DEVELOPMENT OF AN INNOVATION CORRIDOR TESTBED FOR SHARED ELECTRIC CONNECTED AND AUTOMATED TRANSPORTATION

Matthew Barth

Yeager Families Professor of Engineering

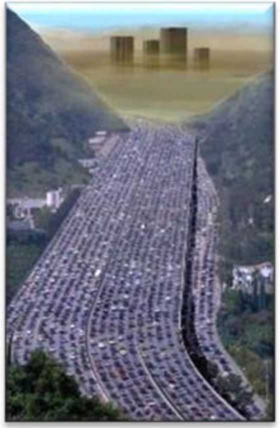
Director of UCR's Center for Environmental Research and Technology

NCST Associate Director at UC Riverside

UCR CE-CERT

National Center for Sustainable Transportation

CE-CERT Research Focus:
Air Quality, Transportation and Energy



Clean Air

Quantifying and Measuring Emissions
Toxic, Ozone and PM formation

Sustainable Transportation

Intelligent Transportation Systems
Connected and Automated Vehicles
Electric and Hybrid vehicle integration
Ecodriving, Shared Vehicle Systems

Renewable Fuels

Aqueous Processing of Biomass to Fuels
Thermochemical Processing of Biomass to Fuels

Renewable Electricity & Smart Grids

Advanced Solar Energy Production
Energy Storage
Energy Management

Climate Change Impacts

Impacts of our fuels
Cloud formation & impacts

UC Riverside Advanced Transportation Research

Shared Mobility:

- **carsharing, ride hailing companies (e.g., Uber, Lyft), and advanced transit**
- **Drivers: Internet connectivity, convenience, and transportation costs**

Electrification:

- **electric drivetrains are becoming more common**
- **New regulations coupled with technological advances in motors, controls, and batteries**

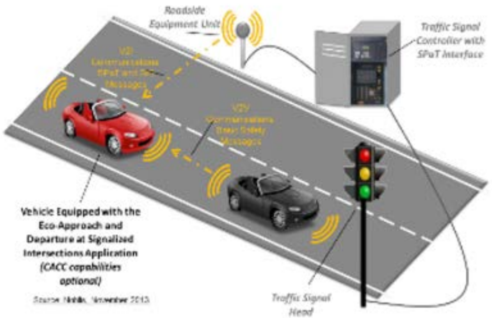
Connectivity:

- **Vehicles are increasingly "connected"**
- **Drivers: cellular communications, dedicated short range communications**

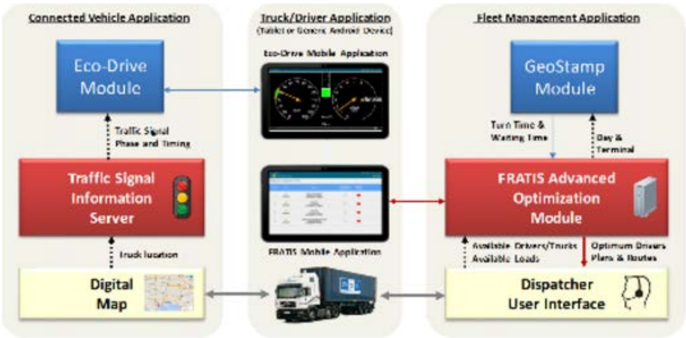
Automation:

- **Vehicle automation is emerging in many forms**
- **Automation comes with many social implications**

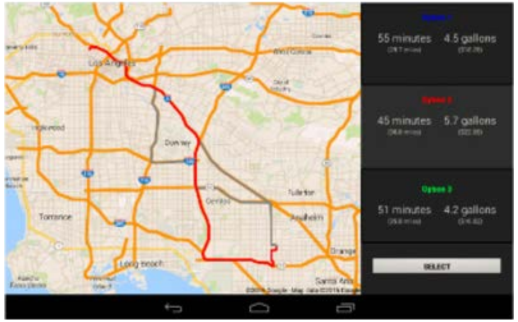
UCR's Connected and Automated Vehicle Application Development and Testing



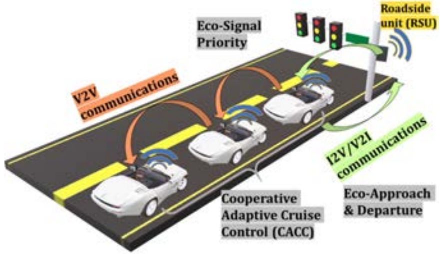
Variations of Intersection Management



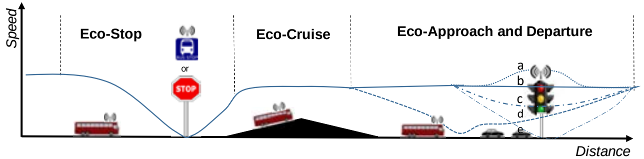
Variations of Dynamic Eco-Driving Techniques



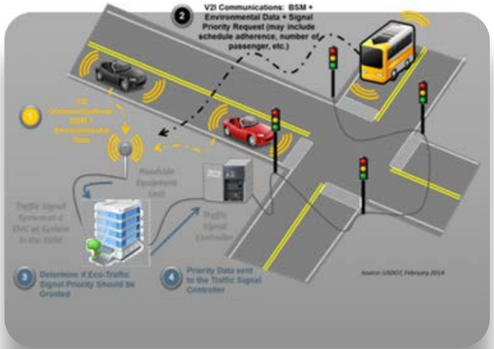
Eco-Routing



Arterial Roadway Management

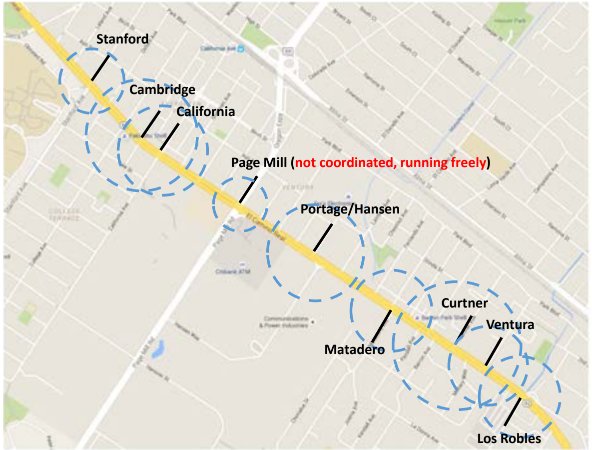


Dynamic Powertrain Management



Sustainable Freight

Example Connected Vehicle Testbeds across California



El Camino Real Testbed
(11 intersections)

City of Riverside Innovation Corridor

Port of LA Freight Eco-driving
(15 Intersections)

City of Riverside: Innovation District

- Enhance Eastside and Northside Neighborhoods
- Better tie together UCR with downtown Riverside
- Enhance Hunter Business Park
- Make Downtown Riverside a regional employment, governmental, arts and entertainment center

