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Eco-Approach and Departure (EAD) Application for Actuated Signals in Real-World Traffic

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ABSTRACT

The connected vehicle Eco-Approach and Departure (EAD) application for signalized intersections has been widely studied and is deemed to be effective in terms of reducing energy consumption and both greenhouse gas and criteria pollutant emissions. Prior studies have shown that tangible environmental benefits can be gained by communicating the signal phase and timing (SPaT) information of the upcoming traffic signals with fixed time control to the driver. However, similar applications to *actuated* signals pose a significant challenge due to their randomness caused by vehicle actuation. Based on the framework previously developed by the authors, real-world testing has been conducted along the El Camino Real corridor in Palo Alto, California to evaluate the system performance in terms of energy savings and emissions reduction. Strategies and algorithms are designed to be adaptive to the dynamic uncertainty for actuated signal and real-world traffic. It turns out that the proposed EAD system can save 2% energy for all trips, and 6% energy for the trip segments within DSRC ranges of road-side units under light traffic conditions. The proposed system can also reduce 7% of CO, 18% of HC and 13% of NOx for all trips. Those results are compatible with the simulation results and validate the previously developed EAD framework.

KEYWORDS: Eco-Approach and Departure, field test, Connected Vehicles, actuated signal

INTRODUCTION AND MOTIVATION

Transportation activity, including both goods and people movement, have been playing a crucial role in fossil fuel consumption and air pollutant emissions. In 2015, the United States consumed approximaely 97.5 quadrillion BTUs (Quads) of energy, and 28.4% of this was used for transportation purposes [1]. According to the estimation from U.S. Environmental Protection Agency (USEPA), transportation activities were responsible for about 26% of the total U.S. greenhouse gas (GHG) emissions in 2014 [2]. Meanwhile, in many areas, vehicle emissions have become the dominant source of air pollutants, including greenhouse gas (GHG), carbon monoxide (CO), volatile organic compound (VOCs), nitrogen oxides (NOx), particulate matter (PM), and polycyclic aromatic hydrocarbons (PAH) [3].

To save energy and reduce air pollutant emissions, more and more rigorous standards and regulations have been established as a strong driving force to promote motor vehicles' fuel economy and reduce their tailpipe emissions [4]. On the other hand, the rapid development in vehicle and communication technologies promotes the prototype applications on eco-driving which improves the transportation energy efficiency by conducting smarter driving styles. In Europe, the Energy Efficiency Intersection (EEI) service of Compass4D project has been implemented to reduce energy use and vehicle emissions at signalized intersections [5]. The eCoMove project funded by the European Commission (EC) built up a cooperative, efficient and ecological transportation system based on vehicle-to-vehicle (V2V) and vehicle-and-infrastructure (V2I/I2V) communication [6]. In the United States, the Applications for the Environment: Real-Time Information Synthesis (AERIS) program has been initialized to investigate the eco-friendly transportation operations in Connected Vehicle (CV) environments [7].

Among all these programs, eco-driving at signalized intersection is particularly promising for fuel saving and emission reduction in urban area, as drivers would effectively reduce stops and idling and avoid unnecessary acceleration and deceleration by receiving signal phase and timing (SPaT) information in advance [8-12]. The Eco-Approach and Departure (EAD) application is one primary example in which drivers are guided to travel through (including to approach and to depart from) signalized intersections in an eco-friendly manner using SPaT and Geometric Intersection Description (GID) information broadcasted by the traffic signals. With the knowledge of incoming signal information, CVs can improve their fuel efficiency by following well-designed speed profiles [13]. This application for fixed-timing signal control has been validated using microscopic simulation models, showing 10-15% reduction on fuel consumption and CO_2 emissions [14]. The EAD concept also works efficiently with congested traffic where preceding queues have to be considered, by utilizing real time vehicle detection and signal information system [15]. The performance can be further enhanced by forming a platoon of equipped vehicles with tight arrival headways [16]. A field study was conducted in the Turner Fairbanks Highway Research Center (TFHRC) in McLean, Virginia in August 2012 to implement EAD in the real world and demonstrate its benefit on energy savings [17]. In addition, previous studies reveal that under actual driving conditions, the driver's behavior adaptability is also an important factor on the effectiveness of EAD [18].

All the above studies were conducted under the assumption of fixed-timing signals whose SPaT information is deterministic and is well-defined for vehicle trajectory planning. The development of EAD application for *actuated* signals is much more challenging as the intervals may be (re)called and/or extended in response to vehicles' (and/or pedestrians') actuations. As an extended work supported by the Exploratory Advanced Research (EAR) program of Federal Highway Administration (FHWA) [19], the authors have developed an EAD application for actuated signals [20], which uses the derived minimum and maximum times to next phase as principal SPaT information and considers the dynamics (e.g., relative speed and distance from radar detection) of the preceding vehicle (along the same lane). This application was first tested in simulation environment where an isolated intersection was modeled with SPaT information from real-world operation of a signal controller. The results showed significant energy consumption and emissions reduction for the EAD-equipped vehicle(s). Especially when the initial arrival speed is relatively low (below 30 mph), the fuel consumption can be reduced by 12%, and emissions can be reduced by 11%~30%, depending on the type of pollutant.

A preliminary field operational testing has been conducted in Riverside, California [21] to evaluate the system performance in terms of energy savings and emissions reduction. Four typical scenarios that cover most of traffic and signal conditions were evaluated. For high entry speed, an EAD system can save 5%-10% energy. For low entry speed, the energy saving may go up to 7%-26%. This field test validated the framework and simulation results in [20]. It is important to note that this experiment was conducted under controlled conditions with predefined signal actuation plans and traffic situations. It is more valuable but challenging if the EAD algorithm is tested in real-world traffic.

In this paper, we present the experiment setup, algorithm design and numerical results for the field testing in a real-world actuated signalized corridor. The following section provides details on vehicle and signal setup, Human-Machine Interface (HMI) design and testbed information. Next, a detailed description of the EAD strategy design is presented, followed by a comprehensive numerical evaluation. The last section concludes the paper with further discussion.

