

Development of an Innovation Corridor Testbed for Shared Electric Connected and Automated Transportation

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for Sustainable Transportation

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16. Abstract As part of the City of Riverside's Smart-City initiative, UC Riverside researchers have developed an <i>Innovation Corridor</i> testbed for enabling shared electric connected and automated transportation research. This Innovation Corridor testbed is located in Riverside California, and consists of a six-mile section of University Avenue between the UC Riverside campus and downtown Riverside. The testbed supports various transportation modes including passenger vehicles, trucks, transit (e.g., RTA buses), bicycles, and various forms of micro-mobility. This corridor is continuously being instrumented with various infrastructure equipment to support research in shared electric connected and automated transportation. Specifically for this project, the corridor has been equipped with roadside communications equipment and advanced traffic signal controllers at several key intersections, to help improve safety, mobility and environmental sustainability. With this initial instrumentation, we have then conducted connected vehicle experimentation that utilize the signal phase and timing (SPaT) data from these intersections to smooth traffic flow and reduce emissions. For this Innovation Corridor, a high-fidelity simulation environment was also developed to evaluate potential connected vehicle strategies. A variety of Eco-Approach and Departure (EAD) connected vehicle experiments have been conducted and evaluated, both in simulation and in the real-world. As part of the simulation ecosystem, we have compared the energy and emissions modeling results to see which best matches the real-world measurements.			
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A National Center for Sustainable Transportation Research Report

September 2021

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Development of an Innovation Corridor Testbed for Shared Electric Connected and Automated Transportation

EXECUTIVE SUMMARY

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. In terms of transportation, the University of California-Riverside and the City of Riverside have developed an “Innovation Corridor”, a six-mile section of University Avenue between the UC Riverside campus and downtown Riverside. This arterial roadway was selected due to its proximity to an expanding transit and alternative transportation network, research institutions associated with UC Riverside, and the ever-expanding entertainment destinations in the downtown region. As part of this project, this Innovation Corridor has been set up as a *testbed* that can be used for Connected and Automated Vehicle (CAV) testing. All of the traffic signal controllers along this corridor have been upgraded to be compatible with SAE connectivity standards. Next, we installed Dedicated Short-Range Communication (DSRC) roadside-units at three key intersections, with plans to expand to the rest of the corridor. At these instrumented intersections, Signal Phase and Time (SPaT) messages are now directly transmitted from the DSRC roadside units and can be received by vehicles equipped with onboard communication equipment. In addition, Radio Technical Commission for Maritime Services (RTCM) position messages and intersection MAP messages are broadcasted via the DSRC roadside units to support geofencing and accurate vehicle positioning.

The goal of this Innovative Corridor is to serve as a key testbed in Southern California for CAV applications, such as connected eco-approach and departure (EAD), eco-transit operation, smart Intersection management, and other applications to improve safety, mobility and environmental sustainability. In addition, a “virtual” testbed has been developed in parallel, where the same University Avenue corridor is simulated using the high-fidelity microscopic traffic simulation model VISSIM. With this simulation platform, it is possible to vary different traffic volumes and simulate different penetration rates of CAVs. The simulated environment is useful for planning real-world experiments and for validating experimental results.

In order to evaluate the capabilities of the Innovation Corridor testbed, we conducted a number of experiments of a specific connected vehicle application. The eco-approach and departure connected vehicle application determines optimal speed profiles for vehicles traveling within an urban transportation network, utilizing signal phase and timing information from the upcoming traffic signals, the map and route information, the downstream traffic conditions, and the vehicle’s state and powertrain limitations. Using our instrumented vehicles, we compared the operation of a vehicle that utilized the EAD application against a similar vehicle operated under normal conditions. From these experiments, it was found that the EAD connected vehicle application implemented along the Innovation Corridor achieved an approximate 6.5% fuel economy improvement. Further, we carried out several emission/energy

model comparisons to demonstrate how connected vehicle environmental impacts can be estimated.

1. Introduction

The general field of Intelligent Transportation Systems (ITS) is expanding rapidly, which is at the heart of four major on-going revolutions in the transportation field. These revolutions include *shared mobility*, *vehicle electrification*, *vehicle connectivity*, and *vehicle automation*. For years, the major goal of ITS has been focused on increased safety and improved mobility. However, another important benefit of ITS is its potential for increased energy efficiency and reduced emissions. These “environmentally-focused” benefits now play an important role in the deployment of intelligent transportation technology, particularly here in California.

It is critical that we manage how shared mobility, vehicle electrification, vehicle connectivity, and vehicle automation change the way we move people and goods. If we allow these transportation revolutions to emerge independently, we may end up with significantly more vehicle miles traveled, leading towards higher emissions and greater fuel consumption. In order to better understand how shared, electric, connected, and automated vehicle technology can be deployed in an integrated fashion that is favorable to the environment, it is important that we evaluate different ideas both in simulation, and in the real-world using designated “testbeds”.

A number of these testbeds are currently being developed across the United States, in order to evaluate how various applications of shared mobility, vehicle electrification, vehicle connectivity, and vehicle automation. In California, for example, there are several active testbeds including the “California ITS Corridor” along El Camino Real in Palo Alto California [1], and the Port of LA Freight Eco-Driving testbed, as shown in Figure 1.

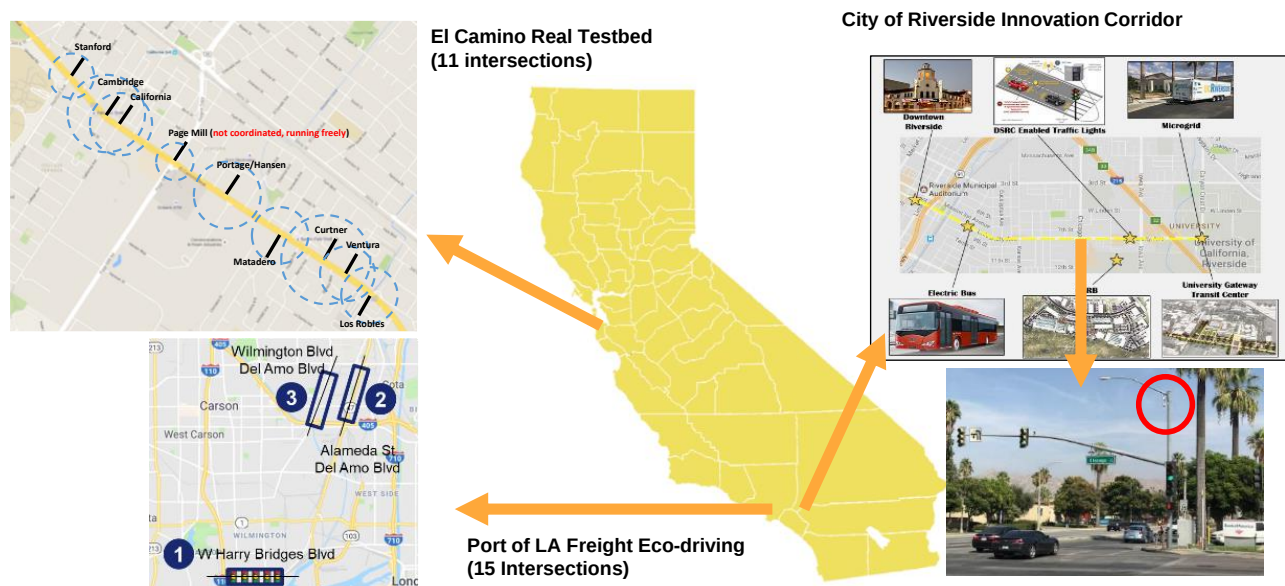


Figure 1. Various vehicle testbeds located in California, being utilized for shared, connected, electric, and automated vehicles.

