UNITED STATES
DEPARTMENT OF TRANSPORTATION

Eco-Approach and Departure at Signalized Intersections: Preliminary Modeling Results

Applications for the Environment: Real-Time Information Synthesis (AERIS) Program

Fall/Winter Webinar Series

November 20, 2013

Presentation Overview

- General Eco-Approach and Departure Concept
- Variations on a Theme: Dimensions of Analysis
- Simulation Modeling Setup and General Results
- Simulation Modeling Sensitivity Analysis
- General Conclusions
- Enhanced Concepts: Combining with Connected Eco-Driving and Cooperative Adaptive Cruise Control

Eco-Approach and Departure Concept

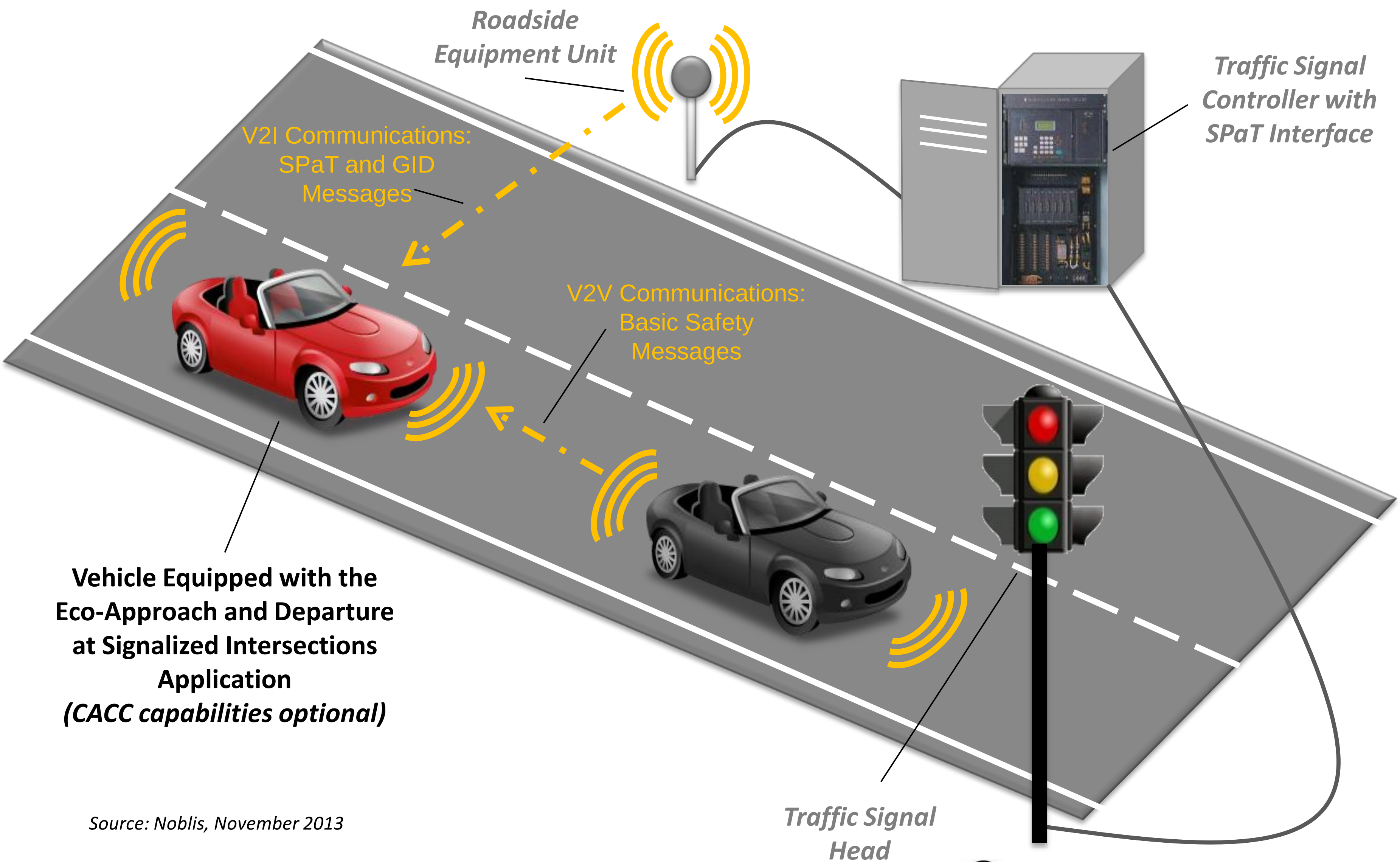
Application utilizes traffic signal phase and timing (SPaT) data to provide driver recommendations that encourage "green" approaches to signalized intersections

Source: USDOT

example scenarios:

1) **Coast down earlier to a red light;**
2) **Modestly speed up to make it (safely) through the intersection on green**

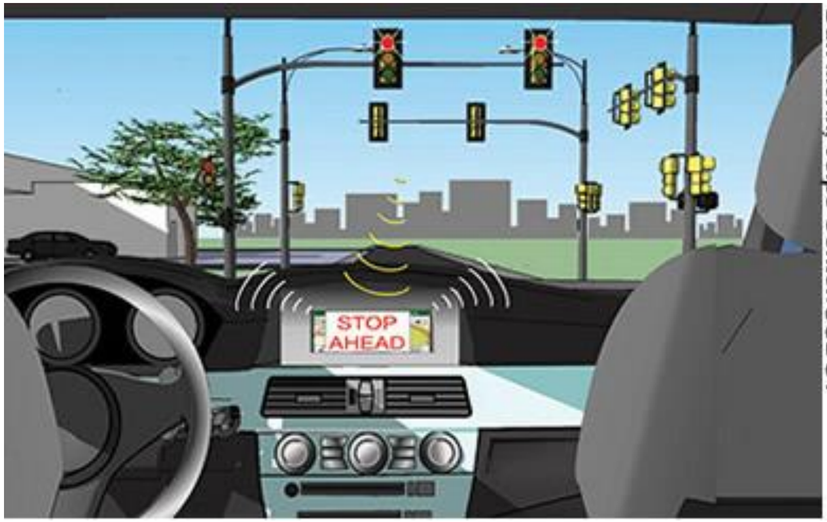
Eco-Approach and Departure at Signalized Intersections



Source: Noblis, November 2013

Signal Phase and Timing (SPaT)

- **Data are broadcast from road side equipment (connected to traffic signal controller) to vehicles (I2V communications)**
- **SPaT information consists of intersection map, phase and timing (10 Hz), and localized GPS corrections**
- **Can be broadcast locally via Dedicated Short Range Communication (DSRC) *and/or* cellular communications**