EXPERIMENT SETUP

The field test was conducted in Palo Alto, California in November 2015. Fig. 1 shows the test corridor and position of all DSRC enabled intersections. The northbound trips started from a parking lot near the intersection of Dinah's Ct and El Camino Real. Two drivers then drove along the El Camino Real corridor, passed through test intersections from Maybell to Stanford Ave., and finished the tests by making left-turns at the intersection of Serra St. The southbound trips started from the roadside parking area between Serra St. and Stanford Ave., and reversed the northbound path. The length of each trip is about 1.7 miles. One vehicle traveled on the inner through lane and the other traveled on the adjacent lane on the right. Two vehicles entered the test corridor at the same time under the same speed for each northbound or southbound trip. They switched lanes every three runs to minimize the potential impact of different traffic conditions on two lanes during the test. Most test runs were made between 10 am and 4 pm or between 8 pm and 9 pm to avoid AM and PM peak hour traffic, because it is expected that heavy traffic might provide too limited room to accommodate any EAD-induced behavior change for an individual equipped vehicle.

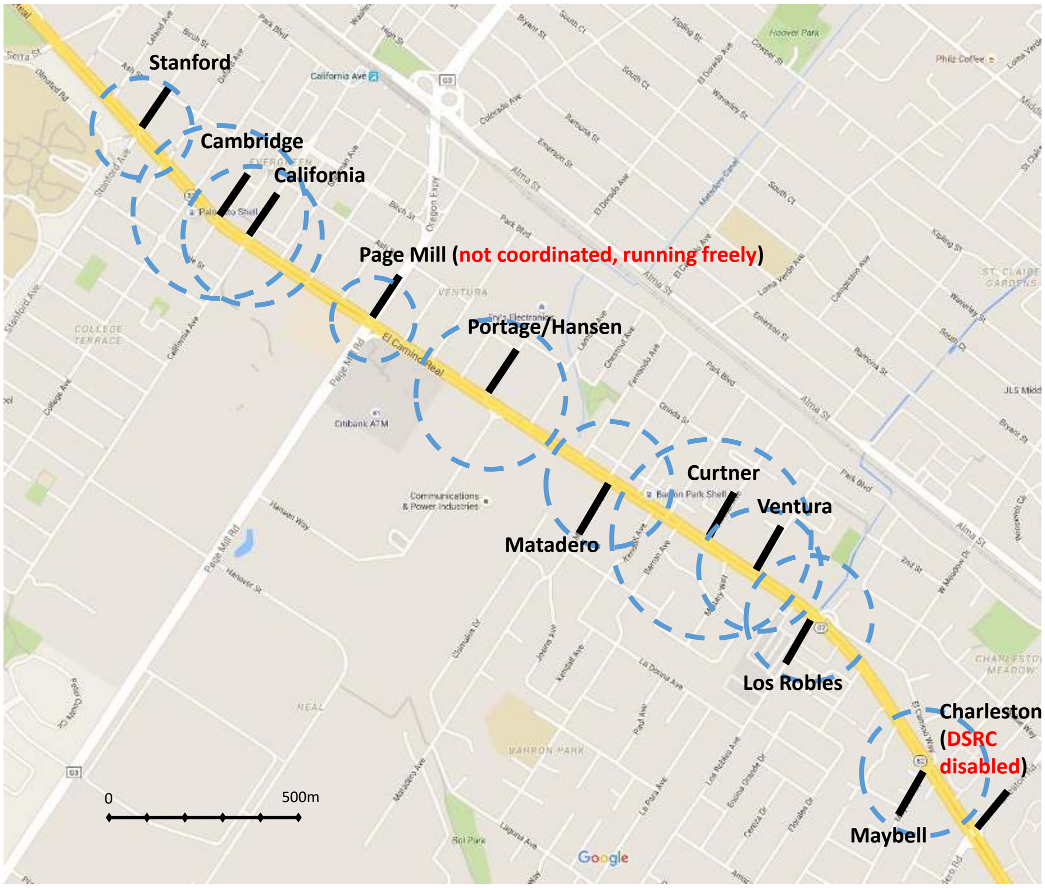


FIGURE 1. Test corridor and DSRC state

Test Vehicles

A 2008 Nissan Altima research test vehicle has been set up for the field test. A real-time automotive radar system was installed in front to detect the relative distance and relative speed of the preceding vehicle. The on-board system receives position information via GPS, and vehicle dynamics information through on-board diagnostics (OBD). This vehicle was also equipped with a Dedicated Short Range Communication (DSRC) modem, an on-board computer, and a 7-inch automotive-grade display to serve as an artificial dashboard. The on-board computer acquired high-resolution vehicle dynamics data (e.g., instantaneous speed and RPM) from the CAN BUS via an OBD-II interface and parsed the SPaT and GID messages received from the DSRC modem at 10 Hz. Based on the GPS location and a developed map-matching algorithm, the vehicle's distance-to- intersection is estimated. The radar detection data were also processed to estimate several key parameters related to the preceding vehicle along the same lane. The EAD algorithm integrated data from multiple sources to calculate the recommended vehicle trajectory. Key information for EAD was then delivered to the driver through the artificial dashboard display.