In the last few years, the City of Riverside in California has made a major push to become a “smart city”, integrating new technologies for transportation, energy, and city management. As part of this smart city plan, the City has created a “Innovation District” in the eastern part of the city, as shown in Figure 2. This district contains part of downtown Riverside, portions of North Main Street, an industrial area north of Third Street near the SR-60/SR-91/I-215 interchange, packinghouses just east of downtown, the Eastside neighborhood and UC Riverside, including the new home of the California Air Resources Board Southern California Headquarters. The goal of the Riverside Innovation District is to serve as a resource to improve the local economy, creating jobs and innovative partnerships. The District will also be used as a model for other developments throughout the Inland Empire and beyond.

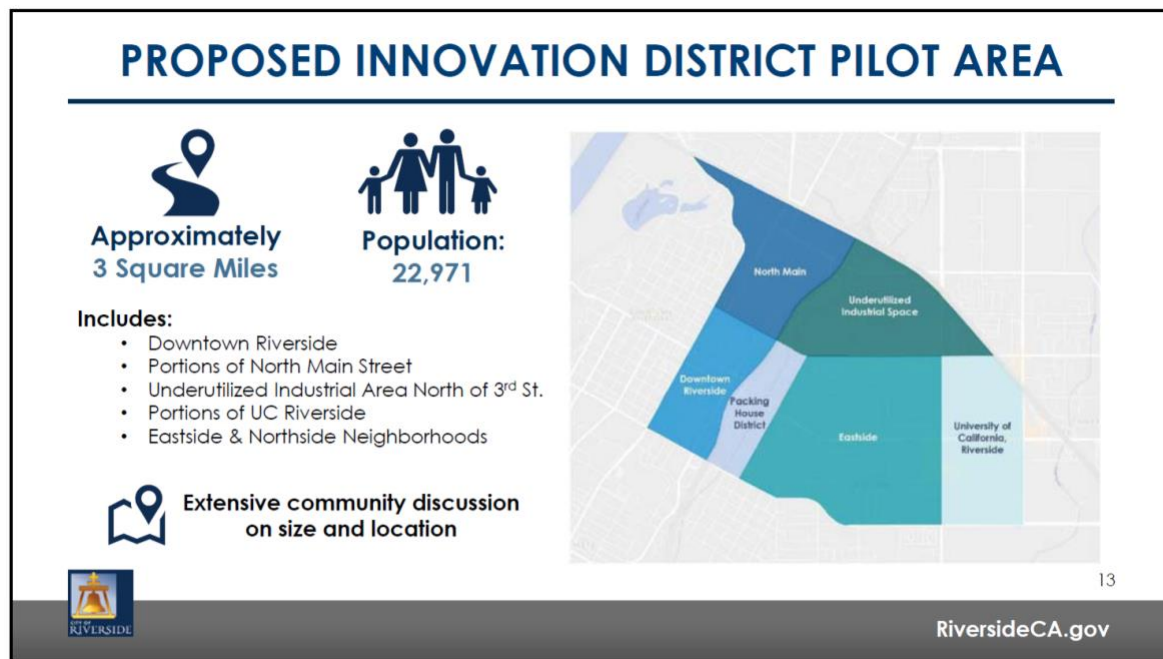


Figure 2. City of Riverside Innovation District

As part of this “Innovation District”, the City of Riverside and UC Riverside have set out to create an “Innovation Corridor”, a six-mile section of University Avenue between the UCR campus and downtown (see Figure 3 and [2]). 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 entertainment destinations in the downtown region. Along the corridor, the traffic signal controllers are being updated to be compatible with SAE connectivity standards. As part of this project, we have also installed Dedicated Short-Range Communication (DSRC) roadside-units in association with several of these traffic signals. With this communications capability, Signal Phase and Time (SPaT) messages from the traffic signal controllers can be directly transmitted to the DSRC units and forwarded to vehicles that are driving on the road. In order for the vehicles to receive these messages, they also must be equipped with onboard DSRC units. Further, positioning correction information (using Radio



Figure 3. Innovation Corridor in The City of Riverside

Technical Commission for Maritime Services (RTCM) protocols) and MAP messages are broadcasted from the roadside DSRC devices to support the vehicle applications.

In addition to the communication capability between the traffic signals and the equipped vehicles, the Innovation District will soon have air quality monitors located along the roadway, and future energy managements systems will be installed to help with the deployment of electric vehicles.

The overarching goal of the Innovative Corridor is to serve as a key testbed in Southern California for connected and automated vehicles applications, such as connected eco-approach and departure (EAD, see next section), eco-transit operation, smart intersection management, and other applications to improve safety, mobility and environmental sustainability. For this particular project, we utilized the Innovation Corridor to conduct connected eco-approach and departure experiments, described later in this report. In addition, we developed a “virtual” testbed in parallel, where the same University Avenue corridor is simulated using the high-fidelity microscopic traffic simulation model VISSIM. With this simulation platform, we will be able to also vary different traffic volumes and simulate different penetration rates of connected vehicles. Finally, different emission models, namely the EPA’s Motor Vehicle Emission Simulator (MOVES) and the Comprehensive Modal Emission Model (CMEM), are compared to real-world testing results.

2. Background

2.1. Connected Vehicle Eco-Approach and Departure Application

Numerous connected vehicle applications have been developed by the research team over the past decades (e.g., see snapshot in Table 1). In this NCST project, we have continued to further develop the connected vehicle Eco-Approach and Departure (EAD) application on Riverside's Innovation Corridor as a case study to demonstrate how connected vehicles can improve both mobility and environmental factors. Like other CAV applications that involve determining optimal speed profiles for vehicles traveling within an urban transportation network, the EAD application utilizes:

- 1) the SPaT data from the upcoming traffic signals;
- 2) map and route information (e.g., stop-bar location, road grade, road speed limit, turning movement);
- 3) downstream traffic conditions such as queue length; and
- 4) the ego-vehicle's state and powertrain limitations (e.g., position via GNSS, instantaneous speed, acceleration/deceleration limit), to determine the optimal recommended speed profile that can minimize the target vehicle's energy consumption and tailpipe emissions when approaching to and departing from signalized intersections.

The EAD application inherently smooths traffic flow, thereby improving mobility. The advisory speed profile and other relevant information are conveyed to the driver typically through a driver-vehicle interface (DVI). Figure 4 presents a generalized system architecture for the EAD application. Technical detail on the application can be found in [3] and subsequent publications.

