An Open Traffic Light Control Model for Reducing Vehicles’ CO₂ Emissions Based on ETC Vehicles

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Abstract—Usually, vehicles’ stop-and-go driving will consume more fuel and emit more CO₂ than constant speed driving. To reduce vehicles’ CO₂ emissions, vehicles’ travel should be smoothed by reducing the stop-and-go times. In this paper, a three-tier structure is proposed to realize dynamic traffic light control for smoothing vehicles’ travel. In tier-1, an electronic toll collection (ETC) system is employed for collecting road traffic flow data and calculating the recommended speed. In tier-2, radio antennas are installed near the traffic lights. Road traffic flow information can be obtained by wireless communication between the antennas and ETC devices. In tier-3, a branch-and-bound-based real-time traffic light control algorithm is designed to smooth vehicles’ travels. After smoothing vehicles’ travels, more vehicles can pass intersections with less waiting time and fewer short-time stops; therefore, the vehicles’ CO₂ emissions can be reduced. Simulation results indicate that the proposed scheme performs much better than the adaptive fuzzy traffic light control method: The average waiting time, short-time stop times, and CO₂ emissions are greatly reduced, and the nonstop passing rate is greatly improved.

Index Terms—Branch and bound (BB), CO₂ emission, electronic toll collection (ETC), real-time traffic light control, speed control, three-tier open model.

I. INTRODUCTION

IN RECENT YEARS, the problem of global warming has seriously become a worldwide concern. It involves issues such as the sea-level-rising problem. During the last 100 years, the global mean sea level has risen between 10 and 25 cm (18-cm average) [1]. Humanity’s living environment has changed through heat waves or extreme weather [2], [3], e.g., the catastrophic floods that hit the European continent in 2002 and the unusual high temperatures seen for prolonged periods in the summer of 2003 [4]. To slow down the speed of our living environment’s deterioration, the reduction of CO₂ emissions has become urgent. As one of the major sources of CO₂, vehicle exhaust emissions have become more serious due to the rapid increase in the numbers of vehicles in the world [5].

A typical driving trip consists of idling, accelerating, cruising, and decelerating [6]. The proportions of a trip spent in these different stages will depend on the driver’s behavior (e.g., aggressive versus mild driving habits), the roadway type (e.g., freeway versus arterial and rural versus urban), and the traffic’s congestion level. The CO₂ emission rates from these stages are different. We treat the trip as the following two parts: 1) idling and 2) driving (accelerating, cruising, and deceleration). Barth et al. carried out experiments [6] indicating that, during an idling period, the engine would consume more fuel and release more CO₂ emissions than in a cruising period; on the other hand, lower waiting times and a constant-speed driving style would lead to less CO₂ emissions. A study in [7] indicated that accelerating and decelerating had a higher emission rate than idling. Furthermore, [6] implied that the most common reason for engine idling is a stop-and-go driving style, because in a short time period, drivers have to decelerate to stop and then accelerate to go. During this period, vehicles would emit more CO₂ emissions. The stop-and-go driving style usually happens when parking or passing through intersections, e.g., taxies that wait in queues to pick up passengers in taxi pickup points and vehicles that wait for traffic lights at intersections. Thus, minimizing the waiting time and avoiding unnecessary stop-and-go driving can smooth travel and then reduce CO₂ emissions.

One of the ways to smooth travel is the traffic light control method. The most widely used control scheme is the fixed-time control, but it cannot meet the requests of optimal waiting times [9]. It easily causes traffic congestion when the traffic flow is heavy. Adaptive traffic control becomes the essential way of solving problems that are brought by fixed-time control. Any real-time adaptive or dynamic traffic control system needs to correctly detect the traffic flow in real time and quickly and efficiently respond to any changes in the current traffic situation. Some adaptive controls use on-street detectors or loops to count the number of vehicles that approach the controlled intersection, e.g., the split, cycle, and offset optimization technique (SCOOT) control system [8] and the Sydney coordinated adaptive traffic (SCAT) system [9]. However, these systems cannot get accurate real-time traffic flow data when the queue grows beyond the length of the detector, the road is oversaturated, or the counted vehicles might change their directions.

Adaptive traffic lights based on wireless communication with the vehicles can employ greater flexibility than the loop detectors placed on each road, because they are provided with more accurate information for the traffic light decision process in real time. One study [10] proposed an adaptive traffic light control for improved traffic coordination at intersections using intervehicle communication. Another study [11] presented a VGrid framework to enhance traffic efficiency, which was based on intervehicle and vehicle-to-roadside wireless communications. In [13] and [14], a dynamic traffic control based on wireless sensor networks using the wireless sensor technology...
to forecast the incoming vehicles in an intersection is designed. Still another study [12] presented the usage of a wireless sensor network to enable drivers to have more energy-efficient city driving through an interactive communication between drivers and traffic lights. In [15], a signal-scheduling scheme to improve the vehicular traffic at crossroads through maximal weight-matching algorithms is developed. In [16], the intersection as a resource that is shared between vehicles of two roads, which should consider different kinds of vehicles, such as public transport and emergency vehicles, is considered.

As aforementioned, traffic light control plays very important roles in smoothing travels by reducing vehicles’ waiting time and the number of short-time stops. Recently, several researchers have examined this way of reducing CO₂ emissions. Oda et al. had proposed a microscopic simulation model to obtain the traffic flow to minimize the waiting time in [17] and employed the CO₂ emissions model in [18] to calculate CO₂ reductions. However, the traffic flow detection method was unclear, and the traffic flow information was not in real time. Inaccurate traffic flow data could not bring the optimal waiting time and accurate CO₂ reductions. Alsabaan et al. had proposed a new geocast protocol for reducing vehicle fuel consumption and emissions in [20]. In this protocol, the authors introduced a recommended speed calculation for reducing vehicles’ numbers of stop times. However, [20] did not consider that keeping a constant speed would release less CO₂ than acceleration or deceleration.