PROPOSED INNOVATION DISTRICT PILOT AREA

Approximately
3 Square Miles

Population:
22,971

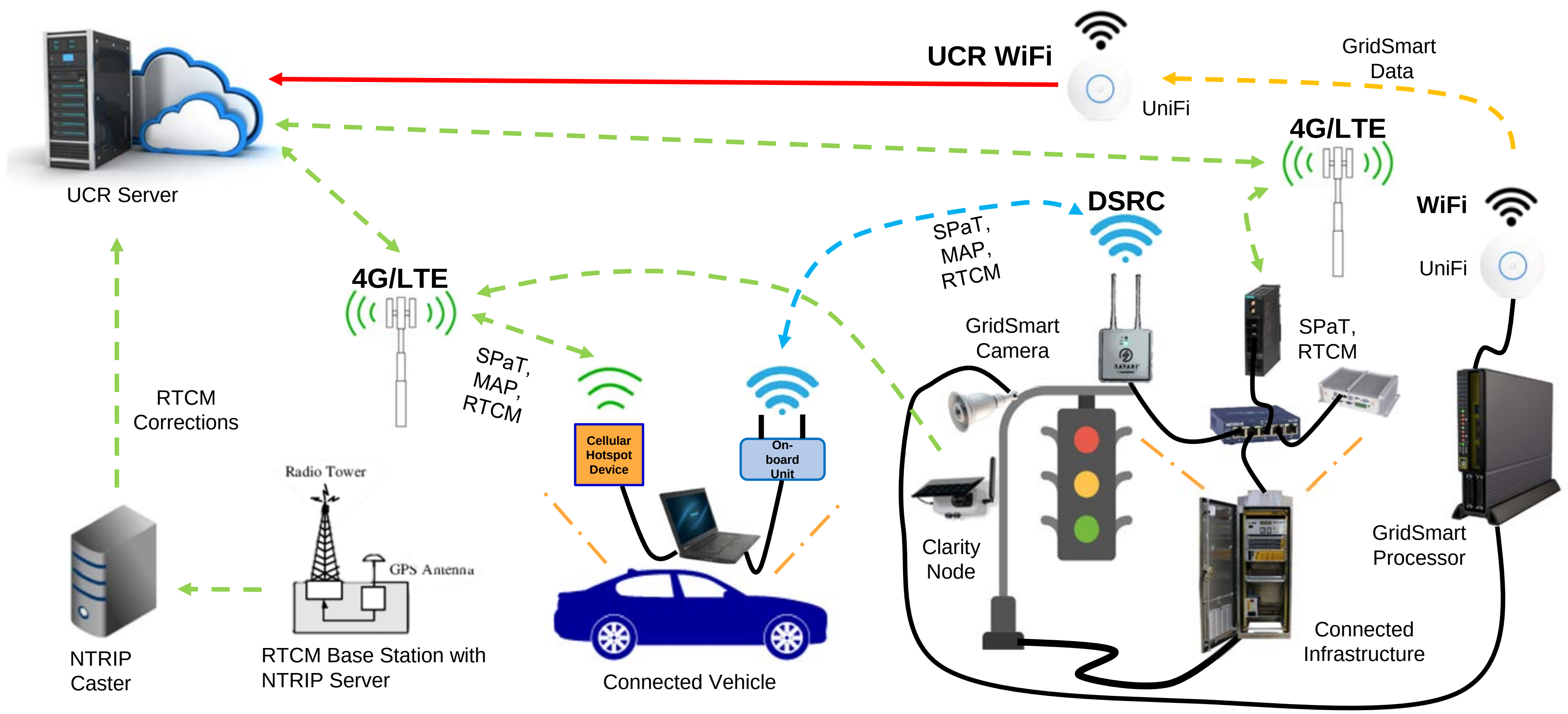
Includes:
- Downtown Riverside
- Portions of North Main Street
- Underutilized Industrial Area North of 3rd St.
- Portions of UC Riverside
- Eastside & Northside Neighborhoods

Extensive community discussion on size and location

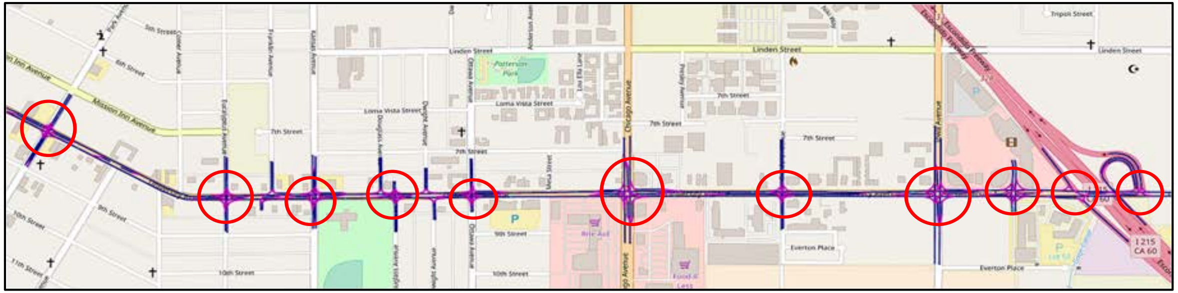
City of Riverside Innovation Corridor: Research Testbed

- Six mile section of University Avenue between UC Riverside and downtown Riverside
- All traffic signal controllers are being updated to be compatible with SAE connectivity standards
- UCR and the City partnered to install Dedicated Short Range Communication modems at several traffic signals
- UCR is also equipping corridor with new generation air quality sensors and video analytics
- Corridor is being used for connected and automated vehicle experiments (light-duty vehicles, ARPA-E hybrid bus, etc.)

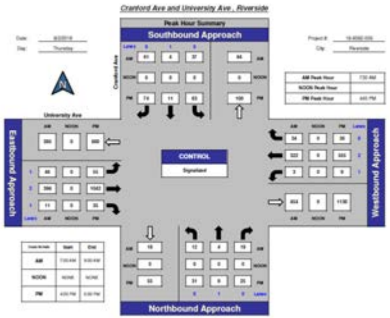
Innovation Corridor Infrastructure Architecture

