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A Novel VANETs-Based Traffic Light Scheduling Scheme for Greener Planet and Safer Road Intersections

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ABSTRACT This paper proposes a novel vehicular ad hoc network-based traffic light (TL) scheduling scheme for reducing CO_2 emissions from vehicles and improving the safety of road intersections where yellow-light-dilemma (YLD)-related accidents frequently occur. The proposed scheme uses adaptive TL scheduling and optimal speed advisory methods to increase traffic throughput and reduce CO_2 emissions of traveling vehicles. In addition, the proposed scheme employs various distributed protocols and algorithms to tackle the YLD problem, which has not been addressed by the previous works in the literature. When the YLD problem arises at a signalized intersection, vehicles in heavily weighted dilemma zones are provided extending yellow signal time to stop or pass through the intersection. A mathematical analysis proves that the proposed protocols and algorithms have low communication overhead and low computational complexity which are equal to $O(N)$. Furthermore, four simulation works are conducted to evaluate the efficiency of the proposed scheme. The outstanding results have demonstrated that the proposed scheme outperforms other existing approaches by approximately 81.9% in terms of the average performance.

INDEX TERMS Adaptive traffic light scheduling, CO_2 emission, yellow-light-dilemma (YLD)-related accidents, vehicular-adhoc-networks (VANETs), wireless sensor networks (WSNs).

I. INTRODUCTION

In the 21^{st} century, road traffic accident is one of major problems raising a serious concern for the mankind. It is outlined in the global status report on road safety 2015 [1] that more than 1.2 million people pass away annually on the roads, making road traffic accidents a leading cause of death globally. Road traffic accident can be found anyplace on the roads, particularly at intersections. According to the National Highway Traffic Safety Administration's (NHTSA) analysis of fatal motor vehicle traffic crashes and fatalities at intersections [2], fatal accidents that happen at intersections account for about 22% of all severe crashes in the United States over a period from 1997 to 2004. Significant factors causing intersection-related collisions such as driver attributed factors, vehicles attributed factors, and environment attributed factors were identified in [3]. Among them, driver's perception error is the most critical factor constituting around 55.7%. In the mean time, the second leading factor is driver's decision error estimating around 29.2%. In fact, when vehicles reach a signalized intersection, drivers' recognition error and drivers' decision error can be caused by a problem known as yellow-light dilemma (YLD) or yellow-light running (YLR). YLD indicates a confusing circumstance in which a driver hesitates to decide to either stop or proceed through the intersection when state of a traffic light (TL) changes from green to yellow [4]. The hesitancy may lead to major traffic collisions. For instance, rear-end collisions with vehicles could arise if a driver decides to stop too early. Moreover, side-impact collisions with side-street traffic could occur if the driver decides to cross the intersection too late.

Beside the road traffic accident issue, human beings are also facing air pollution as another significant issue of

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TABLE 1. Summary of related studies in YLD problem and TLVC domains.

Scheme	Target	TLVC	YLD problem
[4], [26]-[37]	Driver behaviours in the dilemma zone or attributes of the YLD problem	No	Yes
[14]-[18]	CO_2 emission and fuel usage reduction	Yes	No
[19], [20]	CO_2 emission reduction	Yes	No
[9], [21]	Waiting time reduction	Yes	No
Proposed scheme	CO_2 emission, fuel usage, and waiting time reduction, traffic throughput enhancement, YLD problem prevention	Yes	Yes

the 21^{st} century. According to the report of the World Health Organization (WHO) on ambient air pollution [5], one out of every nine deaths was the result of air pollution-related conditions in 2012. One of the main causes of ambient air pollution is an enormous amount of pollution gas emissions from the transportation sector, such as CO_2. The transport sector constitutes about 21% of CO_2 emission globally as given in the report by the United Nations on air pollution from ground transportation [6]. Hence, tremendous research efforts have been made by the academia to reduce the amount of pollution gas from the transportation sector over decades.

The recent rapid advancement of vehicular ad hoc networks (VANETs) has envisioned a great potential to ameliorate the global transportation sector. VANET applications include active road safety applications, traffic efficiency and management applications, and infotainment applications [7]. In active road safety and traffic efficiency management applications, TL control has a significant impact on road traffic accident and air pollution issues. Since vehicles are forced to stop frequently by TLs, they cause various issues such as air pollution, traffic accidents, and waste of fuels, when the TLs are inefficiently scheduled [14].

Accordingly, TL scheduling issues have come under the spotlight and a number of researches and projects have been conducted [8]–[25]. Numerous VANETs-based TL scheduling techniques have been proposed in the technical literature. For example, two pioneer VANETs-based signal control optimizing algorithms, namely an older job first (OJF) and an arterial TL (ATL) were proposed in [8] and [9]. The OJF algorithm maps vehicular traffic signal scheduling problems to scheduling problems of vehicle platoons on processors, while the ATL algorithm hamonizes different TLs to create a traffic schedule. As a subset of VANETs-based approaches, traffic-light-vehicle-communication (TLVC)-based solutions [14]–[21] can cut CO_2 emissions of vehicles effectively, and have enormous potential for reducing intersection-related accidents since vehicles are able to use optimal speed advisory information to control their speeds to cross intersections during the green light phases. Nevertheless, to the best of our knowledge, none of the solutions address the YLD issue.

