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Preliminary Evaluation of Field Testing on Eco-Approach and Departure (EAD) Application for Actuated Signals

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***Abstract* — Prior studies have shown that tangible environmental benefits can be gained by communicating the driver with the signal phase and timing (SPaT) information of the upcoming traffic signal with fixed time control. However, similar applications to actuated signals pose a significant challenge due to their randomness to some extent caused by vehicle actuation. Based on the framework previously developed by the authors, a preliminary real-world testing has been conducted to evaluate the system performance in terms of energy savings and emissions reduction. Four scenarios that covers most of traffic and signal conditions are evaluated. For each scenario, we vary the entry time and speed to thoroughly investigate the performance of the developed Eco-Approach and Departure (EAD) system. It turns out that the EAD system saves 5%-10% energy for high entry speed, and 7%-26% energy for low entry speed. That results is compatible with the simulation results and validate the previously developed EAD framework.**

I. Introduction

It is widely recognized that transportation activities, including both goods and people movement, have been playing a significant role in fossil fuel consumption and pollutant emissions. Many countries have established more and more rigorous standards and regulations as a major driving force to promote motor vehicles' fuel economy and reduce their tail-pipe emissions [1]. On the other hand, thanks to rapid advances in the information and communication technology (ICT), a variety of programs have been launched throughout the world, directly focusing on improving traffic related energy efficiency. Under the umbrella of these programs, numerous prototype applications have been developed. For example, the Energy Efficiency Intersection (EEI) service of the European project Compass4D aims to reduce energy use and vehicle emissions at signalized intersections [2]. Such service may depend on a roadside unit communicating via 802.11p, or a traffic management center (TMC) communicating via 3G/4G. Another example is the eCoMove project funded by the European Commission (EC), whose objective is to set up a more cooperative, efficient and eco-friendly transportation system for all players based on vehicle-to-vehicle (V2V) and vehicle-and-infrastructure (V2I/I2V) communication [3].

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Similarly, in the United States, the U.S. Department of Transportation (USDOT) has initiated the Applications for the Environment: Real-Time Information Synthesis (AERIS) program [4]. In this program, a series of transformative concepts and applications have been explored for eco-friendly transportation operations using the Connected Vehicle (CV) technology. Among all these applications, the Eco-Approach and Departure (EAD) application for signalized intersections which uses the signal phase and timing (SPaT) information from the upcoming traffic signals to guide the driver to approach, to travel through, and to depart from signalized intersections in a "greener" manner, is quite promising for reducing fuel consumption and pollutant emissions [5 – 7]. However, this application was developed under the assumption of fixed-time signals whose SPaT information is deterministic and is well-defined for vehicle trajectory planning.

As an extended work supported by the Exploratory Advanced Research (EAR) program of Federal Highway Administration (FHWA) [8], the authors have developed an EAD application for actuated signals [9], 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 preceding vehicle (along the same lane). Numerical evaluation indicated that the proposed application is effective in terms of energy saving and emissions reduction, especially for roadway segments with relatively low speed limit.

In this paper, we focus on the presentation of setup and preliminary results of the field operational test conducted in Riverside, Southern California. The following section provides some background information on the proposed EAD application for actuated signals. Next, a detailed description of the experiment setup and evaluation methodology is presented in Section III and IV, followed by the results analyses in Section V. The last section concludes the paper with further discussion.

II. Background

A. Fixed-time vs. Actuated Signal Control

Existing traffic signal operation can be divided into two major categories: fixed time (or pre-timed) control and traffic responsive control (e.g., actuated signal control and adaptive signal control) [10]. Fixed time control consists of a series of intervals (i.e., green, yellow and

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red) for all the approaches that are pre-timed in both sequence and duration. In contrast to fixed time control, traffic responsive control is much more flexible, depending on the real-time traffic conditions. The intervals may be called and/or extended in response to actuation or prediction (via vehicle detection). As a major type of traffic responsive control, actuated signal control is much more widely used in the United States. However, it is much more difficult to estimate/predict the SPaT information for actuated signals than fixed time ones, due to the randomness of vehicle arrival pattern in the real world. Therefore, the development of EAD application for actuated signals is much more challenging.