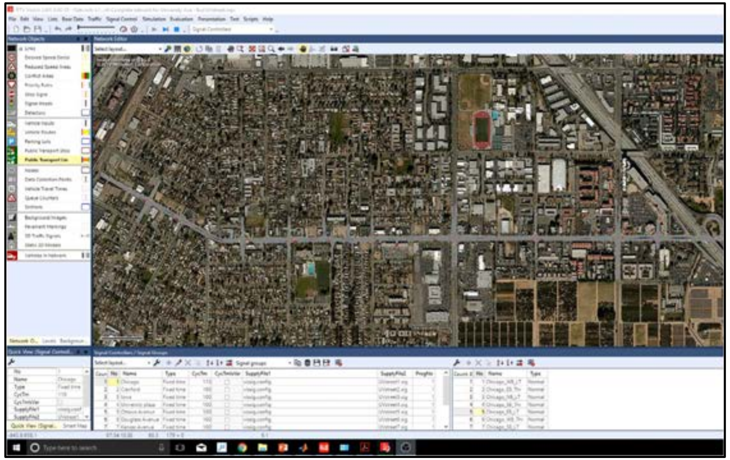


Modeling the Innovation Corridor



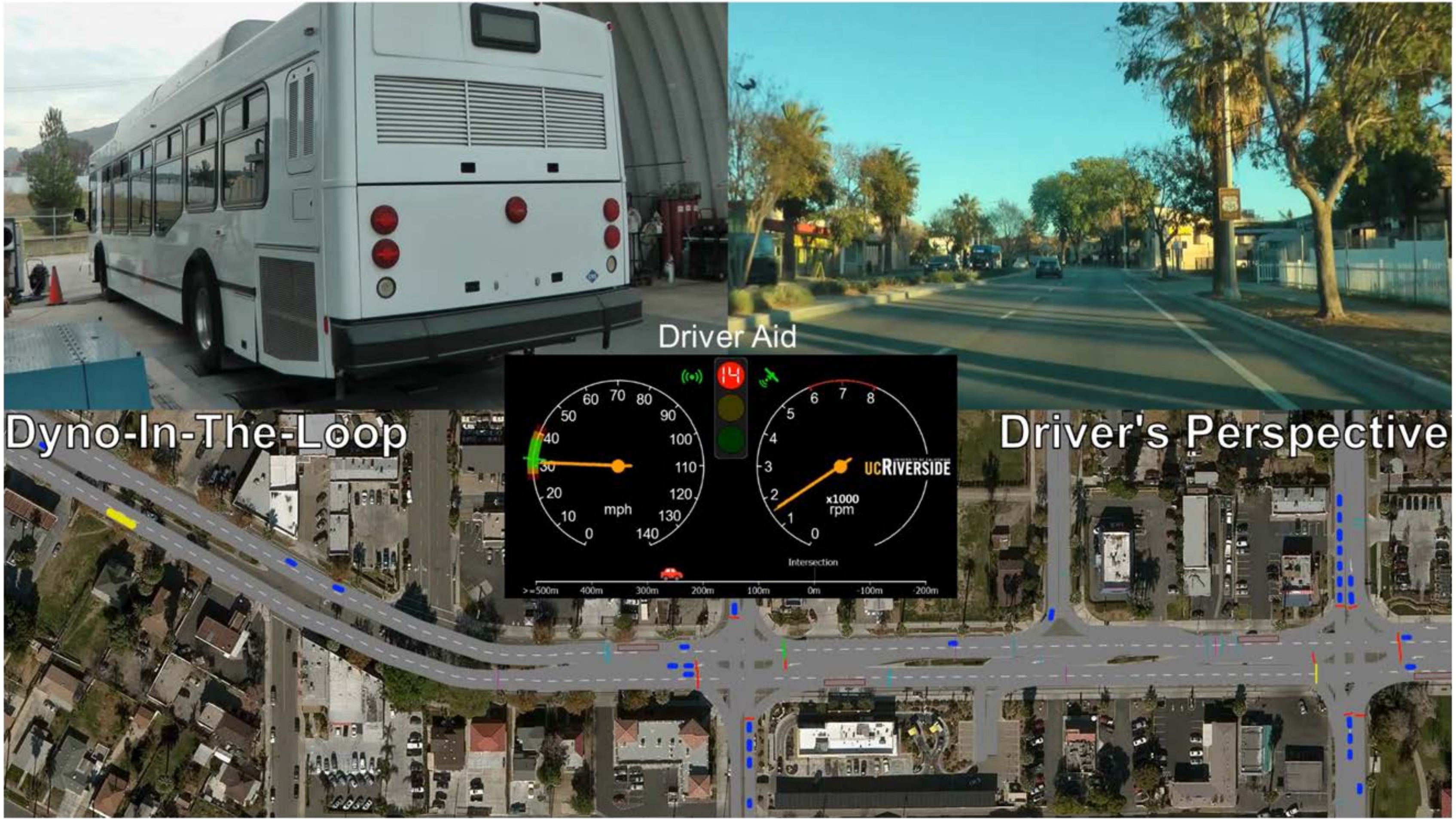
- Complementing real world testing, modeling enables the projection of mobility and environmental benefits from the wide-scale adoption of shared, electric, connected and automated vehicle technologies





- The corridor is used to conduct connected and automated vehicle studies at signalized intersections. Vehicles can communicate with the infrastructure (e.g., signal's phase and timing) and adjust their speed to reduce energy consumption and improve throughput.

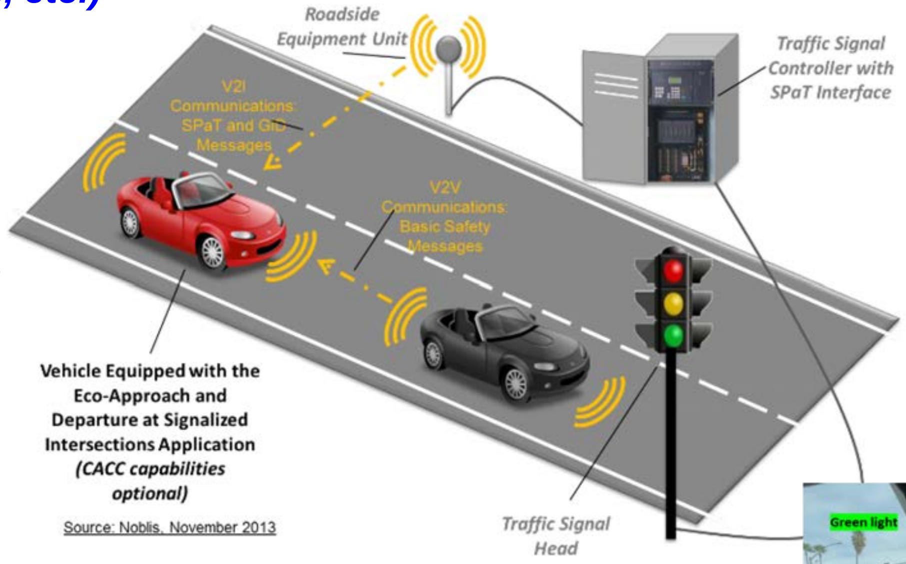
Hardware-in-the-Loop Modeling on the Innovation Corridor



Connected Vehicle Research: Managing Vehicle Dynamics

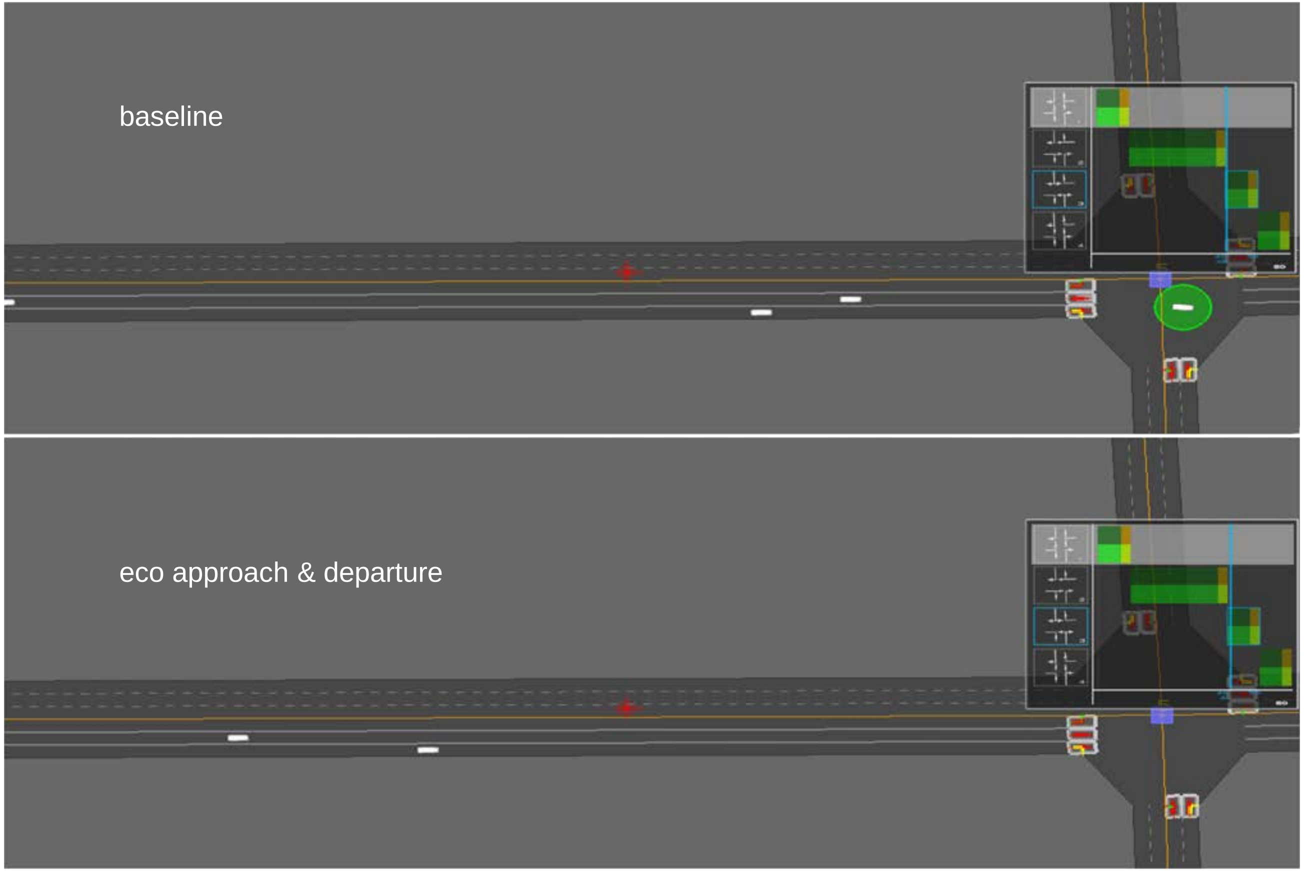
Eco-Approach and Departure at Signalized Intersections (aka GLOSA, TOSCo, Intelligent Signals, etc.)

