Frontiers of Information Technology & Electronic Engineering
www.zju.edu.cn/jzus; engineering.cae.cn; www.springerlink.com
ISSN 2095-9184 (print); ISSN 2095-9230 (online)
E-mail: jzus@zju.edu.cn

Adaptive green traffic signal controlling using vehicular communication*

Erfan SHAGHAGHI[†1], Mohammad Reza JABBARPOUR[1,2], Rafidah MD NOOR[1], Hwasoo YEO[3], Jason J. JUNG[4]

(*[1]Department of Computer Systems and Technology, University of Malaya, Kuala Lumpur 50603, Malaysia*)
(*[2]Department of Computer Engineering, Islamic Azad University, North Tehran Branch, Tehran, Iran*)
(*[3]Department of Civil and Environmental Engineering, Korea Advanced Institute of Science and Technology, Daejeon 305701, Korea*)
(*[4]Department of Computer Engineering, Chung-Ang University, Seoul 156-756, Korea*)
[†]E-mail: erfan_shaghaghi@siswa.um.edu.my

Received Oct. 21, 2015; Revision accepted Feb. 16, 2016; Crosschecked Feb. 21, 2017

Abstract: The importance of using adaptive traffic signal control for figuring out the unpredictable traffic congestion in today's metropolitan life cannot be overemphasized. The vehicular ad hoc network (VANET), as an integral component of intelligent transportation systems (ITSs), is a new potent technology that has recently gained the attention of academics to replace traditional instruments for providing information for adaptive traffic signal controlling systems (TSCSs). Meanwhile, the suggestions of VANET-based TSCS approaches have some weaknesses: (1) imperfect compatibility of signal timing algorithms with the obtained VANET-based data types, and (2) inefficient process of gathering and transmitting vehicle density information from the perspective of network quality of service (QoS). This paper proposes an approach that reduces the aforementioned problems and improves the performance of TSCS by decreasing the vehicle waiting time, and subsequently their pollutant emissions at intersections. To achieve these goals, a combination of vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications is used. The V2V communication scheme incorporates the procedure of density calculation of vehicles in clusters, and V2I communication is employed to transfer the computed density information and prioritized movements information to the road side traffic controller. The main traffic input for applying traffic assessment in this approach is the queue length of vehicle clusters at the intersections. The proposed approach is compared with one of the popular VANET-based related approaches called MC-DRIVE in addition to the traditional simple adaptive TSCS that uses the Webster method. The evaluation results show the superiority of the proposed approach based on both traffic and network QoS criteria.

Key words: Vehicular ad hoc network (VANET); Intelligent transportation systems (ITSs); Clustering; Adaptive traffic signal control; Traffic controller; Fuel consumption
http://dx.doi.org/10.1631/FITEE.1500355 **CLC number:** U491

1 Introduction

The fast growth of vehicle use in recent decades has resulted in the overload of the road network and traffic congestions in urban areas. Moreover, this has prominently affected the increase of vehicular emission, travel time, and considerable economic losses (Litman, 2013). In the report by the U.S. Energy Information Administration (2008), it is estimated that 40% of carbon dioxide emission is associated with vehicles and residences (EIA, 2009). From the other side, the Texas A&M Transportation Institute (Schrank *et al.*, 2012) has reported that the rise of fuel consumption in 2015 was estimated up to 2.5 billion gallons, which is 0.6 billion gallons more than that in 2010 and is equivalent to 131 billion

* Project supported by the UM High Impact Research MoE Grant from the Ministry of Education, Malaysia (No. UM.C/625/1/HIR/MOHE/FCSIT/09)
ORCID: Erfan SHAGHAGHI, http://orcid.org/0000-0003-4461-9334

dollars in cost. Accordingly, traffic specialists have concentrated on the utilization of traffic control policies as a more rational way to approach this problem. Traffic signal control has always been under consideration as the most significant method of traffic control policies in urban areas for the amelioration of traffic flows (Köhler and Strehler, 2010). From the early 1900s, the gradual evolution of traffic signal control from its first concept took place, and has led to current states of traffic signals. Consideration of developing traffic signal controlling systems (TSCSs) can be categorized into three control schemes: fixed-time TSCSs, actuated TSCSs, and adaptive TSCSs (Shelby, 2001; Gordon *et al.*, 2005). The fixed-time TSCSs use a predetermined and measured phase timing plans that operate specifically for different time of the day in accordance with the traffic rush hours. The actuated TSCSs consider the minimum and maximum green time intervals for each phase of traffic signal according to the computed daily traffic demands. The actuated TSCSs use vehicle actuation logic by taking advantage of loop detectors (Bruce, 1984) which are usually mounted in side-movements to detect the presence of vehicles and allocate either the minimum or maximum phase timing interval. Utilization of both fixed-time and actuated TSCSs in today's urban life has become inefficient from the point of view of dealing with unexpected traffic congestions during the day and their inability to generate the accurate traffic signal timing in accordance with the current state of traffic in real time. On the contrary, the adaptive TSCS, as the most advanced scheme of suggested TSCS categories, has been proposed to provide fully real-time feedback of the traffic signal to dynamic variation of traffic demand for each traffic signal's cycle at an intersection. Implementation of adaptive TSCSs has commonly been affected by employing sensors such as loop detectors, video-based traffic monitoring cameras (Puri *et al.*, 2007), and microwave detectors (Dickinson and Wan, 1990) for capturing traffic information. The information computed by the detectors may differ in the matter of density measurement variables. These detectors are physically connected to a traffic signal controller that is placed at the intersection and send the measured information on the density of vehicle clusters in each road segment of the intersection (Tomescu *et al.*, 2012). The utilization of physical detectors, as customary instruments for the computation of vehicular density information, has noticeable drawbacks such as high maintenance costs, a great deal of human intervention and, most significantly, the deficiency of route prediction accuracy due to limited coverage of local area close to the intersection. This study concentrates on a new type of adaptive TSCS that takes advantage of VANET (Yousefi *et al.*, 2006) technology rather than traditional detectors to acquire the movement information of vehicles at an intersection.

2 VANET-based adaptive traffic signal controlling

The idea of optimizing adaptive TSCSs has perpetually been a dilemma for engineering academics from the matter of providing accurate and prompt decision regarding the traffic load balancing and reducing the pollutant emission issues (Stevanovic *et al.*, 2009). By taking advantage of VANET, adaptive traffic signal control can be divided into two main parts. The first part involves the measurement of traffic at the intersection; the second part involves the manner of analysis and assessment of data acquired from the first part to generate the traffic signal timing. The algorithms and techniques used for the second part are mainly acquisition of the known traffic signal timing algorithms such as SCOOT (Robertson and Bretherton, 1991), SCAT (Akçelik *et al.*, 1998), and Webster (Webster and Cobbe, 1966). These techniques deduce a model for either decreasing the average delay per vehicle or decreasing the queue length of vehicles at intersections as a function of cycle time.

The VANET-based adaptive TSCSs proposed in the literature, regardless of the essence of operation, principally use either of the two communication types of V2I and V2X to gather the traffic information. In Huang and Miller (2004), while vehicles are approaching the intersection, their real-time movement information is sent repeatedly to the road side unit (RSU) at the intersection to estimate the traffic density therein. This approach uses the basic traffic signal timing framework including two offshoots, density measurement for signal timing and traffic signal sign propagation. Though the idea is remarkable, it is confronted with excessive load of the network due to the propagation of a large amount of broadcast packets. Moreover, frequent variation of vehicle speed causes inaccuracy in the estimation of vehicle positions near the intersection and imprecision of density assessment for traffic signal timing. Similarly, V2I communications were used by Gradinescu *et al.* (2007). In their approach, while vehicles travel and use one-hop car-to-car communication, RSUs detect the movement information exchanged among them to estimate the traffic density near an intersection. Though this approach can decrease the vehicle delay at an intersection, two noticeable difficulties exist: excessive propagation of broadcast packets, and inaccurate perceiving of vehicle's platoon density close to the intersection. In a similar way, Priemer and Friedrich (2009) suggested the deployment of RSUs beside the loop detectors along the road as a multi-detection method. In this approach, vehicles in the communication range of RSUs broadcast their movement information; thus, traffic information will be assessed from both the RSU and loop detector devices using dynamic programing and complete enumeration. This method, in addition to having similar networking deficiencies as the former approach, suffers from redundancy in assessment of vehicle information, which leads to the time-consuming procedure of detecting iterative information and slows down the traffic measurement. Nafi and Khan (2012) proposed a different approach called the intelligent road traffic signaling system (IRTSS). In this approach, while vehicles approach RSU at the intersection, they receive periodic broadcast messages including traffic information and the current traffic signal sign. Then each vehicle replies its movement information. Accordingly, the traffic controller calculates the traffic saturation at the intersection and provides appropriate traffic signal timing. Though this approach is efficient in decreasing the vehicle waiting time and optimizing fuel consumption, the absence of a comprehensive algorithm for the traffic signal timing and the rise of network contention besides packet loss in congested traffic conditions cannot be neglected. Kwatirayo *et al.* (2013) proposed a different approach by taking advantage of V2I communication for broadcasting the vehicle information to the RSU at the intersection. This approach concentrates more on obtaining realistic traffic information by using a specific algorithm that considers the relative positions of vehicles from the intersection, and groups them into specific platoons with the same destination. Though this approach is efficient in reducing vehicles' travel time and delay at the intersection, the effects of message loss and network contention were not considered in the experiments. In Pandit *et al.* (2013), the deployment of RSUs at the intersection was suggested. Thereby, while vehicles approach the intersection, periodic broadcasting of their movement information is done. This approach formulates traffic signal timing as a job scheduling service. This method groups the vehicles into equally-sized platoons according to their location and speed, names them 'jobs', and then employs an algorithm called 'oldest job first' to control the green-light interval for each movement. This approach is effective in decreasing the vehicles' delay in light and moderate congestion scenarios; however, it is not very effective under heavy traffic loads. Li *et al.* (2014) investigated different types of traffic control policies by taking advantage of V2I communication. In this study, the use of both feedback and feedforward—measurement for the prediction of traffic demands prior to entering the monitoring area, and characteristics of traffic controlling—is suggested. Also, the sending of information regarding vehicles' desired route from the origin to the destination as well as the common movement information periodically sent to RSUs is hypothesized. Accordingly, the traffic controller perceives the entire trajectory that vehicles are aiming to travel and sketches upcoming traffic in a series of time slices to define the effective traffic signal timings. However, the proposed approach involves high demand of information propagation and a large size of transmission data, which are contrary to the limited available network resources and bandwidth in VANET.