Table 1 presents the results of various field tests with EAD technology. As the key component of Applications for the Environment: Real-Time Information Synthesis (AERIS) Research Program, Xia et al. [M4] tested an EAD application on an intersection with pre-timed signal and no traffic. The measured fuel consumption and CO₂ emissions indicated that the EAD application had an average savings of 14%. Altan et al. [4] tested a partially automated version of the EAD application, called the GlidePath Prototype, at Turner-Fairbank Highway Research Center in McLean, Virginia. The tests were done on a closed-traffic intersection. The GlidePath Prototype showed an average fuel consumption savings of 17%.

Hao et al. [5] performed tests using an EAD application developed for actuated signals. The tests were done in real-world traffic on the El Camino Real corridor in Palo Alto, California. The corridor is equipped with eight DSRC enabled intersections. The tests showed a 6% energy savings in segments within DSRC range.

Table 1. Recent CE-CERT Field Studies in Eco-Approach and Departure (2019 snapshot).

Technology	Location	Scenario	Communication	Energy Savings	Ref
EAD with Fixed Signals	Richmond, CA	Single vehicle	4G/ LTE	14%	[3]
	Riverside, CA	Mixed traffic	DSRC	11%-28%	[8]
	McLean, VA	Single vehicle	DSRC	2.5%-18%	[8]
EAD with Actuated Signals	Riverside, CA	Mixed traffic	DSRC	5%-25%	[8]
	Palo Alto, CA	Mixed traffic	DSRC	7%	[5, 7]
	Carson, CA	Mixed traffic	Cellular	8%	[6]
GlidePath	McLean, VA	Single vehicle	DSRC	10%-20%	[4]

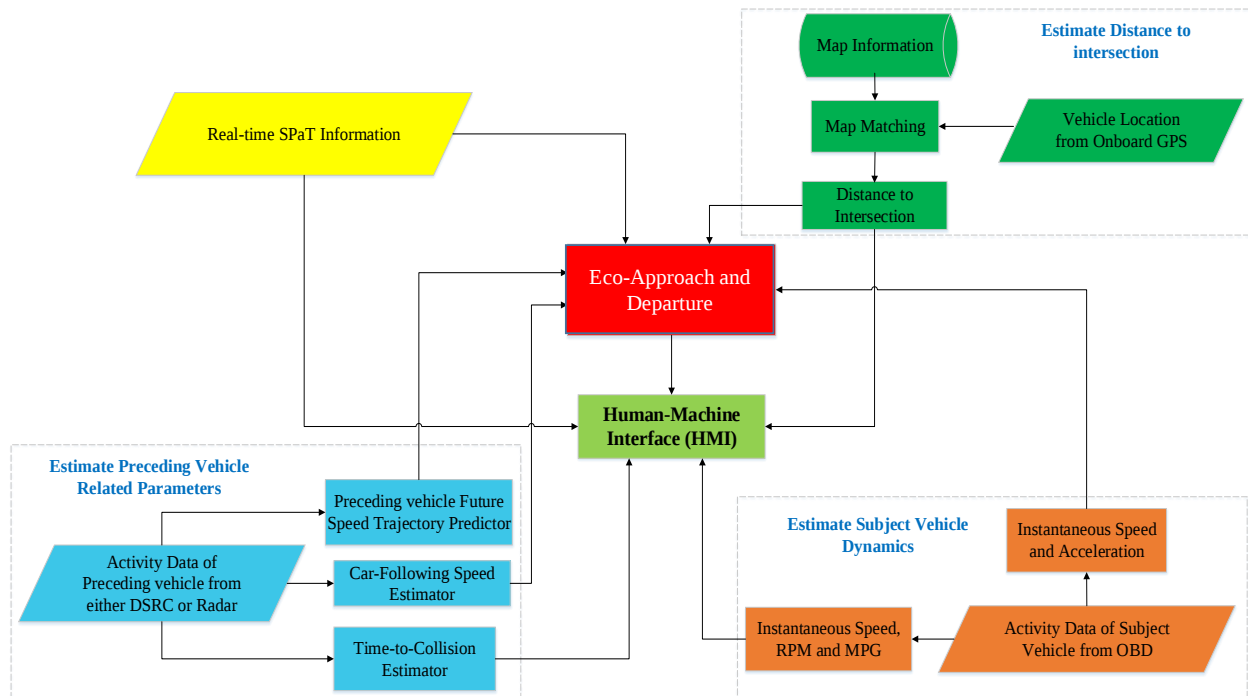


Figure 4. The generalized system architecture of EAD application to be implemented (adapted from [3]).

2.2. Instrumented Connected Vehicles

For real-world testing of connected and automated vehicles, we have utilized our experimental vehicles that are equipped with on-board Dedicated Short Range Communication (DSRC) units that receive not only Global Navigation Satellite System (i.e., GPS) signals for determining vehicle position and speed, but are capable of receiving SAE J2735 messages from other vehicles and the infrastructure. Specific messages include Signal Phase and Timing (SPaT)

information from traffic signals, intersection MAP information, and position-enhancing RTCM messages [9]. As shown in Figure 5, the vehicle's on-board diagnostics (OBD) system is also connected via a CANbus interface to our on-board computer to obtain the vehicle's high-resolution dynamics information in real-time. We have also installed an automotive-grade radar on the front bumper to detect the preceding objects. Data from these various sources are processed and recorded on an on-board computer that also carries out the connected vehicle applications. The computer also provides information to driver via driver-vehicle interface (i.e., the monitor display shown in Figure 5).

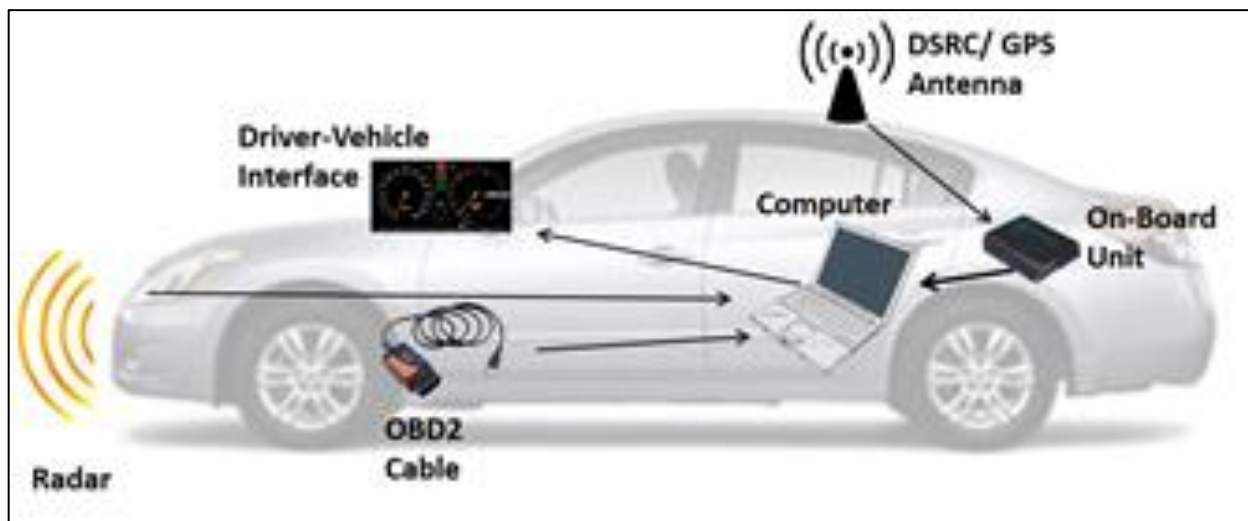


Figure 5. UC Riverside's test vehicle and on-board test platform.

