International Journal of Managing Public Sector Information and Communication Technologies (IJMPICT)
Vol. 2, No. 1, September 2011

DYNAMIC TRAFFIC LIGHT CONTROL SCHEME FOR REDUCING CO_2 EMISSIONS EMPLOYING ETC TECHNOLOGY

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ABSTRACT

With the increasing growth of vehicle numbers in the world, Global warming is becoming a serious issue. Vehicle CO_2 emissions are considered to be one of the main sources of global warming. In order to reduce vehicles CO_2 emissions, a dynamic traffic light control scheme is proposed. In the proposed scheme, we are the first to use Electronic Toll Collection (ETC) devices to obtain real time traffic flow information for a traffic control centre. By the proposed scheme, vehicles can pass through intersections with less waiting time and fewer numbers of stops. By smoothing vehicle travel, CO_2 emissions can be reduced. Compared with fixed time control, the simulation results indicate that the proposed scheme has much better performance: vehicle average waiting time is greatly reduced and CO_2 emissions can also be reduced.

KEYWORDS

ETC vehicles, dynamic traffic light control, CO_2 emissions

1. INTRODUCTION

Currently, the detrimental effects of air pollutants and concerns about global warming are being increasingly reported by the media. The global warming problem has brought many seriously problems, which lead to dangerous interference with the climate system. Due to global warming, the ice in the Polar Regions is melting and sea levels are rising [1]. In terms of the air pollution problem, greenhouse gas (GHG) emissions from vehicles are considered to be one of the main contributing sources to global warming. To slow down the speed of our living environment deterioration, reducing CO_2 emissions is becoming an urgent problem. As one of the major sources of CO_2, vehicle exhaust emissions are becoming a serious issue due to the rapid increase of vehicle numbers in the world. As a result, reducing vehicle CO_2 emissions is one of useful ways to slow down the speed of our living environment deterioration.

Barth et al. carried out a number of experiments [2], the results of which indicated that shorter idling time and constant-speed driving would lead to lower CO_2 emissions. Furthermore, a lower number of stops and short time waiting at traffic red lights are the most common reasons for engine idling. Thus, minimizing waiting time as well as avoiding unnecessary stops can be used to reduce CO_2 emissions. In fact, traffic light control plays a very important role in reducing vehicle waiting time and the number of stops. Therefore, the problem becomes one of how to control traffic lights to smooth vehicle travel.

DOI : 10.5121/ijmpict.2011.2101

Intelligent Transportation Systems (ITS) is a combination of tools such as software, hardware, traffic engineering concepts, and communication technology, which can all be integrated in order to be applied to the transportation system to improve its efficiency and safety [1].

Recently, with the development of ITS, more and more traffic control schemes are designed based on ITS technology to save fuel consumption and reduce CO_2 emissions.

Masszen et al. have proposed an economical and environmentally friendly geocast (EEFG) protocol for minimizing vehicle fuel consumption and emissions in [2]. In this protocol, based on the vehicular network, the authors introduced a recommended speed calculation for reducing vehicle stopping times. Through this scheme, vehicle idling CO_2 emissions can be reduced to some extent. However, vehicle CO_2 emissions are not only related to stop times, but also related to vehicle travel time, especially vehicle engine idling time. In [2], the authors only considered reducing vehicle stop times, and paid little attention to reducing vehicle waiting time. In other words, [2] does not reference vehicle travel time, which can reduce vehicle waiting time when approaching intersections.

Aleksandar et al.'s contribution in [5] is as follows: traffic light timings are optimized for seven optimization objective functions to find the lowest fuel consumption and CO_2 emissions levels. As well, in [8], Solomon et al. used a model-based control approach to reduce emissions while still improving traffic flow. However, neither [3] nor [4] gave details about how to obtain real time road traffic flow information when using proposed algorithm to control traffic flows.

As one of most popular applications of ITS, Electronic Toll Collection (ETC) technology [5] has become a mature technology that is widely used in all over the world. It takes advantage of the communication between inter-vehicle devices (On Board Unit (OBU)) and roadside devices (Road Side Unit (RSU)) to realize highway road pricing with non-stop passing of toll gates by vehicles. Communication between OBU and RSU is based on the Dedicated Short Range Communications (DSRC) technology. Fig. 1 shows the process of automatic toll charging for ETC vehicles.