With the development of intelligent transportation systems (ITSs), electronic toll collection (ETC) technology has matured to where it is widely used for automatic toll collection on highways by nonstop passing the toll gate [21]. In our previous work [19], we employed ETC vehicles to communicate with traffic lights to obtain real-time traffic flow information, and a decision-tree-based traffic light control algorithm was proposed to reduce the waiting time. The simulation results turned out to be promising. However, there are still three issues that need to be dealt with. First, smoothing vehicles’ travels are focused not only on smoothing for one intersection but on the whole trip as well. Thus, the adjacent intersections’ cooperation must be considered. However, in [19], we were mainly concerned with one isolated single intersection and did not pay attention to the cooperation among adjacent intersections. Thus, in this paper, we will consider a road network for smoothing vehicles’ whole trips by adjacent intersections’ cooperation. Second, we were mainly concerned with minimizing the waiting time and did not consider the number of stop times in [19]. According to [6] and [7], accelerating or decelerating during short-time stops more easily leads to CO₂ emissions. Thus, to obtain more accurate results, the stop times should be considered. Third, the proposed decision-tree-based traffic control algorithm in [19] is more suitable for a single intersection. It would have higher computation times when used for road networks. Considering the aforementioned three points, we try to improve and perfect the previous work. This paper is the follow-up. The rest of this paper is organized as follows. The proposed system model is found in Section II. The traffic light control algorithm and the recommended speed calculation method for smoothing vehicles’ travels are described in Section III and evaluated in Section IV. Finally, Section V concludes this paper and proposes future work.

II. SYSTEM MODEL

In this section, a three-tier open model is proposed for adaptive traffic light control, which is mainly aimed at smoothing vehicle travels. In this model, we suppose that all vehicles have installed the Global Positioning System (GPS) devices and ETC in-vehicle devices called on-board units (OBUs). GPS devices are used to collect vehicle state information, such as the current speeds, the distances to the stop line, acceleration, deceleration, and the moving directions (e.g., go straight, turn right, or turn left). OBUs are applied to send traffic flow information to traffic lights by wireless communication. Then, in the traffic control center, traffic lights’ cycles are dynamically adjusted based on the received detected traffic flow information by a certain traffic light control algorithm. Last, an existing CO₂ emissions model is used to calculate the CO₂ amounts.

A. Three-Tier Open Traffic Light Control Model

1) Introduction of the Three-Tier Open Model: From a macroscopic view, a three-tier open model for adaptive traffic control is shown in Fig. 1. We suppose that antennas are installed near (see Fig. 2) the traffic light to collect road traffic flow information and that the antenna has its own maximum radio distance, which depends on its performance.

a) Tier-1: The function of tier-1 mainly concerns collecting road traffic flow information data, sending traffic flow data, receiving traffic light phase data, and calculating recommended speeds. In this tier, vehicle state information will be obtained from the GPS devices. The ETC OBUs devices can communicate with the traffic lights (in tier-2) to send current traffic flow information to the traffic control center (in tier-3) and receive traffic light phase data (e.g., the current phase’s remaining time). When vehicles have received the information from the lights, the OBUs will calculate a recommended speed
for drivers. According to the recommended speed, the drivers can change or keep the current speed to pass through the intersections with shorter waiting time or less number of short-time stops.

b) Tier-2: Tier-2 is mainly responsible for receiving and saving traffic flow data and then sending the control results to the ETC OBUs. This tier consists of the following three parts (see Fig. 1): 1) antennas; 2) storage; and 3) traffic lights.

As aforementioned in tier-1, the ETC OBU devices and antennas can communicate with each other by wireless communications; therefore, the real-time traffic flow information can be sent to the lights. Meanwhile, the traffic control results will be sent to the ETC OBUs, and then, drivers can know the traffic light phases in time. The purpose of the storage is to save the received traffic flow data. The traffic lights are the displays that show the control results.

c) Tier-3: Tier-3 takes responsibility for data processing, which can be divided into three sections.

The first section is data extraction. As vehicles periodically send the traffic flow information to the antenna before passing through the intersection, it may cause some problems. For example, the same data may be received several times or obsolete, and the latest data may exist in storage. Therefore, it is necessary to extract the useful data from the received data.

The second section is traffic light control. The control center periodically acquires the latest traffic flow data from the storage and calculates the optimal light-changing policy for this period. The optimal light-changing policy will shift as new traffic flow information is acquired; therefore, this approach is a dynamic control process. In other words, the control center will control the green or red light's phase duration time according to the real-time fluctuation of traffic flow. The optimal light policy would be calculated by a control algorithm that can realize the lowest waiting time. Therefore, the traffic light control algorithm is the key component to realizing the lowest average waiting time. Because our system is an open system, third-party traffic light control algorithms can be used in this section, such as dynamic-programming-based fuzzy control in [37] and the decision-making-related algorithm in [38]; all these algorithms are acceptable or need more improvements for our model. Working new control algorithms according to the intersection’s real road situation is also available. In Section III, we will provide a branch-and-bound (BB)-based control algorithm.

The third section provides an open interface for third-party applications. Vehicle information, traffic flow data, or CO₂ emissions data can be shared by third-party applications. For example, vehicle makers or magazines may use these data to analyze which vehicle types are used most and which brand is the most popular. Moreover, the real-time road traffic data can be drawn into a dynamic traffic flow map. Based on this map, the city’s traffic monitor center can easily manage the city’s traffic. In addition, the CO₂ reductions can be used to evaluate the quality of the city’s environment.

2) Traffic Flow Detection Process: As aforementioned, we suppose that all the vehicles have installed the ETC devices. In the following paragraphs, we will introduce the traffic flow detection process by the wireless communication between the ETC vehicles and traffic lights. Fig. 2 shows the whole traffic flow detection process.

To easily understand this process, we use three stages to describe it.

