

## Research Article

# An Eco-Driving Advisory System for Continuous Signalized Intersections by Vehicular Ad Hoc Network

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With the vehicular ad hoc network (VANET) technology which support vehicle-to-vehicle (V2V) and vehicle to road side unit (V2R/R2V) communications, vehicles can preview the intersection signal plan such as signal countdown message. In this paper, an ecodriving advisory system (EDAS) is proposed to reduce CO<sub>2</sub> emissions and energy consumption by letting the vehicle continuously pass through multiple intersections with the minimum possibilities of stops. We extend the isolated intersection model to multiple continuous intersections scenario. A hybrid method combining three strategies including maximized throughput model (MTM), smooth speed model (SSM), and minimized acceleration and deceleration (MinADM) is designed, and it is compared with related works maximized throughput model (MaxTM), open traffic light control model (OTLCM), and predictive cruise control (PCC) models. Some issues for the practical application including safe car following, queue clearing, and gliding mode are discussed and conquered. Simulation results show that the proposed model outperforms OTLCM 25.1%~81.2% in the isolated intersection scenario for the CO<sub>2</sub> emissions and 20.5%~84.3% in averaged travel time. It also performs better than the compared PCC model in CO<sub>2</sub> emissions (19.9%~31.2%) as well as travel time (24.5%~35.9%) in the multiple intersections scenario.

## 1. Introduction

Greenhouse gases (GHG) are recognized as the main cause of the global warming, with CO<sub>2</sub> being the primary GHG emitted through human activities. Studies by the IEA [1, 2] show that transport was responsible for 23% of world CO<sub>2</sub> emissions in 2014, as shown in Figure 1(a). Within this, the fastest growth in emissions has been from the road transport sector, as shown in Figure 1(b), which increased by 64% since 1990 and accounted for about three-quarters of transport-related emissions in 2014 [1]. In other words, encouraging environmentally friendly driving practices (eco-driving, hereafter) by eliminating unnecessary vehicle acceleration and braking would reduce fuel consumption and CO<sub>2</sub> emissions and contribute to slowing down global warming. The development of eco-driving systems is thus attracting strong interest from academia, vehicle industry, and governments.

A typical driving trip consists of idling, accelerating, cruising, and decelerating, and the related CO<sub>2</sub> emissions depend on changes in driver behavior, road geometry, or

traffic congestion [3]. Barth and Boriboonsomsin show that when a vehicle is idling it consumes more fuel and emits more exhaust fumes than when it cruises at a steady speed [3]. Similarly, Frey et al. [4] show that accelerating and decelerating cause more emissions than idling. In other words, avoiding unnecessary engine idling periods and stops and optimizing driving speeds will reduce CO<sub>2</sub> emissions and fuel consumption. An eco-driving advisory system (EDAS), which provides smooth driving suggestion according to current traffic dynamics and traffic signal plan, can help drivers travel in an environmentally friendly manner.

With vehicular ad hoc network (VANET), also named as connected vehicle technology, vehicles equipped with an on-board unit (OBU) can communicate with road side units (RSU) by vehicle-to-roadside (V2R/R2V) to preview the traffic signal plans and obtain real-time information such as waiting queue length and signal countdown message. Forward collision warning (FCW), which can detect the distance relative to the vehicle ahead, facilitates vehicle safety driving assistance such as adaptive cruise control (ACC). Assuming

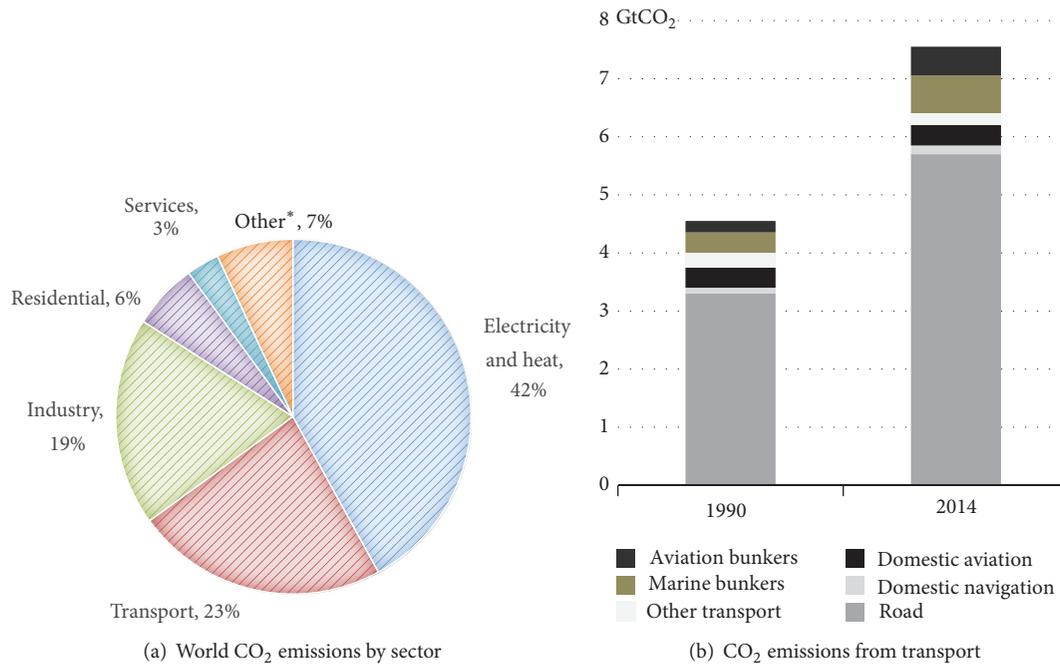


FIGURE 1: Statistics on CO<sub>2</sub> emissions produced by the IEA [1].

that vehicles are equipped with VANET and FCW, OBU can obtain real-time information and calculate the optimal eco-speed to cross an intersection. Our previous work [5] proposed two decision tree based eco-driving suggestion models for an isolated signalized intersection, using OBU to calculate the best eco-driving speed based on real-time information including the traffic signal countdown messages and waiting queue length broadcasted by RSU. These two models are called MaxTM (maximize throughput model) and MinADM (minimize acceleration and deceleration model); simulation results show that MaxTM outperforms MinADM and Open Traffic Light Control Model (OTLCM) [6], being 5% to 102% better than MinADM and 13% to 209% better than OTLCM with regard to CO<sub>2</sub> emissions in the simulation cases, and 8% to 14% better than MinADM and 15% to 231% better than OTLCM in the real traffic cases [5].

MaxTM, MinADM [5], and OTLCM [6] are applied for the isolated intersection scenario; however, in practice vehicles may pass a number of intersections when traveling from origin to destination. In such cases, the isolated intersection eco-driving model may not always be appropriate for use with multiple intersections, since OBU does not acquire the necessary information from the next RSUs, and thus these models cannot provide an optimized speed for the sequential intersections. For example, in Figure 2(a) the vehicle may drive at an unnecessarily high speed if it applies the isolated EDAS model, and it has to stop at the second intersection as it does not have the traffic signal countdown message for the next intersection, as illustrated in Figure 2(b). With the real-time information of the traffic signal timing plans of the sequential intersections, it is possible to design a better eco-driving model to avoid these energy wasting cases, thus lowering fuel consumption and CO<sub>2</sub> emissions.