B. EAD Application for Actuated Signals

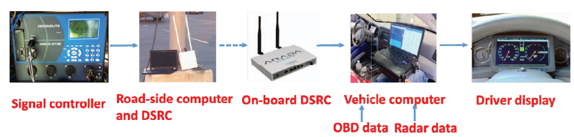
In [9], a framework of EAD application was proposed for actuated signals. As shown in Fig. 1, this system integrates data from multiple sources - SPaT information, GPS location, vehicle dynamics and preceding vehicle information from radar. An algorithm is developed to design the vehicle trajectory dynamically based on the minimum/maximum time to next phase information from SPaT message. A state machine is also introduced in the framework for governing the display of the recommended speed based on the distance, angle and relative speed detection from an automotive radar. This model was tested at a hypothetical actuated signalized intersection in simulation. The results showed significant energy consumption and emissions reduction for the equipped vehicle, especially when the initial arrival speed is relatively low.

C. MOtor Vehicle Emission Simulator (MOVES) and Energy/Emissions Estimation

To evaluate the environmental benefits from the application based on the field data, we used the state-of-the-science emission modeling system, Motor Vehicle Emission Simulator (MOVES) developed by U. S.

Fig. 2. Field study location in Palmyrita Ave, Riverside CA

(a) Signal trailer and test vehicle



(b) Roadside and on-board components in the EAD system

Fig. 3. Test platform for the EAD study

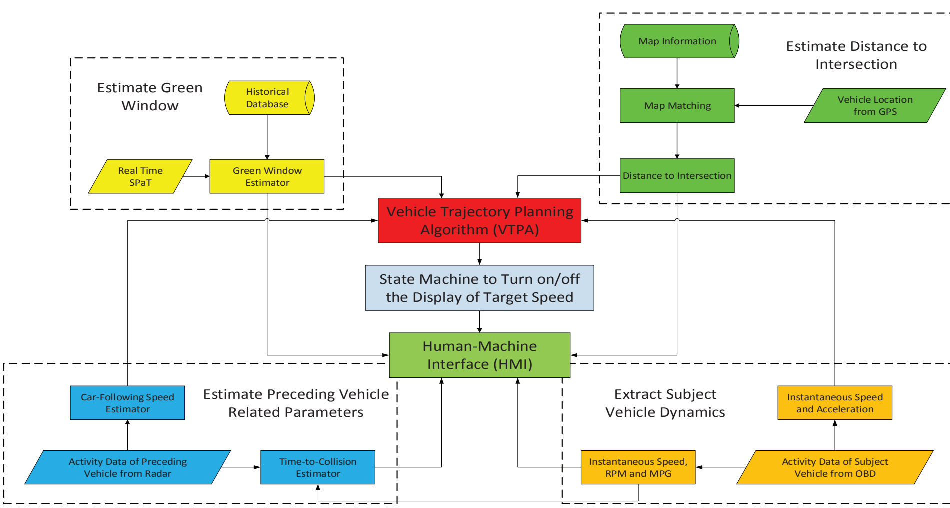


Fig. 1. EAD system architecture (Source:[9])

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Environmental Protection Agency (USEPA) [11]. In essence, MOVES is a multi-scale emission model but can be well applied to second-by-second vehicle dynamics to estimate the energy consumption and tail-pipe emissions.

More specifically, using the testing vehicle's real-time speed (obtained from the on-board diagnostics system) and road grade information (estimated from the GPS location), we may first calculated the second-by-second (with data aggregation) vehicle specific power (VSP) which is defined as the power per unit mass to overcome the road grade, rolling and aerodynamic resistance, and inertial acceleration [12]. Then, we may determine the operating mode (OpMode) for running exhaust emissions by mapping from VSP, vehicle speed and acceleration. With the vehicle OpMode distribution, we may estimate the energy/emissions based on the emission factors from MOVES database.

III. EXPERIMENT SETUP

As shown in Fig. 2, the eco-approach and departure applications for actuated signals were tested at Palmyrita Ave, Riverside CA. The test vehicle approached the imaginary intersection (marked in Fig. 2) from the east, proceeded through the intersection, and then completed the test run on the west side of the facility. The start of the intersection test zone was at 300 meters to the east of the intersection, and then end of the test zone was 100 meters to the west. The speed limit for the test was 35 mph.

A two-phased actuated signal plan was applied in the field test. For each phase, the minimum green time was 20s and the maximum green time was 40s. The yellow time was 4s for all phases. We assume the distance between the stop line and the nearest upstream detector was 50m. The passage time (i.e., green extension) was then set to 3s. The configuration on signal plan has been set up in the traffic signal controller, i.e. Econolite ASC/3-2100, which was deployed within a signal trailer in Fig 3(a).

A 2008 Nissan Altima research test vehicle has been setup for the field test (see Fig 3(a)). A real-time automotive radar system was installed in front to detect the relative distance and relative speed of the preceding vehicle. This vehicle was also equipped with a Dedicated Short Range Communication (DSRC) modem, an on-board computer to calculate the recommended velocity trajectories, and a 7-inch automotive-grade display to serve as an artificial dashboard (i.e., driver vehicle interface or DVI).