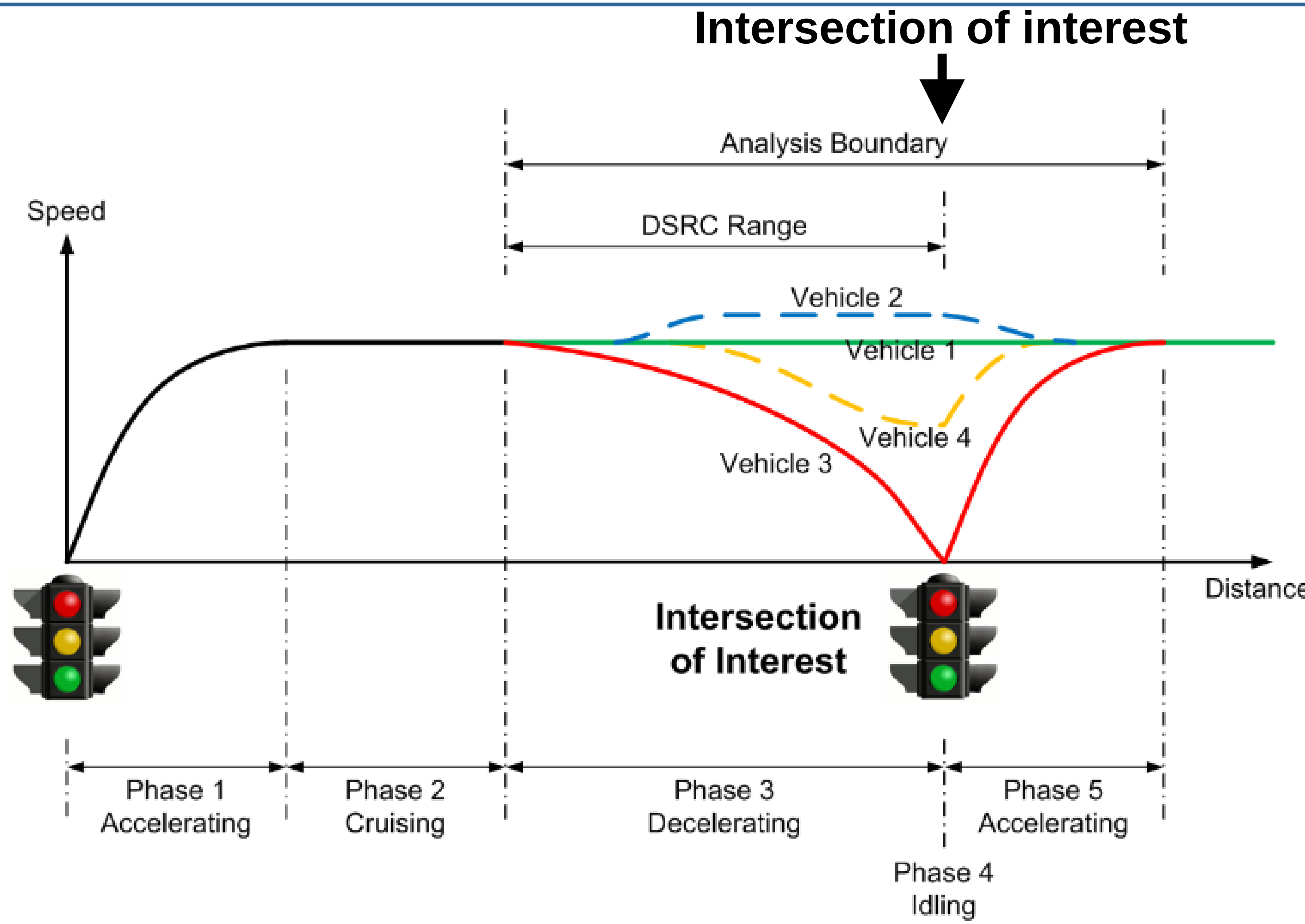


Dan Morin, Volpe Center/USDOT

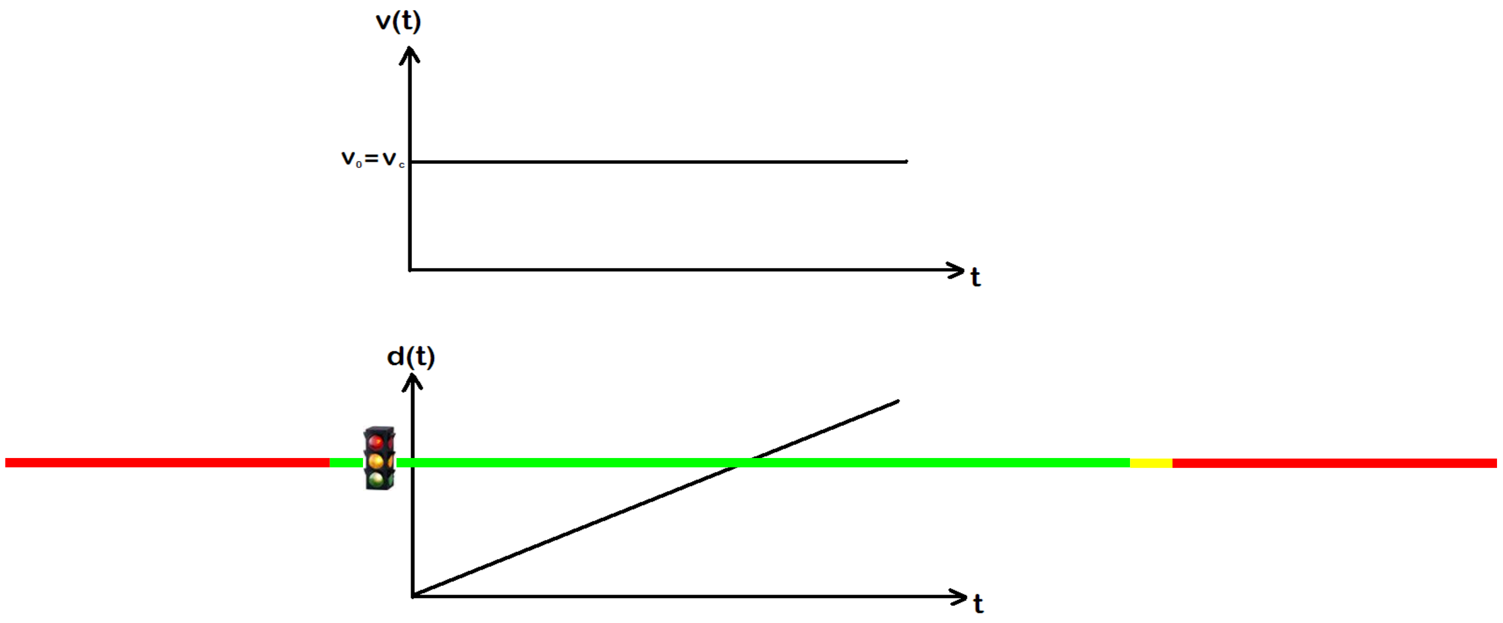
Variations on the General Concept

- **Signal timing scheme** matters: fixed time signals, actuated signals, coordinated signals
- **Single intersection** analysis and **corridor-level** analysis
- **Congestion level:** how does effectiveness change with amount of surrounding traffic
- **Single-vehicle** benefits and total **link-level** benefits
- **Simulation Modeling vs. Field Studies:** pros and cons
- **Vehicle Control:** driver advice vs. partial automation
- **Communications Method:** short range vs. wide-area
- **Analysis Approach:** increasing incremental complexity and using previous results as “building blocks”

