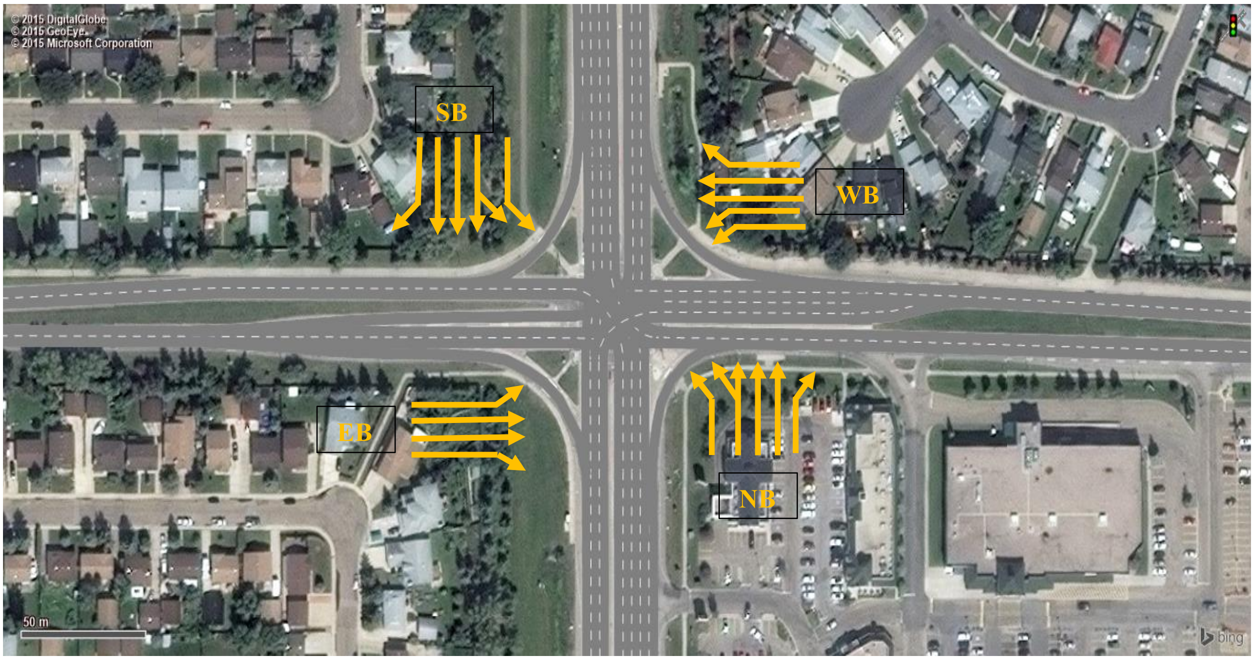

Fig. 6. Snapshot of test intersection in VISSIM 8 (background image from Bing maps).

Vehicle volumes were converted to approximate intersection saturation rates using Intersection Capacity Utilization metric (ICU), provided by Trafficware software (David and John, 2003). The field recorded volumes produced 0.65 ICU across the intersection. These original volumes were altered by uniform factors to generate volumes of 0.35, 0.50, 0.80, 0.95 ICU respectively, as shown in Table 3.

Table 3. Tested volumes along the Castle Downs Road and 97 Street, Edmonton.

	Turning movements											
ICU	**EBL**	**EBT**	**EBR**	**WBL**	**WBT**	**WBR**	**NBL**	**NBT**	**NBR**	**SBL**	**SBT**	**SBR**
0.35	35	296	99	159	225	103	244	514	239	108	452	268
0.50	50	423	141	228	322	148	348	735	341	154	645	383
0.65	65	550	183	296	418	192	453	955	443	200	839	498
0.80	80	677	225	364	514	236	558	1175	509	246	1033	613
0.95	95	804	267	433	611	281	662	1396	605	292	1226	728

The turning movements were allocated to four different stage groups, namely, Stage group-1 (EBL, EBT), Stage group-2 (WBL, WBT), Stage group-3 (NBL, NBT), and Stage group-4 (SBL, SBT). The movements EBR, WBR, NBR, and SBR have free dedicated right turns irrespective of any stage. In CVSC strategy, a four-staged timing plan is applied within a cycle. As mentioned earlier, the sequence to provide green to any of the four stage groups within a cycle, is based on the highest number of vehicles that were stopped with 0kmph, which is found during the end of their red interval.

