Title

Assessing Roadway Infrastructure for Future Connected and Automated Vehicle Deployment in California

Authors

Wu, Guoyuan, PhD
Wei, Zhensong
Oswald, David
et al.

Publication Date

2021-12-01

DOI

10.7922/G2P8497N

RESEARCH REPORT

Institute of Transportation Studies | UNIVERSITY OF CALIFORNIA

Assessing Roadway Infrastructure for Future Connected and Automated Vehicle Deployment in California

Guoyuan Wu, Research Engineer, Center for Environmental Research & Technology, and Adjunct Professor, Department of Electrical and Computer Engineering, University of California, Riverside

Zhensong Wei, Ph.D. Candidate, Department of Electrical and Computer Engineering, University of California, Riverside

David Oswald, Ph.D. Candidate, Department of Electrical and Computer Engineering, University of California, Riverside

Peng Hao, Assistant Research Engineer, Center for Environmental Research & Technology, University of California, Riverside

Matthew Barth, Professor, Department of Electrical and Computer Engineering, University of California, Riverside

December 2021

Report No.: UC-ITS-2020-14 | DOI: 10.7922/G2P8497N

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
UC-ITS-2020-14	N/A	N/A

4. Title and Subtitle Assessing Roadway Infrastructure for Future Connected and Automated Vehicle Deployment in California	**5. Report Date** December 2021 **6. Performing Organization Code** UC Riverside
7. Author(s) Guoyuan Wu, Ph.D. http://orcid.org/0000-0001-6707-6366; Zhensong Wei, http://orcid.org/0000-0003-3523-5689; David Oswald, https://orcid.org/0000-0003-2307-1437; Peng Hao, Ph.D. http://orcid.org/0000-0001-5864-7358; Matthew Barth, Ph.D. http://orcid.org/0000-0002-4735-5859	**8. Performing Organization Report No.** N/A
9. Performing Organization Name and Address Center for Environmental Research & Technology 1084 Columbia Avenue Riverside, CA 92507	**10. Work Unit No.** N/A **11. Contract or Grant No.** UC-ITS-2020-14
12. Sponsoring Agency Name and Address The University of California Institute of Transportation Studies www.ucits.org	**13. Type of Report and Period Covered** Final Report (September 2019 – December 2021) **14. Sponsoring Agency Code** UC ITS

15. Supplementary Notes
DOI:10.7922/G2P8497N

16. Abstract
Roadway infrastructure is key to continued economic growth in California, supporting our daily needs for moving both people and goods. In the era of connected and automated vehicles (CAVs), there is a strong need for testing the new enabling technology and upgrading current infrastructure to support different types of connectivity and automation. This report summarizes the research team's efforts to: a) inventory California's CAV testing facilities and testbeds; b) collaborate with the City of Riverside to upgrade communication capabilities along the Riverside Innovation Corridor and enable both dedicated short range communications (DSRC) and cellular-based communications; c) develop an innovative connected eco-approach and departure (EAD) application for actuated signalized corridors; and d) conduct field operational tests to assess the costs and benefits from infrastructure upgrades. The research shows that despite relatively slower communication time compared to DSRC, cellular-based communications can provide additional benefits to vehicles equipped with eco-driving CAV applications such as EAD, due to its greater communication range. Furthermore, broadcasting Radio Technical Commission for Maritime Services correction messages is a cost-effective solution to improving positioning accuracy for equipped vehicles.

17. Key Words	18. Distribution Statement
Connected vehicles, automated vehicles, test beds, dedicated short range communications, ecodriving, signalized intersections	No restrictions.

19. Security Classification (of this report)	20. Security Classification (of this page)	21. No. of Pages	21. Price
Unclassified	Unclassified	61	N/A

Form Dot F 1700.7 (8-72) Reproduction of completed page authorized

About the UC Institute of Transportation Studies

The University of California Institute of Transportation Studies (UC ITS) is a network of faculty, research and administrative staff, and students dedicated to advancing the state of the art in transportation engineering, planning, and policy for the people of California. Established by the Legislature in 1947, ITS has branches at UC Berkeley, UC Davis, UC Irvine, and UCLA.

Acknowledgments

This study was made possible with funding received by the University of California Institute of Transportation Studies from the State of California through the Public Transportation Account and the Road Repair and Accountability Act of 2017 (Senate Bill 1). The authors would like to thank the State of California for its support of university-based research, and especially for the funding received for this project. The authors would also like to thank Mr. Nathan Mustafa, Mr. Philip Nitollama, and Mr. Felipe Medina with the City of Riverside for their strong support in upgrading the roadside infrastructure along the Riverside Innovation Corridor, and our colleague, Mr. Alexandre Vu for his kind help in field operational tests.

Disclaimer

Institute of Transportation Studies | UNIVERSITY OF CALIFORNIA

Assessing Roadway Infrastructure for Future Connected and Automated Vehicle Deployment in California

Guoyuan Wu, Research Engineer, Center for Environmental Research & Technology, and Adjunct Professor, Department of Electrical and Computer Engineering, University of California, Riverside
Zhensong Wei, Ph.D. Candidate, Department of Electrical and Computer Engineering, University of California, Riverside
David Oswald, Ph.D. Candidate, Department of Electrical and Computer Engineering, University of California, Riverside
Peng Hao, Assistant Research Engineer, Center for Environmental Research & Technology, University of California, Riverside
Matthew Barth, Professor, Department of Electrical and Computer Engineering, University of California, Riverside

December 2021

Report No.: UC-ITS-2020-14 | DOI: 10.7922/G2P8497N

Table of Contents

Table of Contents

List of Tables

List of Figures

Abbreviations

CAV	Connected and Automated Vehicle
CV	Connected Vehicle
C-V2X	Cellular vehicle-to-everything
DSRC	Dedicated Short-Range Communication
EAD	Eco-Approach and Departure
GNSS	Global Navigation Satellite System
LiDAR	Light Detection And Ranging
NTRIP	Networked Transport of RTCM via Internet Protocol
RTCM	Radio Technical Commission for Maritime Services
RTK	Realtime Kinematic
SAE	Society of Automotive Engineers
SECA	Shared, Electric, Connected and Automated
SPaT	Signal Phase and Timing
V2V	vehicle-to-vehicle
V2I	vehicle-to-infrastructure
V2X	vehicle-to-everything

Executive Summary

Executive Summary

Roadway infrastructure is essential for fostering continued economic growth in California, serving as the backbone of multi-modal transportation systems throughout the state. It lays down a solid foundation for the delivery of public services and movement of people and goods. However, infrastructure assets are usually costly and require long-term investment. While the Road Repair and Accountability Act of 2017 (Senate Bill 1) provided nearly $55 billion in funding for repairs and maintenance of California's highway system as well as for improvement of major transportation routes and corridors over ten years, state and local governments still face the challenge of delivering needed infrastructure under tight budgets. With the emergence of Connected and Automated Vehicles (CAVs) technology, which allows equipped vehicles to communicate wirelessly with one another and enabled road infrastructure, it has become even more challenging for public agencies to plan and prioritize the addition of new infrastructure as well as improvements to existing infrastructure to accommodate this innovative technology (i.e., CAVs). Connected vehicle technology exchanges information on vehicle location, traffic signal timing, road conditions, etc. This information can be used to provide onboard driver assistance or even full vehicle automation.

Some typical issues that will need to be addressed for successful CAV deployment include: 1) what infrastructure upgrades and improvements, from both hardware and software perspectives, are needed to support CAV deployment? 2) what benefits can be gained through the investment? and 3) what communication technology should be used for connected vehicles?

In recent years, the City of Riverside, California has made a major push to become a “smart city”, integrating new technologies to improve transportation, energy efficiency, and overall city management. The University of California at Riverside and the City of Riverside have been working in close collaboration to develop an “Innovation Corridor”, a six-mile section of University Avenue between the UC Riverside campus and downtown Riverside. As part of this project, the Riverside Innovation Corridor has been set up as a testbed that can be used to evaluate CAV technology. All the traffic signal controllers along this corridor have been upgraded to be compatible with the wireless messaging standards defined by the Society of Automotive Engineers (SAE). Roadside-units have been installed at three key intersections to broadcast information about traffic signal phase and timing (when the signal will change from green to yellow to red) via wireless communications that can be received within limited distances (e.g., 1000 ft). The City’s traffic engineers are considering whether cellular-based communications are needed in the field to extend the communication range, and how much the broadcasting of standard messages for position correction can improve the vehicle’s GPS location accuracy.

This research project reviewed CAV testing facilities available across the nation and inventoried California’s CAV testbeds. The results have posted to a public web page. The research team worked with the City of Riverside to enable cellular-based communications and broadcasting of position correction messages at the three target intersections. Finally, the team also developed a cellular network-based Eco-Approach and

Departure (EAD) application, which provides a driver with speed guidance to reduce fuel consumption and tailpipe pollution while minimizing travel delay. This EAD application was designed for use by vehicles traveling within actuated signalized corridors using both limited range wireless communication and cellular network communication. It was tested along the testbed to assess its benefits for both improving mobility and environmental sustainability.

We found that the EAD application can reduce fuel consumption and CO_2 emissions by 15.6 percent and shorten average travel time by 6.3 percent, compared to when no speed guidance is provided. In addition, the environmental benefits (in terms of reduction in fuel consumption and CO_2 emissions) from cellular-based EAD algorithms outnumber (by around 3 percent) those from using a limited range wireless communication-based EAD algorithm, due to its greater transmission range where the equipped vehicle has more room or time to adjust its speed to traverse the intersections Although cellular-based CAV communications may result in longer latency in receiving information than using limited range wireless communication protocols, this did not cause any problems with the EAD application (which is not a time-critical application, e.g., collision avoidance). Further tests on standard position correction messaging showed that they are a cost-effective means to improve vehicle's GPS location accuracy at the lane-level, which is essential for numerous CAV applications. Therefore, the deployment of position correction protocols is recommended when upgrading the infrastructure's connectivity capabilities.

Contents

Introduction

Roadway infrastructure is essential for fostering continued economic growth in California, serving as the backbone for the movement of people, goods, and delivery of public services across the state. However, infrastructure assets are usually costly and require long-term investment. The Road Repair and Accountability Act of 2017 (Senate Bill 1) provided nearly $55 billion in funding for repairs and maintenance of California's highway system as well as for improving major transportation routes and corridors over ten years [1]. Still, state and local governments face challenges delivering needed infrastructure under tight budgets.

With the emergence of innovative mobility services and technologies such as Connected and Automated Vehicles (CAVs) local transportation agencies will need to upgrade existing transportation infrastructure with wireless communication systems to accommodate this new technology. CAV uses wireless communications technology and onboard computing to exchange and process vehicle-to-vehicle (V2V) messages and vehicle to infrastructure (V2I) information that support a number of different safety and mobility applications, such as eco-driving assistance systems which provide real-time guidance to drivers on ways to improve fuel efficiency by adjusting vehicle speed and acceleration/deceleration. In the future it will also support the development of automated vehicles. The Federal Communications Commission has allocated 75 MHz of radio spectrum in the 5.9 GHz band to be used for vehicle and infrastructure communications to carry this information. Messages using this bandwidth must adhere to the Society of Automotive Engineers (SAE) J2735 broadcasting standard.

In the short run this new technology will need to be tested under realistic driving conditions before it can be introduced into the market and achieve public acceptance. In the long run, existing transportation infrastructure will have to be upgraded and agencies will have to plan and prioritize the addition of new infrastructure to support different types of vehicle connectivity under different levels of automation [2, 48]. Issues to be addressed regarding CAV deployment include: 1) what infrastructure upgrades and improvements, from both hardware and software perspectives, are needed to support the adoption of CAVs? 2) what costs and benefits may result from the investment? and 3) what communication technology should be used for connected vehicles?

To answer these questions this research project a) inventoried California's CAV testing facilities and created a public web-based database; b) in collaboration with the City of Riverside upgraded the communication capabilities at an established testbed located on the Riverside Innovation Corridor [3] to support both dedicated short-range communications (DSRC) and cellular-based communications; c) developed a corridor-based Eco-Approach and Departure (EAD) application [4, 5] and conducted field operational tests to assess the environmental and fuel consumption benefits from the infrastructure upgrades using the EAD application. The findings presented in this report can inform policy makers in enacting regulations that support the statewide deployment of CAVs, and assist the private sector to develop relevant products.

This report is organized as follows: the next section identifies key CAV testing facilities and testbeds throughout California. In Section II, infrastructure upgrade efforts in the City of Riverside, especially along the Riverside Innovation Corridor, are described. Section III discusses both simulated and real-world tests of the corridor-based EAD by leveraging the communication capability of upgraded infrastructure. The final section concludes the report with key findings and further recommendations.

I. California CAV Testbed Screening and Inventory Documentation

Providing a physical facility where developers and manufactures can test CAV hardware and software is critical for a better understanding how they will perform under real-world operating conditions. Over the years, both state transportation departments and the U.S. Department of Transportation have built such test facilities to accelerate the development and deployment of CAV technologies. For example, the federally funded Connected Vehicle Test Bed consists of a network of 50 roadside-units (RSUs) installed along various segments of live interstate roadways, arterials, and signalized and unsignalized intersections in Novi, Michigan [6], broadcasting SAE J2735 standard messages over DSRC systems.

Another major CAV initiative is the National Connected Vehicle SPaT (Signal Phase and Timing) Deployment Challenge co-sponsored by the American Association of State Highway and Transportation Officials (AASHTO), the Institute of Transportation Engineers (ITE) and ITS America [7]. Broadcast SPaT messages provide information on the current traffic signal phase (green, yellow, or red) and how long until it will change. A connected vehicle receiving this information can inform the driver (or onboard computer in the case of an automated vehicle) whether to accelerate the vehicle to safely cross the intersection or to begin slowing down.

This challenge aimed to provide incentives for state and local public sector transportation infrastructure owners and operators to cooperate with each other to deploy DSRC infrastructure with SPaT (and MAP as well as RTCM) broadcasts in at least one corridor or network (approximately 20 signalized intersections) in each of the 50 states. Radio Technical Commission for Maritime Services (RTCM) correction messages provide Global Navigation Satellite System (GNSS) differential correction information to improve the accuracy of GPS positioning. As another standard message type, MAP is used for all general purpose to describe road geometry.

The SPaT challenge also provided a platform to share lessons and experience when deploying new infrastructure. Figure 1 presents an updated national map showing the test sites where SPaT has been deployed or is planned. More than 26 states were involved in this challenge; 216 signals currently operate with SPaT message broadcasting, and another 2,121 more signals are planned.

Recently, the U.S. Department of Transportation has identified the states with active (and pending) 5.9 GHz intelligent transportation service (ITS) licenses [8] (see Figure 2) and all the sites with operational and planned CV infrastructure deployments in the United States as shown in Figure 3 [9].

Although California is at the cutting edge of intelligent transportation systems, including the development of CAV, there is no comparable list of CAV test facilities across the state. Therefore, the research team compiled such a list and posted it to a College of Engineering – Center for Environmental Research & Technology (CE-CERT) webpage: http://itssrv.engr.ucr.edu/ucits/ and full map: http://itssrv.engr.ucr.edu/ucits/map.html. More detailed information is presented in the following section.