Eco-Approach Scenario Diagram

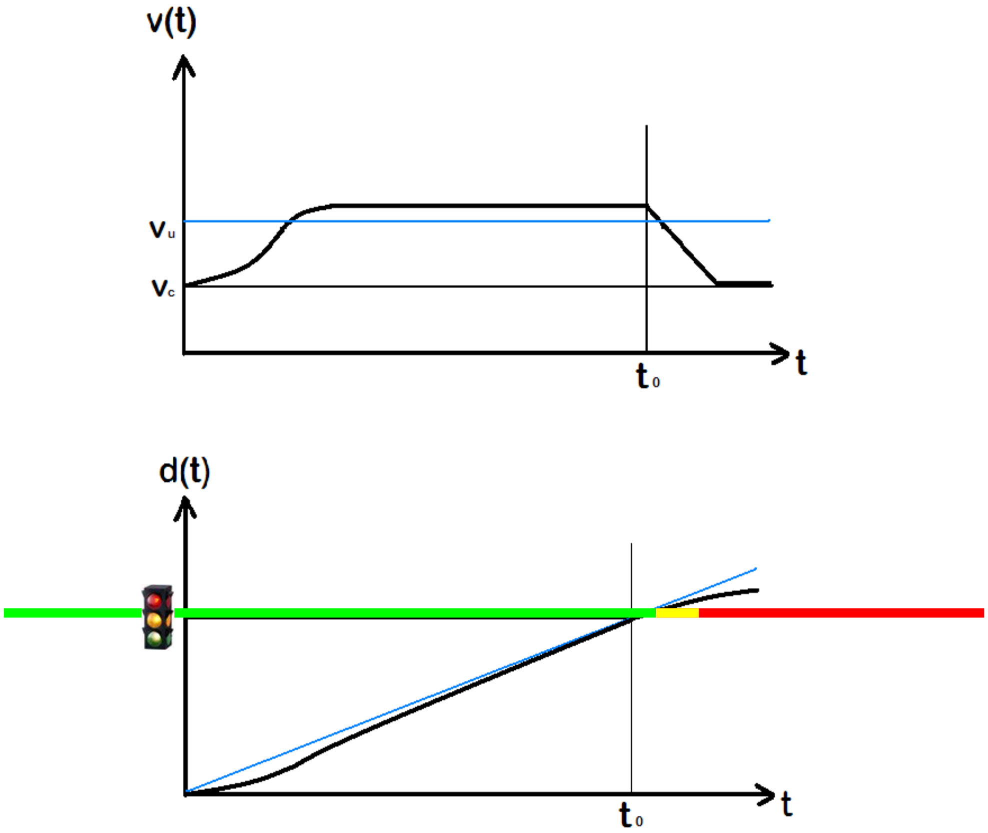


Eco-Approach Driving Scenario 1 (cruise)



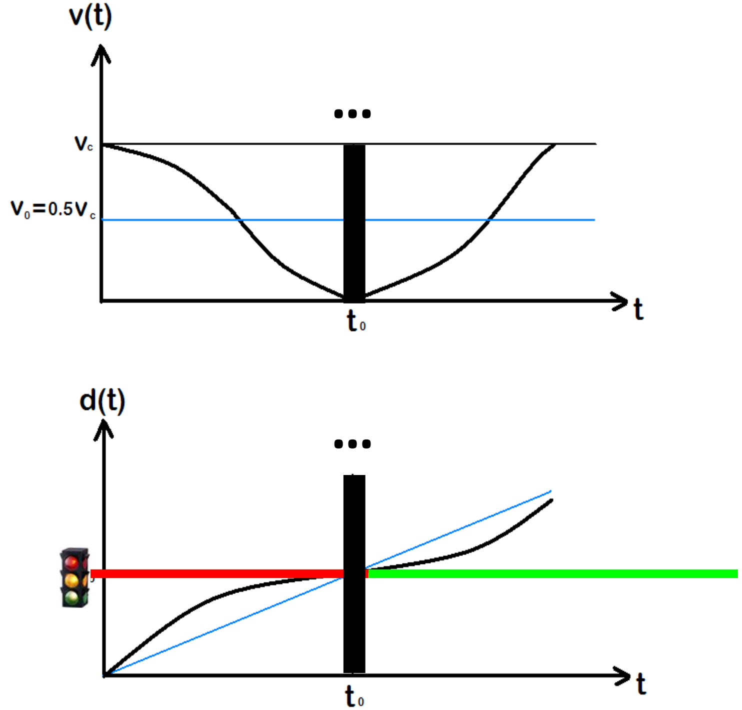
- **Vehicle is able to pass through the intersection on green phase**
- **does not need to slow down or speed up**
- **Best scenario for fuel economy**

Eco-Approach Driving Scenario 2 (speed up)



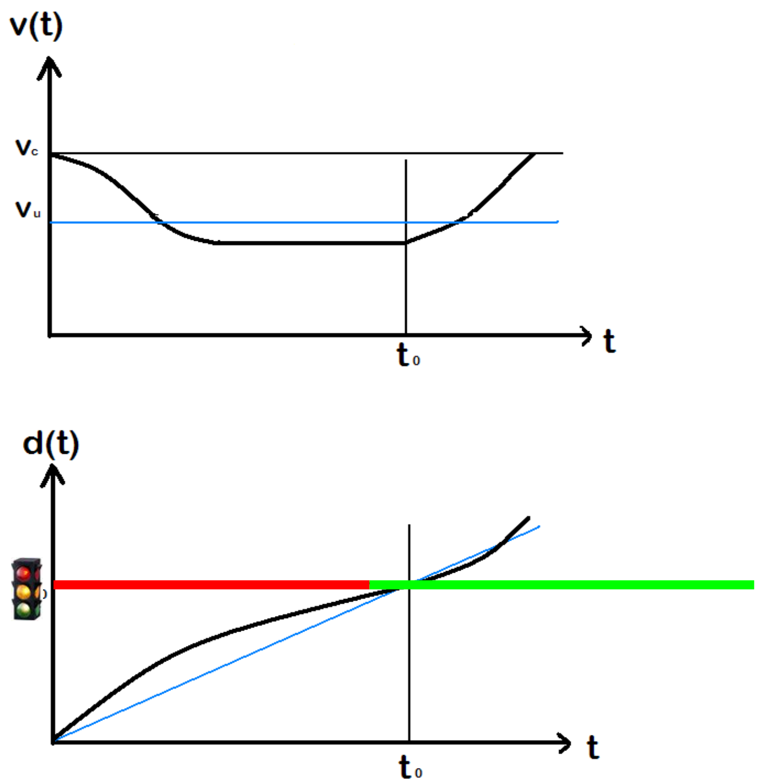
- **Vehicle needs to safely speed up to pass through the intersection on green phase**
- **Energy savings due to not having to stop and idle**

Eco-Approach Driving Scenario 3 (coast down, stop)



- **Vehicle needs to slow down to stop at the intersection**
- **Energy savings due to slowing down sooner**
- **Scenario reference:** M. Li et al., "Traffic energy and emission reductions at signalized intersections: a study of the benefits of advanced driver information," *International Journal of Intelligent Transportation Systems Research*, vol. 7(1), pp. 49-58, 2009.

