A Novel Traffic Light Scheduling based on TLVC and Vehicles' Priority for Reducing Fuel Consumption and CO₂ Emission

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Abstract—This paper proposes a novel and adaptive traffic light scheduling scheme via two-way Traffic-Light-to-Vehicle Communication (TLVC) for fuel consumption and CO₂ emission reduction, namely CO₂Red. In addition to TLVC, a pioneer priority framework is also proposed to give a high priority to heavily-loaded vehicles, which consume and emit larger amount of fuel and CO₂ due to breaking and stoppage. The proposed scheme aims to promote a green driving environment in the land transportation sector by increasing green light hit rate for all vehicles, especially for heavily-loaded vehicles, and reduce the total amount of fuel consumption and CO₂ emission by reducing the number of stops at traffic lights. The simulation results demonstrate that the green light hit rate of all vehicles is greatly improved, especially of heavily-loaded vehicles, which consequently reduces fuel consumption and CO₂ emission in land transportation sector

Index Terms— Adaptive traffic light, Traffic Light-to-Vehicle Communication, CO₂ Emission, Fuel Consumption, Priority, Green communication.

I. INTRODUCTION

THE global warming problem becomes more intensive and raises a serious concern for the mankind. One of the major causes of the problems is large amount of pollution gas emissions from vehicles, such as CO₂, of several countries. CO₂ emission is a result of four primary sources; industrial, agriculture, domestic, and transportation [1]. Fig. 1 shows the percentage of total amount of CO₂ emission of all regions in UK in Year 2012. It is observed that the industrial activities cause the highest percentage of emission at approximately 41.70%. The percentages of emission of the domestic and the transportation systems are roughly at 30.75% and 26.64%, respectively. The agriculture only causes 0.91% in CO₂ emission.

The amount of CO₂ emission from the transportation is approximately 123 million tons (26.64%) of the total 461 million tons in UK, and will continue to increase globally.

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These 123 million tons of emission is considered as a very large amount of emission and seriously needed to be reduced. Besides, due to the advance in vehicular communication and wireless technology driven by Intelligent Transportation Systems (ITS), CO₂ reduction in the transportation becomes feasible to alleviate or slow down the effect of the global warming problem.

There have been diverse projects and frameworks recently carried out in the area of ITS. One of them is the promotion of applications for fuel consumption and CO₂ emission reductions [3], [4], [5], [6], [7], [8], [9], [10]. Vehicular emission is directly related to the number of accelerations and decelerations. To reduce the number of both accelerations and decelerations, vehicles must avoid as many stops as possible. There are several causes making vehicles stop frequently. The major one is traffic lights. A lot of vehicles have to stop at the traffic lights during a red light period and re-accelerate after a green period. This results in unnecessary pollution emission and waste of fuel, especially for heavily-loaded vehicles, such as truck and bus.

To avoid the unnecessary emission, the traffic lights should be able to communicate with vehicles called Traffic-Light-to-Vehicle Communication (TLVC). Via this communication, vehicles are able to learn traffic light scheduling and adjust their speeds accordingly, so that they will reach the traffic lights during the green period. Hence, they do not need to stop unnecessarily. The information exchange helps the drivers aware of the possible green period ahead, obtain the optimal speed, and drive as smooth as possible.

Fig.1 CO₂ emissions per capita in UK of year 2012 [1]

Therefore, the main motivation of the paper is to promote a green driving environment and reduce the amount of CO₂ emission in the land transportation sector by utilizing two-way vehicular communication technology. The paper also proposes a promising priority-based solution to increase a green light hit rate for all vehicles, especially for heavily-loaded vehicles, and reduce the total amount of fuel consumption and CO₂ emission by reducing the number of stops at intersections.

The rest of the paper is organized as follows: challenges, and researches issues related to TLVC are highlighted in Section II. Section III shows the state of the arts of TLVC applications. The proposed scheme of adaptive traffic light scheduling for fuel consumption and CO₂ emission reductions is described in Section IV. Section V shows simulation configurations, scenarios, results and analysis. Finally, Section VI concludes the paper.

II. CHALLENGES AND RESEARCH ISSUES

ITS aims to solve the number of problems related to fuel efficiency and CO₂ emission reduction. In order to reduce fuel consumption and emission rate, TLVC becomes one of the promising solutions by decreasing the number of stops at intersections.