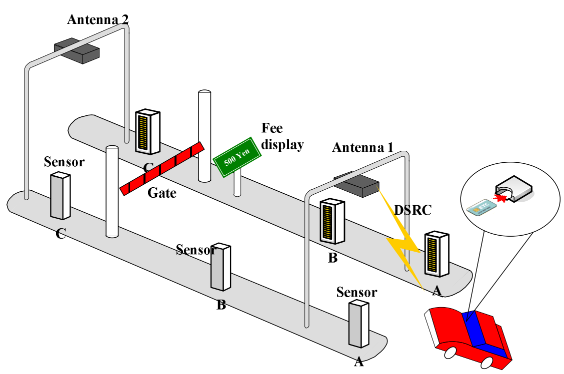


Figure 1. ETC Highway Charging Process

In our previous work [6], based on the ETC technology, we employed a decision tree based traffic light control algorithm to control traffic lights and allow more vehicles to pass through the intersections with less waiting time. The simulation results turned out to be very promising. However, we only evaluated the proposed scheme in a single intersection scenario and did not consider the cooperation between adjacent intersections, and the traffic control algorithm also needed to be improved. Thus, this paper is the follow-up to the previous work in [6]. In this paper, we improved the traffic control algorithm and deployed it in a real road network map.

As part of the current study, we propose an ETC based traffic light control scheme for reducing vehicle CO_2 emissions; also, road traffic flow information can be obtained by wireless communication between the ETC vehicles and the traffic lights, which are used to realize detecting of road traffic flow information in real time. By reducing vehicle waiting time and improving the non-stop rate for passing intersections, vehicle travel can be smoothed, which leads to the reduction of CO_2 emissions.

2. PROPOSED SCHEME

2.1. System Module

To realize dynamic traffic lights control, road traffic flow information must be obtained as accurately and quickly as possible. Here, we use wireless communications between vehicles and traffic lights to obtain road traffic information. The proposed system module is shown in Fig. 2.

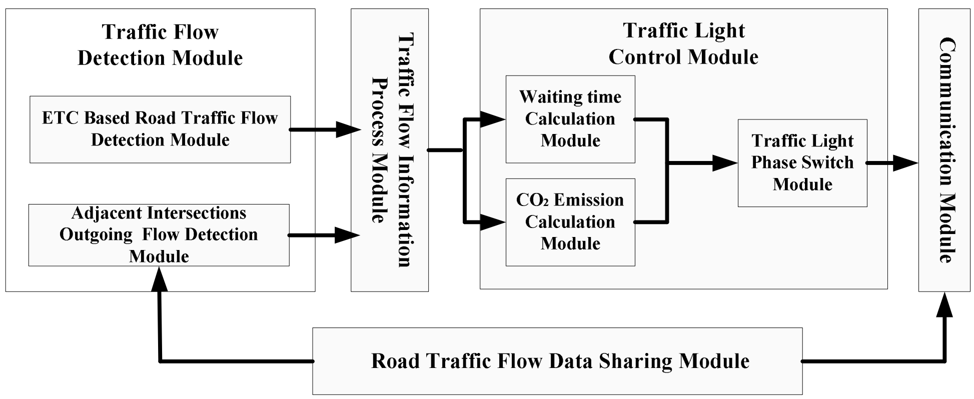


Figure 2. System Module

The system module consists of five sub-modules: Traffic Flow Detection Module (TFDM), Traffic Light Control Module (TLCM), Traffic Flow Information Process Module (TFPM), Communication Module (CM), and Road Traffic Flow Information Sharing Module (RTFISM). Each sub-module has its special function for the whole system. We will give the detail descriptions of each sub-module in the following.

2.1.1. Traffic Flow Detection Module

The purpose of the TFDM is to obtain road traffic flow information in real time. This module consists of two sub-modules: ETC based Road Traffic Flow Detection Module (ERTFDM) and Adjacent Intersection Outgoing Flow Detection Module (AIOFDM). The road traffic information comes from two sources: 1) from the roads that connect to the current intersection, and 2) from the adjacent intersections.

(1) ETC based Road Traffic Flow Detection Module

Assume that each intersection has its own traffic control centre, and suppose all vehicles have installed ETC OBU devices; thus, the road traffic flow information can be obtained by wireless communication between ETC vehicles and traffic lights. The details of the detection process are shown in Fig. 3.