Motivated by the promising capabilities of VANETs-based solutions in general and TLVC-based solutions in particular, the following contributions are made by this paper:

1) To propose a novel adaptive VANETs-based TL control scheme to eliminate YLD-related traffic accidents occurring at intersections, enhance traffic throughput, and reduce CO_2 emissions from traveling vehicles, waiting time of vehicles.
2) To design algorithms and protocols with low communication overhead and low computational complexity for TL controllers, TLs, and roadside devices.
3) To promote eco-driving and safe-driving at signalized road intersections by providing traffic signals and optimal speed advisory information to vehicles.

The rest of the paper is organized as follows. Section II investigates state-of-the-art literature on the YLD problem and TL control applications. The referenced TL scheduling scheme entitled CO_2 RED is described as a preliminary in section III. Section IV formulates the YLD problem. The proposed scheme is introduced in Section V. Section VI presents simulation configurations, results, and analysis. Finally, Section VII concludes the paper.

II. RELATED WORKS

The related studies in the domains of YLD problem and the TLVC are summarized in Table 1. Over the past decade, several researches have been carried out to confront the YLD problem [4], [26]–[37]. Nonetheless, the researches mainly concentrate on identifying the attributes of the YLD problem or driver behaviours in the dilemma zones without providing comprehensive solutions to overcome the issue. For instance, Lu *et al.* [4] conducted a research on the connections between the YLD problem and the factors contributing to the drivers' decision when they encounter the YLD problem. In 2017, Pathivada and Perumal [28] investigated the factors affecting the driver behavior in dilemma zone at signalized intersections in India under mixed traffic conditions. To mitigate the YLD problem, dynamic TL control solutions should be used because they can react to real-time traffic conditions adaptively [31].

In the category of dynamic TL control solutions, TLVC-based solution is the most promising one since it can eliminate the YLD problem by providing drivers with optimal speed advisory information to pass intersections safely and efficiently. Though, the majority of TLVC-based solutions [9], [14]–[21] primarily focus on optimizing traffic flow and minimizing waiting time of vehicles, traffic congestion, fuel and CO_2 emission. The solutions employ vehicle-to-infrastructure (V2I), and vehicle-to-traffic-light (V2TL) communication methods along with dynamic and static TL scheduling techniques.

As an example of the TLVC-based solution, Younes *et al.* [10] introduced a framework known as dynamic TL control (DTLC) at road intersections in 2017. The framework mainly focused on optimizing vehicle waiting time, waiting line length, and traffic throughput. The simulation results have shown that the DTLC outperforms a legacy traffic light controller in terms of waiting line length, waiting time, and traffic throughput by 20%, 25%, 250%. The merit of DTLC lies in the use of a wireless sensor network with robust protocols to collect traffic data, tackle congestion, and improve traffic flow efficiency.

In 2018, a novel TL control technique based on TLVC and the priority of vehicles for minimizing fuel consumption and CO_2 emission was proposed by Suthaputchakun and Sun [14]. The scheme employs TLVC to transfer speed advisory and TL information from TLs to vehicles. Moreover, an adaptive TL scheduling algorithm considering the priority of vehicles was proposed. The simulation results have proven that the scheme (adaptive TL with adaptive vehicle speed) outperforms a semi-adaptive scheme (fixed TL with adaptive vehicle speed) and a conventional scheme (fixed TL together with fixed vehicle speed) in terms of the amount of CO_2 emission and the green light hit rate .

In spite of the research endeavors on TLVC, no studies have investigated the effect of the TLVC-based speed advisory solutions on the YLD problem in the technical literature. Thus, a research effort aiming to bridge the gap is made in this paper. We embrace the CO_2 RED scheme as a referenced TL control model since it is the most recent study in the domain and has a large potential to boost traffic throughput and lower CO_2 emissions from vehicles.

III. PRELIMINARY

As aforementioned, the paper utilizes the CO_2 RED [14] as a referenced scheme, in which an adaptive TL control algorithm for minimizing fuel consumption and CO_2 emission was proposed. As shown in Algorithm 1, it determines an appropriate TL scheduling of the next TL cycle by comparing weighted mean arrival time (WMAT) values of vehicles traveling in each intersected road segment.

The value is computed as follows.

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

where i is an index of communication area, n_i is the total number of vehicles in each area, w_j is the weight of the jth vehicle according to the type of vehicle, d_j is the distance from the jth vehicle to either TL1 or TL2, and s_j is the speed of the jth vehicle. For example, if the WMAT value (t_1) of road segment 1 is greater than t_2 of road segment 2, the first 50s (45s green and 5s yellow) of the TL schedule will be given to TLs of the road segment 1 and becomes 50s red in the road segment 2. Conversely, if the WMAT value (t_1) of road segment 1 is smaller than t_2 of road segment 2, the first 50s (45s green and 5s yellow) of the TL schedule will be assigned to TLs of the road segment 2 and becomes 50s red in the road segment 1.

Algorithm 1 TL Scheduling Method of CO_2 RED Scheme

if $t_1 < t_2$ **then**
 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 = $(t_1 + 5, 95)$,1 Yellow = (95, 100)
else if $t_1 > t_2$ **then**
 Area 1: Green = $(0, t_2 + 5)$, Yellow = $(t_2 + 5, 95)$, Red = (95, 100)
 Area 2: Red = $(0, t_2)$, Green = $(t_2, t_2 + 5)$, Yellow = $(t_2 + 5, 100)$
else
 Area 1: Green = $(0, t_1 - 2.5)$, Yellow = $(t_1 - 2.5, t_1 + 2.5)$, Red = $(t_1 + 2.5, 100)$
 Area 2: Red = $(0, t_1 + 2.5)$, Green = $(t_1 + 2.5, 95)$, Red = (95, 100)
end if