Pioneer concepts [3], [4], [5] allow vehicles to learn a static traffic light schedule via TLVC. The traffic light periodically broadcasts the light scheduling information to vehicles in its vicinity. The exchange of the traffic light schedule information allows the vehicles to adjust speeds according to the light interval to avoid stops during the red light period. The stop avoidance helps to reduce vehicular fuel consumption and emission. However, the vehicles still need to decelerate and accelerate to hit the static green period, which still causes unnecessary fuel consumption and emission.

In contrast to the static traffic light schedule, the schedule should be adjustable so that it becomes optimal for all vehicles [6], [18], [19], [20]. This contributes to reductions of larger amount of CO₂ emission and fuel consumption. For example, most of vehicles do not have to adjust their speeds at all to hit the green light interval. The dynamic schedule can be determined based on vehicles' information, such as positions, speeds, and directions.

Besides, there are different types of vehicles ranging from eco-cars to heavily-loaded vehicles. These vehicles cause diverse fuel consumption and emission rates. For example, heavily-loaded vehicles normally emit and consume larger amount of CO₂ and fuel. Therefore, it becomes important to allow the heavily-loaded vehicles to avoid as many unnecessary stoppages as possible compared to the eco-cars. Consequently, priority scheme, such as a weighted traffic light scheduling, must be taken into account in the system's design as well.

III. THE STATE OF THE ARTS ON TLVC

There are some researches investigating impacts of TLVC on CO₂ emission. This section presents the state of the arts of researches in this area.

The article in [3] proposes new Economical and Environmentally Friendly Geocast (EEFG) protocols and studies impacts of a region of interest (ROI) on fuel consumption and emission, stopping time, recommendation speed, and average acceleration rate. ROI is defined as a distance at which vehicles will be informed about traffic light information. The authors do not focus on communication point of view. It is assumed that at every defined ROI, all vehicles already have the traffic light information. The paper implements VT-Micro, which is a model for fuel consumption and emission based on real data and prediction model with correlation coefficient ranging from 92% to 99%.

Their results show that vehicles need to be informed by the traffic light at least 1 km in advance. At ROI shorter than 1 km, vehicles do not have enough distance to adjust their speeds, and hence they have to stop at the traffic light. However, if the vehicles are informed within 1 km or more, they can avoid stops and hence reduce the amount of fuel consumption and emission drastically. Besides, the larger ROI is defined, the better performance the protocol can achieve.

In [4], the authors aim to study impacts of gear choices and distances (GCD) from the traffic light at which vehicles are informed. The paper implements VISSIM as a vehicular traffic model. VISSIM is a microscopic simulation for multimodal traffic flow modelling, e.g. cars, buses, and trains. In addition, Passenger car and Heavy duty Emission Model (PHEM) is also implemented to determine the amount of fuel consumption and emission from instantaneous changes in speed and acceleration. The paper assumes two types of communications; perfect (precise information system) and fuzzy communications (specific information system is selected with a probability 0.95).

The simulation result shows 0.6 km is an optimal distance for TLVC, because a larger distance does not give significant reductions in terms of fuel consumption and emission. In addition, the reductions of fuel consumption and CO₂ emission via TLVC can save up to 22% and 80% respectively. Gear choices, in addition to speed advice, have been proposed and studied for fuel consumption and CO₂ emission reductions. It could become a feasible solution for future cruise control application as well.

Unexpected events, such as an accident, can occur in vehicular environment. It results in traffic congestions as well as unnecessary decelerations and stops. To alleviate the problem, authors in [5] proposed a protocol to deal with unpredicted events by determining an optimal travel route (OTR); re-routing or staying on the same route. The paper implements Veins (Vehicles in Network Simulation) on OMNeT++ as vehicular traffic and EMIT [11] as fuel consumption and emissions models.

