EARLY FINDINGS FROM FIELD TRIALS OF "ECO-DRIVE" FOR HEAVY-DUTY TRUCKS

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ABSTRACT

Connected vehicle (CV) technologies have the potential to significantly enhance road safety, environmental sustainability, and commute experiences. "Eco-Drive" wirelessly obtains real-time traffic signal phase and timing (SPaT) data, providing audio and visual feedback to truck drivers, allowing drivers to regulate and optimize their speed profiles. This has the potential to smoothen traffic flow, reduce noise, and increase road capacity. Majority of the eco-driving studies have focused on numerical evaluations and microscopic traffic simulations, and mainly for light-duty vehicles. The overarching objective of this paper is to present early findings from field trials of the "Eco-Drive" application using a heavy-duty truck in real-world settings. Evaluating CV technologies in real-world environments is an essential part of the development process and can be done effectively when the private and public sectors work together. The field trials were conducted in the City of Carson, California along two corridors with six "connected" signalized intersections that are capable of broadcasting SPaT data.

Keywords: Air Quality along Truck Corridors, Truck Technology and Emissions, Intelligent Transportation Sytems, Commercial Vehicles

INTRODUCTION

According to a recent statistic, about 29% of the energy consumption (in the US) accounted for transporting freight and moving people [1]. Over 90% of the transportation fuels (in the US) are petroleum-based (i.e., Gasoline or Diesel), and the transportation emission (i.e., greenhouse gases (GHGs)) footprint was the second largest in the nation [2]. To summarize, the transportation sector continues to be a significant contributor to the energy demands and air quality issues facing the society. In a coordinated effort to accommodate the ever-increasing demand for the transportation of goods while also reducing its impact on society, we developed an "Eco-Drive" application as part of the Zero Emission Drayage Truck Demonstration Project [need a reference, maybe a press release]; the project is led by the South Coast Air Quality Management District and funded by the California Climate Investments program to reduce key criteria pollutants, GHGs and petroleum usage.

Eco-driving applications are based on connected vehicle (CV) technologies for enabling vehicle operators to significantly reduce the number of harsh driving maneuvers (complete stops, sudden braking and acceleration, etc.), thereby cutting down fuel consumption and vehicle wear and tear, and enhancing traffic throughput [4]–[8]. This is typically done by incorporating data elements such as signal phase and timing (SPaT) or queue length from connected infrastructures or other vehicles. There are many types of Eco-driving applications.

In the Eco-Approach and Departure (EAD) application, by incorporating data (SPaT and geometric intersection description (GID)) from roadside units (RSUs), real-time driving speed profiles are generated to "guide" vehicle operators to approach and depart from signalized intersections in an environmentally friendly manner [9], [10]. Results from microscopic simulation models showed a 10-15% reduction on the energy consumption and CO2 emissions by applying the EAD application to fixed-timing signalized intersections [11]. In congested traffic conditions, the EAD application also worked effectively where preceding queues could be estimated by leveraging real-time vehicle detection and signal information system [12]. Furthermore, a prior work has underscored the importance of driver behavior adaptability in the effectiveness of the EAD application [13].

Many studies have focused on developing and evaluating eco-driving systems using a combination of analytical techniques and microscopic traffic simulators. Very few have conducted technology evaluations in real-world environments. A field test along the El Camino Real corridor in Palo Alto, CA was conducted to evaluate the EAD application for *actuated signals* in realworld traffic [14]. The tested track is 1.7 miles long, and all intersections are equipped with DSRC RSUs. A test vehicle (2.5 L 4-cylinder) was equipped with an industry-grade radar, GPS, DSRC modem, on-board computer, and an artificial dashboard. It was shown up to 6% energy and emissions reduction can be achieved in real-world traffic. Additionally, a partially automated (longitudinal control) EAD prototype was developed and demonstrated at the Turner-Fairbank Highway Research Center (TFHRC) in McLean, Virginia, and the results showed an average of 17% in energy consumption reduction [15].