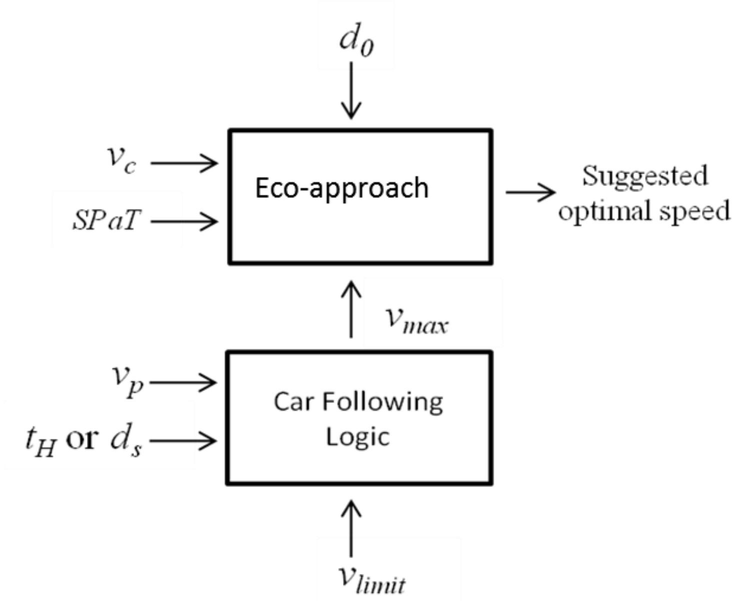
Eco-Approach Driving Scenario 4 (coast down, no stop)

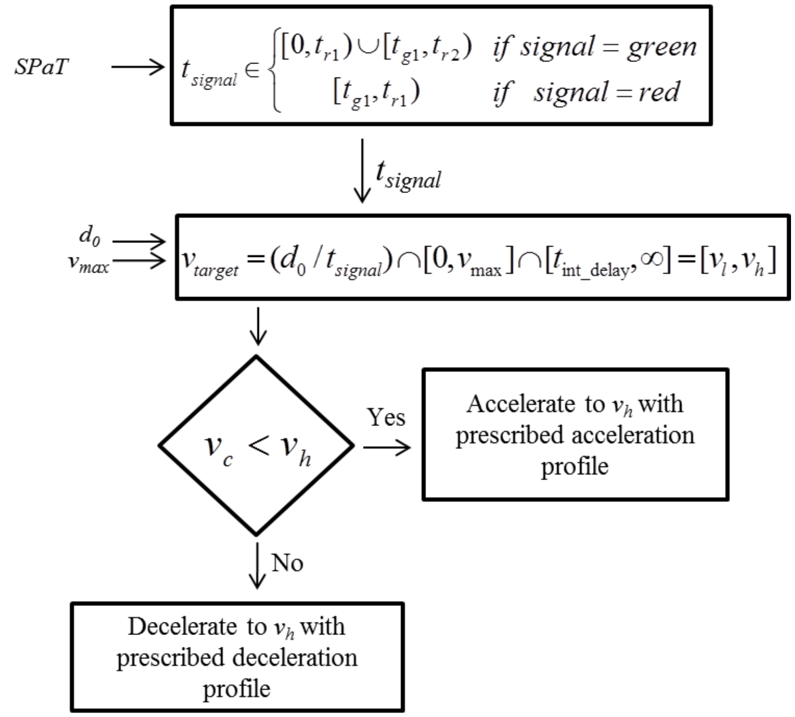


- Vehicle needs to slow down to pass through the intersection on green phase
- Energy savings due to not having to idle

Velocity Planning Algorithm

- **Target velocity is set to get through the green phase of the next signal (time-distance calculation)**
- **Initial velocity may be above or below target velocity**





v_c = the current vehicle velocity
v_p = the velocity of the preceding vehicle
v_{limit} = local speed limit
t_H = safe headway time

Reference 1: M. Barth, S. Mandava, K. Boriboonsomsin, and H. Xia "Dynamic ECO-Driving for Arterial Corridors", *Proceedings of the IEEE Forum of Integrated Sustainable Transportation*, Vienna Austria, 6/2011, 7 pp.
Reference 2: H. Xia, K. Boriboonsomsin and M. Barth, "Dynamic eco-driving for signalized arterial corridors and its indirect network-wide energy/emissions benefits", Journal of Intelligent Transportation Systems: Technology, Planning, and Operations, 17(1), 2013, pp. 31 – 41

Previous Studies & Results with Algorithm

Initial Simulation:

LDV24	Without		With		% Diff. in Avg.	*p*-value of *t*-test
	Avg.	*S.D.*	*Avg.*	*S.D.*		
Fuel (g/mi)	118.3	13.2	103.8	9.3	-12.3	8.7E-06
CO_2 (g/mi)	371.0	41.2	318.8	25.3	-14.1	3.2E-07
TT (sec)	456.7	60.7	451.9	56.9	-1.06	0.635

references:

S. Mandava et al., “Arterial Velocity Planning based on Traffic Signal Information under Light Traffic Conditions”, 2009 *IEEE Intelligent Vehicle Systems Conference*, October, 2009.

M. Barth et al., “Dynamic ECO-Driving for Arterial Corridors”, *Proceedings of the 2011 IEEE Forum on Integrated Sustainable Transportation (FISTS)*, Vienna, Austria, June, 2011.

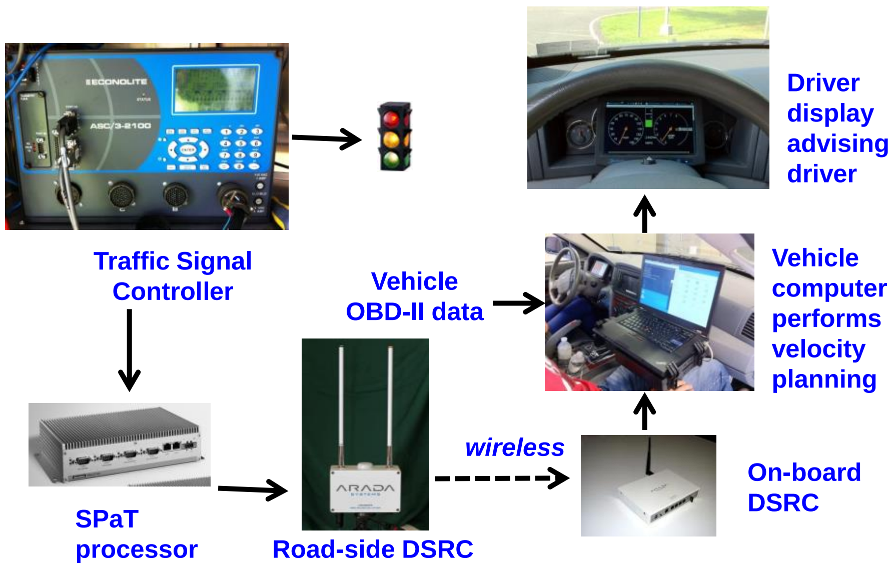
Real-World Results of FHWA EAR project with BMW, UC Berkeley at Richmond Field Station (4/2012):

	uninformed	informed	Improvement
Fuel (l/100km)	10.23	8.84	-13.59%
Travel time (sec/trip)	40.69	40.3	-0.96%

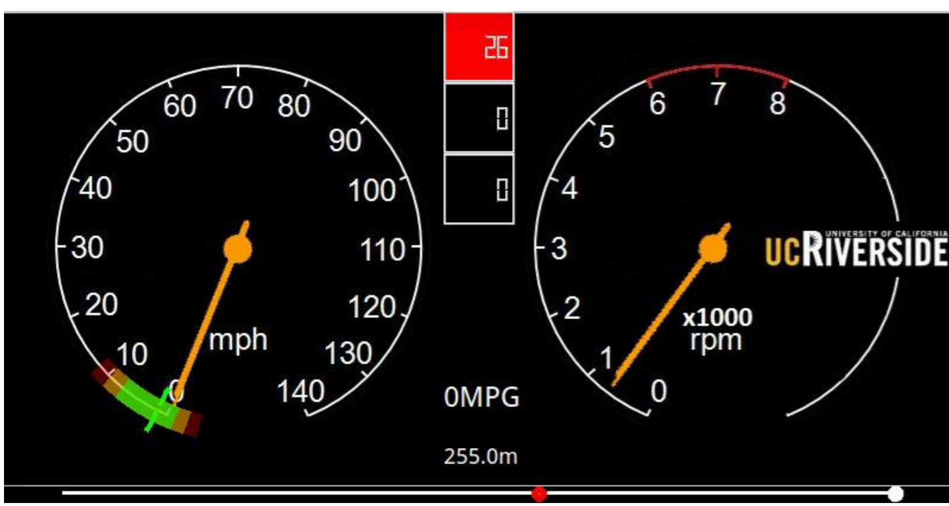
reference:

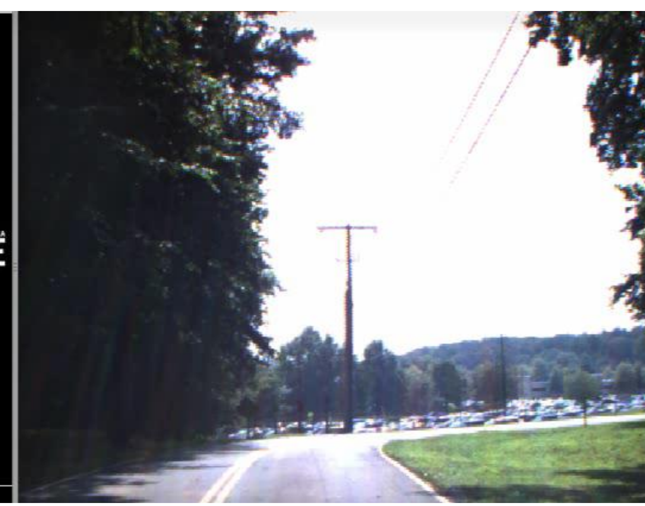
H. Xia et al., “Field Operational Testing of ECO-Approach Technology at a Fixed-Time Signalized Intersection”, 2012 *IEEE Intelligent Vehicle Systems Conference*, Anchorage, AK, Sept 2012.

