ETC ASSISTED TRAFFIC LIGHT CONTROL SCHEME FOR REDUCING VEHICLES' CO$_2$ EMISSIONS

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ABSTRACT

This paper presents a vehicle's CO$_2$ emission reduction scheme by an ETC-assisted real-time traffic light control scheme in vehicular networks. Using Electronic Toll Collection (ETC) devices, real-time road conditions can be obtained by wireless communication between the ETC devices and the traffic lights. A decision tree classification algorithm is used to assign the changing policy for the traffic lights, and then the optimal average waiting time can be calculated. Less waiting time will result in less fuel consumption and fewer CO$_2$ emissions. Compared with the most widely used fixed time control, the ETC-assisted real-time traffic light control scheme has much better performances in reducing the average waiting time, improving non-stop passing rate, and reducing CO$_2$ emission.

KEYWORDS

Traffic light control, vehicles' CO$_2$ reduction, ETC devices, non-stop passing

1. INTRODUCTION

Currently, it seems very clear that CO$_2$ emissions have become the main reason for the current global warming issues. The burning of fossil fuels is now one of the main sources of CO$_2$ emissions, which can be accounted for the increasing use of vehicles in the world, causing CO$_2$ emissions to rapidly increase. If CO$_2$ emissions from automobiles can be reduced, then the total amount of CO$_2$ emissions also can be alleviated to a certain degree.

Engine idling in vehicles consumes more fuel and releases more CO$_2$ than when vehicles' engines are in motion[1]. It is clear that if the idling time of vehicles can be reduced, then the amount of CO$_2$ emissions emitted by vehicles can be decreased. In many ways, vehicle idling time can be measured by the short-time stop times vehicles make at intersections waiting for red traffic signals to change to green signals. Poorly designed traffic light controls are believed to account for longer intersection waiting time; thus, a suitable traffic light control scheme is crucial for reducing vehicle's CO$_2$ emissions.

In recent years, due to the requirements of the Intelligent Transportation System (ITS)[2-4], ETC technology has become a mature technology that is gaining more and more popularity and is used in many countries. ETC takes advantages of the communication between vehicles and roadside devices to calculate the price to charge vehicles traveling on highways. In the highway fee charging process, the vehicles pass though the toll gates by non-stop. For each ETC device in the vehicle, an on board unit (OBU) is used to insert the ETC card to connect with the driver's bank account to charge the toll fee. For toll gates on highways, road side unit (RSU) devices are

deployed on the toll gate. As vehicles approach a toll gate, communication takes place between the OBU and the RSU; then the RSU control opens the gate so the vehicles can pass through. Once vehicles have passed the gate, communication occurs again, causing the gate to close [5].

In view of the convenience of ETC highway toll charging and the wide marketing of ETC vehicles, an ETC-assisted real-time traffic light control scheme is proposed to reduce the vehicles waiting time at intersections by the traffic light controls. By the proposed traffic light controls, vehicles can pass through the intersection within less waiting time, and then the CO_2 emissions of vehicles can be reduced. This paper is the following work of our previous work in [6].

2. PROPOSED SCHEME

2.1. Communication Process between Vehicles and Traffic Lights

2.1.1. Assumption

Assume that all vehicles have installed the ETC devices (treated as OBUs) and that the intersection traffic lights have the antennas (treated as RSUs). In addition, RSUs have a radio coverage area: RSU is center and with the radius range as R (refer to Figure 1). Area with range R is the longest distance available for wireless communication between the OBUs and the RSUs. Only the vehicles in the range R can communicate with the traffic lights directly. Another assumption is that each intersection has its own traffic control center. Besides, the communication between RSU and OBU is available according the Dedicated Short Range Communication (DSRC) technology for ITS.
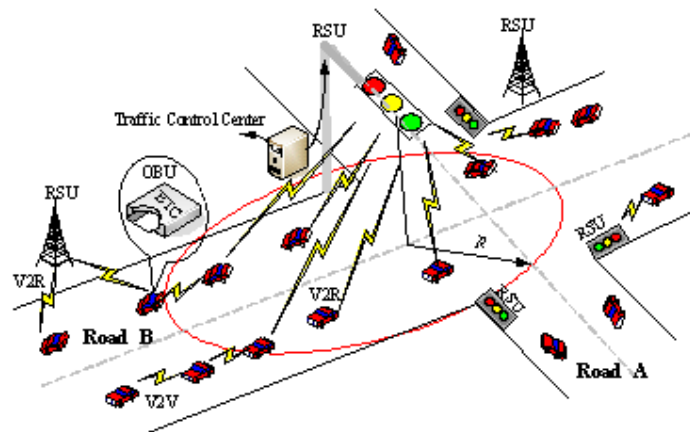