Based on the generated TL schedules, new speeds are computed and delivered to vehicles via TLVC. Vehicles can use the new speeds to pass TLs without stoppage during green interval. The new speed can be computed as follows.

$$S_{new_i} \begin{cases} S_R, & g_{start} \leq \frac{d_i - d_{adj}}{S_R} \leq g_{end} \ and \ hit_g = 1 \\ \frac{d_i - d_{adj}}{g_{end}}, & g_{start} \leq \frac{d_i - d_{adj}}{S_{max}} \leq g_{end} \ and \ hit_g = 1 \\ \frac{d_i - d_{adj}}{g_{start}}, & g_{start} \leq \frac{d_i - d_{adj}}{S_{min}} \leq g_{end} \ and \ hit_g = 1 \\ S_R, & otherwise, \end{cases} \tag{2}$$

where S_{new_i} is a new recommended speed for the ith vehicle, S_R is the default recommendation speed, d_i is a distance between the ith vehicle and the TL, d_{adj} is a minimum distance required for speed adjustment from S_R to S_{new_i}, S_{min} and S_{max} are the minimum and maximum recommended speeds, and g_{start} and g_{end} are the beginning and ending times of the green period, respectively.

The new speed advisory information helps increase the green light hit rates of all vehicles and the total amount of CO_2 emission decreases accordingly. This is because the total amount of CO_2 emission in case of green light hit (CO_{2hit}) is less than the amount of CO_2 emission in case of green light miss ($CO_{2missed}$). The total amount of CO_2 emission of the green light hit case is computed as follows.

$$CO_{2hit} = CO_{2adj1} + CO_{2const} + CO_{2adj2}, \tag{3}$$

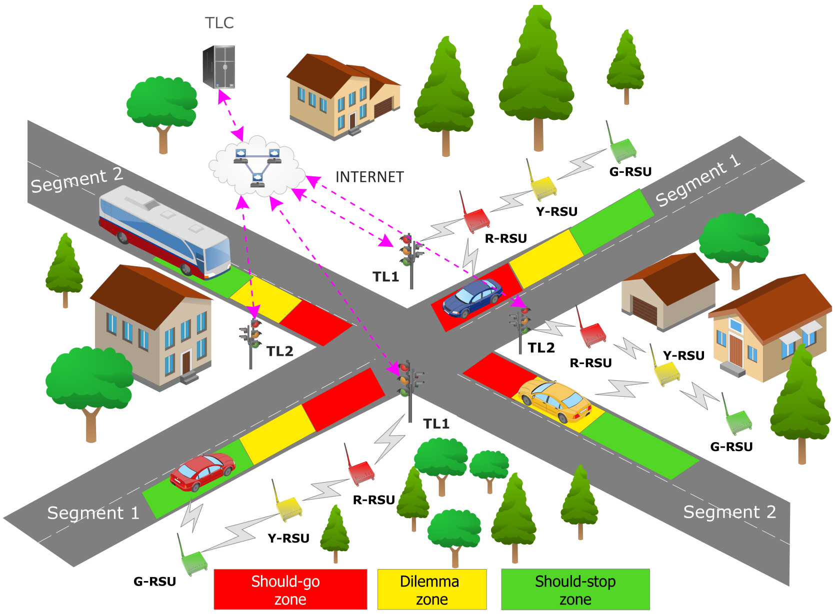

FIGURE 1. Overview of dilemma zones and proposed system models.

where CO_{2adj1} and CO_{2adj2} are the amount of CO_2 emission during the first and second speed adjusting, CO_{2const} is the amount of CO_2 emission during constant moving with a new recommended speed.

The total amount of CO_2 emission of the green light miss case is computed as follows.

$$CO_{2missed} = CO_{2const} + CO_{2dec} + CO_{2stop} + CO_{2acc}, \quad (4)$$

where CO_{2dec} and CO_{2acc} are the amount of CO_2 emission during speed deceleration to 0 km/h and speed acceleration from 0 km/h, CO_{2stop} is the amount of CO_2 emission during stop and wait period. The primary difference between the two cases is CO_{2acc} which makes vehicles emit a large amount of CO_2 to reaccelerate from 0 to 65 km/h to cross the intersection after the red light phase of the TL is ended.

IV. PROBLEM FORMULATION

As it can be seen in Fig. 1, dilemma zones are defined as an intersected region of a should-go zone (Z_{GO}) and a should-stop zone (Z_{STOP}). Vehicles in the Z_{GO} are unable to comfortably accelerate to cross the intersection before the TL state changes to red, while vehicles in the Z_{STOP} are unable to decelerate comfortably to stop behind the stop-line before the TL state switches to red [4]. Vehicles in the dilemma zone (Z_{DLM}) are unable to stop safely or cross the intersection in a comfortable way.

When a vehicle (V_1) reaches a signalized intersection, its location and the state of its frontward TL are two principal factors that can influence the decision whether to accelerate and pass the intersection (D_{GO}) or to decelerate and stop at the intersection (D_{STOP}). Table 2 lists the factors and its corresponding decision of vehicles. It can be observed that the vehicle can make a decision easily most of the time except when the TL color (TL_{COLOR}) is yellow and it is in the Z_{DLM}. In that situation, the vehicle hesitates to stop or go. This could lead to serious traffic accidents.

TABLE 2. Factors influencing the decision of vehicles at signalized intersections.