2012 AERIS Demonstration at FHWA Turner Fairbank Highway Research Center



average fuel saved: 18%





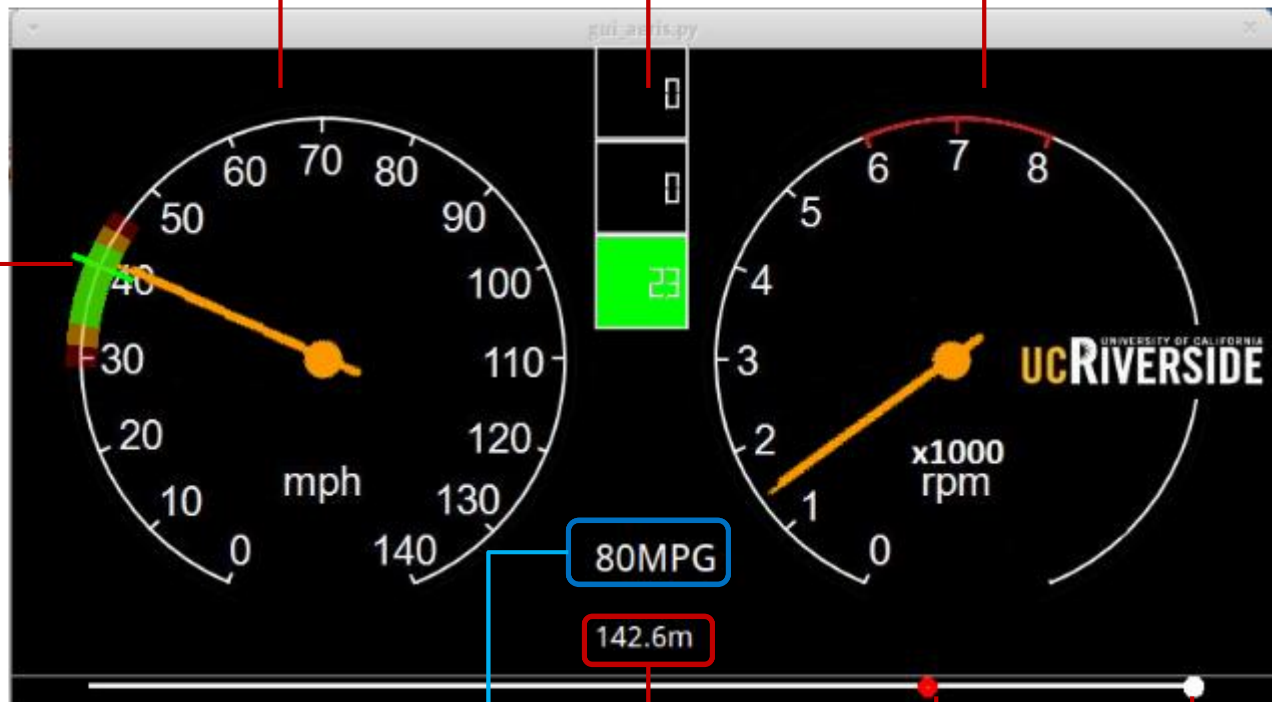
Driver Interface used in Demonstration

Speedometer

SPaT

tachometer

Advisory speed



Real-time MPG

Vehicle location Indicator

Distance to intersection

Intersection location Indicator

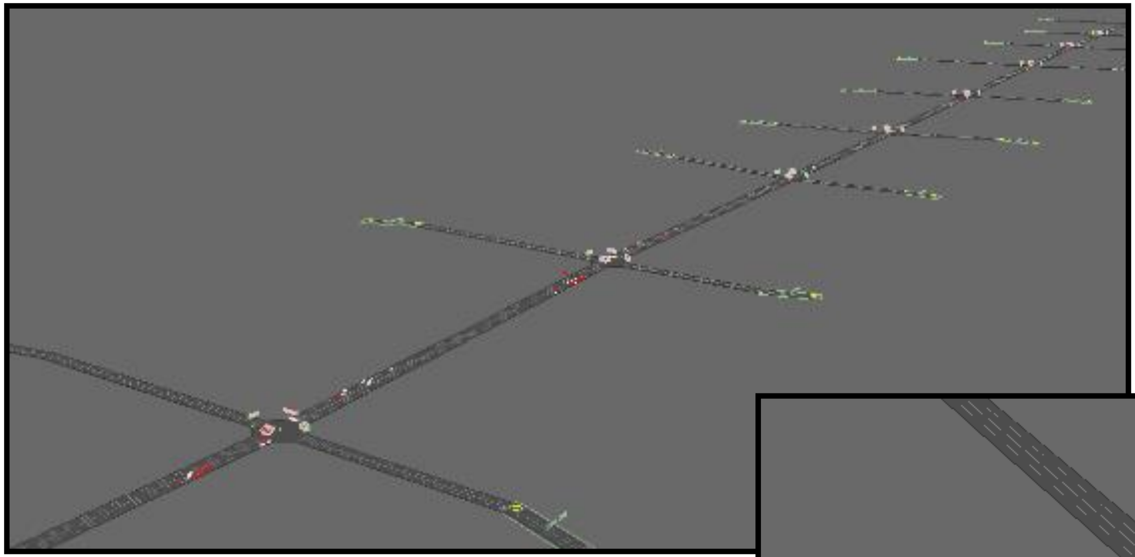
Simulation Modeling

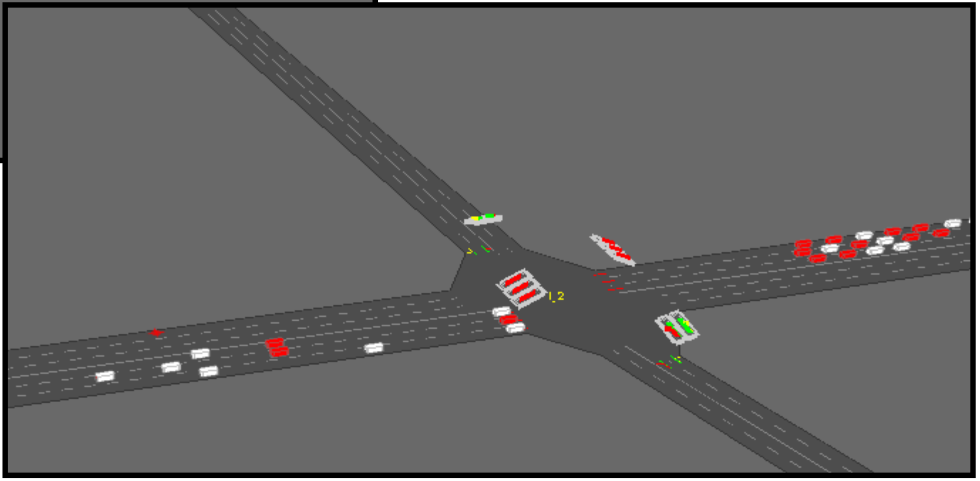
Modeling Objectives

- Conduct detailed simulation modeling and test benefits under different traffic conditions, network conditions, technology penetration rates, and other variables
- Modeling initially focused on a "generic intersection"
- Simulation parameters (car-following logic, lane-change behavior) calibrated using NGSIM data sets
- Modeling focused on El Camino Real network with real-world traffic and network data (Palo Alto, CA)
- Later tie-in with travel demand models and other AERIS concepts

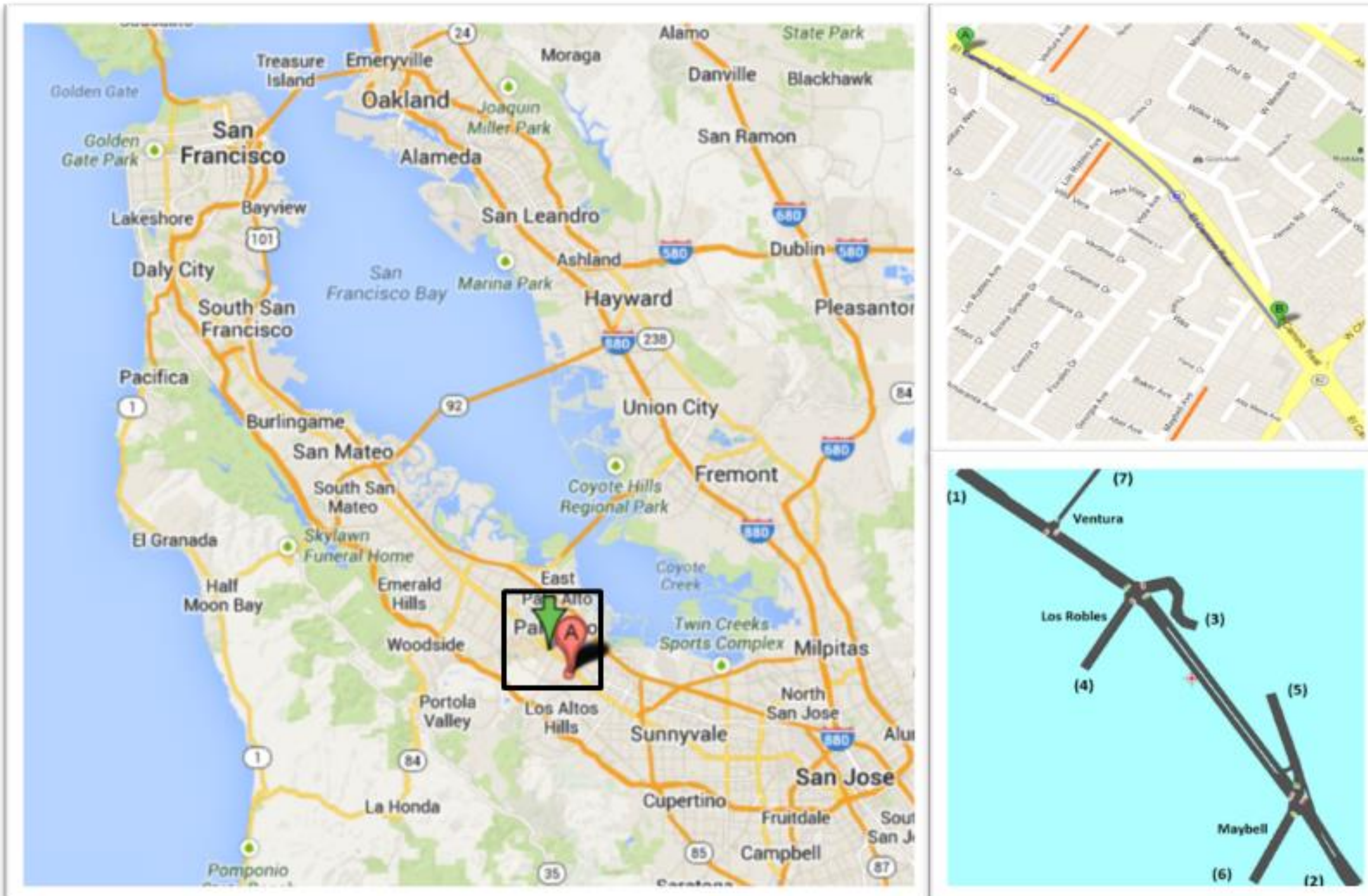
Modeling Setup

- **Paramics traffic simulation model with API plug-ins (eco-approach method, energy/emissions models)**