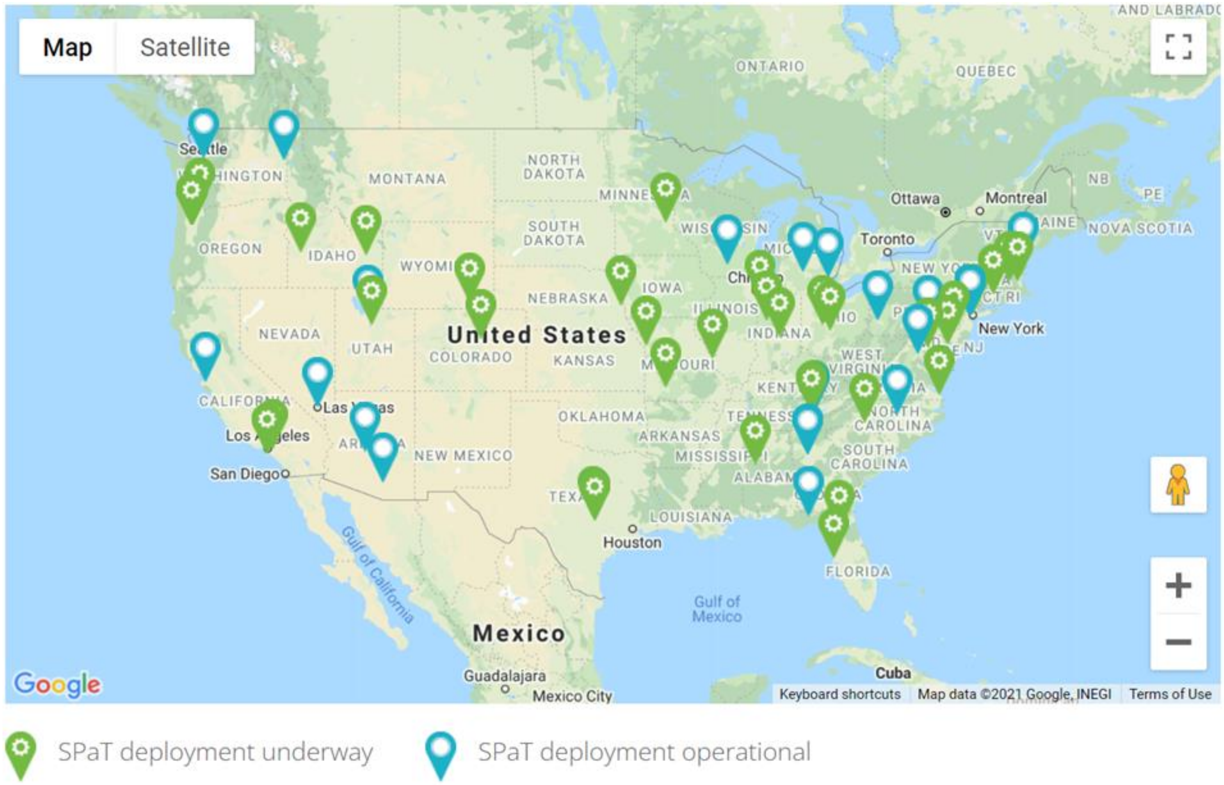
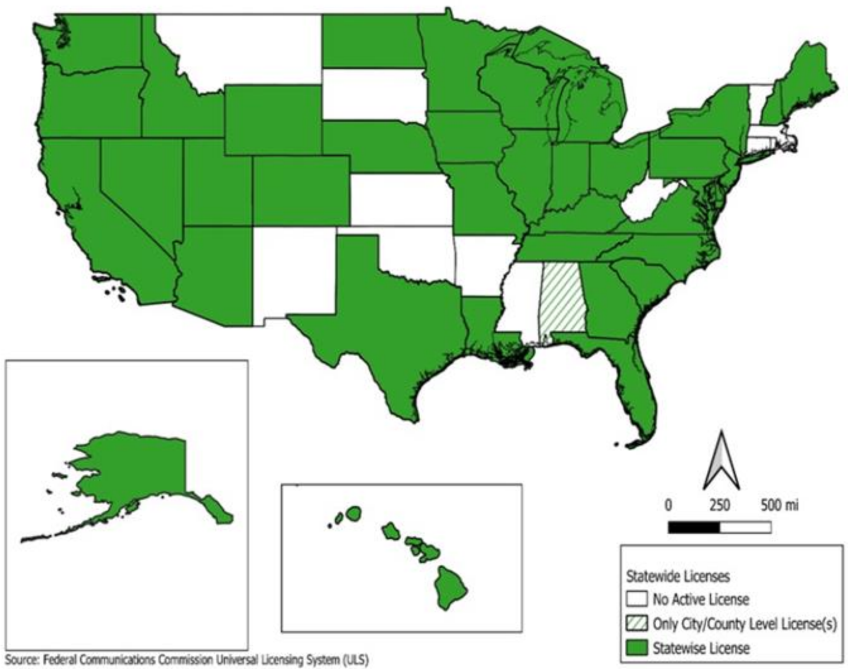


Figure 1. Locations Involved in the SPaT Challenge



Pending Applications to the FCC for Use of the Safety Band (by State)*

State	Applications
CA	2
CO	25
FL	499
GA	12
MD	1
MI	4
NY	50
OH	28
PA	2
WY	2
TOTAL	625

*As of March 26, 2021

Figure 2. States with Applications for 5.9GHz Service Licenses

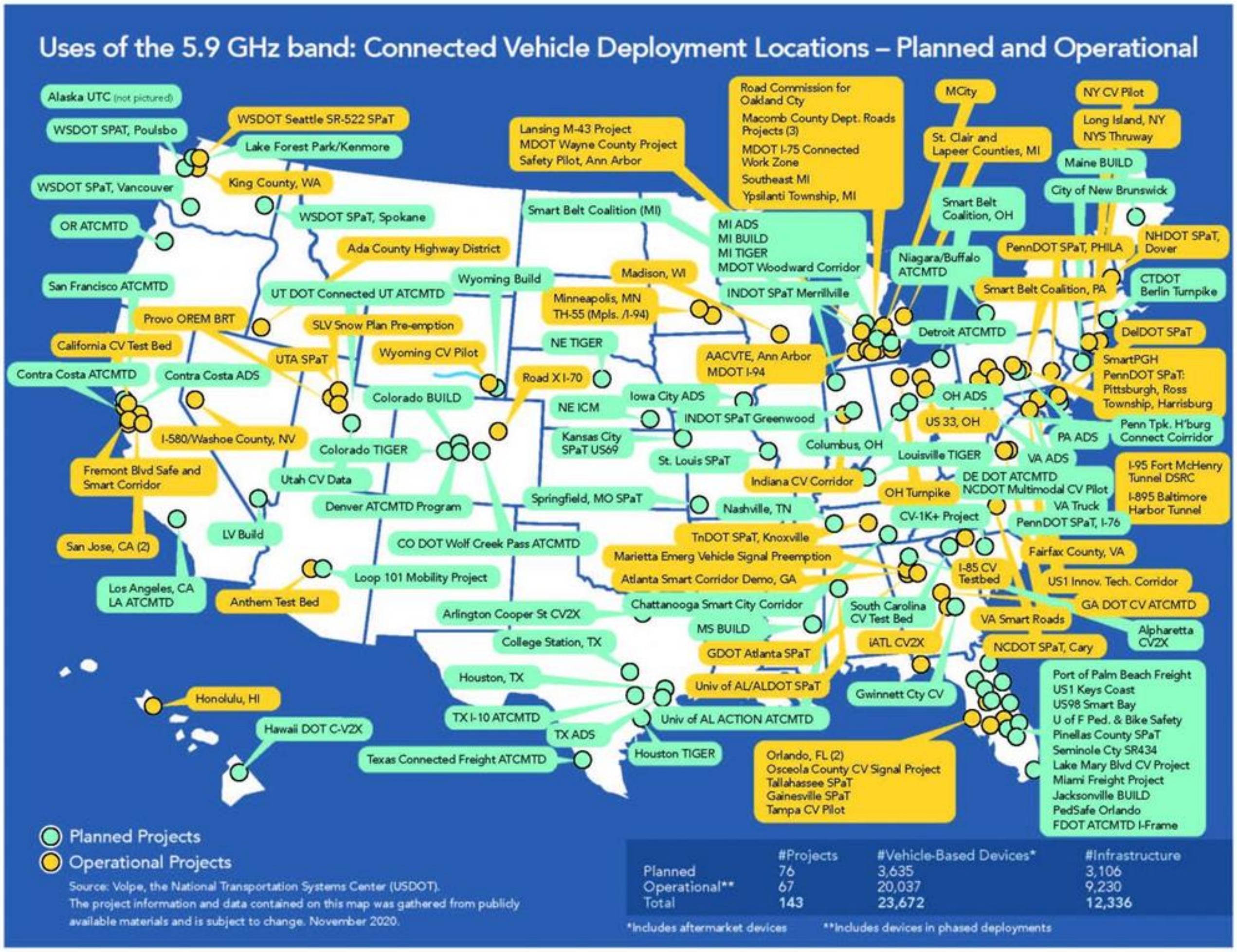


Figure 3. Nationwide Operational Connected Vehicle Deployments

Connected Vehicle Testbeds in California

Here, we briefly review five major connected vehicle test facilities in California: 1) the California Connected Vehicle Testbed; 2) GoMentum Station; 3) Southern California CAV Testbed; 4) Riverside Innovation Corridor; and 5) the San Diego Regional Proving Ground. Figure 4 presents the live map tool (accessible at http://itssrv.engr.ucr.edu/ucits/) that the research team created for this purpose. Please note that this map tool may be updated and expanded as more CAV facilities are built throughout the state and the United States, or even across the globe.

The California Connected Vehicle Testbed

The *California Connected Vehicle Testbed*, the first public connected vehicle testbed, is located along El Camino Real (State Route 82), which is a signalized major road with over 50,000 daily vehicles running between San

Jose and San Francisco (as shown in Figure 5). It was built in 2005 by the California Department of Transportation (Caltrans) working with the Metropolitan Transportation Commission (MTC) and the California PATH program at UC Berkeley. The original testbed was located in Palo Alto, California, crossing 11 consecutive intersections through a two-mile section of SR-82 and has been extended to 16 consecutive intersections along a three-mile stretch. Currently, the testbed is in the process of adding 15 more intersections that will bring its length to 7 miles.

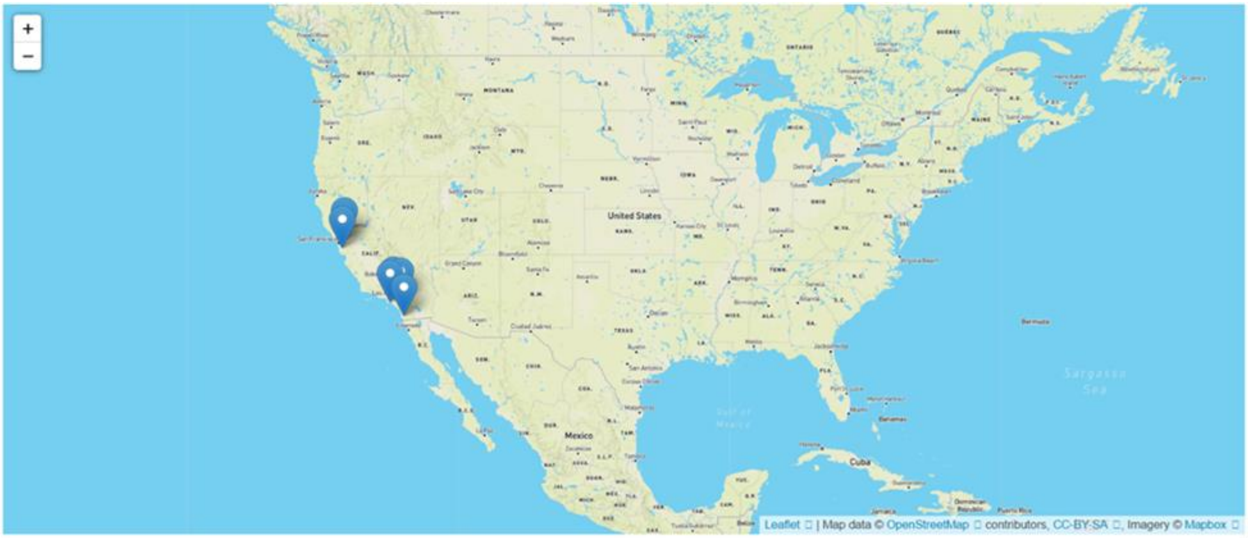
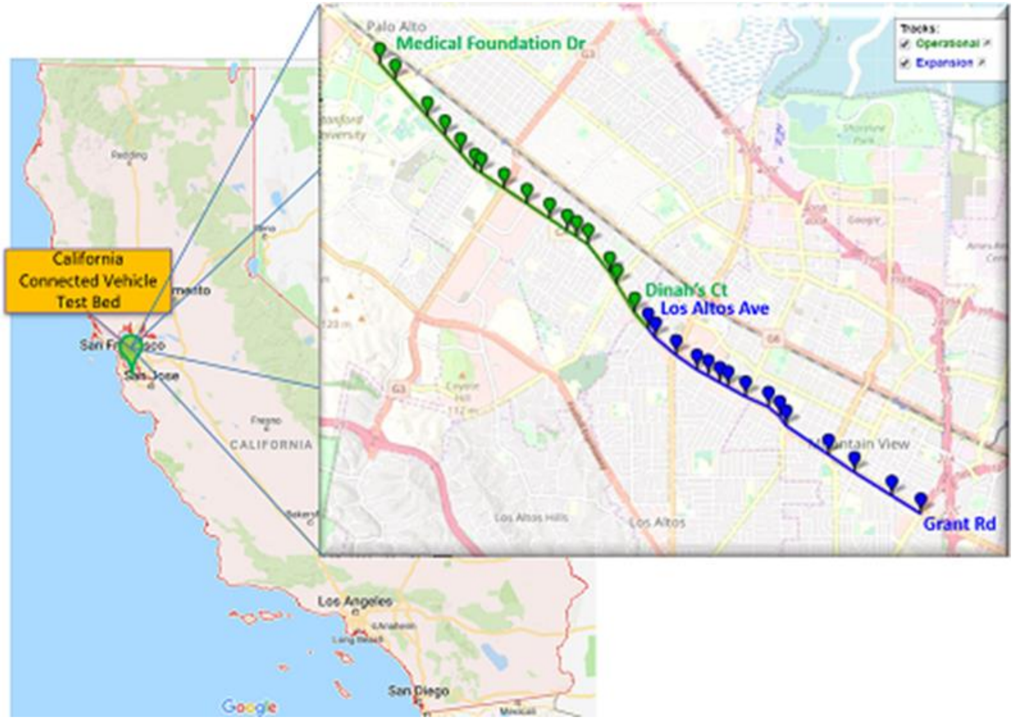
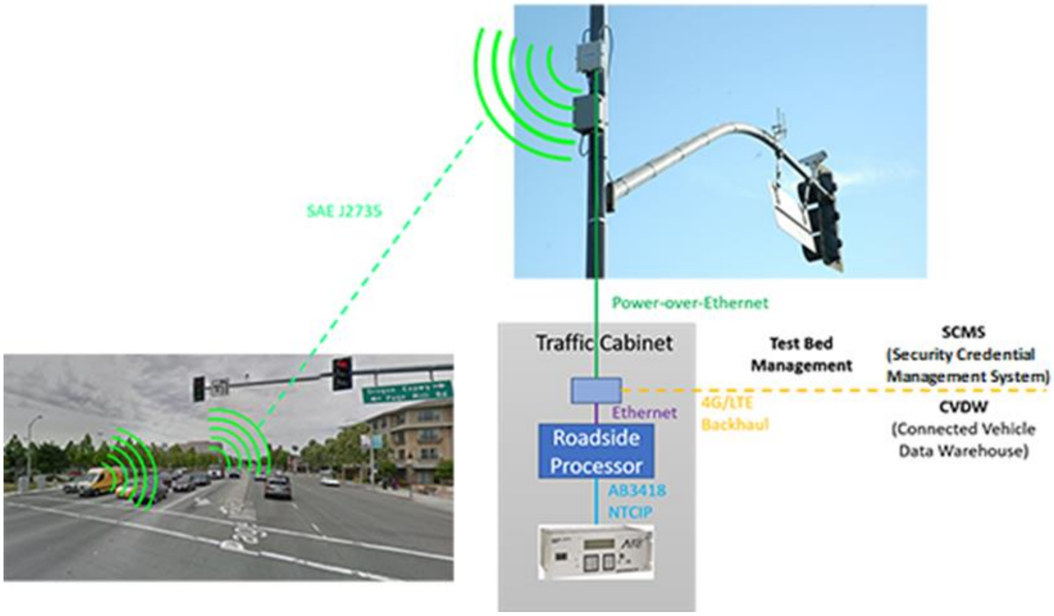


Figure 4. Live Map Tool Developed by this Project



(a) Location of California Connected Vehicle Testbed



(b) Typical Setup of an Equipped Intersection along the Testbed

Figure 5. California Connected Vehicle Testbed

Wireless connectivity including DSRC, 4G/LTE cellular, and C-V2X technologies, has been provided to enable communication between intersections and vehicles (or other mobile devices) in an operational environment. The latest version (published in March 2016) of SAE J2735 standard messages, such as BSM (Basic Safety Message), MAP, SPaT, RTCM, and SRM (Signal Request Message), are broadcast and the Security Credential Management System (SCMS) will be available in the near future. Readers who are interested in more information about this testbed may refer to the California CV Testbed webpage [10].