ZONE TYPES	RED	GREEN	YELLOW
Z_GO	STOP	GO	GO
Z_STOP	STOP	GO	STOP
Z_DLM	STOP	GO	*HESITATE*

V. PROPOSED SCHEME

A. SYSTEM MODELS

In the proposed scheme, the following assumptions about the road model, the TL model, the TL controller model, the traffic model, the vehicle model, and the roadside traffic sensor model are made. Fig. 1 illustrates a general overview of the models.

1) Road model: a typical intersecting road model is used. The model has two opposite segments and each segment has one or more lanes. Each lane contains three zones (Z_{GO}, Z_{DLM} and Z_{STOP}) located near the intersection.
2) TL model: traditional TL placement is used. The TLs at the same road segment always show the same colors. The TLs at the different road segments always show the opposite colors. A TL controller is embedded into the TL to control the TL adaptively. In addition, it acts as a gateway exchanging information with RSUs via radio communications.

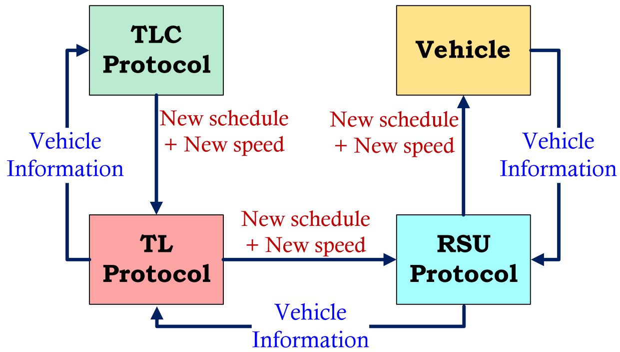

FIGURE 2. Data flow of proposed system.

3) TL controller model: TL controllers (TLCs) are online servers remotely controlling TLs via the Internet. TLCs collect the information of TLs such as their current states, schedules, and collected vehicle information. Based on the information, TLCs can create and distribute new schedules to TLs.
4) Traffic model: The proposed TL scheduling algorithm is independent of vehicle arrival model. Vehicles can proceed in any direction and arrive in a stochastically arbitrary manner.
5) Vehicle model: each vehicle is provided with an on-board device that is capable of exchanging information wirelessly with RSUs and TLs. The device also has a display unit showing TL countdown information and speed advisory information.
6) Roadside traffic sensor model: a roadside unit (RSU) is installed at the starting point of each zone to communicate with vehicles present in that zone. Each lane has 3 RSUs and a TL. The RSUs are linked to each other and the TL to form a multi-hop wireless sensor network. The TL acts as a gateway of the network. For example, vehicles in Z_{STOP} can exchange information with a green RSU (G-RSU). The G-RSU relays the collected information to its gateway which is a TL via a yellow RSU (Y-RSU) and a red RSU (R-RSU). A response message containing TL information is delivered sequentially from the gateway to the vehicles through R-RSU, Y-RSU, and G-RSU.

B. SYSTEM DATA FLOW

Fig. 2 describes the data flow of the proposed system. TLC protocol, TL protocol, RSU protocols are embedded in the TLC, the TL, and the RSU, respectively. The TLC protocol receives vehicle information as an input from the TL protocol and outputs a new TL schedule and new optimal speed advisory information. After receiving the new TL schedule and new speed advisory information from the TLC protocol, the TL protocol sends the information to the RSU protocol. Likewise, the TL protocol receives vehicle information from the RSU protocol. The RSU protocol is responsible for communicating with vehicles by sending the new TL schedule and new speed advisory information, and receiving vehicle information.

C. TLC PROTOCOL

Algorithm 2 TLC Protocol

```
1:  if V_info is received then
2:      Calculate t_i for TL1 and TL2
3:      Execute Algorithm 1 to generate SC_new
4:      Send SC_new to TL1 & TL2
5:  end if
6:  if YLD_flag is received then
7:      if V_info is received then
8:          Calculate t_extra && S_new using V_info
9:          if YLD_flag is from TL1 then
10:             Send t_extra && S_new to TL1
11:         else if YLD_flag is from TL2 then
12:             Send t_extra && S_new to TL2
13:         end if
14:     end if
15: end if
```

TLC protocol is stored and executed at the TLC. The goal of the protocol is to generate a new TL schedule to adaptively control TLs installed at an intersection. Algorithm 2 explains details of the protocol. From line 1 to 5, the following procedure is executed when the TLC receives vehicle information from TL1 and TL2 after their TL cycles expire.

1) Calculating the proposed weighted mean arrival time (PWMAT) values for TL1 and TL2.
2) Executing Algorithm 1 with the PWMAT values as parameters.
3) Getting a newly generated schedule from Algorithm 1.
4) Sending the new schedule to TL1 and TL2.

From line 6 to 15, when the TLC receives a flag indicating the occurrence of the YLD at a TL, the following procedure is executed.

1) If the TLC receives vehicle information from the TL that sends the flag, extending time and new speed values are calculated by Eq. 6 and Eq. 7, respectively.
2) The TLC checks whether the flag is from TL1 or TL2
3) If the flag is from TL1, the TLC sends the extending time and the new speeds to TL1.
4) If the flag is from TL2, the TLC sends the extending time and the new speeds to TL2.

D. TL PROTOCOL

TL protocol is stored and executed at TLs. The goal of the protocol is to control a TL to exchange TL information and vehicle information with the TLC and its RSUs. Algorithm 3 explains details of the protocol. From line 1 to 9, the following procedure is executed when the TL finishes a cycle.

1) Requesting vehicle information from its corresponding RSUs.