As mentioned previously, EPICS requires the provision of a reference signal plan and stage dependent parameters that define boundaries for the optimization. The stage dependent parameters for different values of ICU are fine tuned to obtain the lowest Performance Index. Table 4 presents a four-staged reference signal plan and the parameters that are used in EPICS optimization. It should be noted that the signal plan presented in Table 4 is not the actuated signal plan generated by EPICS, but the reference fixed-plan that is required for EPICS optimization in Eq. (10), to know the deviation from its actuated signal plan.

Table 4. EPICS Reference Signal Plan and Stage Parameters

ICU	Movements/ Stages	Earliest start	Latest End (s)	Minimum length (s)	Maximum length (s)	Preferred start	Preferred end	Cost/sec Preferred	Cost/sec Non-Preferred
0.35	NL, NT	0	38	5	8	0	8	0	0
	SL,ST	0	38	5	7	11	18	0	0
	EL, ET	0	38	5	6	21	27	0	0
	WL,WT	0	38	5	5	30	35	0	0
0.5	NL, NT	0	38	5	8	0	8	0	0
	SL,ST	0	38	5	7	11	18	0	0
	EL, ET	0	38	5	6	21	27	0	0
	WL,WT	0	38	5	5	30	35	0	0
0.65	NL, NT	0	42	8	9	0	9	0	0
	SL,ST	0	42	8	8	12	20	0	0
	EL, ET	0	42	5	7	23	30	0	0
	WL,WT	0	42	5	6	33	39	0	0
0.8	NL, NT	0	63	13	16	0	16	0	0
	SL,ST	0	63	13	14	19	33	0	0
	EL, ET	0	63	10	12	36	48	0	0
	WL,WT	0	63	5	9	51	60	0	0
0.95	NL, NT	0	127	15	37	0	37	0	0
	SL,ST	0	127	15	32	40	72	0	0
	EL, ET	0	127	12	26	75	101	0	0
	WL,WT	0	127	8	20	104	124	0	0

In all the tests of CVSC, EPICS, and Fixed-time signal control, simulation is run for 3900 seconds in which the first 300 seconds was used as warm-up period. The results of various scenarios are based on the average of 10 random seeds. Same random seeds were used in comparing all the signal control strategies. It should be noted that the green times and cycle lengths in both CVSC strategy and EPICS solution are not constant and are varying according to their respective working principles. In fixed-time control, the cycle times calculated by Webster's method are found to be 38, 38, 42, 63, and 127 seconds for the ICU's 0.35, 0.50, 0.65, 0.80, and 0.95 respectively, and the green times are determined according to the splits of the expected demand, with at least 5 seconds for each stage. Cars, Buses, and Heavy goods vehicles (HGV) are used in the simulation. The proportion of Cars, Buses, and HGV's in the original volumes were found to be 95%, 3%, and 2% respectively.

4.2. Simulation scenarios and results

Two sets of scenarios were evaluated in which traffic conditions were varied by varying ICU's, and varying the proportions of Cars. Buses and HGV's in total flow in order to test the CVSC algorithm's performance in different traffic conditions. To compare the evaluation results of all the signal controls, travel time delay and average number of stops per vehicle were used as MOE's.

Scenario 1: Variation in ICU

In this scenario, input flow from Table 3 is assigned according to different ICU values. The proportion of Cars, Buses, and HGV's in the total flow were taken as 95%, 3%, and 2% respectively. The minimum and maximum desired speeds of Cars, Buses and HGV's are taken as 48-58 kmph, 40-45 kmph, and 40-45 kmph respectively. The results of this scenario are shown in Fig. 7.