As shown in Fig 3(b), the traffic signal controller was connected to a separate PC that decoded the output datagrams from the controller and wrapped them up into the Signal Phase and Timing (SPaT) messages. These messages were then sent to the roadside DSRC modem through the User Datagram Protocol (UDP), and then were broadcast at 10 Hz. When the test vehicle approached within the DSRC range, the on-board DSRC unit received the SPaT messages and transmitted them to the on-board PC. That PC integrated the SPaT, radar detection and vehicle dynamics (via the on-board diagnostics reader) to compute the recommended speed. The recommended speed was finally shown in the 7-inch monitor, along with the distance to intersection and signal count-down information.

IV. EVALUATION METHODOLOGY

To comprehensively evaluate possible signal and traffic conditions for eco-approach and departure at an actuated-signalized intersection, we defined four typical scenarios at Palmyrita Ave as shown in Table I. For each scenario, we ran the experiment and collected the trajectory data for both informed drivers and uninformed drivers.

Table I. Four scenarios for EAD test

		Cross street	
		Mild traffic	Heavy traffic
Main street	Mild traffic	? Minimum green Minimum red Likely to be leading vehicle Target speed display: On	? Minimum green Maximum red Likely to be leading vehicle Target speed display: On
	Heavy traffic	? Maximum green Minimum red Likely to be following vehicle Target speed display: Off	? Maximum green Maximum red Likely to be following vehicle Target speed display: Off

A. *Scenario 1: Mild Traffic for Main Street and Cross Street*

In this scenario, we tested the situation when the traffic from all directions was light and the test vehicle did not follow any other vehicle. In addition, we further assumed that all queues could be discharged during the minimum green time. No green extension was actuated for each phase. For the study phase along the main street, the green time was 20s (minimum green), the yellow time was 4s, and the red time was 24s (20s for minimum green in the other phase, 4s for yellow).

In the field test, the test vehicle entered the DSRC communication range or intersection test zone (i.e. 300m far from the stop line) at different time points throughout the entire signal cycle (every 10-seconds). The drivers was able to see the signal state for the signal trailer or the count-down display from the monitor. We tested two different entry speeds, 35 mph and 25 mph. Here the entry speed was defined as the speed when the vehicle was 300m from the stop line. To precisely control the time and speed as the vehicle entered the intersection test zone, we started the test runs at the roadside parking lot that was 400m far from the stop line. The vehicle left the curb about 10s ahead of the target entry time, and then accelerated to the entry speed before entering the intersection test zone.

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B. *Scenario 2: Mild Traffic for Main Street, and Heavy Traffic for Cross Street*

The first scenario associated with to the case where no green extension was made during the test for both main street and cross streets. Next we tested the scenario when the traffic was mild for the main street, but was heavy for the cross street. Since the main street traffic (where the test vehicle was traveling) was light, it was reasonable to assume the the test vehicle does not follow any other vehicle. The green time for the cross street phase then extends to the maximum value. Therefore, for the study phase, the green time is 20s, the yellow time is 4s, and the red time is 44s (40s for maximum green in the other phase, 4s for yellow).

Note that in this experiment, the vehicle extensions were triggered by manually pressing the touchpad, so we had to apply the same green extension strategy to the controller cycle by cycle. In that manner, we can guaranteed a consistent and repeatable signal actuation input. However, it is still different from the condition under fixed signal timing, as the eco-approaching algorithm made decisions dynamically based on both minimum and maximum remaining timing rather than a fixed count-down information when approaching.

We also tested the performance of the radar and state machine when the study vehicle was following another vehicle in Scenario 3 and 4.

C. *Scenario 3: Heavy Traffic for Main Street and Mild Traffic for Cross Street*

In this scenario, we tested the radar based safe headway detection module. This module may work under multiple circumstances, e.g. 1) The study vehicle approached to the end of the queue during the red time; 2) The study vehicle approached to a slower vehicle in front;3) Other vehicles cut in front of the study vehicle or the study vehicle changed its lane.

As the preceding vehicle in this test was assumed to be an unequipped one without any positioning or communication devices, it is difficult to precisely control its position when it was moving or even changing lanes. Therefore, in this study we only considered the first circumstance by introducing a stopped vehicle as the preceding vehicle. Note that the queuing scenarios only happened when the study vehicle approached to the intersection in the red time (i.e. stop if no vehicles in front). We do not need to consider the other cases that the vehicle arrived during the green time and passed the intersection without any stop or delay.