Built on top of authors' previous work on light-duty vehicles, an "Eco-Drive" application for heavy-duty trucks has been developed in this study. Since heavy-duty trucks play a significant role in transportation-related (especially on goods movement) energy consumption and pollutant emissions, we have adapted the existing eco-driving system to heavy-duty trucks to better shape our contemporary transportation system. Furthermore, different from our previous implementation with DSRC, we have used 4G-LTE to enable cellular-based wireless communications in this study, given its benefits of scalability and wider coverage. We have implemented a simplified ecodriving algorithm to calculate the recommended speed for the test truck in real time. The algorithm has been strategically integrated with other system components, such as Global Navigation Satellite Systems (GNSS), on-bard maps, radar, X Electronic Control Unit (XECU), and live SPaT streams. A user-friendly driver-vehicle interface (DVI) has been designed, so the driver can follow the recommended speed to drive the truck to achieve the goal of energy savings. A field test of the developed connected eco-driving system has been conducted in Carson, California with a heavy-duty diesel truck, along a test route with six equipped signalized intersections capable of broadcasting their SPaT information.

ARCHITECTURE OF "ECO-DRIVE" APPLICTION

In this section, the architecture of the proposed "Eco-Drive" application is introduced, with illustrations of both software and hardware components installed. As can be seen from Figure 1, the whole system is divided into five different modules: communication, localization, perception, planning, and control, whose respective functions are elaborated below.