From Fig. 7, it can be seen that the CVSC strategy outperformed the fixed-time solution and EPICS adaptive solution in both measures of effectiveness. For various ICU's, CVSC strategy has reduced 5.7% to 25.2% of travel time delay and 2.1% to 9.9% of average number of stops per vehicle, when compared to the EPICS solution, with benefits being higher at higher ICU's. When compared to the fixed-time control, CVSC strategy has reduced between 15.4% and 41.1% of travel time delay and between 10.4% and 14.4% of average number of stops per vehicle. When queues were formed at higher ICU's, EPICS estimates the queues according to the method of Liu et al. (2009), by using the vehicle information from fixed detectors and optimize the delay based Performance index for 100s horizon period. While the step-by-step process of CVSC strategy serves all the vehicles that were queued-up during the red interval, then serves more vehicles till the average free flow speed of all the vehicles in the green interval reaches 90%, and utilizes the Reserve-time period by extending the green till the Flow-ratio is nearer to 1.0. This process has made the CVSC strategy to perform better than both the fixed-time solution and EPICS optimized solution.

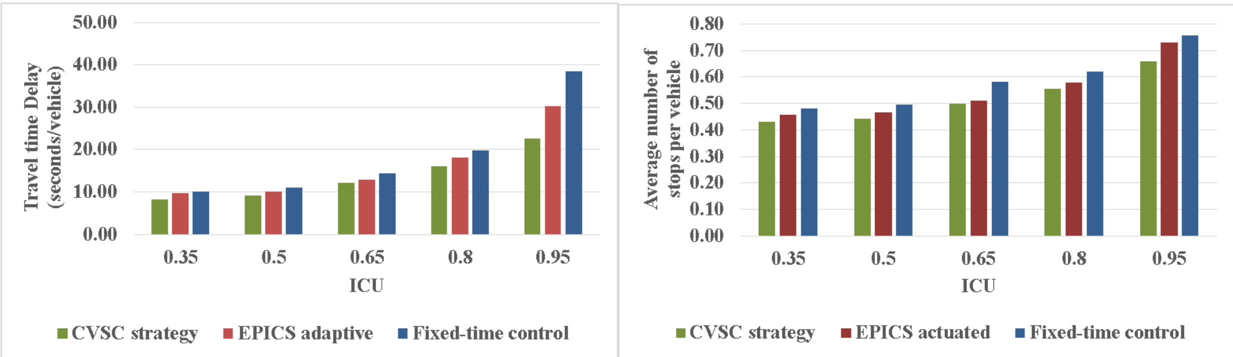

Fig. 7. Performance of CVSC strategy at various ICU's.

Scenario 2: Variation in proportion of vehicle types in total flow

In this scenario, ICU is kept constant at 0.65 and the proportion of Cars, Buses and HGV's are varied in the total input flow (see Table 5).

Table 5. Variation in Vehicle Type Proportion.

ICU	Percent Cars in total flow	Percent Buses in total flow	Percent HGV's in total flow	Car Desired speed (kmph) (Min-Max)	Bus Desired speed (kmph) (Min-Max)	HGV Desired speed (kmph) (Min-Max)
0.65	85%	9%	6%	48-58	40-45	40-45
0.65	90%	6%	4%	48-58	40-45	40-45
0.65	95%	3%	2%	48-58	40-45	40-45

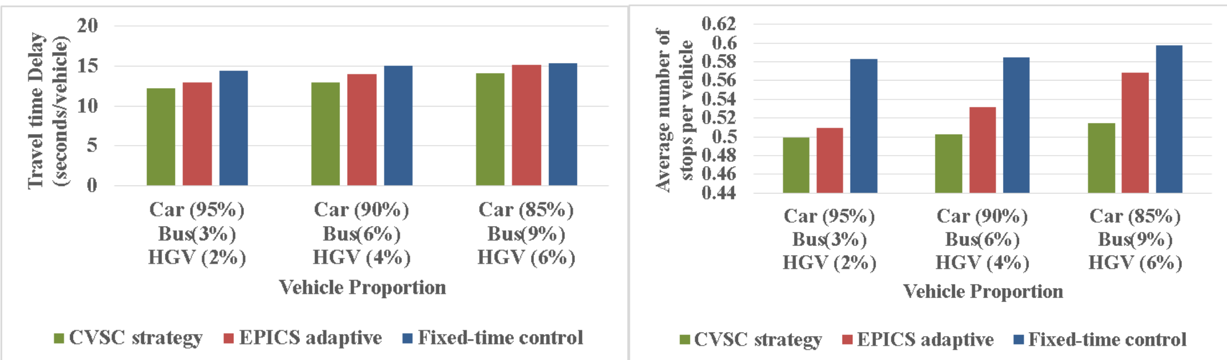

Fig. 8. Performance of CVSC strategy at various vehicle type proportions.