- **Application utilizes traffic signal phase and timing (SPaT) data to provide driver recommendations that encourage "green" approaches to signalized intersections**
- **Example scenarios:**
  - **Coast down earlier to a red light;**
  - **Modestly speed up to make it (safely) through the intersection on green**
- **Energy Savings: 10% - 20%**
- **Modest mobility improvements**



Demo at: https://youtu.be/j9Tg2g9YTjc

Simulation Modeling…



UC RIVERSIDE CE-CERT RESEARCH

Eco-Approach and Departure at Signalized Intersections: Field Studies

Variables under Study:

- *Mixed traffic*
- *Multi-intersections*
- *Actuated signal prediction*
- *Turning movements*
- *Road grade*
- *lane positioning*
- *MAP messaging*
- *Roadside messages (queue prediction)*
- *Combination with CACC*

Technology	Location	Scenario	Communication	Energy Savings	Ref
EAD with Fixed Signals	Richmond, CA	1	4G/LTE	14%	[1]
	Riverside, CA	1	DSRC	11%-28%	[2]
	McLean, VA	1	DSRC	2.5%-18%	[2]
EAD with Actuated Signals	Riverside, CA	1	DSRC	5-25%	[3]
	Palo Alto, CA	2	DSRC	7%	[4]
GlidePath (HMI-assisted)	McLean, VA	1	DSRC	10-20%	[5]

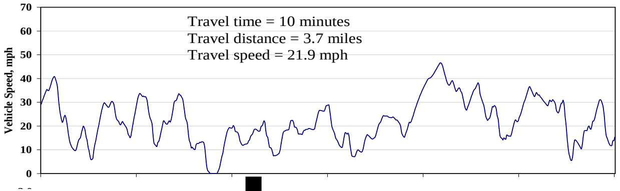
Scenario 1: Single Vehicle; Scenario 2: Mixed Traffic

Research Paper: *Evaluating the Environmental Impacts of Connected and Automated Vehicles - Potential Shortcomings of a Binned-Based Emissions Model*

- **Goal: compares different energy and emissions modeling approaches for analyzing connected and automated vehicles**
- **Also measured energy and emissions from a set of vehicles**
- **Model comparison: EPA MOVES model and CMEM modal emissions model**
- **Hypothesis: because MOVES uses a binning approach, it is likely underestimating the true energy and emissions savings that occur when connected and automated vehicle applications smooth traffic flow**

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

Project-Level Emission Modeling



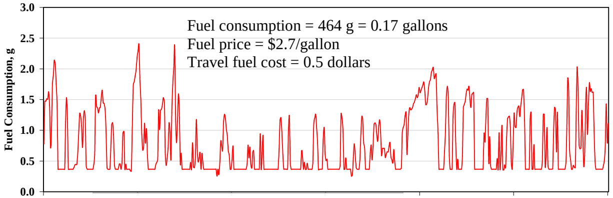
vehicle activity (velocity trajectory and grade if available)

or:

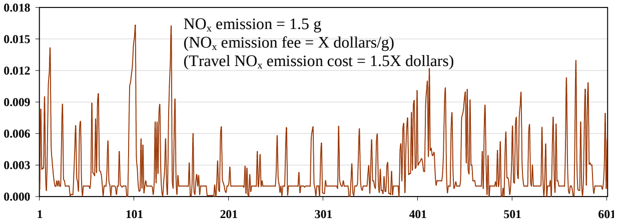
traffic simulation

Emissions Modeling

vehicle calibration parameters and emissions factors



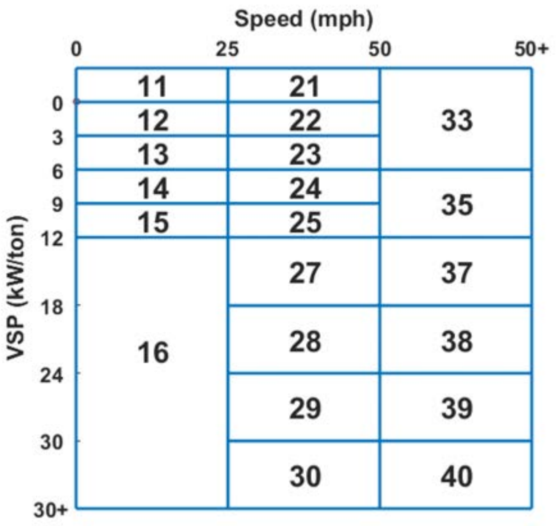
fuel consumption



emissions

Motor Vehicles Emission Simulator (MOVES)

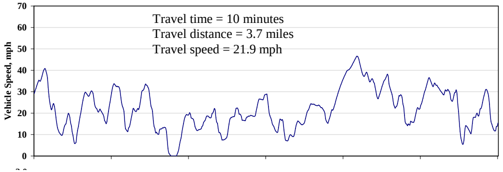
- **Data-Driven Emission Model**
- **Developed by the U.S. Environmental Protection Agency (EPA)**
- **Uses a Binning Approach for Vehicle Operation Mode (OpMode) and Emission Factors**



- **Vehicle Specific Power (VSP) is an estimate of the power demand on the engine during driving**
- **Calculated using the second-by-second speed values in a driving schedule, along with information about the type of vehicle being operated.**
- **Equation:**
  – VSP = (A* Speed + B * Speed^2 + C * Speed^3 + Mass * Speed * Accel) / Mass
  – Where:
    – VSP is in KW/Metric Ton
    – Speed is in meters/second (mps)
    – Accel is in meters/second^2
    – A is rolling resistance term in KW / mps
    – B is friction term in KW / mps^2
    – C is aerodynamic drag term in KW / mps^3
    – Mass is in metric tons (1000 kg)

Comprehensive Modal Emission Model (CMEM)

Vehicle Activity (velocity trajectory)



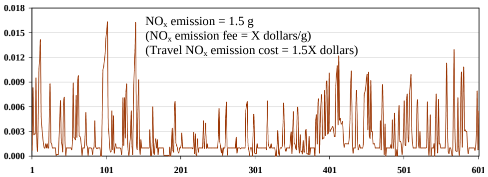
Grade (optional)