First, when vehicles approach an intersection, they send the road traffic flow data to the antenna (see Fig. 2). If the vehicle is in the radio coverage area of the antenna, the ETC OBU devices can directly communicate with the antenna. However, if the vehicle is not in this area, it has to send the data to the front vehicles, which can relay the data to the antenna by multihop communication. Obviously, each vehicle performs the following two functions: 1) to relay other vehicles’ states data and 2) to send its own data. The communication between the OBUs and the antennas is similar to the ETC toll-charging process: The OBUs periodically broadcast the vehicles’ motion states data, and when vehicles approach the radio coverage area, the antennas receive these states data; thus, the road traffic flow data can be acquired. After data extraction, the traffic control center in tier-3 periodically picks up the traffic flow information data from the storage in tier-2 (see Fig. 2). In this process, the control center acquires the latest road traffic flow before vehicles arrive at the stop line; in other words, the control center can “predict” the arriving vehicles’ queues in real time.
Second, after the traffic control center calculates the optimal light duration time for the next light cycle, the antenna sends the control results to the vehicles. After the vehicles have received the information from the lights, the OBUs will calculate a recommended speed for drivers. Then, the drivers can change to the recommended speed or keep current speeds to pass through the intersection. The purpose of calculating the recommended speed mainly consists of the following two aspects: 1) It is used to inform the drivers how they can pass through the intersection with less waiting time and with less number of stops, and 2) it is aimed to avoid entering the dilemma zone by changing the speed for the drivers’ safety. We will illustrate the details of speed calculation in Section III-B.

Third, after the vehicles have passed through the intersection, they also need to send motion states data to the antenna (see Fig. 2) so that the data can be shared by the following intersections. This approach provides useful traffic flow data for the whole city’s traffic control. In short, this traffic flow detection process allows ETC vehicles that want to pass the intersection to send their “requests” to the light, and then, the light adaptively changes its cycle and duration time according to the requests.

In fact, based on the ETC vehicles, the traffic information can be obtained in real time. However, when vehicles send traffic information to the traffic lights, the radio interferences among vehicles would appear. Although in tier-3, the data extraction section can alleviate this problem in a certain degree, this problem cannot ease to zero. Therefore, how we can get a more correct traffic information through the ETC vehicles and how we can mine the useful information from a mass of received traffic flow data still needs to be done in our future work. This problem is the issue that we will mention in Section II-C1d. In this paper, we suppose that the received traffic flow information is correct and with no interference.

### B. CO₂ Emission Estimation Model

A vehicle’s CO₂ emission is greatly affected by the road and traffic flow conditions. On one hand, different road conditions have different fuel consumption rates and CO₂ emission rates. Urban roads usually have higher emission rates than rural roads, and ramp roads need more fuel than smooth roads [6]. On the other hand, when the road conditions are fixed, different traffic conditions would also lead to different CO₂ emissions [22]. Congestion would lead to more emissions; for example, about 11% of all fuel consumed by automobiles is wasted during congestion [22].

Therefore, to estimate the CO₂ emissions, a suitable estimation model should be selected to meet the aforementioned factors. Traditionally, a simple estimating method is based on the assumption that each vehicle type has a given coefficient of exhaust per unit running distance, and this coefficient is multiplied by vehicle-kilometer for each vehicle type to estimate total emissions [23]. This method can be applied for rough estimation, but it is very simple and neglects too many factors for rigorous calculation. In addition, another estimation model is based on a statistical model [24], [25], which is used for instantaneous emissions. However, it defines engine and positive tractive power variables. When estimating CO₂ emissions, these two variables should be included; thus, the computational effort can be high.

Considering the realistic characteristics of urban roads, Oguchi et al. [18] designed an emission model for estimating vehicles’ CO₂ emissions. This model is derived from experiments by testing real-time traffic conditions on urban roads in Tokyo, Japan. The model is presented by the following two formulas:

\[
E = K_C (0.3T + 0.028D + 0.056A_{ee})
\]

(1)

\[
A_{ee} = \sum_{k=1}^{K} \sigma_k (\nu_k^2 - \nu_{k-1}^2)
\]

(2)

where the parameters stand for the following notation:

- \(E\): CO₂ emissions [g];
- \(K_C\): coefficient between gasoline consume and CO₂ emissions;
- \(D\): travel distance (in meters);
- \(T\): total travel time for the distance \(D\) (in seconds);
- \(A_{ee}\): acceleration energy equivalent (in square meters per square seconds);
- \(\nu_k\): speed at time \(k\) (in meters per second);
- \(\sigma_k\): \(\sigma_k = 1\) if \(\nu_k > \nu_{k-1}\); otherwise, \(\sigma_k = 0\).

This model is used to calculate a vehicles’ CO₂ emissions. The model of (1) has the following three variables: 1) the vehicle’s travel time \(T\); 2) the travel distance \(D\); and 3) the \(A_{ee}\) value. The travel times of each vehicle are evaluated to sum up the free-flow travel time and the delay time. If the study section is fixed, the travel distance must be constant. The \(A_{ee}\) value can be calculated by the vehicle travel mode in acceleration and deceleration, as shown in (2). Equation (1) indicates that, when the \(D\) is fixed, a vehicle’s CO₂ emissions mainly rest with the \(T\) and the speed \(\nu\). Therefore, when the road conditions are fixed, a vehicle’s CO₂ emission is limited to \(T\) and \(\nu\). Even for the same vehicle and under the same road condition, \(T\) and \(\nu\) will be different based on the different realistic traffic conditions. Because the traffic condition will affect the vehicle’s speed, acceleration, and deceleration, the travel time will also change. Thus, the total number of vehicles will be different with different traffic conditions. However, this condition does not mean that the model is not suitable for calculating the current CO₂ emissions, because this model is used for calculating one vehicle’s emissions and then the total number of vehicles’ emissions. For example, this model is cited in [17] and [29] to calculate the CO₂ emissions when traffic conditions do not change and also in [26]–[28] to calculate the CO₂ emissions with traffic condition changes. Thus, it is sufficient to calculate emissions when traffic conditions changed.