The results show that the higher the proportion of HGV's and Buses, the higher is the travel time delay and average number of stops per vehicle (see Fig. 8). This is because, due to the lower speeds of Buses and HGV's in total flow causes the Cars that are travelling behind them, to reduce their speeds. In this scenario, the CVSC strategy has also shown better performance compared to both the fixed-time and EPICS solutions. When the Car proportion was 95% in total flow, CVSC strategy showed 5.7% lesser travel time delay and 2.1% lesser stops compared to the EPICS solution. For the same case, when compared to the fixed-time solution, CVSC strategy showed 15.4% lesser travel time delay and 14.4% lesser stops. When the Car proportion was lowered to 85% in total flow, CVSC strategy showed 6.6% lesser travel time delay and 9.4% lesser stops compared to the EPICS solution. For the same case, when compared to the fixed-time solution, CVSC strategy showed 8.3% lesser travel time delay and 13.8% lesser stops.

Analysis of the vehicle location estimations

As mentioned in the methodology of CVSC strategy, to obtain Flow-ratio, the positions of the vehicles are estimated for the future period of Reserve-time using the car-following model. Fig. 9 shows a plot between Reserve-time period vs estimated and actual vehicle locations, on lane-1 of NB approach, during one particular stage. On the secondary vertical axis, Flow-ratio values were plotted for the period of Reserve-time. As per CVSC strategy, once the Speed-ratio has reached 90%, the actual positions and speeds of all the vehicles of that green stage, which are before the stop-line are given as input to the car-following model (as in Fig. 2) and their positions are estimated for every second for the future period of Reserve-time (see Fig. 9). The Flow-ratio values (as in Fig. 3) were also determined for the future period of Reserve-time (secondary vertical axis in Fig. 9). It should be noted that the Flow-ratio values in Fig. 9 are determined based on the cumulative departure flows and cumulative arrival flows of all the approaches.

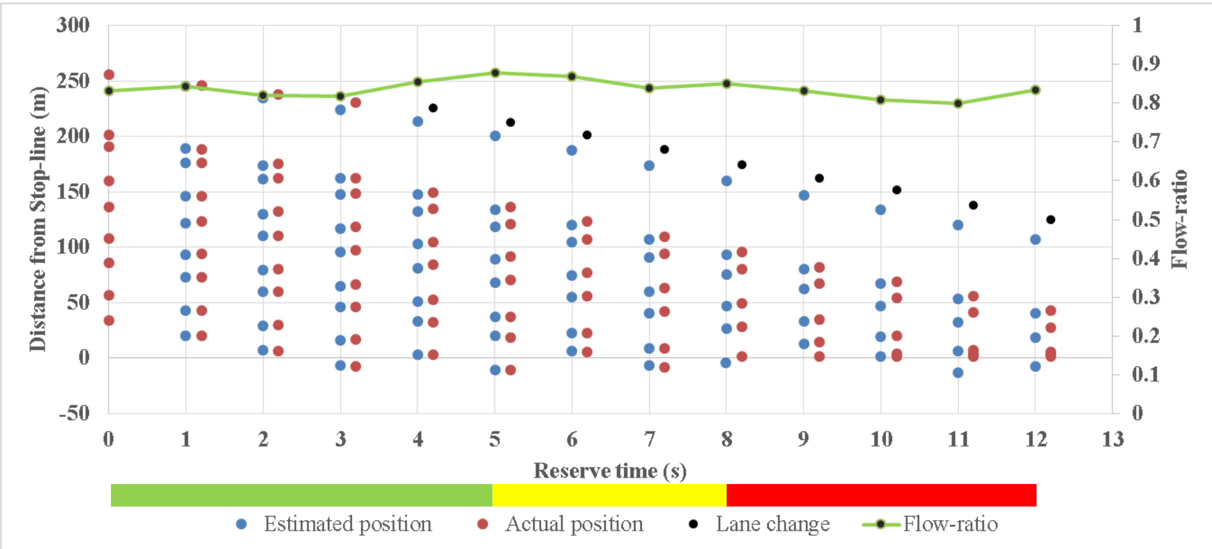

Fig. 9. Estimated and actual vehicle location trajectories.