In this paper we extend our previous works [5, 7] to develop an EDAS that help drivers to avoid unnecessary acceleration, braking, engine idling periods, and stops and to optimize the driving speed in a continuous multiple intersections scenario. Several studies in the literature discuss the multiple intersection scenario. Alsabaan et al. proposed an EEFG model [8] by using decision tree to measure the optimal speed to pass multiple intersections. They then improved this in 2013 [9] by dividing the road region into two parts, one passable and the other unpassable. Asadi and Vahidi [10] use a predictive cruise control (PCC) algorithm in a mathematical programming model to calculate the most economic cruise speed without changing the velocity to pass through sequential intersections. Similar to the underlying concept of the MaxTM, the speed suggested by PCC [10] can be as high as the free flow speed in order to maximize the throughput in conditions when this is possible. The results of their work show that the proposed model can reduce fuel consumption by up to 47% compared to the baseline model. Katsaros et al. [11] proposed GLOSA (Green Light Optimized Speed Advisory), which combines GPS information with common vehicle sensors to obtain more accurate road slope estimates, which are then used to optimize the fuel consumption of the vehicle, thus achieving a 7% reduction in fuel consumption comparing to the baseline. In summary, while a number of works have proposed eco-driving advice systems for multiple intersections [8–11] they are all insufficient or inefficient for practical applications due to the following issues not fully considered.

(1) *Safe Car Following*. Previous studies either do not consider the issue of safely following cars [6, 8, 11] or following a car with a fixed time gap [5]. This approach may result

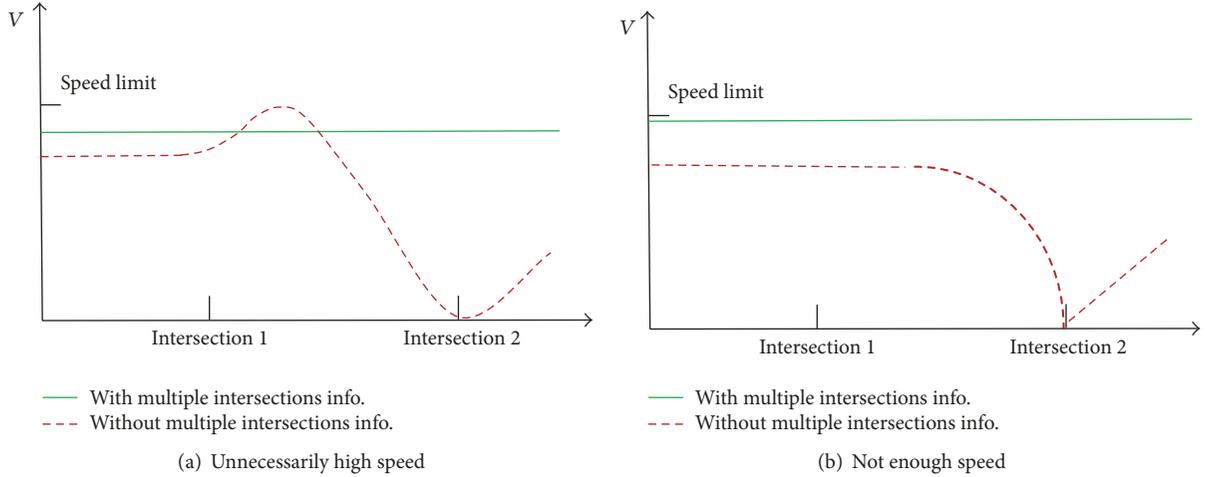


FIGURE 2: Comparison of the system with and without multiple intersection data.

in wasting road capacity at low speed conditions and may cause accidents at high speed ones. A dynamic time gap mechanism, based on the relative speed and distance of the preceding vehicle and the host vehicle, will increase the usage of road capacity.

(2) *Queue Clearing*. When vehicles are stopped by the traffic signals, the time needed for the waiting queue dissipating cannot be neglected, especially when we aim to enable a vehicle to pass smoothly through an intersection without stopping. In related works [6, 8–11], this issue is not considered so that the model would not be practical for realistic applications. Waiting queue dissipating time, which is related to the time needed from current time to the last vehicle in the waiting queue passing through the vehicle, must be considered. When the issue of queue clearing is considered, the resulting eco-driving model will be more accurate and of greater practical use.

(3) *Gliding Mode*. Only three vehicle moving control modes (acceleration, deceleration, and maintaining current speed) are applied in the traditional models [6, 8–11]. However, vehicle gliding mode (free from gas pedal) leverages the engine brake to slow the vehicle without additional fuel consumption, thus causing less  $\text{CO}_2$  emissions than these control modes. When the traffic signal plans are known in advance, vehicles can apply gliding to slow down to the suggestion speed.

In contrast to previous works, we take the above issues into consideration and propose more realistic and accurate suggestions with regard to the optimal eco-driving speed. Safety is the major concern so that the proposed model must follow the safe car following rule, speed limit, and traffic signal regulations. Two eco-driving strategies are proposed and compared in the continuous intersections scenario, namely, the maximized throughput model (MTM) and smooth speed model (SSM). These are illustrated in Figure 3, in which the green time window upper bounded by  $S_H(i)$  and lower bounded by  $S_L(i)$  (both in red dotted line) are

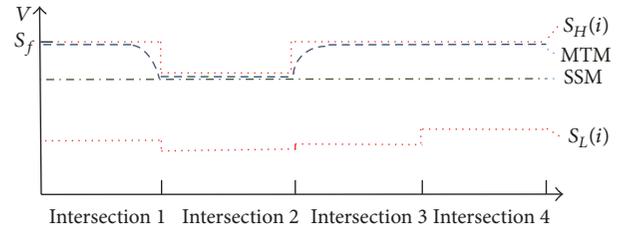


FIGURE 3: Comparison of two strategies: MTM and SSM.

first discovered in four continuous signalized intersections. The MTM strategy (blue dashed line) keeps the suggested speed as high as possible to avoid blocking the following vehicles, thus maximizing the throughput. On the other hand, the SSM strategy (green dashed line) adopts the smooth moving speed upper bound to avoid unnecessary acceleration and deceleration.

The rest of this paper is organized as follows. The assumptions, terminologies, and VANET protocol are presented in detail in Section 2. The algorithms used in MTM and SSM are proposed in Section 3. Two simulation experiments are then discussed in Section 4, including an isolated intersection scenario and multiple intersections scenario, and the proposed system models are compared with the PCC [10], OTLCM [6], and MaxTM [5] strategies. Finally, Section 5 concludes this paper and presents some directions for future works.