Figure 1. Vehicle-light Communication Process

2.1.2. Communication Processes for Collecting Road Conditions

As shown in Figure 1, if vehicles are in the radio coverage range R, these vehicles can communicate with the traffic light directly by the Vehicle to Road side units (V2R) communication. By contrast, if vehicles are not within the radio coverage area, they need to send request packets to the vehicles at the front by Vehicle to Vehicle communication (V2V) and multi-hop communication. Then, once the front vehicles have moved into the radio coverage area, they can actively send the request packets to the traffic lights. When the vehicles have passed through the intersection, they also need to send their states to the passed intersection. By the adjacent intersection's cooperation, vehicles can pass through the intersections efficiently.

The packets contain this kind of information: about the vehicles' speed, vehicles' moving direction, and some other related information. After receiving the requests from the vehicles, the

traffic lights send these packets to the traffic control center (refer to Figure 1). These real time received packets can be treated as the real time road conditions. The control center analyzes the received requests and works out the optimal duration time of the different traffic light color (green, red), and also calculate when it should change to another color (red to green, or green via yellow to red) light. Then, the control center sends the calculated results to the traffic lights, and the traffic lights send the results to the vehicles. The results packets include several pieces of information, such as when the traffic light will be changed and how long the green light will last for this traffic light cycle. To ensure cooperation among the adjacent intersections, when vehicles move away from the intersection, they also need to communicate with the traffic lights. The merit of vehicle-light communication is clear because it allows the traffic controls to know the real-time road conditions in advance.

2.2. Some metric indexes

2.2.1. The length of waiting queues

The length of a waiting queue consists of two parts: one is the number of vehicles that have arrived at the intersection when the light is red, and the other is the number of waiting vehicles that remain at the end of the previous green light.

For simplicity of the presentation and simulation, we set the length of vehicle queues (*Queue_L*) equal to the number of vehicles in waiting queues. Thus, the threshold of the maximum length of waiting queues (*Max_Queue_L*) is equal to the number of vehicles when the road is saturated. The maximum passing length of queues stands for the maximum number of vehicles that can pass through the intersection during a given green light time (*Max_Pass_L*).

2.2.2. Average waiting time at intersection

Set *t(i)* is the total time involved for vehicles pass the intersection, including the intersection delay; and $t_0(i)$ is the optimal time involved without intersection delay.

The average waiting time *W (i)* can be defined as[7]:

$$W(i) = \frac{1}{|C|} \sum_{i \in C} (t(i) - t_0(i))$$

(1)

C is the set of all vehicles passing through the intersection during a given period time.

2.2.3. CO_2 emission estimation

For simplicity, we introduce a CO_2 emissions rate estimation formula to calculate the reduction of CO_2 during the idling period. The CO_2 emission rate E_{CO_2} calculation formula is shown in the Eq.(2), which was discussed by [8]:

$$E_{CO_2} = \begin{cases} \alpha_{CO_2} + \beta_{CO_2}V + \delta_{CO_2}V^3 + \zeta_{CO_2}aV, & if \ P_{tract} > 0 \\ \alpha'_{CO_2}, & if \ P_{tract} = 0 \end{cases}$$

(2)

The parameters α_{CO_2}, β_{CO_2}, δ_{CO_2}, and ζ_{CO_2} in Eq.(2) are calibrated parameters that have constant values, and a stands for vehicle acceleration (m/s^2). The unit for the CO_2 emissions rate is grams per second (g/s). In Eq.(2), the CO_2 emissions of the vehicles are related to positive tractive power noted as P_{tract}, which is the function of speed *V*. When the speed is equal to zero while an engine is idling (waiting for the red light to change is an idling state), the P_{tract} =0. For passenger

vehicles, α'_{CO_2} is a positive constant, which is equal to 0.973 (does not consider vehicle stop times).