Maslekar *et al.* (2011b) proposed a new type of adaptive TSCS by taking advantage of V2X communication. In this approach, a new algorithm called 'direction based clustering for the dissemination of information' was introduced. The proposed method for gathering information in this approach is a combination of clustering and opportunistic dissemination techniques. Accordingly, different groups of vehicles are formed depending on their movement directions close to the intersection; afterward, by comparing the locations of vehicles through V2V communication, the closest vehicle to the intersection will be chosen for sending the information of existing vehicles in the group to RSU, which is deployed at the intersection, through periodic broadcast messages. In this approach the arrival time of vehicles will be recorded to perceive the traffic condition near the intersection. The main deficiency of this approach is the intricate and lengthy procedure of choosing the leader vehicle that has the responsibility of communicating with RSU. Moreover, calculation of the arrival time of all the vehicles is time consuming and makes the traffic assessment intricate. Similarly, in Chang and Park (2013) the V2X-assisted adaptive TSCS was suggested. In this approach, vehicles are assigned in groups of each lane and, by the initiation of the red-light interval, each group starts its procedure of group leader election through sending packets to compare timestamps and closeness of vehicles to the stop line. The group leader broadcasts its nomination and waits to receive the members' information, followed by replying the acceptance message to each member. The algorithm proposed in this approach for calculating the traffic density comprises the queue length of vehicles and the average waiting time at the junction. Despite the proficiency of this approach in decreasing the vehicles' waiting time and improving the communication overhead in comparison with V2I assisted approaches, the great deal of vehicle propagation for choosing the group leader besides the necessity of replying the acknowledgment packets from the group leader and utilization of periodic broadcasts by each vehicle can lead to network channel congestion, which proved to severely threaten the network propagation performance (Jabbarpour *et al.*, 2014). Moreover, the lack of providing any border for group membership causes faraway vehicles to be counted in the group although they may be farther than what is needed to be counted. Maslekar *et al.* (2011a) proposed another approach based on V2X communication called C-DRIV. In this approach, density measurement for different platoons of vehicles is performed based on their direction at the intersection. The clustering initiates from a specific border from the intersection and vehicles detect their cluster leader through V2V communication. Upon placing the cluster leader in the communication range of the RSU at the intersection, it starts periodically broadcasting density information in every time stamp, up to the time of crossing the intersection. The main drawback of this approach is the scattering of the clustering procedure due to the existence of the ambiguous procedure of choosing the cluster leader. In other words, the wide border area for performing the clustering and high mobility of vehicles (especially their overtaking) in this area affect the stability and increase the number of cluster leaders during the clustering, resulting in a failure of the clustering operation. Maslekar *et al.* (2013) suggested a new model for providing the V2X-assisted TSCS as the modified version of their previous approach C-DRIVE. The new approach called MC-DRIVE uses V2X communication, similar to that of Maslekar *et al.* (2011a), as a matter of grouping the vehicles. In this approach there are a number of reference points specified with equal distances close to the intersection. The clustering starts with the vehicle named header, which is responsible for choosing the farthest vehicle in its transmission as a cluster leader. The chosen cluster leader is responsible for broadcasting the query packet periodically at each reference point, informing vehicles about its presence to get replies from the ones traveling in the same direction. Finally clustering will be terminated when one of the cluster members crosses the closest reference point to the intersection. This is the time the cluster leader sends the cluster density information to RSU. Though this approach has been effective in decreasing the average vehicle delay at the intersection and improving the network QoS over V2I-assisted approaches, the long and intricate procedure of cluster leader election is not effective as a matter of time and rise of network data traffic. All in one, a review of the recently proposed VANET-assisted adaptive TSCSs demonstrates that consideration of comprehensive TSCSs is that preserve the effective performance of traffic load balancing and network QoS utilization concurrently has always been disputable. Moreover, the employment of innovative ideas in VANET for improving the operation of TSCSs besides inspecting the effects of using such approaches on the decrease of pollutant emissions has perpetually been marginalized in the literature.

3 AGTSC-VC traffic signal controlling system

3.1 Operation design

The operation structure of the proposed TSCS called 'adaptive green traffic signal controlling using vehicular communications' (AGTSC-VC) is defined in two main steps: (1) VANET-assisted traffic information gathering, and (2) traffic density assessment and traffic signal timing generation. The first step of this operation comprises the procedure of communicating the vehicles with each other and with the traffic controller through V2V and V2I communications to provide the information regarding the traffic status and prioritization of each movement at the intersection. The second step of the AGTSC-VC operation goes through the assessment of intersection's traffic using the vehicles' queue length estimations and generating the adaptive traffic signal timing in accordance with the current status of traffic near the intersection. The equations and algorithms used in this step provide the ability of detecting the oversaturated movements at the intersection during each traffic signal cycle, and anticipation for extending the traffic signal timing of the adjacent intersections that will be affected by the supposed oversaturated traffic.

3.2 VANET-assisted traffic information gathering

As the first step, VANET-assisted traffic information gathering concentrates on the deployment of the VANET platform for estimating vehicles' density close to the intersection. This study assumes that all the vehicles are equipped with an on-board unit (OBU), a wireless transceiver, and a Global Positioning System (GPS) including digital maps. All the communications among the vehicles and infrastructure are implementing through wireless access in vehicular environments (WAVE) spectrum using the standard IEEE 802.11p, which is referred to as dedicated short range communication (DSRC) (Eichler, 2007). The deployment of a single traffic controller RSU at each intersection is considered, in addition to the capability of transmitting the traffic information among the adjacent traffic controller RSUs through a physical backbone link. Fig. 1 illustrates the deployment of the proposed approach in an urban area.

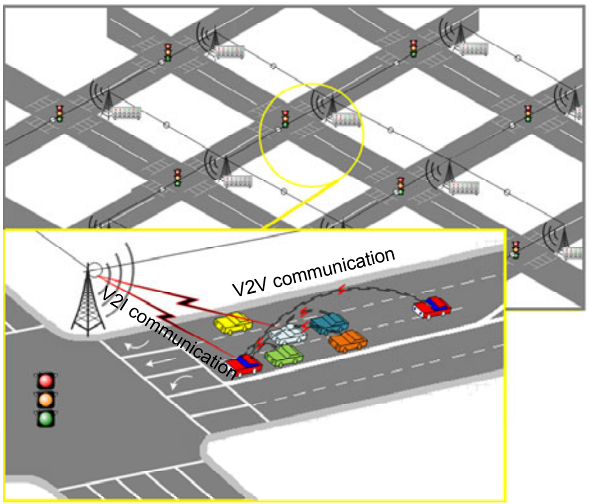

Fig. 1 Deployment of AGTSC-VC in an urban area

3.2.1 Clustering and density estimation

The necessity of providing the utmost precision and instant procedure of data gathering for the traffic controller in this step implies the employment of an effective data dissemination strategy among the vehicles. For this aim, in AGTSC-VC the traffic density information for each movement of the intersection will be provided through a specified area called the 'expected-zone'. Vehicles will detect themselves in this area once they cross a boundary called the 'start point', heading toward the intersection (Fig. 2). Vehicles will be grouped into different clusters at the intersection depending on their future direction. In each cluster, there will be a vehicle called the cluster header, which has the responsibility of calculating the number of vehicles in its cluster. The cluster header uses the propagation of the packets called 'header-packet' to inform the vehicles within its cluster regarding its presence.

After entering the expected-zone, each vehicle that is traveling toward the intersection begins the

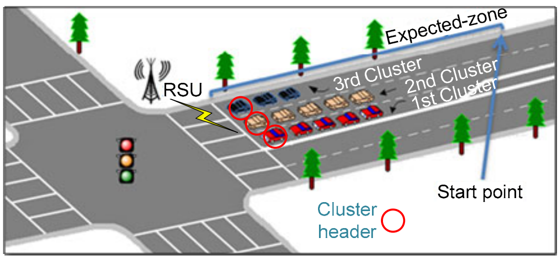

Fig. 2 Grouping the vehicles in different clusters in the expected-zone (RSU: road side unit)

process of cluster header detection by receiving the header-packet.

On entering the expected-zone, a vehicle will continue to detect the header-packet, until it reaches the first idle state, spending 3 s in this condition; at this moment if it has not received any header-packet identical to its own movement direction, it will assume itself as the cluster header and begin broadcasting the header-packet right away. The assumption of a three-second idle state is to ensure that vehicle's halt is due to the red-light interval clustering and not a temporary instant stop. Fig. 3 depicts the structure of the header-packet, where the 'packet type ID' specifies the type of broadcast packet to differentiate the header-packet from other types of broadcast packets. 'Cluster header ID' identifies the cluster header for further communication with the cluster members. 'Cluster ID' specifies and distinguishes the vehicles' clusters. 'Direction' states the movement direction of the cluster to enable the vehicles to recognize whether they belong to the cluster or not. 'Member ID' specifies the vehicles that have already joined the cluster.

For each movement direction, there is a process of nominating the cluster header according to the traffic signal principles. Hence, depending on the permitted or protected right turn, there may be either two or three cluster headers in the expected-zone during each red signal interval. The cluster header is required to broadcast the header-packet periodically until the traffic signal enters the green-light interval. The vehicles in the expected zone will respond to the cluster header regarding their participation to the cluster, after detecting the header-packet and verifying the cluster direction with their own. Fig. 4 presents the reply-packet structure. In this structure, the 'vehicle ID' field specifies the vehicle that is going to join the cluster. 'Cluster header ID' and 'cluster ID' fields have similar qualifications of their peers in the header-packet. The 'vehicle type' field contains a flag variable to differentiate between freight vehicles and passenger vehicles. Finally, the 'subsequent direction' field states the direction that the vehicle is going to take in the subsequent intersection. The use of GPS and digital map allows the vehicles to send this information simply through an unsigned integer

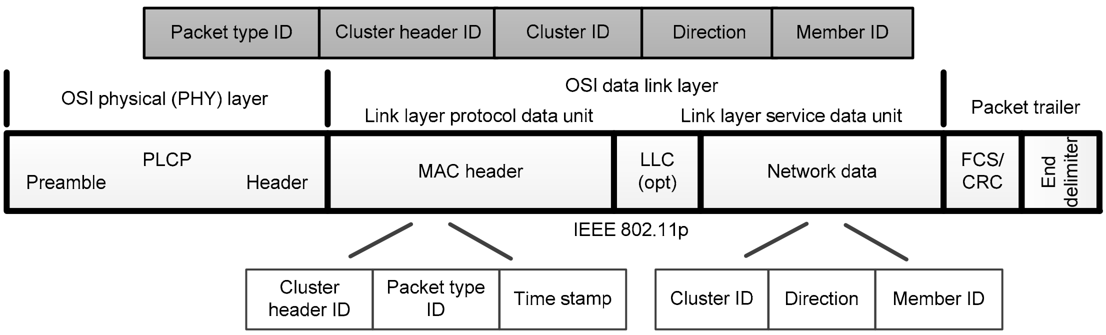

Fig. 3 Structure of header-packet

PLCP: physical layer convergence protocol; OSI: open system interconnection; LLC: logic link control; FCS: focus control system; CRC: cyclic redundancy check

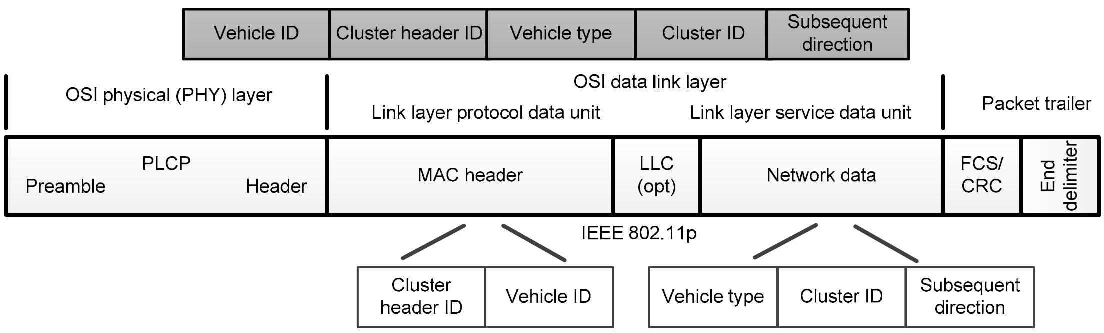

Fig. 4 Structure of reply-packet

PLCP: physical layer convergence protocol; OSI: open system interconnection; LLC: logical link control; FCS: focus control system; CRC: cyclic redundancy check or string value. Moreover, since for each cluster member there are only one single following intersection and three options to choose from, this field does not bring an excessive load of computing or overheads to the network. There will be more discussion about the vehicles' subsequent directions further on in this approach.