Calibration Vehicle Parameters

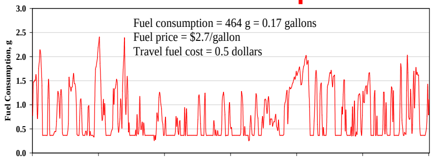
General Vehicle Parameters

CMEM

Emissions



Fuel Consumption



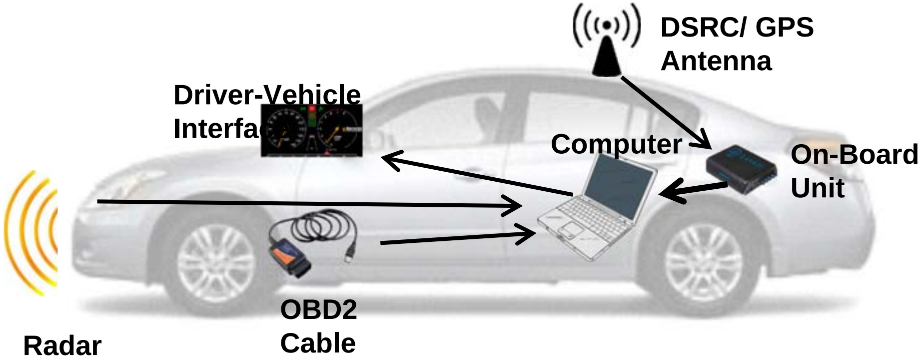
Category #	Vehicle Technology Category
	Normal Emitting Cars
1	No Catalyst
2	2-way Catalyst
3	3-way Catalyst, Carbureted
4	3-way Catalyst, FI, >50K miles, low power/weight
5	3-way Catalyst, FI, >50K miles, high power/weight
6	3-way Catalyst, FI, <50K miles, low power/weight
7	3-way Catalyst, FI, <50K miles, high power/weight
8	Tier 1, >50K miles, low power/weight
9	Tier 1, >50K miles, high power/weight
10	Tier 1, <50K miles, low power/weight
11	Tier 1, <50K miles, high power/weight
24	Tier 1, >100K miles
26	Ultra Low Emission Vehicle (ULEV)
27	Super Ultra Low Emission Vehicle (SULEV) / Partial Zero Emission Vehicle (PZEV)
	Normal Emitting Trucks
12	Pre-1979 (<=8500 GVW)
13	1979 to 1983 (<=8500 GVW)
14	1984 to 1987 (<=8500 GVW)
15	1988 to 1993, <=3750 LVW
16	1988 to 1993, >3750 LVW
17	Tier 1 LDT2/3 (3751-5750 LVW or Alt. LVW)
18	Tier 1 LDT4 (6001-8500 GVW, >5750 Alt. LVW)
25	Gasoline-powered, LDT (> 8500 GVW)
40	Diesel-powered, LDT (> 8500 GVW)
	High Emitting Vehicles
19	Runs lean
20	Runs rich
21	Misfire
22	Bad catalyst
23	Runs very rich
	Heavy Duty Diesel Trucks
45	1994 to 1997, 4-stroke, Elec. FI HDDT
46	1998, 4-stroke, Elec. FI HDDT
47	1999 to 2000, 4-stroke, Elec. FI HDDT

28 LDV

3 HDDV

Experiments

- Tests were performed along the Innovation Corridor (3 intersections)
- Two light-duty vehicles were tested at the same time with real-world traffic
  - One vehicle was employing the eco-approach and departure application
  - One vehicle driving normally
- Model parameters were calibrated specifically for the test vehicles



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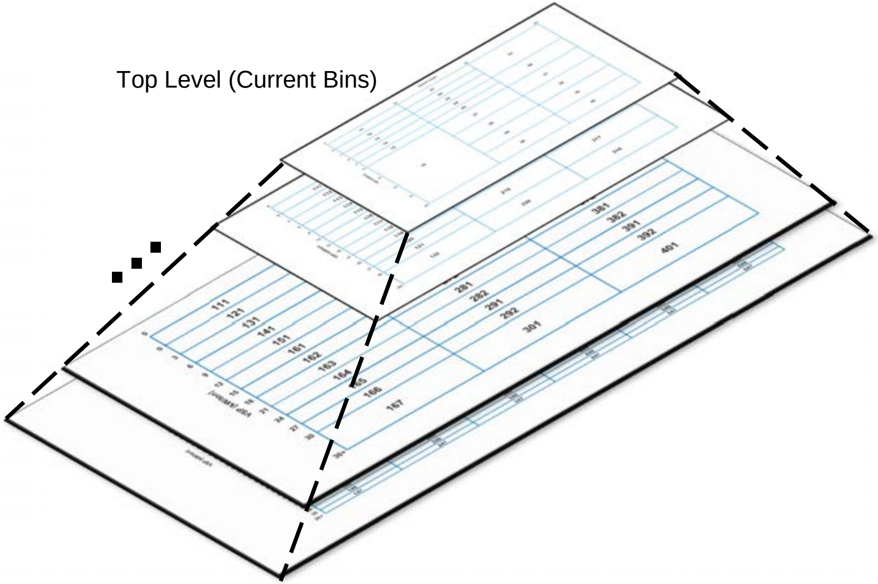
Experiment Video

Results

		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%

Paper Conclusions and Future Work

- **Binning model overestimated overall fuel consumption by 13.1%**
- **Traffic Smoothing effects tend to get washed out in MOVES due to bin size**
- **MOVES can be preserved and enhanced with a sub-binning approach**
- **MOVES could be used at different "resolutions" using a Bin-Pyramid approach; original MOVES model is preserved**



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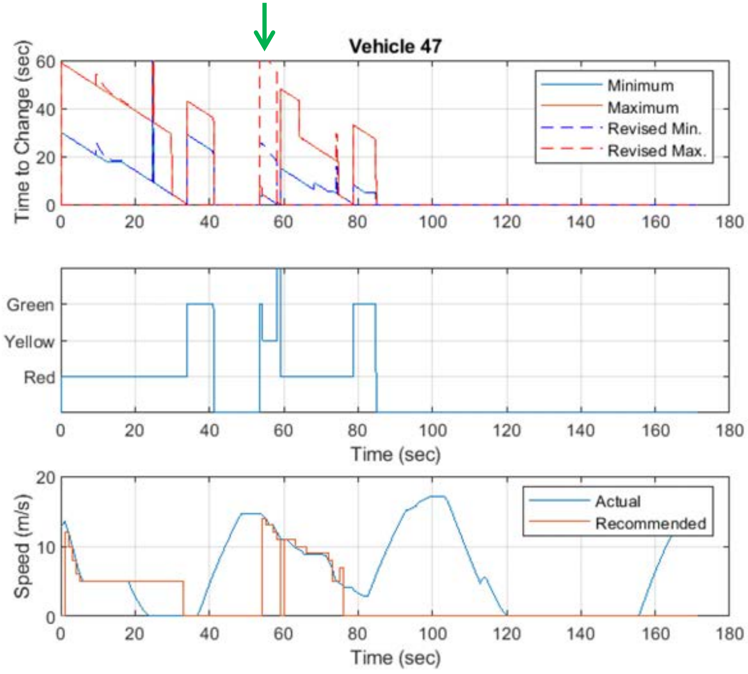
Current Work: Improved Results for Actuated Signals