From Fig. 9, it can be observed that the Reserve-time period for that particular green stage was found to be 12.0 seconds. 9 vehicles were found to be travelling on this lane, whose actual positions were plotted at the 0^{th} second. These actual positions of the 9 vehicles were then taken into the car-following model and their positions were estimated and plotted for the future period of a Reserve-time with 12.0 seconds. The estimated maximum Flow-ratio value was 0.878, which is at the 5^{th} second of the Reserve-time period. Hence the green time was extended for 5 seconds and the stage was terminated at the 5^{th} second of the Reserve-time period. The Mean Absolute Percentage Error (MAPE) between the estimated and actual positions of the vehicles on lane-1for that particular case as shown in Fig. 9, is found to be 3.14%. Since the Cars' desired speed range is taken as 48-58 kmph, whose standard deviation is only 5kmph (less deviation) from the mean speed, it is believed that the estimated vehicle positions were found to be closer to the actual positions with lower MAPE. It should also be noted that, during the estimation of future vehicle positions, lane-changing behavior was not considered. Hence, the error in estimating the vehicles that change lanes during Reserve-time period was not considered in calculating MAPE. However, they were unable to cross the stop-line before the time-step where the Flow-ratio is maximum and hence the error in estimation of vehicle positions due to lane-change behavior is negligible in determining the Flow-ratio.

Green-time comparisons

In this section, the green intervals of CVSC, EPICS and Fixed-time controls are compared for the critical stage (NB approach). Fig. 10 shows the stage length and cycle length comparisons during 1 hour simulation, for the critical stage of 0.95 ICU case.

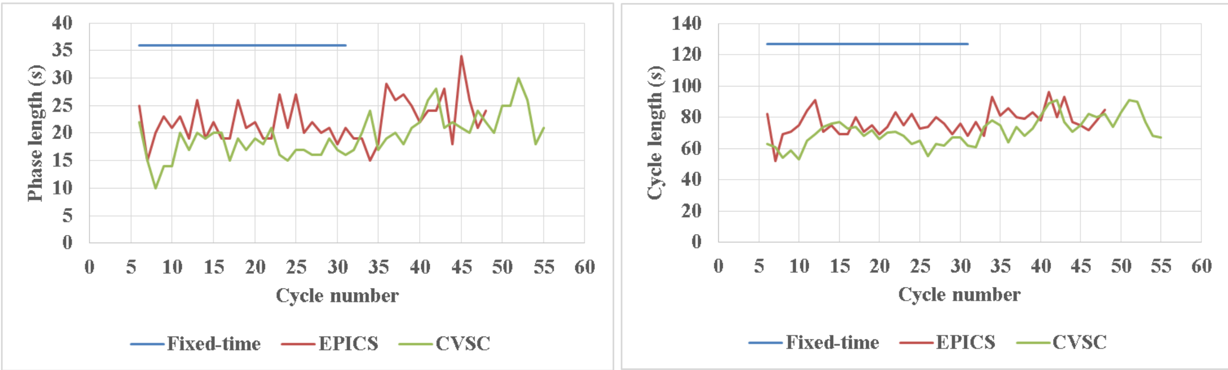

Fig. 10. Green-time comparisons between CVSC, EPICS and Fixed-time controls.

Note that the first 5 cycles were considered as warm-up period and were not shown in the graph. It can be observed that CVSC strategy with 100% penetration rate, consistently has lower green times and more number of cycles compared to EPICS and fixed-time control, which has resulted in lower delays and lower number of stops in all the scenarios .

