Green wave-based virtual traffic light management scheme with VANETs

Li-Der Chou*

Department of Computer Science and Information Engineering,
National Central University,
Taoyuan, 32001, Taiwan
and
National Center for High-performance Computing,
National Applied Research Laboratories,
Hsinchu, 30076, Taiwan
Email: cld@csie.ncu.edu.tw
*Corresponding author

Tsung-Yi Shen and Chia-Wei Tseng

Department of Computer Science and Information Engineering,
National Central University,
Taoyuan, 32001, Taiwan
Email: millershen@gmail.com
Email: ncu100582018@gmail.com

Yao-Jen Chang

Department of Electronic Engineering,
Chung Yuan Christian University,
Taoyuan, 32023, Taiwan
Email: yjchang@cyu.edu.tw

Yen-Wei Kuo

Department of Computer Science and Information Engineering,
National Central University,
Taoyuan, 32001, Taiwan
Email: 965402015@cc.ncu.edu.tw

Abstract: Green intelligent transportation systems (GITS) have received significant attention in recent years. Traffic congestion, which is an important research topic on intelligent transportation systems (ITS), is rapidly becoming one of the most serious problems affecting urban areas. This study utilises the vehicular ad hoc networks (VANETs) technology to build a virtual traffic light (VTL) environment to reduce traffic congestion. The objective of this study is to adjust the traffic light signal time length on-demand to enable vehicles to pass through numerous intersections rapidly, thereby saving energy and reducing fuel consumption. The traffic phase combination algorithm and VTL operation mechanism are also addressed to improve the traffic congestion situation in urban areas. Simulation results indicate that the proposed scheme can increase the percentage of traffic flow and the average speed of all vehicles in all intersections, thereby saving energy.

Keywords: VANETs; vehicular ad hoc networks; VTL; virtual traffic light; green wave; green ITS; intelligent transportation systems; speed guidance.


Biographical notes: Li-Der Chou received his MS and PhD in Electronic Engineering from National Taiwan University of Science and Technology, Taipei, Taiwan in 1991 and 1995, respectively. He is currently the Deputy Director General with the National Center for High-Performance Computing, Taiwan, the Board Member of the Taiwan Network Information Center and a Distinguished Professor with the Department of Computer Science and Information
1 Introduction

Transportation vehicles releasing substantial amount of carbon dioxide and other toxins are proven to be the leading cause of air pollution. To overcome these problems, saving energy and reducing carbon dioxide emissions have become the top priorities of governments and the construction industry. In particular, developing an intelligent transportation system (ITS) that can integrate an efficient traffic control scheme can increase transportation system efficiency, thereby reducing traffic congestion, fuel consumption and carbon emissions.

Green intelligent transportation systems (GITS) (http://www.greenits.ca; http://ecomove-project.eu) applications and services are specifically designed to reduce energy consumption and air pollution emissions in transportation systems. The major objectives of GITS are to improve energy efficiency and to reduce carbon dioxide emissions. Air pollution is primarily a consequence of traffic congestion, which is a major problem in urban areas. To improve energy efficiency and reduce air pollution, GITS proposed a new mode of transportation in a global innovation.

Vehicular ad hoc networks (VANETs) are the short-distance communication network of moving cars. VANET comprises several sensors embedded on vehicles. An extensive variety of sensor technologies have been reported in the literature (Kanzaki et al., 2010; Chung et al., 2009; Chang and Wang, 2010). The on-board unit (OBU) and road-side unit (RSU) are the two most important components of VANET applications. VANETs comprise two communication architectures, namely, vehicle-to-vehicle (V2V) communication and vehicle-to-infrastructure (V2I) communication. The main objective of VANETs is to ensure the safety and comfort of passengers. Improving safety in driving is also highly important (https://play.google.com/store/apps/details?id=com.mbi.safemate; Saiprasert and Pattara-Atikom, 2012). Apart from road safety problems, traffic congestion control is an important research issue involving VANETs. Motivated by the ideas of reducing deployment costs and dynamically regulating vehicular traffic flow at intersections, inter-vehicle communications-based virtual traffic lights (VTLs) are envisioned to replace traditional infrastructure-based traffic lights (Chou et al., 2013; Tonguz, 2011; Ferreira et al., 2010; Tielert et al., 2010).