2.3. Decision Tree-based ETC-assisted Real-Time Traffic Light Control

2.3.1. Decision tree and decision forest

A decision tree is a decision classifier method that uses a tree-like graph or model to show the number of decisions or possible consequences [9, 10]. In this paper, the decision tree is used to control different traffic flow situations. Different traffic flow situations are coped with different control methods, and we treat these different control methods as the branches or leaves of the decision tree. Thus, under the control of traffic control center, a lot a control methods for a large number of intersections can be treated as a forest. As for a city's traffic light control system, we can use decision forest to control the traffic lights.

For simplicity of our presentation, we suppose each different intersection has its own unique ID (the ID is noted as *Ii*), and each intersection has its own traffic flow situations, which make up the branches of the trees; further, each branch has its own traffic light control method.

In the following, we will discuss the proposed traffic light control scheme for two types of intersections: isolated intersection and non-isolated intersection.

2.3.2. Traffic light control for isolated intersection

For the isolated intersection control, we do not need to consider the adjacent signalized intersections. In order to illustrate the proposed scheme, look back at Figure 1 as an example that introduces the decision tree control algorithm. The scenario in Figure 1 represents a 4-way isolated intersection, which has two intersecting roads, labeled Road A and Road B. Four traffic lights are deployed on each lane sharing one control center, and each traffic light has an initial fixed time control policy. We divide this tree into four branches based on the number of vehicles in the each waiting queues. Then four control methods were introduced to deal with these four branches separately. Figure 2 shows the detail of one decision tree control algorithm.
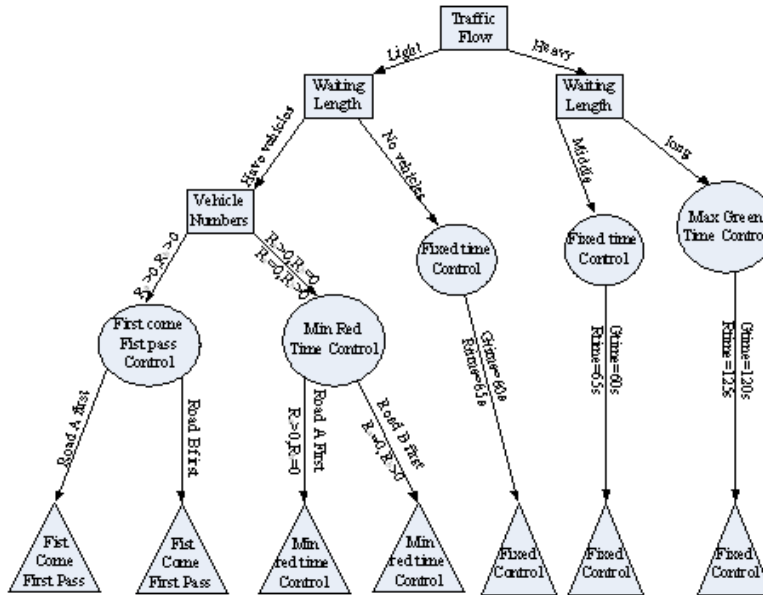

Figure 2. A Decision Tree Control Scheme for One Intersection

The decision tree has three kinds of nodes represented by three different geometric shapes, which is shown in Figure 2. The rectangle block belongs to the decision node that is used to execute the entire process. The circles nodes are used for selecting the next decision. The triangles are the end nodes, which are applied to the end process. As discussed above, the control center can capture the road conditions about R/V seconds ahead of when vehicles will arrive at the intersection(R is the radio range of RSU, and V is the speed of vehicle). So the control center can renew the road conditions at every R/V seconds.