TABLE I
COMPARISON OF RELATED RESEARCHES IN TLVC

Protocol	Objectives	Underline Network Architecture	Type of Communication	Adaptive Traffic Light	Vehicle's Priority
EEFG	Fuel & CO ₂ Reduction	Vehicular Ad Hoc Network	One-Way Vehicle to Traffic Light Communication	No	No
GCD	Fuel & CO ₂ Reduction	Vehicular Ad Hoc Network	One-Way Vehicle to Traffic Light Communication	No	No
OTR	Fuel & CO ₂ Reduction	Vehicular Ad Hoc Network	One-Way Vehicle to Traffic Light Communication	N/A	No
GLOSA	Fuel & CO ₂ Reduction	Vehicular Ad Hoc Network	One-Way Vehicle to Traffic Light Communication	Yes	No
ITLC	Waiting Time Reduction	Vehicular Ad Hoc Network	One-Way Vehicle to Traffic Light Communication	Yes	No
WN-DTLM	Waiting Time Reduction	Wireless Sensor Network	One-Way Sensor to Traffic Light Communication	Yes	No
CO ₂ Red	Fuel & CO ₂ Reduction	Vehicular Ad Hoc Network	Two-Way Vehicle to Traffic Light Communication	Yes	Yes

The simulation results show that an advice mainly depends upon how long the event will remain. If the event tends to last for a long time, re-routing becomes an appropriate solution. In contrast, if the event lasts for short period, it is better for vehicles to stay on the same route, since taking another route may cause higher amount of fuel consumption and emissions as well as longer travel time. Therefore, in the future, a navigation system must be more intelligent to optimize traffic flows in case of several unexpected events occurred.

GLOSA [6] aims to enable fully and semi-adaptive traffic lights based on vehicular communications. GLOSA transformed the state graph of the traffic light controller into a transition graph which focuses on signal changes and their occurrence probability. The results show that in 80 % of all cases GLOSA could predict signal changes 15 seconds in advance to enable GLOSA for adaptive traffic lights.

ITLC [18] is proposed to reduce the waiting delay time and increase the number of vehicles crossing each road intersection. ITLC utilizes Vehicular Ad Hoc Networks (VANET) to detect and evaluate the traffic characteristics of each traffic flow at each road intersection. The paper implements SUMO as a vehicular traffic model. The results show that ITLC can reduce the waiting time by 25% and increase throughput of each road intersection by 30%. However, reducing the waiting time at the intersection may not contribute to a major reduction of fuel consumption and CO₂ emission, because the vehicles have to re-accelerate after the waiting time (even it is the shorter delay), which results in the equivalently huge amount of fuel consumption and CO₂ emission. To reduce fuel consumption and CO₂ emission, the traffic flow must be as smooth as possible with minimum number of stops.

WN-DTLM [19], [20] deploys wireless sensors along the roadside to gather information regarding the real-time vehicular traffic flow. This information is then used by fuzzy logic controller to determine a real-time regulation of phase sequence and green time duration of the traffic light. The paper focuses on performance comparison of two different wireless sensors, i.e., IEEE802.15.4 and Bluetooth. The results show that using of IEEE802.15.4 provides lower packet lost while using of Bluetooth gains shorter communication latency. The paper also aims to reduce the average waiting time of

vehicles at intersection. Thus, this does not guarantee the optimization of fuel consumption and CO₂ emission as previously explained. In addition, the deployment of Wireless Sensor Network (WSN) in WN-DTLM incurs some additional cost and maintenance, while in fact the vehicles themselves can act as the sensor nodes gathering and transmitting more accurate information than WSN to the dynamic traffic light management directly.

In this paper, a novel priority-based adaptive traffic light scheduling scheme for fuel consumption and CO₂ emission reduction, namely CO₂Red, is proposed. CO₂Red adopts two-way Traffic-Light-to-Vehicle Communication (TLVC) to exchange real-time information among all approaching vehicles and a traffic light controller to provide an optimal traffic light scheduling in real-time. To the best of our knowledge, there is no work in the literature dealing with vehicle's priority. Our proposed CO₂Red is the pioneer approach implementing a priority framework to give a high priority to heavily-loaded vehicles, which consume and emit larger amount of fuel and CO₂. More detail of the proposed CO₂Red can be seen in the following section.

Table I shows a comparison of the works in the literature. It is noticed that some of them provide only static traffic scheduling, i.e. EEFG, GCD, and OTR. The static traffic schedule may not work perfectly in some cases. For example, one vehicle must stop during the red light period, even though there is no other vehicle at that intersection at all. This is considered as an unnecessarily stop.

In fact, the vehicle may be able to pass the traffic light without a stop if the green light period lasts a little bit longer and if the traffic light is more intelligent and can learn information of all approaching vehicles. GLOSA, ITLC, WN-DTLM, and CO₂Red are the approaches in the literature that achieve in providing dynamic traffic light schedule. However, due to one-way communication, vehicles are only able to transmit their information to traffic light controllers for determining an optimal traffic light schedule, but they cannot learn such schedule in advanced and miss a chance to adjust their speeds accordingly to pass the intersection during the green light.