Traditional signal systems utilise a predefined signal timing. Improper traffic signal timing may cause traffic congestion and delays. Therefore, an efficient traffic signal timing control policy is highly important. The green wave mechanism (Coensel et al., 2012) leads the traffic signal coordination control, which can improve the traditional fixed traffic light scheme. Green wave technology is the driver in the forward direction for improving safety and for an improved energy-consuming economy (Warberg et al., 2008). A green wave occurs when a series of traffic lights is coordinated to enable continuous traffic flow in one main direction over several intersections. The traditional green wave operation is implemented on the roadside with fixed speed. This operation is implemented to enable vehicles to drive through green signals continuously. The ideal situation is the on-demand green wave-coordinated speed with flexibility control that reflects the current or anticipated traffic conditions.
The evolution of intelligent traffic control systems will improve urban traffic congestion, such that all vehicles in the network, particularly high energy-consuming vehicles, can avoid unnecessary stops. Such priority guarantees that transit vehicles constantly see a green light at the instant they arrive at an intersection. Thus, improved traffic signal coordination results in vehicles driving through numerous intersections without stopping. Moreover, intelligent traffic signals can efficiently control traffic flow during congested conditions, thereby reducing fuel consumption and saving energy.

This study discusses the management of VTLs based on vehicle wireless network technology. This scheme can improve traffic congestion and reduce the construction costs of traffic lights. Most studies on VTL schemes are limited to a single intersection environment. However, traffic flow is affected when roads are interconnected. The current study considers that phase combination and the VTL green wave control mechanism will improve transportation in urban areas in terms of average speed and saving energy.

The major contributions of this study are summarised as follows.

- the traffic signal phase combination algorithm can reduce conflict points at intersections and can achieve operational benefits
- the green wave-based VTL mechanism can guide vehicle speed, thereby reducing waiting time and saving energy

The remainder of this paper is organised as follows. Section 2 reviews the related studies. Section 3 discusses the design of the green wave speed guidance VTL protocol for VANETs. Section 4 presents the simulation results. Section 5 concludes this paper and presents a potential plan for future research.

2 Related studies

Given that environmental preservation is currently a major global issue, the intelligent traffic control of vehicles is poised to gain mass acceptance from the general public. ITS technology offers considerable promise in managing travel demands and operation of facilities in the future. Congestion control is important for controlling traffic in urban areas. Previous studies focused on traffic signal control schemes, particularly those discussing the best green timing interval and fixed sequence traffic signals.

In Binbin et al. (2011), a self-adaptive traffic signal control scheme is used to supervise multiple intersections. Real-time traffic data were collected through wireless sensors. Various road sensors detect the number of vehicles at an intersection, waiting time, number of stops of vehicles and vehicle density. Thus, the optimal green signal time length can be calculated using the adjacent intersection’s traffic data and traffic conditions as references.

In Houli et al. (2010), an adaptive multi-objective control scheme depends on a traffic state reinforcement learning the urban traffic signal control. Each intersection deploys an agent collecting immediate traffic condition data at the intersection. Agents in VANETs can exchange traffic information to obtain the optimal target vehicle stop number, average waiting time and the next intersection’s maximum queue length. Buses and emergency vehicles using the adaptive priority control scheme can be more efficient than those using the traditional traffic signal control method. In Chin et al. (2011), a traffic signal timing management (TSTM) system uses genetic algorithms to optimise traffic signal time. To reduce emissions and improve energy efficiency, rapid acceleration/deceleration and idling must be avoided. The dynamic velocity recommendations are based on real-time traffic signal messages wherein vehicle velocity is adjusted with the green light (Mandava et al., 2009).