For simplicity of the presentation, the number of requests in road A and road B set as R_a, and R_b, respectively. Suppose that there are still R/V seconds for the lights to change to another color: the control center must calculate the best green time for the coming vehicles. According to the length of waiting queues (*Queue_L*), we sort the road conditions into four kinds, and four control methods are proposed to deal with these four kinds of road conditions.

As shown in Figure2, to estimate the traffic flow, we divide it into two groups: heavy traffic in rush hour and light traffic for off-rush hour (the intermediate state is sorted to the off-rush hour situation). The proposed control concerns mainly on the situation when traffic flows are light. The decision tree shown in Figure2 is consisted of the following branches:

i)   When the traffic flow is light, and no requests to pass have been received from vehicles (R_a=0, R_b=0), we treat it as no vehicles will approach the intersection in the next R/V seconds; thus, there is no need to change the current control method. We simply set it as the initial fixed time control.

ii) If requests from vehicles have been received from only one road—for example, received only from road A(R_a>0, R_b =0), and suppose current in road A is the red light. After the red light in road A appears for the minimum red light time (*Min_red_time*), and then the green light for the intersection of road A is turned on. We call this control method as the Min red time control, which means that vehicles on road A can pass through the intersection without having to wait for the entire red light time; instead the control reverts to the *Min_red_time*. Therefore, vehicles in road A just need to wait for a *Min_red_time*. If the current red time is already more than the *Min_red_time*, then the red light changes to a green light immediately so vehicle can go through the intersection without having to stop at all.

iii) If requests have been received from both roads (R_a >0, R_b >0), when the traffic flow is light, vehicles on the first road sending requests to the lights are the first to pass. This means if vehicles on road A make the first request to the light control center, the light will change to green for road A first, and the green light duration time will ensure that all the requested vehicles in road A are allowed to pass through the intersection before the light changes to red for road A, and then turns green for road B. We refer to this control as first requests, first pass control. However, when the traffic flow is heavy, we sort the controls into two kinds based on the length of waiting queues: *Queue_L<= Max_Pass_L* and *Max_Queue_L >Queue_L>> Max_Pass_L*.

• When the traffic flow is heavy, if *Queue_L<= Max_Pass_L*, we treat this as an in-between situation for which the current fixed time is suitable. In this case, we make no changes to the current control settings, and we refer this as fixed time control, which is the same as initial fixed time control.

• When the traffic flow is heavy, if *Max_Queue_L >Queue_L>> Max_Pass_L*, this is considered a very long waiting queue. In order to allow more vehicles to pass the intersection as quickly as possible, we set the green time to the maximum green

duration*(Max_green_time)*, because more vehicles can pass the intersection in the longer traffic cycle time than in the shorter one.

iv) And the last condition that is related to traffic controls occurs when the queues in both roads are much longer than *Max_Queue_L*, which denotes a large traffic jam. We don't consider this condition in this paper, but we plan to deal with it in future research.

2.3.3. Traffic light control for non-isolated intersection

Different with the isolated intersections, the non-isolated intersections are affected by the adjacent intersections. Here, we use the cooperation between the adjacent intersections for sharing the received traffic flow information, to ensure vehicles to pass the next adjacent intersection with "green wave" traffic lights. Therefore, the traffic flow information for the non-isolated intersections is come from two parts, one is from the adjacent intersections, and the other is from the vehicles which will approach these intersections. When the non-isolated intersections have received these two parts traffic flow information, the traffic control center will implement the decision tree based control scheme; this process is the same as the control for isolated intersection, which have discussed in the Parts 2.3.2.

3. PERFORMANCES AND EVALUATION

The primary goal of the proposed scheme is to reduce the CO_2 emissions emitted from vehicles by minimizing the intersection waiting time. Based on Matlab simulation software, and compared with traditional fixed-time control schemes, the performance evaluation of the proposed scheme is presented in this section.