Only CO₂Red provides two-way communication to broadcast the optimal traffic light schedule back to vehicles so

that they can properly adjust their speeds to hit the green light period without waiting at the intersection, and hence it succeeds in fuel consumption and CO₂ emission reduction. In addition, it is very important to allow the heavily-loaded vehicles to avoid as many unnecessary stoppages as possible compared to the smaller vehicles. However, there is no existing approach in the literature taken this vehicle's priority in to account for traffic light schedule determination except the proposed CO₂Red. Therefore, the novel CO₂RED is one of promising schemes to deal with both adaptive traffic light scheduling and the priority scheme for diverse types of vehicles.

In summary, the research contributions of this paper can be explained in three folds as follows;

1. Promoting green driving environment by reducing the amount of fuel consumption and CO₂ emission in the land transportation sector.

2. Utilizing two-way vehicular communication for exchanging real-time vehicular traffic information, determining optimal traffic light schedule, and distributing the optimal traffic light schedule back to vehicles so that the vehicles can adjust their velocity accordingly to hit the green light period..

3. Taking vehicle's priority into account for traffic light schedule determination. Since heavily-loaded vehicles generally consume and emit larger amount of fuel and pollution, these vehicles must have higher priority to pass the intersection without stop.

There are also some major challenges regarding an implementation of CO₂Red in the future, which can be summarized as follows;

1. The real-time, complex, and computationally expensive optimization solutions for the traffic light scheduling may be challenging for the implementation. To tackle this challenge, the traffic light controllers, which are fixed along the roadside, can be equipped with high performance computing resource to perform this complex and computationally expensive optimization. The other possible solution is a utilization of Cloud Computing technology [21], [22], [23] to perform this computationally expensive operation instead of running this operation on the traffic light controllers.

2. Vehicular communication technology may also raise a challenge in terms of communication reliability and latency. However, this vehicular communication is promising because there are a lot of standards [12], [13] as well as researches [14], [15], [16], which aim to improve the communication performance. For example, Intelligent Transportation System (ITS) provides a framework for the vehicular communications. A Licensed Dedicated Short Range Communications (DSRC) based on IEEE 802.11a is allocated for Wireless Access in Vehicular Environments (WAVE). A draft standard is also assigned as IEEE 802.11p and IEEE P1609.1-4 for this technology.

However, the Cloud Computing and vehicular communication technologies and their standards are out of the scope of this paper. Therefore, it will not be discussed in more detail in this paper due to the space limitation.

IV. PROPOSED CO₂RED SCHEME

Observing from Table 1, we propose a novel CO₂Red scheme; a two-way vehicular communication and a priority framework for an adaptive traffic light scheduling for fuel consumption and CO₂ emission reduction.

A. Fuel Consumption and CO₂ Emission Models

Fuel consumption and CO₂ emission can be estimated using a wide range of models in the literature. EMIT model [11] is one of them which is broadly accepted. This model supports diverse emissions including CO₂, CO, hydrocarbon (HC), and nitrous oxide (NO_x). Fuel consumption and emission are precisely calculated based on acceleration and deceleration, as well as chemical effects through a catalytic converter. Total tractive power requirement at vehicle's wheels, P_{tract} , is calculated using equation (1).

$$P_{tract} = A.s + B.s^2 + C.s^3 + M.a.s + M.g.\sin(\mu.s) \quad (1)$$

P_{tract} : Total tractive power requirement at the wheels (kW)

s : Vehicle's speed (m/s)

a : Vehicle's acceleration (m/s²)

A : Rolling resistance term (kW/m/s)

B : Speed correction to rolling resistance term (kW/(m/s)²)

C : Air drag resistance term (kW/(m/s)³)

M : Vehicle's mass (kg)

g : Gravitational constant (9.81 m/s²)

μ : Road grade (degrees)

Based on the value of P_{tract} , CO₂ emission at a tailpipe and fuel consumption rate can be calculated using equations (2) and (3) respectively [8].

$$TP_{CO_2} = \begin{cases} \alpha_{CO_2} + \beta_{CO_2}.s + \delta_{CO_2}.s^3 + \zeta_{CO_2}.a.s, & \text{if } P_{tract} > 0 \\ \alpha'_{CO_2}, & \text{if } P_{tract} = 0 \end{cases} \quad (2)$$

$$FR = \begin{cases} \alpha_{FR} + \beta_{FR}.s + \delta_{FR}.s^3 + \zeta_{FR}.a.s, & \text{if } P_{tract} > 0 \\ \alpha'_{FR}, & \text{if } P_{tract} = 0 \end{cases} \quad (3)$$

where α , β , δ , ζ , and α' are coefficients for CO₂ emission and fuel consumption of which values are shown in Table II.