2.3. Motor Vehicles Emission Simulator (MOVES)

For this project, we also make use of different vehicle emission models to estimate energy and emissions of vehicle activity. One such model is the energy and emissions model called MOVES: Motor Vehicles Emission Simulator, developed and maintained by the U.S. Environmental Protection Agency (EPA, see [10]). This model was originally developed in the year 2000 and has periodically updated it ever since. MOVES is used for a wide variety of applications, including a number of regulatory processes (see [10] for further details). MOVES can operate as either a "macroscopic" or "microscopic" model, depending on how it is used. When used as a microscopic model (i.e., project-level mode), MOVES is very data intensive, requiring estimates of vehicle activity, energy and emissions rates for the specific vehicles, and a number of other inputs. MOVES can then estimate the emissions of all vehicles on a road segment, based on aggregated data. The MOVES model encompasses the relationship between vehicle characteristics, operating conditions and the emission/fuel consumption rates from large datasets collected in both the laboratory and on the road using on-board portable emissions measurement systems [10].

MOVES categorizes all vehicles into source types and estimates the emission rates of the vehicles in one source type under specific operation modes (opmode). Consequently, when an individual vehicle is evaluated with MOVES, the average behavior of all vehicles of the same

source type is given. Therefore, when evaluating the emission and fuel consumption of one specific vehicle, MOVES is not able to distinguish this vehicle from the average vehicle of the same source type [11]. It also uses a binning technique for its operation modes, using bins that generated for different levels of vehicle specific power (VSP) and average speed.

For MOVES, the user defines vehicle types, speed data, traffic activities, geographical areas, pollutants, vehicle operating attributes, and meteorology parameters as the inputs of the model; then the model provides estimates of total emission inventories or emission factors [11, 12].

2.4. Comprehensive Modal Emissions Model (CMEM)

Another effective emissions model is the Comprehensive Modal Emission Model (CMEM), which was originally developed as an NCHRP project (NCHRP 25-11, see [13]). This model is a microscopic *physical* emissions model that estimates the emissions of individual vehicles [14]. CMEM is an instantaneous model and was developed to capture the physical relationships between vehicle characteristics, operating conditions, and the emission/fuel consumption rates. One advantage of this model and approach is that it is possible tailor many of the physical parameters to fit a very specific type of vehicle and its detailed operation. It has been used extensively for a number of studies (see, e.g., [11, 12, 15, 16, 17]).

Both MOVES and CMEM takes the attributes of an individual vehicle, along with its second-by-second speed profile as input, and predicts second-by-second fuel consumption and tailpipe emissions of carbon monoxide (CO), carbon dioxide (CO₂), hydrocarbons (HC), and oxides of nitrogen (NO_x). Like MOVES, CMEM can predict energy and emissions from individual vehicles or be applied to estimate the energy and emissions impacts of an entire fleet of vehicles [17].

2.5. Emission Model Comparisons

Over the years, there has been a number of studies that have been carried out to compare the various vehicle emissions and energy models. In 2002, Cappiello et al. [18] presented a statistical emissions model called EMIT (EMISSIONS from Traffic), where CMEM and EMIT were compared to measured data. For fuel consumption rate, CMEM had a -2.2% error, while EMIT had a 5.3% error. However, the data used by Cappiello et al. came from the same database that was used to develop CMEM, so the results are somewhat biased. In 2003, Rakha et al. [19] compared CMEM, MOBILE5a, and MOBILE6, which are the EPA's predecessors to MOVES, and VT-Micro. In this comparison, the different models have various advantages and disadvantages [19].

Chamberlin et al. [20] developed a microsimulation of a three-leg intersection and used MOVES and CMEM to evaluate the different intersection control strategies. In the study, only NO_x and CO were considered; MOVES and CMEM showed similar results for NO_x but had disparities for CO outputs.

Zhang et al. [11] used MOVES and CMEM to evaluate the fuel consumption and emissions for a variable speed limit application. In the study, the I-710 freeway in California was built in VISSIM

and used historical data from the California Department of Transportation. The study showed that CMEM and MOVES were qualitatively similar, but there were discrepancies in the actual values output from the two models.

Many connected and automated vehicle applications typically use MOVES to evaluate simulations or estimate emission outputs. For example, Abou-Senna et al. [21] used MOVES to estimate emissions for a limited access highway simulation built in VISSIM. Liu et al. [22] used smoothing techniques on EPA eco-autonomous driving cycles. The emission results were estimated using MOVES. Xu et al. [23] simulated transit eco-driving methods using an algorithm that limits vehicle specific power while preserving the average speed, and the MOVES was used for the analysis.

3. Connected Vehicle Testbed Development

3.1. Real-World Testbed

As described in Section 1, the research team developed and utilized a 6-mile segment of University Avenue in Riverside California as a “testbed” for connected vehicle experiments. The city of Riverside already had plans of upgrading University Avenue. The research team contacted the city to help upgrade University Avenue in hopes of developing a local “testbed” to conduct research. Previously, the research team would travel to Palo Alto, CA to conduct any connected-vehicle research. The new “testbed” is equipped with communication devices, surveillance devices, and air quality monitors.

A detailed map of this innovation corridor testbed is shown in Figure 6. This arterial corridor connects the main UC Riverside campus with Riverside’s downtown area, and has numerous shops and other structures along the route. This corridor was selected due to its proximity to an expanding transit and alternative transportation network, research institutions associated with UCR, and the ever-expanding entertainment destinations in the downtown region. The arterial roadway also serves a number of different neighborhoods in Riverside’s Eastside region. Along the corridor testbed, there are a number of different signalized intersections that are being managed as part of the testbed infrastructure, as indicated by the red circles in Figure 6. For these intersections, the traffic signal controllers have been updated to be compatible with SAE J2739 connectivity standards. In particular, Dedicated Short Range Communication (DSRC) roadside-units (RSUs) have been mounted on several major intersections (e.g., Iowa Avenue at University Avenue, Cranford Avenue, and Chicago Avenue at University Avenue). Signal Phase and Timing (SPaT) messages are now directly transmitted from these traffic signal controllers to the DSRC RSUs and forwarded to the vehicles equipped with onboard units (OBUs). Simultaneously, positioning correction information Radio Technical Commission for Maritime Services (RTCM) protocols and MAP/GID (Geographic Intersection Description) are also broadcasted via DSRC devices to support advanced field operation testing that needs geo-fencing and accurate positioning. In addition to the DSRC RSUs, cellular modems have been also equipped at these intersections to support long-range communications (e.g., vehicle-to-cloud). The overall data architecture is shown in Figure 7.