3.1. Simulation Setup

We will evaluate the performance of the proposed scheme in realistic area which is located in Shinjuku-ku, Tokyo, Japan, as shown in Figure 3. We divided this map into two cases. In Case A, we set S as source and M destination, and in Case B, we set S as source and D as destination. In Case A, there is one intersection, marked as intersection 0(*I0*) in Figure3. In Case B, there are two intersections, marked as intersection 0 and 1(*I0* and *I1*). For the case A, we do not consider the traffic flow influence from *I1,* treating the I0 as an isolated intersection. By contrast, in case B, the *I0* and *I1* are non-isolated intersections.

Figure 3. Simulation Map (Case A: from S to M, Case B: from S to D)

Suppose the fixed time traffic control scheme is being implemented in the scenario as shown in Figure3. The initial fixed traffic light duration times for $I0$ are this: green light: 60 s; red light: 65 s; yellow light: 5 s. For $I1$, these are the duration times: green light: 40 s; red light 45 s; yellow light: 5s. (Pedestrians are not considered in this simulation.). According to the DSRC technology [11, 12], the longest radio distance must be less than 1000 meters. Besides, based on the DSRC performances and considering realistic road length and the performance of RSUs, the range of the radio radius R in simulation is set as 100 meters. Suppose each vehicle's arriving (veh/h) follows a normal distribution. Traffic flow volume and other related parameters in the simulation are described in Table 1.

Table 1. Parameters for simulation

Name	Value
Traffic flow. unit: vehicle /hour (veh/h)	3, 10, 50, 100, 500, 300, 500, 900, 1100, 1300, 1700, 2100, 2500
Simulation time	10 hours
Max_green_time	150 seconds
Duration time of yellow light	5 seconds
Min_red_time	25 seconds
$t_0(i)$	2 seconds
Max_Queue_L	150 vehicles
Max_Pass_L	25 vehicles

3.2. Acknowledgements

Four aspects are provided to evaluate the performances of the proposed ETC-assisted traffic light control scheme: average intersection waiting time, waiting time probability distribution, non-stop passing rate, and CO_2 emissions reductions.

1)   Average intersection waiting time

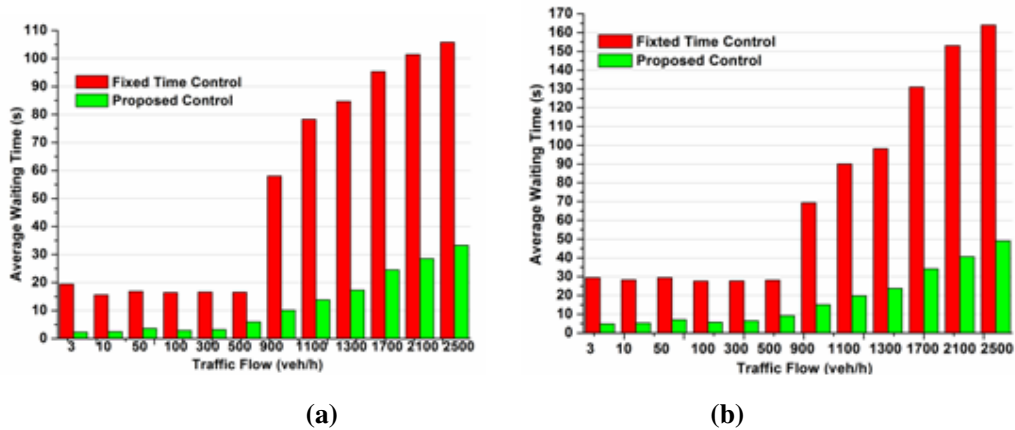(a)   (b)

Figure 4. Average Waiting Time for Two Cases: (a) case A, and (b) case B.

In Figure 4, we described the average waiting time when vehicles are traveling from S to M through an isolated intersection in case A and two adjacent intersections from S to D in case B. From the data shown in Figure 4, it can be concluded that the ETC-assisted control scheme gives a better performance on the aspect of average waiting time than the fixed time control does. This

because the duration time of traffic lights can be changed dynamically according to the received requests from vehicles.