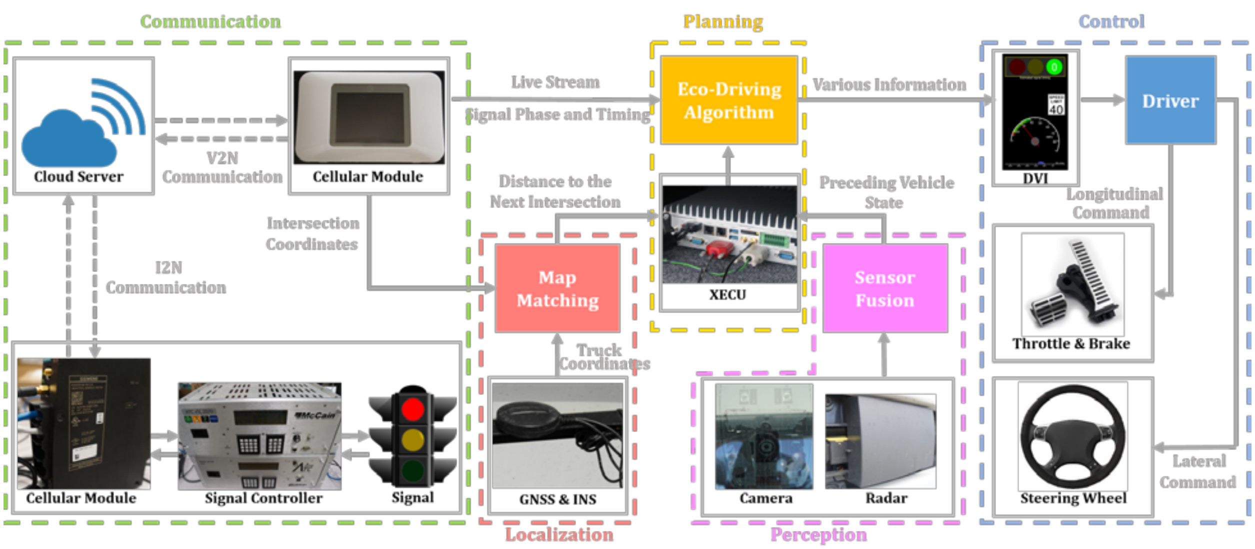

FIGURE 1: Architecture of the connected eco-driving system for heavy-duty trucks

Communication Module

The communication module facilitates real-time and reliable *vehicle-to-network* (V2N) and *infrastructure-to-network* (I2N) communications. Although short-range communication technology such as DSRC is widely used by various CAV applications, their low scalability and asynchronous disadvantage may lead to several issues. As a substitute, 4G-LTE has been adopted to enhance V2N and I2N communications given its versatile communications types from one-to-one to one-to-multiple transmissions, with both simulations and field experiments conducted by researchers all over the world during the past decade [16], [17]. In our connected eco-driving system, we also install a 4G-LTE cellular module with AT&T SIM card on board to enable V2N communication. Note that, compared to DSRC, one major disadvantage of 4G-LTE is its relatively longer latency. However, based on the our findings in our field implementation of this study, the latency introduced by 4G-LTE is about 100 ms, which is satisfactory for the connected eco-driving system.

Each signal head on the test track is controlled by a McCain 2070E controller, which is a rugged, multi-tasking field process and communication system configurable for a variety of traffic management applications. Additionally, each controller is equipped with a SIEMENS RM1224 mobile wireless router for 4G-LTE connection, so the raw SPaT data could be sent to the cloud server through I2N communication. Then the 4G-LTE cellular module on the truck can request the live stream of SPaT information from the cloud server at every second.

Localization Module

The localization module of the connected eco-driving system consists of hardware component, a global navigation satellite system (GNSS) and inertial navigation system (INS), and software component, a map matching algorithm. The GNSS & INS component serves as a combined satellite & inertial-based navigation system, which can be optionally augmented by terrestrial reference stations [18]. This component can provide precise position, movement, and posture measurements for the self-localization and altitude determination of the truck by differential correction. On the test truck, a versatile U-BLOX NEO-M8N GNSS module is installed to locate the truck's position. This GNSS module has a navigation sensitivity of -167 dBm, which provides outstanding positioning accuracy in scenarios where urban canyon or weak signals are involved. For the map matching component, a pre-built map of the testing field is available on board, with information such as the intersection ID, signal group ID, signal location, road type, road name and direction, and road speed limit. The truck's coordinates (*i.e.*, longitude, latitude, and heading) received from the GNSS & INS component can then be matched to the pre-built map by the proposed map matching algorithm, where the details of the algorithm will be introduced later.

Perception Module

Different from the communication module that provides information about the signal status (*i.e.*, SPaT information), the perception module can provide information about other surrounding vehicles (especially if they are not CAVs). We adopt the forward sensing kit to detect any preceeding vehicles, bicycles, and/or pedestrians. The Volvo EU Production Radar Unit together with the forward-looking camera can detect the movement of preceding vehicle, and send its dynamics information to the sensor fusion component. Once the detected objects are classified by the sensor fusion component, the desired information is sent to the eco-driving algorithm. Given the measured relative speed and distance between the truck and its preceding vehicle, the timeto-collision value can be computed. If the time-to-collision value is lower than a preset threshold, the suggested speed for the truck driver will be turned off on the DVI, and the driver will drive the truck without any auxiliary information.

Planning Module

The planning module is the core of the proposed connected eco-driving system. The XECU of the truck is equipped with a ruggedized computer, which has access to multiple channels of CAN data from different sub-networks of the truck. It receives the distance to the next signal from the localization module, preceding vehicles' states from the perception module, and the speed of the truck from CAN message.

The "Eco-Drive" algorithm is embedded in the XECU, based on a Microsoft .NET 4.7 framework with C# language. Data query, recommended speed calculation, and the signal display are all updated at 10 Hz frequency to achieve the consistency, while the communication module is operating at 1 Hz due to the restriction on infrastructure. All the concurrent tasks are handled by threading in the main thread with shared memory. Upon receiving all this information, the recommended speed of the truck at the next time step for the driver will be computed, and sent to the DVI along with some other information. On the other hand, we also utilize a package called log4net for archiving the raw data and the computation results.