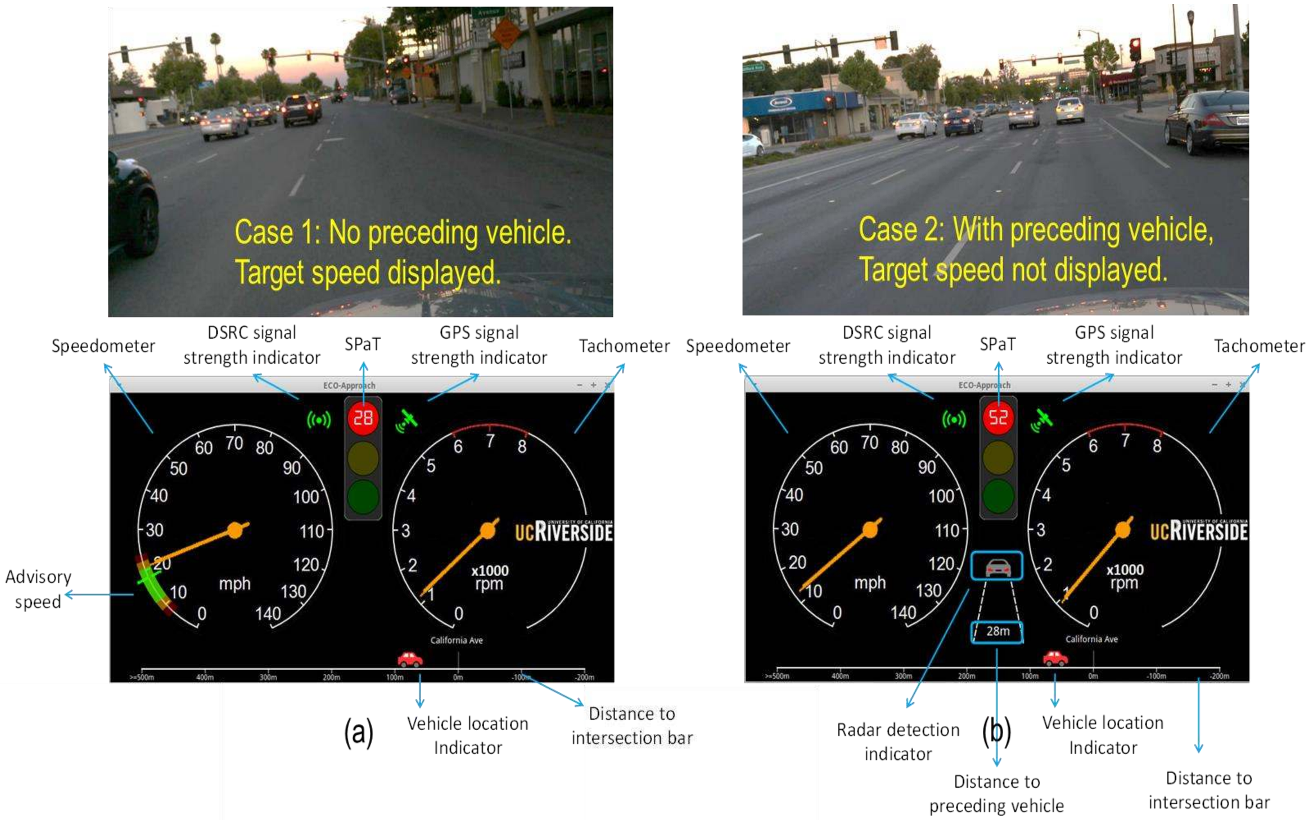


FIGURE 2. Human-Machine Interface under different traffic conditions

Human-Machine Interface (HMI) Design

We proposed a graphic user interface (GUI) that presents a number of items to the driver mainly for test and development purposes (see Fig. 2). As shown in the figure, the following were displayed:

1) The vehicle's current speed (i.e., speedometer);
2) The engine's Revolutions Per Minute (RPM);
3) An "advisory" speed as calculated from the velocity planning algorithm;
4) The SPaT countdown information for the current signal phase;
5) Signal strength indicators for DSRC and GPS, respectively;
6) Radar detection indicator (i.e., indicating if a vehicle was within the radar detection range);
7) Distance to the preceding car within the radar detection range (in meters);
8) Distance to the intersection (in meters);
9) Vehicle and intersection location indicators.

Fig. 3(a) shows the case when there was no preceding vehicle nearby in the same lane. The target speed estimated from the trajectory planning algorithm was then displayed at the speedometer. Fig. 3(b) shows the case when radar detected a preceding vehicle which was 28 m in front. The display of target speed was then turned off to avoid any distraction. Instead, the HMI displayed a vehicle icon at the center of the artificial dashboard, with the distance shown at the bottom.

Actuated Signal Control

Unlike the fixed-timing control where all the approaches are pre-timed in both sequence and duration, the actuated signal controllers which are widely deployed in U.S. operate in a much more flexible way in response to the real-time traffic and pedestrian conditions. However, due to the uncertainty of the vehicle (and/or pedestrian) arrival pattern at the intersection, it is much more difficult to predict the remaining time (i.e. time-to-change) of each phase (or even the phase sequence) for actuated signals than fixed-timing ones. In practice, the minimum time-to-change and maximum time-to-change for the current phase are broadcasted via SPaT message, providing boundary values for signal timing prediction.

The test corridor in this paper was operated under coordinated actuated traffic signal control during the field test. The northbound and southbound through movements were controlled as the synchronized phases with guaranteed green time while the phases of other approaches were governed by the actuations. For the green time of synchronized phases, the minimum time-to-change was computed as the difference of minimum green and the elapsed green time in the phase, and the maximum time-to-change were calculated as the time to max out point or force-off point, depending on which comes earlier. For the green time of non-signalized phases, both the minimum and maximum time-to-change were calculated with respect to their force-off points. For the red time, the minimum and maximum time-to-change were calculated as the sum of minimum/maximum time-to-change of the preceding green phases, yellow intervals, and red clearance intervals.

The signal state datagrams were transmitted from Caltrans 2070 controller via AB3418 protocol over serial RS-232 communications. They were encoded into SPaT messages (in compliance with SAE J2735 standard [ref]) which were broadcasted over DSRC at 10 Hz. Note that in the El Camino Real testbed, the time-to-change information only occupied one object per phase in the SPaT message. Therefore, from a conservative perspective, only minimum time-to-change was provided for the green phase, while maximum time-to-change was provided for the red phase.

EAD ALGORITHM DESIGN FOR ACTUATED SIGNALS

System Architecture

In [20], we developed a generalized trajectory planning algorithm for the EAD application that is compatible with actuated signals. As shown in Fig. 3, multiple data sources, such as SPaT information, GPS location, vehicle dynamics and preceding vehicle information from radar, are integrated in this system. The maximum/minimum time-to-change for the current phase is extracted from SPaT message broadcasted by Road-side DSRC Unit (RSU). The distance to the intersection is calculated after map matching based on the current GPS location. Vehicle dynamics from the vehicle’s on-board diagnostics (OBD) port, and activity data of the preceding vehicle from a forward looking automotive radar are also collected by the EAD system. A vehicle trajectory planning algorithm is developed to provide speed recommendation based on the state of the subject vehicle, preceding vehicle, and upcoming traffic signal. To avoid distraction when the subject vehicle follows preceding vehicles, a state machine is introduced for governing the display of the recommended speed based on detection from radar. Noted that the proposed EAD framework is also applicable to fixed signals, as fixed signals can be considered as actuated signals with equal minimum and maximum time-to-change for each phase.