TABLE II
DEFAULT VALUES OF ALL COEFFICIENTS IN EMIT MODEL [8]

Coefficient	CO ₂ Emission	Fuel Consumption
α	1.11	0.365
β	0.0134	0.00114
δ	1.98e-06	9.65e-07
ζ	0.241	0.0943
α'	0.973	0.299

Fig.2 CO₂ efficiency of gasoline vehicles [2]

Fig. 2 shows CO₂ efficiency; a distance covered by emitting 1 gram of CO₂, of different vehicles' speeds determined by the EMIT model. It is observed that the efficiencies are in a bell shape according to vehicles' speeds. At low velocity, the efficiencies drastically increase once vehicles' speed is increased. Up to a certain point, which is the optimal speed, increasing of speed on the other hand decreases the efficiencies. Thus, the recommended speed of gasoline vehicles, S_R , is approximately 65 km/h and a recommended range of speeds is from 55 to 75 km/h. Because driving too fast or too slow can cost higher fuel consumption and CO₂ emission, drivers should be informed and educated to change their driving behaviors according to the recommended range of driving speed.

B. Two-Way Vehicular Communications

By sharing vehicles' information, such as their positions, speeds, directions, and types, among vehicles and traffic light controllers, the traffic light controllers can determine an optimal traffic light schedule and broadcast this information back to all approaching vehicles so that most of the vehicles do not have to or rarely adjust their speeds. Therefore, two-way communications along with the adaptive traffic light scheduling will help to reduce these unnecessary decelerations and accelerations by taking into account vehicle's information for determination of an optimal traffic light schedule accordingly.

Fig. 3 illustrates a scenario of two-way vehicular communications for an adaptive traffic light scheduling. There are two areas of consideration. Information of all vehicles directing to a junction in Area₁ will be used for traffic light scheduling determination of TL₁ and vice versa. After the traffic light scheduling determination, each TL transfers the scheduling information back to the vehicles in the involving area.

Fig.3 Simulation scenario of the two-way TLVC

C. Weighted Mean Arrival Time

In addition to the two-way vehicular communications, this paper also proposes a priority framework to optimize a weighted traffic light scheduling. As presented in the challenges and issues section, information related to heavily-loaded vehicles, such as truck and bus, has to be priorly taken into account, because these vehicles normally consume larger amount of fuel and also emit higher amount of CO₂. If one of them misses a green period, it will cause a huge waste of energy and intensify environmental pollution. Thus, information of heavily-loaded vehicles must be higher weighted than that of small vehicles.

Based on the information received from all approaching vehicles, the traffic light controller determines a weighted vehicular mean arrival times; an average time that all vehicles arrive at the traffic lights, of both areas; t_1 and t_2 , as shown in Equation (4).

$$t_i = \frac{\sum_{j=1}^{n_i} w_j \left(\frac{d_j}{s_j} \right)}{\sum_{j=1}^{n_i} w_j} \quad (4)$$

i : an index of communication area 1 or 2

n_i : total number of vehicles in each area

w_j : Weight of j^{th} vehicle according to vehicle's type

d_j : Distance from j^{th} vehicle to either TL₁ or TL₂

s_j : Speed of j^{th} vehicle which equals S_R by default

In this paper, it is assumed that the weight (w_j) of the heavily-loaded vehicles is two-time higher than that of the small vehicles. The mean arrival times are used to determine the optimal green time for vehicles in both areas so that most of them do not have to adjust their speeds to hit the green light period.

D. Adaptive Traffic Light Scheduling

According to the weighted vehicular mean arrival times of each area, the traffic light controller determines an appropriate traffic light scheduling of the next traffic light cycle regarding the following algorithm. In this article, a traffic light cycle is set to a period of 100 seconds according to the other research [3], [4], [5], [6], [7].