Shenyang et al. (2011) proposed an arterial road that is the best coordinated using a signal control system with dynamic speed guidance and dynamic signal (DSDS) protocol. The priority areas and vehicle priority decision mechanism are used to adjust signal timing and provide optimal driving speed without stopping. In Balaji et al. (2010), a multi-agent reinforcement learning signal control scheme is used to improve vehicle delay time and speed. The regional traffic information collection and traffic signal controller at each intersection agent automatically exchange traffic information with neighbouring agents.

The aforementioned proposed approaches for VANETs exhibit the following drawbacks. Sensors are expensive, and the simultaneous transmissions of large amount of packet may increase interference and collisions. Multi-agent and roadside speed indicators are deployed in each traffic signal and are difficult to reach. Calculations for the traffic signal time length only consider the number of vehicles waiting in the queue. This process is also insufficient when applied to practical situations. To address these problems, this study proposes a green wave speed guidance using the VTL protocol to reduce traffic congestion in urban areas and save energy.

3 Green wave speed guidance through VTL

VANET-enabled VTLs are generated on-demand, such as when vehicles are approaching an intersection. Developing VTLs using VANETs through the V2V communication for an effective dynamic traffic light coordination control is the main goal of the proposed scheme.

Information disseminated through the VANET indicates that the proposed mechanism provides a decision on the length of green time for each phase. A phase is defined as any unique combination of vehicle or pedestrian phases that occur simultaneously. An example of a phase is the opposing northbound/southbound left turns or eastbound/westbound turns with concurrent eastbound/westbound pedestrian movements. Section 3.2 presents the details of this example. Different traffic signal phase combinations in an intersection are defined in the aforementioned section. These combinations can reduce the conflict
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3.1 Assumptions
This study provides the following assumptions. The actual conditions for the proposed system may vary.

- VANETs are reliable and have enough bandwidth to enable real-time simulation.
- All vehicle drivers have good driving behaviour; no vehicle attempts to change the VTL signal except those that run a red light. All vehicles obey the VTL indication of driving.
- All vehicles have global positioning system (GPS) devices, which provide highly reliable, accurate, and real-time GPS correction signal. The Nationwide differential gps system (NDGPS) is between 10 and 15 cm (http://www.gps.gov/systems/augmentations).
- All vehicles are equipped with an 802.11p wireless network communication device, and the same roads have digital map data. All vehicles have a consistent map. At an intersection, each VTL leader can know all the adjacent sections of vehicle location.
- V2V wireless network transmission does not interrupt the signal and is highly secure, thereby ensuring the accuracy of the message transmission.
- Each vehicle’s destination is evidently known by the GPS navigation, which can obtain the travel direction of the vehicle at the intersection.
- Finally, no hardware failure occurs.

3.2 Traffic signal phase combination algorithm
A cycle is the process where traffic in every direction of rotation obtains a green light to pass through an intersection. A phase refers to the right of way demand from the green and red lanes. Pedestrians can pass by a collection consisting of vehicles or other pedestrians passing by.

The traditional traffic control methods implemented in an intersection involves increased instances of turn left, go straight, and turn right signal phases. Reserving the turn left phase and the pedestrian-free street takes considerable time. A significantly large intersection increases waiting time because of the gap interval growth. A potential queue blockage caused by the long wait cycle can result in an imbalanced lane use. Thus, determining a replacement method to solve congestion and to achieve green wave for regular lanes is necessary.

The key factor of the traffic congestion is the conflict points of an intersection. Figure 1 shows the scenarios depicting the intersection point of conflict. The red points in the figure denote the crossing points. The phase combination algorithm denotes that the VLT leader determines a combination of the green phase at each intersection that provides a passable direction at the intersection. The crossing point definitions are described as follows.

- The coordinates of the centre of each lane width are acquired at the intersection.
- Figure 2 shows the traffic direction at the intersection. The incoming indication vehicle enters the intersection and the outgoing indication vehicle leaves the intersection. The incoming lane and outgoing lane’s centre points coordinates are connected with a straight line.
- The first degree polynomial in two variables is resolved. The solution is the crossing point.

The signal phase selection algorithm is described as follows. A total of 12 phases are involved in the proposed algorithm. Any phase combination will not contain any crossing point when this algorithm is used.