In Fig. 3, suppose each traffic light has an antenna (RSU) installed on it, and that the max radio distance is R. Only the vehicles which are in the area of the radio distance can communicate with the light directly.

Vehicles that are not in the radio coverage area of RSU need to send request packets to the front vehicles by multi-hop. Then, once the front vehicles move into the radio coverage area, the vehicles can send the request packets to the traffic lights directly. The packets contain information about the vehicles' speeds, moving directions, etc. After receiving requests from the vehicles, the traffic lights send these packets to the traffic control centre (refer to Fig. 3). The control centre analyses the received requests and works out the optimal green duration time and green changing time. Finally, the control centre sends the results to the traffic lights, and the traffic lights send the results to the vehicles. The result packets include information such as when the traffic light will be changed and how long the duration of lights is in this cycle. One point should be noted: not only vehicles moving toward the intersection need to communicate with the lights; vehicles moving away from the intersection also need to communicate with the traffic lights, as this information will be shared by the adjacent intersections. The merit of vehicle-light communication is clear, considering that traffic lights can obtain real time road traffic flow information in advance.

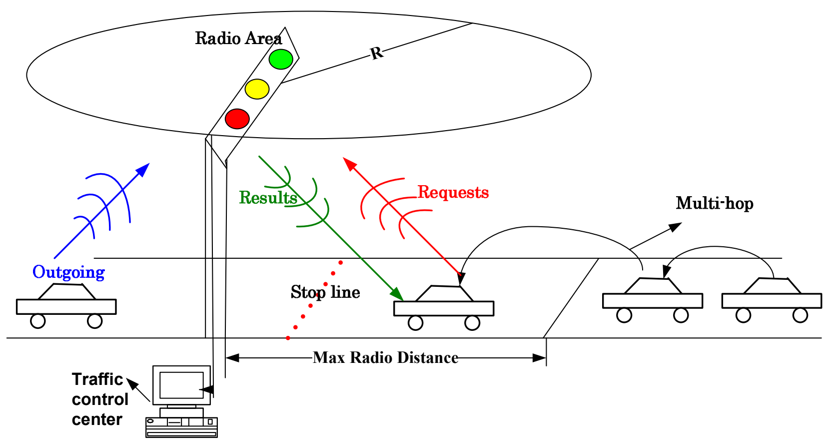


Figure 3. ETC based Road Traffic Detection

According to the DSRC standard, the longest radio distance for vehicle-to-roadside communication must be less than 1000 meters. Besides, for public safety intersections, the transmission power for downlink and uplink are limited to less than 40 dBm. Further, according to [10], when transmission power is 17 dBm (50mW), about 80% of the messages can be received 200 meters away; and when transmission power is 10 dBm (10 mW), about 100% of the messages can be received 100 meters away. For traffic control, the safety of drivers and pedestrians must be the first priority; thus, we must ensure the messages can be received 100% of the time. So, in this paper, the antenna's radio distance is set to 100 meters.

(2) Adjacent Intersection Outgoing Flow Detection Module

The road traffic flow information is obtained from the out-going lanes of adjacent intersections. When vehicles have passed through one intersection, the passed traffic flow information will be sent to the next adjacent intersection for smoothing the entire travel time of the vehicles. So, at the next intersection, the number of vehicles that will pass is more accurate compared with just considering one isolated intersection.

2.1.2. Traffic Flow Information Process Module

This module encompasses traffic flow information processing. The main function of this module is information extraction. As vehicles periodically send the road traffic flow information to the traffic lights before passing through the intersection, it is easy to cause certain problems. For example, the same information may be received several times from the same vehicle, or obsolete and current traffic flow information may both exist at the same time. Therefore, it is necessary to extract the useful information from the received information data.

In this paper, we are mainly concerned with the traffic control aspects, and we pay little attention to the information processing parts; we will deal with the information extraction aspect in future works.

2.1.3. Traffic Light Control Module

As shown in Fig. 2, the traffic light control module is made up of three sub-modules: Waiting Time Calculation Module; CO_2 Emission Calculation Module; and Traffic Light Phase Switch Module.

(1)Waiting Time Calculation Module

Define the average waiting time to be:

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

Where C is the set of all vehicles passing the intersection during a given period of time; $t(i)$ is the total time cost, including the intersection delay; and $t_0(i)$ is the optimal time cost without intersection delay.