The allocation of the 'member ID' field in the header-packet helps the vehicle that is receiving the header-packet for the second or subsequent times to check whether its ID exists among the cluster members; otherwise, it will continuously send the reply-packet until it receives a response. Accordingly, the cluster header in this approach is exempt from replying to the confirmation message. In AGTSC-VC, while the cluster header receives the reply-packets, it calculates the number of vehicles in its cluster as the density of the cluster. During the calculation, it considers each freight vehicle as a flow of two passenger vehicles. In addition, it calculates the number of vehicles that will be placed in each 'subsequent direction' group.

By beginning the green-light interval and departing the vehicles from the idle state, the termination of clustering will occur. Hence, after perceiving the departure of the vehicle from the idle state and keeping the movement for 3 s, the mounted OBU on the cluster header vehicle starts broadcasting the traffic-load-packet to the traffic controller RSU of the intersection. The structure of this packet is shown in Fig. 5. In this structure, 'packet type ID', 'cluster header ID', and 'direction' have the same aforementioned characteristic; the 'density' field specifies the number of vehicles in the cluster. The 'subsequent cluster' field comprises three different integer values to specify the density of the vehicles that aim to travel to the left, straight, and right directions, respectively, in the subsequent intersection.

Fig. 6 depicts the subsequent cluster options for the vehicle in the cluster. The significance of this ability is revealed in the central urban areas; such areas have an orthogonal outline of several adjacent junctions to connect several road segments together (Lahart *et al.*, 2013). Therefore, if any movement confronts an oversaturated traffic, it will conclusively affect the contiguous intersections. In AGTSC-VC, by taking advantage of the information obtained from 'subsequent cluster' fields and using the traffic density assessment algorithms, the traffic controller is able to detect the densities of oversaturated clusters that are going through the specific movement direction of the following intersections, and alter the cycle time of the following intersections beforehand, to prevent spreading the congestion in contiguous junctions. The procedure of anticipation in traffic signal controlling of contiguous intersections will be clarified further in the second step of this approach.

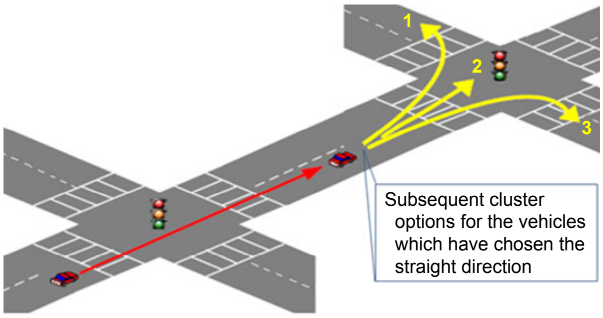

Fig. 6 Subsequent cluster options for straight direction clustering

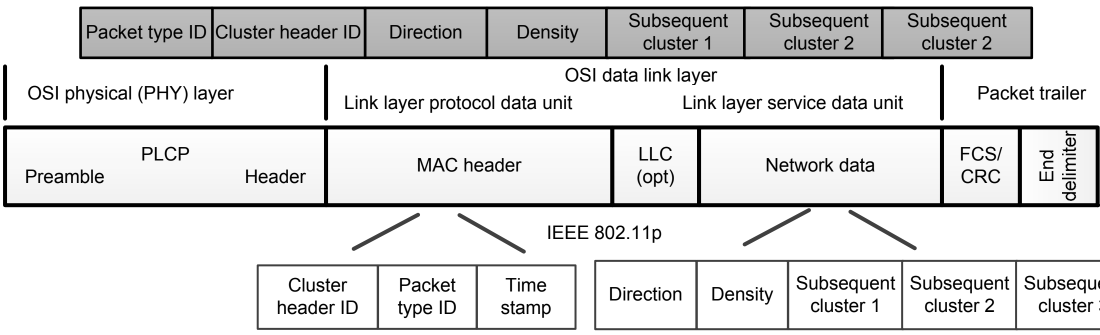

Fig. 5 Structure of traffic-load-packet

PLCP: physical layer convergence protocol; OSI: open system interconnection; LLC: logical link control; FCS: focus control system; CRC: cyclic redundancy check

According to what was mentioned earlier, by starting the green-light interval and terminating the clustering, the cluster formation will iterate a new one in the succeeding red-light interval. In AGTSC-VC, by receiving the traffic-load-packets from all the cluster headers during a single cycle of the traffic signal, the traffic controller acquires the overall density information of the intersection and applies adaptive timing for the next cycle. Fig. 7 illustrates the process of gathering the traffic-load-packet information for a four-phase TSCS sample.

3.2.2 Prioritized movement signalling

Consideration of movement prioritization for green-light interval of traffic signal in each intersection has perpetually been momentous to assist emergency and prioritized vehicles to spend less time waiting in the traffic behind the intersection. However, this option is ordinarily involved with human interventions. AGTSC-VC takes advantage of VANET technology to detect the prioritized vehicles when moving toward the intersection, and consequently obviates the need for assigning this responsibility to individuals. To achieve this aim, in AGTSC-VC, a packet called 'preference-packet' transmits the movement information of the prioritized vehicle that is approaching the intersection to the traffic controller RSU ahead. The preference-packet is broadcast repeatedly by the prioritized vehicle during its movement; thus, on the vehicle approaching the intersection and being placed in the propagation range of the traffic controller RSU, the RSU detects this packet (by using its 'packet type ID') and considers the movement information of the prioritized vehicle for calculating its estimated time of arrival at the intersection under the current status of traffic at the intersection. The structure of the preference-packet is shown in Fig. 8. In this structure, 'packet type ID', 'vehicle ID', and 'direction' fields have the same characteristics as mentioned previously. The 'location' field specifies the 2D coordinates (latitude and longitude) of the vehicle in the road segment heading toward the intersection, and the 'velocity' field specifies the vehicle speed. The values of both 'location' and 'speed' fields change continuously by periodically broadcasting the preference-packet as the vehicles approach the intersection. They will be differentiated by the packet time stamps. Then, the traffic signal prioritization and extension of green-light interval for the

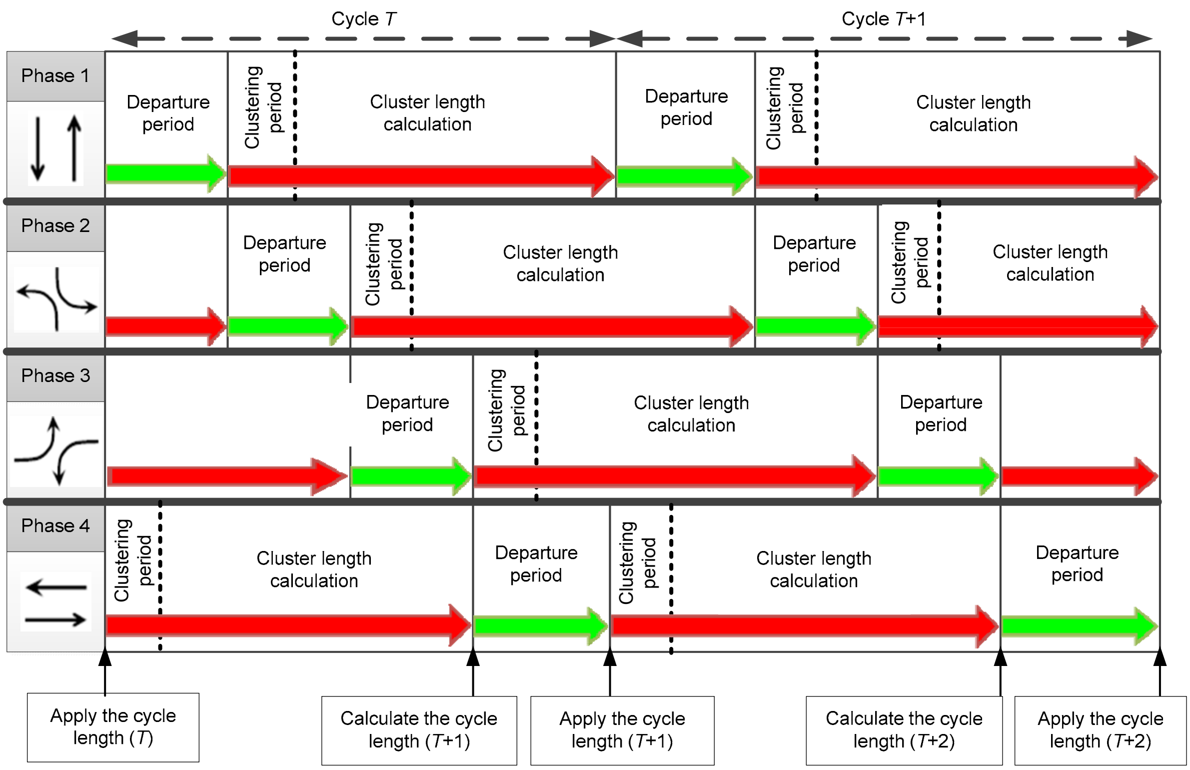

Fig. 7 Arrangement of clusters' density information and generating the traffic signal timing at the traffic controller

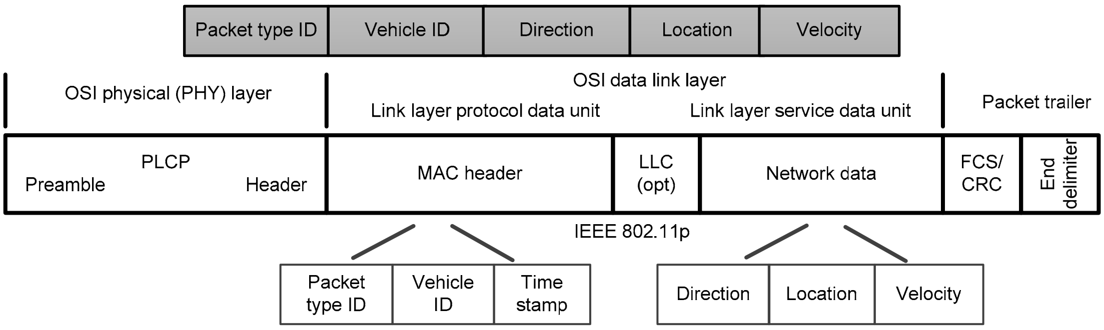

Fig. 8 Structure of preference-packet

PLCP: physical layer convergence protocol; OSI: open system interconnection; LLC: logical link control; FCS: focus control system; CRC: cyclic redundancy check

prioritized movement will be determined at the traffic controller by using the movement information of the preference-packet.

3.3 Traffic assessment and traffic signal timing

The assessment of traffic densities at the intersection and calculation of traffic signal timings by taking advantage of VANET-assisted movement information constitute the second step of the AGTSC-VC operation. For this aim the modified combination of techniques and concepts proposed in the Traffic Signal Timing Manual (STM) (Koonce *et al.*, 2008) and known Webster's equations (Webster, 1958; Webster and Cobbe, 1966) are used for the assessment of traffic density near the intersection. Moreover, the method suggested by Liu *et al.* (2005) for calculating the vehicles' travel time in urban areas is used to implement the prioritized traffic signal timing of AGTSC-VC.