Control Module

Once the recommended speed is computed by the ecodriving algorithm in the planning module, the control module of the connected eco-driving system starts to play. A DVI is shown on the monitor right above the dashboard of the truck. With the auxiliary help from the DVI, the driver controls the longitudinal movement of the truck via the throttle and brake, and controls the lateral movement by steering wheel.

Three typical scenarios are shown in Figure 2. As can be seen from these subplots, the top of the DVI shows the upcoming signal phase, but not necessarily the signal timing. We only show the signal timing when the truck is at full stop (shown as the right subplot), but hide that information in other scenarios (the left and middle subplot) to avoid distraction to the driver while driving the truck. The right hand side of the DVI is the speed limit of the current roadway segment, which is acquired from the pre-built map. The artificial speedometer is put at the bottom of the DVI with a green band to demonstrate the recommended speed range for the truck driver.

As can be seen from the right subplot, if a vehicle is detected in front of the truck within a certain range, a vehicle icon is shown in the middle of the DVI, and the upper bound of the recommended speed is bounded by the speed of the preceding vehicle. If the computed time-to-collision value is lower than a preset threshold, the DVI would display a warning message instead of showing the SPaT information, allowing the driver to disengage the eco-driving system and be aware of potential rear-end collision.

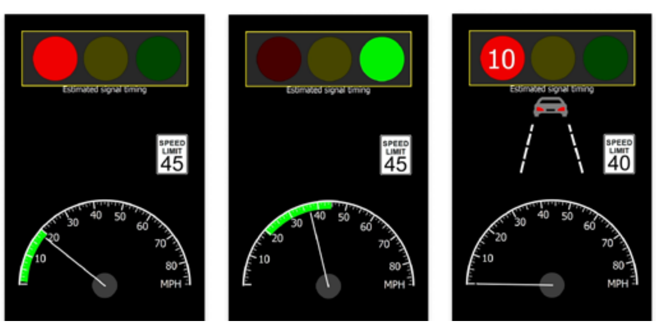

FIGURE 2: Screen shots of DVI designed for the truck driver.

ALGORITHMS

Next, we briefly introduce two crucial algorithms in the "Eco-Drive" application: The MAP matching algorithm in the localization module, and the ecodriving algorithm in the planning module.

MAP matching Algorithm

The first step of our map matching algorithm is to find the projection point of truck's current latitude and longitude on the nearest lane of the hard-coded map. Since we calculate the distance on the surface of the earth, Haversine formula can be applied as:

$$d = 2r \cdot sin^{-1}(\sqrt{sin^2(\frac{\Delta\varphi}{2}) + cos(\varphi_1)cos(\varphi_2)sin^2(\frac{\Delta\lambda}{2})}) \quad (1)$$

where d is the distance between two points on the sphere, r is the radius of the earth, ϕ_1, ϕ_2, $\Delta\phi$ represent the latitude of the first point, the latitude of the second point, and the difference between ϕ_1 and ϕ_2, respectively, $\Delta\lambda$ is the longitude difference between the two points. Since the direction to the next signal should be consistent with the current heading of the truck, we verify this procedure by using inner product:

$$\hat{h} \cdot \hat{u} > 0 \qquad (2)$$

where $\hat{h}$ is the current heading of the truck and $\hat{u}$ is the direction of the intersection. Given that the GNSS signal might drift from the current lane of the road, errors could be generated and accumulated if we directly compute the distance to the intersection node. Therefore, we utilize the triangle formed by the truck's coordinate and its two adjacent nodes' coordinates to calculate the real distance from the projection point of the truck to the intersection.