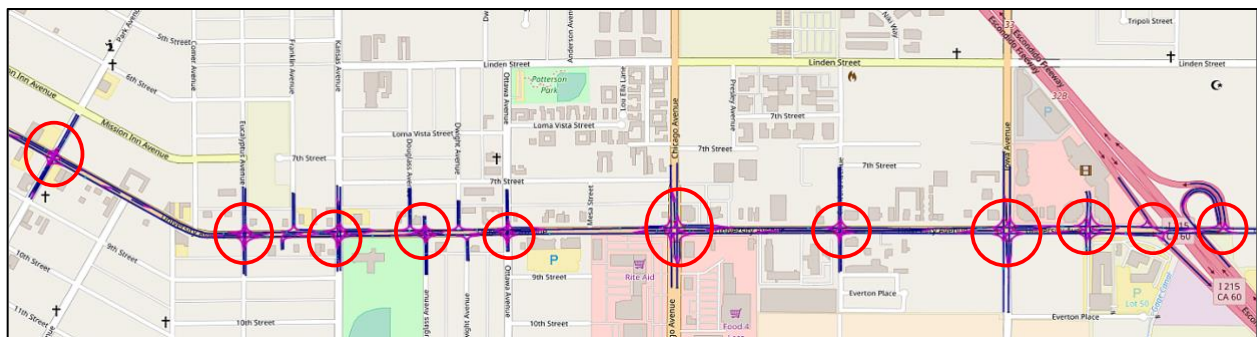


Figure 6. Innovation Corridor (i.e., a segment of University Avenue in Riverside California).

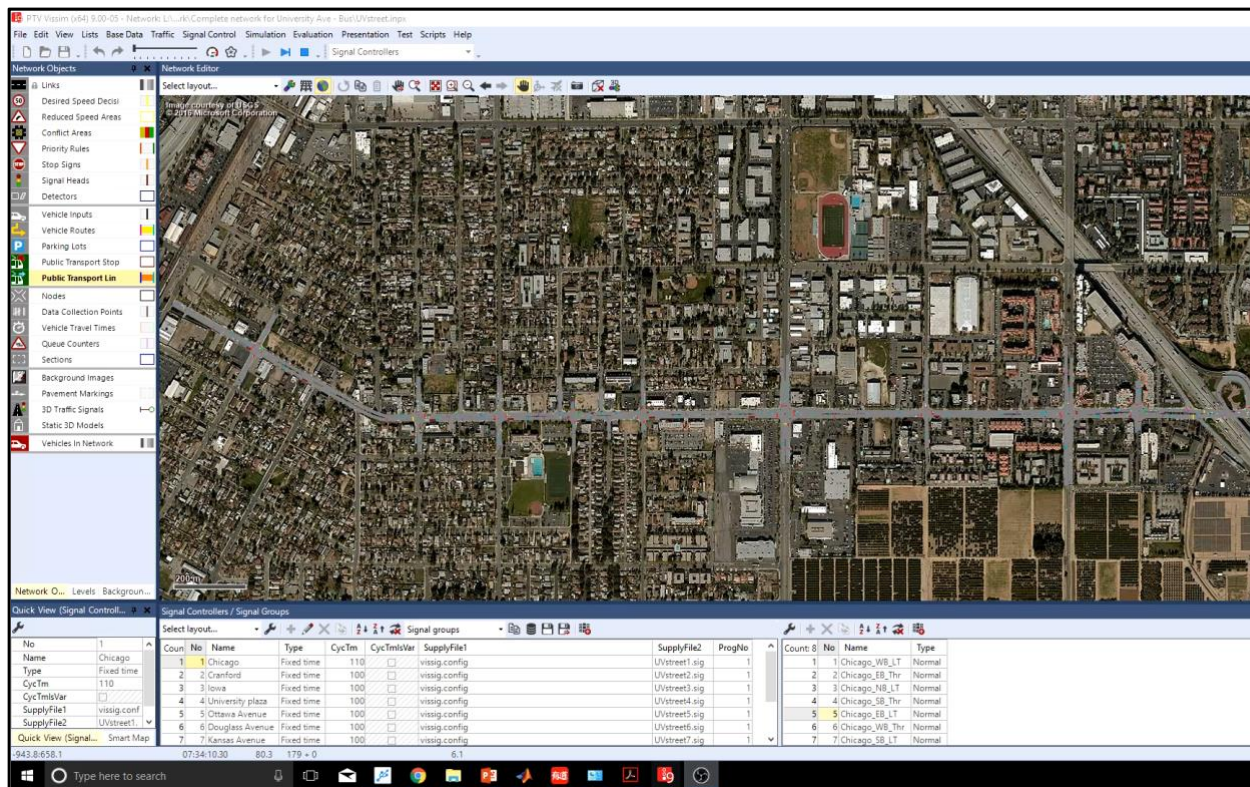


Figure 8. Snapshot of the VISSIM Traffic Simulation Model of Riverside’s Innovation Corridor

When conducting a simulation study of a specific geographical area, the accuracy of the simulation results depends heavily on the input traffic level. The Innovation Corridor roadway network is divided into links and nodes, where nodes are the traffic intersections and links are the roadway segments that connect them. The traffic volume on each link in the network was carefully calibrated using the latest available traffic count data measured in the field.

In the VISSIM simulation environment, infrastructure-to-vehicle communications was accomplished in VISSIM using sockets. The connected vehicle application algorithms are simulated in VISSIM using the Drivermodel DLL to control vehicle behavior, and a socket was used to connect the Drivermodel DLL to a C++ program which used sockets to connect to the virtual traffic signal controllers. In this way, SPaT data are passed from the simulated traffic signal controllers to the connected vehicles. There are programmable delays in the communication in the simulation, corresponding to some finite delays that occur in the real world.

4. Connected Vehicle Experiments on the Innovation Corridor

Once the Innovation Corridor testbed and parallel traffic simulation were setup, this project also utilized these research tools to evaluate a particular connected vehicle application. Specifically, a version of the EAD connected vehicle application (described in detail in Section 2) was carried out to not only estimate the fuel consumption savings of the connected vehicle application, but also to compare emission modeling methodologies. Details of these experiments and results are described in a published paper (see [25]) and is summarized in this section.

The overall aim of the EAD connected vehicle algorithm used in our testing is to reduce the idling time at intersections, and avoid unnecessary accelerations, while also allowing for safe driving. The EAD algorithm calculates an optimal acceleration to minimize fuel consumption as described in [26]. For the experiments, the signal controllers along the innovation corridor were set up to transmit SPaT information, providing a timestamp for the minimum time remaining and maximum time remaining to the connected vehicles in the experiment.

The flowchart for the EAD algorithm used in the experimental vehicles is shown in Figure 9. Like other EAD algorithms, the objective is to provide a recommended trajectory to the driver that will have the vehicle pass the intersection as the signal turns green. The major difference of this EAD algorithm is that for the red-light case, the maximum time is used in order to check safety and determine if the vehicle needs to accelerate. For the other cases, the minimum time is used as the pivotal measure for planning. Full details of this algorithm are provided in [26].