3.3.1 Density-based traffic signal timing

The results demonstrated in urban traffic engineering references (NRC, 2000; Kraft *et al.*, 2009) have shown that the minimum delay of traffic at intersections is obtained when the green-light interval of the traffic signal phases is in proportion to the corresponding ratios of traffic flow to the intersections' saturation flow rates. The saturation flow rate is described as the number of vehicles that are able to traverse an intersection per hour in a dense flow of traffic by assuming constant green interval and eliminating lost time (Webster, 1958; Koonce *et al.*, 2008). On the other hand, the lost time is considered as the total of three portions: (1) the beginning of each green-light interval, (2) a portion of yellow light-interval, and (3) all-red clearance interval, which is not usable for vehicles to cross the intersections. The first part of this time interval includes the delay of signal change recognition by the first driver in the intersection's clustering. The second part involves a portion of the yellow interval which dissuades drivers from crossing the intersection. Finally, the third part is the time interval after the yellow-light interval during which all the phases show the red light prior to displaying the green light for the subsequent phase of traffic signal. The all-red clearance interval is the efficient short time interval considered to ensure that all vehicles in the last phase of the traffic signal have been released from the intersection, thereby preventing the possibility of making chaotic traffic flow for the vehicles of the following phase. Fig. 9 presents the concepts (saturation flow and lost time) through traffic signal operation by considering the traffic flow using the variable per car per hour (pcph).

Subtracting the lost time from all the phases of the traffic signal's cycle enables the traffic controller to obtain an effective green interval, provided for

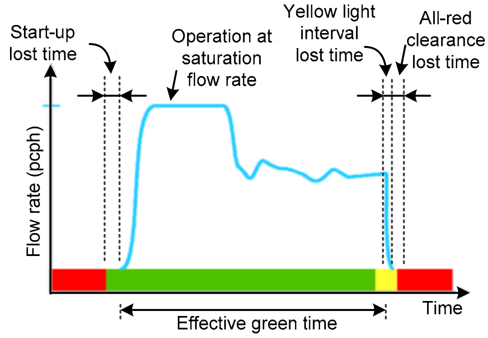

Fig. 9 Operation of traffic flow in the signalized intersection

each movement. The effective green interval can be calculated as

$$\mathrm{EG}=G+Y+\mathrm{All\_}R-\mathrm{LT}, \quad (1)$$

where G is the green interval, Y is the yellow interval, All_R is the all-red clearance interval, and LT is the lost time. Obtaining the effective green interval for each phase is very significant for the traffic controller to make a rational decision about the traffic signal timing. In Eq. (1), the parameters Y, All_R, and LT are considered fixed. Hence, the amount of effective green interval varies by changing the amount of green-light interval in each phase. The consideration of yellow-light interval and all-red clearance interval periods is highly dependent on the drivers' reaction time, the safe stopping distance of vehicles, and the layout of the intersection's road segments.

Koonce *et al.* (2008) proposed a method to obtain the average queue length of vehicles by taking advantage of the volume of the traffic. AGTSC-VC takes advantage of this method by using the following equation to calculate the current volume of each movement close to the intersection in different phases of the traffic signal:

$$v(\mathrm{vphpl})=\frac{3600\mathrm{Queue}_{\mathrm{avg}}}{\mathrm{CL}-\mathrm{EG}}, \quad (2)$$

where CL is the current cycle time of the intersection, EG is the effective green interval for the movement, and $\mathrm{Queue}_{\mathrm{avg}}$ is the number of passenger vehicles for that specific movement, which is obtained using the first phase of the presented TSCS.

There have been various studies devoted to define the fixed rate of the intersection's saturation flow. AGTSC-VC employs a method from Bester and Meyers (2007), which considers all the conditions of road segments that affect the alteration of saturation flow rate. Eq. (3) clarifies the saturation flow (SF) rate calculation that can be obtained for each movement of intersection:

$$\mathrm{SF}=990+288(\mathrm{TL})+8.5(\mathrm{SL})+26.8(\mathrm{GT}), \quad (3)$$

where TL is the number of through lanes for specific movement, SL is the speed limit in the area, and GT defines the gradient of the road segment.

By estimating the volume of each movement during one signal cycle using Eq. (2) and by specifying the saturation flow rate of each movement direction using Eq. (3), the traffic controller is able to calculate the following cycle time and green-light intervals adaptively in accordance with the traffic flow of each movement. Eq. (4) shows the calculation of the adaptive cycle time and Eq. (5) provides the calculation of the green phase proportions for each movement direction of traffic signal in AGTSC-VC. These equations are modified versions of the Webster equations (Webster, 1958; Webster and Cobbe, 1966). The modifications are incorporated to manipulate the anticipation of signal timings of adjacent intersections during congested traffic conditions.

$$\mathrm{CL}(T)=\frac{1.5\mathrm{LT}+5}{1-\frac{1}{X_{\mathrm{C}}}\sum_{i=1}^{n}\left(\mu_i\cdot\frac{v_i(T)}{\mathrm{SF}_i}\right)}, \quad (4)$$

$$\mathrm{EG}_i(T)=(\mathrm{CL}(T)-\mathrm{LT})\cdot\frac{\mu_i\frac{v_i(T)}{\mathrm{SF}_i}}{\sum_{i=1}^{n}\left(\mu_i\cdot\frac{v_i(T)}{\mathrm{SF}_i}\right)}, \quad (5)$$

where T is the present cycle time, v_i represents the volume of the movement, where i is the index of the current intersection, μ_i is the expanding factor of signal timing for the congested movement that leads to the current intersection (this parameter will be clarified later on in this study), LT is the lost time, n is the number of critical movement groups, v_i/SF_i represents the maximum flow ratio among the movement of the critical movement group which is represented by i, and $1/X_{\mathrm{C}}$ specifies the desired degree of road segment utilization (usually defined as 0.9 for realistic judgment). A critical movement group is a group of movements that are able to cross the intersection concurrently without interfering with each other. Generally, all the movements belonging to the same phase of the traffic signal will be served in the same green-light interval.

The expanding factors (μ_i) for traffic signal timings of each intersection are calculated by the traffic controller of the previous intersection, which perceives the specific congested movement traveling toward the following intersection. The decision making of the expanding factor starts with the evaluation of the traffic status of the intersection when the traffic controller is computing the traffic signal timing. To achieve this, utilization of the quick estimation method (QEM) proposed by Koonce *et al*. (2008) is suggested. Fig. 10 presents the flowchart of the algorithm based on QEM, which is taken in AGTSC-VC to calculate the value of the expanding factor.

This algorithm arranges the movements of traffic signal into a desired sequence of phases and divides the movements into two groups. Each group comprises two pairs of movements and each pair comprises movements of consecutive phases. For each group, the movement pair, the one that holds the most volume of traffic, is selected and named the critical volume. Afterward, by accumulating the values of critical volumes from both groups, the overall critical volume of the intersection will be obtained. Next, information regarding the traffic status of the intersection can be obtained using

$$\text{Traffic}_{\text{index}} = \text{OCV}/[1730 \cdot \text{PHF} \cdot f_{\text{a}}(1 - \text{LT/CT})], \quad (6)$$

where $\text{Traffic}_{\text{index}}$ specifies the ratio of the current traffic intersection's volume to the maximum sustainable capacity of the intersection under a prevailing condition and aids the traffic controller in perceiving the traffic status of the intersection, OCV is the overall critical volume of the intersection (1730 is the reference capacity value (vphpl) that the Highway Capacity Manual (HCM) (NRC, 2000) suggests for central urban areas), PHF is the peak hour factor, which is considered as one for the central urban areas, and f_{a} is the adjustment factor for area type, which is considered as 0.9 for central urban areas (Koonce *et al*., 2008).

Koonce *et al*. (2008) proposed a set of thresholds to assess the intersection traffic status by using the acquired $\text{Traffic}_{\text{index}}$. AGTSC-VC considers these thresholds and defines their correlated assessments for use in the calculation procedure of the expanding factors (Table 1).

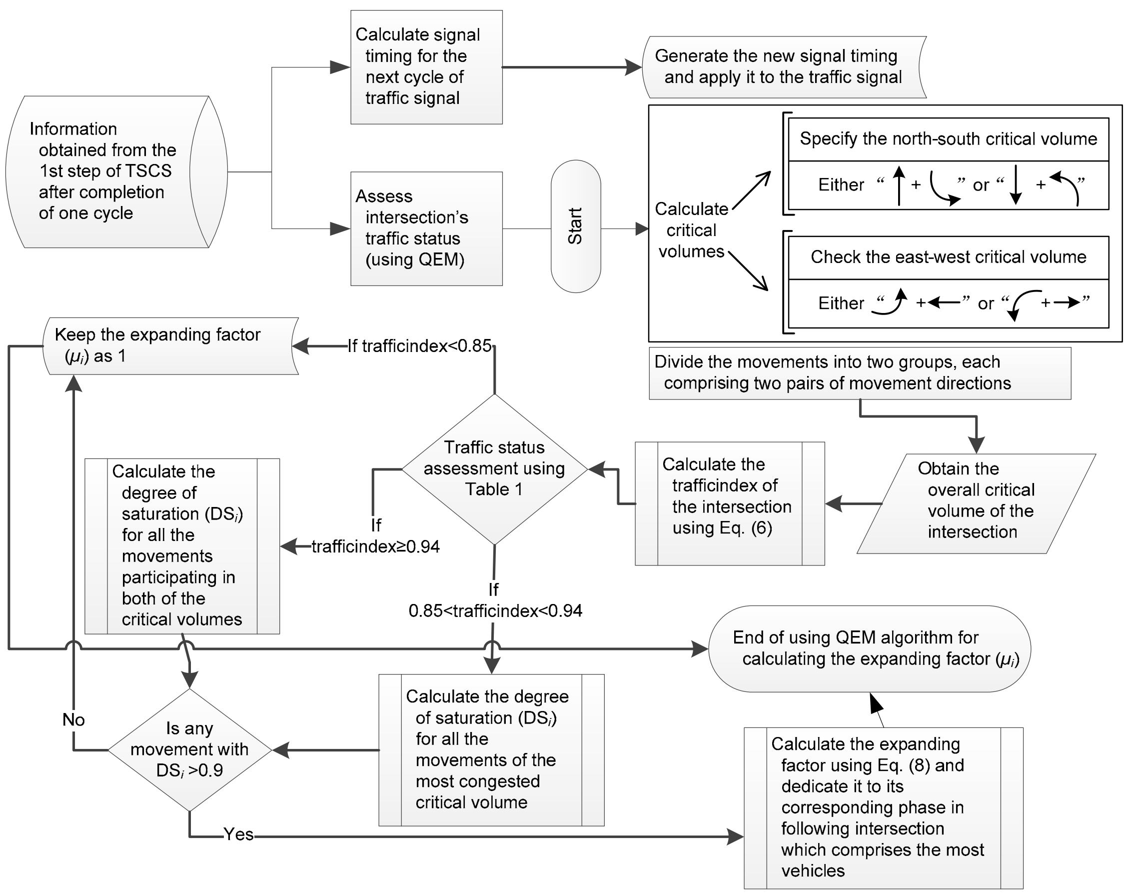

Fig. 10 Procedure of using the QEM-based algorithm in AGTSC-VC (QEM: quick estimation method)

In the next step of decision making, which takes place in conditions 2 and 3 of Table 1, the traffic controller checks the degree of saturation individually for each of the movement directions that are participating in the critical movement. If the degree of saturation for the specific movement exceeds 0.9, the expanding factor is chosen for its corresponding phase of the following intersection, which has dedicated the most vehicles to itself (by using the subsequent cluster information in that traffic-load-packet).

Table 1 Required assessments for the obtained values of $\text{Traffic}_{\text{index}}$

Condition	Assessment
$\text{Traffic}_{\text{index}}\leq 0.85$	Traffic flow is below capacity.
$0.85<\text{Traffic}_{\text{index}}<0.94$	Flow is close to the capacity of intersection. The green light extension must apply to the subsequent intersection's phase, where the most congested critical volume is leading to it.
$0.94\leq\text{Traffic}_{\text{index}}$	Flow is unstable. The green light extension must be applied to the subsequent intersection's phases so that the congested critical volumes are leading to them.