- With fixed-timed signals, it is easy to plan vehicle speed trajectories driving through intersections
- Fixed-time signals will provide the highest energy/emission savings
- It is much more challenging to plan vehicle dynamics for **actuated signals** (e.g., cross traffic can trigger a light change)
- We are improving the trajectory planning algorithms for actuated signals, resulting in improved energy/emissions savings

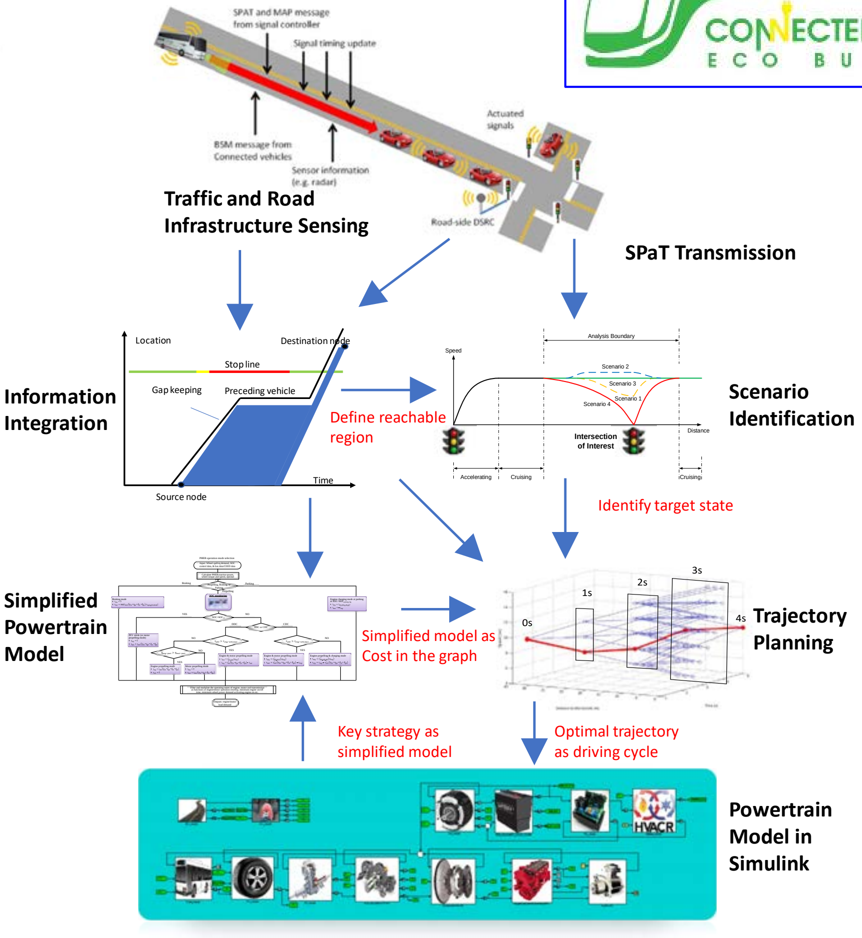
Extended Planning Horizon



Additional Current and Future Activities Utilizing the Innovation Corridor

Connected Eco-Bus

an ARPA-E NEXTCAR project



Key Technical Achievements:

- **Developed an innovative vehicle-powertrain eco-operation system for plug-in hybrid electric buses through co-optimization of vehicle dynamics and powertrain controls, achieving 20+% energy efficiency increase**
- **Developed three key innovative velocity trajectory planning modules: *Eco-Approach and Departure at Signalized Intersections; Eco-Stop and Launch;* and *Eco-Cruise***
- **Developed innovative powertrain modules: *Efficiency Based Powertrain Controls, Intelligent Energy Management***
- **Developed a new hardware-in-the-loop development and testing approach called *Dyno-in-the-Loop (DiL)* testing**

Connected Eco-Bus Efficiency Breakdown Table

Efficiency Improvements Due to Control Strategies:

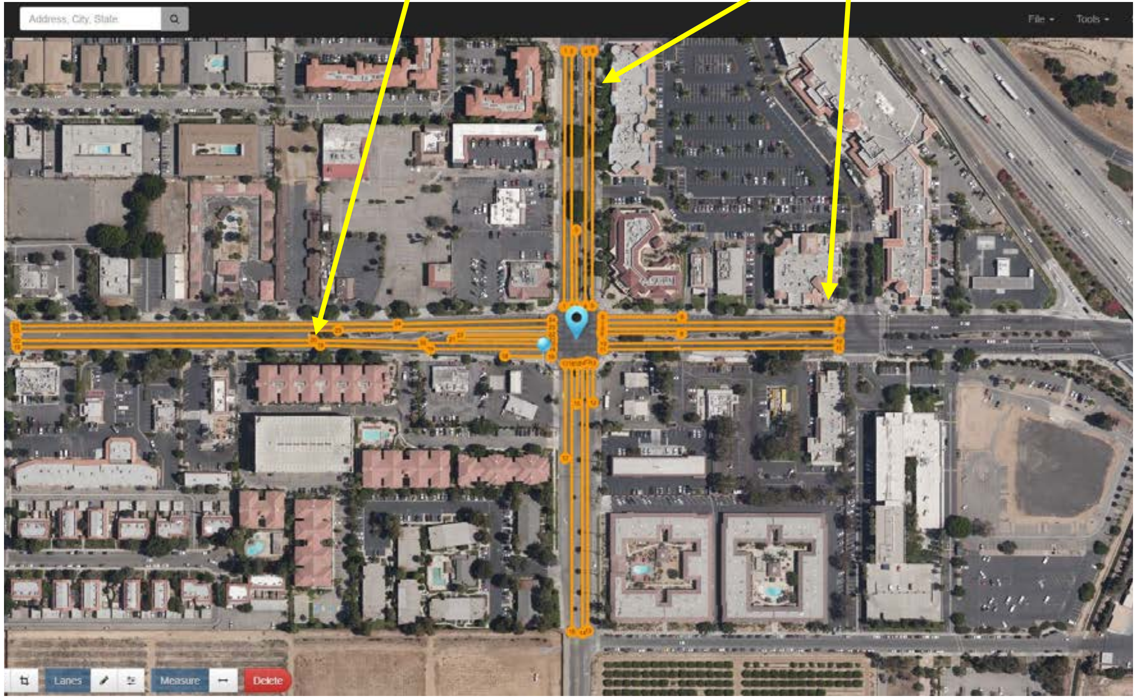
Strategy		Description	Savings	Source
Vehicle Dynamics (VD) Control	Eco-Approach and Departure	Determines energy-efficient speed profile based on Signal Phase and Timing information	5% - 20%	Traffic simulation & field studies
	Eco-Stop and Launch	Determines energy-efficient speed profile for decelerating to and accelerating from bus stops and stop signs	3% - 17%	Numerical simulation
	Eco-Cruise	Determines cruising speed profile based on look-ahead traffic and terrain conditions	Up to 10%	Numerical simulation
	Integrated VD	Combined vehicle dynamics control strategies on target corridor	8% - 14%;	Traffic simulation;
Powertrain (PT) Control	Efficiency-Based PT Control	Optimizes both the engine and motor/generator operation by managing transmission and battery state-of-charge	13 - 15%	Simulation
	Intelligent Energy Management	Optimizes power split between ICE and electric motor for the vehicle speed and power demand profiles	3 - 8%	Simulation
Integrated VD&PT Control		Integration of above strategies with VD&PT co-optimization on target corridor	18% - 24% 16% (DiL)	Simulation DiL