GoMentum Station

As one of the largest dedicated secure testing facilities in the United States for validation and verification testing of CAV technologies, the 2,100-acre *GoMentum Station*, which is located in Concord, California and operated by AAA Northern California, Nevada and Utah, offers a variety of dynamic and real-world testing environments for autonomous vehicles in a safe closed-course setting (see Figure 6). Its state-of-the-art vehicle-to-everything (V2X) lab, consists of five consecutive signalized intersections, and is equipped with advanced traffic signal controllers, video vehicle detectors, advanced IP (Internet Protocol) switches, traffic signal cabinets, and DSRC/C-V2X/5G equipment. It is well suited for public agencies to perform interoperability tests of V2X technologies and evaluate various traffic management applications that may enhance safety and reduce congestion on their streets. For more information about the GoMentum Station, readers may check with its Test Drive the Future website [11].

(a) Map of GoMentum Station Testbed

(b) Various Real-world Settings for Different Test Scenarios

Figure 6. GoMentum Station Testbed

Southern California CAV Testbed

Over the past few years, the University of California at Riverside (UCR) has been working with the Los Angeles County Metropolitan Transportation Authority (LA Metro), Los Angeles County's Department of Public Works, the City of Carson, the City of Los Angeles Department of Transportation, and the Port of Los Angeles to deploy 15 connected traffic signals near the port to support the deployment of a variety of connected vehicle applications related to freight movements. These equipped intersections are located along three major arterials (Alameda St., South Wilmington Avenue and West Harry Bridges Boulevard as shown in Figure 7) operating with a significant volume of drayage trucks commuting daily between ports and warehouses.

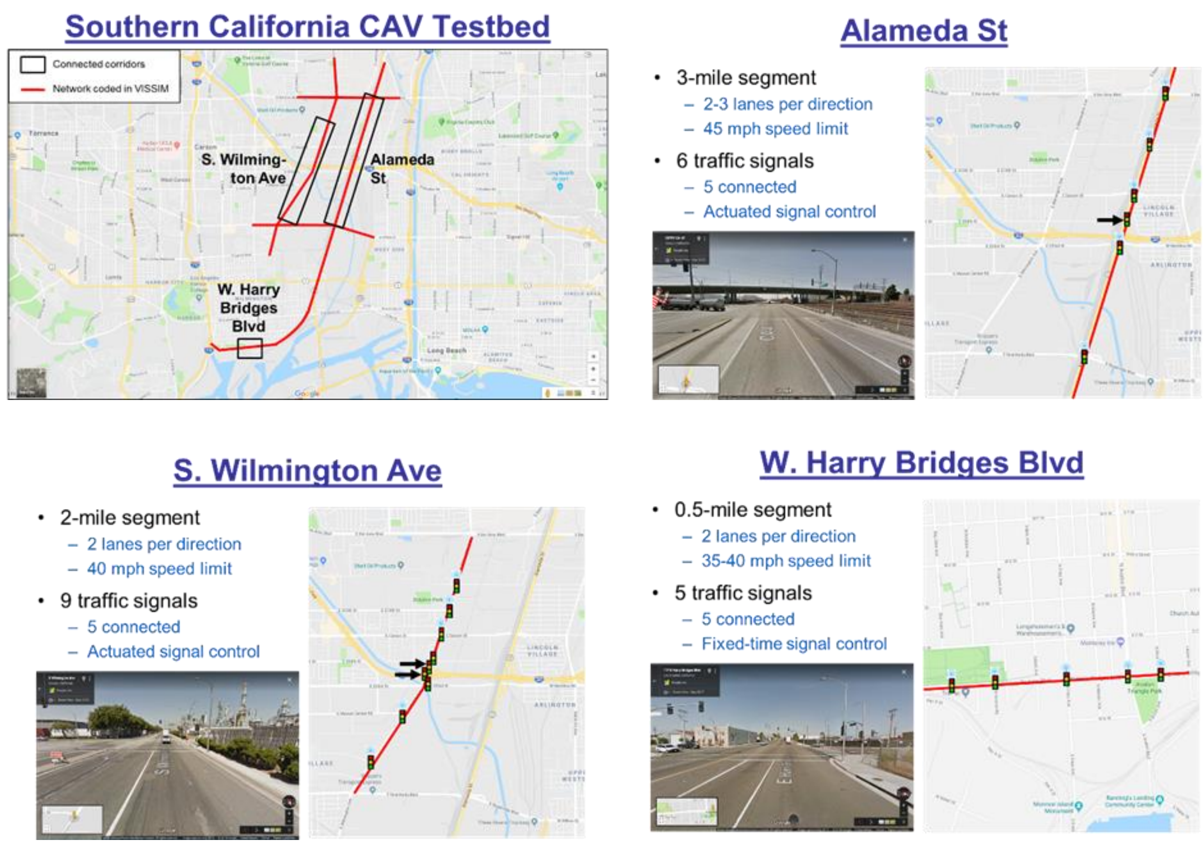


Figure 7. Three Major Arterials Constituting the Southern California CAV Testbed

The *Southern California CAV Testbed* can be used to validate and evaluate a variety of connected vehicle applications by any type of vehicle and is currently being used for testing the EAD application for heavy-duty trucks, developed by the UCR research team [12, 13]. Figure 8 depicts the system architecture, which is enabled by 4G/LTE cellular communications [14]. Real-time SPaT information is sent to the Traffic Signal Information System (TSIS) server at UCR. Vehicles traveling on the testbed can request and receive SPaT information from the TSIS server over the cellular network.

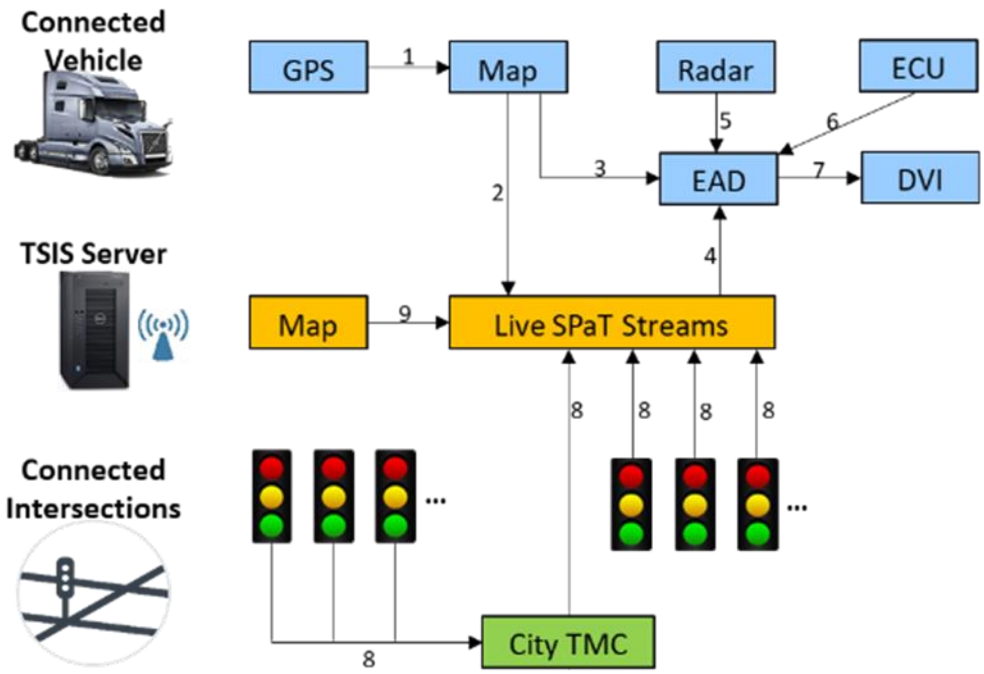


Figure 8. System Architecture of UCR Truck EAD at Southern California CAV Testbed (ECU: Engine Control Unit; DVI: Driver-Vehicle Interface).

Riverside Innovation Corridor

Over the past few years, UC Riverside has partnered with the City of Riverside, creating the *Riverside Innovation Corridor*, a six-mile section of University Avenue between the UCR campus and downtown (see Figure 9) [15]. This area was selected due to its proximity to an expanding transit and alternative transportation network, research institutions associated with UC Riverside, and the ever-expanding downtown entertainment destinations. As part of this project, traffic signal controllers along the corridor have been upgraded to be compatible with SAE connectivity standards. With help from the City of Riverside, the research team has also installed DSRC roadside-units at several of these traffic signals. With this communications capability, SPaT messages from the traffic signal controllers can be directly transmitted to the DSRC units and forwarded to vehicles equipped with onboard DSRC units. Furthermore, positioning correction information using RTCM protocols, and MAP messages can be broadcast from the roadside DSRC devices to support various connected vehicle applications.

In addition to communication capability between traffic signals and equipped vehicles, the Innovation District has been installing infrastructure-based sensors (e.g., LiDARs and fish-eye cameras) and air quality monitors along the roadway, and in the future charging stations will be installed to help with the deployment of electric vehicles. The Riverside Innovation Corridor will serve as a key testbed in Southern California for EAD, eco-transit operation, smart intersection management, and other CAV applications to improve safety, mobility and environmental sustainability.

Figure 9. Overview of Riverside Innovation Corridor

San Diego Regional Proving Ground

As one of ten automated vehicle proving ground sites in the nation selected by the U.S. Department of Transportation in 2017, the *San Diego Regional Proving Ground* (RPG) operated by the San Diego Association of Governments in partnership with the Caltrans District 11 and the City of Chula Vista, provides an ideal location for testing highly automated and self-driving vehicles and also direct access to global leaders in the cybersecurity and wireless industries located nearby.

By leveraging its access to world-class academic institutions in machine learning, robotics, and high-performance computing, the San Diego RPG fosters innovation to improve system safety as well as personal and commercial mobility across all modes, and fully supports the regional commitment to advancing autonomous vehicle deployment. Figure 10 presents the location of the San Diego RPG and respective sketch plan of staging facilities.

Figure 10. San Diego Regional Proving Ground and Associated Staging Facilities

II. Infrastructure Upgrade Effort by the City of Riverside, California

UC Riverside researchers have been working closely with the City of Riverside to develop the Riverside Innovation Corridor testbed, for enabling Shared, Electric, Connected and Automated (SECA) transportation research. The testbed will support a variety of transportation modes including passenger vehicles, trucks, transit (e.g., RTA buses), bicycles, walking and various forms of micro-mobility. This corridor is continuously being upgraded with new technologies to facilitate research in SECA transportation systems.

In addition to upgrading the firmware of traffic signal controllers to be compatible with the latest version of the SAE J2735 standard (March 2016), three intersections along the Innovation Corridor have been equipped with DSRC roadside-units as well as cellular routers to enable broadcast SPaT, Geographic Intersection Description, or MAP messages over both DSRC and cellular communications networks. These three intersections are (from west to east) Chicago Avenue and University Avenue, Cranford Avenue and University Avenue, and Iowa Avenue and University Avenue, as indicated by red stars in Figure 11.

Figure 11. Intersections along Riverside Innovation Corridor Upgraded with DSRC and Cellular Communications Capabilities

Furthermore, RTCM correction messages can be broadcast to enable lane-level vehicle positioning and improve the system efficacy of CAVs. Figure 12 shows traffic engineers from the City of Riverside assisting the research team install cellular routers (RUGGEDCOM RM1224 by SIEMENS) at the intersection of Iowa Avenue and University Avenue. Note that to enable dual broadcast (i.e., via both DSRC and cellular network communications) of SPaT messages from the traffic signal controller (Econolite's Cobalt ATC Traffic Controller), the research team had to add a separate computer (Cincoze Rugged Ultra Compact Fanless Computer), which resulted in additional costs to the infrastructure upgrade.

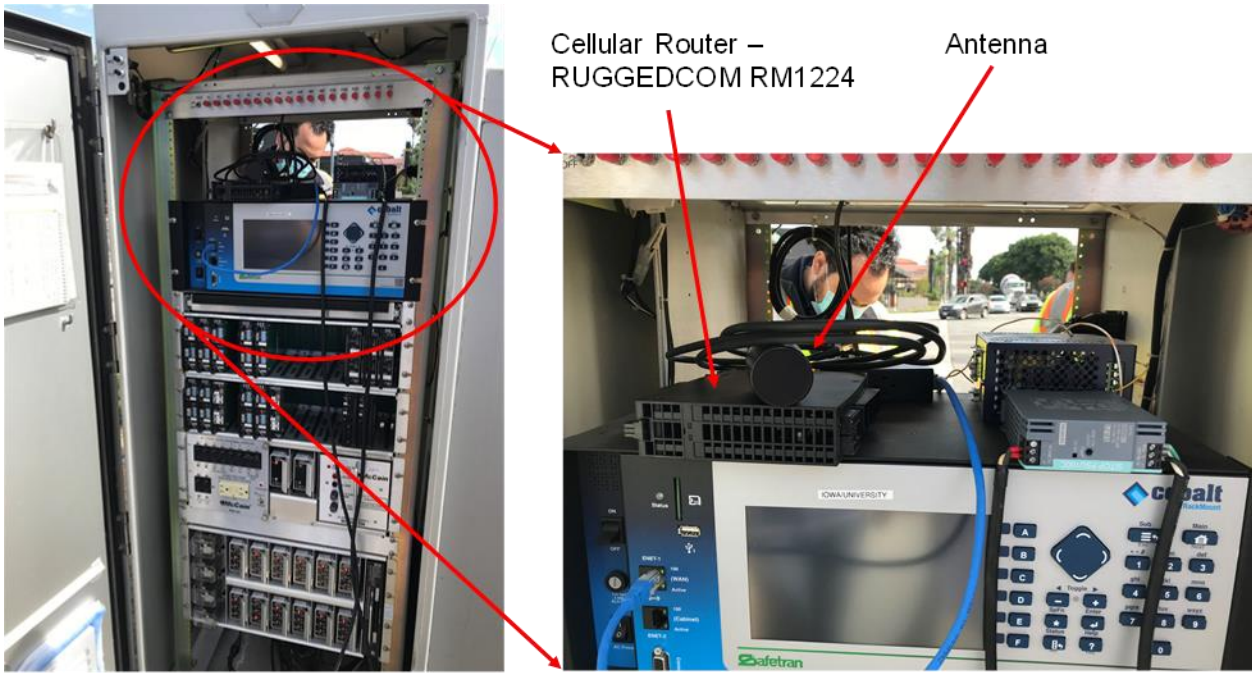


Figure 12. City of Riverside's Traffic Engineers Helping Install Cellular Router at the Intersection of Iowa Avenue & University Avenue

Regarding the system architecture for digital infrastructure, the research team had extensive discussions with the City of Riverside on two different options as shown in Figure 13. The first option (decentralized) was to set up a router at each intersection which could connect to the signal controller directly and enable messages to be broadcast over the air. The UCR server is able to back up the SPaT data, estimate the green window of each intersection along the coordinated signalized corridor (based on historical data), and provide this information to the test CAV as needed. The second option (centralized) was to enable access to the City's Traffic Management Center, so that the UCR server could request the associated SPaT data and coordination plans, and provide the processed information to the test CAV. The city's traffic engineers suggested the research team choose the first option, decentralized system architecture, for greater flexibility in subsequent field operational tests of CAV applications, given the lack of optical fiber (due to budget constraints) to connect the traffic signal controller cabinets to the City's Traffic Management Center and to simplify data flows.