Eqs. (7) and (8) show the calculation of the degree of saturation and expanding factor for movement i, respectively:

$$\text{DS}_i=\frac{v_i}{\text{SF}_i\dfrac{\text{EG}}{\text{CL}}}, \tag{7}$$

$$\mu_i=\frac{v_i(T)/\text{DF}_i}{v_i(T-1)/\text{SF}_i}, \tag{8}$$

where T and $T-1$ are the present cycle time and preceding cycle time, respectively. By calculating the expanding factor, the traffic controller allocates it to the single movement among the three subsequent cluster options, the one that has the largest number of vehicles. Then it sends this parameter to the following intersection's traffic controller. As mentioned, the default value of the expanding factor for calculation of signal timing of each intersection is considered as 1, unless the traffic status of specific intersection compels the traffic controller to use Eq. (8) and compute the new value for the following intersection.

3.3.2 Priority-based traffic signal timing

Considering that the prioritization of traffic signal timing is initiated once, the information from the preference-packet is obtained at the RSU of the intersection. For this aim, the traffic controller needs to consider the estimated arrival time of the prioritized vehicle to the stop line of the intersection. AGTSC-VC takes advantage of the method proposed by Liu *et al.* (2005) to estimate this time interval. For this estimation, the aggregated traffic volume (V) of the road segment between points A and B in which the prioritized vehicle is traveling is required to be considered (Fig. 11). V_A and V_B are obtained from the traffic controllers' RSUs of two following intersections close to points A and B, respectively, providing the data used for the last traffic signal cycle of each intersection.

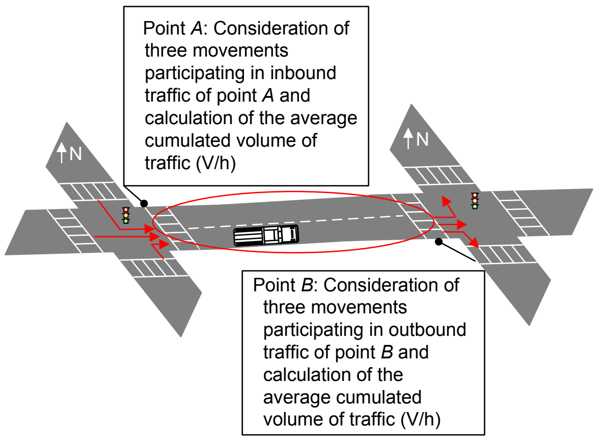

Fig. 11 Estimation of inbound and outbound traffics for prioritized movements

The minimum and maximum variability of velocity in accordance with the traffic density distribution between points A and B can be calculated by

$$v^{\max}(\rho)=\frac{v_1^{\max}}{1+\mathrm{e}^{\mu_1(\rho-\rho^{\max})}}, \tag{9}$$

$$v^{\min}(\rho)=\frac{v_1^{\min}}{1+\mathrm{e}^{\mu_2(\rho-\rho^{\min})}}, \tag{10}$$

where $\rho=\alpha(V_B-V_A)/l$, l is the distance from the prioritized vehicle and the following intersection's stop line, α is used as the adjusting parameter for the density unit ρ, $v_1^{\min}$ and $v_1^{\max}$ are the initial minimum and maximum speeds that vehicles can take after crossing the first intersection (as the fixed parameters), respectively, μ_1 and μ_2 are used as the average variable speeds with the same dimension of speed, and $\rho^{\min}$ and $\rho^{\max}$ are the minimum and maximum density obtained from the last four traffic signal cycle assessments, respectively.

Eq. (11) shows the calculation of the expected arrival time E(AT) of the prioritized vehicle to the intersection ahead:

$$E(\mathrm{AT})=\int_{v^{\min}(\rho)}^{v^{\max}(\rho)}\frac{1}{v}\cdot\frac{1}{\sqrt{2\pi}\sigma}\exp\left[-\frac{(v_p-\mu)^2}{2\sigma^2}\right]\mathrm{d}v,\quad(11)$$

where $\sigma=(v^{\max}-v^{\min})/4$ and $\mu=(v^{\max}+v^{\min})/2$, and v_p is the speed obtained from the preference-packet. In AGTSC-VC, the confident range is set as 6σ, considering more realistic vision from the distribution of speeds as the function of density.

By calculating the expected arrival time, if the phase that serves the green light conforms to the movement direction of the prioritized vehicle, it will be extended further by subtracting the remaining green-light interval from the expected arrival time (subtracting condition: greater than zero). In other cases, the permitted moving phase will be terminated, and the green light will be applied for the prioritized movement. After terminating the green-light interval of the prioritized movement, the traffic signal timing continues from the phase that was interrupted earlier.

4 Study network and evaluation

For the experiment environment, an area of 2000 m×2000 m is extracted as the main structure of the road map of a central urban area from OpenStreetMap (Haklay and Weber, 2008) using osm.xml format. The concentration of evaluation is confined to the area composed of 6×6 streets, which constitute 36 intersections. For this aim, the Java Open Street Map (JOSM) Editor (Scholz, 2011) is used to edit the dispensable attributes and set raw information of street networks, existing buildings, and traffic light in each intersection. Fig. 12 presents the exported map and its editing environment in JOSM. To evaluate the performance of network and traffic

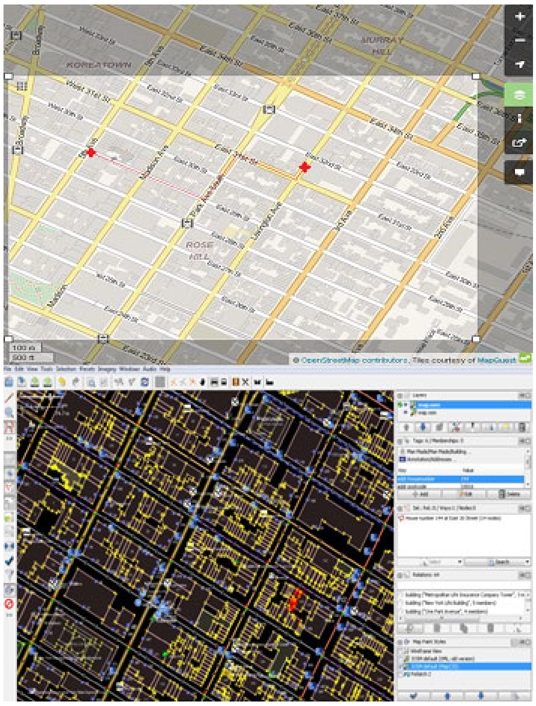

Fig. 12 Exported road map and filtered attributes in a Java open street map application (References to color refer to the online version of this figure)

parameters, Veins 2.2 Simulation Framework (Sommer *et al.*, 2011b) is used. This framework was initially proposed as a suite for realistic simulation of IVC in modular frameworks. It works with two distinct simulators: OMNET++ (Varga and Hornig, 2008) for simulation of network concepts, and SUMO (Krajzewicz *et al.*, 2012) for simulation of traffic performance.

4.1 Simulation setup

SUMO, which is a highly portable and open source traffic simulator with microscopic features, is used to apply the following settings: all the streets in the road network are further designed in a two-way movement with allocation of two lanes for each movement, in addition to the expanded outline of three lanes for outbound traffic that enters the intersection. The traffic signal control plan as depicted in Fig. 7 includes four phases, each serving two rights of way, in addition to permissive right turn for any outbound traffic reaching the intersection. To apply the traffic signal control plan and timings, the ‘tls_csv2SUMO’ tool is used to build the timing programs on the traffic light logic file of SUMO. The traffic routes for vehicles are applied using either the specified routes or the randomization of trips by taking advantage of the DUAROUTER application of SUMO. The yellow-light interval and all-red clearance interval of traffic signals are considered with fixed values of 3 s and 2 s, respectively. These values are chosen according to the HCM Transportation Research Board Recommendation for urban areas (NRC, 2000). Two types of vehicles (based on the length) are chosen, with 90% passenger vehicles and 10% freight vehicles. Vehicles may accelerate or decelerate with a speed limit of 60 km/h for the entire area. Two attributes of speedFactor and speedDev with values of 1.0 and 0.1, respectively, are used to result in a distribution of chosen maximum speed (between 80% and 110% of the speed limit) among drivers, to achieve more realistic traffic behavior. The maximum number of 470 vehicles is used in the most congested scenario. The gradient of all road networks for the computation of the saturation flow rate is assumed to be 0, and the total lost time for each phase of the traffic signal is considered as 5 s (including 1.5, 1.5, and 2 s for the first, second, and third portions of lost time, respectively). The TraCI component is used for synchronizing the generated traffic scenarios of SUMO into the OMNET++ simulator. For implementation of traffic controller RSUs, a single static node is configured at each intersection. To make the performance evaluation more realistic, the obstacle model (Sommer *et al.*, 2011a) of the Veins simulation framework considering signal attenuation due to buildings and construction is used. All parameters for MAC and physical layer communication are defined in the IEEE 802.11p spectrum as 5920 Hz frequency (SCH), 6 Mb/s data rate, and QPSK modulation. The communication range for all nodes is defined as 300 m with a transmission power of 20 mW (13 dBm). The environmental noise considered for this simulation is merely confined to the thermal noise of –104 dBm, owing to the negligible external noise sources in the 5.9 GHz frequency. The packet generation rate is defined as 5 times per second. Table 2 presents a brief description of important parameter values used in both network and traffic simulations.

Table 2 Configuration parameters of traffic and network simulation

Parameter	Configuration
Traffic simulation area	2000 m×2000 m, 6×6 two-way streets
Number of intersections	36
Proportion of vehicles for each type	10% freight vehicle 90% passenger vehicle
Maximum number of vehicles	470
Vehicle length	5 m, 10 m
Speed limit	60 km/h
Speed distribution	speedFactor=1.0, speedDev=0.1
Minimum gap of vehicles	2 m
Driver impatience value	0.7 (using gaps to move)
Start point	250 m from junction
Gradient	0
Traffic signal operation	4 phases
Intersection traffic principle	Permissive right turn; prohibited U-turn
Yellow-light interval	3 s
Traffic signal lost time	5 s
Maximum simulation time	400 s
Number of runs for each scenario	3
Signal attenuation model	Vein building obstacle
Channel bandwidth	10 MHz
Channel frequency	5.9 GHz
Beacon generation rate	5 Hz
Link/MAC layer protocol	IEEE 802.11p
Channel	180 (SCH)
Data rate	6 Mb/s
Vehicle antenna height	1.895 m
RSU antenna height	4.8 m
Transmission power	13 dBm
Noise floor (thermal noise)	–104 dBm
Receiver sensitivity	–85 dBm
Minimum contention window	15
Symbol duration	8 μs
SINR for preamble capture	5 dB
SINR for frame body capture	10 dB
Packet size (header, reply, and traffic load packets)	150, 180, and 200 bytes, respectively
Slot time	13 μs
SIFS time	32 μs
Preamble length	32 μs
PLCP header length	8 μs
Modulation	QPSK
Communication range	300 m

RSU: road side unit; SINR: signal to interference plus noise ratio; SIFS: short interframe space; PLCP: physical layer convergence procedure

4.2 Performance evaluation and results

To evaluate the network and traffic performance of the proposed approach, we compare it with the MC-DRIVE (Maslekar *et al.*, 2013) approach, which is one of the successful recent VANET-based adaptive TSCSs. Furthermore, the performance of simple traditional adaptive TSCS (TATSC), which takes advantage of loop detectors for gathering the traffic data at the intersection and uses the Webster method for traffic signal timing, is included in the evaluation of the traffic parameters. The simulation scenarios for the evaluation of each parameter are explained individually in the following paragraphs. The indicated values in the evaluation of each parameter are obtained by repeating the simulation run and taking the average values for three times.