Heron's formula can be given as:

$$A = \sqrt{s(s - d_{tn1})(s - d_{tn2})(s - d_{n1n2})} \qquad (3)$$

where A is the area of the triangle whose sides have lengths d_{tn1} (truck to the previous node), d_{tn2} (truck to the next node), and d_{n1n2} (the previous node to the next node), and s is the semi-perimeter of the triangle defined as

$$s = \frac{d_{tn1} + d_{tn2} + d_{n1n2}}{2} \qquad (4)$$

Then, we can compute the height h of the triangle by the area and the base-side d_{n1n2}, where h is considered as the error distance due to the drift of GNSS signal from the current lane. Based on h and d_{tn2}, we could use Pythagorean theorem to compute the distance d_{pn2} from the projection point of the truck to the downstream node. Finally, the distance from the truck to the next signal d_{sig} can be calculated by adding the resulted distance with the lengths of all downstream segments before the signal:

$d_{sig} = d_{pn2} + d_{n2n3} + d_{n3n4} + ... + d_{n(m-1)n(m)}$ (5) where $n(m)$ is the node with respect to the next signal.

Eco-Driving Algorithm

Although we developed several versions of eco-driving algorithms before (*e.g.*, piece-wise trigonometric algorithm [9], [11], graph-based algorithm [19] [20]), in this system, we develop a simplified version of eco-driving algorithm for two major reasons:

- Compared to previous eco-driving algorithms, this simplified version of algorithm is easier to implement on real vehicles, and also more attractive in terms of real-time performance;
- This version of algorithm computes a feasible speed range instead of a single value, and provides an easy-to-follow speed band on the DVI for the truck driver. Since the ability to precisely follow the recommended speed is limited and varied by the driver, and the response time of the driver to maneuver the truck may be longer than light duty vehicles, the feasible speed range option should be more robust and user-friendly for truck drivers.

In this subsection, we demonstrate the algorithm with parameters d_{sig} as distance to the intersection, $t_{current}$ as the time left of current signal, and v_{lim} as the speed limit of the roadway. The reference speed v_0 of the truck can then be given as

$$v0 = dsig/tcurrent \tag{6}$$

We then categorize the eco-driving algorithm into two different scenarios based on the current signal phase:

1) Red Phase:

$$\begin{cases} vlower = 0, vupper = v0 & , if\ v0 \leq vlim \\ vlower = 0, vupper = vlim & , otherwise \end{cases} \tag{7}$$

When the signal phase at the upcoming intersection is red, the lower bound of the suggested speed v_{lower} would always be zero. However, the upper bound v_{upper} would be set to the speed that the truck can pass the intersection just at the moment it turns green without stopping. The highest speed is also constrained by the speed limit v_{lim} of the roadway.

2) Green Phase:

$$\begin{cases} vlower = v0, vupper = vlim & , if\ v0 \leq vlim \\ vlower = 0, vupper = 0 & , otherwise \end{cases} \tag{8}$$

On the other hand, when the signal at the upcoming intersection is green, the upper bound v_{upper} of the recommendation would be the speed limit, and the lower bound v_{lower} is set to the lowest speed that the truck can pass the intersection during the current green phase. Under the circumstances that even using the highest speed (*i.e.*, speed limit) the truck still cannot pass the intersection, the algorithm will suggest the driver to slow down and wait for the next green phase.

FINDINGS

Figure 3 shows the Volvo VNL heavy-duty diesel truck deployed in our field experiments, which is a 2015 Volvo VNL model with a 13L diesel engine (455 HP) and a maximum cruise speed of 115 km/h. Also in Figure 3 is the test route where six signalized intersections on Wilmington Blvd. and Alameda St. are equipped with communication modules. The respective SPaT information can be sent to the cloud and allow our connected truck to fetch the data.