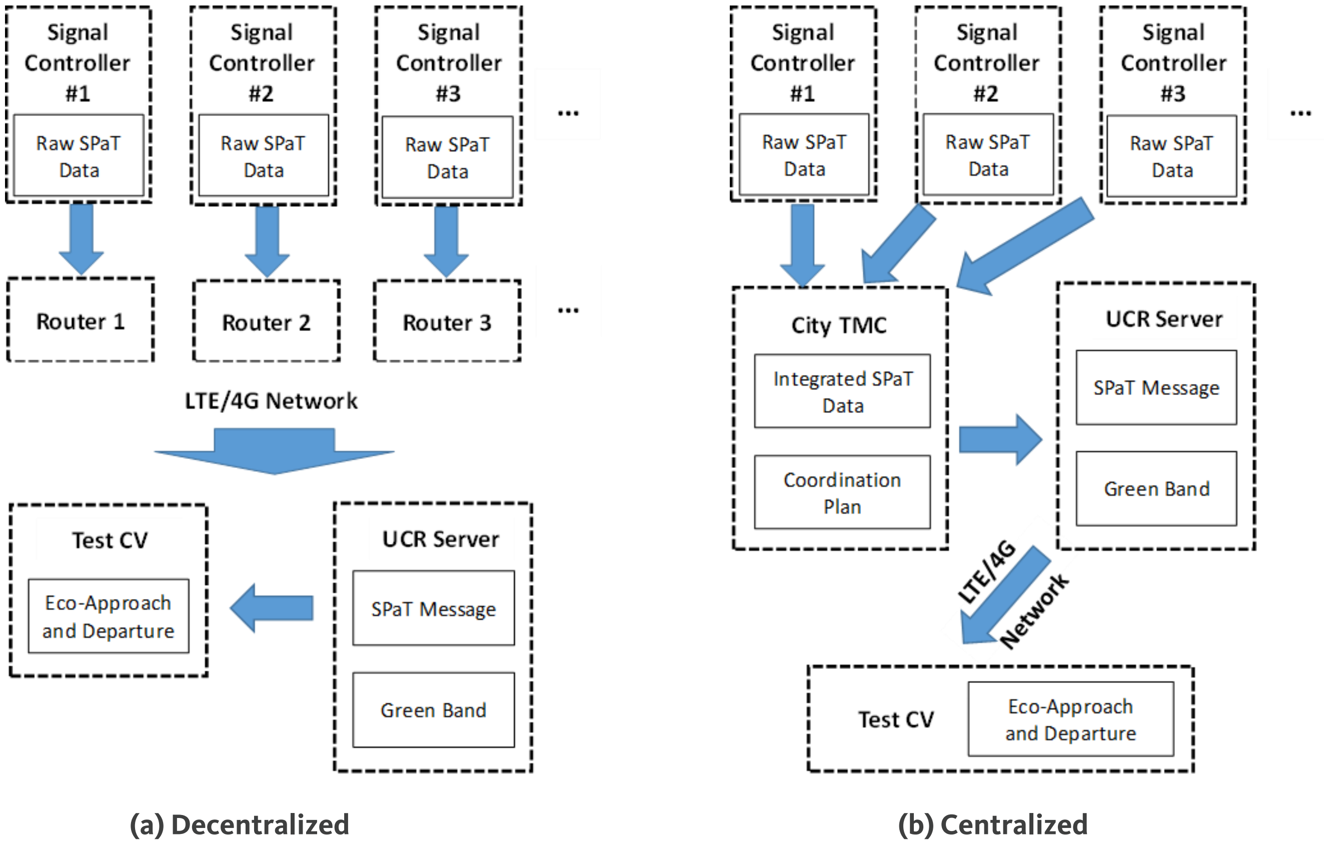


Figure 13. Candidate System Architectures for Enabling Cellular-based Communications

With help from the City of Riverside, the research team also upgraded the signalized intersections to broadcast RTCM messages which can deliver code and carrier corrections signals to the GNSS and reduce positioning errors in a cost-effective way. This is critical to many CAV applications that require reliable and accurate lane-level position information. RTCM corrections may be transmitted over the Internet, using the Networked Transport of RTCM via Internet Protocol (NTRIP) [16]. If sent over the Internet, these corrections can be downloaded directly into the test vehicle through a cellular connection or packaged into an RTCM message and transmitted to the test vehicle using DSRC. Figure 14 presents the system architecture used in this study for delivering RTCM messages via DSRC.

The research team and the City of Riverside continue to upgrade the infrastructure along the corridor by expanding other capabilities beyond wireless communications. For example, one of the sensor-rich intersections, Iowa Avenue and University Avenue, has been equipped with various high-resolution traffic and air quality surveillance systems, including GridSmart Fisheye cameras (see Figure 15), Ouster LiDAR OS1-64 (see Figure 16), and Clarity air quality monitors. These surveillance systems can not only provide data on individual vehicle movements and accurate vehicular counts or turning movements for different modes but can also detect and track other road users such as pedestrians, bicyclists, and micro-mobility users (e.g., electric scooter riders). Figure 17 presents the system architecture of Riverside's sensor-rich intersections that will enable the development and deployment of other emerging CAV applications, such as roadside-assisted cooperative automated driving. For example, roadside sensors can capture detailed traffic information and share with equipped vehicles to improve traffic performance (e.g., safety, throughputs) at intersections.

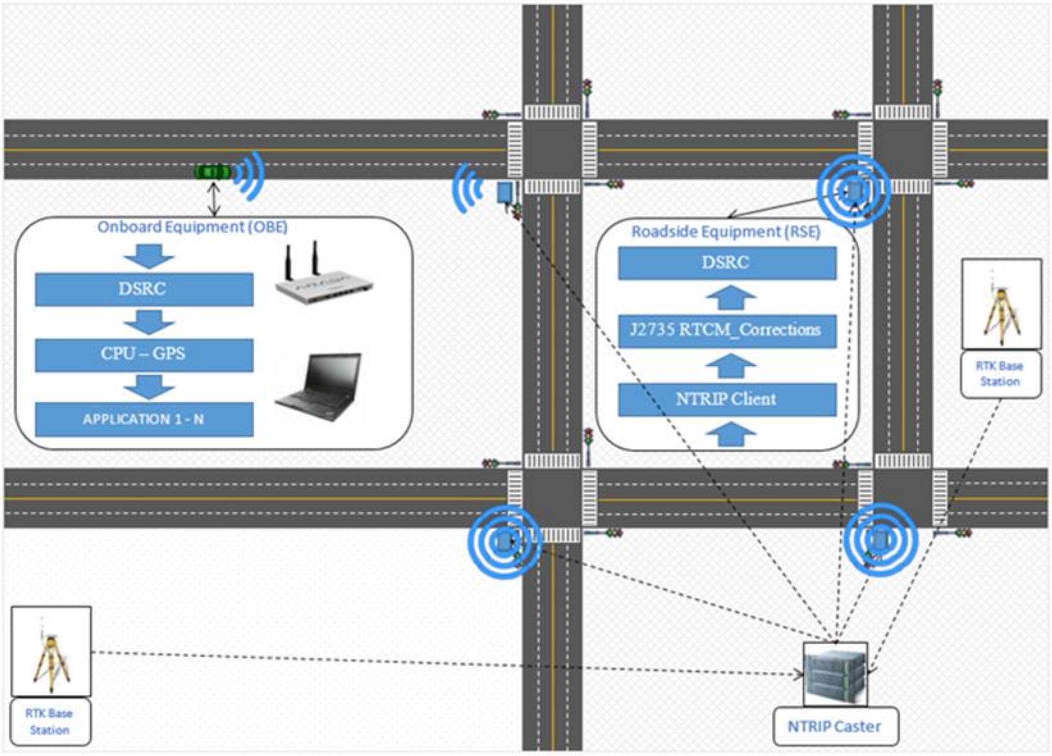


Figure 14. System Architecture for Transmitting RTCM Correction Messages via DSRC

(a) At Traffic Controller Cabinet **(b) Installing Camera on Street Lamp Post**

Figure 15. Photos of GridSmart Fisheye Cameras Installation

(a) At Traffic Controller Cabinet **(b) Installing LiDAR on Signal Pole**

Figure 16. Photos of Ouster LiDAR OS1-64 Installation

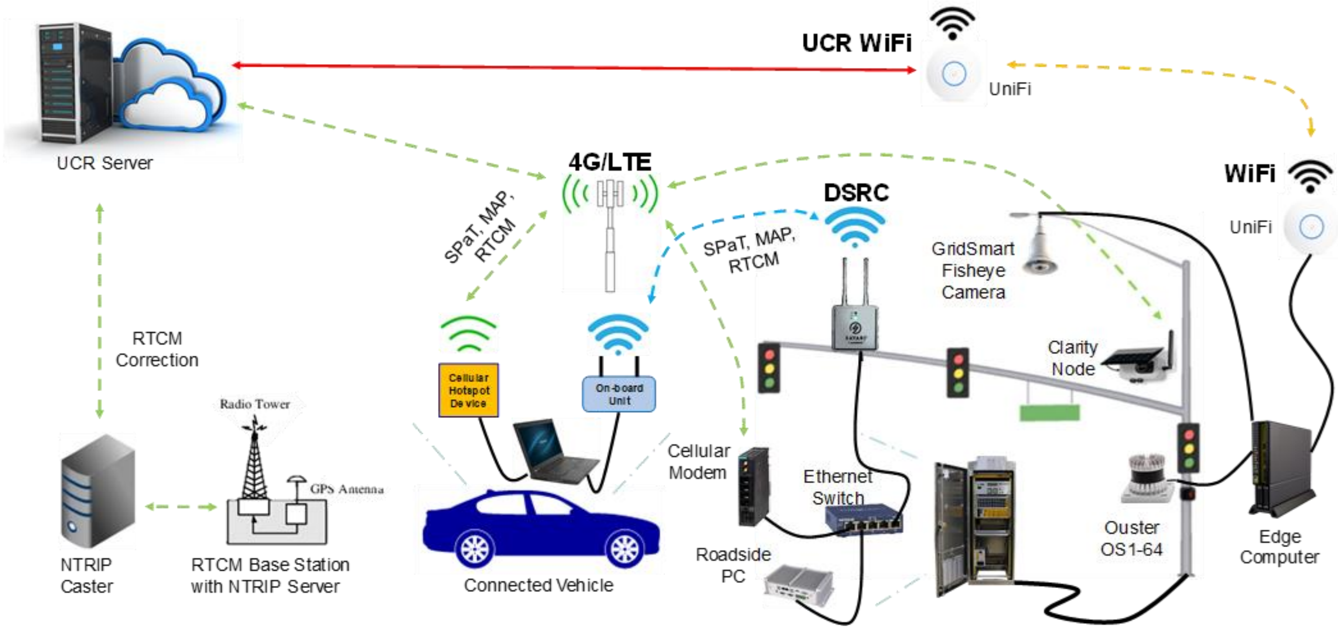


Figure 17. System Architecture of the Iowa Avenue and University Avenue Intersection

III. Developing a Connected Eco-Approach and Departure Application for Actuated Signalized Intersections

In order to maximize the potential mobility and environmental sustainability gains from the infrastructure upgrades the UCR team developed an innovative EAD application known as the Connected Eco-Approach and Departure for Actuated Signalized Intersections [17] application. Unlike most existing EAD applications that are designed for an isolated signalized intersection, the UCR-developed EAD application evaluated in this project can utilize the SPaT information of all downstream actuated signals in the travel corridor to optimize the vehicle's travel in terms of fuel consumption without compromising its travel time. It is noted that actuated signals adjust the length of the green signals based on detected traffic volumes, rather than having a fixed time for each phase. This adds uncertainties in signal phase and timing that could significantly complicate the optimization of vehicle's trajectory planning.

Overview of the Problem

When a connected vehicle enters a corridor with multiple connected actuated signalized intersections, it receives SPaT information from all the signals from which the vehicle's computer can calculate an optimal set of speeds (speed profile) for the entire corridor. An eco-driving vehicle would then follow the suggested speeds. In the proposed connected eco-driving framework, four types of information are fed into the algorithms to derive the most energy-efficient solution for the equipped vehicle:

- Distance to intersection (*D*): the road distance from the vehicle's current GPS location to the stop line of the next intersection
- Vehicle speed (*V*): the current speed of the vehicle, measured by on-board diagnostics or GPS devices
- Time (*t*): current time stamp
- SPaT information (*W*): the phase status of traffic signal: when the current phase began, how long the current phase has lasted, and estimated minimum and maximum time until the next phase change for all intersections in the corridor. We denote them as W_1, W_2, ... W_n for all *n* intersections in the corridor.

Using simultaneous data from multiple intersections (instead of just one intersection) presents three major challenges: 1) how to utilize the information and manage the uncertainties of all the actuated signals and develop an adaptive strategy; 2) how to balance travel time, speed and energy consumption over the entire corridor; and 3) how to calculate the optimal speed profile to achieve eco-driving. In the following subsections, we first discuss existing EAD models and their limitations and introduce the stochastic SPaT model that can accommodate the model framework. Then, we describe how we balance speed and travel time with energy consumption to achieve an optimal solution for an entire corridor. Finally, we propose a dynamic programming (DP) based model framework to efficiently determine the optimal solution.

Existing Connected Eco-Approach and Departure Applications

Most existing EAD strategies were developed based on isolated intersections or a limited number of intersections, but even a limited intersection by intersection approach did not lead to optimal results over longer distances. [18]. For example, Mandava et al. [19] proposed an algorithm to inform the practice of eco-driving—driving at a steady controlled speed to minimize fuel consumption and pollution generated—along an urban arterial. It was extensively evaluated and validated through both driving simulations [20] and field testing (with a light-duty vehicle [21] and a heavy-duty truck [12 – 14]). The algorithm showed very good real-time performance and substantial benefits in reducing fuel consumption and tailpipe emissions in both advanced driver assistance systems [22] and partially automated vehicle control systems [23]. However, significant efforts may be required to adapt the algorithm for customized powertrain models and handle rolling terrain rather than city streets. Rakha and Kamalanathsharma [24] developed a constant deceleration-based eco-driving strategy to avoid full stops at signals, followed by further improvement using a multi-stage dynamic programming and recursive path-finding principles, and evaluation with an agent-based model [25]. Asadi and Vahidi [26] proposed a predictive cruise control concept, to balance fuel use and trip time by utilizing traffic signal status information. The first step is to determine a target speed based on avoiding red lights whenever possible (green window), while the second step adjusts the target speed based on collected real time information.-Katsaros et al. [27] developed a Green Light Optimized Speed Advisory (GLOSA) system whose goal was to minimize average fuel consumption and average stop delay at a traffic signal. By considering the queue discharging process, Chen et al. [28] developed an eco-driving algorithm for a vehicle approaching and leaving a signalized intersection to minimize both emissions and travel time, but this study did not take account of the grade of the roadway. Jin et al. [29] , developed a system that can be used with signalized or non-signalized intersections, as well as freeways and can consider road grade and powertrain dynamics, however it involved longer computing times. Li et al. [30] used the Legendre Pseudo-Spectral method and knotting technique to overcome the discrete gear ratio issue in the optimal control for eco-driving at signalized intersections. Huang and Peng [31] used a simplified powertrain model and their approach was designed to optimize vehicle speed through intersections, which aimed to keep a balance between the solution optimality and computational time.

When considering EAD applications in a real-world environment, many studies have taken a “reactive” approach to cope with the problem of “queuing” or stop-and-go traffic caused by preceding vehicles’ slowing down. With this approach the subject vehicle was following too close to the car ahead or had to assume traffic signals were running fixed-time mode [32 – 34]. To address these issues, some researchers specifically focused on tackling the queuing effects for EAD by applying shockwave theory [35] or data-driven techniques [36] to predict the queue length or in essence the trajectory of the subject vehicle’s predecessor. Other strategies addressed the uncertainties in traffic signal timing by attempting to improve the prediction of signal phasing and timing [37] or by developing more robust eco-driving strategies [17, 38].