## 2. Eco-Driving System Protocol

Assume that each traffic signal controller is equipped with an RSU, and each vehicle is equipped with an OBU which integrates a location module (ex. GPS) and FCW module to detect the speed and distance of the front vehicle. With these capabilities, the main purpose of the OBU is to calculate the recommended speed ( $S_r$ ) and provide driving suggestions (speed up/maintain speed/slow down/glides) to pass through as many intersections as possible by considering all the collected real-time information.

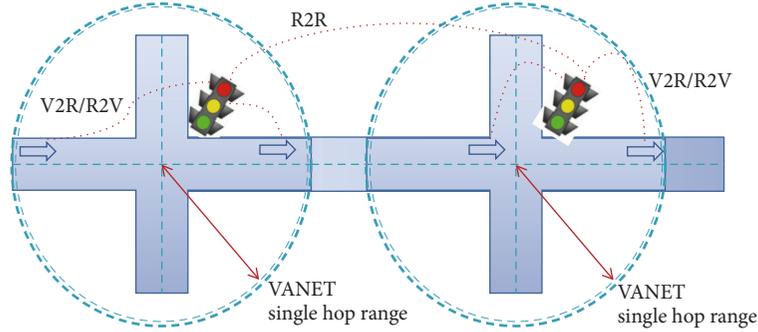


FIGURE 4: Eco-driving advisory system communication schematic.

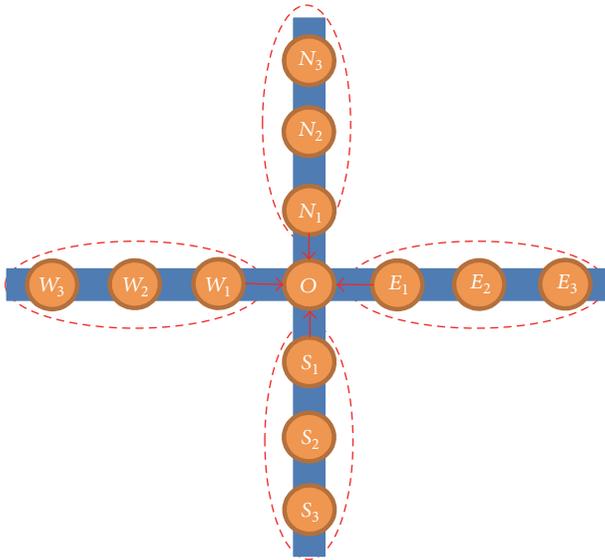


FIGURE 5: RSU-to-RSU information exchange schematic.

The EDAS model is designed on top of the VANET environment with V2R/R2V communication, as illustrated in Figure 4. OBU can collect RSU broadcasted information beyond the range of visual contact. RSU-to-RSU (R2R) communication among the neighborhood RSUs is also included in the system protocol to exchange the signal timing plan and waiting queue length information. As illustrated in Figure 5, every RSU ( $R_O$ ) will exchange real-time information with three neighborhood RSUs ( $R_{Di}$ ) in each direction, including data on the waiting queue, signal phase timing plan, road length, and traffic conditions.

The communication protocol of EDAS is designed as illustrated in Figure 6, which is composed of six steps of R2R, V2R, and R2V communication, as listed in Table 1 and explained as below.

*Step 1* (R2R exchange basic configuration and signal plan). Each RSU, as the host RSU itself, will exchange its information with twelve neighborhood RSUs. The exchanged information, as shown in (1), is organized as two parts including basic configuration and signal plan. Basic configuration of an RSU ( $R_s$ ), as defined in (1), includes RSU ID ( $R_i$ ), location

TABLE 1

Parameters	Value
Road length (m)	200 m; 400 m; 600 m
Traffic volume (vph)	50; 100; 200; 400; 800
Traffic signal (sec) (green/red)	30/30; 45/45; 60/60
Spatial depth	Four intersections
Temporal depth	Four cycles
VANET range (m)	200
Cruise gliding acceleration	$-0.15 \text{ m/s}^2$
Idle gliding speed ( $S_{\min}$ )	2 m/s

( $X, Y$ ), road length to the next intersection in four directions ( $L(n, s, e, w)$ ), and BSS (basic service set) identification in 802.11p (SSID). Traffic signal plan and current traffic information ( $R_p$ ), as defined in (2), consisted of cycle time ( $T_p$ ), main direction (north-south) green split ( $T_g$ ), current phase ( $P_c$ , 0 indicates currently signal is green in north-south direction and red in east-west direction and 1 indicates the reverse case), and countdown remaining seconds in north-south and east-west direction ( $R(n-s, e-w)$ ). With the above definitions, the R2R data exchange protocol is defined in (3), which includes RSU configuration ( $R_s$ ), traffic signal plan ( $R_p$ ), and timestamp ( $T_s$ ).

$$R_s = \{R_i, X, Y, L(n, s, e, w), \text{SSID}\} \quad (1)$$

$$R_p = \{T_p, T_g, P_c, R(n-s, e-w)\} \quad (2)$$

$$\text{R2R} : \{R_s, R_p, T_s\}. \quad (3)$$

*Step 2* (RSUs broadcast synchronized message to OBUs). Each RSU periodically broadcasts message to notify all the vehicles (OBUs) with the range of its transmissions. These messages are used to synchronize the OBUs and wake them up if they are not currently in working status. The message format is shown in (4), including broadcast RSU information ( $R_s$ ) and timestamp for time synchronization. When an OBU receives one or more RSU broadcasted messages from different RSUs, it first decides which one is the host OBU based on the relative location and moving direction and computes the recommended speed using its current location,

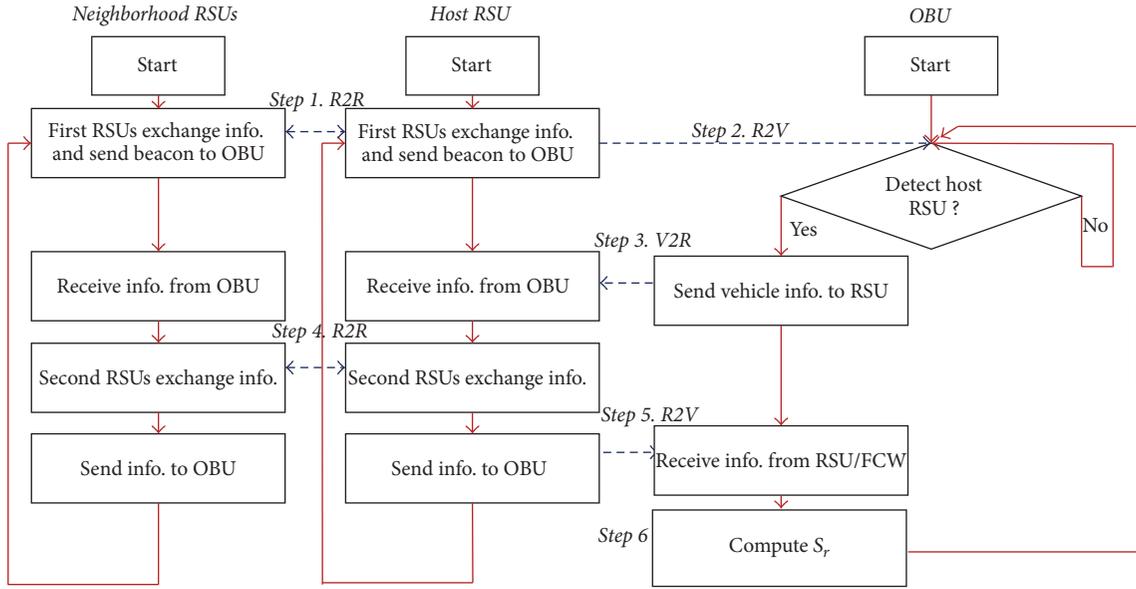


FIGURE 6: EDAS communication protocol.