5. Conclusions and future work

A real-time traffic signal control algorithm using connected vehicle technology (CVSC) is presented in this paper. The algorithm assumes various penetration rates of GPS equipped vehicles and uses the position and speed information of all vehicles in a traffic stream at every time-step. Green times are set to serve completely the actual queue identified during the red interval. The strategy aims at minimizing the difference between arrival flow and departure flow by maintaining the ratio of the sum of cumulative departure flows on all approaches to the sum of cumulative arrival flows on all approaches (Flow-ratio) nearer to 1.0. Wiedemann Car-following model is used for the estimation of the future vehicle positions that were used in calculating the Flow-ratio. The CVSC algorithm runs completely based on the real-time CV data collected at every time-step, except for the short duration of the Reserve-time. During Reserve time period, the algorithm estimates the future vehicle's positions using the car-following logic and applies the Flow - ratio concept to extend the green time. The preliminary testing of its performance suggests potential for taking advantage of the more detailed, real-time, and geographically extensive data which might be obtained from connected vehicles, resulting in a potential for increased performance in relation to the current state-of-the-art approaches, which were developed to take advantage of more limited data. Simulations were performed on an isolated intersection of the city of Edmonton, Canada, in VISSIM 8 software. Different scenarios were tested, including varying ICU's, varying the proportion of Cars, Buses and HGV's in the total flow, and varying the GPS penetration rates. With 100% penetration rate, the proposed CVSC strategy outperformed the reference, fixed-time control and advanced detector based, EPICS adaptive strategy, in reducing the travel time delays and average number of stops per vehicle. The overall results seem to show a significant potential for the combined use of more real-time, geographically distributed information from connected vehicles, and of the development of new heuristics, capable of taking advantage of the detailed data. More significant testing of CVSC strategy is still needed.

Currently, the authors are working to tackle situations where, under lower GPS penetration rates, the proposed CVSC strategy estimate and takes into full consideration of the real-time locations and speeds of the vehicles that are not equipped with GPS.

References

Ahmane, M., Abbas-Turki, A., Perronnet, F., Wu, J., Moudni, A.E., Buisson, J., Zeo, R., 2013. Modeling and controlling an isolated urban intersection based on cooperative vehicles. Transportation Research Part C: Emerging Technologies. 28, 44–62.

Braun, R., Kemper, C., and Weichenmeier, F., 2008. Travolution—Adaptive Urban Traffic Signal Control with an Evolutionary Algorithm. In *Proceedings of the 4th International Symposium Networks for Mobility*, Germany.

David, H., and John, A., 2003. Intersection Capacity Utilization (ICU)-Evaluation procedures for intersections and interchanges. Trafficware, USA.

Department for Transport (DfT), 1997. *The MOVA signal control system*. Traffic advisory leaflet 3/97, UK.

Edmonton, 2015. Traffic volumes and turning movements. Transportation data for the city of Edmonton. http://www.edmonton.ca/transportation/traffic_reports/traffic-volumes-turning-movements.aspx (accessed 25.09.15).

Fan, B., Stancil, D. D., and Krishnan, H., 2010. Toward understanding characteristics of dedicated short range communications (DSRC) from a perspective of vehicular network engineers. ACM Press, 329.

Federal Highway Administration (FHWA), 2015. Connected vehicle – Real-time traveler information program. <http://ops.fhwa.dot.gov/travelinfo/infostructure/aboutinfo.htm> (accessed 20.05.15).

Feng, Y., Head, K. L., Khoshmagham, S., and Zamanipour, M., 2015. A real-time adaptive signal control in a connected vehicle environment. Transportation Research Part C: Emerging Technologies. 55, 460-473.Gartner, N. H., 1983. OPAC: A Demand-Responsive Strategy for Traffic Signal Control. In Transportation Research Record. Transportation Research Board 906, 75-81.

Goodall, N. J., 2013. Traffic Signal Control with Connected Vehicles. Dissertation, Virginia, USA, 2-10.

Guler, S. I., Menedez, M., Meier, L., 2014. Using connected vehicle technology to improve the efficiency of intersections. Transportation Research Part C: Emerging Technologies. 46, 121–131.