### C. Related Issues With the Three-Tier Model

Currently, ETC OBUs are mainly used for highway automatic toll charging. As far as we know, the are the first to use
ETC OBUbs to detect the traffic flow. Therefore, using the ETC devices to control traffic lights still has several challenges. In the following discussion, we will examine the related issues and address feasible reasons and solutions.

a) Antenna’s maximum radio distance: According to the dedicated short-range communications (DSRC) standard, for public safety intersections, the transmission powers for downlinks and uplinks are limited to less than 40 dBm, and the maximum distance is 1000 m [39]. According to [40], when the transmission power is 17 dBm (50 mW), about 80% of the messages can be received 200 m away, and when the transmission power is 10 dBm (10 mW), about 100% of the messages can be received 100 m away. For traffic control, the safety of drivers and pedestrians must be the first priority; thus, we must ensure that messages can be received 100%. Therefore, we set the maximum radio distance equal to 100 m.

b) Drivers’ reaction time and traffic lights’ switch frequency: If the traffic light duration time is very short or switches at a very high frequency, drivers’ reaction time may not catch up with the frequency changing. Therefore, it would be very dangerous for the drivers. Besides, no one likes to wait a very long time for a red light. Considering the drivers’ reaction and toleration time, we introduce the minimum green light time (min_green) and the maximum red light time (max_red) into our scheme, which means that, regardless of whether the current traffic is heavy or light, the light’s duration time must be longer than min_green and shorter than max_red (refer to Sections III-A1 and IV-B).

c) Additional CO₂ emissions from the ETC system: As we know, any electronic equipment will release CO₂ when they are in the active mode. In this paper, we employ the ETC devices to control the traffic flow to achieve CO₂ reductions, and the ETC devices will also bring inevitable additional CO₂ emissions. However, if the ETC devices’ emission amounts are much less than the reduction amounts for vehicles’ nonstop-passing intersections or highway toll gates, we can ignore the additional CO₂ emissions, which are brought about by the ETC devices. It is easy to find the evidence to support this point in [41].

d) Radio interference among vehicles: When vehicles send the traffic flow information to the antennas, it could lead to radio interference among several vehicles. The tier-3 data extraction function can ease this problem to some extent but cannot solve the problem at the root. In our future work, we will find some data dissemination methods in vehicular ad hoc networks to resolve this problem.

e) Number of ETC Vehicles on the road: Recently, ETC charging has become popular worldwide; for example, in Japan, until June 2011, the number of ETC-installed vehicles reached 6 million, and the utilization ratio is up to 85% [30]. However, not all vehicles installed the ETC devices after all. How we can deal with the problem of detecting traffic flow information from non-ETC vehicles should be considered. Currently, some researchers employ smart cameras to detect vehicles based on the background subtraction from the detected vehicle images [43]. Meanwhile, some other researchers use visible light communication between a light-emitting diode (LED) traffic light and a high-speed camera to get the traffic flow information [44]. In our future work, we will consider using cameras to obtain the traffic flow information for non-ETC vehicles.

III. CONTROL ALGORITHM FOR SMOOTHING TRAVEL

To realize the goal of reducing vehicles’ CO₂ emissions, we plan to smooth vehicles’ travels by the following two ways: 1) to control the traffic lights to let vehicles pass the intersections with less waiting time, which aims at reducing the idling period CO₂ emissions; and 2) to recommend vehicles a suitable speed before entering the intersection, which is used to reduce vehicles’ running period CO₂ emissions.

A. Traffic Light Control Algorithm

1) Problem Specification: By the wireless communication between traffic lights and ETC vehicles, the real-time road conditions can be detected. The goal of traffic light control is to reduce the detected vehicles’ waiting time and let more vehicles pass through the intersection in a minimum time. The more that the waiting time is reduced, the more that vehicles will arrive and pass through the intersection in less waiting time.

To evacuate the detected vehicles in the waiting queues, we need to allocate the passing order for vehicles. The problem turns out to be an order-decision problem. Here, we adopt a BB [47] method to deal with the order-decision problem.

In [47], the authors proposed a BB traffic light control approach to control an isolated intersection. However, it was unfit for our problems: it was mainly concerned with evacuating vehicles that were already detected and did not consider drivers’ safety problems. As aforementioned, we introduce min_green and max_red for drivers’ reaction and toleration times, respectively. Therefore, we propose an improved BB algorithm called the safety-based branch-and-bound (SBB) algorithm. For simplicity, we use the same parameter notations as in [47] to present the improved BB algorithm, as shown in Table 1.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Definition</th>
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<tbody>
<tr>
<td>r</td>
<td>the index of road $r \in {1,2}$;</td>
</tr>
<tr>
<td>$n_r$</td>
<td>the number of vehicles in road $r$;</td>
</tr>
<tr>
<td>$V^g_r$</td>
<td>the vehicle in road $r$, $1 \leq q \leq n_r$;</td>
</tr>
<tr>
<td>$T^g_r$</td>
<td>time that vehicle $V^g_r$ needs to cross the intersection;</td>
</tr>
<tr>
<td>$C^r$</td>
<td>total red light time plus the wasted time for acceleration when the traffic light changes from road $r'$ to $r$, $r' \neq r$;</td>
</tr>
<tr>
<td>$q_r$</td>
<td>number of vehicles that have passed the intersection in road $r$;</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>indicates if there is a changing time of the intersection;</td>
</tr>
<tr>
<td>$W^g_r$</td>
<td>waiting time for the $V^g_r$ vehicle in road $r$</td>
</tr>
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</table>

2) SBB Approach: The total evacuation time consists of the following two parts: 1) the time for all detected vehicles to pass through the intersection and 2) the time that is wasted on changing the green lights between two roads [47]. Searching the lower total evacuation time is called the searching root’s lower
bound $LB_{\text{root}}$. Therefore, the evacuation time can be presented in the following equation:

$$
LB_{\text{root}} = \sum_{r=1}^{2} \sum_{q=1}^{n_r} P_r^q + C_2^1.
$$

(3)

Because the traffic lights need at least one change from one road to another, which are linked in the same intersection, the search process can be subdivided into a dichotomous searching: one branch allows the next vehicle in the current active road to pass the intersection, and the other branch is used to change the green lights to the second road, set the second road as active, and then allow the vehicle in the second road to pass [47]. We call this approach search each node’s lower bound $LB_{\text{node}}$, which is shown in the following equation:

$$
LB_{\text{node}} = T(V^q_{(q_1,q_2,r)}) + \sum_{q=q_1+1}^{n_1} P_1^q + \sum_{q=q_2+1}^{n_2} P_2^q + \lambda
$$

(4)

where $T(V^q_{(q_1,q_2,r)})$ stands for the time spent for the last vehicle in road $r$ after $q_1$ vehicles in road 1 (R1) and $q_2$ vehicles in road 2 (R2) have passed the intersection. In addition, there was a change of the green lights after the pass of $V_r^q$, and in the equation, $\lambda$ is defined as

$$
\lambda = \begin{cases} 
C_r'^r, & \text{if } n_r' - q_r' > 0 \\
0, & \text{if } n_r' - q_r' = 0.
\end{cases}
$$