The green time for the main street phase extended to the maximum value. For the other phase, the green time was the minimum due to the light traffic. For the study phase, the green time was 40s, the yellow time was 4s, and the red time was 24s.

D. *Scenario 4: Heavy Traffic for Main Street and Cross Street*

In the last scenario, the traffic for all directions were assumed to be congested, so that the green times extended to the maximum for both phases. Similar to Scenario 3, the test vehicle was assumed to approach the end of the queue during the red time. Another vehicle that stopped near the intersection was introduced to trigger the radar detection.

The green times for the main street and cross street phase extended to the maximum values. For the study phase, the green time was 40s, the yellow time was 4s, and the red time was 44s. The cycle length reached it maximum (88s) for this scenario.

V. PRELIMINARY RESULTS

In the field test at Palmyrita Ave, Riverside, CA, the test runs were classified into two categories – informed and uninformed. The informed drivers approached and departed from the intersection by following the recommended speed from the EAD system. The uninformed drivers passed the intersection in a normal fashion without any guidance. We assumed the uninformed drivers were untrained and time saving oriented. For both informed and uninformed runs, the second-by-second vehicle trajectories were archived for data analysis in this section.

As stated in Section IV, the drivers were asked to enter the intersection test zone at specific time at specified speed. In the test, that instruction might not be perfectly followed. The errors for entry time were about ±2s, and the errors for entry speed were about ±3mph.

A. *Leading vehicle: Scenario 1 and 2*

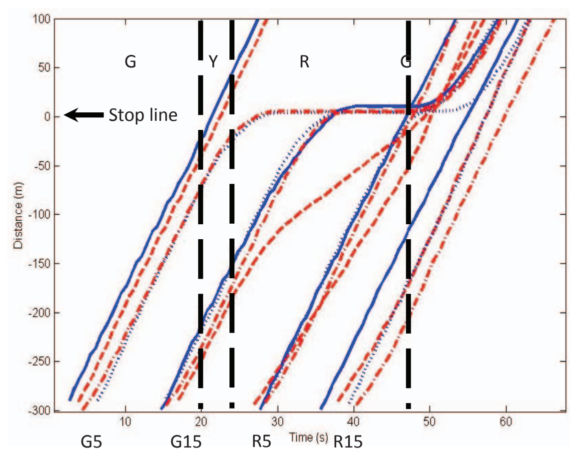

Fig. 4. Vehicle trajectories for Scenario 1

We first discuss Scenario 1 and 2 – two scenarios that the test vehicle was the leading vehicle in a light traffic street. For Scenario 1, as shown in Fig. 4, four different entry times in a cycle were tested: the 5th s in Green

(G5), the 15th s in Green (G15), the 5th s in Red (R5), and the 15th s in Red (R15). Starting from each entry time, four curves are plotted based on the trajectories of four driving patterns: solid curves (informed drivers, 35 mph as the entry speed), dashed curves (informed drivers, 25 mph), dotted curves (uninformed drivers, 35 mph) and dash-dot curves (uninformed drivers, 25 mph).

For different entry time and speed, different driving behaviors can be found from Fig. 4. For G5 case, two informed vehicles accelerated or maintained speed to pass the intersection before the signal turns red, while the uninformed vehicles had to stop for the next green phase. According to Table II, the energy savings for 35mph and 25mph entry speed are 43% and 20%, respectively. However, this significant improvement could be partially explained by the minor difference in entry time, as the vehicle just arrived at the intersection during the yellow time.

TABLE II. PERCENTAGE ENERGY SAVING FOR SCENARIO 1

	G5	G15	R5	R15	Avg	Avg w/o G5
35mph	43.4	13	34.1	-9.3	20.3	12.6
25mph	19.5	8.3	5.2	6.4	9.9	6.6

For G15 case, when the entry speed was 35 mph, the informed vehicle decelerated earlier to prepare for a smooth and comfortable stop. When the entry speed was 25 mph, the informed vehicle slowed down 150m in front of the stop line to follow a non-stop trajectory plan. The energy reduction is about 10% for both entry speeds.

If the test vehicle arrived at the beginning of the red time (R5), the informed vehicle could anticipate the starting time of the upcoming green time and control its speed to pass the intersection without a stop or significant deceleration. As the stop was avoided, a considerable amount of environment benefits were achieved when the entry speed was 35 mph. When the entry speed was 25 mph, the informed vehicle chose to speed up when the green window was guaranteed. That late-acceleration mode would make the travel time slightly increased and the energy slightly reduced. For R15 case, as the vehicle could directly pass the intersection without any delay, the informed drivers do not have substantial advantage compared with uninformed drivers. The only improvement could be made from wisely accelerating to the speed limit if the entry speed was low.