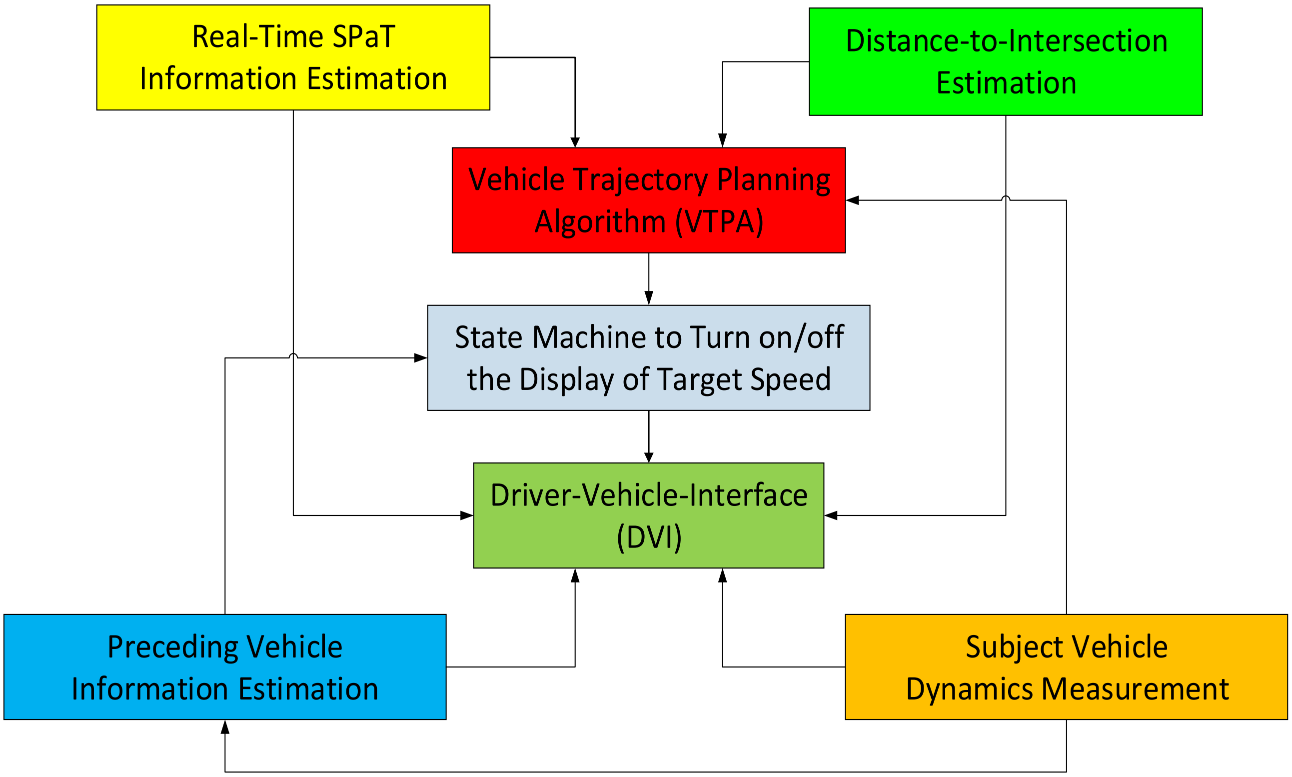


FIGURE 3. System Architecture

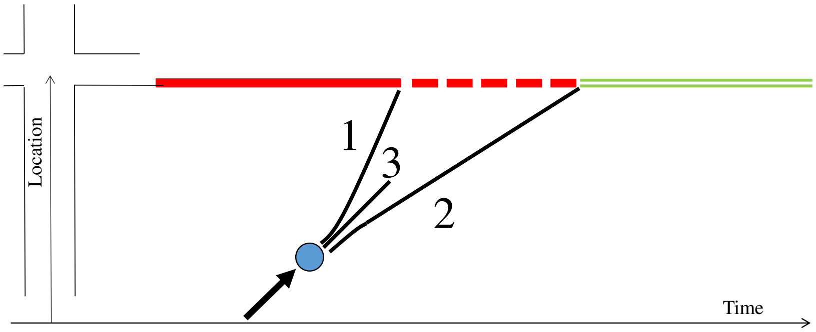
To ensure a safe, comfortable, time-efficient and eco-friendly trip in the approach and departure process in real-world traffic, the following objectives are considered when developing the EAD algorithm:

1) *Safety* is the primary goal and basic requirement for any CV applications. In EAD algorithm, we set up multiple rules to guarantee that the vehicle can keep safe distance with preceding vehicles while obeying traffic rules, e.g. not speeding and not crossing on red;
2) The second objective is to *avoid or minimize idling* at the intersection; and
3) The third is to *avoid unnecessary acceleration and deceleration*.

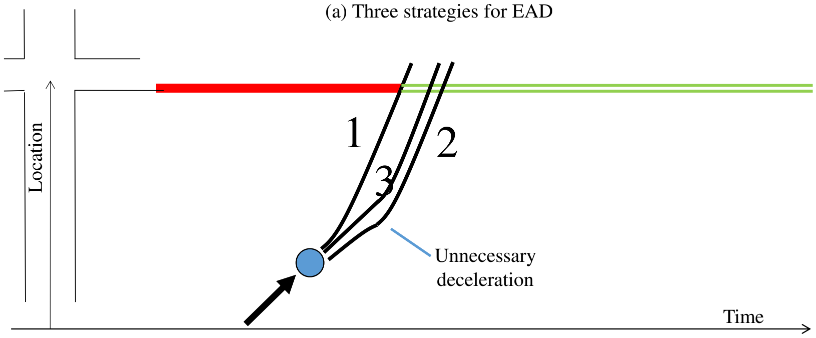
They work together to reduce fuel consumption and emissions.

EAD Strategy for Actuated Signals

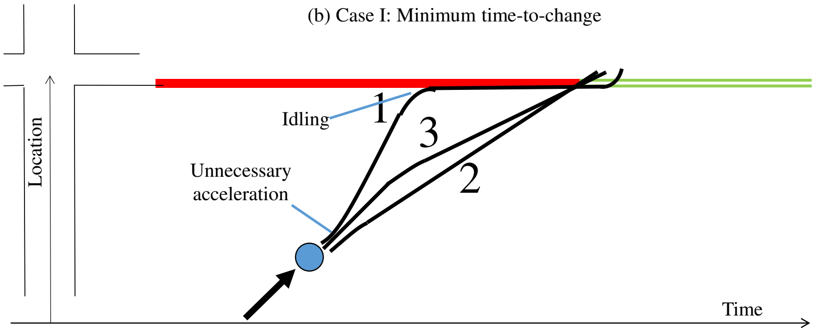
Unlike previous studies for fixed-timing signals, the EAD for actuated signals in real-world traffic needs to be adaptive to the dynamic uncertainty in the states of both signals and traffic. It is unrealistic to design a perfect trajectory when the vehicle is still far away from the intersection. At the beginning of a green/red phase, it is difficult to accurately predict the remaining time as there is significant uncertainty in actuations and thus extension period of the active phase. The minimum and maximum time-to-change usually have large gap in the beginning, and converge to the same value when the phase comes to the end. We define remaining gap as the difference between the maximum and minimum time-to-change. If the remaining gap is small or even zero, the signal information is reliable so that the vehicle just follows the optimal trajectory calculated from speed profile design algorithm [13] to minimize the fuel consumption. If the remaining gap is large, then the remaining time of the current phase is still uncertain. The optimal trajectory corresponding to a certain time-to-change may work poorly under other possible time-to-change events.