Algorithm 3 TL Protocol

1: **if** TL_{cycle} is ended **then**
2: Send RQ_{vInfo} to RSUs
3: **if** V_{info} is received **then**
4: Send V_{info} to TLC
5: Wait for SC_{new} returned from TLC
6: Calculate S_{new} for each vehicle based on SC_{new}
7: Send S_{new} && SC_{new} to RSUs
8: **end if**
9: **end if**
10: **if** TL_{color} is yellow **then**
11: Send RQ_{vInfo} to Y-RSU
12: **if** V_{info} is received **then**
13: Send V_{info} && YLD_{flag} to TLC
14: Wait for t_{extra} && S_{new} returned from TLC
15: **if** t_{extra} && S_{new} are received **then**
16: Add t_{extra} to current yellow light countdown timer.
17: Add t_{extra} to the countdown timer of the TLs of the other road segment.
18: Send S_{new} to Y-RSU.
19: **end if**
20: **end if**
21: **end if**

2) If the TL receives vehicle information from the RSUs, it sends the received vehicle information to the TLC and waits to receive a new TL schedule from the TLC. With the new TL schedule, it is able to calculate new speeds for each vehicle staying in the responsible zones of RSUs. Finally, it delivers both new speeds and new schedule to the RSUs.
3) Receiving TL schedules and new speeds from TL and transferring the information to vehicles present in the responsible zones of RSUs.

From line 10 to 21, when a TL's color turns yellow, the following procedure is executed.

1) Requesting vehicle information from its yellow RSU.
2) If the TL receives vehicle information from the yellow RSU, it sends the received vehicle information and the YLD flag to the TLC.
3) Waiting for extending time and new speeds returned from the TLC.
4) If the extending time and the new speeds are received, the TL adds the extending time to the current yellow light's countdown timer and the countdown timers of the TLs of the other road segment.
5) Sending the new speed to its yellow RSUs.

E. RSU PROTOCOL

Algorithm 4 explains details of RSU protocol. It is stored and executed at RSUs. The goal of the protocol is to control a RSU to perform the following tasks:

Algorithm 4 RSU protocol

1: **if** RQ_{vInfo} is received **then**
2: Start collecting vehicle information in zone X
3: Send V_{info} to corresponding TL
4: **end if**
5: **if** S_{new} && SC_{new} are received **then**
6: Broadcast S_{new} && SC_{new} to vehicles inside zone X
7: **end if**
8: **if** S_{new} is received **then**
9: Send S_{new} to vehicles in Y-RSU
10: **end if**

1) Collecting vehicular sensor information regarding vehicle speeds and positions in the responsible zones of RSUs. For example, the G-RSU is responsible for collecting vehicular sensor information of vehicles present in the green zone.
2) Transferring the vehicular sensor information to the TL and the TLC.
3) Receiving TL schedules and new speeds from TL and distributing the information to vehicles present in the RSU's responsible zone.

From line 1 to 4, a RSU executes the following procedure when it receives the vehicle information request from the TL.

1) Collect vehicle information in the responsible zone of the RSU.
2) Send the collected vehicle information to the corresponding TL of the RSU.

From line 5 to 7, if the RSU receives new speeds and a new schedule from the TL, it broadcasts the information to vehicles present in its responsible zone. From line 8 to 10, if the Y-RSU receives new speeds from the TL, it sends the information to vehicles present in its responsible zone.

F. PROPOSED WEIGHTED MEAN ARRIVAL TIME (PWMAT)

In the proposed scheme, the weight of the zone X (w_x^j), where the jth vehicle is inside, is added to Eq. 1. Hence, *PWMAT* taking into account the Z_{DLM} can be computed as follows.

$$t_i = \frac{\sum_{j=1}^{n_i} w_x^j w_j \left(\frac{d_j}{s_j}\right)}{\sum_{j=1}^{n_i} w_x^j w_j}, \tag{5}$$

It is assumed that the weight (w_x^j) of the Z_{DLM} is two-times higher than that of the Z_{GO} and Z_{STOP}. By utilizing the weight, TLs of a road segment that have more vehicles in the Z_{DLM} will be prioritized in the TL scheduling process conducted by the TLC.

G. ADAPTIVE TL SCHEDULING METHOD

In a regular situation where there is no vehicle detected in the Z_{DLM}, the proposed scheme employs the dilemma-zone based *PWMAT* value and the TL scheduling algorithm of the CO_2 RED scheme to obtain an appropriate schedule for TL1 and TL2. This is done by Algorithm 1. In addition, if vehicles encounter the YLD, the TL controller will reschedule the yellow light by increasing the remaining time of the yellow light phase. The amount of extending time required to reschedule TL1 and TL2 is computed as follows.

$$t_{extra} = \frac{\sum_{y=1}^{n_z} w_y \left(\frac{d_y}{s_y}\right)}{\sum_{y=1}^{n_z} w_y}, \tag{6}$$

where n_z is the total number of vehicles in a dilemma-zone, w_y is the weight of the yth vehicle according to vehicle's type, d_y is the distance from the yth vehicle to either TL1 or TL2, and s_y is the speed of the yth vehicle.

H. SPEED ADVISORY METHOD

In the regular situation, the proposed scheme adopts the speed advisory method of the CO_2 RED scheme. The speed advisory method is described in Eq. 2.