Recently, a few studies have focused on developing eco-driving strategies along entire corridors with multiple signalized intersections [4, 5, 39 – 41], where one of the major challenges is to balance minimizing fuel use against the time needed to compute the most efficient speeds for driving on a long roadway stretch. In this project, we developed an innovative EAD algorithm to use along a signalized corridor, which can better balance optimality and computational time. This is presented in the following section.

Model Framework for Multiple Signalized Intersections

Like other CAV applications that involve determining optimal speeds for traveling vehicles, the team's EAD application utilizes: 1) SPaT data from the upcoming traffic signals; 2) map and route information (e.g., stop line location, road grade, road speed limit, turning movement (e.g., left turn, right turn); 3) downstream traffic conditions such as queue length; and 4) the ego-vehicle's states and powertrain limitations (e.g., global position from GNSS, instantaneous speed, acceleration/deceleration limit) to determine the optimal recommended speed that can minimize the vehicle's energy consumption and tailpipe emissions when approaching to and departing from signalized intersections, without compromising travel time. Figure 18 presents the system architecture for the EAD application installed on the test CAV. In addition to simultaneously processing data from multiple signals in the corridor, our model employs a statistical approach capable of handling actuated signals that do not have fixed phased timing, as explained in the next section.

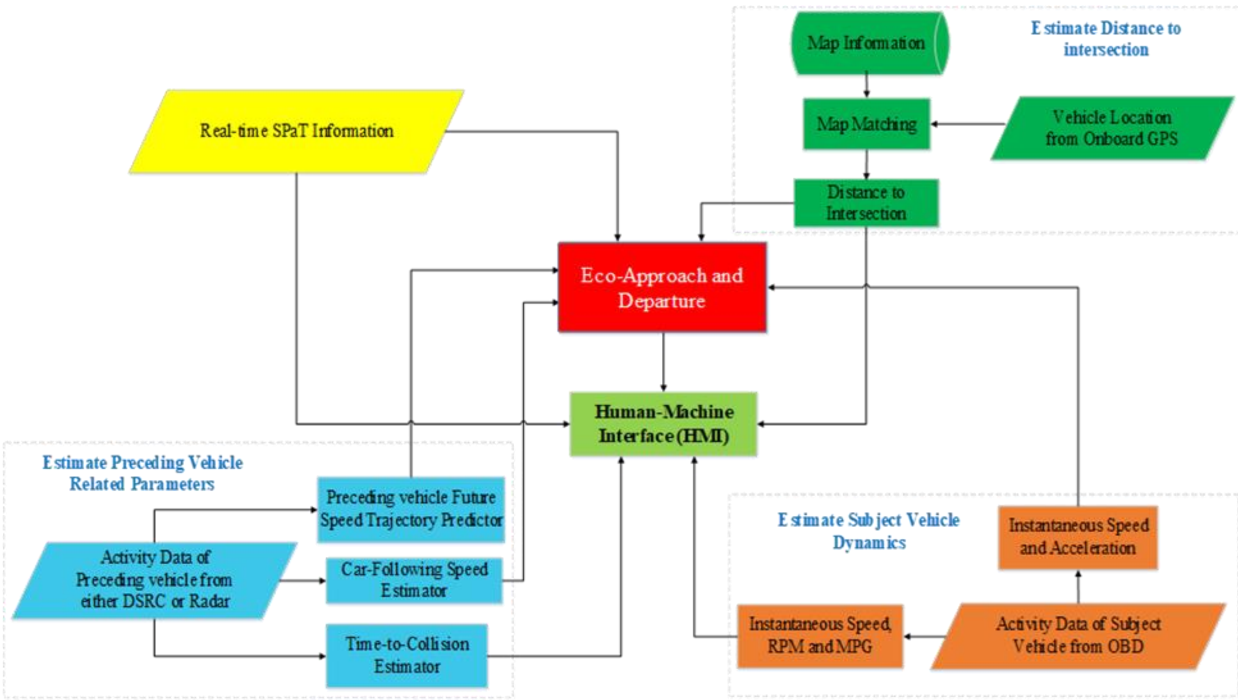


Figure 18**. System Architecture of Connected EAD Application Implemented in this Project**

Statistical Model Using Actuated SPaT Data

Since the actuated signals actively respond to the presence of queued cross traffic at an intersection by changing their signal timing, the SPaT pattern will be quite different for every cycle. This uncertainty increases the difficulties of deriving an energy efficient speed profile for vehicles operating in the corridor. Most existing eco-driving methods make certain assumptions about actuated SPaT information. Some assume that the minimum time-to-change, or maximum time-to-change, or both, usually converge to a similar value that is close to the real time-to-change when the phase comes to an end. Then, they derive an energy efficient speed profile based on the estimated time-to-change using the SPaT information. However, the real-world SPaT data show that this assumption does not hold in many cases. Figure 19 shows a SPaT example involving a vehicle approaching a real-world intersection. It compares the minimum and maximum remaining time provided in the first second of the phase, along with the exact phase duration. For the green phase, the exact phase duration is not well bounded by the minimum and maximum values, especially for four cases where the green time is significantly extended due to minor phase being skipped. For the red phase, the minimum and maximum values provide a wide range for the remaining time, which also causes difficulties in predicting the phase duration. These issues pose significant challenges to predicting the actual remaining time in a phase using SPaT information, and thus in deriving an energy efficient speed profile for the equipped vehicle to follow.

To solve the problem of uncertain minimum and maximum time-to-change SPaT information, we regard them as dummy parameters. We then define the SPaT state W_i as a set of three parameters: elapsed time in the current phase(sec) W_{iT}, estimated minimum time to change for the current phase(sec) W_{imin}, and estimated maximum time to change for the current phase(sec) $W_{i\max}$, respectively, for intersection *i*. Note that we assume the occurrences of SpaT messages from any two intersections are mutually independent.

A directional SPaT graph Is constructed to calculate the probability of one SPaT state transitioning to the next. The node of the graph represents a specific SPaT state $W_i = (W_{iT}, W_{i\min}, W_{i\max})$. A directional edge is connected between two nodes if the current SPaT state has transitioned to the next state, and the weight of the edge represents the frequency of this state transition, which can be estimated from the historical SPaT data.

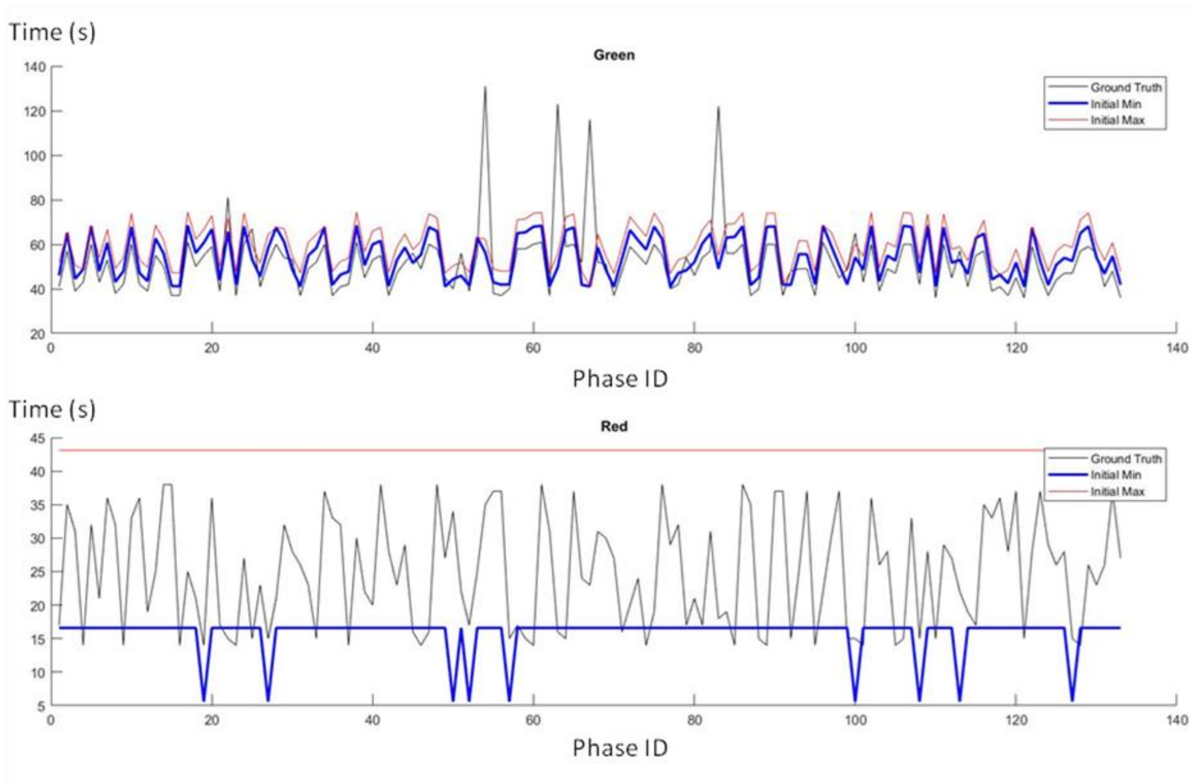


Figure 19. Sample SPaT Messages from a Real-World Actuated Signalized Intersection

Figure 20 shows an example of the proposed directional SPaT graph in the red phase. The numbers in each red node represent from top to bottom the elapsed time in the current phase, estimated minimum time to change, estimated maximum time to change. For a given red state W_i = {20,15,40}, the exact remaining time of the red phase can be 1s, 2s, 3s or more. After the SPaT graph is constructed, the probability of one state transitioning to the next can be calculated using the weight of the edge divided by the total weight of the outgoing edges.

Time, Speed and Energy Consumption

To achieve the most energy efficient speed trajectories given the dynamic state of the vehicle (such as location, speed), the time spent and final speed at the intersection should also be considered, as longer travel time with slower travel speed would usually lead to lower energy consumption but undesirable travel delays. A heuristic way to solve this problem is to give a large time penalty (P_t) to each time step in the trajectory and to give a speed penalty (P_v) if the final speed is less than the target speed (e.g., speed limit). But this solution would have the vehicle always passing through the intersection as soon as possible and neglecting any fuel savings from slower travel speeds. Therefore, we propose a reasonable method to convert travel time and final speed of the vehicle into a measure of energy consumption, so that the whole system can be optimized based on one global measurement, as detailed in the Figure 20.

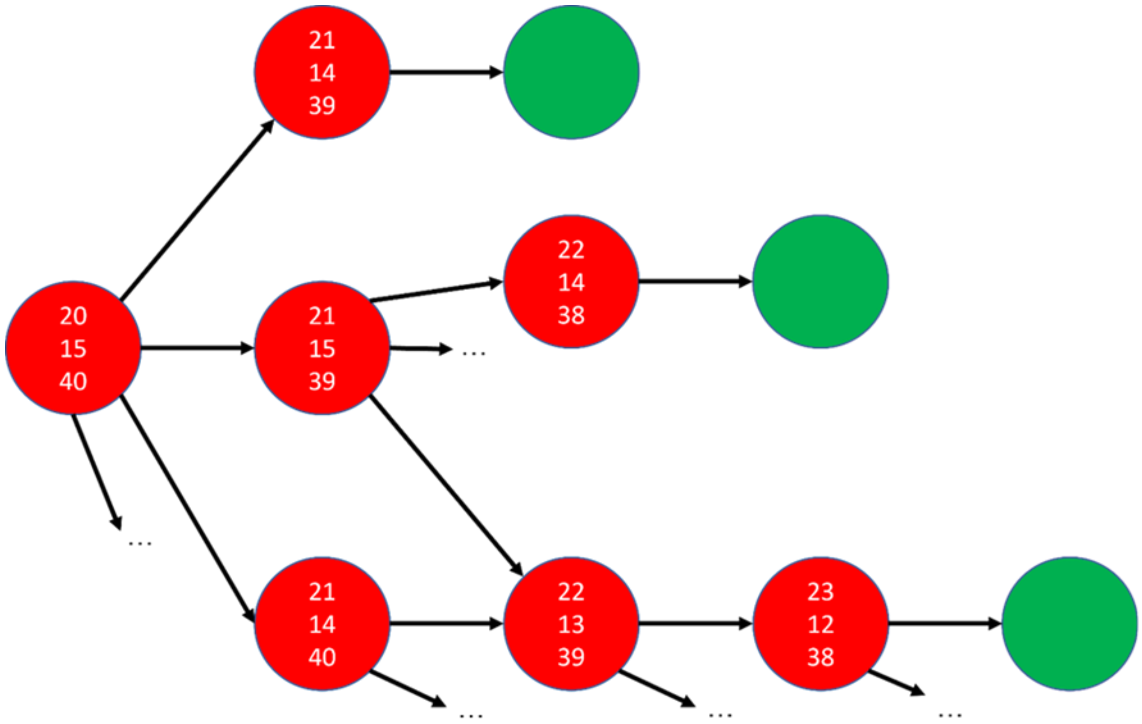


Figure 20. An Example of Directional SPaT Graph

To calculate the time penalty in terms of energy, we assume the target speed at the intersection is v_t. For the travel time difference t_{dif}, we consider two trajectories *A* and *B*. Trajectory *A* has constant speed v_t. Trajectory *B* has an acceleration and deceleration pattern with the same minimum total travel time, so that the travel distance of trajectory *B* is $t_{dif} \times v_t$ is larger than the travel distance of trajectory *A* while the initial and final speed are both v_t. The energy penalty for t_{dif} is calculated as the energy difference between the two trajectories. The function is then formulated as follows:

$$\begin{aligned} & Minimize\ T \\ & s.t. \quad t_A = t_B = T \\ & \quad Dis_A - Dis_B = t_{dif} \times v_t \end{aligned}$$

where t_A and t_B denote the total travel times of trajectory *A* and *B*, respectively; and Dis_A and Dis_B denotes the total travel distances of trajectory *A* and *B*, respectively. To calculate the energy penalty per second, we divide the total energy difference by the total travel time.

For the energy speed penalty, we consider two trajectories *A* and *B* with the speed difference v_{dif},. Trajectory *A* has constant speed v_t. Trajectory *B* has an acceleration and deceleration pattern with the same minimum total travel time so that the travel distance of trajectory *B* is same as the travel distance of trajectory *A*, while the initial and final speed for *B* are v_t - v_{dif} and v_t, respectively. The energy penalty for v_{dif} is calculated as the energy difference between the two trajectories.

DP-based Model Framework

In Hao et al. [12], a graph-based trajectory planning algorithm was developed to calculate the optimal solution to EAD. In that work, we assigned a unique 3-D coordinate (t, D, V) to describe the dynamic state of the equipped vehicle, which corresponds to the nodes in the graph. The edges in the graph represent the movement of the vehicle, i.e., state transition from one-time step to the next. The cost on edge is the energy consumption during this state transition process. To formulate this graph model, we discretize the time and space into fixed time step Δt and distance grid Δd. The vehicle speed domain is therefore discretized with $\Delta d/\Delta t$ as the step. The energy consumption minimization is formulated as a problem to find the shortest path from the source node Vs (t, D, V) to the destination node Vd (T, 0, V') in the directed graph, where t, D and V are the current time, distance and speed of the vehicle, respectively. T is the target passage time at the stop line. For the scenario of arrival at the red phase, T can be identified as the start of the green phase plus a buffer time, i.e., $T = T_g+\tau_b$. V' is the target speed when the vehicle passes the stop line. Dijkstra's algorithm [42] is then applied to solve this single-source shortest path problem. This method shows good performance in energy efficiency but takes relatively long computational time in creating the graph and solving it.

To achieve higher computational efficiency and better compatibility with stochastic models using the SPaT messages from multiple intersections, we reformulate this as a dynamic programming problem in this project which the following objective:

Given any initial state (t, D, V, W), find the optimal valid actions that minimize the expected total cost over the rest of the path to the target state (T, 0, V', W').