As the road traffic flow information data can be obtained several seconds in advance of vehicles arriving at the intersection's stop line, so the control centre can pre-calculate the waiting time for each lane. This calculation algorithm will be described in Section 2.2.

(2) CO_2 Emission Calculation Module

To calculate the vehicles' CO_2 emissions, we need a model. As real time CO_2 emissions amounts are sensitive to many factors (e.g., travel distance, roadway types, individual driving behaviours), it is difficult to consider all these factors within one model or formula. Therefore, we introduce a CO_2 emission estimation model to describe the relationship between CO_2 emissions and a condition of vehicle motion, which is proposed by Oguchi et al. in [9]. This model is shown in the following formulas:

$$E = 0.3K_C T + 0.028K_C D + 0.056K_C Aee \tag{2}$$

$$Aee = \sum_{k=1}^{K}\sigma_k(v_k^2 - v_{k-1}^2) \tag{3}$$

E : CO_2 emissions [g];
K_C : Coefficient between gasoline consumption and CO_2 emissions (K_C =2.31 g/cc*);*
D : Travel distance [m];
T : Travel time for the distance D [second];
Aee: Acceleration Energy Equivalent [m^2/s^2];
v_k : The speed at time k [m/s];
σ_k : When accelerating, this equals 1; otherwise, it equals 0.

There are three variables in the model of formula (2): vehicle travel time (T), travel distance (D) and *Aee* value. Travel times of each vehicle are evaluated to sum up free-flow travel time and delay time. Travel distance must be constant if the study section is fixed. *Aee* value can be calculated by vehicle travel mode in acceleration and deceleration, as shown in formula (2). The three coefficients (in formula (2), 0.3, 0.028 and 0.056, respectively), which are evaluated by experimental approach, take different values in accordance with individual vehicle type.

(3) Traffic Light Phase Switch Module

The traffic light phase switch module will execute the control commands that come from the traffic control centre. The traffic light's colour and duration time both are carried out by the traffic light phase switch module.

2.1.4. Communication Module

The communication module is used for sharing road traffic flow information with adjacent intersections and also for the whole city's traffic control. One intersection will send its road traffic data to its neighbour, and in turn these data will help the neighbours give out a better traffic light cycles for vehicles. Through the communication module, adjacent intersections will cooperate with one another to smooth vehicle travel and avoid traffic congestion.

2.1.5. Road Traffic Flow Data Sharing Module

The function of this sub-module is to share real time road traffic flow information with adjacent intersections. Through cooperation at each intersection, the control centre will give out a better estimation of the current traffic light cycle. Besides, the traffic flow data in this module can also be shared by the whole city's traffic control centre or used by third party applications.

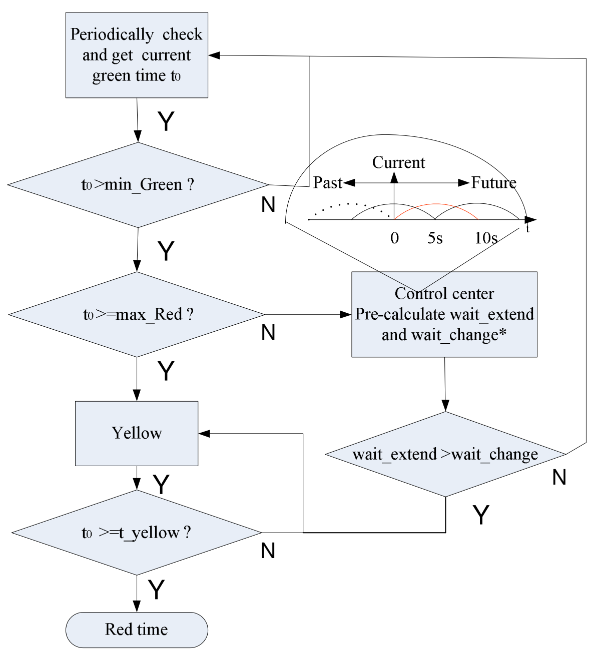
2.2. Traffic Light Control Algorithm

Traffic light control is mainly focused on two parts:

1) To change the current colour phase to another; suppose the another colour light's duration time is set as t_c seconds, then the corresponding waiting time as *wait_change*.