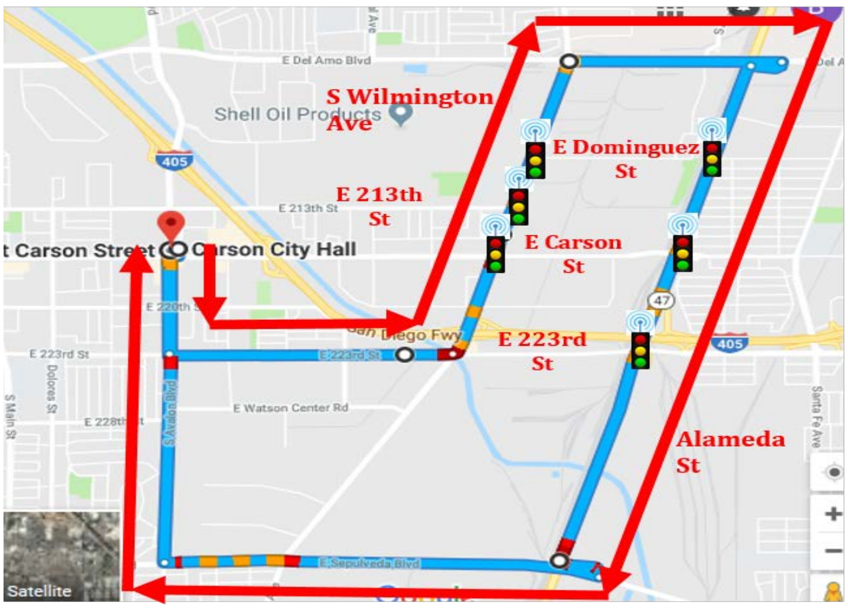

FIGURE 3: Top: Field implementation is conducted by the heavy-duty truck in the City of Carson. Bottom: Field implementation route in Carson, CA with six equipped signalized intersections.

For a comparative study, the truck ran a few times along the test route with and without the “Eco-Drive” application. As it was driven in real traffic environment, where the traffic flow may vary over time of the day, it is not fair to quantitatively compare the energy consumption between different test runs. Therefore, in this section of the paper, we select results generated during four test runs, where two of them are with the “Eco-Drive” application and the other two are without it (*i.e.,* baseline). To make this comparison as fair as possible, all four selected test runs are conducted at the same intersection with clear downstream traffic, which means the movement of the truck is not affected by other vehicles on the road. Also, in each scenario shown in Figures 4 and 5, the truck approaches the intersection from the same distance with the same SPaT status (shown as the color bar below the X axis). Therefore, the difference between two trajectories.

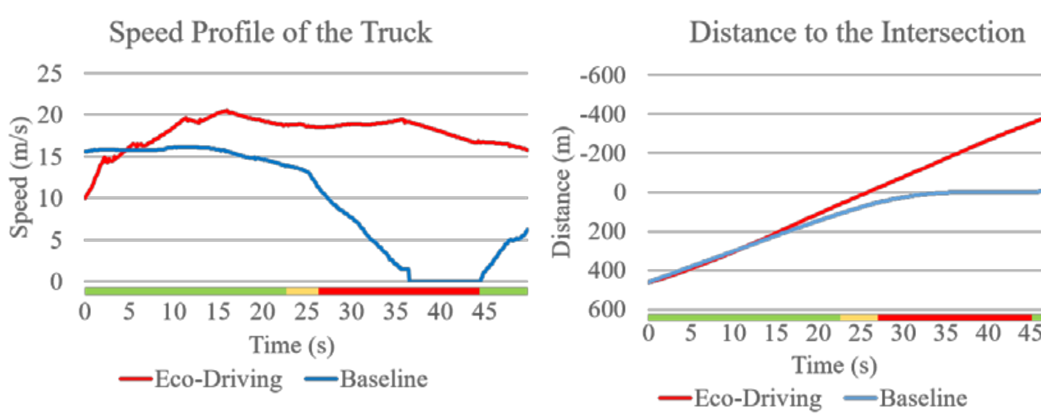

FIGURE 4: Acceleration scenario comparisons.

Figure 4 shows the comparison results on the acceleration scenario between the connected eco-driving system and the baseline. The baseline curves show the truck starts to heavily decelerate at 23 seconds when the driver sees the amber light 150 m away from the intersection, and stops fully at the intersection stop line at 35 seconds. However, with the “Eco-Drive” application, the truck accelerates prior to the signal turning Amber. Therefore, it can travel through the intersection without a full stop before the signal turns Red.