In Figure 3(a), if the lane E to lane S direction has no vehicle, then this phase can change to 6(a); if the lane E to lane W direction has no vehicle, then this phase can change to 5(a) or 7(a). In Figure 3(b), if the lane W to lane N direction has no vehicle, then this phase can change to 6(a); if the lane W to lane E direction has no vehicle, then this phase can change to 5(a) or 7(a). In Figure 4(a), if the lane S to lane W direction has no vehicle, then this phase can change to 6(b); if the lane S to lane N direction

Figure 1 Intersection point of conflict (see online version for colours)

Figure 2 Incoming and outgoing directions (see online version for colours)
has no vehicle, then this phase can change to 5(b) or 8(b).
In Figure 4(b), if the lane N to lane E direction has no
vehicle, then this phase can change to 6(b); if the lane N to
to lane S direction has no vehicle, then this phase can change
to 5(b) or 8(b). The phase in Figure 5(a) can change to 3(a),
3(b), 7(a) or 7(b); the phase in Figure 5(b) can change to
4(a), 4(b), 8(a) or 8(b); the phase in Figure 6(a) can change
to 3(a), 3(b), 8(a) or 8(b); the phase in Figure 6(b) can
change to 4(a), 4(b), 7(a) or 7(b); the phase in Figure 7(a)
can change to 3(a), 4(b), 5(a) or 6(b); the phase in Figure 7(b)
can change to 3(a), 4(a), 5(a) or 6(a); the phase in Figure 8(a) can change to 3(a), 4(a), 5(b) or 6(a); and the
phase in Figure 8(b) can change to 3(b), 4(b), 5(b) or 6(a).

Figure 9 shows all the straight lines in the intersection.
Each phase is formalised into the following linear
equations.

Figure 3 (a) E-lane vehicles allowed phase and (b) W-lane
vehicles allowed phase (see online version for colours)

Figure 4 (a) S-lane vehicles allowed phase and (b) N-lane
vehicles allowed phase (see online version for colours)

Figure 5 (a) E-lane and W-lane vehicles turn left phase and (b)
S-lane and N-lane vehicles turn left phase (see online
version for colours)

Figure 6 (a) E-lane and W-lane vehicles go straight phase and
(b) S-lane and N-lane vehicles go straight phase (see online version for colours)

Figure 7 (a) E-lane vehicles turn left and N-lane go straight
phase and (b) W-lane vehicles turn left and S-lane go
straight phase (see online version for colours)

Figure 8 (a) S-lane vehicles turn left and E-lane go straight
phase and (b) N-lane vehicles turn left and W-lane go
straight phase (see online version for colours)

Figure 9 All straights and coordinates between incoming and
outgoing directions (see online version for colours)
E-lane to W-lane equation:
\[ y = 2, \quad (-4 \leq x \leq 4); \] (1)

W-lane to E-lane equation:
\[ y = -2, \quad (-4 \leq x \leq 4); \] (2)

E-lane to S-lane equation:
\[ 4x - 5y = 11, \quad (-1 \leq x \leq 4, -3 \leq y \leq 1); \] (3)

W-lane to N-lane equation:
\[ 4x - 5y = -11, \quad (-1 \leq x \leq 4, -3 \leq y \leq 1); \] (4)

E-lane to N-lane equation:
\[ x + y = 6, \quad (3 \leq x \leq 4, 2 \leq y \leq 3); \] (5)

W-lane to S-lane equation:
\[ x + y = -6, \quad (-4 \leq x \leq -3, -3 \leq y \leq -2); \] (6)

S-lane to W-lane equation:
\[ 4x + 5y = -11, \quad (-4 \leq x \leq 1, -3 \leq y \leq 1); \] (7)

N-lane to E-lane equation:
\[ 4x + 5y = 11, \quad (-1 \leq x \leq 4, -1 \leq y \leq 3); \] (8)

S-lane to N-lane equation:
\[ x = 2, \quad (-3 \leq x \leq 3); \] (9)

N-lane to S-lane equation:
\[ x = -2, \quad (-3 \leq x \leq 3); \] and
\[ x - y = 6, \quad (3 \leq x \leq 4, -3 \leq y \leq -2). \] (10)

To summarise the preceding descriptions, the procedure for determining the phase combination algorithm is described as follows.