(5)

The calculation of the parameter $T(V^q_{(q_1,q_2,r)})$ is

$$
T(V^q_{(q_1,q_2,r)}) = T(V^{q'}_{(q_1',q_2',r')}) + C_r'^r + P_r^q + W_r^q.
$$

(7)

In (7), $C_r'^r = 0$ for $r' = r$, and the waiting time of the $q$th vehicle in road $r$ can be obtained by

$$
W_r^q = \max \begin{cases} 
0, A_r^q - T(V^{q'}_{(q_1',q_2',r')}) & \text{if } r' = r \\
0, A_r^q - T(V^{q'}_{(q_1',q_2',r')}) - C_r'^r & \text{if } r' \neq r.
\end{cases}
$$

(8)

Equations (3)-(9) have been presented and studied in [47], and to make them more readable, we list again these equations in this paper.

Suppose that there is an intersection that consists of two roads: R1 and R2. Assuming that the first vehicle that is detected belonged to R1, the green lights are already on for R1 at 0 s. The first vehicle in R1 $V_1^1$, which has arrived at the stop line and is ready to pass, is denoted as $A_1^1 = 0$ s, and the starting time of the sequence is denoted as $t_0 = 0$. For the optimal sequence, the first order to pass must be $V_1^1$ [47]. From here, we start our search sequence.

As an improvement of the algorithm in [47], we use the depth-first search as the search method, and the search algorithm is shown in Algorithms 1 and 2. For safety, we add $\max_{\text{red}}$ and $\min_{\text{green}}$ into comparisons with the total evacuation time, and the improved root’s lower bound search algorithm is listed in Algorithm 1. The node’s lower bound search algorithm is the same as in [47], and we provide it again for this paper’s integrality, as listed in Algorithm 2.

Algorithm 1: SBB algorithm—LB search.

1. time ← $LB$(root)
2. Branching(root)
3. for $i = 2$ to $(n_1 + n_2 - 1)$ do
4. Branching($\min(LB(\text{left node}), LB(\text{right node}))$)
5. $i ← i + 1$
6. $time ← \min(LB(\text{left node}), LB(\text{right node}))$
7. end for
8. for $j ← 1$ to activenode do
9. Branching($\text{list}[j]$)
10. if $LB(\text{node}) < time$ then
11. $prune$ this branch
12. else if (reach a leaf node)
13. $time ← \min(LB(\text{left node}), LB(\text{right node}))$
14. if $\max_{\text{red}} ≥ time > \min_{\text{green}}$ then
15. $time ← time$
16. else if ($time ≤ \min_{\text{green}}$
17. $time ← \min_{\text{green}}$
18. else if ($time ≥ \max_{\text{red}}$
19. $time ← \max_{\text{red}}$
20. end if
21. end if
22. RETURN($time$)
23. end for

Algorithm 2: SBB algorithm—Order search [47].

1. Branching(node)
2. $LB$(node)
3. $\triangleright$ use (3) and (4)
4. CHANGESEQUENCE(i)
5. $\triangleright$ change the node sequence at $i$
6. $LB$(newnode)
7. if $i < n_1 + n_2 - 1$ then
8. $\text{list}[$node$] ← \max(LB(\text{left node}), LB(\text{right node}))$
9. $\triangleright$ add active nodes to list
10. activenode $←$ activenode + 1
11. else if ($\max(LB(\text{left node}), LB(\text{right node})) ≤ time$
12. $\text{list}[$node$] ← \max(LB(\text{left node}), LB(\text{right node}))$
13. activenode $←$ activenode + 1
14. end if

Because there are two directions, if the green light is on for one road and there are still vehicles on another road, we need at least one change of the lights to ensure that all the vehicles in the two roads can pass the intersection. After the branching of each node, we compare the $LB$ of two branches, choose the smaller $LB$, and keep on subdividing the problem based on this smaller $LB$ node. After a number of iterations, we can find a
sequence order. This order is called the current best order, and the LB value of that node is the current best value.

However, there still are some nodes that have not completed the whole branch search. We compare the current best value to these nodes’ LB value. If the LB values of these nodes are bigger than the current best value, we no longer need to search these nodes, because there is no hope of finding a better order than the current best order. If the LB values of these nodes are smaller than the current best value, we keep on the iteration of those nodes. During the comparison, iteration, and canceling, if we can find a new complete order that has a better value than our current best value, we call this order the new current best order, and its value is called the new current best value. This searching process has been presented in [47].

Last, we compare the current best value with max_red and min_green to ensure drivers’ reaction and toleration times. Then, we renew the current best value, as shown in Algorithm 1. This way, we can find the optimal solution of our problem.

3) Computation Complexity Analysis:
   a) Traditional depth-first-based BB complexity analysis [48]: Let $b$ denote the branching factor of each node, $n$ the depth of the search tree, and $p_0$ the probability that a node has the same value as its father node. According to [48], the conclusion about the complexity of depth-first-based BB is as described follows.

   *Theorem [48]:* The expected number of nodes expanded by the depth-first search for finding an optimal goal node of a random tree $T(b, n, 0)$ as $d \to \infty$ is given as follows:

1. $O(\beta^n)$ when $b p_0 < 1$, where $1 < \beta < b$ is a constant;
2. $O(n^3)$ when $b p_0 = 1$;
3. $O(n^2)$ when $b p_0 > 1$.

   b) Our improved algorithm: We have the following cases.

   - The worst case for the searching process is that it has to expand all the nodes in the searching space, and the complexity of the worst case is exponential [46], set as $O(2^n)$.

   When the lower bound function is exact, this is the best case. Therefore, the complexity can be linear from the root node to the goal node, which is set as $O(n)$.

   - In our search process, if we set green lights to one road, we need to have at least one change for the vehicles in the other road so that all the vehicles in two-direction roads can pass through the intersection. Thus, we only have two branches. We compare the lower bound of the two branches and keep subdividing the problem from the node with the smaller lower bound. To find the sequence [see (4)] from the root node to the goal node (this approach is the vehicle passing order searching process), it needs $n$-time iterations (see Algorithm 2). In the sequence-finding process, the evacuation time [see (3)] is also calculated and compared, and the compared process needs $n$-time iterations (see Algorithm 1). Thus, the process for getting the evacuation time needs $n \times n$-time iterations. Hence, the complexity is $O(n^2)$.