(a) Three strategies for EAD



(b) Case I: Minimum time-to-change



(c) Case II: Maximum time-to-change

FIGURE 4. Comparison of different EAD strategies

Fig. 4 shows an example on comparison of different EAD strategies. In this scenario, the vehicle is 150 m from the intersection and the speed is 25 mph. The maximum and minimum time-to-change are 30 s and 10 s respectively. As shown in Fig. 5(a), Curve 1 is the optimal trajectory when the actual time-to-change is minimum time-to-change, and Curve 2 is the optimal one for the maximum time-to-change. Two strategies are defined based on those curves. Under Strategy 1, the vehicle follows Curve 1 until the minimum time-to-change increase. Under Strategy 2, the vehicle follows Curve 2 until the maximum time-to-change decrease. We then evaluate the performance of both strategies under two situations. In Case I, the actual time-to-change equals minimum time-to-change. Strategy 1 has good performance since it is dedicatedly designed for this case. On the other hand, Strategy 2 consumes more time and fuel as the deceleration at the beginning shows to be unnecessary. The vehicle has to accelerate from lower speed to the speed limit after the update of the upcoming signal state. The performances of Strategy 1 and 2 are completely reversed in Case II when the actual time-to-change equals maximum time-to-change. Strategy 2 is the dedicated solution for this case, while Strategy 1 proves to be inefficient right after the signal timing update as the acceleration at the beginning is unnecessary and a stop is inevitable. In summary, the predefined speed profile to a certain possible time-to-change usually ask the vehicle to accelerate/decelerate early, which may prove to be unnecessary if the actual signal condition is beyond expectation. To increase the adaptiveness to the dynamic uncertainty, we develop a new strategy (i.e. Strategy 3) that asks the vehicle to keep the current speed if an acceleration-first strategy (e.g. Strategy 1) and a deceleration-first strategy (e.g. Strategy 2) coexist for the current time-to-change information. Fig. 5 shows that unnecessary acceleration/deceleration can be avoided by implementing Strategy 3, leading to good performance for both cases.

Modified EAD Algorithm

In the micro-simulation [20] and field test in Riverside, California [21], the SPaT messages are coded under the Battelle DSRC format [see ref] so that both maximum and minimum time-to-change are transmitted to the vehicles. A rule based method [20] was developed based on this assumption. In this paper, we modify this model to accommodate the new SPaT message format in the controllers along El Camino Real corridor.

Considering the impact of drivers' adaptability to eco-driving [18], we introduce a buffer time (t_b) to guarantee safety even when the driver does not accurately follow the advised trajectory. The EAD algorithm is then developed based on the effective time-to-change which considers the buffer time. For the green time, the maximum/minimum effective time-to-change (denoted as $g_{\max}/g_{\min}$) is the sum of maximum/minimum remaining green time ($G_{\max}/G_{\min}$) and yellow time (Y), minus the buffer time (t_b).

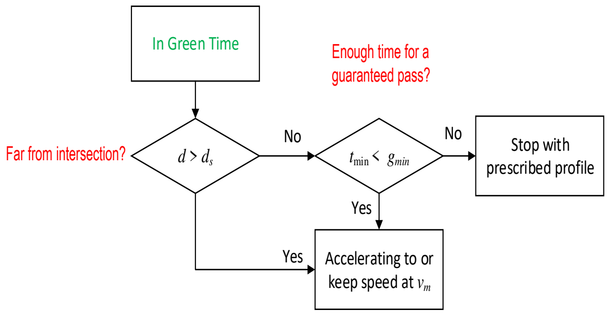
$$\begin{aligned} g_{\max} &= G_{\max} + Y - t_b \\ g_{\min} &= G_{\min} + Y - t_b \end{aligned} \qquad (1)$$

Similarly, we can derive the effective time-to-change for the yellow time ($y=y_{\max}=y_{\min}$) and for the red time ($r_{\max}/r_{\min}$) by (2) and (3)

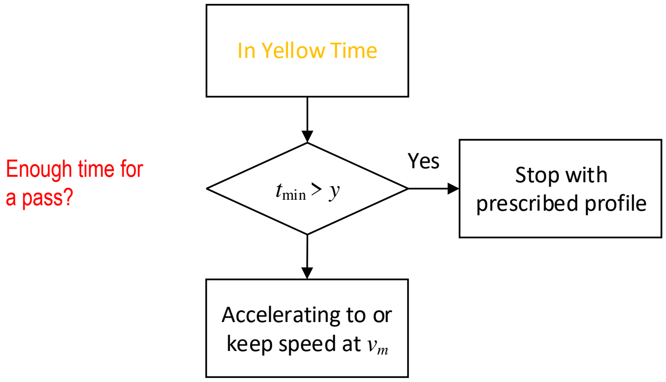
$$y = Y - t_b \qquad (2)$$

$$\begin{aligned} r_{\max} &= R_{\max} + t_b \\ r_{\min} &= R_{\min} + t_b \end{aligned} \qquad (3)$$