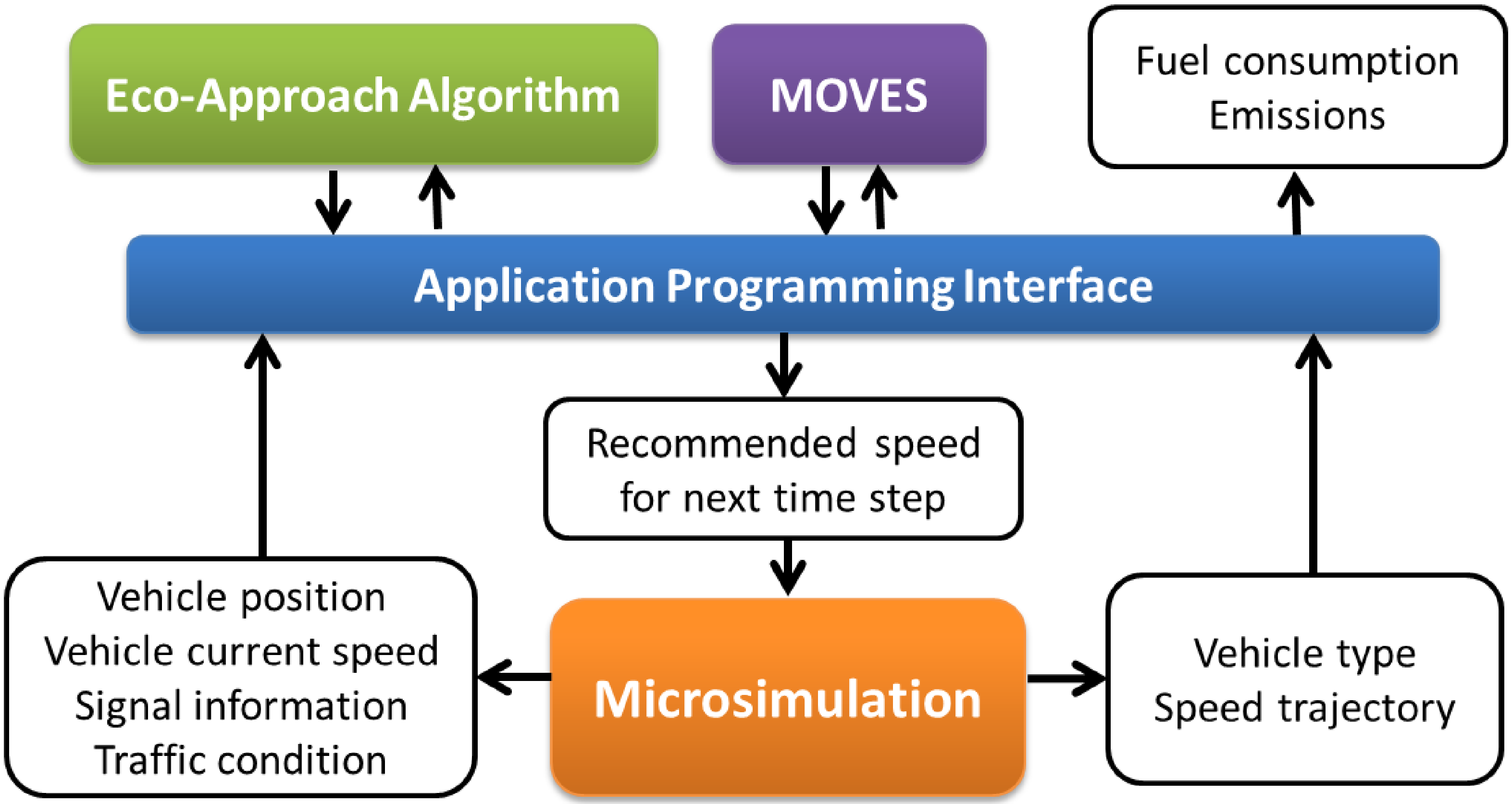




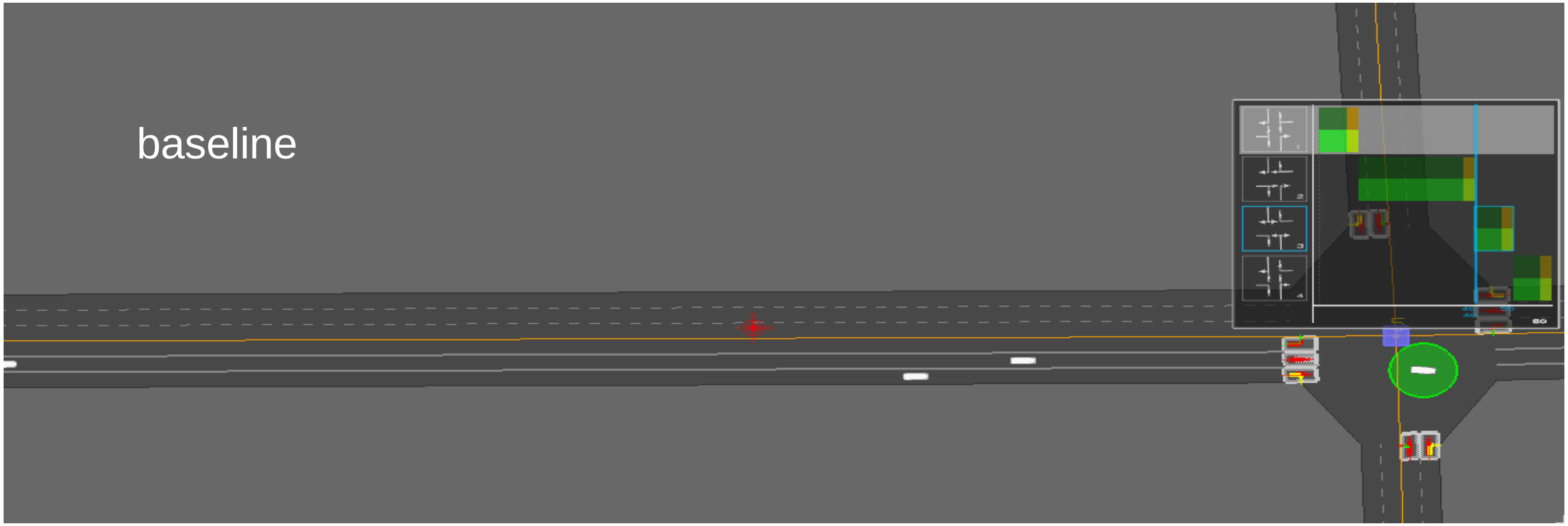
Region of Modeling: El Camino Real in Northern California

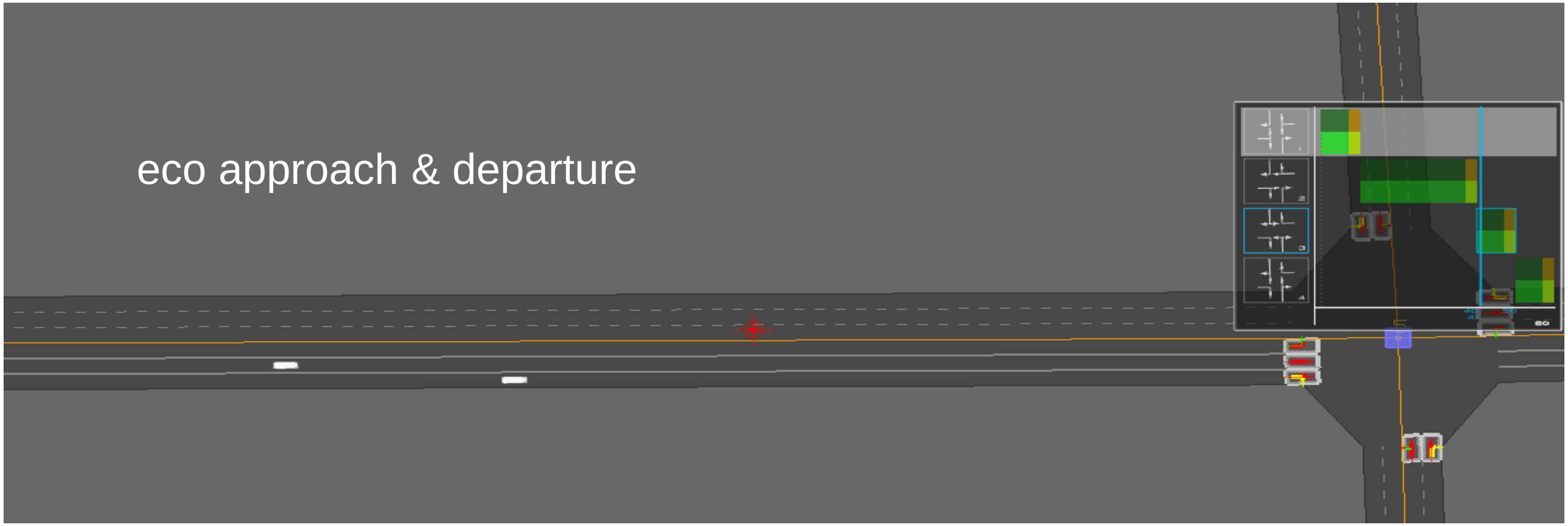


Modeling Tools and Interaction



Videos





General Modeling Results:
Hypothetical 11-Signalized Intersection Corridor

Single Vehicle Energy, Emissions and Travel Time Comparisons

	Baseline		Eco-Approach		Improvement
	Avg.	*S.D.*	*Avg.*	*S.D.*	
Fuel (g/mi)	167.87	1.97	146.91	2.56	12.48%
CO_2 (g/mi)	439.60	3.57	381.49	3.72	13.22%
TTPM (sec/mi)	122.08	1.43	121.18	1.23	0.73%

How would this benefit a user?