- The intersection centre is set as the origin of the coordinates. \((x, y)\) represents the centre point of any one-lane centre.

- In each section of the lanes, the direction for entering the intersection denotes incoming vehicles, and the direction for a vehicle moving away from an intersection denotes outgoing vehicles (Figure 9).

- Each incoming and outgoing points are connected, and the shortest path is selected. No U-turn is present in this case.

- The incoming coordinates \((x_i, y_i)\) and outgoing coordinates \((x_j, y_j)\) are selected through the following linear equation:
\[ y - y_i = \frac{y_j - y_i}{x_j - x_i}(x - x_i). \] (12)

- The vehicle forward direction and various sections of the number of lanes indicate that the conditions of the constraints \(x_{\text{lane}}\) and \(y_{\text{lane}}\) are acquired for the number of lanes.
\[
\begin{align*}
-x_{\text{lane}} - 1 &\leq x \leq x_{\text{lane}} + 1 \\
y_{\text{lane}} - 1 &\leq y \leq y_{\text{lane}} + 1,
\end{align*}
\] (13)

- In providing the general formula for all phases at the intersection, the point slope and standard forms of linear equations are given by equation (14). In changing parameters \(a, b,\) and \(c\), the properties of the different traffic phases can be explored.
\[
\begin{align*}
A_1x + B_1y &+ C_1 \\
A_2x + B_2y &+ C_2
\end{align*}
\] (14)

### 3.3 VTL operation mechanism

This section discusses the VTL scheme based on the wireless network technology of vehicles. VTLs are created if they are necessary, and they could only be created at times when they are useful for current traffic conditions. Researchers have been developing a VTL system placed inside a vehicle; this system can facilitate the improvement of the traffic congestion situation. The VTL technology will enable traffic lights to be created on demand when vehicles are attempting to cross an intersection. Figure 10 shows the VTL operation mechanism. Figure 11 shows the flowchart of the VTL status update process.
segment. The new vehicle sends a VTL request frame, including lane IE information, to inform the VTL leader about the intersection’s current traffic information ahead of time. The beacon interval of a vehicle is 500 ms. If the vehicle ahead receives the VTL status of the vehicle at the intersection, then the former replies with the VTL response frame that includes the VTL status informing the rear vehicle. The vehicle can acquire the green phase state and can calculate the required recommended driving speed. Section 3.4 describes the speed guidance calculation mechanism. Vehicles receiving the VTL request frame forward the lane information to the VTL leader and the leaders on each road through the lane update frame. If the VTL status is updated, then the VTL leader sends the VTL’s updated frame to notify all vehicles of the updated VTL status.

In the VTL’s status update process, the lane leader broadcasts a fixed period of road, collects the number of vehicles in the lane and calculates the time required for the green light to signal. The lane leader can receive the road traffic information broadcasted by the VTL leader every 500 ms. The VTL operation is set by the VTL leader in each intersection. The candidates for VTL leader are selected by the lane leader in each lane. The VTL leader is set in the red light signal, and the beacon cycle is 100 ms. The identification of the VTL leader should change to any one of the leaders at the intersection before the VTL leader crosses the intersection. If the VTL status has been set, then the lane leaders and all crossing vehicles can know the current VTL status. If the VTL leader disappears, then the other lane leaders will detect the disappearance after a 100 ms beacon interval and randomly set a new VTL leader. The VTL leader periodically broadcasts the beacon and lane IE’s information to provide traffic information at the intersection.