Here we say the transition from State 1 to State 2 is a "valid" action if it satisfies:

- Time at State 2 is consecutive with time at State 1: $t_2 = t_1+\Delta t$;
- Consistency on distance and speed: $D_2 = D_1-V\Delta t$;
- SPaT at State 2 is consecutive with SPaT at State 1 based on the historical SPaT data;
- Speed constraint: $V_2 = V_1+x_1\Delta t$ and $V_{min}\leq V_2\leq V_{max}$, where V_{min} and V_{max} are the minimum and maximum speed allowed, respectively;
- Acceleration constraint: $a_{min}\leq x_1\leq a_{max}$, where a_{min} and a_{max} are the maximum deceleration rate and maximum acceleration rate, respectively.

Then we say State 1 is the valid parent state of State 2, and State 2 is the valid child state of State 1. Based on the criteria above and given state (t, D, V, W), the valid actions are included in the set of {$t+\Delta t$, $D-V\Delta t$, $V+x\Delta t$, $W\rightarrow W'$} where $a_{min}\leq x_1\leq a_{max}$ and $V_{min}\leq V+x\Delta t\leq V_{max}$.

The acceleration rate x is therefore the key variable to define a valid action. According to the powertrain model in Hao et al. [12], the acceleration is also important in energy estimation for any type of vehicle or powertrain. We can formulate a powertrain-specific function $H(V, x, \Delta t)$ to represent the cost as the study vehicle varies its speed from V to $V+x\Delta t$ in Δt time. We then use $M(t, D, V, W)$ to represent the minimum total cost at state (t, D, *V*, *W*), which corresponds to a series of optimal valid actions from the initial state to the final state. This problem is then formulated iteratively as follows:

$$M(t, D, V, W) = \min_x \left(H(V, x, \Delta t) + \sum \mu_{W \to W'} M_{W'} \right)$$
$$s.t. \quad a_{min} \le x \le a_{max}$$
$$V_{min} \le V + x \le V_{max}$$
$$M_{W'} = M(D - V\Delta t, V + x\Delta t, t + \Delta t, W')$$

where *W'* is the possible SPaT state in the next time step; $M_{W'}$ = M{*t+Δt*, *D-VΔt*, *V+xΔt*, *W'*} is the residual cost if the next SPaT state is *W'*; and $\mu_{W \to W'}$ is the probability that the next SPaT state is *W'*. The sum of probabilities $\mu_{W \to W'}$ equals to 1. Note that *W* consists of messages from the current intersection as well as its following intersections in the corridor.

We also define the values of boundary states at or beyond the stop line. If the vehicle arrives at the stop line at the target time at target speed, then *M*(*T*, *0*, *V'*, *W'*)=0. For other cases:, 1) if the vehicle passes the stop line ($d < 0$), the total cost function is set to infinity, i.e., *M*(*t*, *D*, *V*) =+∞; or 2) if the vehicle arrives at the stop line at the speed other than the target ($d=0$, $v \neq V$), then the total cost function would consider a speed penalty, i.e., *M*(*t*, *D*, *V*) + P_v. Based on all the aforementioned assumptions, this problem is formulated as a multiple-source single-destination shortest path problem. It can be solved using a variational *Dijkstra* algorithm, in which two nodes are linked only if their states are consecutive in time. Assuming there is a total of *n* intersections in the corridor, the proposed framework can solve for *M* and *x* for the n_{th} intersection, where the SPaT message only contains information from the n_{th} intersection. After that, *M* and *x* for the $(n-1)^{th}$ intersection will be constructed with the final state being defined as the initial state of the n^{th} intersection, and *W* contains information from two intersections. Using similar approaches, the cost and action corresponding to each state in the corridor can be calculated.

Simulation Study and Results

Simulations were conducted in MATLAB [49] to test the proposed method and compare it with the baseline (i.e., without any driving guidance).

Table 1 below shows the assumptions for all the simulations in the red and green light phase.

Table 1. Simulation Assumptions and Parameters

Symbol	Description	Value
n	Number of intersections	2
D	Distance of each intersection	400 m
v_t	Targeted speed of the host vehicle at intersection	10 m/s

v_{max}	Maximum speed	18 m/s
v_{min}	Minimum speed	0 m/s
a_{max}, - a_{min}	Maximum and minimum acceleration	2 m/s^2
Δd_{TL}, Δt, Δv	Minimum interval in the state parameters	1

The SPaT data applied in the algorithm were collected from the eastbound lanes of University Avenue, at Cranford Avenue and University Avenue, and Chicago Avenue and University Avenue. The data were preprocessed so that only the time periods of 12pm – 2pm from July 1, 2021 to July 31, 2021 were included which introduces less phase plan variations and uncertainties in the graph construction, which makes the suggested speed more accurate for achieving energy savings. All the time parameters are rounded to integers to decrease the number of nodes in the SPaT graph.

We compare three other algorithms to test the energy efficiency performance of the proposed corridor-based EAD algorithm: 1) an intersection-based EAD algorithm; 2) a baseline (without the EAD algorithm) human-driven algorithm with 1m/s^2 maximum acceleration; and 3) baseline (without EAD algorithm) human-driven algorithm with 2m/s^2 maximum acceleration. The intersection-based EAD algorithm uses the same optimization function as the corridor-wise EAD algorithm but without SPaT information from the next intersection. The baseline driving behaviors were developed as follows: when the host vehicle enters the study zone, it accelerates to the posted speed limit using maximum acceleration, then gradually decelerates at a constant rate after reaching the safety distance until the vehicle stops at the intersection. The safety distance is the shortest distance the vehicle needs to stop at the stop line with the maximum deceleration. If the traffic signal changes to the green phase during this process, the vehicle will immediately accelerate with the maximum acceleration and pass through the intersection as quickly as possible.

To compare the energy consumption between the proposed and baseline method, a total of 60,000 seconds of historical SPaT messages at each intersection of the corridor were tested with different phase-entry times and initial velocities. The energy penalty for speed and travel time is also added to account for the time and speed difference. Table 2 and Table 3 show the average energy consumption before and after the energy penalty is added, and the travel time between the four methods at different initial speeds, i.e., 1 m/s (2.2 mph) and 18 m/s (40.3 mph). The saving percentage is calculated based on the baseline case with 1m/s^2 maximum acceleration.

Table 2. Simulation Results for Four Methods with Initial Speed of 1 m/s (2.2_mph)

Algorithm	**Without Penalty**		**With Penalty**		**Savings**	
	Energy (kJ)	Time (s)	Energy (kJ)	Time (s)	Energy (kJ)	Time (s)
Corridor EAD	58.7	78.8	66.6	78.8	***11.8%***	3.5%

Intersection EAD	59.9	79.5	69.9	79.5	7.4%	2.6%
Baseline $2m/s^2$	65.9	76.6	72.6	76.6	3.9%	***6.2%***
Baseline $1m/s^2$	60.8	81.6	75.6	81.6	0.0%	0.0%

As can be seen from the two tables, without compromising travel time, the energy consumption of the proposed corridor EAD algorithm is always the minimum among all four algorithms—with energy saving as high as 11.8 percent and 8.8 percent for the initial velocity of 1 m/s and 18 m/s, respectively. Smaller energy savings for larger initial speeds may be due to higher initial kinetic energy and less space to adjust the speed trajectory for the host vehicle.

Table 3. Simulation Results for Four Methods with Initial Speed of 18 m/s (40.3 _mph)

Algorithm	Without Penalty		With Penalty		Savings	
	Energy (kJ)	Time (s)	Energy (kJ)	Time (s)	Energy (kJ)	Time (s)
Corridor EAD	37.9	74.3	44.5	74.3	***8.8%***	-1.0%
Intersection EAD	38.0	75.2	47.5	75.2	2.6%	-2.3%
Baseline 2m/s2	39.9	72.4	46.6	72.4	4.4%	***1.5%***
Baseline 1m/s2	37.4	73.5	48.8	73.5	0.0%	0.0%

Figure 21 below compares the sample trajectories between the corridor-wise EAD and baseline human-driven with 2 m/s^2 maximum acceleration. As can be seen from the figure, the corridor-wise EAD algorithm avoids most of the red phases on both intersections and can reach a higher speed when passing through the destination. On the other hand, the baseline vehicle has to stop at the intersections and wait for the green phase, which wastes energy when the light changes and the vehicle accelerates back to the speed limit.

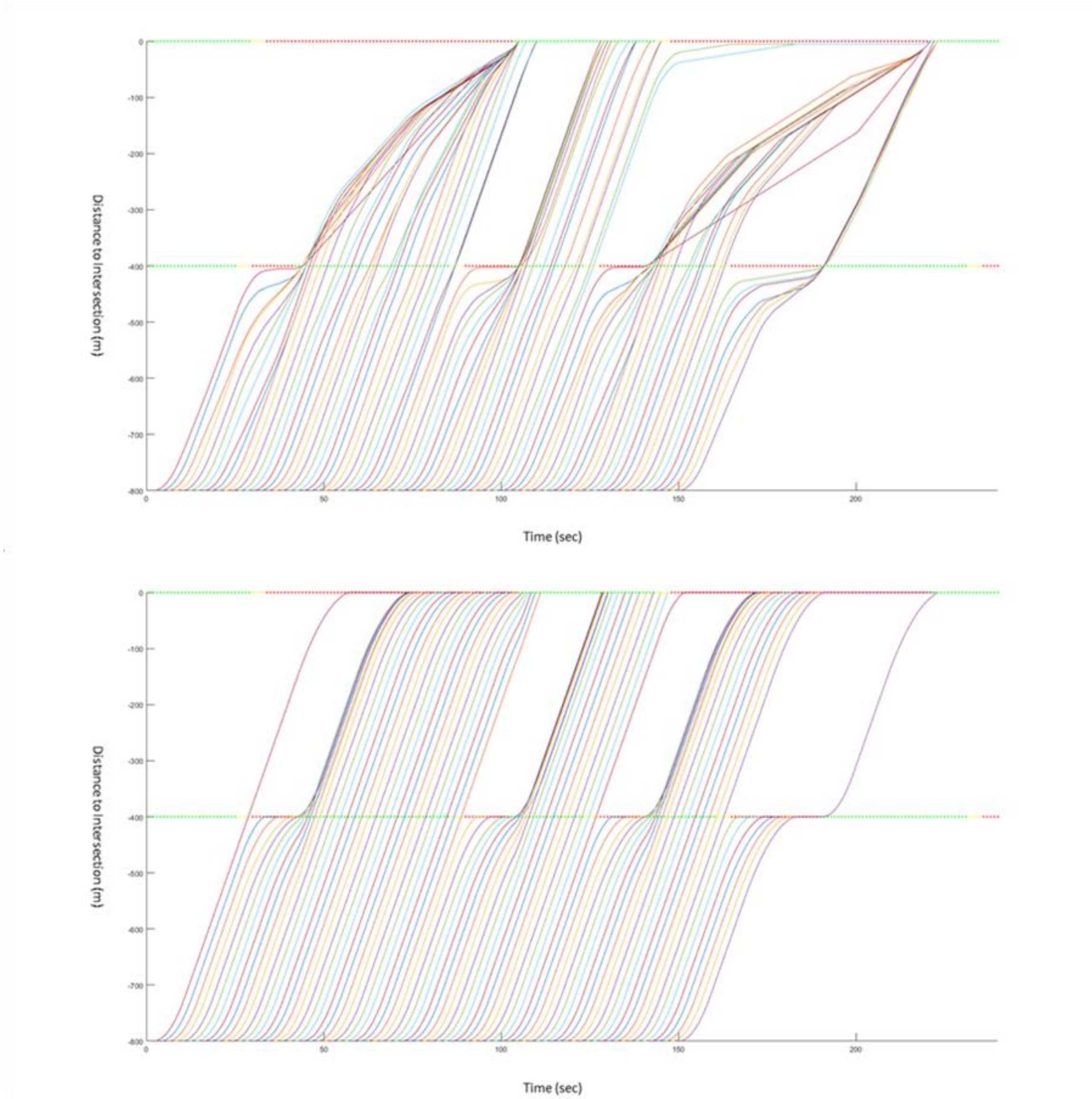


Figure 21. Example Trajectories of Corridor-wise EAD (top) and Baseline (bottom) for Initial Speed of 1 m/s

Field Testing the EAD Application

To further evaluate the costs and benefits in energy, emissions and mobility from upgrading infrastructure connectivity, we conducted a series of experiments using our existing CAV test vehicle—a Nissan Altima equipped with different communication technologies (DSRC on-board unit or cellular WiFi hotspot) and enabled with different EAD algorithms (intersection-by-intersection or corridor-wise)—and a Toyota Corolla serving as the baseline vehicle.

Test Track Layout

Testing was performed eastbound along University Avenue. Figure 22 shows the route taken along University Avenue, mainly covering two intersections: Cranford Avenue and University Avenue, and Iowa Avenue and University Avenue, from 320 meters upstream of Cranford Avenue to 50 meters downstream from Iowa Avenue. Two student drivers alternately drove the two test vehicles side-by-side along the inner through lane and outer through lane. Both vehicles entered the corridor at the same time and followed the dashed red line, as shown in the figure. The system architecture for the field operational tests is presented in Figure 23, where the blue vehicle represents the Nissan Altima (connected vehicle) while the white vehicle represents Toyota Corolla (baseline vehicle). In addition, to account for the communication delay, we further differentiated between *mobile computing* (EAD algorithms running on-board) and *cloud computing* (EAD algorithms running on the UCR server).

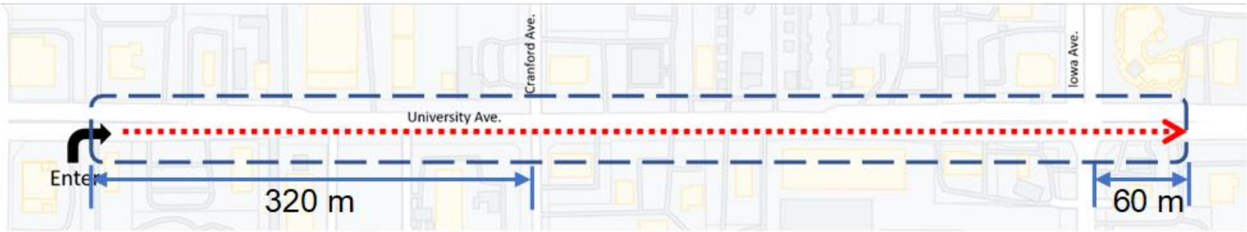


Figure 22. Test Route in the Field

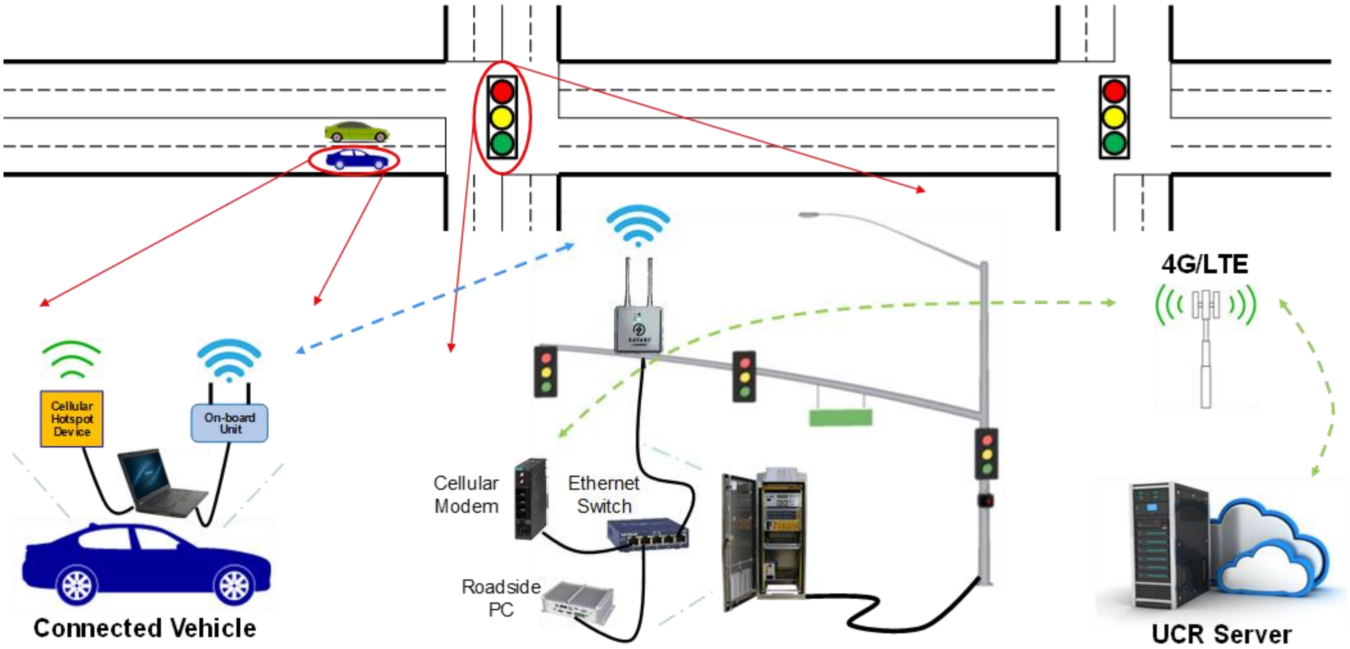


Figure 23. System Architecture for Field Operational Tests

We tested four combinations of communications technologies and EAD algorithm:

- Combo 1: DSRC-based communications; intersection by intersection, onboard computing, EAD algorithm as in Hao et al. [17]
- Combo 2: cellular-based communications; intersection by intersection, onboard computing, EAD algorithm as in Hao et al. [17]
- Combo 3: cellular-based communications; intersection by intersection, cloud computing, EAD algorithm developed in this project (but with SPaT messages from the following intersections masked)
- Combo 4: cellular-based communications; corridor-wise, cloud computing, EAD algorithm developed in this project.