2) To extend the current colour phase: suppose the extend time as t_e seconds, and in this situation, the waiting time noted as: *wait_extend*

Thus, how to decide the light's colour and duration time becomes the key point of this proposed control algorithm. Take one intersection with two arms as an example to explain the proposed traffic light control algorithm, the proposed control algorithm is shown in Fig. 4.



*wait_extend: if extend the current green time, the average waiting time
wait_change: if change red light to the current road, the average waiting time

Figure 4. Traffic Control Algorithm

Suppose vehicles average speed is 10 m/s, and the max radio distance is 100 meters; thus, the control centre can forecast the road traffic flow information about 10 seconds in advance. Suppose the control centre updates the received road traffic conditions every 5 seconds, and the light's extend time is less than 5 seconds. That is to say, the current colour can be extended from 0 to 5 seconds. Thus, we propose a dynamic pre-calculate algorithm to control the traffic lights. Assume current traffic light is green colour, the main idea of the Fig.4 can be explained as following:

Step 1: Check the road conditions (every 5 seconds) and get the current green light time t_0 ;

Step 2: If "extend the green time" is noted, and the extended time is from 0 to 5 seconds, then find out how long it should be extended to lead to the lowest average waiting time. Take extend time as $t_e (0 < t_e \leq 5)$ as example, when extend about t_e seconds, the control will have the least average waiting time, and set the least average waiting time as *wait_extend*. Similarly, if "change current to red" is noted, the red light must last at least *min_Red* seconds, set t_c =*min_Red* and calculate the average waiting time as *wait_change*.

Step 3: Compare *wait_extend* with *wait_change*;

If *wait_extend* > *wait_change*, which means extending the current light will lead to more waiting time, changing the green light to red will have better performance than extending it;

If *wait_extend* < *wait_change*, which means extending the current light will have less waiting time compared with changing the light, so the current light will be extended for t_e seconds;

Step 4: Implement the control results, and go to Step 1.

In fact, when the traffic control centre gives out the light phase switching results, the lights will send the results to the vehicles. Thus, drivers will change their speeds to meet the lights' duration times and avoid unnecessary stops. For one thing, the vehicle average waiting time will be shorter; and for another, vehicle stop times will be reduced at the same time. We will test the proposed control scheme in a real intersection map in Section 3.

3. A CASE STUDY

3.1. Case Introduction

In this part, the proposed scheme is tested in a real scenario located in the area of Shinjuku-ku, in Tokyo, Japan. The fixed time traffic light control scheme is applied in this scenario, shown in Figure. 5.

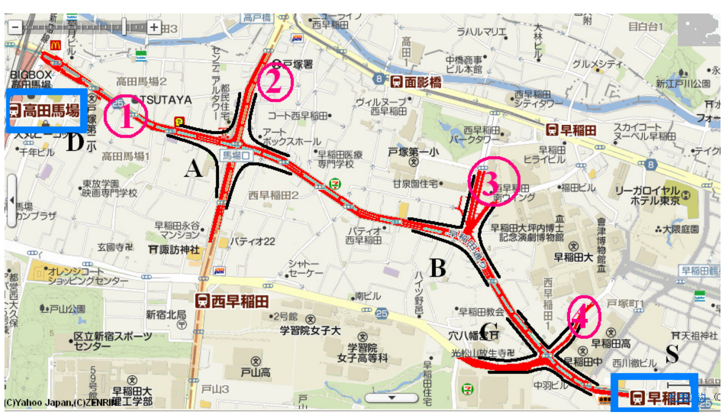


Figure 5. Simulation Map

Set Waseda station as departure and Takadanobaba station as destination, marked as S and D separately in Fig. 6. From S to D, there are three intersections, marked as A, B and C. In reality, Road 4 is the way to Waseda campus; most of the time, this road is used by students, so the traffic flow in this road is usually is very low. Road 1 is the main road that is connected to Road 2, Road 3 and Road 4, respectively. During rush hour, the traffic flow in each road has the following relations: Road 1: Road 2: Road 3: Road 4 = 4:4:2:1. For more information about this scenario, refer to Fig. 5 and Table 1.

Table 1. Parameters in reality.