In a critical situation when the YLD problem arises, new optimal speed advisory information delivered to vehicles in the Z_{DLM} can be computed as follows:

$$S_{new_i} \begin{cases} S_R, & y_{start} \leq \frac{d_i - d_{adj}}{S_R} \leq y_{end} \text{ and } hit_y = 1 \\ \frac{d_i - d_{adj}}{y_{end}}, & y_{start} \leq \frac{d_i - d_{adj}}{S_{max}} \leq y_{end} \text{ and } hit_y = 1 \\ \frac{d_i - d_{adj}}{y_{start}}, & y_{start} \leq \frac{d_i - d_{adj}}{S_{min}} \leq y_{end} \text{ and } hit_y = 1 \\ 0, & otherwise, \end{cases} \tag{7}$$

where y_{start} and y_{end} are the beginning and ending times of the yellow period correspondingly. For the first three cases, the ith vehicle can adjust the speed between S_{min} and S_{max} to hit the yellow period. Otherwise, the vehicle misses the yellow period and has to stop at the TL to avoid traffic accidents.

VI. SIMULATION RESULTS AND ANALYSIS

Extensive simulation works are conducted to evaluate the performance of the proposed scheme in this section. The experiments are run on a desktop computer equipped with an Intel core i5 4460 processor, 16 Gb of RAM, and Microsoft Windows 10 operating system. The simulation tool is developed using C/C++ languages and employs the discrete event system specification (DEVS) formalism for modeling and analysis of discrete event systems. The simulator is designed to simulate all specific scenarios described in this section. Basically, it uses an arbitrary distribution method to generate traffic load and controls the TLC, TLs, RSUs based on the proposed protocols. Although standard urban mobility simulators such as SUMO and VISSIM have been widely used in the academia, they lack adequate support for modeling specific scenarios involving the YLD problem, the proposed speed advisory method and the proposed wireless sensor network. Therefore, a customizable simulator is preferred in this paper. Furthermore, it is assumed that the TLC, TLs, RSUs and all vehicles can effectively exchange traffic scheduling information with each other.

TABLE 3. Simulation parameters.

Parameters	Default values
Number of communication areas	2
Number of zones in each road segment	1 to 3
Number of lanes per road	2
Default speed of vehicles (S_R)	65 km/h
Minimum speed of vehicles (S_{min})	55 km/h
Maximum speed of vehicles (S_{max})	75 km/h
TL informing distance	0-2000 m
Length of Z_{GO}	20 m
Length of Z_{DLM}	30 m
Weight of Z_{DLM} (w_x)	2
Weight of Z_{GO} (w_x)	1
Weight of Z_{STOP} (w_x)	1
Weight of normal vehicles (w_j)	1
Weight of heavily-loaded vehicles (w_j)	2
CO_2 emission and fuel consumption	EMIT [19]
Number of simulations	1000 times

TABLE 4. Performance metrics.

Item	Unit
Number of TL violation cases	integer
Average waiting time per vehicle	second (s)
Average amount of CO_2 emission per vehicle	gram (g)
Traffic throughput	vehicles per minute

At the beginning of this section, the simulation parameters and metrics are described, and then simulation results are given. We present a mathematical analysis at the end of this section.

A. SIMULATION PARAMETERS AND METRICS

Simulation parameters and their default values are listed in Table 3. The proposed scheme utilizes the default parameter list of the CO_2 RED scheme [14]. Additionally, the number of zones in each road segment and their weights are provided. The lengths of the Z_{GO} and Z_{DLM} are also specified as 20m and 30m, respectively. The number of road lanes is set to 2. CO_2 emission can be measured using a widely accepted EMIT model [19].

Simulation works comparing performances of the conventional scheme, the DTLC scheme, the CO_2 RED scheme and the proposed scheme are conducted. Their performance metrics are given in Table 4. The conventional scheme refers to traditional TLs using fixed signal control method. The DTLC considers only adaptive TL scheduling method whilst the CO_2 RED uses a strategy considering adaptive TL scheduling and optimal speed advisory methods.