Therefore, the number of scenarios (considering drivers, lanes, and algorithm/technology combinations) are 2 (drivers) × 2 (through lanes) × 4 (combos) = 16 (scenarios). To mitigate the random effects, each scenario is repeated with 5 runs (both vehicles are driving in parallel). So, there were a total of 80 runs in the field.

To evaluate the system performance under the various algorithm/technology combinations, we focused on both mobility in terms of average travel time across the test area as shown in Figure 22, and environmental impacts including fuel consumption and emissions of CO_2, CO, HC and NOx which were estimated by the Comprehensive Modal Emission Model (CMEM) [43] previously developed by the research team. CMEM was chosen because it is more accurate than the Motor Vehicle Emission Simulator (MOVES) used by the U.S. Environmental Protection Agency [44] when assessing the environment-related metrics for CAV applications at the microscopic level or involving transient behaviors (i.e., based on second-by-second vehicle states) [45].

Test Connected Vehicle

The Nissan Altima test vehicle was equipped with an on-board DSRC unit that could receive not only GPS signals for determining the vehicle's position and speed but also SAE J2735 messages from the road infrastructure and other connected vehicles. Specific messages include SPaT information from traffic signals, intersection MAP information, and position-enhancing RTCM correction messages. As shown in Figure 24, the vehicle's on-board diagnostics system is connected via a CANBus interface (OBD-II ELM-327 cable) to our on-board computer (running Ubuntu) to obtain the vehicle's high-resolution (at 10 Hz) dynamics information in real-time. The vehicle was also equipped with a cellular WiFi hotspot to enable communication through cellular networks. Data from various sources are processed and recorded on the on-board computer. Depending on the system setup, the EAD algorithm is carried out either on-board or at the UCR server. The computer also provides information to the driver through a driver-vehicle interface (the monitor display shown in Figure 24). For both vehicles, data from the OBD-II and GPS were logged on the respective on-board computer for further analysis.

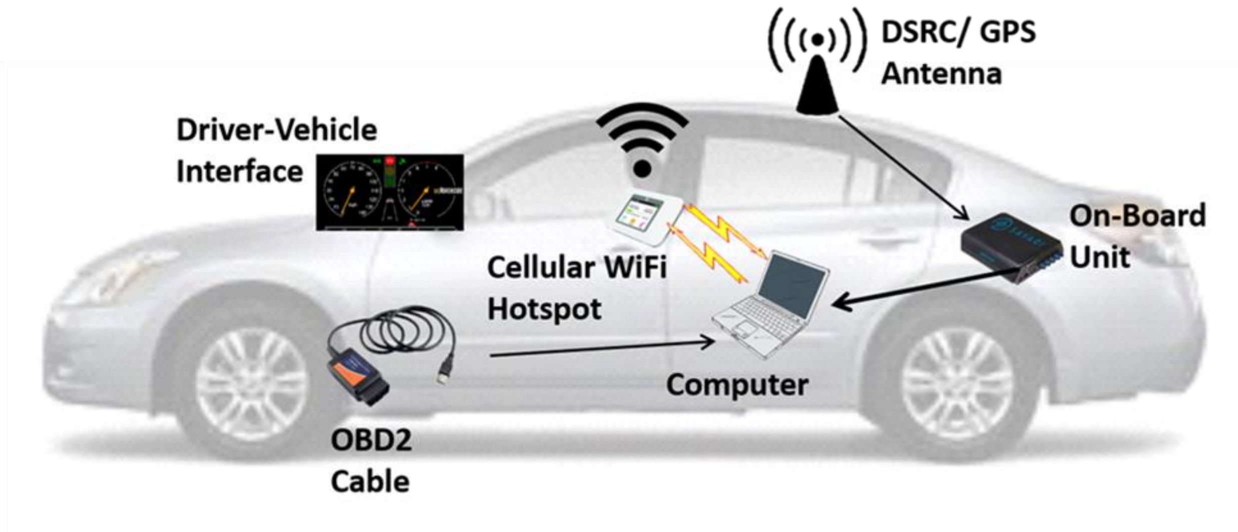


Figure 24. UC Riverside's Connected Vehicle and On-board Components

Results

Table 4 summarizes the major results in terms of the relative improvement of the different "Combos" over the baseline scenario. As shown in the table, the developed EAD algorithm for actuated signals can provide significant environmental benefits, using either DSRC or cellular networks. The corridor-wise EAD algorithm (i.e., "Combo 4") outperforms the other combos in terms of mobility (travel time savings), fuel consumption, as well as CO_2 and HC emissions.

Table 4. Summary of Key Statistics on Improvement for Field Operational Tests Using Different Combinations of Algorithm/Communication Technology

Combo	Lane	Statistics	Travel Time	Fuel	CO2	CO	HC	NOx
1	Inner	Mean	6.9%	15.6%	15.5%	32.1%	-7.3%	29.0%
		STD	0.19	0.17	0.17	0.16	0.26	0.15
	Outer	Mean	-14.0%	9.5%	9.4%	26.7%	-33.6%	27.3%
		STD	0.27	0.25	0.25	0.41	0.29	0.30
	Overall	Mean	-3.5%	12.5%	12.5%	29.4%	-20.5%	28.1%
		STD	0.23	0.21	0.21	0.29	0.28	0.23
2	Inner	Mean	-4.6%	15.3%	15.2%	27.4%	-13.3%	23.8%
		STD	0.05	0.09	0.09	0.18	0.10	0.19
	Outer	Mean	-12.8%	13.0%	12.9%	24.6%	-12.9%	25.3%

Combo	Lane	Statistics	Travel Time	Fuel	CO2	CO	HC	NOx
		STD	0.33	0.22	0.22	0.46	0.30	0.36
	Overall	Mean	-8.7%	14.1%	14.1%	26.0%	-13.1%	24.5%
		STD	0.19	0.15	0.15	0.32	0.20	0.27
3	Inner	Mean	-5.4%	8.8%	8.8%	17.2%	-22.5%	17.2%
		STD	0.05	0.08	0.08	0.19	0.14	0.17
	Outer	Mean	2.4%	22.1%	22.0%	44.1%	-10.1%	40.2%
		STD	0.06	0.07	0.07	0.12	0.16	0.11
	Overall	Mean	-1.5%	15.5%	15.4%	30.6%	-16.3%	28.7%
		STD	0.06	0.07	0.07	0.15	0.15	0.14
4	Inner	Mean	10.7%	19.6%	19.6%	22.5%	4.0%	21.2%
		STD	0.29	0.19	0.19	0.18	0.34	0.15
	Outer	Mean	2.0%	11.6%	11.6%	16.0%	-7.8%	16.2%
		STD	0.03	0.10	0.10	0.25	0.11	0.21
	Overall	Mean	6.3%	15.6%	15.6%	19.3%	-1.9%	18.7%
		STD	0.16	0.15	0.14	0.22	0.23	0.18

In addition, cellular-based EAD applications outperform the DSRC-based approach from the environmental perspective (e.g., Combo 2 vs. Combo 1). Some potential reasons could be the limited communication range of DSRC and the proximity to buildings and trees that may influence the DSRC wireless channel by creating radio signal reflections and diffraction. Most runs on the inner through lane are smoother than those on outer through lane, possibly due to the fact that the outer lane may experience more congestion since it is connected to the on-ramp of I-215 South freeway and experienced much more frequent interruptions during the test period.

Other Experiments

In addition to evaluating the mobility and environmental sustainability performance of different EAD algorithms, the research team performed experiments at the test site to estimate the time needed to transmit information using both DSRC and cellular networks and determine how accurately the upgraded system can locate where individual vehicles are with relation to other vehicles on the road and to the road network.

Latency Analysis

To determine the significance of any delays in receiving cellular messages compared to those using DSRC technology, the test vehicles were driven along the testbed using the same on-board computer to simultaneously record the time taken for both DSRC (one-way communication by listening to the SPaT messages broadcast from roadside units) and cellular communication (two-way communication by requesting the SPaT messages and reckoning back from the UCR server). We performed four runs and Table 5 summarizes the key results. As shown in the table, the average delay for the DSRC-enabled scenarios was under 0.1 second while that of cellular-based communications varied from 0.13 to 0.26 second on average. The standard deviation of communication latency for DSRC is much smaller (reduced by the range of 74.7% – 85.6%) than that of the cellular network. However, based on the field operation test results, shown in Table 4, the delays associated with using the cellular network do not result in negative effects on the connected EAD application. We hypothesize that a human driver may well tolerate such delays when using the application for eco-driving guidance compared to safety-critical scenarios such as collision avoidance.

Table 5. Summary of Key Statistics on Latency Tests

Test Run Index	No. of Samples	DSRC (μ sec[a])		Cellular[b] (μ sec)	
		Mean	STD[c]	Mean	STD
1	6	36,457	5,701	131,933	23,628
2	92	51,717	27,247	184,059	107,857
3	15	72,749	25,633	259,401	178,378
4	80	49,442	22,918	175,802	128,575

[a] μ sec = 10^{-6} seconds.
[b] Results for cellular communication have been divided into half, assuming each one-way communication has the same latency.
[c] STD means *standard deviation*.

Positioning Accuracy Analysis

In this study, we assessed the positioning accuracy of two consumer-grade test GNSS receivers that might be installed in a CAV compared to a survey-grade reference receiver, which was used to obtain ground truth, or the accurate real-world position of the test vehicle.

One test receiver was a u-blox NEO-M8P (approximate cost $200 USD) single-frequency Realtime Kinematic (RTK)-capable GNSS receiver. RTK is a technique that improves the accuracy of the receiver by receiving and processing correction messages from a satellite. The other was a u-blox NEO-M8L embedded in a Savari MobiWAVE, an aftermarket DSRC unit, which is a typical connected vehicle positioning system [46]. The NEO-M8L is capable of receiving Space-Based Augmentation System (SBAS) corrections and has an integrated 3-axis accelerometer and gyroscope that can be used for dead reckoning. The reference receiver was the Trimble 5700, a dual-frequency RTK-capable GNSS receiver.

During the test, the GNSS receivers were all placed in the cabin of the Nissan Altima, with their antennas mounted on top of the vehicle along the centerline of the vehicle and spaced approximately equally apart (see Figure 25). Mounting all receivers on the same vehicle allowed them to be tested simultaneously and in close proximity. This was intended to minimize the effect of location- and time-dependent factors that impact GNSS position accuracy, such as satellite geometry and the vehicle's surrounding environment (e.g., buildings, trees, and other vehicles).

The Trimble receiver used a survey-grade antenna, the u-blox a small patch antenna, and the Savari a combined DSRC/GNSS antenna for reception of GNSS signals and transmission/reception of DSRC messages.

For the test, the Nissan vehicle was parked out or doors and multiple measurements were obtained from each receiver. Figure 26 plots data from one of the tests. Each receiver's position measurements are normalized so that (0, 0) corresponds to the receiver's true position. The Savari position fixes (without RTCM correction) wander as far as 6 meters from the true position, whereas the u-blox (with RTCM correction) and especially Trimble measurements (ground truth) are tightly grouped around the true position.

Table 6 shows the results of all the test runs, where "u-blox" refers to the NEO-M8P, and "Savari" refers to the u-blox receiver (without RTCM correction) embedded in the Savari DSRC unit. Both the Trimble (ground truth) receiver and u-blox NEO-M8P unit used RTCM corrections, enabling their RTK mode. As would be expected of a survey-grade receiver in RTK mode, the Trimble demonstrated an average error of only 1-2 centimeters. The u-blox NEO-M8P unit's errors were generally on the order of 10 centimeters (about 4 inches). The average error of the Savari unit was about 2-3 meters, suggesting that it would not be able to provide lane-level accuracy even when the vehicle was not moving. In addition to the tests in the City of Riverside, we also performed other tests (e.g., urban canyon dynamic tests) in downtown Los Angeles and along the California Connected Vehicle Testbed (SR-82). For more information about the test results of RTCM correction on positioning accuracy of the equipped vehicle, please refer to Williams, et al. [47].

Figure 25. Three Receivers Were Installed on Test Vehicle for Measuring Positioning Accuracy

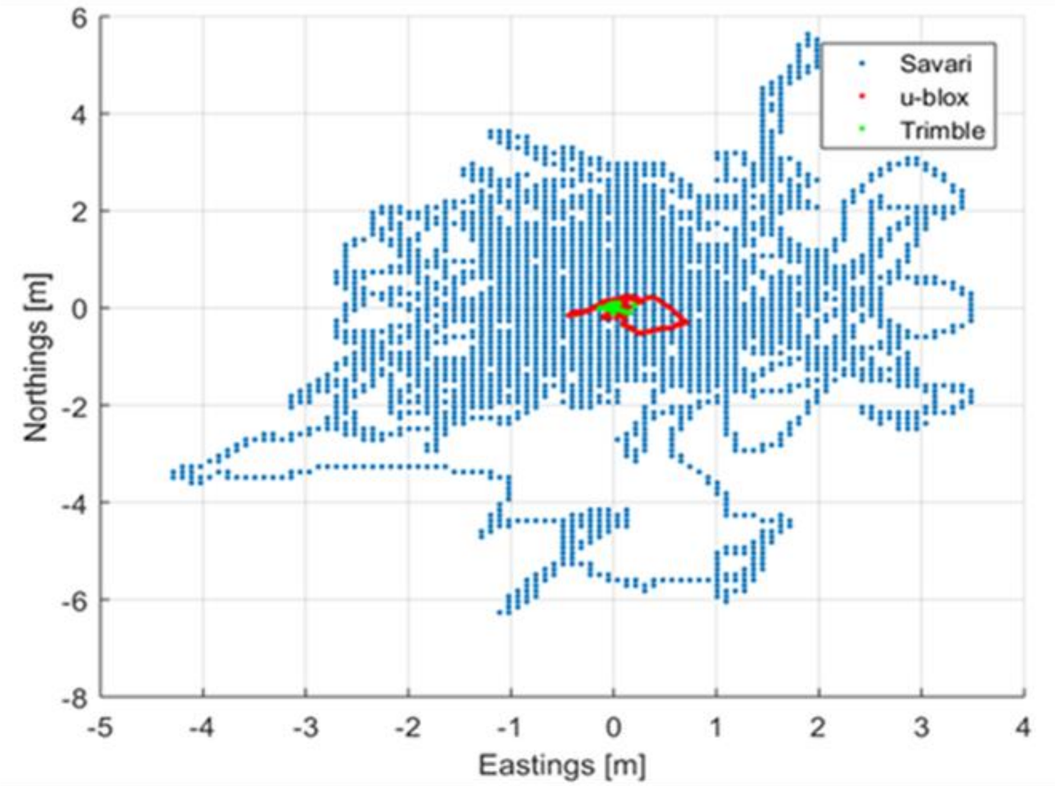


Figure 26. Location Data from One Static Test for the Open-Sky Experiment

Table 6. Static Test Results for the Open-Sky Experiment

Test Duration	Average Error (m)		
	Trimble	u-blox	Savari
2.5 hrs	0.01	0.26	3.22
2 hrs	0.01	0.01	2.87
1.5 hr	0.01	0.41	1.97
Average of all tests	0.01	0.23	2.69

IV. Key Findings

In this project, the research team worked together with the City of Riverside and evaluated the costs and benefits of upgrading wireless communication capability of the roadway infrastructure at designated signalized intersections to support future CAV deployment. We first reviewed the major CAV test facilities across the entire state, and produced an easily maintained and updated map that can be accessed through a public webpage. We also collaborated with the city's traffic engineers to continue building up the Riverside Innovation Corridor by: a) upgrading traffic signal controllers to enable broadcasting SAE J2735 (ver. March 2016) standard messages (including RTCM corrections); b) installing DSRC roadside units and cellular routers at designated intersections; and c) equipping those intersections with advanced infrastructure-based surveillance systems (e.g., LiDARs, fisheye cameras, and air quality monitoring units), all as part of Riverside's Smart City Initiative. To quantify the benefits in upgrading the wireless communication capability, we also developed an innovative connected Eco-Approach and Departure application for multiple actuated signalized intersections and conducted field operational tests to evaluate the system performance in terms of both improved mobility and environmental sustainability using different wireless communication technologies (DSRC vs. cellular network) and different eco-driving algorithms. In addition, we performed preliminary experiments comparing communication delays between using DSRC and the cellular network; and b) the positioning accuracy of three different GPS receivers.