A number of connected vehicle experiments were performed along the Innovation Corridor spanning three traffic intersections described in Section 3 (i.e., Iowa Avenue at University Avenue, Cranford Avenue, and Chicago Avenue at University Avenue). Specifically, each test run started 100m east of Iowa Ave. to 100m west of Chicago Ave., then a U-turn was made and then return to 100m east of Iowa Ave. The entire length of each run was approximately 1.38 miles.

For the experiments, two instrumented vehicles were tested simultaneously. One test vehicle was utilized that fully implemented the connected vehicle EAD application, while the other vehicle was used as a comparison vehicle, driven normally with traffic without the EAD application. The experiments were conducted during the middle of the day (i.e., between 10:00AM and noon, and 1:30PM to 3:30PM) on a typical weekday.

During the experiments, the actual fuel consumption from the vehicles were recorded in real-time, along with detailed trajectory information (i.e., vehicle speed and position at 1 Hz). Once the vehicle trajectories were collected, they were used as input to the MOVES and CMEM emissions models to also estimate the fuel consumption. Both of these emission models were specifically calibrated for the light-duty test vehicles.

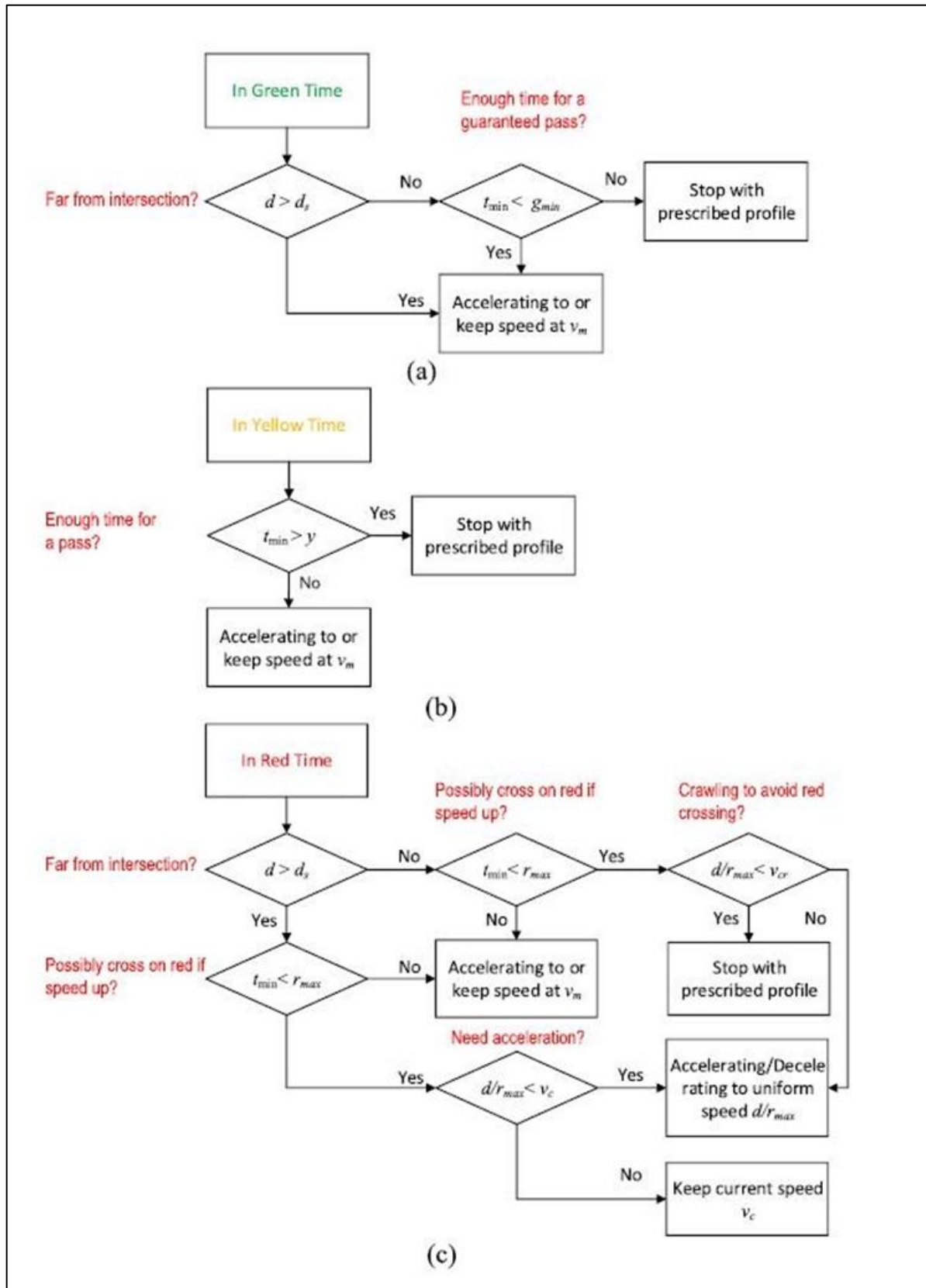


Figure 9. Flowchart for Eco-Approach and Departure algorithm (from [26])

Images from the experimental tests are shown in Figure 10. In these figures, the different scenarios are shown when the vehicle approaches the intersection under different phase conditions. The information is provided to the vehicle, and an optimal speed trajectory is calculated and transmitted to the driver via the driver interface.



Figure 10. EAD experiments carried out on University Avenue.

5. Results

5.1. Traffic Simulation Model Experimentation

Prior to the real-world experiments, traffic simulation model runs were carried out, simulating the planned experiments. The overall fuel consumption results of these simulation runs are given in Table 2. It can be seen that VISSIM combined with the MOVES-based model estimated that using the EAD application improved fuel consumption by 11.5%, while the VISSIM-CMEM combination estimated that the fuel consumption improved by 30.4%. It is to be noted that the optimized trajectories from the EAD algorithms were carried out exactly by the vehicle controller in the simulation, and the simulation had a limited set of specific scenarios. In the real world, the driver is given the optimized trajectories as advice, and typically has trouble following the speed trajectories exactly. Therefore, it is expected that the simulation results will always be higher than what is measured in the real-world.