speed, front vehicle speed and distance (from FCW), and the information collected from the host RSU, as explained in the next section.

$$R2V : \{R_s, T_s\}. \quad (4)$$

*Step 3* (OBUs send information to RSUs). After receiving a synchronized message from the host RSU, an OBU will be in active mode and periodically broadcast information including OBU ID ( $O_i$ ), current speed ( $S_c$ ), moving direction ( $S_d$ ), current acceleration ( $A_c$ ), and position ( $X, Y$ ), as shown in (5). The OBU also starts to detect the distance and speed of the front car via FCW at the same time.

$$V2R : \{O_i, S_c, S_d, A_c, X, Y\}. \quad (5)$$

*Step 4* (RSUs exchange dynamic traffic information collected from OBUs). An RSU exchanges dynamic traffic information with the neighborhood RSUs in this step, calculating the waiting queue length in each directions by estimating the vehicles' positions using the collected OBU information. Each host RSU updates the neighborhood RSUs array each time an RSU exchange event occurs. The exchange message format is defined in (6), including RSU ID ( $R_i$ ), current phase and signal plan ( $R_p$ ), waiting queue length in each direction ( $Q(n, s, e, w)$ ), and timestamp  $T_s$ .

$$R2R : \{R_i, R_p, Q(n, s, e, w), T_s\}. \quad (6)$$

*Step 5* (RSUs broadcast dynamic signal message to OBUs). In this step, the summarized information of all the RSUs, including the RSU itself ( $R_o$ ) and the twelve neighborhood RSUs ( $R_{d,i}$ ), organized as an array as shown in (7), is periodically broadcasted to OBU. The information includes the RSU basic information ( $R_s$ ), traffic signal timing plan ( $R_p$ )

and waiting queue ( $Q$ ) of host as well as neighborhood RSUs, and timestamp  $T_s$ .

$$R2V : \{R_o [R_s, R_p, Q(n, s, e, w)], \quad (7)$$

$$R_{d,i} [R_s, R_p, Q(n, s, e, w), T_s\}.$$

*Step 6* (OBU calculates recommended speed). To calculate the suggested eco-speed, the OBU integrates the collected RSUs array information broadcasted in Step 5, GPS status (location, speed, and moving direction), and front vehicle information, including  $S_p$  (speed of front vehicle), and  $D_p$  (distance to the front vehicle) from FCW. The OBU itself repeats this step several times based on dynamic GPS status and FCW information until the new R2V packet arrives.

### 3. Eco-Driving Advisory System

With the EDAS protocol, OBU can collect the up-to-date information about upcoming traffic signals including RSU locations, road segment length, and traffic signal timing plan, and real-time traffic information, such as the waiting queue length in each direction for each subsequent RSU, and vehicle flow information collected from the host RSU. The goal of the EDAS is to calculate the optimal speed and suggest driving actions to maximize the possibility of moving through the subsequent intersections without stopped or waiting behind the signal. By comparing the current moving speed, the suggested speed will be converted into suggested driving actions such as speed up/brake/maintain speed/glide and can be presented in colored LED bar-liked graphical user interface.

Two critical decisions need to be made before calculating the recommended speed ( $S_r$ ) based on the collected real-time information, and then the three eco-driving strategies are applied, as shown in Figure 7. The suggested driving

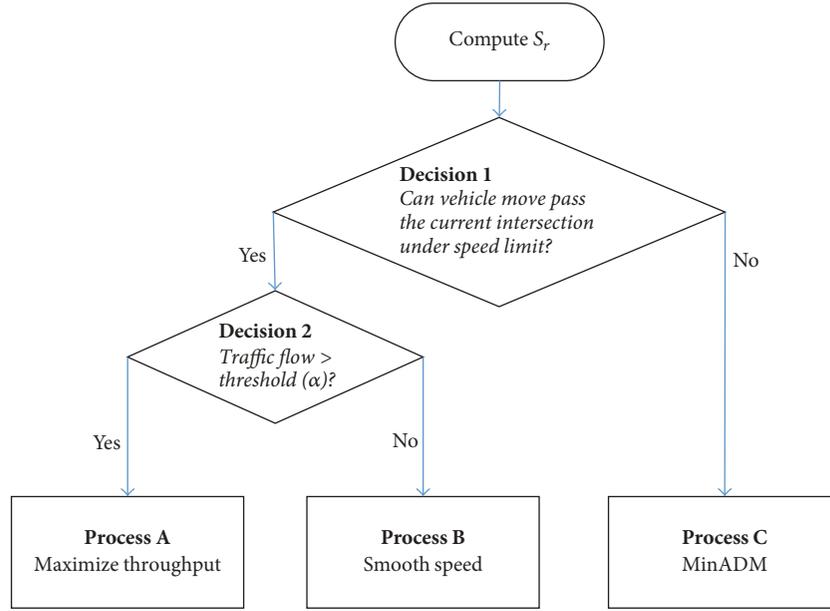
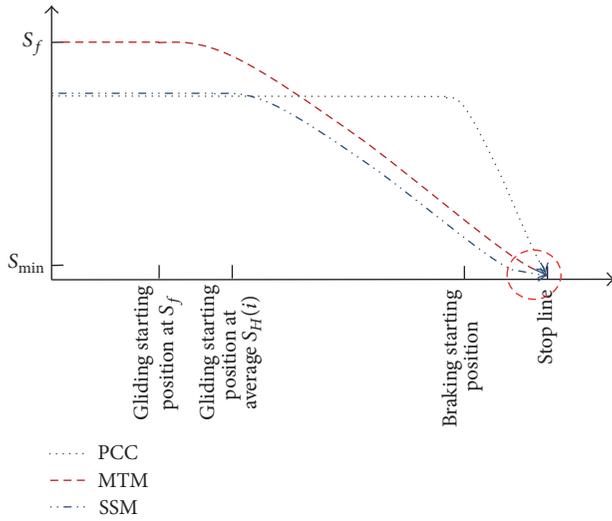
FIGURE 7: Three strategies are applied in computing  $S_r$ .