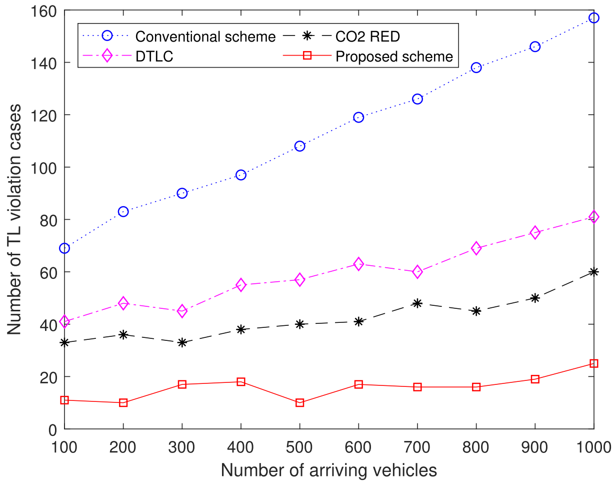

FIGURE 3. **Comparison of number of TL violation cases.**

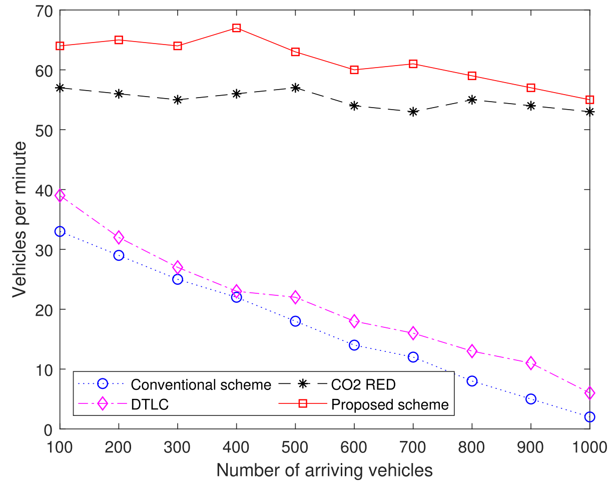

FIGURE 4. **Comparison of throughput.**

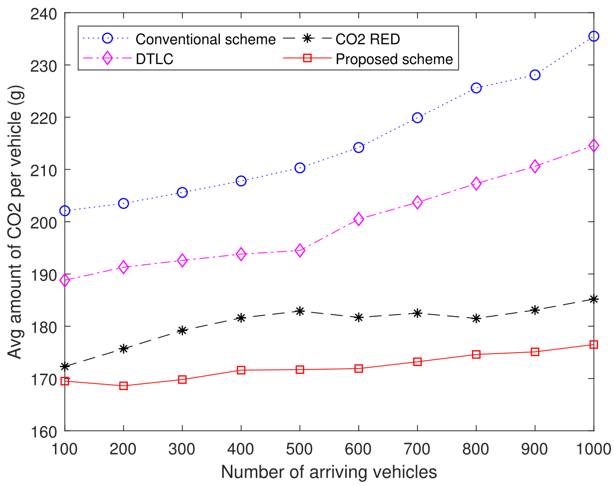

FIGURE 5. **Comparison of CO_2 emission.**

The proposed scheme applies a strategy considering adaptive TL scheduling method, optimal speed advisory method, and the YLD problem. In the first simulation work regarding the number of TL violation cases, the scheme that has the smallest number of TL violation cases is considered to be the best scheme. In the second simulation work relating to the traffic throughput, the scheme with the higher throughput is better than others. In the third simulation work on the average amount of CO_2 emission per vehicle, the better scheme can be achieved with the lower amount of CO_2 emissions. In the last simulation work concerning the average waiting time per vehicle, the lower waiting time means the better scheme.

B. SIMULATION RESULTS

The first simulation work measures and compares the number of TL violation cases of all schemes. The results are presented in Fig. 3. The conventional scheme has the highest number of TL violation cases (103 cases on average) since vehicles are unaware of traffic signals information and optimal speed advisory information early. If they know the information early, they may adjust their speeds to stop at TLs or pass the intersection.

The DTLC scheme has the second highest number of TL violation cases (54 cases on average) due to the same reason. In the scheme, no traffic signals information and optimal speed advisory information is transfered to vehicles from TLCs, the TLCs only collect information regarding the number of waiting vehicles. Otherwise, the proposed scheme and the CO_2 RED scheme achieve fewer number of TL violation cases because they provide the information to vehicles early such that the vehicles can adjust their speeds. The proposed scheme achieves a better result (14.5 cases on average) than the CO_2 RED scheme (38.5 cases on average) since the CO_2 RED scheme overlooks the YLD problem which influences the number of TL violation cases directly. In summary, the performance gains of the proposed scheme are approximately 85.9%, 73.1%, and 62.3% in comparison with the other schemes.

The second simulation work examines the throughput (number of vehicles passing an intersection per minute) of all schemes. As represented in Fig. 4, the proposed scheme (56 vehicles per minute on average), the CO_2 RED (50 vehicles per minute on average), the DTLC scheme (19 vehicles per minute on average) and the conventional scheme (15 vehicles per minute on average) take the first, second, third and fourth places, respectively. The result demonstrates again the advantages of the proposed scheme and the CO_2 RED scheme which utilize adaptive TL scheduling and optimal speed advisory strategies. In brief, the average throughput gains between the best scheme and the other schemes are approximately 273%, 194%, and 12%. The throughput gain is partly generated from line 8 of the TLC protocol. Because vehicles are given extending time to pass intersections when the YLD problem occurs, the throughput is increased as a result.

Fig. 5. shows the result of the third simulation work comparing the average amount of CO_2 emission of all schemes.

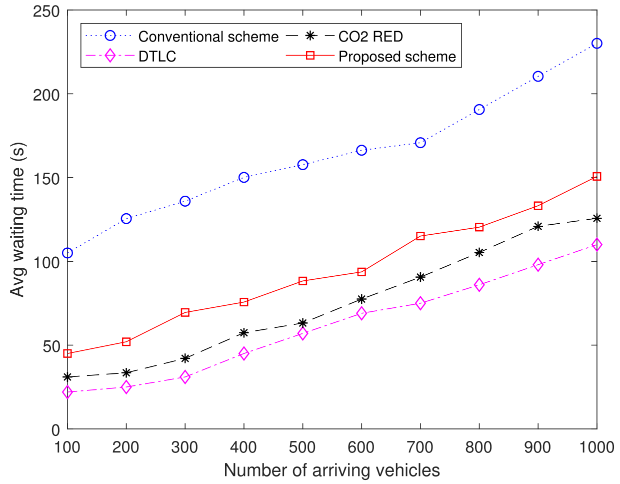

FIGURE 6. Comparison of average waiting time of vehicles.

It is observed that vehicles emit the lowest amount of CO_2 with the proposed scheme (156.5 g/vehicle on average) while the conventional scheme makes vehicles emit the highest amount of CO_2 (195.7 g/vehicle on average). Moreover, the CO_2 RED scheme has the second lowest amount of CO_2 (164.1 g/vehicle on average) and the DTLC scheme has the second highest amount of CO_2 (181.6 g/vehicle on average). Compared to the conventional scheme, the proposed scheme reduces the amount of CO_2 by approximately 43.01 g/vehicle on average. This significant reduction is proportional to the throughput gain of the proposed scheme in the second simulation work because more vehicles can maintain optimal speeds which means less CO_2 emission. In comparison with the CO_2 RED scheme, the proposed scheme achieves better result because most of the vehicles trapped in the YLD problem are allowed to cross the intersection while the CO_2 RED scheme does not consider that situation. In summary, the average CO_2 emission gains between the best scheme and the other schemes are roughly 20%, 13.8%, and 4.6%.