Although Figure 4 does show the improved performance, it does not show the waiting time distributions; e.g., in case A (Figure4(a)), when the traffic flow is equal to 1700 veh/h, the average waiting time is about 95 s with fixed time control and 25 s with the proposed control. However, it does not provide any information about how many vehicles are required to make the waiting time longer than 95 s (25 s) or shorter than 95 s (25 s). Hence, we need to show the distributions of the waiting times. We use Figure 5 to give an example that shows the waiting time distributions when the traffic flow is equal to 1700 veh/h in the two cases.

2)   Waiting time probability distributions

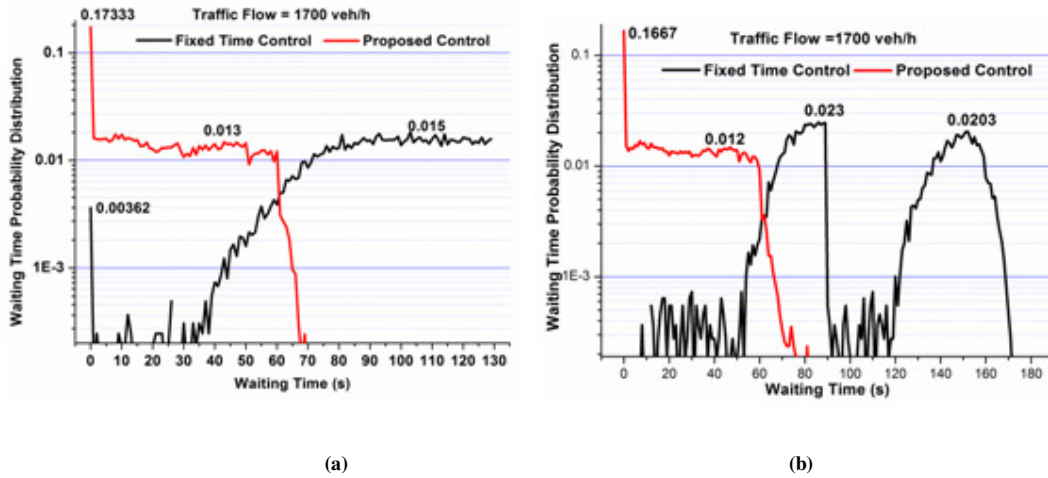(a)   (b)

Figure 5. Waiting Time Probability Distributions for Two Cases, Traffic Flow =1700 veh/h: (a) case A and (b) case B.

In Figure 5 (a), when the waiting time = 0 s, it means that the current traffic light is green, and vehicles can pass the intersection without having to stop. Thus Figure 5(a) indicates that the ETC-assisted control (p=0.17333) achieves a higher probability of vehicles being able to pass the intersection without stopping than with fixed time control (p=0.00362) in a heavy state of traffic flow (1700 veh/h). In other words, when the traffic flow is equal to 1700 veh/h, using the proposed control, the average waiting time is 25s, and about 17.333% vehicles can pass through the intersection without any waiting or stopping. In contrast, using fixed time control, only about 0.362% vehicles can pass through the intersection without any waiting. Similarly, when the waiting time is longer than 70 s, for the fixed time control, the probability is about equal to 0.015, and for the proposed control, there are no curves that indicate that vehicles will be required to wait for more than 70 s in the proposed control scheme. This means, each vehicle' waiting time is less than 70 s in the proposed control. The same reasons can explain the curves in Figure5 (b).

Compare with Figure5 (a) and (b), in the fixed time control situations, when the waiting time equals to zero (non-stop pass), the probability in case B (p=0) is much lower than in case A (p=0.00362). The reasons for this issue are due to the case B has two intersections. Clearly, the probability for one vehicle to pass two intersections without any stop is lower than pass only one intersection. And in the proposed control, the non-stop passing probability is almost the same (Case A: p=0.17333, Case B: p=0.1667). By the cooperation of adjacent intersections, the traffic control center can know the traffic flow information in advance before vehicles arriving at the second intersection. Thus when vehicles pass through the first intersection, the control center will

ensure them to pass the second intersection by non-stop or less number of stop times or less waiting time.