In fact, the number of vehicles (nodes) is limited in the actual traffic control process. Therefore, the best and worst extreme two cases rarely occurred. Therefore, the complexity of the proposed algorithm is $O(n^2)$. In addition, this is the third case that is listed in the aforementioned traditional complexity conclusion.

   c) Simple test: Taking an isolated intersection (four-arm two-lane type) as an example, we will evaluate and record the computation time during the process for finding the minimum average waiting time. Suppose that vehicles need 2 s to pass the intersection and 3 s for the green light from the current road turning to the other road, i.e., $P_g = 2$ s, $C_r = 3$ s.

The test is run on a Windows XP system with a mobile AMD Sempron 1.6-GHz single processor and 1.3-GB random access memory (RAM) and is based on the MATLAB R2009a software. We run 1000 traffic light cycles for each traffic flow rate and suppose that the traffic flow in the two crossed roads is equal. The relationship between the 1000 cycles’ computing time and the traffic flow rate is listed in Table II.

As listed in Table II, we can conclude that the computing time to obtain the optimal passing order increases as the traffic flow rate grows. Taking the traffic flow rate of 1 000 000 veh/h as an example, the computation time for 1000 traffic light cycles is 224.695 s, and it is about 0.224695 s for one traffic light cycle. In other words, when the traffic flow is equal to 1 000 000 veh/h, we only need less than 0.3 s to get the best vehicles passing through order. In fact, realistic traffic flows are usually less than 1 000 000 veh/h. Hence, under this condition, our scheme can control the traffic light in realistic situations.

### B. Calculation of the Recommended Speed

A typical driving trip consists of idling, accelerating, cruising, and decelerating [6]. Usually, the decelerating, idling, and accelerating periods have higher emission rates than the cruising period [6], [42]. To reduce vehicles’ CO$_2$ emissions, the best way is to have the cruising period go as long as possible. Temporary stop-and-go (from cruising to idling by deceleration and then from idling to cruising by acceleration) should be reduced as much as possible. When vehicles prepare to pass through intersections, the stop-and-go driving style commonly occurs. For example, in rush hours, vehicles have to pass intersections by going slowly and temporarily stopping. Therefore, if we can inform the drivers how they can pass the intersection before they arrive at the intersection, the number of temporary stop-and-go’s can be reduced.

More importantly, if the drivers cannot get any information about the traffic light states, they may drive into a dilemma zone (see Fig. 3) in either time or space before arriving at the
intersections [45]. Crashes could happen with the rear vehicles or with side-road vehicles. Therefore, if we inform drivers to change their speed in advance, crashes will be avoided. Hence, a recommended speed (denoted as \( S_{\text{Rec}} \)) is necessary not only to reduce the number of stop times but for drivers’ safety as well.

In [20], a recommended speed calculation method is given that could be used for reducing vehicles’ number of stop times. However, it was mainly concerned with reducing the number of stop times, which did not consider that the unchanged current speed (cruising period) would save more fuel than the change in speed. In addition, it did not consider the dilemma-zone problems. Based on these conditions, we modify the calculation method and give a more reasonable approach.

It is easy to get the distance \( d \) between vehicles and traffic lights by the GPS devices. As aforementioned, the traffic light will send the results packets to the vehicles. After receiving the packets, the following information will be obtained and then used to calculate the recommended speed:

1) distance \( d \) (see Fig. 3);
2) current traffic light cycle \( C_{\text{cycle}} \) (see Fig. 3), current light phase, and duration time of the three phases in the current cycle \( T_g, T_r, \) and \( T_y \), where \( C_{\text{cycle}} = T_g + T_r + T_y \),
3) remaining time of the current light phase \( L_g, L_r, \) and \( L_y \).

In our proposal, the duration time of green, yellow, and red lights can be different in different traffic cycles, because the traffic light dynamically changes the lights’ duration time according to the real-time traffic flow information. Based on the aforementioned information, the OBU devices installed in the vehicles can calculate the recommended speed for drivers. We set the maximum allowed speed for drivers, which is denoted as \( S_{\text{max}} \), and the minimum speed is denoted as \( S_{\text{min}} \) (in the driving states, it is unequal to zero).

To better understand this recommended speed calculation, we will explain the meanings of each symbol before our calculation as follows.

\( t_0 = d/S_{\text{current}} \): How much time would be spent on passing the distance \( d \) when driving at the current speed \( S_{\text{current}} \)?

\( t_1 = d/S_{\text{max}} \): How much time would be spent on passing the distance \( d \) when driving at the maximum speed \( S_{\text{max}} \)?

Case 1: Current Light Phase Is Green: We have the following three cases.

1) If the remaining green light time \( L_g \) is long enough for the vehicle to go through \( d \) at the speed of \( S_{\text{current}} \), then the system should inform the drivers to keep the current speed. Thus, the recommended speed \( S_{\text{Rec}} \) is the current speed \( S_{\text{current}} \), which can be written as follows:
   \[
   t_0 \leq L_g < t_0, \quad S_{\text{Rec}} = S_{\text{current}}. \tag{10}
   \]

2) If the remaining green light time \( L_g \) is not long enough for the vehicle to go through \( d \) at the speed of \( S_{\text{current}} \) but \( L_g \) is long enough for the vehicle to go through at \( S_{\text{max}} \), then the system should inform the drivers to accelerate to the \( S_{\text{max}} \). That is, vehicles can pass through the intersection in the current traffic light cycle by accelerating to \( S_{\text{max}} \), in which there is no need to wait for the next traffic light cycle. Therefore, the recommended speed is equal to \( S_{\text{max}} \), i.e.,
   \[
   t_0 < L_g < t_0, \quad S_{\text{Rec}} = S_{\text{max}}. \tag{11}
   \]

3) If the remaining green light time \( L_g \) is very short such that it is impossible for vehicles to pass through \( d \) even at the maximum speed \( S_{\text{max}} \), then vehicles have to wait for the next traffic cycle or the next several cycles when the waiting queue is very long (after the vehicles that are located in the front have passed through). In this situation, vehicles have to decelerate to wait for at least one red phase time plus one yellow phase time. The equation form of \( S_{\text{Rec}} \) can be written as follows:
   \[
   t_0 > L_g, \quad S_{\text{Rec}} = \min \left( \max \left( \frac{d}{t_y}, S_{\text{min}} \right), S_{\text{max}} \right). \tag{12}
   \]

In the equation, \( t_y \) stands for
   \[
   t_y = (N_g - 1)C_{\text{cycle}} + L_g + T_r + T_y + M - D
   \]
where \( N_g = (t_0 - L_g)/C_{\text{cycle}} \), and it stands for the number of traffic light cycles needed to wait. We have also used the following notations.