In general, the energy savings are 20% for 35 mph entry speed and 10% for 25 mph, respectively. If we ascribe the large improvement for G5 case to the difference in arrival time, the percentage energy saving is still 13% and 7% respectively.

We then apply similar method to Scenario 2 in which the red time extended to 44s. As shown in Table III, the percentage energy savings are 5% and 13% for 35 mph and 25 mph entry speed, respectively.

TABLE III. PERCENTAGE ENERGY SAVING FOR SCENARIO 2

	G5	G15	R5	R15	R25	R35	Avg
35mph	40.3	-8.4	3.8	-9.8	5.9	-0.8	5.2
25mph	41.1	12	7.1	7.1	10.2	-0.8	12.8

B. Following vehicle in a queue: Scenario 3 and 4

When the test vehicle was traveling in the heavy traffic, the EAD system may frequently turn off the display of recommended speed due to queues and slow vehicles. In this study, we design a specific situation. A preceding vehicle stopped 20m from the stop line during the red time. The test vehicle then approached the intersection, then decelerated and stopped after the front vehicle. For both informed and uninformed vehicles, we collected and compared the vehicle trajectories before the full stop. The trajectories for the waiting and acceleration were not considered because the target speed was not displayed and the informed driver was not guided by EAD system after the stop.

TABLE IV. PERCENTAGE ENERGY SAVING FOR SCENARIO 3

	G25	G35	Avg
35mph	11.6	8.5	10
25mph	15.3	37.3	26.3

TABLE V. PERCENTAGE ENERGY SAVING FOR SCENARIO 4

	G25	G35	R5	R15	Avg
35mph	0.7	-2.1	17.8	10.2	6.6
25mph	25.8	20.3	32.6	25	25.5

Although the preceding vehicle somewhat interrupted the designed trajectory plan for the informed vehicle, we can still find the benefits of the EAD system from Fig. 5, Table IV and Table V. In Fig. 5, we show the informed and uninformed vehicle trajectories with different entry time and entry speed for Scenario 4. When the entry speed was 35 mph, the informed vehicle had a relatively smoother deceleration trajectory. When the preceding vehicle was within the range of accurate detection (35m), the drivers would make further deceleration be their own judgement to stop right behind the preceding vehicle. According to Table IV and V, the energy savings are 10% for Scenario 3 and 7% for Scenario 4, respectively.

When the entry speed was 35 mph, the energy savings for informed vehicle are more significant (i.e. about 25% for both Scenario 3 and 4). The major reason is that the informed vehicles would anticipate the upcoming stop and did not accelerate any more. Instead, the uninformed vehicle might have some redundant acceleration and deceleration when approaching to the queues.

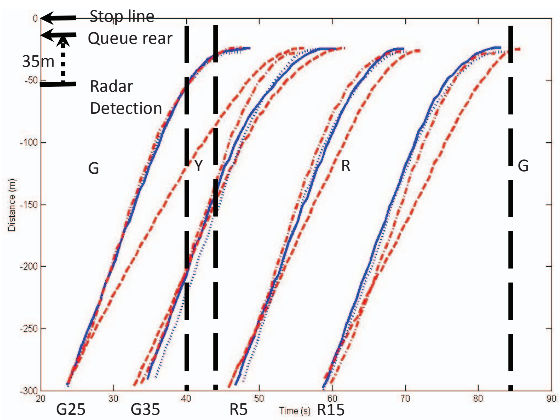

Fig. 5. Vehicle trajectories for Scenario 4

VI. Conclusions

In this paper, we present the field experiment on eco-approach and departure application for actuated signals conducted at Palmyrita Ave, Riverside CA. The experiment location, test platform, signal timing plan for the field test are introduced. The methodology for the experiment and evaluation is also discussed in this paper. In the field test, four scenarios that covers most of traffic and signal conditions are evaluated. For each scenario, we vary the entry time and speed to thoroughly investigate the performance of the EAD framework. It turns out that the EAD system saves 5%-10% energy for high entry speed, and 7%-26% energy for low entry speed. That results is compatible with the simulation results and validate the previously developed EAD framework.

In the future, more field experiments will be conducted to further investigate the potential of eco-approaching and depart systems, especially for the vehicle in traffic. More sophisticated preceding vehicle detection and reaction methods will be developed to achieve eco-stop after a queued vehicle. The acceleration and deceleration profile will also be refined to optimize the energy and emission saving.

VII. Acknowledgements

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