### 3.4 Green wave speed guidance through VTL

This section describes the green wave speed guidance through the VTL scheme. Figure 12 shows an example to describe a scenario involving this mechanism. A vehicle drives through five intersections. If the vehicle’s speed is 60 km/h, then it needs to stop three times. This case shows that the vehicle needs additional acceleration, stopping and restarting. If the vehicle’s speed is 20 km/h while travelling through the second intersection, then it should wait for the red light, thereby resulting in unnecessary energy consumption. If the situation in front of the traffic signals can be determined in advance through VANET, which suggests the driving speed beforehand, then this information can prevent unnecessary stops by predicting traffic light switching intervals and stopping points. In this case, if the vehicle’s speed is calculated by the green wave-based VTL and is adjusted between 40 km/h and 50 km/h, then the vehicle can pass through the five intersections without stopping. This vehicle follows the green wave-based VTL’s speed advice, reduces waiting time and saves energy.

**Figure 12** Time–space diagram of a coordinated timing plan (see online version for colours)

<table>
<thead>
<tr>
<th>Distance</th>
<th>Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-40 km/h</td>
<td>60 km/h</td>
</tr>
<tr>
<td>40-50 km/h</td>
<td>40 km/h</td>
</tr>
</tbody>
</table>

Table 1 shows the table notation used in this study. The detailed calculation procedures of the speed guidance are described as follows.

Figure 13 shows the speed guidance decision tree. Each vehicle can receive the VTL status and calculate the speed guidance. During a green light, the available green light speed $s_{\text{green}}$ can be calculated using equation (15). The VTL status of the vehicle in front is included in the calculation. If the time is determined at the end of the green light, then the available speed $s_{\text{red}}$ can be calculated using equation (16). $s_{\text{green}}$ and $s_{\text{red}}$ should not be greater than $s_{\text{limit}}$, which is
calculated using equation (17). In considering the effect of vehicle density of the vehicle in front, the maximum driving speed $s_{\text{max}}$ referenced in Kimura et al. (2011) is shown in equation (18).

$$s_{\text{max}} = \begin{cases} s_{\text{green}}, & \text{if } s_{\text{green}} \leq s_{\text{limit}} \\ s_{\text{red}}, & \text{if } s_{\text{green}} > s_{\text{limit}} \end{cases}$$

$$s_{\text{max}} = s_{\text{limit}} \left(1 - \frac{\psi}{\psi_b}\right)$$

When the vehicle is approaching the intersection, the driver should decide whether to accelerate or to maintain speed through the intersection, or to gently stop to wait for the red light. With the proposed mechanism to provide speed guidance for drivers, the vehicle’s speed can adjust accordingly to facilitate the effectiveness of the policy in the city.

### 3.5 Vehicle energy consumption

A vehicle is able to move because of the driving force acting on the surface of the tyre. This force can overcome the air resistance of the vehicle, the tyre rolling resistance, and the gradient resistance when climbing a hill or slope. The remainder of the total force is the thrust transmitted to the wheel; therefore, energy consumption is calculated based on the running state of the vehicle traction power. The traction power represents the combination of speed acceleration, vehicle weight, vehicle road drag and other factors. Equation (20) shows the total energy consumption of the vehicle (Camara et al., 2012; Lei et al., 2011).

$$E_{\text{total}} = \frac{1}{\eta} \int_0^t \left( M g \sin \theta + \frac{1}{2} \rho \, C_d \, A_f \, v^2 \right) v \, dt,$$

where $\eta$ is the coefficient of the mechanical transmission performance, $M$ is the quality of the vehicle weight to 1700 kg, $A_f$ is the acceleration of the vehicle, $R$ is the rolling resistance coefficient (0.01), $g$ is the acceleration due to gravity (9.81 m/s²), $\rho$ is the air density default (1.2 kg/m³), $C_d$ is the friction coefficient (0.3), $A_f$ is the vehicle frontal area (2.2 m²), $v$ is the vehicle’s speed, $\theta$ is the default value (0), $st$ is the start time and $et$ is the end time of the vehicles, which denotes the end of the travel time.

### 4 Simulation

This section provides details of the contents of the experiment, environmental setting and the related parameter setting. The simulation experiments are conducted using the Multi-agent transport simulation toolkit 4.1 (MATSim) (http://www.matsim.org/).

MATSim is an open source software development project that develops agent-based software modules intended for use with transportation planning models. MATSim provides a framework to implement large-scale transport simulations. This platform contains numerous modules that can work together and be used independently.