\( D \) transmission delay from the lights to the vehicles;
\( M \) duration time for vehicles to change the speed from \( S_{\text{current}} \) to \( S_{\text{Rec}} \).

Case 2: Current Light Phase Is Red: We have the following three cases.

1) If the traffic light will be changed to green before vehicles arrive at the stop line at the speed \( S_{\text{current}} \), the system should inform the drivers to keep the current speed \( S_{\text{current}} \), i.e.,
   \[
   L_r < t_0 < L_r + T_y, \quad S_{\text{Rec}} = S_{\text{current}}. \tag{13}
   \]
2) If the vehicles cannot arrive at the stop line within the time of the remaining red light $L_r$ plus the green time $T_g$ at the speed of $S_{\text{current}}$ but the vehicles drive at the speed of $S_{\text{max}}$, they can catch up within the green time $T_g$, and then, the system should inform the drivers to accelerate to $S_{\text{max}}$, i.e.,

$$S_{\text{Rec}} = S_{\text{max}}.$$  \hspace{1cm} (14)

3) If, even at the $S_{\text{max}}$ speed, vehicles still cannot arrive at the stop line before the light changes from green to yellow, vehicles have to wait for at least one more traffic light cycle. In this case, the vehicles have to decelerate. $S_{\text{Rec}}$ is calculated by the following equation:

If $t_1 > T_g + L_r + C_{\text{cycle}}$, then

$$S_{\text{Rec}} = \min (\max ((d/t_y), S_{\text{min}}), S_{\text{max}}).$$  \hspace{1cm} (15)

In the equation, $t_y = (N_r C_{\text{cycle}} + L_r + M - D)$, and $N_r = (t_1 - L_r - T_g)/C_{\text{cycle}}$.

Case 3: Current Light Phase Is Yellow: As aforementioned in Section II-C, vehicles can communicate with higher reliability with the traffic light within 100 m. Vehicles that are not in the 100-m area can communicate with the front vehicles by multihop communication. Thus, drivers will get the information about the yellow light duration time and remaining time at a distance of 100 m away. In addition, OBUs give a recommended speed for drivers, and drivers can change their speed in advance. Therefore, in our scheme, the dilemma-zone problem can be avoided.

Compared with the red light period situation, vehicles need to wait for one more yellow light time. The speed calculation is similar to the situation when the current phase is a red light (see Section III-B2). To save space, we give only the calculation formulas as follows.

1) If $L_y + T_r < t_0 \leq L_y + T_r + T_y$, then

$$S_{\text{Rec}} = S_{\text{current}}.$$  \hspace{1cm} (16)

2) If $L_y + T_r + T_y < t_1 \leq L_y + C_{\text{cycle}}$, then

$$S_{\text{Rec}} = S_{\text{max}}.$$  \hspace{1cm} (17)

3) If $L_y + C_{\text{cycle}} \leq t_1$, then

$$S_{\text{Rec}} = \min (\max ((d/t_y), S_{\text{min}}), S_{\text{max}}).$$  \hspace{1cm} (18)

In the equation, $t_y$ stands for $t_y = N_y C_{\text{cycle}} + T_r + L_y + M - D$, and $N_y = (t_1 - T_r - L_y - T_y)/C_{\text{cycle}}$.

Equations (10), (13), and (16) are recommended for drivers to pass the intersection without any speed changes. Equations (11), (14), and (17) are suggested for drivers to accelerate to $S_{\text{max}}$ to pass the intersection in the current traffic light cycle to avoid stops. Equations (12), (15), and (18) tell the drivers that it is impossible to pass the intersection in the current traffic cycle and it is better to change the current speed to wait for the next traffic light cycles to pass.
6:00 P.M., the vehicles’ arrival rate in R4 is 930 veh/lane/h, and for each lane in R4, the arrival rate is the same. Because we set the traffic flow relationship between R1, R2, and R4 as 1 : 2 : 3, the arrival rate is 310 veh/lane/h for R1 and 620 veh/lane/h for R2.

B. Simulation Setup

For simplicity, the following assumptions are considered.
1) If vehicles have to stop, we suppose that vehicles stop only one time within one traffic light cycle.
2) Vehicles can choose the following two ways from S to D or from D to S: 1) by R1 or 2) by R2.
3) Antennas receive the road traffic flow information data without packets dropping and transmission delay ($D = 0$).
4) The duration time for a vehicle to change its speed from $S_{\text{current}}$ to $S_{\text{Rec}}$ is 3 s ($M = 3$).
5) Vehicles’ arrival is subject to Poisson distribution.
6) Setting the $\max _{\text{red}}$ as 90 s and $\min _{\text{green}}$ as 15 s, the traffic light cycle dynamically changes according to the real-time traffic flow. Its value is confined to the scope of {30, 180} s. The allowed $S_{\text{max}}$ is 60 km/h, and $S_{\text{min}}$ is 10 km/h (in driving states).

C. Simulation Comparison Object: Adaptive Fuzzy Traffic Light Control

We will compare the proposed algorithm with the adaptive fuzzy control method. Usually, the adaptive fuzzy control method is mainly concerned with adjusting the extension time of the green light phase time according to the detected traffic flow information [36]. We have the following two key parts: 1) to design a fuzzy logic controller and 2) to detect the traffic flow conditions.

There are three stages when designing a fuzzy logic controller. The first stage is the selection of performance variables, i.e., inputs and outputs. The second stage is the determination of the fuzzy rules set, which is presented by linguistic labels. This stage uses the If–Then statement to indicate the relationship between the inputs and the outputs. The third stage is the defuzzification process for converting the outputs’ value to a crisp value [31].