FIGURE 8: Eco-driving strategies comparison of the three models.

behaviors of the proposed eco-driving strategies MTM and SSM as well as the comparative eco-driving model PCC [10] are illustrated in Figure 8. The major difference between the MTM, SSM, and PCC [10] is that the proposed models apply vehicle gliding concept to leverage the engine brake. MTM adopts free flow speed ( $S_f$ ) and thus applies gliding earlier than the SSM, which adopts smooth speed at upper bound of the speed range ( $S_H(i)$ ). On the other hand, PCC [10] has to brake the vehicle in front of the stop line, where the averaged acceleration is much larger than gliding mode. The three modes, two decision criteria, and some issues about eco-driving are discussed in detail below.

**Decision 1: Isolated or Multi-Intersections Mode.** The top decision node determines if a vehicle should apply multi-intersection mode or isolated intersection mode by calculating

whether a vehicle can pass through the current intersection under its current conditions with the appropriate speed limit. The decision goes to the left subtree if the answer to Decision-1 is “Yes,” and otherwise it goes to the right subtree, where a modified isolated intersection model, the simplified MinADM, will be applied.

To find out whether a vehicle can pass the intersection under current traffic signal phase  $P_c$  (green (0), red (1)), phase remain time ( $R(n-s, e-w)$ ), we can check if the speed needed for the vehicle to move the distance  $D_i$  by time period  $G_t$  falls into the speed limit range  $[S_f, S_{\min}]$ , as shown in (10).  $G_t$  is defined as the remaining green time if the current signal is green, and as the remaining red time plus the queue clearing time ( $T_Q$ ) if the current signal is red, as illustrated in (9). The waiting queue clearance time ( $T_Q$ ), as defined in (8), is obtained from the literature [12].

$$T_Q = \sum_{k=1}^K (|D_k - D_h|) \quad (8)$$

$$G_t = \begin{cases} R_i(ns), & \text{if } P_c = 0 \\ R_i(ew) + T_Q, & \text{if } P_c = 1 \end{cases} \quad (9)$$

$$\text{Decision 1} = \begin{cases} \text{Y,} & \text{if } \left[ \frac{D_i}{G_t} \right] \in [S_f, S_{\min}] \\ \text{N,} & \text{if } \left[ \frac{D_i}{G_t} \right] \notin [S_f, S_{\min}]. \end{cases} \quad (10)$$

**Decision 2: Apply the MTM or SSM Strategy.** Once Decision-1 is “Y,” which means the vehicle can pass through current intersection without stop, the multi-intersections mode should be applied. In Decision-2, the EDAS will decide whether MTM or SSM should be adopted. As shown in Figure 3, the MTM strategy tries to maximize the traffic

throughput so that the suggested speed will be as high as possible while remaining under the speed limit to reduce the possibility of blocking upstream vehicles. The SSM strategy, on the other hand, tries to minimize the acceleration and deceleration to keep the vehicle moving as smoothly as possible. The choice between these two strategies will be a compromise solution. On peak hours, adopting SSM may result in more serious traffic congestion, as it may block the upstream vehicles so that the number of vehicles stopped by the signal will rise, thus making fuel consumption and CO<sub>2</sub> emissions worse. On the other hand, adopting the MTM strategy on off-peak hour may increase the fuel consumption due to unnecessary acceleration.

For this reason we set a compromise factor  $\alpha$  as the threshold to alternate between the throughput oriented and smooth speed models. The value of  $\alpha$  is determined by the sensitivity test, and once  $\alpha$  is determined OBU can decide to apply MTM or SSM based on the vehicle volume information collected from the host RSU.

$$EDAS = \begin{cases} \text{MTM,} & \text{if } \alpha \geq \text{threshold} \\ \text{SSM,} & \text{if } \alpha < \text{threshold.} \end{cases} \quad (11)$$

*Process A: Maximized Throughput Model.* In the MTM and SSM cases, the target of EDAS is to provide the optimal driving speed suggestion so that vehicles can move through multiple sequential intersections without being stopped by a signal. In order to maximize throughput and reduce the possibility of blocking the upstream vehicles, MTM suggests driving at as high a speed as possible while remaining safe and under constraints such as the speed limit, safely following the car in front, and so on. OBU suggests the highest speed under the calculated speed range to pass the next intersection when the vehicle passes the current intersection. By using highest speed  $S_H(i, j)$  and lowest speed  $S_L(i, j)$  from (12) which are the speeds needed to pass the  $i$ th intersection at the beginning and ending time of the green signal at the  $j$ th cycle is calculated, where  $TP_i$  and  $TG_i$  are the cycle time and green time of the  $i$ th intersection, respectively. For example,  $S_H(2, 1)$  indicates the speed needed to drive through the second intersection at the first green second of the next signal cycle ( $j = 1$ ).  $S_r(3)$  indicates the suggested speed to pass the third intersection, which is computed by calculating all the possible speeds in all possible cycles ( $j = 0$  to 4) and intersecting this with the speed limitation  $[S_f, S_{\min}]$ . Based on this, the highest legal speed in the lowest cycle will be the MTM eco-driving suggested speed ( $S_R$ ).

$$S_H(i, j) = \begin{cases} \frac{D_i}{R_i(ns) + j * TG_i}, & \text{if } P_c = 0 \\ \frac{D_i}{R_i(ew) + T_Q + j * TP_i}, & \text{if } P_c = 1 \end{cases} \quad (12)$$

$$S_L(i, j) = \begin{cases} \frac{D_i}{R_i(ns) + j * TP_i}, & \text{if } P_c = 0 \\ \frac{D_i}{R_i(ew) + TG_i + j * TP_i}, & \text{if } P_c = 1. \end{cases}$$

As illustrated in Algorithm 1, MTM first calculates the speed needed to pass the  $i$ th intersection at the  $j$ th cycle in the first green period ( $S_H(i, j)$ ) or the last green period ( $S_L(i, j)$ ); that is, it finds the green band for the vehicle to sequentially drive through the intersections without any signal stops. By using the MTM strategy, OBU will choose the highest speed in the legal speed range which is available by intersecting the calculated speed range ( $[S_H(i, j), S_L(i, j)]$ ) with the legal speed range ( $[S_f, S_{\min}]$ ). The  $MaxSR[i]$  array in Algorithm 1 is applied to keep the calculated highest speed in each cycle. It is initialized as zero and is assigned the calculated speed during the iterations and will remain at zero if there is no legal speed that can be assigned because the intersection of the two speed ranges is empty. The results of the MTM are presented in the suggested speed array  $S_r[i]$ . For example, the array  $S_r = [60, 60, 50, 0]$  indicates that the vehicle can continuously drive through three intersections without stopping, and the suggested speeds for these intersections will be 60, 60, and 50 km/hr.