### Table 1

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Nomenclature</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_{\text{green}}$</td>
<td>Speed guidance to pass through the next intersection when getting green</td>
</tr>
<tr>
<td>$S_{\text{red}}$</td>
<td>Speed guidance to pass through the next intersection when getting red</td>
</tr>
<tr>
<td>$S_{\text{min}}$</td>
<td>Minimum running speed guidance</td>
</tr>
<tr>
<td>$S_{\text{max}}$</td>
<td>Maximum running speed guidance</td>
</tr>
<tr>
<td>$S_{\text{now}}$</td>
<td>Current speed of the vehicle</td>
</tr>
<tr>
<td>$S_{\text{limit}}$</td>
<td>Speed limit on the road segment</td>
</tr>
<tr>
<td>$d_p$</td>
<td>Distance from stop line to present vehicle</td>
</tr>
<tr>
<td>$t_a$</td>
<td>Acceleration time</td>
</tr>
<tr>
<td>$t_r$</td>
<td>Reaction time after obtaining the speed guidance</td>
</tr>
<tr>
<td>$t_d$</td>
<td>Transmitted delay time with speed guidance</td>
</tr>
<tr>
<td>$t_g$</td>
<td>Time of green signal</td>
</tr>
<tr>
<td>$t_{\text{red}}$</td>
<td>Time of red signal</td>
</tr>
<tr>
<td>$t_{\text{arrival}}$</td>
<td>Time of vehicle arrival at the intersection</td>
</tr>
<tr>
<td>$\Psi_b$</td>
<td>Jam density threshold between vehicle $\beta_b$ and the intersection</td>
</tr>
<tr>
<td>$\Psi$</td>
<td>Present density between this vehicle and the intersection</td>
</tr>
</tbody>
</table>

### Figure 13

Speed guidance decision tree (see online version for colours)
MATSim is mainly used for large-scale traffic simulations and is primarily employed to assess the likely results of various infrastructure or road network changes. Table 2 shows the main parameters of the simulations.

**Table 2** Critical parameters used in MATSim

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulator</td>
<td>MATSim 0.41</td>
</tr>
<tr>
<td>OS</td>
<td>Windows 7</td>
</tr>
<tr>
<td>CPU</td>
<td>Intel Core 2 CPU 2.13 GHz</td>
</tr>
<tr>
<td>MAC protocol</td>
<td>IEEE 802.11p</td>
</tr>
<tr>
<td>Area</td>
<td>2000 × 2000 (m²)</td>
</tr>
<tr>
<td>Map</td>
<td>Taipei City, Taiwan</td>
</tr>
<tr>
<td>Number of lanes</td>
<td>By real map settings</td>
</tr>
<tr>
<td>Transmission range</td>
<td>250</td>
</tr>
<tr>
<td>Transmission protocol</td>
<td>UDP</td>
</tr>
<tr>
<td>Number of vehicles</td>
<td>500 to 5000</td>
</tr>
</tbody>
</table>

Figure 14 shows our simulation map. The actual map of Taipei has multiple intersections. The street network is imported from Open Street Map (http://openstreetmap.tw/). Figure 15 shows the simulation state of MATSim. The green dots on the map represent vehicles. The simulator randomly spreads vehicles on each road, and the virtual traffic signal is configured in each lane.

The speed guidance VTL (S-VTL) and GS-VTL mechanisms are implemented through simulation. The fixed time traffic signal (F-TL), DSDS (Shenyang et al., 2011) and AVTLM (Chou et al., 2013) mechanisms are compared with the proposed protocol. The priority areas and vehicle priority decision mechanism in DSDS are used to adjust signal timing and provide optimal driving speed without stopping. AVTLM-M proposes an approach adopting the VTL cycle based on current traffic and vehicle types through VANETs for multiple intersections. In our simulation, the effect of vehicle density on average speed, average stops and energy savings of all vehicles through different VTL signal mechanisms are evaluated.