Name	Value
A(Green, Yellow, Red) *	(35, 5, 40) seconds
B(Green, Yellow, Red)	(45, 2, 47) seconds
C(Green, Yellow , Red)	(50, 5, 55) seconds
Distance between A, B	700 meters
Distance between B, C	400 meters
Distance between S, D	2000 meters
Average speed	10 m/s

*Green, Yellow, and Red: Three color lights' duration time in reality.
A traffic light cycle= Green+Red+Yellow

3.2. Simulation Set Up

Simulation is based on Matlab software. Vehicles arriving are subject to random Poisson distribution, and we use the random function in Matlab to simulate vehicles' arrivals. As the fixed time control is the most widely used traffic light control scheme, we will compare our proposed scheme with it in the same traffic flow situations. From S to D, vehicle average travelling time, average waiting time, non-stop passing rate and CO_2 emissions are the main research objects in simulation.

3.2.1. Assumptions

For simplicity of the presentation, the following assumptions are considered:

(1) All vehicles have installed the ETC OBU devices.

According to [10] and [11], in Tokyo, almost all vehicles have the ETC OBU devices installed and the utilization ratio is more than 87.6%. Thus, in our case, we assume that all vehicles have the ETC OBU devices installed.

(2) The max radio distance is 100 meters.

We have discussed in Section 2.1.1 that in order to ensure driver safety, the receive rate must to reach 100%, so in simulation we set R equal to 100 meters.

(3) Antennas receive road traffic flow information data without packets dropping.

Given that the simulation mainly concerns the traffic control aspect, we suppose that the antennas can receive all the request packets from vehicles without packet dropping or interferences. The received data are stored in special storage and the traffic control centre periodically obtains the current road traffic conditions data from the storage. In simulation, we used periodically generated random numbers to simulate the received vehicle conditions data.

(4) Minimum green\red time and maximum green\red time.

Considering drivers' reaction time, if the traffic phase changed at a high frequency, the drivers may not react as quickly as the lights changing. Thus, it is necessary to consider the minimum green light duration time (*min_Green, min_red*). By contrast, too-long red duration time will exceed the scope of the drivers' tolerance, so maximum red light time (*max_Red, max_Green*) will also be considered.

(5) Stop times

Suppose that vehicles stop only one time during a traffic light cycle. Furthermore, we set vehicles running at a constant speed; deceleration and acceleration also are constant (refer to Table II). Besides, for intersections A and C, we consider that the vehicles go straight through, without turns; and for intersection B, vehicles from Road 3 turn right and left are equal. Other simulation parameters are listed in table 2.

Table 2. Parameters in Simulation.

Name	Value
Acceleration lasting time	5 seconds
Deceleration lasting time	5 seconds
Simulation time	5 hour
Traffic flow	10, 25, 50, 100, 300, 500 vehicles /hour
min_Green*	10 seconds
max_Green*	60 seconds
t_yellow*	5 seconds
Max radio distance	100 meter
Average speed	10 m/s

*min_Red=min_Green+Yellow, max_Red=max_Green+Yellow
t_yellow: yellow light duration time

3.2.2. Simulation Results

The simulation results consist of the following items:

(1) Average travel time from S to D. See Fig. 6.

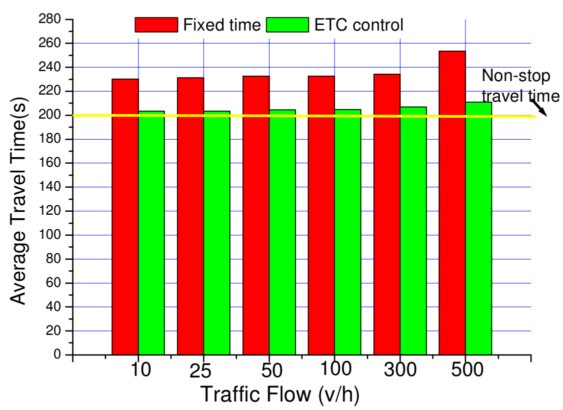


Figure 6. Vehicle average travel time from S to D

Fig. 6 indicates that proposed control has a better performance than fixed time control in the aspect of average travel time. More importantly, the average travel time approximates the yellow line (in Fig. 6), which stands for non-stop travel time. In other words, compared with the fixed time control, vehicles can go through three intersections with shorter waiting time. In particular, the proposed control has better performance when traffic flow is light than when traffic is heavy.

(2) Average total waiting time among A, B, and C. See Fig.7.

Fig. 7 shows the total waiting time in these three intersections: A, B and C. Compared with the fixed time control, the proposed control can be reduced more than 70% (from 71.2% to 77.8%) of the total waiting time.