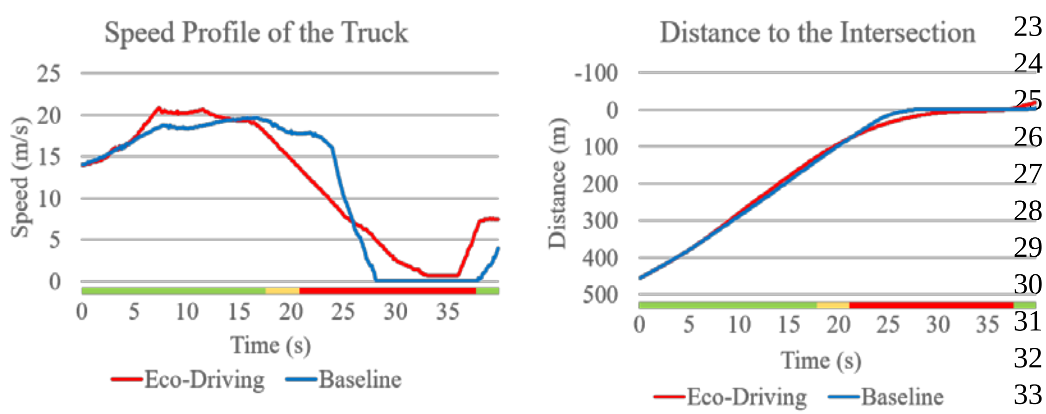

FIGURE 5: Deceleration scenario comparisons.

Figure 5 shows the comparison results on the deceleration scenario between the connected eco-driving system and the baseline. The baseline curves show the truck starts to decelerate at 18 seconds while the driver sees the Amber light 150 m away from the intersection, and stops fully at the intersection stop line at 28 seconds. However, with the “Eco-Drive” application, the truck decelerates prior to the signal turining Amber, and conducts a relatively smoother deceleration toward the intersection. Therefore, it can pass the intersection right after the signal turns to Green with a low speed, instead of experiencing a full stop.

The US EPA MOVES model has also been used to calculate the fuel consumption of aforementioned four test runs, where in each scenario the starting and ending speed are the same (Figures 4 and 5 only show partial trajectories) [21]. The results of MOVES show the potential of the “Eco-Drive” application to achieve 9% and 4% fuel savings in the acceleration and deceleration scenario, respectively.

Those four test runs shown above, along with many other test runs we have conducted, prove the proposed the “Eco-Drive” application can smooth the speed variations of the truck, avoid unnecessary full stop at the intersection, and therefore reduce the fuel consumption of the heavy-duty truck. Another major finding of this field implementation is that, the cellular-based wireless communication approach vehicles to receive SPaT information from anywhere (not limited to a certain distance to the intersection), so the “Eco-Drive” application can be implemented to a much larger scale. A disadvantage of this approach is an extra 100 ms communication delay compared to DSRC approximately, but this delay does not affect the behavior of this system to a large extent.

The video of the field implementation could be watched online using the following link: https://www.youtube.com/watch?v=1CR4vMh8ufE

CONCLUSIONS

The vision of a connected vehicle infrastructure test bed for “Eco-Drive” resulted in an unprecedented partnership between a number of public agencies and private companies. This paper describes the complete system architecture for the “Eco-Drive” application. The system was implemented along two signalized arterials near the San Pedro Bay ports in Southern California, and with an aim to reduce emissions and energy use to improve the health and quality of life in communities disproportionately affected by heavy truck traffic. Novel MAP-matching and Eco-Drive algorithms have been proposed and will be evaluated over the next several months. Potential next steps include quantifying reductions in key criteria pollutants and GHGs, vehicle and system-level energy efficiencies, queue prediction at intersections, and automating the longitudinal speed and acceleration control.

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AUTHOR CONTRIBUTION STATEMENT

The authors confirm contribution to the paper as follows: study conception and design:

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