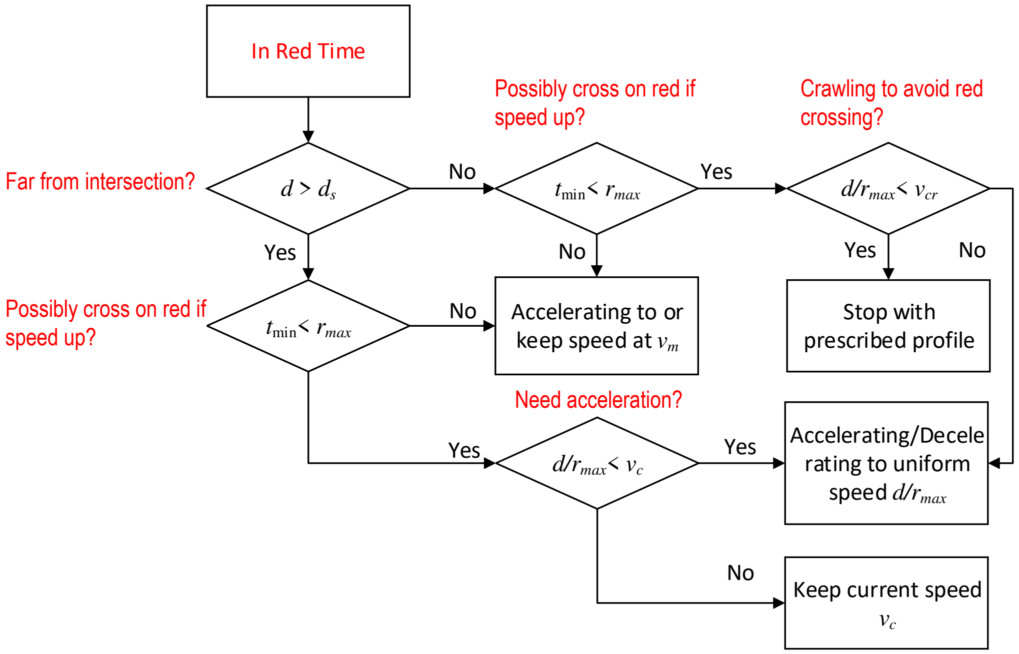
We also define the threshold distance d_s as the minimum distance for a vehicle to make a safe stop from the current speed comfortably. It is computed based on the deceleration speed profile model in [13]. If the vehicle is close to the intersection (i.e., $d \le d_s$), a safety-prior rule is implemented to guarantee that the vehicle never passes the intersection on red time. A conservative strategy is made based on the minimum time-to-change for the green time and maximum time-to-change for the red time, which are the boundaries of guaranteed green phase. If the vehicle is far from the intersection (i.e., $d > d_s$), more focus can be put on time and energy saving perspective. Some strategies such as Strategy 3 in the previous are implemented to accommodate the dynamic uncertainty of the signal conditions. Assume $t_{\min}$ is the minimum travel time for the vehicle to reach the stop line. As shown in Fig. 5, strategies are differentiated by comparing $t_{\min}$ with the effective time-to-change. The objective speed of the vehicle can be the speed limit v_m, the current speed v_c, the estimated uniform speed based on the start of green $v_u=d/r_{\max}$, or 0 if a stop is inevitable. The proposed flow chart in Fig. 6 modifies the one in [20] by considering the absence of minimum time-to-change for the red phase and maximum time-to-change for the green phase. For example, when approaching in the green phase, if the vehicle is far away from the intersection, the EAD algorithm in [9] uses maximum time-to-change to check if it is possible to pass the intersection before the red time starts, and then decide to accelerate or stop based on that. If the maximum time-to-change is not provided, the vehicle has to accelerate to speed limit and make decision to stop or pass when it is within d_s distance of the intersection.



(a) Approaching in green time



(b) Approaching in yellow time



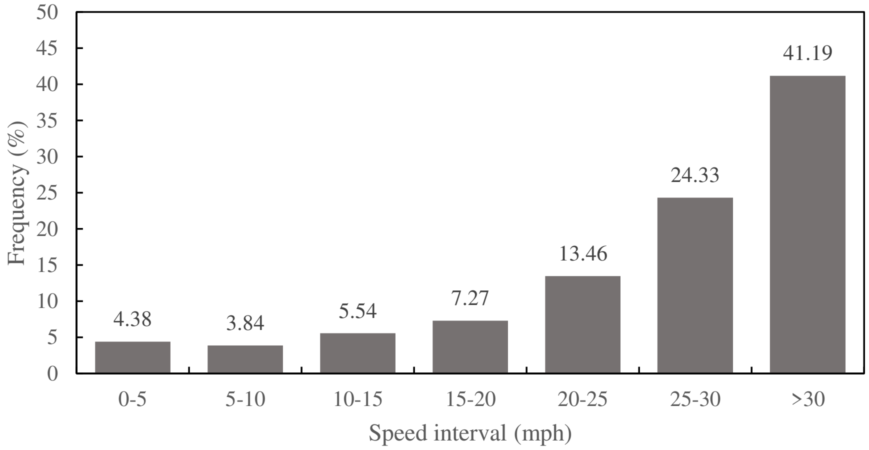
(c) Approaching in red time

FIGURE 5. Flowchart of the modified EAD algorithm

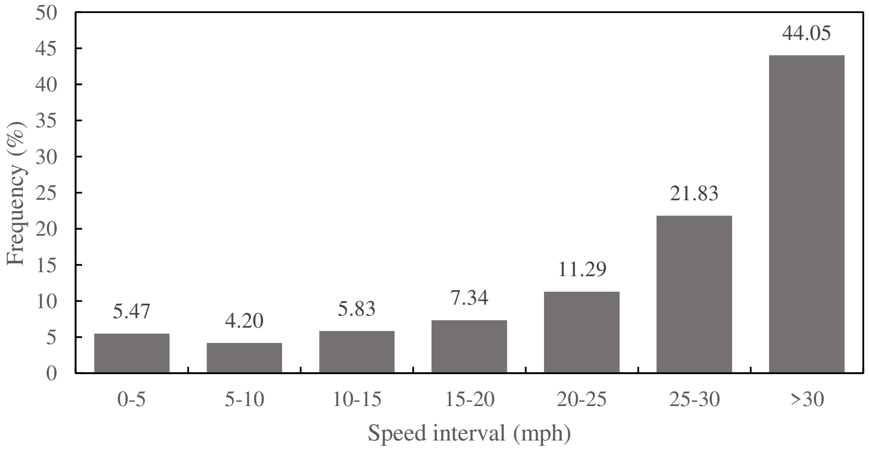
NUMERICAL RESULTS

Impact of EAD on Vehicle Dynamics

We first analyze how the EAD algorithm impacts the vehicle dynamics and driving behavior. Fig. 8 shows the speed distribution for all trips with informed and uninformed drivers respectively based on second-by-second instantaneous speed data. With the assistance of EAD system, the percentage of low-speed mode (i.e. speed between 0~15 mph) drops significantly. Specifically, the idling or near-idling cases (i.e. speed between 0~5 mph) for the vehicle with informed driver is reduced by 22%. Those findings prove that the proposed EAD system can diminish unnecessary idling, even when the signal is actuated and the traffic condition is uncertain. Fig. 6 also indicates that the EAD system reduces the percentage of relatively high speed cases (i.e. above 30 mph, considering the speed limit of 35 mph). That means the informed driver can better control the vehicle speed to avoid unnecessary acceleration and deceleration if the SPaT message is provided.