Traffic Light Scheduling Algorithm

If $t_1 < t_2$

Area 1: Green = $[0, t_1]$, Yellow = $(t_1, t_1 + 5]$, Red = $(t_1 + 5, 100]$

Area 2: Red = $[0, t_1 + 5]$, Green = $(t_1 + 5, 95]$, Yellow = $(95, 100]$

Else if $t_1 > t_2$

Area 1: Red = $[0, t_2 + 5]$, Green = $(t_2 + 5, 95]$, Red = $(95, 100]$

Area 2: Green = $[0, t_2]$, Yellow = $(t_2, t_2 + 5]$, Red = $(t_2 + 5, 100]$

According to the traffic light algorithm shown above, if the average arrival time of vehicles in Area₁ (t_1) is shorter than that of vehicles in Area₂ (t_2), the first 50 seconds of the traffic light schedule will be 45-second green and 5-second yellow in Area₁ and become 50-second red in Area₂. This makes most of vehicles of both areas rarely adjust their speeds. In contrast, if t_1 is greater than t_2 , the first 50 seconds of the schedule will be 45-second green and 5-second yellow light in Area₂ and becomes 50-second red in Area₁ instead.

However, in the worst case of $t_1 = t_2$, we assign green period to Area₁ followed by Area₂. This means that vehicles in Area₁ need to move faster to hit the first 45-second green time, and vehicles in Area₂, in contrast, need to slow down to wait for the later green time. This situation is unavoidable since the average arrival times of vehicles in both areas are equal. However, this case may not happen often.

E. The Optimal Speed

Once a vehicle receives information related to the traffic light scheduling, it determines whether or not it can adjust its speed to the hit green period.

In a case that the vehicle can adjust its speed to pass the traffic light during green interval, it will change to the new optimal speed and pass the traffic light without stoppage. Then, the vehicle changes its speed back to the default recommended speed again. The new optimal speed can be calculated according to equation (5).

$$s_{new_i} = \begin{cases} s_R, & g_{start} \leq \frac{d_i - d_{adj}}{s_R} \leq g_{end} \text{ and } hit_g = 1 \\ \frac{d_i - d_{adj}}{g_{end}}, & g_{start} \leq \frac{d_i - d_{adj}}{s_{max}} \leq g_{end} \text{ and } hit_g = 1 \\ \frac{d_i - d_{adj}}{g_{start}}, & g_{start} \leq \frac{d_i - d_{adj}}{s_{min}} \leq g_{end} \text{ and } hit_g = 1 \\ s_R, & \text{Otherwise} \end{cases} \quad (5)$$

where s_{new_i} is a new recommended speed for i^{th} vehicle, s_R is the default recommendation speed at 65 km/h, d_i is a distance between vehicle i and the traffic light, d_{adj} is a minimum distance required for speed adjustment from s_R to s_{new_i} , s_{min} and s_{max} are minimum and maximum recommended speeds, respectively, and g_{start} as well as g_{end} are beginning and ending times of the green period.

For the first three cases, vehicle i can adjust the speed between s_{min} and s_{max} to hit the green period. Otherwise, the vehicle misses the green period. Thus, it continues moving with the default recommendation speed, s_R , for minimizing CO₂ emission, but eventually it has to stop at the traffic light.

The total amount of CO₂ emission in a case of a green light hit consists of three parts; CO₂ emission during speed adjusting (CO_{2-adj1}), moving constantly with a new recommended speed ($CO_{2-const}$), and speed adjusting to the default recommended speed (CO_{2-adj2}) after the vehicle passing the traffic light as shown in equation (6).

$$CO_{2-hit} = CO_{2-adj1} + CO_{2-const} + CO_{2-adj2} \quad (6)$$

On the other hand, in a case that the vehicle cannot adjust its speed to the hit green period, it will keep moving with the current speed; the default recommended speed. It eventually has to stop at the traffic light and wait for a green light. Then, it will re-accelerate to the default recommended speed again. These stoppage and re-acceleration cause larger amount of emitted CO₂ than that in the hit case.