Fig. 13 presents the evaluation of the overhead ratio, i.e., the ratio of the total transmitted overhead data (bytes) through the network to the total size of the packets (bytes) transmitted in the network, to assess the efficiency of bandwidth utilization. In this evaluation scenario, the dissemination of V2V network packets in all the four edges of a single intersection under different volumes of traffic during one cycle of traffic signal is considered, and the total overhead ratios of the packets in both MC-DRIVE and AGTSC-VC are compared. The long procedure of group leader election including the propagation and comparison of the location packets in MC-DRIVE causes more dissemination of broadcast and unicast packets in this approach—on average, about 37.9% more than the V2V packets transmitted in AGTSC-VC in an equal cycle. In this evaluation, AGTSC-VC experiences about a 30.1% less overhead ratio in the most congested scenario (1400 vphpl). The difference of the generated overhead ratio between the two approaches for the scenarios with less than 600 vphpl volume of traffic is not considerable (on average about 11.3%). However, this difference becomes considerable while exceeding the traffic volume of 950 vphpl. This shows that AGTSC-VC can operate more effectively with regard to efficient usage of bandwidth in congested traffic scenarios such as central urban areas.

Fig. 14 illustrates the evaluation of network throughput, i.e., the total amount of data received at the destination node per unit time. In this evaluation scenario, the total network throughput at RSUs is applied for both MC-DRIVE and AGTSC-VC under the regular traffic condition with an average volume of 900 vphpl.

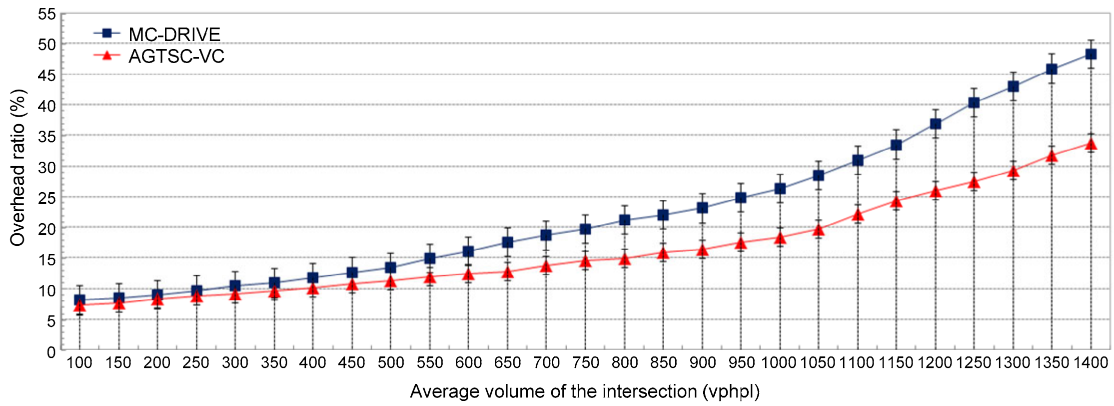

Fig. 13 Packet overhead ratio comparison in a single intersection

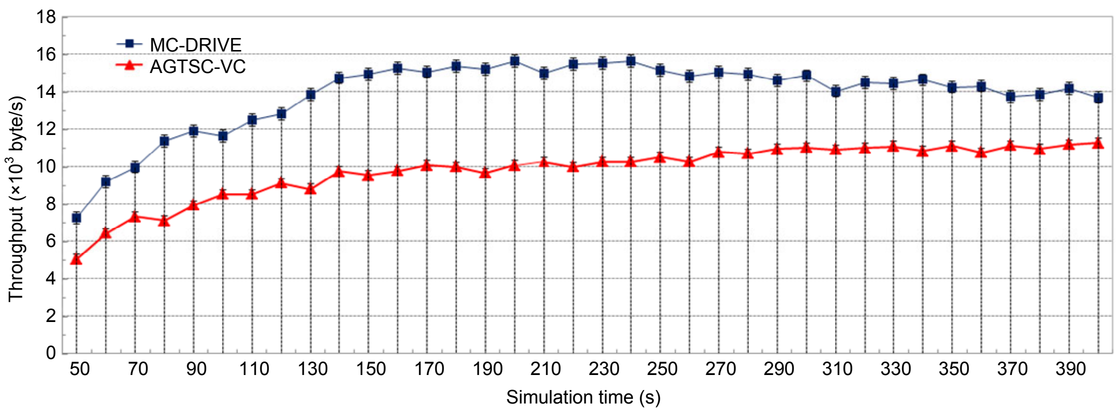

Fig. 14 Comparison of total network throughput of road side units during different time stamps

In this evaluation, the boundary of computation is confined to send and receive the clusters' density information from the vehicles (cluster headers or group leaders) to RSUs during different time stamps of the 400 s simulation. The different procedures of broadcasting the packets to the RSU in AGTSC-VC (spending much fewer intervals for broadcasting the traffic information packets to RSUs, in comparison with MC-DRIVE) cause the propagation of more packets in the MC-DRIVE approach rather than in AGTSC-VC, and hence receive more data bits at RSUs in a constant time interval. This behavior causes AGTSC-VC to obtain on average about 38% less throughput than MC-DRIVE does. However, it is observed that the average throughput in MC-DRIVE has initiated the overall diminishing trend from 180 s of the simulation in a manner that it takes 11.8% less time until the end of simulation. This is due to the dramatic rise of uplink traffic load and increase of the contention level as the matter of continuous rebroadcasting of traffic information from all the movements for long time intervals. On the other side, AGTSC-VC traces a fluctuating rise in average network throughput over the entire simulation time, which proves its less network uplink traffic.

Fig. 15 presents the evaluation of the packet delivery ratio. In this evaluation scenario, the total packet delivery ratio for transmitting and delivering the traffic information from the vehicles (cluster headers or group leaders) to RSUs during different time stamps of the simulation in the same traffic scenario is shown. The results obtained show that the total packet delivery ratio at RSUs in AGTSC-VC is on average 15.8% more than that in MC-DRIVE. The results demonstrate the decrease of network contention, packet loss, and existence of lower uplink traffic load in the AGTSC-VC approach. The comparison of the packet delivery ratio trend between the first 30 s and the last 30 s of simulation shows that AGTSC-VC has a 4.6% descending trend, while MC-DRIVE has a 14.7% decline under the same condition. This result demonstrates a more qualified procedure of propagating the density information packets in AGTSC-VC from the point of view of network QoS.

Fig. 16 presents the evaluation of precision in density estimation of the vehicles at the intersection. In this evaluation scenario, different numbers of vehicles each dedicated for traveling along a specific movement direction are injected to the single road segment of intersection. The accuracy of each approach as the correct estimation of the vehicles in each cluster is evaluated. In this evaluation, AGTSC-VC shows better performance in comparison with MC-DRIVE and TATSC. The results prove that the simplicity of data types in the density estimation process of the cluster header in AGTSC-VC leads to

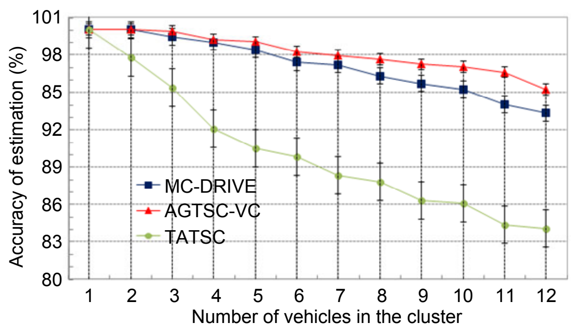

Fig. 16 Comparison of accuracy in cluster density estimation

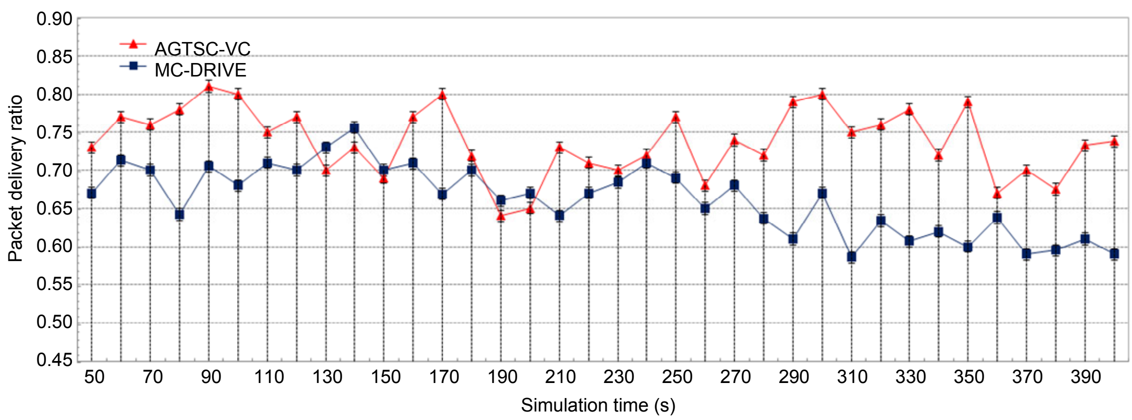

Fig. 15 Comparison of the total packet delivery ratio of RSUs during different time stamps

the desired precision of estimation. In this evaluation, AGTSC-VC, MC-DRIVE, and TATSC experience 5.1%, 7.1%, and 15.9% imprecision in the most congested scenario, respectively.

Fig. 17 and Table 3 present the evaluation of convergence time (as the time eliminated by the traffic controller to process and assess the density information and generate traffic signal timing). In this evaluation, different volumes of traffic are injected to the intersection to assess the convergence time by gradually increasing the average traffic volume. This time interval is considered from the initiation of the time at which the availability of density information of all the intersection's movements at the traffic controller becomes complete until the generation of traffic signal timings is done. The comparison of the results obtained from the three approaches, i.e., AGTSC-VC, MC-DRIVE, and TATSC, shows that TATSC operates in a shorter period of time, due to its simple and naïve procedure of calculating the traffic signal in TATSC. On the other hand, due to the addition of the QEM-based algorithm to its traffic signal timing algorithm, AGTSC-VC is confronted with more processing time than the other two approaches (on average about 30.5% more than MC-DRIVE and 52.8% more than TATSC). Although this higher ratio is considerable, consideration of convergence time scale in milliseconds implies that the time gap of the all-red clearance interval of the last traffic signal's phase can support AGTSC-VC's convergence time.