Further, in the fixed control, there are two peak values (p=0.023, when waiting time is about 90 s; and p=0.0203, when waiting time is about 150s). The reason for this issue is due to the case B having two intersections. When pass through the each intersection, vehicles have to wait, two times wait for traffic light will lead to two peak value. By contrast, traffic control center can obtain the real time traffic flow in advance and the traffic flow information can be shared by the adjacent intersections, which can ensure vehicles pass the two adjacent intersections in a "green wave", thus, there is no two peak values in the proposed control. Besides, in the case B, in the proposed control situation, each vehicle waiting time is less than about 80 s (there is no curve when waiting time longer than 80s).

3)   Non-stop passing rate

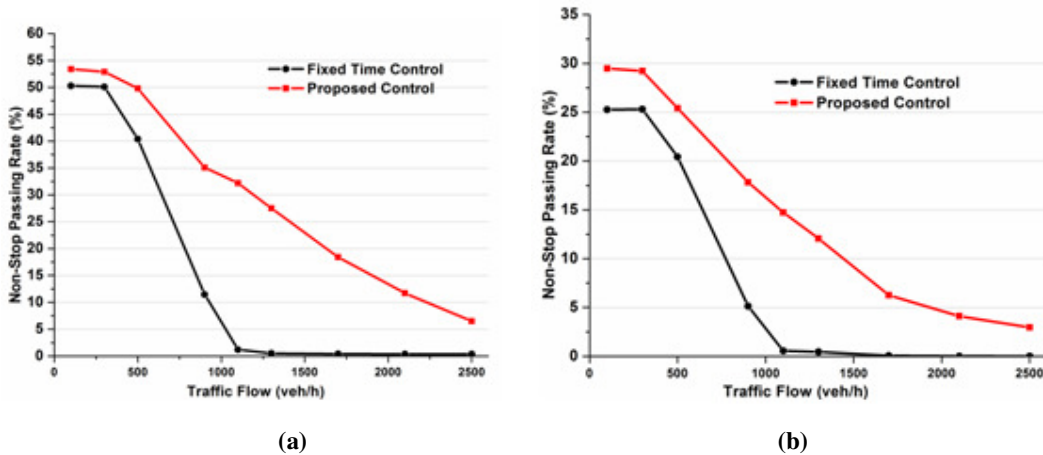(a)   (b)

Figure 6. Non-stop Passing Rate for Two Cases: (a) case A, and (b) case B.

As illustrated in Figure 6, the non-stop passing rate is much higher when the traffic flow is light than heavy. It is easy to explain the reason: when the traffic flow is light, e.g., there are several vehicles on road A, but there are no vehicles on road B. Thus the control center just need turn the green light to road A until received requests from road B. By contrast, if both the road A and road B have many vehicles, the control center can not ensure the vehicles on road B are not waited when vehicles on Road A are passing through the intersection. In other words, when the traffic flow is light, there is always enough space for the control center to change the green traffic light between the two intersecting roads; however, in heavy traffic flow situations, it is impossible to have enough time space to change the traffic light between two roads.

4) CO_2 emission amounts and reductions

Using Eq.(2) to calculate the CO_2 emission amounts, then we get the Figure 7, which provides data on the average CO_2 emission amounts of vehicles when they pass through an isolated intersection in case A and two adjacent intersections in case B under the same traffic flow situations. The two different colored curves stand for the amounts of idling period CO_2 emissions under two different traffic light controls: the fixed time control and the ETC-assisted control. For easily to understand the reduction amounts, we choose five traffic flow situations (traffic flow=100, 300, 1300, 2100, 2500 veh/h) in Figure 7 to show the CO_2 reduction percentages, which is listed in Table 2.