(a) Speed distribution for the vehicle with informed driver



(b) Speed distribution for the vehicle with uninformed driver

FIGURE 6. Impact of EAD on speed distribution

Energy and environmental Impact of EAD

To evaluate the energy and environmental Impact of EAD, we apply the Comprehensive Modal Emissions Model or CMEM [ref] to estimate fuel consumption and air pollutant emissions based on second-by-second trajectory collected from both vehicles. We normalize two vehicle as light-duty sample vehicles in CMEM for a fair comparison. Table II shows the energy and environmental performance of both informed and uninformed vehicles on all northbound and south bound trips, including the trip segments that were not applicable to EAD for the informed driver. It turns out that the EAD system saves 2% energy for all trips. The proposed system also reduced 2% of CO_2, 7% of CO, 18% of HC and 13% of NOx. That means the reduction on air pollutant emissions is more significant than that on fuel consumption.

In Fig. 7 we further show the trip-by-trip fuel consumption comparison along with the trip travel time. The percentage of travel time and fuel saving for EAD enabled vehicle is plotted in solid curve and dashed curve respectively. In general, a time-saving trip also consumes less fuels, which coincides with common sense. Specifically, two vehicles may have diverse performance of fuel consumption if one vehicle passed the intersection before the red time and the other did not. As the proposed HMI could notify the driver ahead of time if the remaining green time is short, he may accelerate to avoid a stop. As a result, the average trip time for the informed driver is 2% less than that of the uninformed driver.

TABLE 1 Performance on All Trips

Driver	*Fuel (g/mile)*	*CO2 (g/mile)*	*CO (g/mile)*	*HC (g/mile)*	*NOx (g/mile)*
Informed	102.9	321.7	2.66	0.13	0.29
Uninformed	104.8	327.4	2.86	0.16	0.34
Saving in %	1.9	1.8	6.7	17.6	12.8

TABLE 2 Performance on EAD Activated Segments

Driver	*Fuel (g/mile)*	*CO2 (g/mile)*	*CO (g/mile)*	*HC (g/mile)*	*NOx (g/mile)*
Informed	101.3	317.0	2.48	0.13	0.27
Uninformed	107.9	335.8	3.66	0.18	0.35
Saving in %	6.1	5.6	32.4	29.7	24.3

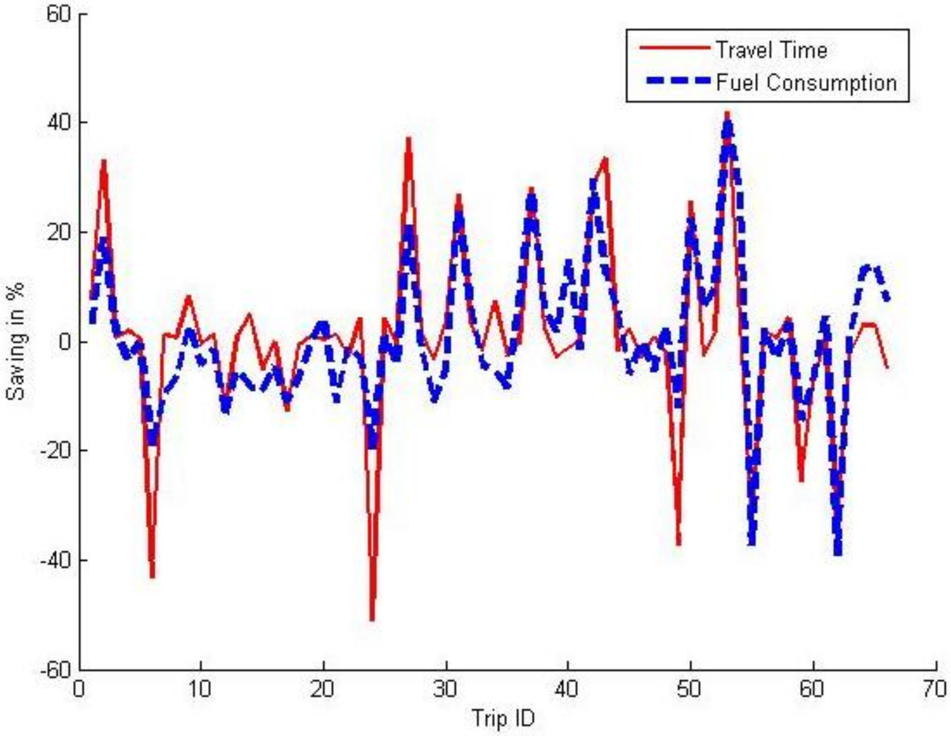


FIGURE 7. Trip travel time and fuel consumption

We then focus on the trip segments where EAD algorithm did take effect. To activate the display of EAD speed, the vehicle has to be travelling within the DSRC communication range of the downstream intersection, and without the detection of preceding vehicles by the forward facing radar. Therefore, we first applied a range filter based on Table I to exclude trips out of the DSRC communication range. We then searched for the trip segments that are not significantly impacted by preceding vehicles. As the test corridor is a busy arterial even in the off-peak hour, it is difficult to find an approaching process without any preceding traffic or queues. We relax the criterion for EAD activated segments. When the vehicle approached a certain intersection within the DSRC coverage, if the EAD algorithm was activated and the target speed was displayed for more than 50% of that distance, we considered this trip segment as an EAD activated segments. EAD was applied to about 22% of the entire mileage during the test. The corresponding trip segments for uninformed driver were also collected for comparison. As shown in Table III, EAD system reduced fuel consumption by 6%, and reduced 6% of CO_2, 32% of CO, 30% of HC and 24% of NOx. For the uninformed driver, the fuel consumption per mile near the intersection is higher than that of the entire trip, due to frequent stop-and-go maneuvers and/or speed oscillations. With the help of EAD system, the fuel consumption and emissions were reduced below the average level of overall trips.