Table 2. Simulation Eco-Approach and Departure Evaluation

		No EAD	EAD	Improvement
MOVES-Based Binning	CO ₂ (g/mi)	541.04	479.02	11.46%
	Fuel (g/mi)	163.62	144.86	11.5%
CMEM	CO ₂ (g/mi)	589.08	409.84	30.43%
	Fuel (g/mi)	178.14	123.94	30.4%

5.2. Real-World Experiment Results

As described in the previous section, fuel consumption was measured for both vehicles in the experiments, and the speed trajectories from the test vehicles were provided to both MOVES and CMEM to estimate fuel consumption. The fuel consumption estimates given from the emission models CMEM and MOVES were compared to the measured fuel consumption. The results of a direct comparison between the measured values and the estimated values are shown in Table 3. It can be seen that the MOVES-based model overestimates the fuel consumption and CO₂ emissions by approximately 13%. This is most likely due to the fact that the MOVES-based approach's default bins can under-estimate traffic smoothing effects. A traffic smoothing effect can cause a large amount of data points to shift slightly, but in the MOVES-based model those data points would remain in the same OpMode bin. Also, CMEM is calibrated in greater detail, and the MOVES-based model does not consider specific vehicle operation activities, such as vehicle fuel shutoff events that occur during decelerations. Similarly, CMEM also over predicts emissions by approximately 5%, but to a lesser extent than the MOVES-based approach. Both MOVES and CMEM depend on a number of calibration

factors, and if those factors are slightly off, the overall estimations will have some error. When comparing the efficacy of connected vehicle applications, we generally examine *relative* performance (i.e., with and without the connected vehicle technology), therefore the *absolute* estimates are not as important.

Table 3. Emissions Model Absolute Value Comparison

Method	Fuel Consumption	CO ₂
	Avg. g/mile	Avg. g/mile
Measured	144.66	457.84
CMEM	152.29	481.99
	+5.27%	+5.27%
MOVES-based Binning Model	163.58	517.72
	+13.08%	+13.08%

Next, we compare the results from the EAD-equipped vehicle and the EAD non-equipped vehicle, examining measured fuel consumption, and estimated fuel consumption from MOVES and CMEM. Table 4 shows these results. As described earlier, the measured values were recorded in real-time simultaneously, so that each vehicle experiences the same traffic conditions. Each time the test corridor was entered, both vehicles entered at the same time and stayed in different lanes to not influence each other. The CO₂ emissions and fuel consumption stated in Table 4 are the average grams per mile where the total grams from the measured values and the outputs from both models are individually summed, and then divided by the total miles travelled. The percent improvement column from Table 4 is the percentage fuel consumption decrease between the non-equipped EAD vehicle and the EAD-equipped vehicle.

It can be seen that based on the actual fuel consumption measurements, the EAD-equipped vehicle obtained a 6.6% fuel economy improvement. In comparison, CMEM estimated a 4.6% improvement, and MOVES predicted a 2.6% improvement. In general, we see that the MOVES-based model typically underestimates the benefits of connected vehicle application by approximately half, whereas the CMEM estimate was closer to the actual measured improvement.

Table 4. Real-world Eco-Approach and Departure evaluation.

		No EAD	EAD	Improvement
Actual	CO ₂ (g/mi)	430.7	402.3	6.6%
	Fuel (g/mi)	137.63	128.5	6.63%
CMEM	CO ₂ (g/mi)	439.9	419.83	4.5%
	Fuel (g/mi)	138.97	132.5	4.65%
MOVES-based binning	CO ₂ (g/mi)	475.4	462.69	2.67%
	Fuel (g/mi)	151.87	147.8	2.7%

6. Conclusions and Future Work

In this project, the primary goal was to establish a connected vehicle testbed locally in Riverside California, to support a variety of experiments. In parallel, a traffic simulation implementation of the Innovation Corridor was also developed from both planning and validation purposes. This goal was met, as described in this report. It is expected that the Innovation Corridor testbed will be further developed over time, building on the advanced traffic signal controllers and the DSRC roadside-units there were mounted at the key intersections. As an initial test application, we examined how the connected vehicle eco-approach and departure application would perform, using two vehicles operated in normal traffic conditions. The fuel consumption and emissions of these vehicles were compared, along with a comparison of two emission models.

It was found that this connected vehicle application provides an approximately 6% fuel economy improvement, based on actual measurements. Further, the CMEM estimation methodology gave a 4.6% improvement, and the MOVES estimation methodology gave a 2.6% improvement. One of the reasons why the MOVES model might be underestimating the overall improvement is due to its binning modeling approach. In Figure 11, we show the MOVES opmode bins and the data points from the connected vehicle application. The MOVES opmode bins are defined by several Vehicle Specific Power (VSP) ranges and three vehicle speed ranges. It can be seen that one opmode bin can be used for a wide range of VSP and vehicle speeds, and each data point will generate the emissions/energy rate associated with the bin in which the data point falls. If a connected vehicle application is implemented and the instantaneous VSP value goes down slightly, it still may be captured in the same bin. As a result, the benefit of the connected vehicle application will not be captured. Therefore, one main conclusion is that the coarse binning methodology of MOVES typically underestimates the benefits of traffic smoothing. It is recommended that sub-bins be also defined so that greater sensitivity can be achieved using the MOVES model, as described in [25].

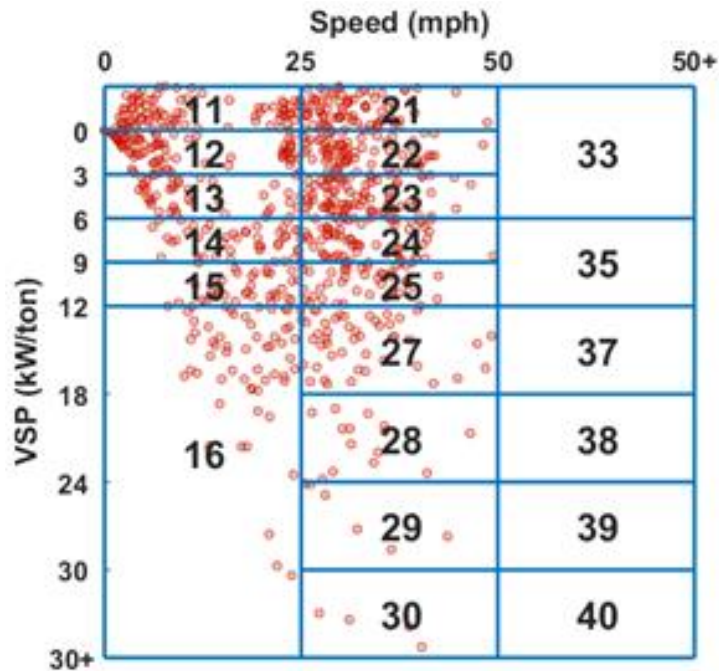


Figure 11. MOVES binning method showing MOVES opmod bins with measured test data.

Overall, this project was a success. The Innovation Corridor will serve as a critical testbed in Southern California for Connected and Automated Vehicles (CAVs) applications, such as connected eco-approach and departure, eco-transit operation, smart Intersection management, and other applications to improve safety, mobility and environmental sustainability.