The overall waiting time of vehicles at the intersection is an essential traffic parameter to assess the performance of any adaptive TSCS under different traffic conditions. In this study, the parameter called 'average delay per vehicle' proposed by Webster and Cobbe (1966) is used as the key

Table 3 Comparison of convergence time in different traffic scenarios

Average volume of the intersection (vphpl)	Convergence time (ms)		
	MC-DRIVE	AGTSC-VC	Traditional ATSCS
100	240.21	383.23	177.23
200	246.30	379.42	184.17
300	253.55	380.14	183.40
400	259.30	386.32	182.40
500	261.40	379.94	185.10
600	267.74	385.24	179.76
700	272.14	395.11	186.12
800	275.50	389.61	181.68
900	279.40	398.84	194.23
1000	283.80	390.33	178.13
1100	286.90	401.06	186.10
1200	290.10	394.22	190.12
1300	292.80	402.18	184.10
1400	295.90	400.07	187.19

parameter for this evaluation. It considers two important factors: (1) the uniform waiting delay rate of vehicles while stopping at the intersection, and (2) the waiting delay experienced by vehicles arriving at the time of queuing up in the bottleneck, near the intersection. Eq. (12) shows the calculation of the average delay per vehicle (ADPV) at the intersection:

$$\begin{aligned}\mathrm{ADPV}=&\frac{\mathrm{CL}\left(1-\frac{\mathrm{EG}_i}{\mathrm{CL}}\right)^2}{2\left[1-\frac{\mathrm{EG}_i}{\mathrm{CL}}\cdot V_i\Big/\left(\frac{\mathrm{EG}_i}{\mathrm{CL}}\cdot\mathrm{SF}_i\right)\right]}\\&+\frac{\left[V_i\Big/\left(\frac{\mathrm{EG}_i}{\mathrm{CL}}\cdot\mathrm{SF}_i\right)\right]^2}{2V_i\left[1-V_i\Big/\left(\frac{\mathrm{EG}_i}{\mathrm{CL}}\cdot\mathrm{SF}_i\right)\right]}\\&-0.65\left(\frac{\mathrm{CL}}{v_i^2}\right)^{\frac{1}{3}}\left[V_i\Big/\left(\frac{\mathrm{EG}_i}{\mathrm{CL}}\cdot\mathrm{SF}_i\right)\right]^{2+5\frac{\mathrm{EG}_i}{\mathrm{CL}}}.\end{aligned} \tag{12}$$

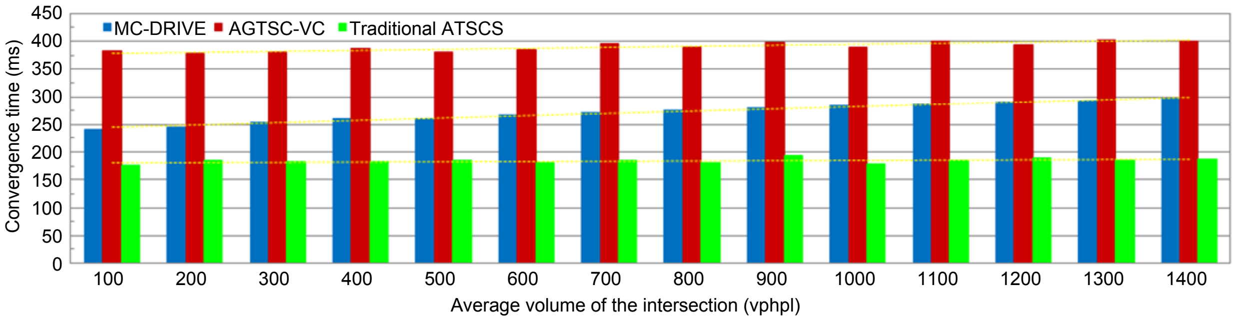

Fig. 17 Comparison of convergence time in different traffic scenarios (References to color refer to the online version of this figure)

By employing the data obtained from the simulation (after completion of each traffic signal cycle) and substituting them into Eq. (12), a general scheme of vehicles' wasted time at the intersection will be provided. Webster defined the ratio ADPV/CL as the relative waiting delay per vehicle at the intersection to make the evaluation more tangible. Accordingly, this evaluation parameter is used to judge the efficiency of AGTSC-VC in comparison with its rivals.

The evaluation of ADPV is performed in two separate scenarios. Fig. 18 presents the first evaluation scenario in which different volumes of traffic are injected in the particular movement direction of the intersection (north-straight direction) to assess the traffic signal timing and the performance when unpredicted volumes of traffic enter the intersection's edges. This evaluation is performed without considering the expanding factor for generating the traffic signal timing in AGTSC-VC. In this evaluation, the performance of AGTSC-VC is somewhat superior. This superiority becomes more apparent as the volume of movement increases from 800 vphpl upward. This occurs such that the relative waiting delay per vehicle in AGTSC-VC decreases by 9.4% and 13.4% in the most congested volume of movement in comparison to MC-DRIVE and TATSC, respectively.

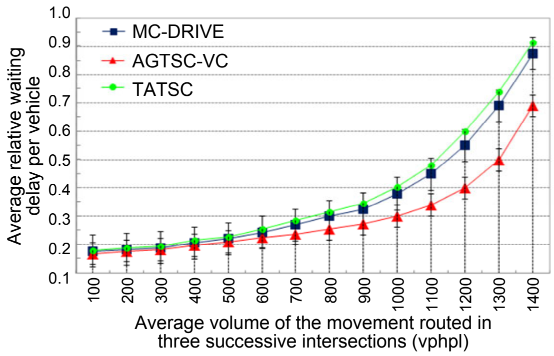

Fig. 18 Comparison of relative waiting delay per vehicle in one single intersection

Fig. 19 shows the second evaluation scenario of relative delay per vehicle, performed by conducting the traffic movement in three successive intersections. In this scenario, the gradual increase in the traffic volume in a particular movement is directly routed to two following adjacent intersections. In this evaluation, consideration of $Traffic_{index}$ and utilization of the expanding factor in the calculation of traffic signal timing of ATSC-V leads to a clear superiority of AGTSC-VC.

The utilization of the expanding factor in the second evaluation causes AGTSC-VC to gain 21.08% improvement (decrease of the relative waiting delay) during the interval of 700–1400 vphpl, in comparison with its performance in a single intersection. On the other hand, the lack of anticipation-based traffic signal timing in MC-DRIVE and TATSC causes excessive waiting delay for vehicles in these two approaches during the interval 1000–1400 vphpl, so MC-DRIVE and TATSC encounter 3.4% and 4.5% rise in the relative waiting delay vphpl, respectively, in comparison with their performance in a single intersection during this interval.

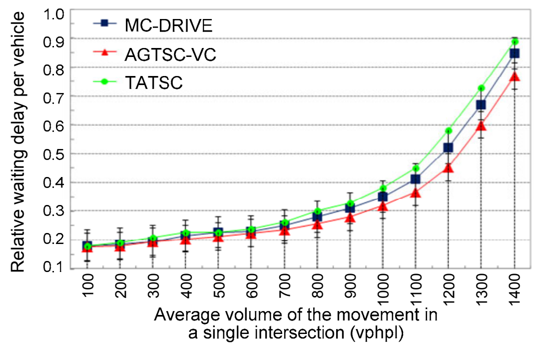

Fig. 19 Comparison of relative waiting delay per vehicle in three successive intersections

Fig. 20 shows the evaluation of priority-based traffic signal timing, i.e., the time spent by the prioritized vehicle for traveling the specified distance. In this evaluation, the route comprises six consecutive intersections from Lexington Avenue to 5th Avenue (depicted with red mark in Fig. 12), and the travel time of the prioritized vehicle under the average traffic volume of 1200 vphpl in the specified route is assessed. The provision for prioritized vehicle detection and green-light interval extension in AGTSC-VC results in the prioritized vehicle spending a noticeably shorter time on traveling through the six intersections. On the other hand, in MC-DRIVE and TATSC, the lack of this option results in a greater amount of travel time for the prioritized vehicle. The horizontal lanes in Fig. 20 represent the location of the traffic signal in the road network. The results demonstrate that the lack of prioritized vehicle detection in MC-DRIVE and TATSC leads to several time-consuming halts behind the intersections. However, this behavior is not observed for AGTSC-VC. Based on the results obtained, the utilization of priority-based traffic signal timing in AGTSC-VC results in a decrease in the travel time of prioritized vehicle by about 38.2% and 44.8%, respectively, in comparison with the MC-DRIVE and TATSC approaches under the congested traffic volume of 1200 vphpl.

To evaluate the effectiveness of AGTSC-VC in reducing fuel consumption and pollutant emission, a method presented in Akçelik and Besley (2003) and Akçelik *et al.* (2012) is used. This method provides a general estimation of pollutant emissions in the form of an intersection analysis package by considering three main parameters (traffic, road, and vehicle) and monitoring the velocity (V) and acceleration (a) of the vehicles near the intersection. Accordingly, Eq. (13) shows the calculation of fuel consumption rate (mL/s) per unit time measured. Eq. (14) shows the direct estimation of carbon dioxide (CO_2) emission rate (g/s) from the instantaneous fuel consumption rate obtained from Eq. (13).

$$f_t(\text{Fuel}) = \alpha + \beta_1 P_\text{T} + \left[\frac{\beta_2 M_\text{V} a^2 V}{1000}\right]_{a>0}, \quad P_\text{T} > 0. \tag{13}$$

$$F_t(\text{CO}_2) = f_{\text{CO}_2} \cdot f_t(\text{Fuel}). \tag{14}$$

In Eq. (13),

$$P_\text{T} = \min(P_\text{max} \cdot P_\text{C} + P_\text{I} + P_\text{G}),$$
$$P_\text{C} = b_1 V + b_2 V^3,$$
$$P_\text{I} = M_\text{V} a V / 1000,$$
$$P_\text{G} = \frac{9.81 M_\text{V} (G/100) V}{1000}.$$

Table 4 shows a brief description of the parameters in this calculation for evaluating the approaches, according to the factors defined by Akçelik and Besley (2003) and Akçelik *et al.* (2012). Fig. 21 shows the utility efficiency of CO_2 pollutant emission for each approach. In this evaluation, the impact of gradual increase of the CO_2 emission rate per vehicle is estimated per kilometer. The x-axis in Fig. 21 represents the number of vehicles injected in the simulation scenario, and the y-axis represents the

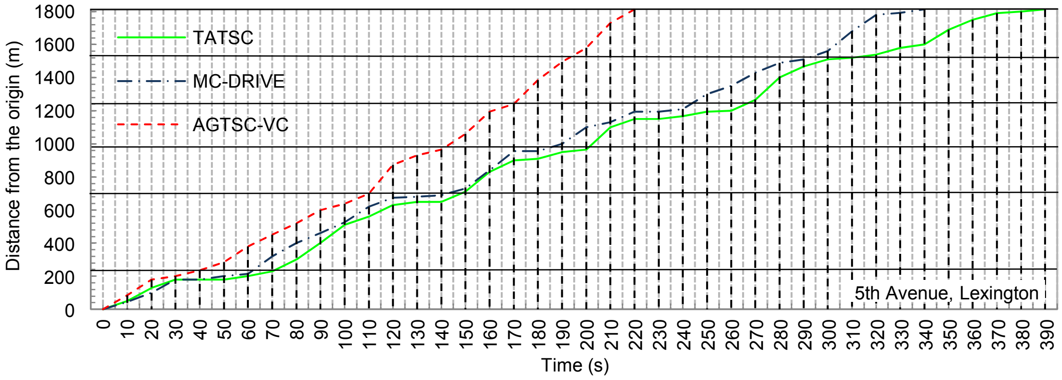

Fig. 20 Comparison of prioritized vehicle's travel time in six successive intersections

Table 4 Parameter for the calculation of pollutant emission

Parameter	Description	Passenger vehicle	Freight vehicle
α	Constant idle fuel consumption rate (L/h)	1.35	1.57
β_1	Efficiency parameter for relating fuel consumed to the total provided power (mL·s²/(kJ·m))	0.09	0.08
β_2	Efficiency parameter for relating fuel consumed during positive acceleration to the product of the acceleration rate	0.03	0.02
P_max	Maximum engine power (kW)	85	130
b_1	Vehicle parameter related to rolling resistance (kN)	0.222	0.255
b_2	Vehicle parameter related to aerodynamic drag (kN·s²/m²)	0.0007	0.0009
M_V	Vehicle mass (kg)	1400	5500
G	Road grade (%) (in this study it is considered as zero)	N/A	N/A
f_{CO_2}	CO_2 to fuel consumption rate of fuel (g/mL)	2.5	2.6

average CO_2 emission rate calculated per kilometer. In this evaluation scenario, the superiority of AGTSC-VC is conspicuous from the view point of decreasing the CO_2 emission. The results demonstrate that AGTSC-VC decreases the CO_2 emission on average by about 8.7% and 12.4%, in comparison with MC-DRIVE and TATSC, respectively.