In Table 2, when the traffic flow is equal to 100 veh/h, in the ETC-assisted control, vehicles idling period CO_2 emissions can be reduced about 82.5% (79.4%) compared with the fixed time control in Case A (Case B). And when the traffic flow is equal to 2500 veh/h, the reduced percentage is about 68.5% (70.8%) for Case A (Case B).
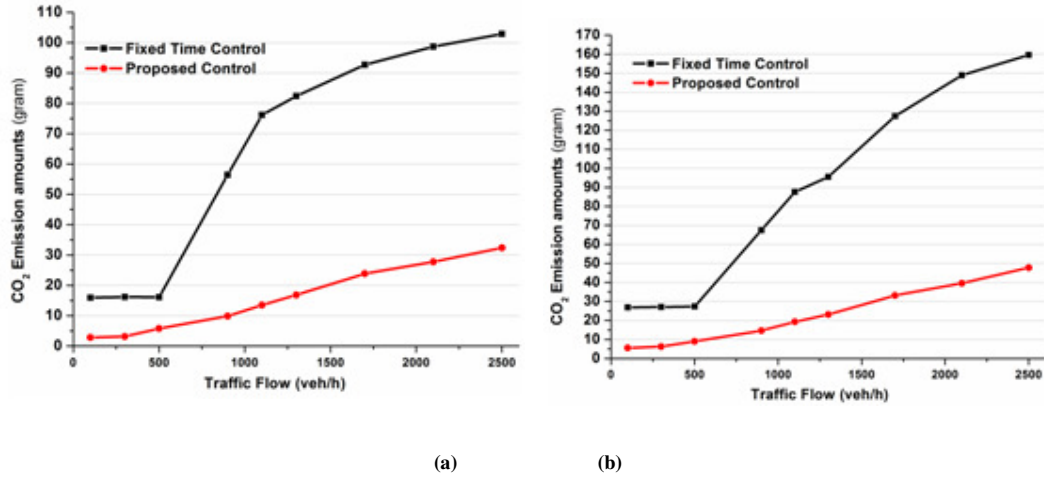

(a)   (b)

Figure 7. CO_2 Emission Amounts during Waiting Time in Two Cases:
(a) case A, and (b) case B.

Table 2. CO_2 Reduction Percentages

Traffic flow (veh/h)	100	300	1300	2100	2500
Case A	82.5%	80.7%	79.6%	71.8%	68.5%
Case B	79.4%	76.9%	75.5%	73.45%	70.8%

The Figure 7 and Table 2 both indicate that with the increase of traffic flow, the CO_2 reduction percentages decrease both in case A and case B. The reason is that, in light traffic flow situations, more vehicles can go through the intersection without stopping (refer to Figure 6); hence, more vehicles can pass through intersections without idling CO_2 emissions. The CO_2 reduction mainly comes from vehicles' non-stop passing. Moreover, in heavy traffic flow states, vehicles have a very low rate for non-stop passing through the intersections, and the CO_2 reduction mainly caused by less waiting time. Thus, the CO_2 reduction percentages are to be lower in heavy traffic situations than in light traffic situations.

4. CONCLUSION

An ETC-assisted real-time traffic light control scheme was proposed to reduce vehicles CO_2 emissions from idling period in vehicular networks. The real-time road conditions were obtained by wireless communication between ETC devices of vehicles and the traffic lights. Vehicles sent out passing requests to the traffic lights, so the traffic control center obtained the real-time road conditions by these requests. The traffic control center dynamically adjusts the traffic lights cycle and lights duration time based on the collected real time traffic flow conditions by the decision tree algorithm. We used two cases to illustrate the proposed scheme, and the simulation results indicated that the ETC-assisted control scheme had a better performance than the fixed-time control scheme: decreased waiting time, higher probability for non-stop passing, higher probability for shorter waiting time, and less CO_2 emissions. Compared with the fixed-time control, the CO_2 emissions can be reduced about 82.5% and 79.4% when traffic flow equal to 100

veh/h; and about 68.5% and 70.8% when traffic flow equal to 2500veh/h, in two cases respectively.

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