References

- [1] Caltrans (2020) “California Connected Vehicle Testbed”, see <http://www.caconnectedvehicletestbed.org/index.php/>.
- [2] UCR CE-CERT (2020) “Innovation Corridor”, see <https://www.cert.ucr.edu/transportation-systems-vehicle-infrastructure-interaction/city-riverside-innovation-corridor>.
- [3] H. Xia, K. Boriboonsomsin, F. Schweizer, A. Winckler, K. Zhou, W. Zhang, M. Barth, “Field operational testing of eco-approach technology at a fixed-time signalized intersection,” *IEEE 15th International Conference on Intelligent Transportation Systems*, Anchorage, Alaska, USA, 2012.
- [4] O. Altan, G. Wu, M. Barth, K. Boriboonsomsin, J. Stark, “GlidePath: eco-friendly automated approach and departure at signalized intersections,” *IEEE Transactions on Intelligent Vehicles*, Vol. 20, no. 4, December 2017.
- [5] P. Hao, G. Wu, K. Boriboonsomsin, M. Barth, “Eco-approach and departure (EAD) application for actuated signals in real-world traffic.” *IEEE Transactions on Intelligent Transportation Systems*, Vol. 20, no. 1, January 2019.
- [6] Wang, Z., Hsu, Y.-P., Vu, A., Caballero, F., Hao, P., Wu, G., Boriboonsomsin, K., Barth, M., Kailas, A., Amar, P., Garmon, E., Tanugula, S. (2019) “Early Findings from Field Trials of Heavy-Duty Truck Connected Eco-Driving System”, *2019 IEEE Intelligent Transportation Systems Conference (ITSC)*, Auckland, New Zealand, October 2019.
- [7] P. Hao, G. Wu, K. Boriboonsomsin, M. Barth, “Preliminary evaluation of field testing on eco-approach and departure (ead) application for actuated signals,” *International Conference on Connected Vehicles and Expo*, 2015.
- [8] H. Xia, “Eco-approach and departure techniques for connected vehicles at signalized traffic intersections,” Doctoral dissertation, University of California, Riverside, 2014.
- [9] Society of Automotive Engineers (SAE), (2020) “Dedicated Short Range Communication message set”, see <https://www.sae.org/standards/development/dsrc>.
- [10] U.S. EPA (2020), “MOVES: Motor Vehicles Emission Simulator”, see <https://www.epa.gov/moves>
- [11] Y. Zhang, P. A. Ioannou, “Environmental impact of combined variable speed limit and lane change control: a comparison of MOVES and CMEM model,” *International Federation of Automatic Control*, Vol. 49, no. 3, pp 323-328, 2016.
- [12] S. Bai, D. Eisinger, D. Niemeier, “MOVES vs. EMFAC: a comparison of greenhouse gas emissions using los angeles county,” *In Proceedings of the Transportation Research Board 88th Annual Meeting*, Washington, DC, USA, 11–15 January 2009.

- [13] National Cooperative Highway Research Program 25-11 (2020), "CMEM: Comprehensive Modal Emissions Model", see <https://trid.trb.org/view/859153>.
- [14] UCR CE-CERT (2020), "CMEM: Comprehensive Modal Emissions Model", see <https://www.cert.ucr.edu/cmем>.
- [15] V. Franco, M. Kousoulidou, M. Muntean, L. Ntziachritos, S. Hausberger, P. Dilara, (2013) "Road vehicle emission factors development: a review," *Atmospheric Environment*, Vol. 70, pp 84-97, 2013.
- [16] E. Demir, T. Bektas, G. Laporte, "A review of recent research on green road freight transportation," *European Journal of Operational Research*, Vol. 237, pp 775-793, 2014.
- [17] G. Scora, B. Morris, C. Tran, M. Barth, M. Trivedi, "Real-time roadway emissions estimation using visual traffic measurements," *IEEE Forum on Integrated and Sustainable Transportation Systems*, Vienna, Austria, 2011.
- [18] A. Cappiello, I. Chabini, E. K. Nam, A. Lue, M. Abou Zeid, "A statistical model of vehicle emissions and fuel consumption." *IEEE 5th International Conference on Intelligent Transportation Systems*, Singapore, 2002.
- [19] H. Rakha, K. Ahn, A. Trani, "Comparison of mobile5a, mobile6, vt-micro, and cmem models for estimating hot-stabilized light-duty gasoline vehicle emissions," *Canadian Journal of Civil Engineering*, Vol. 30, no. 6, pp 1010-1021, 2003.
- [20] R. Chamberlin, B. Swanson, E. Talbot, J. Dumont, S. Pesci, "Analysis of moves and cmem for evaluating the emissions impacts of an intersection control change," *Transportation Research Board 90th Annual Meeting*, 11-0673, 2011.
- [21] H. Abou-Senna, E. Radwan, K. Westerlund, C. D. Cooper, "Using a traffic simulation model (vissim) with an emissions model (MOVES) to predict emissions from vehicles on a limited-access highway," *Journal of the Air & Waste Management Association*, Vol. 63, no. 7, pp 819-831, 2013.
- [22] J. Liu, K. M. Kockelman, A. Nichols, "Anticipating the emissions impacts of smoother driving by connected and autonomous vehicles, using the MOVES model," *In Proceedings of the Transportation Research Board 96th Annual Meeting*, Washington, DC., 2017.
- [23] Y. Xu, H. Li, H. Liu, M. O. Rodgers, R. L. Guensler, "Eco-driving for transit: An effective strategy to conserve fuel and emissions," *Applied Energy*, Vol. 194, pp 784-797, 2017.
- [24] PTV VISSIM, "PTV VISSIM Traffic Simulator", see <https://www.ptvgroup.com/en/solutions/products/ptv-vissim/>, accessed 2020.
- [25] Oswald, D., Scora, G., Williams, N., Hao, P., & Barth, M. (2019). "Evaluating the Environmental Impacts of Connected and Automated Vehicles: Potential Shortcomings of

a Binned-Based Emissions Model”, *Proceedings of the 2019 IEEE Intelligent Transportation Systems Conference (ITSC)*. doi:10.1109/itsc.2019.8917014.

- [26] P. Hao, G. Wu, K. Boriboonsomsin, M. Barth, “Eco-approach and departure application for actuated signals in real-world traffic.” *IEEE Transactions on Intelligent Transportation Systems*, Vol. 20, no. 1, January 2019.

Data Management

Products of Research

In this project, we collected vehicles' characteristics and trajectory data from the microscopic traffic simulator, PTV VISSIM, as well as real-world data from instrumented vehicles. These data were used for evaluating the performance of the Eco-Approach and Departure application.

Data Format and Content

The data are output from PTV VISSIM via application programming interfaces (APIs). The files are in .csv format. The contents of each file include vehicle ID, vehicle speed (in mph), MOVES estimate of fuel consumption (in grams), and CMEM estimate of fuel consumption (in grams) on the basis of one simulation time step (1 Hz).

Real-world data files are in .csv format. The contents of each file include vehicle speed (in mph), air/fuel ratio, mass air flow, fuel consumption (grams), vehicle speed from gps (in mph), CMEM estimate of fuel consumption (in grams), and MOVES estimate of fuel consumption (in grams) collected every second (1Hz).

Data Access and Sharing

The data are made available publicly via the UC Riverside instance of DataDRYAD: <https://datadryad.org/stash>, which is licensed under a [CC0 1.0 Universal \(CC0 1.0\) Public Domain Dedication](#) license. The DOI for the dataset is <https://doi.org/10.6086/D1VH5W>

Reuse and Redistribution

The data should be restricted for research use only. If the data are used, our work should be properly cited:

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