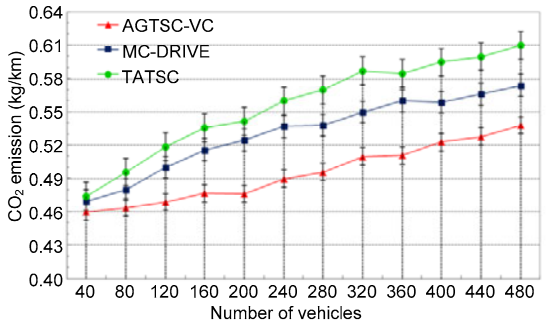

Fig. 21 Impact of the number of vehicles on the pollutant emission rate

5 Conclusions

This study presents a new VANET-based adaptive green TSCS named AGTSC-VC, which takes advantage of V2X communications to improve the traffic conditions at intersections. The proposed approach uses three types of packets, header-packet, reply-packet, and traffic-load-packet, to provide traffic density information during vehicle clustering at the intersection. To perform traffic assessment and analysis, AGTSC-VC uses a modified combination of traffic signal generation algorithms from the STM and Webster methods. AGTSC-VC is able to make prioritization in traffic signal operation by detecting the broadcasted packet called 'preference-packet' from prioritized vehicles when they are moving toward the intersection. The most distinct ability of AGTSC-VC is the improvement in traffic flow and delay of vehicles in congested traffic conditions over wide urban areas consisting of several adjacent intersections. The performance of the proposed approach is compared with those of the MC-DRIVE approach and the traditional adaptive TSCSs of Webster. The evaluation results demonstrate the superiority of AGTSC-VC in improving the important traffic parameters such as accuracy of vehicle density estimation, decreasing the waiting delays of vehicles at the intersection, conspicuously reducing the CO_2 emission rates at the intersection, and decreasing the travel time of prioritized vehicles. Moreover, the evaluation of network parameters in comparison with MC-DRIVE shows improvement of network QoS parameters including the network overhead and packet delivery ratio in AGTSC-VC. Further progress of this approach as future work will involve the development of more comprehensive TSCSs, which can provide the information of congested routes and their suggested replacement for each cluster of vehicles at the intersections.

References

Akçelik, R., Besley, M., 2003. Operating cost, fuel consumption, and emission models in aaSIDRA and aaMOTION. 25th Conf. of Australian Institutes of Transport Research, p.1-15.

Akçelik, R., Besley, M., Chung, E., 1998. An evaluation of SCATS Master Isolated control. Proc. 19th ARRB Transport Research Conf., p.1-24.

Akçelik, R., Smit, R., Besley, M., 2012. Calibrating fuel consumption and emission models for modern vehicles. IPENZ Transportation Group Conf., p.1-13.

Bester, C., Meyers, W., 2007. Saturation flow rates. SATC.

Bruce, R.L., 1984. Loop Detector for Traffic Signal Control. US Patent 4 430 636 A.

Chang, H.J., Park, G.T., 2013. A study on traffic signal control at signalized intersections in vehicular ad hoc networks. *Ad Hoc Netw.*, **11**(7):2115-2124. http://dx.doi.org/10.1016/j.adhoc.2012.02.013

Dickinson, K., Wan, C., 1990. An evaluation of microwave vehicle detection at traffic signal controlled intersections. 3rd Int. Conf. on Road Traffic Control, p.153-157.

Eichler, S., 2007. Performance evaluation of the IEEE 802.11p WAVE communication standard. IEEE 66th Vehicular Technology Conf., p.2199-2203. http://dx.doi.org/10.1109/VETECF.2007.461

Gordon, R.L., Tighe, W., Siemens, I., 2005. Traffic Control Systems Handbook. US Department of Transportation, Technical Paper No. FHWA-HOP-06-006, Federal Highway Administration, Office of Operations, Washington, D.C., USA.

Gradinescu, V., Gorgorin, C., Diaconescu, R., *et al.*, 2007. Adaptive traffic lights using car-to-car communication. IEEE Vehicular Technology Conf., p.21-25.

Haklay, M., Weber, P., 2008. Openstreetmap: user-generated street maps. *IEEE Perv. Comput.*, **7**:12-18. http://dx.doi.org/10.1109/MPRV.2008.80

Huang, Q., Miller, R., 2004. Reliable wireless traffic signal protocols for smart intersections. ITS America Annual Meeting.

Jabbarpour, M.R., Md Noor, R., Khokhar, R.H., *et al.*, 2014. Cross-layer congestion control model for urban vehicular environments. *J. Netw. Comput. Appl.*, **44**:1-16. http://dx.doi.org/10.1016/j.jnca.2014.05.002

Köhler, E., Strehler, M., 2010. Traffic signal optimization using cyclically expanded networks. 10th Workshop on Algorithmic Approaches for Transportation Modelling, Optimization, and Systems, p.114-129. http://dx.doi.org/10.4230/OASIcs.ATMOS.2010.114

Koonce, P., Rodergerdts, L., Lee, K., *et al.*, 2008. Traffic Signal Timing Manual. Report No. FHWA-HOP-08-024, Federal Highway Administration, Washington, D.C., USA.

Kraft, W.H., Homburger, W.S., Pline, J.L., 2009. Traffic Engineering Handbook. ITE, Washington, D.C., USA.

Krajzewicz, D., Erdmann, J., Behrisch, M., *et al.*, 2012. Recent development and applications of SUMO—simulation of urban mobility. *Int. J. Adv. Syst. Meas.*, **5**(3-4):128-138.

Kwatirayo, S., Almhana, J., Liu, Z., 2013. Adaptive traffic light control using VANET: a case study. 9th Int. IEEE Wireless Communications and Mobile Computing Conf., p.752-757. http://dx.doi.org /10.1109/IWCMC.2013.6583651

Lahart, J., Conroy, E., Curley, R., *et al.*, 2013. Design Manual for Urban Roads and Streets. Technical Paper, Department of Transport, Tourism and Sport of Ireland, Dublin, Ireland.

Li, L., Wen, D., Yao, D., 2014. A survey of traffic control with vehicular communications. *IEEE Trans. Intell. Transp. Syst.*, **15**(1):425-432. http://dx.doi.org/10.1109/TITS.2013.2277737

Litman, T., 2013. Factors to Consider When Estimating Congestion Costs and Evaluating Potential Congestion Reduction Strategies. https://trid.trb.org/view.aspx?id=1267787

Liu, H., van Zuylen, H.J., van Lint, H., *et al.*, 2005. Prediction of urban travel times with intersection delays. Proc. IEEE Intelligent Transportation Systems, p.402-407. http://dx.doi.org/10.1109/ITSC.2005.1520198

Maslekar, N., Boussedjra, M., Mouzna, J., *et al.*, 2011a. C-DRIVE: clustering based on direction in vehicular environment. 4th IFIP Int. Conf. on New Technologies, Mobility and Security, p.1-5. http://dx.doi.org/10.1109/NTMS.2011.5720653

Maslekar, N., Boussedjra, M., Mouzna, J., *et al.*, 2011b. VANET based adaptive traffic signal control. IEEE 73rd Vehicular Technology Conf., p.1-5. http://dx.doi.org/10.1109/VETECS.2011.5956305

Maslekar, N., Mouzna, J., Boussedjra, M., *et al.*, 2013. CATS: an adaptive traffic signal system based on car-to-car communication. *J. Netw. Comput. Appl.*, **36**(5):1308-1315. http://dx.doi.org/10.1016/j.jnca.2012.05.011

Nafi, N.S., Khan, J.Y., 2012. A VANET based intelligent road traffic signalling system. IEEE Telecommunication Networks and Applications Conf., p.1-6. http://dx.doi.org/10.1109/ATNAC.2012.6398066

National Research Council (NRC), 2000. Highway Capacity Manual. Transportation Research Board, Washington, D.C., USA.

Pandit, K., Ghosal, D., Zhang, H.M., *et al.*, 2013. Adaptive traffic signal control with vehicular ad hoc networks. *IEEE Tran. Veh. Technol.*, **62**(4):1459-1471. http://dx.doi.org/10.1109/TVT.2013.2241460

Priemer, C., Friedrich, B., 2009. A decentralized adaptive traffic signal control using V2I communication data. 12th Int. IEEE Conf. on Intelligent Transportation Systems, p.1-6. http://dx.doi.org/10.1109/ITSC.2009.5309870

Puri, A., Valavanis, K., Kontitsis, M., 2007. Statistical profile generation for traffic monitoring using real-time UAV based video data. Mediterranean Conf. on Control & Automation, p.1-6. http://dx.doi.org/10.1109/MED.2007.4433658

Robertson, D.I., Bretherton, R.D., 1991. Optimizing networks of traffic signals in real time: the SCOOT method. *IEEE Trans. Veh. Technol.*, **40**(1):11-15. http://dx.doi.org/10.1109/25.69966

Scholz, I., 2011. Java OpenStreetMap Community. OpenStreetMap Editor. https://josm.openstreetmap.de/

Schrank, D., Eisele, B., Lomax, T., 2012. TTI's 2012 Urban Mobility Report. Texas A&M Transportation Institute, Texas, USA.

Shelby, S.G., 2001. Design and Evaluation of Real-Time Adaptive Traffic Signal Control Algorithms. PhD Thesis, University of Arizona, Tucson, USA.

Sommer, C., Eckhoff, D., German, R., *et al.*, 2011a. A computationally inexpensive empirical model of IEEE 802.11p radio shadowing in urban environments. IEEE 8th Int. Conf. on Wireless On-Demand Network Systems and Services, p.84-90. http://dx.doi.org/10.1109/WONS.2011.5720204

Sommer, C., German, R., Dressler, F., 2011b. Bidirectionally coupled network and road traffic simulation for improved IVC analysis. Mobile Computing. *IEEE Trans.*, **10**(1):3-15. http://dx.doi.org/10.1109/TMC.2010.133

Stevanovic, A., Stevanovic, J., Zhang, K., *et al.*, 2009. Optimizing traffic control to reduce fuel consumption and vehicular emissions. *Transp. Res. Rec.*, **2128**:105-113. http://dx.doi.org/10.3141/2128-11

Tomescu, O., Moise, I.M., Stanciu, A.E., *et al.*, 2012. Adaptive traffic light control system using ad hoc vehicular communications network. *U.P.B. Sci. Bull. D*, **74**:68-78.

U.S. Energy Information Administration (EIA), 2009. Emissions of Greenhouse Gases in the United States 2008. Technical Report No. DOE/EIA-0573(2008), Office of Integrated Analysis and Forecasting, U.S. Department of Energy, Washington, D.C., USA.

Varga, A., Hornig, R., 2008. An overview of the OMNeT++ simulation environment. Proc. 1st Int. Conf. on Simulation Tools and Techniques for Communications, Networks and Systems & Workshops, p.60. http://dx.doi.org/10.4108/ICST.SIMUTOOLS2008.3027

Webster, F.V., 1958. Traffic Signal Settings. Technical Paper, Her Majesty's Stationery Office, London, UK.

Webster, F.V., Cobbe, B.M., 1966. Traffic Signals. Technical Paper, Her Majesty's Stationary Office, London, UK.

Yousefi, S., Mousavi, M.S., Fathy, M., 2006. Vehicular ad hoc networks (VANETs): challenges and perspectives. Proc. IEEE 6th Int. Conf. on ITS Telecommunications, p.761-766. http://dx.doi.org/10.1109/ITST.2006.289012