Comprehensive Analysis of the Benefit of EAD

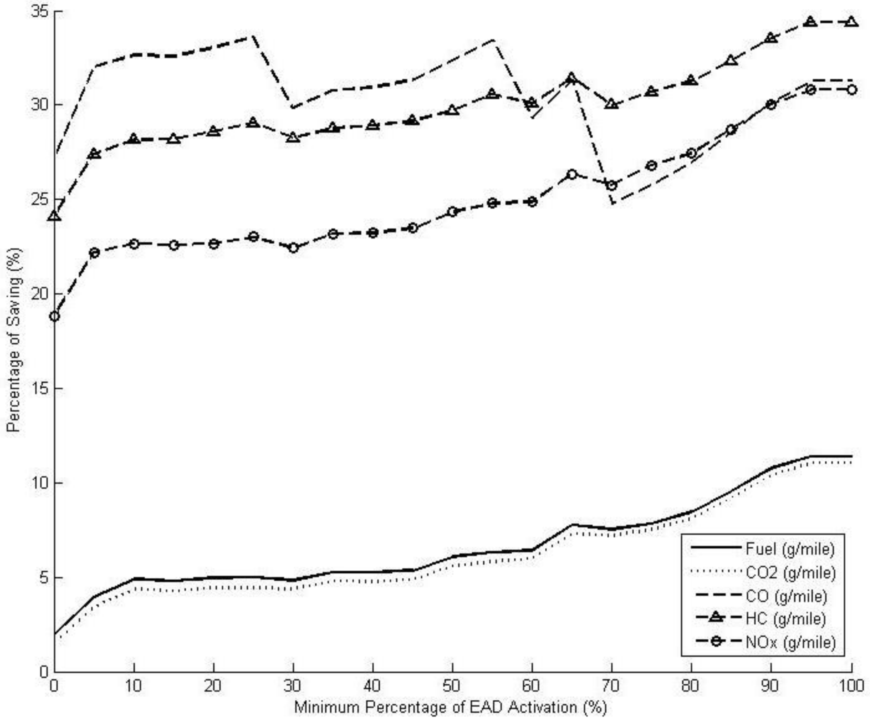


FIGURE 8. Energy and emission benefit vs. EAD activation threshold

In the previous subsection, we show that the benefit of EAD is more significant if we focus on the segment and time period that the proposed system was exactly activated, using 50% EAD activation threshold as an example. Now we further explore the impact of the preceding traffic to the performance of the EAD system.

In Fig. 8, we show the energy and emission benefit of the EAD system in terms of the EAD activation threshold when the vehicle travels within the DSRC communication range. As both the DSRC signal and GPS signal are good within that range, the EAD target speed is displayed if there is no preceding vehicle nearby according to the state machine. Therefore, Fig. 8 can be considered as a surrogate evaluation of the impact of the traffic condition no the EAD system. In general, the percentage of energy and emission saving increases as the EAD activation threshold goes up. If the EAD activation threshold is zero (i.e. all traffic conditions are included, even if the vehicle follows other vehicles during the entire approach), the average fuel saving is 1.9%, approximately the same as the average fuel saving for all trips in Table II. If the EAD activation threshold is 100% (i.e. no preceding traffic), the average fuel saving rises to 11.4%. The reduction of the greenhouse gas emissions has similar increasing trend with that of fuel consumption. For the other types of air pollutants, the environmental benefit is much more significant. When the EAD activation threshold varies from 0 to 100%, the reduction on hydrocarbon increases from 24% to 34%, while the reduction on nitrogen oxide increases from 19% to 31%. For the carbon monoxide, the reduction fluctuates around 30%. As shown in this figure, the proposed EAD system is more applicable to light traffic conditions when there is no or few slow vehicles or queues in front.

CONCLUSIONS

In this paper, we developed an EAD system for actuated signals and tested it in real-world traffic. The EAD strategies are designed to be adaptive to the dynamic uncertainty of actuated signals. In the field test, a study vehicle traveled through 10 intersections that were operated by the Dedicated Short Range Communications (DSRC) enabled signal controllers. Meanwhile, the on-board EAD system of the equipped vehicle calculated eco-friendly trajectories in real time using data from multiple sources - SPaT information and GPS location from DSRC, vehicle dynamics from OBD and preceding vehicle information from radar. When there was no preceding vehicle nearby, the recommended speed was displayed in a graphic user interface (GUI). Otherwise, the display of target speed was turned off to avoid any distraction. For the comparison purpose, an uninformed driver in another vehicle passed through same test intersections in the adjacent lane simultaneously. It turns out that the EAD system effectively reduced the idling or near-idling cases by 22%. The EAD system saves 2% energy for all trips, and 6% energy for the EAD activated trip segments. The proposed system also significantly reduced air pollutant emissions (7% of CO, 18% of HC and 13% of NOx) for all trips. The reduction of emissions could be doubled if we focus on the EAD activated trip segments. The proposed system is more efficient for light traffic conditions where there is no or few preceding vehicles nearby. The impact of the traffic condition diversity of two lanes on the experiment results was also discussed in this paper.

The proposed work demonstrated the benefit of the EAD system in the real-world traffic environment where the real traffic and signal condition are complex and unpredictable. Directions for future research can be summarized as follows:

(1) As discussed in the numerical experiment section, the proposed EAD system is more efficient for light traffic conditions, as preceding vehicles may interrupt the predefined strategies. In the future, we will develop an enhanced EAD strategy to better accommodate the activity of preceding vehicles, especially in the situation that there exist mixed connected and conventional preceding vehicles at the intersection. To this end, it is essential to predict preceding vehicles' movement accurately based on vehicle activity data via inter-vehicle communication technology through Basic Safety Message or sensing technologies (e.g. radar or LiDAR).

(2) In this field test, intersections are coordinated and sometimes closely spaced with each other (e.g. intersections of California and Cambridge Ave). If we extend the model from intersection level to corridor level by considering the geographic information and coordinated signal plan, the performance on energy and emission saving will be further enhanced.

(3) The proposed EAD system is a driver assistance system. The driver's perception-reaction time and capability to follow the recommended trajectories directly affect the driving performance. The negative impact of human factor can be diminished by introducing driver-in-the-loop design or vehicle automation to the system, such as longitudinal control for single vehicle and Cooperative Adaptive Cruise Control (CACC) for platoons.

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