The traffic flow information detection uses special detection tools that are placed at a certain distance from the intersection to detect the traffic flow. The detection tools can be sensors [31], advanced video image processing [33], or inductive loops [34]. For comparison, we suppose that the detection tools are deployed in a certain distance from the intersection and the maximum number of vehicles that can be detected is 30 vehicles [31], [35]. We adopt a fuzzy control model that is designed in [31], [32], and [36]. We apply the input and output variables, which are widely used by some researchers in [31], [32], [35], and [36]. Set the following three variables as the inputs:

1) Arrival: Number of vehicles that arrive at the intersection during the green light phase period. The membership functions is {Zero, Small, Medium, Many}.
2) Queue: Number of vehicles during the red light phase period. The membership function is {Zero, Small, Medium, Many}.
3) Volume: Total number of vehicles that enter an intersection from all directions. The membership function is {Small, Medium, Large}.

Set one variable as the output, i.e., Extension (the extension time of the green light phase). The membership function is {Zero, Short, Medium, Long}.

The control rules are divided into three groups of small, medium, and large according to the volume. There are seven rules for the small group, nine rules for the medium group, and seven rules for the large group. The total number of the control rules is 23 [36]. The rule is set similar to the following format.

When $\text{Volume} = \text{small}$, if $\text{Arrival} = \text{small}$ and $\text{Queue} = \text{zero}$, then $\text{Extension} = \text{short}$.

D. Simulation Results

The simulation results consist of the following six items.

1) The average travel time from S to D is shown in Fig. 6.
2) The average waiting time from S to D is shown in Fig. 7.
Figs. 6 and 7 indicate that, compared with the fuzzy control method, the proposed control algorithm has better performance in terms of the expected average travel time and the waiting time, particularly during the daytime period from about 7:00 A.M. to 8:00 P.M. This is because the fuzzy control method mainly depends on extending the green light time to achieve a lower waiting time. In the proposed scheme, we are concerned with not only minimizing the waiting time but with giving drivers speed suggestions that can help drivers pass the intersection by nonstop or fewer stop times as well. In addition, when passing through several intersections, the adjacent intersections will share the traffic condition information, which will help vehicles pass through the next intersections in a “green-wave” trip.

3) The nonstop passing rate from S to D is shown in Figs. 8–10. Fig. 8 shows the nonstop rate for passing several intersections with no stops. During off-rush hours, the proposed scheme has a higher passing rate than the fuzzy control method, but during rush hours, the improvements are not very clear. In off-rush hours, by the proposed control, vehicles can communicate with the light before vehicles arrive at the stop line; therefore, the traffic light will turn green to these vehicles in time. However, for the fuzzy control method, the control center cannot change the traffic light in real time. To more clearly show the improvement in the nonstop passing rate, we use I3 and I4.

In Fig. 9, when the traffic flow is light, taking 11:00 P.M. as an example, the nonstop passing rate can be reached more than 46% compared with the adaptive fuzzy control method’s approximately 40%. That is, when the traffic flow is not heavy, vehicles have a higher chance of passing through the intersection without stops. The same reasons can be explained for Fig. 10.

The difference between I3 and I4 is the traffic flow. For I3, it is the joint for R1 and R5, whereas for I4, it is the joint for R2 and R4. The traffic flow in R4 is much higher than in R5 (refer to Fig. 5). Because I3 has lower traffic flow, even during the rush hours (from 7:00 A.M. to 8:00 P.M.), the nonstop passing rate can reach 20%. For I4, due to the heavy traffic flow, the nonstop passing rate is almost equal to zero during rush hours.

4) The average stop times from S to D are shown in Fig. 11. Based on Fig. 11, when the traffic flow is light, e.g., from 00:00 A.M. to 2:00 A.M. and 11:00 P.M.,
the average stop times are almost close to zero (R2) in the proposed scheme. During rush hours, i.e., from 8:00 A.M. to 6:00 P.M., the stop times are much reduced (about ten times) compared with the fuzzy control method (about 15 times).

5) The average CO$_2$ emissions from S to D are shown in Fig. 12.

6) The CO$_2$ reductions are shown in Figs. 13 and 14.

Through (1), we can calculate the average CO$_2$ emissions for each vehicle from S to D in R1 and R2 with two different control schemes. Based on Figs. 12–14, it is easy to get an indication that, during rush hours (from 5:00 A.M. to 9:00 A.M. and from 6:00 P.M. to 8:00 P.M.), the proposed traffic scheme can reduce the CO$_2$ emissions by about 60% compared with the adaptive fuzzy control method in R1 and more than 50% in R2.

In the adaptive fuzzy control method, vehicles cannot get any information about the current traffic light phases. Thus, when vehicles approach intersections, they have to wait for traffic lights to change. In contrast, in the proposed scheme, the control center can obtain the traffic flow information from the ETC-installed vehicles in real time. Therefore, the traffic lights’ cycles can dynamically be changed according to the real-time traffic flow situations. In addition, based on the received information from traffic lights, the ETC devices can give drivers a recommended speed to avoid unnecessary stops; thus, vehicles can pass through the intersection with less waiting time and fewer short-time stops. Therefore, the shorter waiting time and fewer stop times bring a reduction of CO$_2$ emissions.

V. CONCLUSION

In this paper, a real-time traffic light control scheme has been proposed. This control system was constructed from a three-tier open model. Tier-1 and tier-2 were mainly concerned with road traffic flow detection. A recommended speed calculation method was proposed in tier-1, which was used to avoid dilemma-zone conflicts and unnecessary short-time stops. With ETC vehicles, the traffic control center in tier-3 could get accurate real-time traffic flow information. Considering drivers’ reactions and tolerance times, an improved BB-based traffic light control algorithm was designed in tier-3. Less waiting time and fewer short-time stops could be achieved by the proposed model. Thus, less CO$_2$ emissions could also be realized. Compared with adaptive fuzzy control method, the proposed scheme performed better in terms of reducing...
the vehicles’ average waiting times, number of stops, and CO₂ emissions, whereas the nonstop passing rate was also improved.

In future works, the influence brought by the different ETC penetrations and the communication fail should also be considered.

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