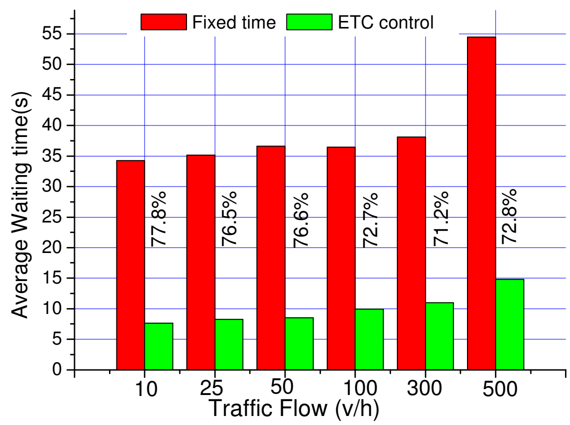


Figure 7. Vehicle average waiting time from S to D

(3) Non-stop passing rate from S to D. See Fig. 8.

Here, we define: non-stop travel time = (Distance)/Speed =2000/10=200(s). If the travel time equal to 200s, we say this vehicle is going through these three intersections without any stops. Fig. 8 demonstrates that the non-stop rate is more than 50%.

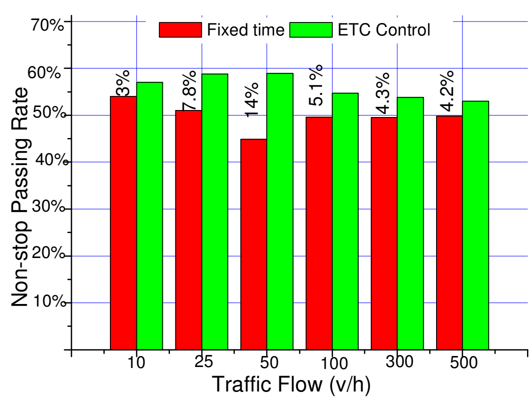


Figure 8. Vehicles non-stop passing rate from S to D

Comparing Fig. 7 and Fig. 8, we find an issue: the average waiting time is reduced greatly while the non-stop rate is improved only from 3% to 14%. This is because we set a minimum red (green) light time, which means when the light needs to change from one colour to another; vehicles have to stop to wait for at least the minimum red light time if vehicles have already arrived at the stop lines. That is the reason why the waiting time declined greatly, but the non-stop rate did not improve much.

(3) Average CO_2 emissions for vehicle from S to D. See Fig. 9.

Fig. 9 implies that the CO_2 emissions can be reduced at least 5.6% compared with the fixed time control. According to formula (2), vehicle travel time and stop times play important parts in CO_2 reduction.

Referring to Fig.7 and Fig. 8, we get the following conclusions: the reduction of waiting time and improvement of non-stop rate both play very important roles in CO_2 reductions.

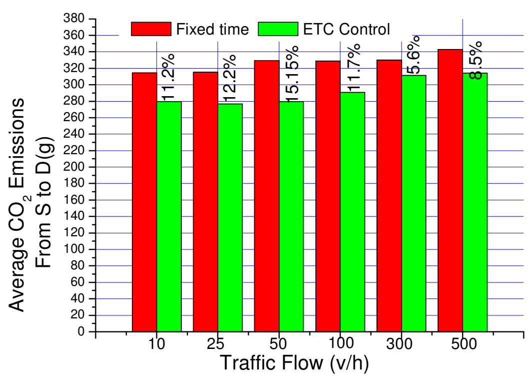


Figure 9. Vehicle average CO_2 emissions from S to D

4. CONCLUSIONS

This paper presents a dynamic traffic light control scheme for reducing vehicle CO_2 emissions. The proposed scheme module consists of five sub-modules: TFDM, TFIPM, TLCM, CM and RTFISM, and functions of each sub-module are given out. We are the first to use ETC devices to detect traffic flow information. With this method, real time traffic flow information can be sent to the traffic centre as accurately and quickly as possible. As well, we proposed a dynamic pre-calculation control algorithm for smoothing vehicle travel. The simulation results indicate that compared with fixed time control, the proposed scheme has much better performance: vehicle average waiting time is greatly reduced and the CO_2 emissions can be reduced to some extent.

Currently, our proposal is evaluated by simulation, and we will take experiments to evaluate our scheme in the future work.

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