*Process B: Smooth Speed Model.* If there is a low volume traffic flow then the MTM strategy may not be energy efficient, because unnecessary acceleration would not help the vehicle to pass through more intersections than the SSM strategy. The SSM suggests a smooth driving speed that passes as many intersections as possible at a stable speed. This enables more economic driving as well as a more comfortable experience, since it avoids sudden acceleration or deceleration. Here we introduce a parameter  $\beta$  to let the advised speed range from  $S_H(i, j)$  to  $S_L(i, j)$ , and the recommended speed  $S_r$  in SSM can be obtained from

$$S_r(i) = S_L(i, j) + \beta * (S_H(i, j) - S_L(i, j)). \quad (13)$$

*Process C: Isolated Intersection Model (MinADM).* In this process, the vehicle condition is that it has to stop by the signal at the intersection under the current signal phase (either green or red), and there is no need to consider the probability of blocking any vehicles that are behind it. We thus adopt the minimized acceleration and deceleration model (MinADM), which is simplified from a model proposed in our previous work [5]. In this model, OBU is only concerned with maintaining speed and deciding when to begin slowing down by gliding [5]. The recommended speed  $S_r$  in this model is obtained from (14) and (15).

(1) When the current phase is green

$$S_r = \begin{cases} S_c + A_g \cdot t, & \text{if } \frac{S_c^2}{-2 * A_g} \leq d_I \leq \frac{S_c^2}{-2 * A_g} \\ S_c, & \text{otherwise.} \end{cases} \quad (14)$$

(2) When the current phase is red

$$S_r = \begin{cases} S_c + A_g \cdot t, & \text{if } \frac{S_c^2}{-2 * A_g} \leq d_I - Q \leq \frac{S_c^2}{-2 * A_g} + D_h \\ S_c, & \text{otherwise.} \end{cases} \quad (15)$$