LANE-LEVEL MAPPING AND POSITIONING

- **Many Connected and Automated Vehicle applications require lane-level positioning accuracy and maps**
- **Achieving lane-level position accuracy in all conditions is challenging**
- **Research is underway to establish lane level accuracy for the Innovation Corridor**

Waypoint between start of lane and end of lane

Lanes Extend to other Intersections



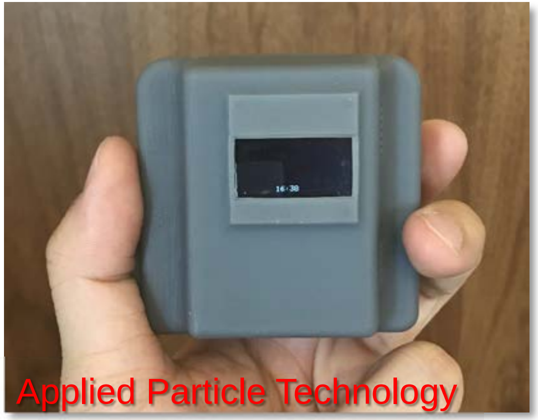
Williams, N., & Barth, M. (2020) "A Qualitative Analysis of Vehicle Positioning Requirements for Connected Vehicle Applications", *IEEE Intelligent Transportation Systems Magazine*, doi:10.1109/mits.2019.2953521

Air Quality Frontier: Decision-Enabling Technology

Smart calibrated flexible monitoring

High-resolution mobile monitoring

Wearable pollutant sensors

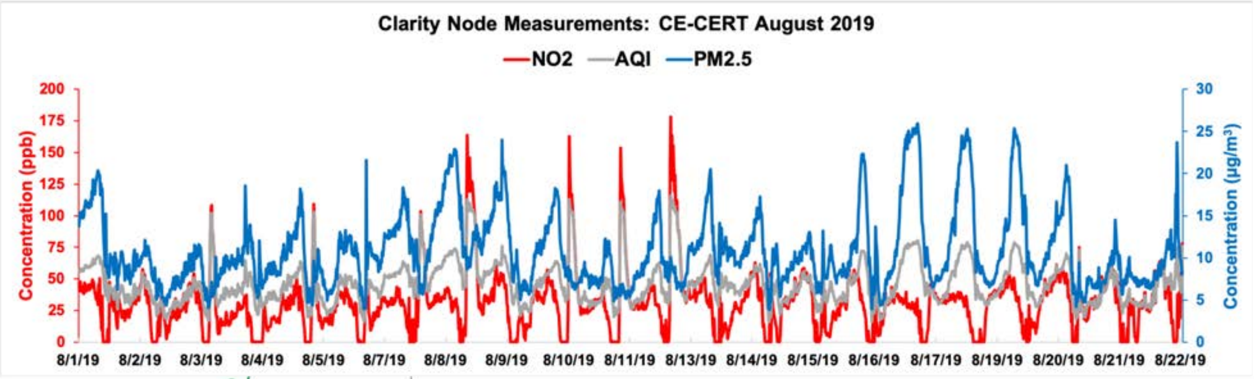


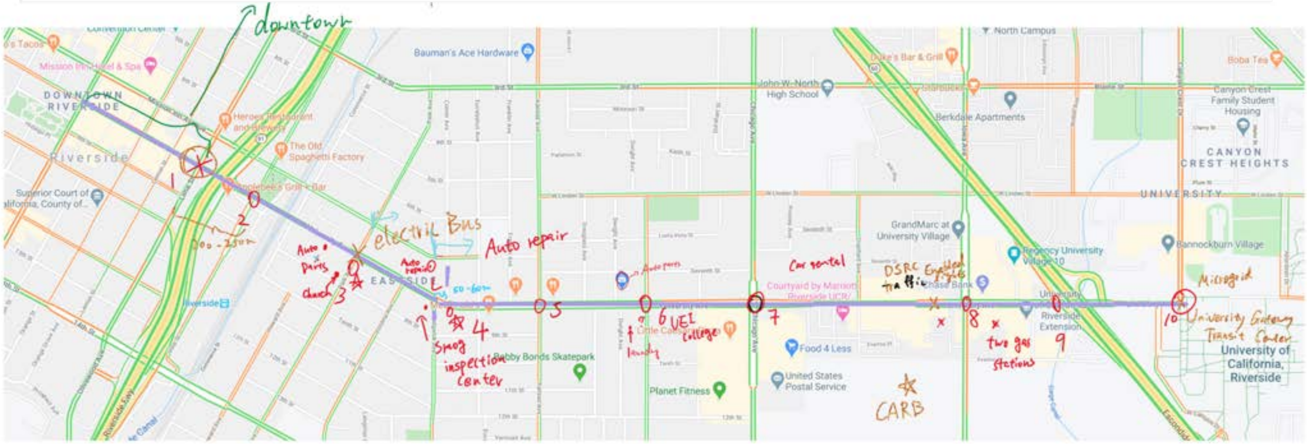
Near real-time integrated models

Air Quality Monitoring along Riverside's Innovation Corridor

Goals:

- **Deploy a 10-node Clarity monitoring network along the Innovation Corridor**
- **Monitor $PM_{2.5}$ and NO_2 at high-traffic intersections, upwind and downwind of US-91 and US-60**
- **15 second measurements uploaded directly to the cloud**



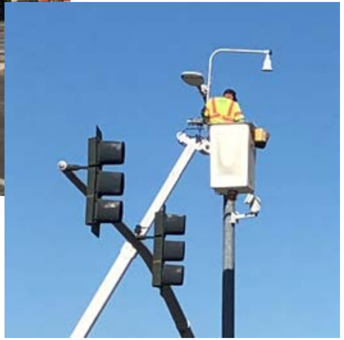


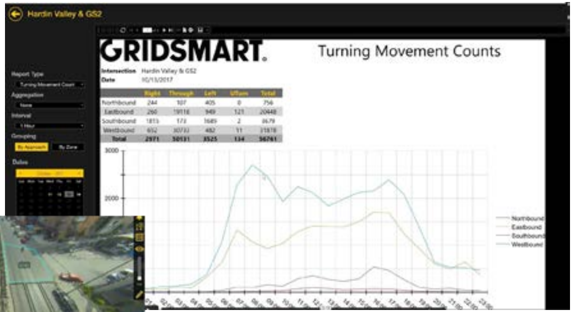
Professor Sunni Ivey:
https://www.iveylab.com/