The total amount of CO₂ emission during a missed green light period can be calculated as in equation (7). It consists of CO₂ emission during a constant 65 km/h moving ($CO_{2-const}$), speed deceleration (CO_{2-dec}) to 0 km/h, stop and wait period (CO_{2-stop}), and speed acceleration to default recommended speed (CO_{2-acc}) after the traffic light turned to green.

$$CO_{2-missed} = CO_{2-const} + CO_{2-dec} + CO_{2-stop} + CO_{2-acc} \quad (7)$$

The primary different between equations (6) and (7) is CO_{2-stop} . However, a major increase in CO₂ emission of the missed-green light case is not mainly affected by CO_{2-stop} , but CO_{2-acc} . The vehicle need to re-accelerate from speed 0 to 65 km/h after the traffic light turned to green. During this period, the vehicle consume very large amount of fuel and hence emit very large amount of CO₂ as well. While in a green-light hit case, the vehicle just change speed from non-zero speed to 65 km/h. The amount of CO₂ emission of the green-light hit case, therefore, becomes much lower than that of the green-light missed case.

(a) Comparison of total amount of CO₂ emission of each vehicle

(b) Comparison of total CO₂ efficiency of each vehicle

Fig. 4 Comparison of CO₂ emission and CO₂ efficiency between the hit and missed green light cases

The comparison of CO₂ emission and CO₂ efficiency of both green-light hit and missed periods is shown in Fig. 4. In this test, we set d_{adj} to 200 m., and d_i of all vehicles to 2,000 m. The values of g_{start} and g_{end} are set to 50s and 95s respectively. The last 5s is assigned to be yellow period. S_R is set to 65 km/h, and S_{newi} is ranged from 10 to 140 km/h regardless of values of S_{min} and S_{max} to observe amounts of CO₂ emission at different speeds.

As it was expected, in the recommendation range of speed (55-75 km/h), vehicles emit less amount of CO₂ when they hit the green period as shown in Fig. 4(a). Out of this range, the green-light missed case outperforms the green-light hit case because in the green-light missed case vehicles continue moving at the default recommended speed, S_R , which is a speed that emits smallest amount of CO₂. Therefore, the overall emission becomes lower than that of vehicles moving slower than 55 km/h or faster than 75 km/h.

The similar tendency is observed from Fig. 4(b). Only between the recommendation speeds of 55-75km/h, the green-light hit case outperforms the green-light missed case by resulting in the higher CO₂ efficiency.

TABLE III
DEFAULT VALUES OF ALL PARAMETERS USED IN THE SIMULATIONS

Parameters	Default Values
Number of Communication Areas	2
Number of Vehicles of Each Area	100 - 1,000 vehicles
Default Speed of Vehicles, S_R	65 km/h
Maximum Speed of Vehicles, S_{min}	55 km/h
Maximum Speed of Vehicles, S_{max}	75 km/h
Traffic Light Informing Distance	50 - 2,000 m
Weight of normal vehicles, w_i	1
Weight of heavily-loaded vehicles, w_i	2
CO ₂ Emission and Fuel Consumption Model	EMIT [8]
Number of Simulations	500 times

V. SIMULATION RESULTS AND ANALYSIS

In this section, we aim to evaluate performance of the proposed CO₂Red based on simulations. We assume that all vehicles effectively receive information related to traffic scheduling by any means of communications [17].

A. Simulation Configurations

The simulation scenario is shown in Fig. 3. There are two communication areas. The total number of vehicles in each area is varied from 100 to 1,000 vehicles. The default speed, S_R , of all vehicles is 65 km/h. S_{min} and S_{max} are set to 55 and 75 km/h respectively. The distance of each vehicle to the traffic light is randomly assigned ranging from 50 to 2,000 m. Adjusting distance, d_{adj} , is set to 200 m. 10% of the vehicles are heavily-loaded vehicles. Weight of heavily-loaded vehicles is set to 2, while the rest is set to 1. We also assume CO₂ emitted by heavily-loaded vehicles is two-time higher than that of the normal cars. Each simulation has been running for 500 times to guarantee a confidence interval. All default parameter values are shown in Table III.

B. Simulation Scenarios

We conduct several simulations to compare performance of three different scenarios; adaptive traffic light and adaptive vehicle speed, fixed traffic light but adaptive vehicle speed, and fixed traffic light and fixed vehicle speed.

The adaptive traffic light and adaptive vehicle speed is a scenario which the traffic light scheduling can be calibrated regarding information of all approaching vehicles. At the same time the vehicles are also able to change to the optimal speeds according to the received dynamic traffic light scheduling. This approach can be easily achieved by utilizing the two-way communication as in CO₂Red. Therefore, this scenario represents the performance evaluation of the proposed CO₂Red.