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Input:  $N$ ,           // number of intersections
       $M$ ,           // number of cycles
       $RSU[i]$ ;      // RSU array ( $D_i, R_i(ns), R_i(ew), TG_i, TP_i$ )
Output:  $S_r[i]$ ,     // suggested speed for passing intersections:  $1 \cdots N$ 
(1) // finding out min, max speed for passing through  $i$ th intersection at  $j$ th cycle
(2)   for ( $i = 1; i \leq N; i++$ ) {           // iterate  $N$  intersections
(3)     for ( $j = 0; j < M; j++$ ) {         // iterate  $M$  cycles,  $j = 0$  means current cycle
(4)       if ( $P_c = 0$ ) {                 // current signal is green
(5)          $S_H(i, j) = D_i / (RSU[i] \cdot R_{ns} + j * RSU[i] \cdot TG)$ ; //
(6)          $S_L(i, j) = D_i / (RSU[i] \cdot R_{ns} + j * RSU[i] \cdot TP)$ ;
(7)       } else {                       // current signal is red
(8)          $S_H(i, j) = D_i / (RSU[i] \cdot R_{ew} + RSU[i] \cdot T_Q + j * RSU[i] \cdot TP)$ ;
(9)          $S_L(i, j) = D_i / (RSU[i] \cdot R_{ew} + RSU[i] \cdot TG + j * RSU[i] \cdot TP)$ ;
(10)      }
(11)    }
(12)  }
(13) // calculate the suggested speed for each intersection  $i$ 
(14)   for ( $i = 1; i \leq N; i++$ ) { // iterate  $N$  intersections
(15)      $MaxSR[i] = 0$ ; // initialize suggested speed
(16)     for ( $j = 0; j < M; j++$ ) { // iterate  $M$  cycles to get max legal speed
(17)       if ( $(S_f < S_L(i, j))$ ) continue; // no solution
(18)       if ( $(S_H(i, j) \leq S_f)$ )  $S_r[i] = S_H(i, j)$  else  $S_r[i] = S_f$ ;
(19)       if ( $(MaxSR[i] < S_r[i])$ )  $MaxSR[i] = S_r[i]$ ; // choose the fastest
(20)     }
(21)      $S_r[i] = MaxSR[i]$ 
(22)   }
(23)   Output  $S_r[i]$ 

```

ALGORITHM 1: MTM eco-driving suggested speed ( $S_r$ ).

*The Issue of Safely Following Cars.* In EDAS the top priority is the issue of safely car following, whatever the suggested speed is, OBU must obey the car following rule to prevent the vehicle from being closer than the safe distance. In such cases, OBU will dynamically calculate the suggested speed to maintain a safe distance from the front vehicle.

If the FCW module detects a front vehicle, OBU will switch to car following mode due to safety concerns. In this study, we apply ISO 15623 [13] to keep a safe distance between the focal vehicle and the one in front. As shown in (16), the safe distance ( $D_s$ ) can be calculated by the vehicle's current speed ( $S_c$ ), front car current speed ( $S_p$ ), average maximum deceleration of both the vehicles ( $A_d$ ), OBU refresh time  $t$ , and additional safe headway space ( $D_h$ , and in this study we set this as 1 meter). The suggested safe speed  $S_s$  for maintaining the safe distance  $D_s$  in the car following mode is defined in (17), which can be inferred by combining Newton's three law of motions with (16).

$$D_s = S_c \cdot t + \left( \frac{S_c^2 - S_p^2}{2A_d} \right) + D_h \quad (16)$$

$$S_s = 2S_p - S_c + A_p \cdot t - \frac{2}{t} (D_s - D_p) \quad (17)$$

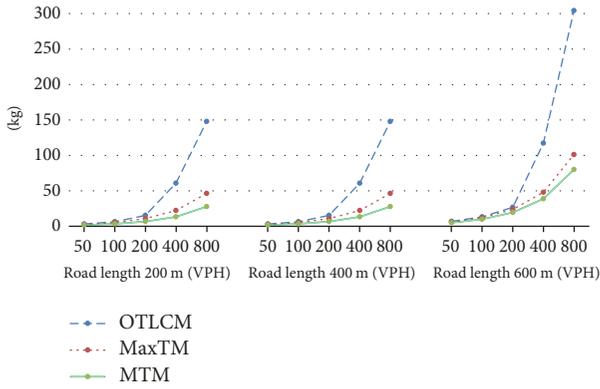
*Driving Action Suggestion.* With the suggested moving speed  $S_r$  (without a front vehicle) or  $S_s$  (with a front vehicle), OBU can suggest appropriate eco-driving actions, including

speeding up, maintaining current speed, gliding (no pressure applied on the gas pedal), maintaining the safe speed, or braking by comparing the suggested speed ( $S_s$  or  $S_r$ ) and the vehicle's current speed ( $S_c$ ).

#### 4. Simulation Study and Discussions

Three experiments are designed to evaluate the performance of the proposed MTM and SSM by comparing them with three related models. In the isolated intersection scenario, MTM is compared with MaxTM [5] and OTLCM [6]. In the multiple intersection scenario, MTM and SSM are compared with MaxTM [5] and PCC [10]. The third experiment tests 10 real cases collected from local city traffic bureau in isolated scenario. The performance of all the models is evaluated and simulated using Arena [14], a general simulation software which is effective in modeling and analyzing processes or flows.

To simplify the proposed model and without loss of generality, the traffic signal in the yellow (Y) period is combined with that in the green (G) period, and all the red (AR) periods are combined into the red (R) period. The assumptions used in all the simulation experiments are as follows: (1) all the vehicles are with traditional combustion engine, hybrid electric vehicle (HEV), and plugin hybrid electric vehicle (PHEV) are not considered in this work; (2) each traffic signal is equipped with an RSU, and the OBU penetration rate is 100%; (3) there are no lane changes or overtaking; (4) drivers always follow the recommend speed;

FIGURE 9: CO<sub>2</sub> emission comparison in isolated intersection case.

(5) there is only one type of vehicle; (6) all the signal cycle times and green splits (the fraction of a cycle when the signal is green) are the same in one simulation; and (7) both RSU and OBU adopt the one-hop message broadcasting mechanism. The simulation parameters are summarized in Table 1. The VANET one-hop communication range is 200 m, the road length parameters are 200~600 m, the traffic volume (in each direction) parameters range from 50 to 800 vph, and the traffic signal green-red period parameters are 30/30, 45/45, and 60/60. For each OBU, four sequential intersections are simultaneously considered in the spatial dimension, and four cycles are considered for each RSU in the temporal dimension.

To evaluate and compare the CO<sub>2</sub> emissions we adopt the Models for Projecting Energy Consumption and Air Pollutants Emissions (MPECAPE) [15], which considers microscopic CO<sub>2</sub> emissions and was developed by the Institute of Transportation, Ministry Of Transportation and Communications (MOTC) in Taiwan. It is established in 2007 by MOTC using emissions data collected from various types of vehicles considering multiple vehicle driving scenarios, including on highways and in townships and urban areas.

*Experiment 1* (isolated intersection scenario). In an isolated intersection located in the center of four road segments in four directions, each road segment has two lanes connected in two directions, one for each direction. The proposed MTM is compared with MaxTM [5] and OTLCM [6] with regard to CO<sub>2</sub> emissions and average travel time, as shown in Figures 9 and 10, respectively. The results show that in the case of road lengths 200 m, 400 m, and 600 m, the CO<sub>2</sub> emission of MTM is less than MaxTM [5] and OTLCM [6] models on the cases from sparse traffic condition (50 vph) to congested condition (800 vph). The travel time simulation also shows the similar result; MTM has the best performance averaged travel time and the travel time variability is very stable in all the road length and traffic volume combination cases.

*Experiment 2* (multiple intersections scenario). A cross road network topology consisting of thirteen intersections, as shown in Figure 5, is applied in the experiment. The assumptions and parameters are the same as those in Experiment 1. The two proposed strategies, MTM and SSM, are compared

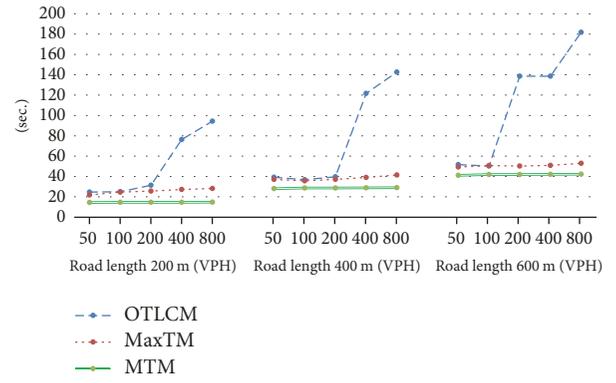
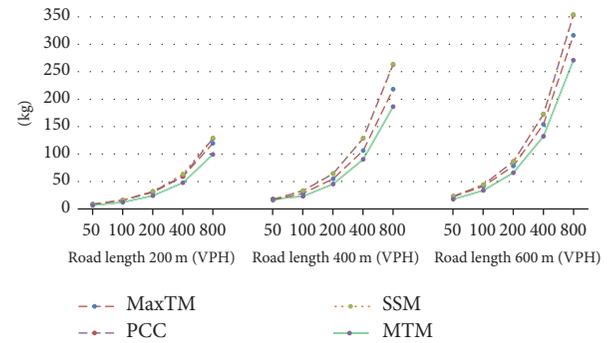


FIGURE 10: Averaged travel time comparison in isolated intersection case.

FIGURE 11: CO<sub>2</sub> emission comparison in multiple intersections case.