Figure 16 shows that the number of vehicles on the extent of traffic signal mechanism affects the average speed of all vehicles. The horizontal axis represents the number of vehicles, whereas the vertical axis represents the average speed of all vehicles; the unit is expressed in km/h. Figure 10 shows that when the number of vehicles ranges from 500 to 2500, all speed guide VTL mechanisms outperform F-TL. When the number of vehicles reaches 2500 units, GS-VTL performs better than the others. When the number of vehicles increases to 3000, the average speed of all mechanisms rapidly declines. As vehicle density increases, the speed of the vehicles decreases. The probability of vehicles meeting at the intersections increases; thus, all mechanisms gradually converge as the number of vehicles increases. The average speed of 4000–5000 vehicles is 10 km/h or below.
Figure 17 shows that the number of vehicles affects the traffic signal system’s average waiting time for all vehicles. When the number of vehicles is 500, the average time for all mechanisms is higher than that for F-TL. The average waiting time can be reduced from 73.5% to 58.9%. Compared with AVTL-M, GSVTL reduces the waiting time from 35.5% to 16.4%. This reduction is due to the dynamic signal phase combinations mechanism; thus, no conflict occurs between the vehicles moving through the intersection. In the proposed mechanism, the green light can reduce unnecessary waiting time when a vehicle approaches the traffic light. Compared with DSDS, GS-VTL reduces the waiting time from 29.4% to 12.8%. This reduction is the result of DSDS only providing an indication of the speed with vehicle traffic intersection in front of the intersection. DSDS disregards vehicle density and conflict points at the intersection, thereby affecting its performance compared with that of GS-VTL.

Figure 18 shows the average number of stop times with the varying number of vehicles. When the number of vehicles is 2000, compared with DSDS and AVT-M, GS-VTL reduces the stop rate by 26.3% and 25.4%, respectively. This reduction is due to the dynamic signal phase combination mechanism of GS-VTL. The vehicle does not encounter conflict when passing through the intersection, resulting in unnecessary waiting time. Moreover, the guidance speed VTL operation mechanism enables vehicles to encounter a green light at the intersection. As the number of vehicles ranges from 4500 to 5000, the average number of vehicles’ stop times for all VTL mechanisms are similar. When the density of the vehicles is high, the green wave speed guidance by VTL becomes relatively ineffective.

Figure 19 shows the energy savings with varying number of vehicles for different VTL mechanisms compared with F-TL. The average energy consumption percentage of GS-VTL is from 39.4% to 12.2%. When the number of vehicles is 2500, GS-VTL performs at 39.4%, which is the highest energy savings rate compared with those of other VTL protocols. The reason for such distinction is that the green wave traffic conditions have a significant effect on energy saving. Compared with DSDS and S-VTL, AVTL-M has relatively low energy efficiency because the latter does not guide the vehicle’s forward speed; the energy savings percentage is between 7.8% and 2.11%. Compared with V-TL, GS-VTL can achieve higher energy conservation with varying number of vehicles because of the reduction of the conflict points in the intersection and the green wave speed guidance through the VTL scheme.

In summary, DSDS can provide speed guidance for a drive but disregards the possible crossing points at the intersection. AVTL-M considers traffic density but does not provide speed guidance for a drive. Compared with the existing approaches, our proposed algorithm can prevent crossing points at the intersection and provide speed guidance, thereby making it more efficient than existing approaches.
5 Conclusion and future studies

The study uses the GS-VTL protocol to improve the traffic congestion situation in urban areas. The phase combination algorithm can facilitate an efficient traffic flow at intersections and prevent unnecessary stops. The VTL green wave control mechanism provides guidance for vehicle speed, reduces waiting time and saves energy. The simulations are performed using MATSim. The simulation results show that the proposed GS-VTL protocol with green wave speed guidance and phase combinations can outperform other existing VTL protocols. This result shows that the proposed GS-VTL has a better performance compared with the other VTL schemes.

Additional scenarios should be considered for future studies to realise the VTL mechanism in the actual environment. For example, the vehicle-to-person communication, wireless signal contention and early warning notification should be addressed.

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