CAMERA SYSTEMS AND VIDEO ANALYTICS

GRIDSMART Video Analytics System

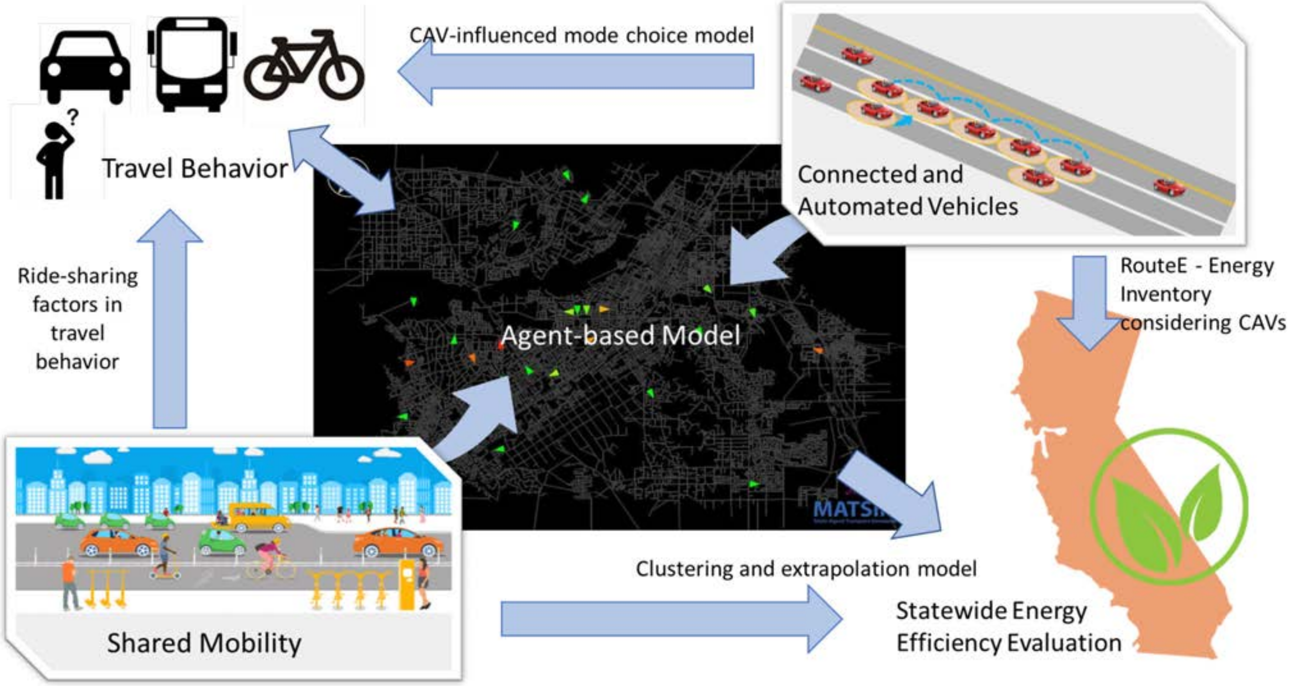
- Currently being installed at University and Iowa intersection
- Will provide accurate traffic counts, turning movements, etc.
- Potential to track not only vehicles, but also bicycles and pedestrians





Focus on Shared Mobility in Riverside

- **CE-CERT is leveraging it travel demand activity based modeling**
- **Using BEAM (Behavior, Energy, Autonomy, Mobility) model developed at LBNL**



Modeling Shared Mobility in Riverside

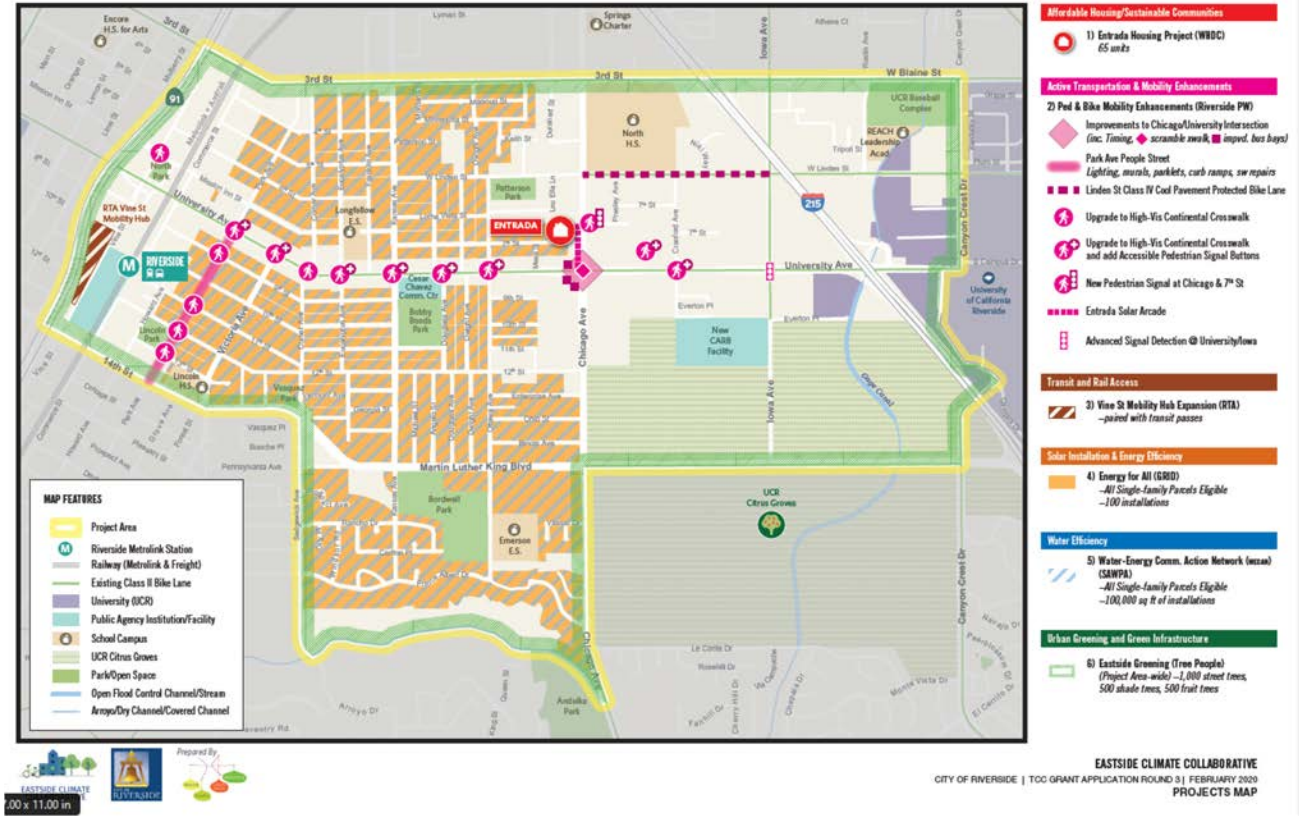
- **Specific Scenario Evaluation:**
  - StratoShare carsharing system rollout & Expansion Plans
  - City of Riverside TNC Policies: pick up and drop offs at specific locations
  - City of Riverside Micro-Mobility Policies: considering geo-fencing locations
  - Transit: Light Rail, Bus Rapid Transit, Clean Bus Rule

- **Metrics:**
  - Mobility improvements (traffic throughput)
  - VMT reductions by enabling other modes
  - Energy and emissions reductions
  - Access in disadvantaged communities

Demo at: https://www.youtube.com/watch?v=C-owmP8laGA&feature=youtu.be

City of Riverside TCC Grant (Strategic Growth Council)

UCR & City Collaboration



UCR Tasks:

- Track and Analyze metrics and data
- Provide Training
- Provide Recommendations for implementing strategies & technologies
- Synergize other on the ground projects

Conclusions and Future Activities

- **Continue to expand the capabilities and use of the Innovation Corridor Testbed → part of the CalTestBed program (California Energy Commission)**
- **Expand research and real-world experiments in shared, electric, connected, and automated vehicles**
- **Integrate transportation and air quality data and models**
- **Future: expand vehicle communication capability: DSRC → C-V2X, 5G**
- **Future: co-optimization of intersection management and vehicle dynamics**
- **Migrate developed technology to other testbeds and pilots**

THANK YOU!

Kanok Boriboonsomsin
Researcher Engineer

Guoyuan Wu
Associate Research Engineer

Peng Hao
Assistant Research Engineer

Mike Todd
Principal Development Engineer

Nigel Williams
Assistant Specialist (postdoc)

Alexander Vu
Assistant Development Engineer

Cesunica Ivey
Assistant Professor

David Oswald
PhD Student

Saswat Nayak
PhD Student

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