with MaxTM [5] and PCC [10] with regard to CO<sub>2</sub> emissions and average travel time, as shown in Figures 11 and 12, respectively. In multiple intersections simulation, all the performances of these four models are quite well; MTM outperforms the other three models SSM, PCC [10], and MaxTM [5] in both CO<sub>2</sub> emissions, average travel time. Two interest points are revealed in this experiment. First, the performances of PCC [10] and SSM are almost the same due to the similar strategy and idea behind these models (except the gliding). Second, although MaxTM [5] is an isolated model which without the real-time knowledge of multiple intersections, it performs better than the PCC [10] and SSM. This may due to when SSM tries to smoothly pass through the multiple intersections, the green band (ranged from  $S_H(i, j)$  to  $S_L(i, j)$ ) will be narrower when the number of previewed intersections increased. This will result in the suggestion speed ( $S_r$ ) advised by the SSM being much less than the MaxTM [5], which blocks the upstream vehicles and increases the possibilities of stops by signal for them.

*Experiment 3* (real data collected from Tainan traffic bureau). In addition to these simulation cases, 10 real traffic cases including AM and PM peak hours as well as normal hours (as listed in Table 2) collected from the Transportation Bureau of Tainan City Government are also simulated. The collected parameters including road length, traffic flow volume, and traffic signal plan (green and red splits) are stated in Table 3. The proposed MTM is compared with MaxTM [5] and

TABLE 2: Case definition of the real traffic cases.

Case name	Duration	Classification
C1, C6	7:00 to 12:00 am	Hybrid
C2, C7	12:00 to 17:00 am	Normal
C3, C8	7:00 to 9:00 am	AM peak
C4, C8	17:00 to 19:00 pm	PM peak
C5, C10	19:00 to 24:00 pm	Night time

TABLE 3: Sample parameters of the real traffic cases simulation.

Case name	Time plan offset	VD ID	Road length	Traffic flow	Timing plan $T_G$	Timing plan $T_R$
C1	Initial	V009600	180 m	279.72	80 s	40 s
C2	Initial	V009600	180 m	383.80	80 s	40 s
C3	Initial	V009600	180 m	360.85	80 s	40 s
C4	Initial	V009600	180 m	526.06	90 s	40 s
C4	105 min	-	-	-	80 s	40 s
C5	Initial	V009600	180 m	419.02	80 s	40 s
C5	120 min	-	-	-	75 s	45 s
C5	195 min	-	-	-	55 s	35 s
C6	Initial	V052370	170 m	312.5	75 s	45 s
C7	Initial	V052370	170 m	443.35	75 s	45 s
C8	Initial	V052370	170 m	398.59	75 s	45 s
C9	Initial	V052370	170 m	507.54	95 s	35 s
C9	105 min	-	-	-	75 s	45 s
C10	Initial	V052370	170 m	401.51	75 s	45 s
C10	195 min	-	-	-	63 s	27 s

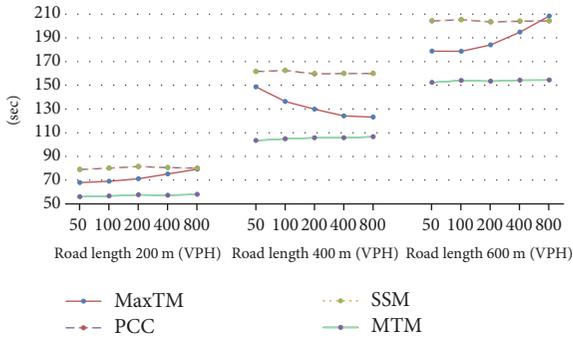


FIGURE 12: Averaged travel time comparison in multiple intersections case.

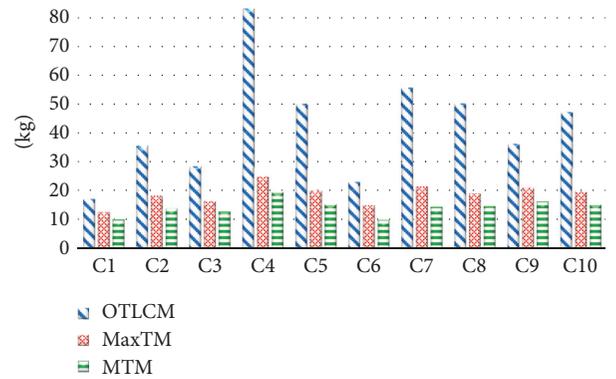


FIGURE 13: CO2 emission comparison in 10 real traffic cases.

OTLCM [6] with regard to CO<sub>2</sub> emissions and average travel time, as shown in Figures 13 and 14, respectively. The results show that the MTM outperforms MaxTM [5] and OTLCM [6] models in CO<sub>2</sub> emissions and average travel time on all the 10 cases.

### 5. Conclusions

With VANET, OBU on the vehicle can collect the information from RSUs and preview the intersection signal plans so that it can decide the optimal eco-driving speed to pass through multiple intersections with the minimum possibilities of stops. This work proposes a hybrid model that combines three

strategies including MTM, SSM, and MinADM to provide eco-driving suggestions. With the proposed EDAS, the suggested driving actions can help vehicles avoid unnecessary acceleration and braking and unnecessary stops. Moreover, several practical issues with regard to applying EDAS in the real world are taken into consideration including a safe and efficient car following mode, signal queue clearing time, cruise gliding, and idle gliding.

Traditionally, three indexes are applied to measure the performance of an intersection in traffic management science, including minimizing waiting queue length, minimizing vehicle waiting time, and maximizing the average cycle

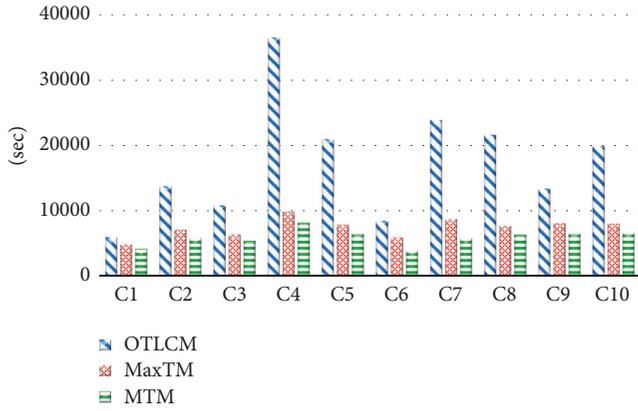


FIGURE 14: Travel time comparison in 10 real traffic cases.

time throughput. These indexes are generally considered to be positively correlated to each other, and thus if one index improves so will the two others. We adopt a strategy of maximizing the average cycle time throughput, and the simulation testing yielded promising results. Originally the MTM is designed for multiple intersections cases; however, the results show that it is 18.6%~40.1% better than MaxTM [5] and 25.1%~81.2% better than OTLCM [6] in CO<sub>2</sub> emissions, 16.6%~47.7% better than MaxTM [5], and 20.5%~84.3% better than OTLCM [6] in averaged travel time when MTM is applied to the isolated intersection scenario. For the multiple intersections scenario, the proposed MTM and SSM outperformed the PCC [10] model as well as the MaxTM [5]. Comparing to PCC [10], MTM is 19.9%~31.2% better in CO<sub>2</sub> emissions and 24.5%~35.9% better in travel time.

In real applications eco-driving recommendations depend heavily on traffic conditions [5]. While the maximize throughput strategy has good performance in congested as well as normal traffic conditions, it may not be suited for the case of very low traffic flow in off-peak hours, since the chance of blocking the rear vehicles is very low. In such conditions the SSM approach should be applied, as it may have better performance than in the MTM. In future work the traffic congestion threshold ( $\alpha$ ) will be studied in more detail and decided by sensitivity test experiments. Moreover, the smooth speed control parameter ( $\beta$ ), which is applied to decide the suggested speed in SSM (as shown in (13)), can be further studied to acquire the optimal driving speed. Once these issues have been dealt with, the MTM and SSM can be combined into one eco-driving advisory system that is more practical for use with continuous signalized intersections.

## Notations

$R_i, R_s, R_p$ : RSU ID, configuration, and signal plan  
 $R_o, R_{d,i}$ : Host RSU,  $i$ th neighborhood RSU in direction  $d$   
 $O_i$ : OBU ID  
 $n, s, e, w$ : North, South, East, West  
 $n-s, e-w$ : North and south direction, East and west direction

$X, Y$ : Longitude and latitude  
 $T_p$ : Cycle time period  
 $T_g(n-s)$ : Green light time period in north-south direction  
 $T_s$ : Time stamp  
 $P_c$ : Current phase (0 = green, 1 = Red) in main direction (north-south)  
 $R(n-s, e-w)$ : Countdown remaining period  
 $L$ : Road length ( $L_n, L_s, L_e, L_w$ )  
 $Q_d$ : Queue length in direction  $d$   
 $T_Q(d)$ : Queue dissipating time for direction  $d$   
 $S_f$ : Free flow speed (Or speed limit)  
 $S_{min}$ : Min speed limit  
 $S_r$ : Recommend speed  
 $S_s$ : Safety speed for car following  
 $S_c$ : Current speed  
 $S_p$ : Front car speed  
 $S_d$ : Direction  
 $S_H(i, j)$ : Pass speed upper limit for  $i$ th signal at  $j$ th cycle  
 $S_L(i, j)$ : Pass speed bottom limit for  $i$ th signal at  $j$ th cycle  
 $A_c$ : Current acceleration  
 $A_p$ : Acceleration of the front car  
 $A_g$ : Cruise gliding deceleration  
 $D_p$ : Front car distance  
 $D_h$ : Minimum discharge headway  
 $D_k$ : Headway of the  $k$ th queued vehicle  
 $SSID$ : RSU Wi-Fi SSID  
 $\alpha$ : Traffic congestion threshold  
 $\beta$ : SSM control parameter.

## Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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