In a case of fixed traffic light but adaptive vehicle speed, only speeds of vehicles can be adjusted according to the static traffic light scheduling. This case only needs one-way communication from the traffic light controller to all approaching vehicles. This simulation is used as a benchmark for a performance comparison, because it represents the state of the arts, such as EEFG, GCD, and OTR.

In the last simulation, both traffic light and vehicle speed are fixed, and hence no communication is required in the system which represents the traditional and currently-implemented traffic light controllers.

(a) Comparison of CO₂ emission of all three scenarios

(b) Comparison of green light hit rate of all three scenarios

(c) Comparison of green light hit rate of both heavily-loaded and normal vehicles of all three scenarios

Fig. 5 Performance evaluation results in terms of CO₂ emission and green-light hit rate

C. Simulation Results and Analysis

Fig. 5(a) shows a comparison of an average amount of CO₂ emission of all three scenarios. It is observed that with the adaptive traffic light and adaptive vehicle speed, the vehicles emit the lowest amount of CO₂ and hence consume the smallest amount of fuel as well. This is because the traffic light cycle is scheduled according to the speeds of all approaching vehicles. Thus, most of vehicles hit the green-

light period without a need of speed adjustment (keep running at the lowest CO₂-emission speed). Consequently, they emit the lowest amount of CO₂.

In case of the fixed traffic light but adaptive vehicle speed which represents the work in the literature, the higher number of vehicles needs to adjust their speed to hit the green-light period. The higher number of speed adjustments results in the larger CO₂ emission compared to the previous case.

In the fixed traffic light and fixed vehicle speed, due to the fixed traffic light scheduling and the fixed vehicle speed, the larger number of vehicles misses the green-light period. Therefore, they need to stop and re-accelerate at the intersections resulting in the largest amount of fuel consumption and CO₂ emission.

Fig. 5(b) demonstrates a comparison of the green-light hit rate of all three scenarios. The adaptive traffic light and adaptive vehicle speed gives the highest hit rate while the fixed traffic light and fixed vehicle speed gives the lowest. This is a result from our proposed adaptive traffic light scheduling.

Fig. 5(c) demonstrates a comparison of green light hit rate of both heavily-loaded, such as truck, and normal vehicles of all three scenarios. The hit rates of truck and normal vehicle are identical for all scenarios except for the case of the adaptive traffic light and adaptive vehicle speed. The hit rate of truck in this case is higher than that of normal vehicle due to the proposed priority framework in CO₂Red. The weight scheme gives higher priority to heavily-loaded vehicles while scheduling the optimal traffic light cycle. This leads to a major save of fuel consumption and massive reduction of CO₂ emission as previously observed from Fig. 5(a).

VI. CONCLUSION

This paper proposed a pioneer CO₂Red scheme, an adaptive traffic light scheduling for fuel consumption and CO₂ emission reductions in road junction with a two-way information exchange between vehicles and traffic lights, and a priority scheme for heavily-loaded vehicles. The simulation results show that in the case of the adaptive traffic light and adaptive vehicle speed, which represents the proposed CO₂Red, the amount of CO₂ emission is reduced by 0.5-1.0 gram per vehicle compared to the case of the fixed traffic light but adaptive vehicle speed, which represents the works in the literature. It also shows the great reduction of CO₂ emission by 3.5-4.0 gram per vehicle compared the traditional and currently-used traffic light controllers. This reduction will become more significant once the number of vehicles on the road is larger. In addition, CO₂Red also achieves approximately 2.5% and 15% increase in term of the green light hit rate compared to the literature approaches and the traditional traffic light controllers, respectively.

Regarding the implementation of the novel vehicle's priority scheme, it shows that CO₂Red achieves in providing the heavily-loaded vehicles with approximately 3% higher in term of the green light hit rate compared to the small vehicles, while the recent literature approaches give the equal green light hit rate to all vehicles regardless the vehicle's types. Thus, CO₂Red can lead to the massive reductions of CO₂

emission and fuel consumption, especially for the heavily-loaded vehicles, in the land transportation sector.

In the future, apart from the simulation and mathematical analysis conducted in this paper, a field test may also be conducted to confirm the outperformance of CO₂Red. In addition, other optimization techniques are also needed to be studied and compared in detail to provide global optimization of the traffic light scheduling.

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