He, Q., Head, K. L., and Ding, J., 2012. PAMSCOD: Platoon-based arterial multimodal signal control with online data. Transportation Research Part C: Emerging Technologies. 20, 164-184.

Henry, J. J., Farges, J. L., and Tuffal, J., 1983. The PRODYN Real Time Traffic Algorithm. *Proceedings of the 4th IFAC/IFIP/IFORS Symposium on Control in Transportation Systems*, Germany, 305-310.

Herrera, J.C., Work, D., Ban, X., Herring, R., Jacobson, Q., and Bayen, A., 2010. Evaluation of Traffic Data Obtained via GPS-Enabled Mobile Phones: The Mobile Century Field Experiment. Transportation Research C. 18, 568-583

Hunt, P.B., Bretherton, R. D., Robertson, D. I., and Royal, M. C., SCOOT online traffic signal optimsation technique. Traffic Engineering and Control. 23, 190-192.

Institute of Transportation Engineers (ITE), 2015. Connected vehicle. US Department of Transportation Research and Innovative Technology Administration. <http://www.ite.org/connectedvehicle/overview.asp.> (accessed 26.07.15).

Intelligent Transportation Systems Joint Program Office. (ITSJPO), 2015. Connected Vehicle Policy and Institutional Issues. < http://www.its.dot.gov/connected_vehicle/connected_vehicle_policy_plan.htm> (accessed 27.10.2015).

Intelligent Transportation Systems Joint Program Office. (ITSJPO), 2016. Connected vehicles. < http://www.its.dot.gov/cv_basics/index.htm > (accessed 10.02.2016).

John, A., 2008. Vehicle-infrastructure integration (VII) initiative-Benefit-cost analysis version 2.3 (draft). Technical Report. FHWA, U.S Department of Transportation.

Koonce, P., 2008. Traffic Signal Timing Manual. Publication FHWA-HOP-08-024. FHWA, U.S Department of Transportation.

Lee, J., Park, B., and Yun, I., 2013. Cumulative travel-time responsive real-time intersection control algorithm in the connected vehicle environment. Journal of Transportation Engineering. 139, 1020–1029.

Liu, H., Wu, X., Ma, W., Hu, H., 2009. Real-time queue length estimation for congested signalized intersection. Transportation Research Part C: Emerging Technologies. 17(4), 412-427.

Mauro, V., and Di Taranto, C., 1989. UTOPIA CCCT'89 - *AFCET Proceedings*, Paris.

Mirchandani, P., and Head, L., 2001. RHODES: A real-time traffic signal control system: architecture, algorithms, and analysis, Transportation Research Part C. 9(6), 415-432.

NHTSA, 2014. U.S. Department of Transportation Issues Advance Notice of Proposed Rulemaking to Begin Implementation of Vehicle-to-Vehicle Communications Technology. <http://www.nhtsa.gov/About+NHTSA/Press+Releases/NHTSA-issues-advanced-notice-of-proposed-rulemaking-on-V2V-communications> (accessed 15.10.14).Priemer, C., and Friedrich, B., 2009. A decentralized adaptive traffic signal control using V2I communication data. 12th International IEEE Conference on Intelligent Transportation Systems, 1-6.

PTV AG., 2015a. PTV VISSIM 8 User Manual. PTV Planung Transport Verkehr AG, Karlsruhe, Germany.

PTV AG., 2015b. PTV EPICS User Manual. PTV Planung Transport Verkehr AG, Karlsruhe, Germany.

Sims, A. G., and Dobinson, K. W., 1980. The Sydney Coordinated Adaptive Traffic (SCAT) system philosophy and benefits. IEEE Transactions on Vehicular Technology. 29(2), 130-137.

Stevanovic, A., 2010. Adaptive Traffic Control Systems: Domestic and Foreign State of Practice – A Synthesis of Highway Practice. NCHRP Synthesis 403, USA.

Wiedemann, R., and Reiter, U., 1992. Microscopic traffic simulation: The simulation system MISSION, background and actual state. *Technical Report Project. ICARUS (V1052)*, CEC, Brussels.