The last simulation work compares all schemes in terms of the average waiting time of vehicles. As depicted in Fig. 6, the DTLC scheme achieves the lowest waiting time (56.1s on average) whereas the proposed scheme only takes the third place. The worst scheme is still the conventional scheme (149.3s on average). The proposed scheme performs poorly in this simulation work (150.7s on average) because when the TLs of a road segment give extra yellow time to solve the YLD problem, the TLs of the other road segment need to increase their red time by an equal amount of extending time. Meanwhile, the DTLC scheme uses a force early TL change method to shorten the waiting time of vehicles. Yet, this method results in low throughput.

C. MATHEMATICAL ANALYSIS

1) COMMUNICATION OVERHEAD

Lemma 1: Total communication overhead is $O(N_v)$, where N_v is the maximum number of vehicles present in the TL informing range. *Proof:* the total communication overhead is computed as follows:

$$\text{comm}^o_{total} = comm^o_{veh} + comm^o_{rsu} + comm^o_{tl} + comm^o_{tlc}, \quad (8)$$

where $comm^o_{veh}$, $comm^o_{rsu}$, $comm^o_{tl}$, $comm^o_{tlc}$ are total communication overheads of arriving vehicles, RSUs, TLs, and the TLC. First, because each vehicle sends a message containing its information to the RSU and receives a message containing the optimal speed information and the new TL schedule from the RSU, $comm^o_{veh}$ is $O(2N_v)$. Second, the RSU protocol involves collecting vehicle information and broadcasting new optimal speed information and new TL schedule to vehicles. Hence, based on lines 2, 3, 6, 9 of the RSU protocol, $comm^o_{rsu}$ can be calculated as $O(2N_v+N_r)$, where N_r is the number of RSUs. Third, the TL protocol includes transmitting vehicle information requests to RSUs, sending vehicle information to the TLC and delivering new optimal speed information and new TL schedule to RSUs. As a result, based on lines 2, 4, 7, 11, 13, 18 of the TL protocol, $comm^o_{tl}$ is equal to $O(N_v + 2N_{tl})$, where N_{tl} is the number of TLs. Fourth, the TLC protocol involves sending new optimal speed information, new extending yellow time and new TL schedule to RSUs. Based on lines 4, 10, 12 of the TL protocol, $comm^o_{TLC}$ is calculated as $O(3N_{tl})$. Finally, $comm^o_{total} = O(2N_v)+O(2N_v+N_r)+O(N_v+2N_{tl})+O(3N_{tl}) = O(2N_v) = O(N_v)$ since N_v is always greater than N_{tl} and N_r.

2) COMPUTATIONAL COMPLEXITY

Lemma 2: Total computational complexity is $O(N_v)$, where N_v is the maximum number of vehicles present in the TL informing range. *Proof:* the total computational complexity is computed as follows:

$$\text{comp}^c_{total} = comp^c_{rsu} + comp^c_{tl} + comp^c_{tlc}, \quad (9)$$

where $comp^c_{rsu}$, $comp^c_{tl}$, $comp^c_{tlc}$ are computational complexities of RSUs, TLs, and the TLC. Firstly, because the RSU protocol simply involves exchanging messages with vehicles and TLs, $comp^c_{rsu}$ is equal to $O(1)$. Secondly, since the TL protocol uses a loop to calculate new speed information for each vehicle and adds extra yellow time to TL countdown timers, $comp^c_{tl}$ can be computed as $O(N_v + 1) = O(N_v)$. Thirdly, the TLC protocol's computational complexity consists of calculating t_i for TLs, executing algorithm 1, and calculating t_{extra} and S_{new}. Because the calculation of t_i, t_{extra}, and S_{new} loops through N_v vehicle information, it takes $O(3N_v)$ time to complete. Since the algorithm 1 solely compares TLs' t_i, it takes $O(1)$ time to run. Therefore, $comp^c_{tlc} = O(3N_v) + O(1) = O(N_v)$ and $comp^c_{total} = O(1) + 2O(N_v) = O(N_v)$.

VII. CONCLUSION AND FUTURE WORKS

The paper has proposed a novel smart VANETs-based TL scheduling scheme for reducing CO_2 emissions of vehicles and improving the safety of road intersections where YLD-related accidents often occur. The proposed scheme borrows the idea of using adaptive TL scheduling and optimal speed advisory methods from the CO_2 RED scheme to increase traffic throughput and reduce CO_2 emissions from vehicles. Furthermore, various protocols and algorithms have been proposed to relieve the YLD problem by giving higher weights to dilemma zones and extra yellow signal time to vehicles present in the zones. The proposed protocols and algorithms have low computational complexity and low communication overhead. Four simulation works are carried out to compare the performance of the proposed scheme with other three schemes. The proposed scheme achieves better performance than the others in terms of the number of TL violation cases, the traffic throughput, and the average amount of CO_2 emission per vehicle. The performance gains are 73.3%, 159.6%, and 12.8%. In the future, an optimization effort using genetic algorithms will be made to enhance the average waiting time per vehicle performance metric. Afterwards, field trials will be conducted to verify the simulation results.

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