The major findings from this project are:

- We are on the cusp of a seismic shift to emerging transportation technologies and services, such as CAVs. Numerous infrastructure upgrades have been carried out across the nation to support CAV deployment. To maintain its advantage in next-generation intelligent transportation systems, the State of California needs to pay more attention to investing in roadway infrastructure.
- The corridor-wise EAD outperforms intersection-by-intersection EAD, as the signal phase and timing information of multiple downstream intersections can be utilized for better speed profile planning. This may justify the City of Riverside' investment on the addition of cellular network for infrastructure upgrade.
- Although there are uncertainties in modelling SPaT messaging for actuated signalized intersections, broadcasting SPaT messages and other SAE J2735 standard messages via cellular networks can provide additional environmental benefits to vehicles equipped with corridor-wise connected Eco-Approach and Departure applications, compared to DSRC-based broadcasting due to the greater communication range of cellular networks.
- In our field tests, the communication delays in using cellular networks are in the range of 200 ms, which is much higher than that of DSRC. However, such delays did not compromise the system performance of the EAD application, though they could be an issue for more time-critical applications.
- Enabling the broadcasting of RTCM corrections is a cost-effective way to improve positioning accuracy of equipped vehicles at the lane level, which lays a solid foundation for numerous CAV applications.

As a future step, the research team will leverage the roadway infrastructure upgrades undertaken by the City of Riverside to explore a variety of strategies and CAV applications for safer, greener, more efficient, and more reliable multi-modal traffic management along the signalized corridor. The City and research team have already taken the next step in this partnership through the successful receipt of Affordable Housing and Sustainable Communities program funds which will provide additional investment into technology enhancements along the Riverside Innovation Corridor.

References

[1] California Department of Finance, Governor's Budget Summary — 2018-19. http://www.ebudget.ca.gov/2018-19/pdf/BudgetSummary/Infrastructure.pdf

[2] Sperling, D. *Three Revolutions: Steering Automated, Shared, and Electric Vehicles to a Better Future*. 2nd Edition, Washington, DC: Island Press, 2018. ISBN: 9781610919050

[3] Oswald, D., Hao, P. Williams, N., and Barth, M. Development of an Innovation Corridor Testbed for Shared Electric Connected and Automated Transportation. Final Report, NCST-UCR-RR-21-20, September 2021.

[4] Wu, G., Hao, P., et al. Eco-Approach and Departure along Signalized Corridors Considering Powertrain Characteristics. *SAE International Journal of Sustainable Transportation, Energy, Environment & Policy*, Vol. 2, No. 1, 2021, pp. 25 – 40

[5] Yang, H. Almutairi, F., and Rakha, H. Eco-Driving at Signalized Intersections: A Multiple Signal Optimization Approach. *IEEE Transactions on Intelligent Transportation Systems*, Vol. 22, No. 5, 2021, pp. 2943 – 2955

[6] U.S. Department of Transportation. Connected Vehicle Test Bed. Accessed on December 15, 2021. https://www.its.dot.gov/research_archives/connected_vehicle/dot_cvbrochure.htm

[7] National Operations Center of Excellence (NOCoE). The SPaT Challenge. Accessed on December 15, 2021. https://transportationops.org/spatchallenge

[8] U.S. Department of Transportation. States with Active 5.9 GHz Intelligent Transportation Service (ITS) Licenses (as of March 26, 2021). Access on December 15, 2021. https://www.transportation.gov/research-and-technology/states-active-59-ghz-intelligent-transportation-service-its-licenses

[9] U.S. Department of Transportation. Operational Connected Vehicle Deployments in the U.S. Accessed on December 15, 2021.https://www.transportation.gov/research-and-technology/operational-connected-vehicle-deployments-us

[10] Caltrans. California CV Testbed. Accessed on December 15, 2021. https://caconnectedvehicletestbed.org/index.php/index.php

[11] GoMentum Station. Test Drive the Future. Accessed on December 15, 2021. https://gomentumstation.net/

[12] Hao, P., Boriboonsomsin, K., Wang, C., Wu, G., and Barth, M. Connected Eco-Approach and Departure (EAD) System for Diesel Trucks. Proceedings of the 97th Annual Meeting of Transportation Research Board, Washington, DC, 2018

[13] Esaid, D., Hao, P., Wu, G. et al. Machine Learning-based Eco-Approach and Departure: Real-Time Trajectory Optimization at Connected Signalized Intersections. *SAE International Journal of Sustainable Transportation, Energy, Environment & Policy*, Vol. 3, No. 1, 2021

[14] Z. Wang, Hsu, Y-P, Vu, A., Caballero, F., Hao, P. Wu, G., Boriboonsomsin, K., Barth, M., Kailas, A., Amar, P., Garmon, E., Tanugula, S. Early Findings from Field Trials of Heavy-duty Truck Connected Eco-Driving System. 2019 IEEE Intelligent Transportation Systems Conference (ITSC), pp. 3037 – 3042

[15] Bourns College of Engineering – Center for Environmental Research & Technology (CE-CERT) at University of California, Riverside. Innovation Corridor. Accessed on December 15, 2021. https://www.cert.ucr.edu/transportation-systems-vehicle-infrastructure-interaction/city-riverside-innovation-corridor

[16] Weber, G., Dettmering, D., and Gebhard, H. "Networked Transport of RTCM via Internet Protocol (NTRIP)." In F. Sanso (ed.), *A Window on the Future of Geodesy*, Berlin: Springer, 2005, pp. 60 – 64.

[17] Hao, P., Wu, G., Boriboonsomsin, K. and Barth, M. Eco-Approach and Departure (EAD) Application for Actuated Signals in Real-World Traffic. *IEEE Transactions on Intelligent Transportation Systems*, Vol. 20, No. 1, 2019, pp. 30 – 40.

[18] Kamal, M.A.S., Mukai, M., Murata, J., and Kawabe, T. Ecological Driver Assistance System Using Model Based Anticipation of Vehicle-Road-Traffic Information. *IET Journal of Intelligent Transportation Systems*, Vol. 4, No. 4, 2010, pp. 244 – 251.

[19] Mandava, S., Boriboonsomsin, K. and Barth, M. Arterial Velocity Planning based on Traffic Signal Information under Light Traffic Conditions. The 12th International IEEE Conference on Intelligent Transportation Systems, St. Louis, MO, October 2009.

[20] Xia, H., Boriboonsomsin, K. and Barth, M. Dynamic Eco-Driving for Signalized Arterial Corridors and Its Indirect Network-Wide Energy/Emissions Benefits. *Journal of Intelligent Transportation Systems*, Vol. 17, 2013, pp. 31 – 41.

[21] Xia, H., Boriboonsomsin, K., Schweizer, F., Winckler, A., Zhou, K., Zhang, W-B, and Barth, M. Field Operational Testing of ECO-Approach Technology at a Fixed-Time Signalized Intersection. The 15th IEEE Intelligent Transportation Systems Conference, Anchorage, AK, September 2012.

[22] Wu, G., Boriboonsomsin, K., Xia, H., and Barth, M. Supplementary Benefits from Partial Vehicle Automation in an Eco-Approach and Departure Application at Signalized Intersections. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2424, 2014, pp. 66 – 75.

[23] Altan, O., Wu, G., Barth, M., Boriboonsomsin, K., and Stark, J. GlidePath: Eco-Friendly Automated Approach and Departure at Signalized Intersections. *IEEE Transactions on Intelligent Vehicles*, Vol. 2, No. 4, 2017, pp. 266 – 277.

[24] Rakha, H. and Kamalanathsharma, R. Eco-driving at Signalized Intersections Using V2I Communication. The 14th IEEE Conference on Intelligent Transportation Systems (ITSC), Washington, D.C., USA, October 2011

[25] Kamalanathsharma, R. and Rakha, H. Multi-Stage Dynamic Programming Algorithm for Eco-speed Control at Traffic Signalized Intersections. The 16th International IEEE Conference on Intelligent Transportation Systems, the Hague, Netherlands, October 2013.

[26] Asadi, B. and Vahidi, A. Predictive Cruise Control: Utilizing Upcoming Traffic Signal Information for Improving Fuel Economy and Reducing Trip Time. *IEEE Transactions on Control Systems Technology*, Vol. 19, No. 3, 2011, pp 707 – 714.

[27] Katsaros, K., Kernchen, R., Dianati, M., Rieck, D., and Zinoviou, C. Application of Vehicular Communications for Improving the Efficiency of Traffic in Urban Areas. *Wireless Communications and Mobile Computing*, Vol. 11, 2011, pp. 1657 – 1667.

[28] Chen, Z., Zhang, Y., Lv, J., and Zou, Y. Model for Optimization of Eco-driving at Signalized Intersections. Transportation Research Record, No. 2427, 2014, pp. 54 – 62.

[29] Jin, Q., Wu, G., Boriboonsomsin, K., and Barth, M. Power-Based Optimal Longitudinal Control for a Connected Eco-Driving System. *IEEE Transactions on Intelligent Transportation Systems*, Vol. 17, No. 10, 2016, pp. 2900 – 2910.

[30] Li, S., Xu, S., Huang, X., Cheng, B., and Peng, H. Eco-Departure of Connected Vehicles with V2X Communication at Signalized Intersections. *IEEE Transactions on Vehicular Technology*, Vol. 64, No. 12, 2015, pp. 5439 – 5449.

[31] Huang, X. and Peng, H. Speed Trajectory Planning at Signalized Intersections with Sequential Convex Optimization. Proceedings of the 2017 American Control Conference, Seattle, WA, USA.

[32] Huang, K., Yang, X., Lu, Y., Mi, C., and Kondlapudi, P. Ecological Driving System for Connected/Automated Vehicles Using a Two-Stage Control Hierarchy. *IEEE Transactions on Intelligent Transportation Systems*, Vol. 19, No. 7, 2018, pp. 2373 – 2384.

[33] Wan, N., Vahidi, A., and Luckow, A. Optimal Speed Advisory for Connected Vehicles in Arterial Roads and the Impact on Mixed Traffic. *Transportation Research Part C: Emerging Technology*, Vol. 69, 2016, pp. 548 – 563.

[34] Jiang, H., Hu, J., An, S., Wang, M., and Park, B. Eco Approaching at an Isolated Signalized Intersection under Partially Connected and Automated Vehicles Environment. *Transportation Research Part C: Emerging Technology*, Vol. 79, 2017, pp 290 – 307.

[35] He, X., Liu, H., and Liu, X. Optimal Vehicle Speed Trajectory on a Signalized Arterial with Consideration of Queue. *Transportation Research Part C: Emerging Technology*, Vol. 61, 2015, pp. 106 – 120.

[36] Ye, F., Hao, P., Qi, X., Wu, G., Boriboonsomsin, K., and Barth, M. Prediction-based Eco-Approach and Departure at Signalized Intersections with Speed Forecasting on Preceding Vehicles. *IEEE Transactions on Intelligent Transportation Systems*, Vol. 20, No. 4, 2019, pp. 1378 – 1389.

[37] Mahler, G. and Vahidi, A. An Optimal Velocity-Planning Scheme for Vehicle Energy Efficiency through Probabilistic Prediction of Traffic-Signal Timing. *IEEE Transactions on Intelligent Transportation Systems*, Vol. 15, 2014, pp. 2516 – 2523.

[38] Sun, C., Shen, X., and Moura, S. Robust Optimal Eco-Driving Control with Uncertain Traffic Signal Timing. 2018 Annual American Control Conference (ACC), Milwaukee, WI, USA.

[39] Ozatay, E. et al. Analytical and Numerical Solutions for Energy Minimization of Road Vehicles with the Existence of Multiple Traffic Lights. The 52nd IEEE Conference on Decision and Control, 2013.

[40] Lin, Q., Du, X., Li, S., and Ye, Z. Vehicle-to-Infrastructure Communication Based Eco-Driving Operation at Multiple Signalized Intersections. 2016 IEEE Vehicle Power and Propulsion Conference, December, DOI: 10.1109/VPPC.2016.7791809.

[41] De Nunzio, G., Canudas De Wit, C., Moulin, P., and Di Domenico, D. Eco-Driving in Urban Traffic Networks using Traffic Signals Information. *International Journal of Robust and Nonlinear Control*, Vol. 26, 2016, pp. 1307 – 1324.

[42] Dijkstra, E. W. A Note on Two Problems in Connexion with Graphs. *Numerische Mathematik*, Vol. 1, 1959, pp. 269 – 271.

[43] Barth, M., An, F., Younglove, T., Scora, G., Levine, C., Ross, M., and Wenzel, T. Comprehensive Modal Emission Model (CMEM), Version 2.0 User's Guide. University of California at Riverside, 2000

[44] U.S. Environmental Protection Agency. Motor Vehicle Emission Simulator (MOVES). Accessed on December 15, 2021. https://www.epa.gov/moves

[45] Oswald, D., Scora, G., Williams, N., Hao, P., and Barth, M. Evaluating the Environmental Impacts of Connected and Automated Vehicles: Potential Shortcomings of a Binned-Based Emissions Model. 2019 IEEE Intelligent Transportation Systems Conference (ITSC), pp. 3639 – 3644.

[46] Hailemariam, M., Schneeberger, J., Anderson, J., Chang, J., and O'Hara, A. Connected Vehicle Pilots Phase 2 Interoperability Test-Test Report. Publication FHWA-JPO-18-707. Intelligent Transportation Systems Joint Program Office, U.S. Department of Transportation, 2018.

[47] Williams, N., Wu, G., Vu, A., Barth, M., and Zhou, K. Using RTCM Corrections in a Consumer-Grade Lane-Level Positioning System for Connected Vehicles. *SAE International Journal of Connected and Automated Vehicles*, 2022 (in press).

[48] Society of Automotive Engineers. Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles J3016 (ver. 202104), April 2021

[49] The MathWorks Inc. MATLAB version: R2020b, Natick, Massachusetts: The MathWorks Inc. https://www.mathworks.com