- **Six-mile corridor, average traffic congestion**
- **Light-duty vehicle, 24 mpg, gasoline costs $4/gallon**
- **Unequipped vehicle spends $1 in fuel to traverse corridor**
- **Equipped vehicle spends ~$0.87 in fuel to traverse corridor**
- **Driving 16,000 miles/year → $346 of savings per year**
- **SUV vehicle: savings of $560/year**
- **Fleet operator (150 vehicles): $84,000/year**

Modeling Results: Multiple Intersections

Uncoordinated Signal Control:

- **Signal timing is set to be uncoordinated between intersections (no "green wave")**
- **Eco-approach algorithm applied on all three intersections, cross traffic included in analysis**
- **The links in this network are short, which affects the effectiveness of the eco-approach algorithm**
- **Typical Fuel (CO_2) Savings: 5% - 10% overall**

Scenario	V/C	Penetr%	Energy(kJ/mi)	CO2 (g/mi)	CO (g/mi)	HC (g/mi)	NOx (g/mi)	PM (g/mi)	TT/veh
baseline	1.00	0	8997.08	647.70	13.55	0.45	1.87	0.13	125.12
	0.77	0	8887.79	640.62	13.69	0.45	1.91	0.13	118.31
	0.38	0	8760.11	630.78	13.91	0.44	2.03	0.15	108.16
Eco-Approach & Departure	1.00	100	8621.25	621.46	11.69	0.42	1.82	0.11	133.60
	0.77	100	8425.44	607.35	12.19	0.42	1.55	0.10	121.76
	0.38	100	7846.91	564.88	11.06	0.38	1.80	0.12	109.78
saving %	1.00	100	4.18	4.05	13.69	7.19	2.56	11.70	-6.78
	0.77	100	5.20	5.19	10.94	7.53	19.07	24.37	-2.92
	0.38	100	10.42	10.45	20.50	14.05	11.39	19.68	-1.50

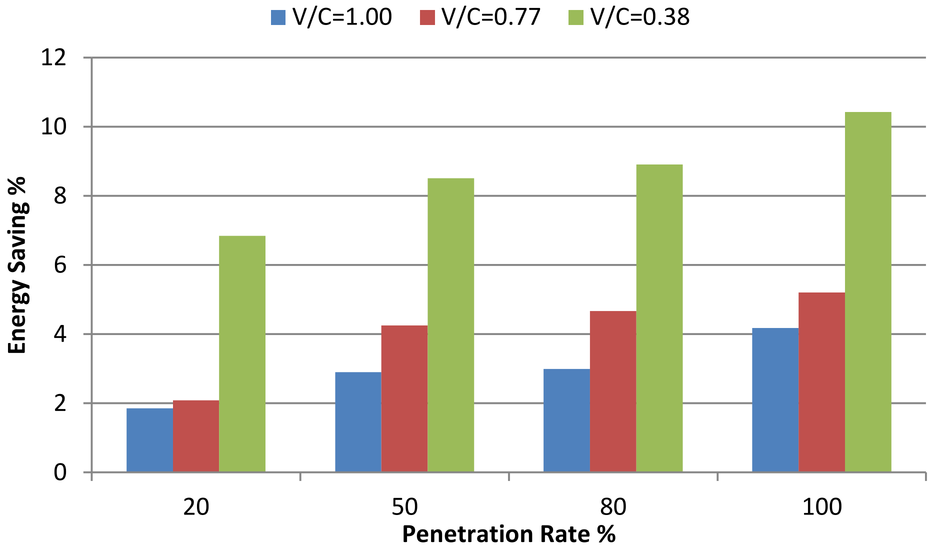
Modeling Results: Multiple Intersections

Coordinated Signal Control:

- **Signal timing is set to be coordinated between intersections (real-world)**
- **Coordinated signal control results in ~8% fuel reduction over uncoordinated**
- **Eco-approach algorithm applied on all three intersections, cross traffic included in analysis**
- **Fuel (CO_2) Savings: 4% - 5% overall**

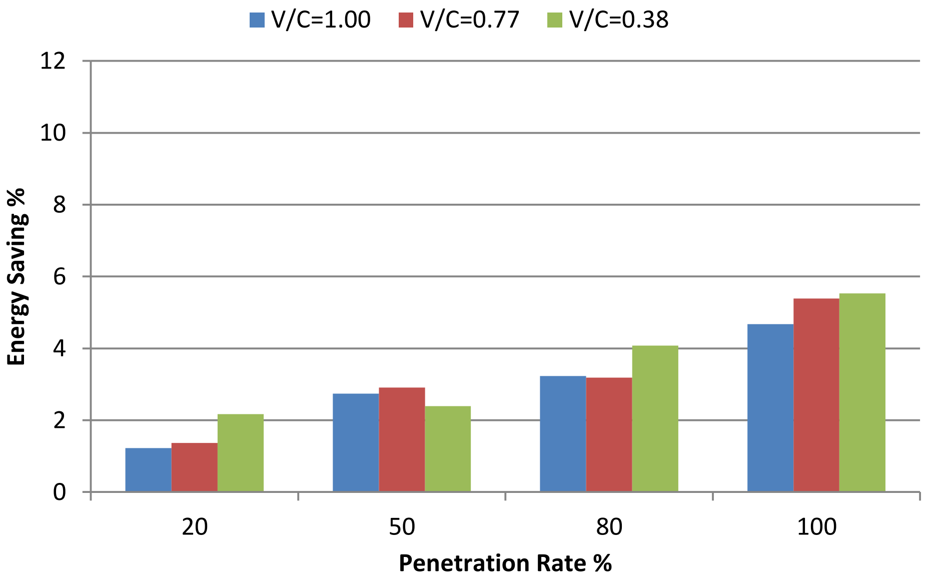
Scenario	V/C	Penetr%	Energy(kJ/mi)	CO2 (g/mi)	CO (g/mi)	HC (g/mi)	NOx (g/mi)	PM (g/mi)	TT/veh
baseline	1.00	0.00	8347.75	601.02	13.00	0.41	1.83	0.13	98.94
	0.77	0.00	8183.43	589.55	12.98	0.41	1.85	0.13	94.20
	0.38	0.00	7910.53	569.18	13.07	0.40	1.69	0.13	90.48
Eco-Approach & Departure	1.00	100.00	7957.46	574.17	11.33	0.38	1.55	0.10	105.67
	0.77	100.00	7742.33	557.89	11.83	0.38	1.41	0.10	103.58
	0.38	100.00	7473.06	537.58	10.46	0.36	1.48	0.09	97.59
saving %	1.00	100.00	4.68	4.47	12.80	7.16	15.45	20.84	-6.80
	0.77	100.00	5.39	5.37	8.87	7.10	23.48	25.70	-9.95
	0.38	100.00	5.53	5.55	19.97	10.36	12.49	25.57	-7.87

Modeling Results: Penetration Rate



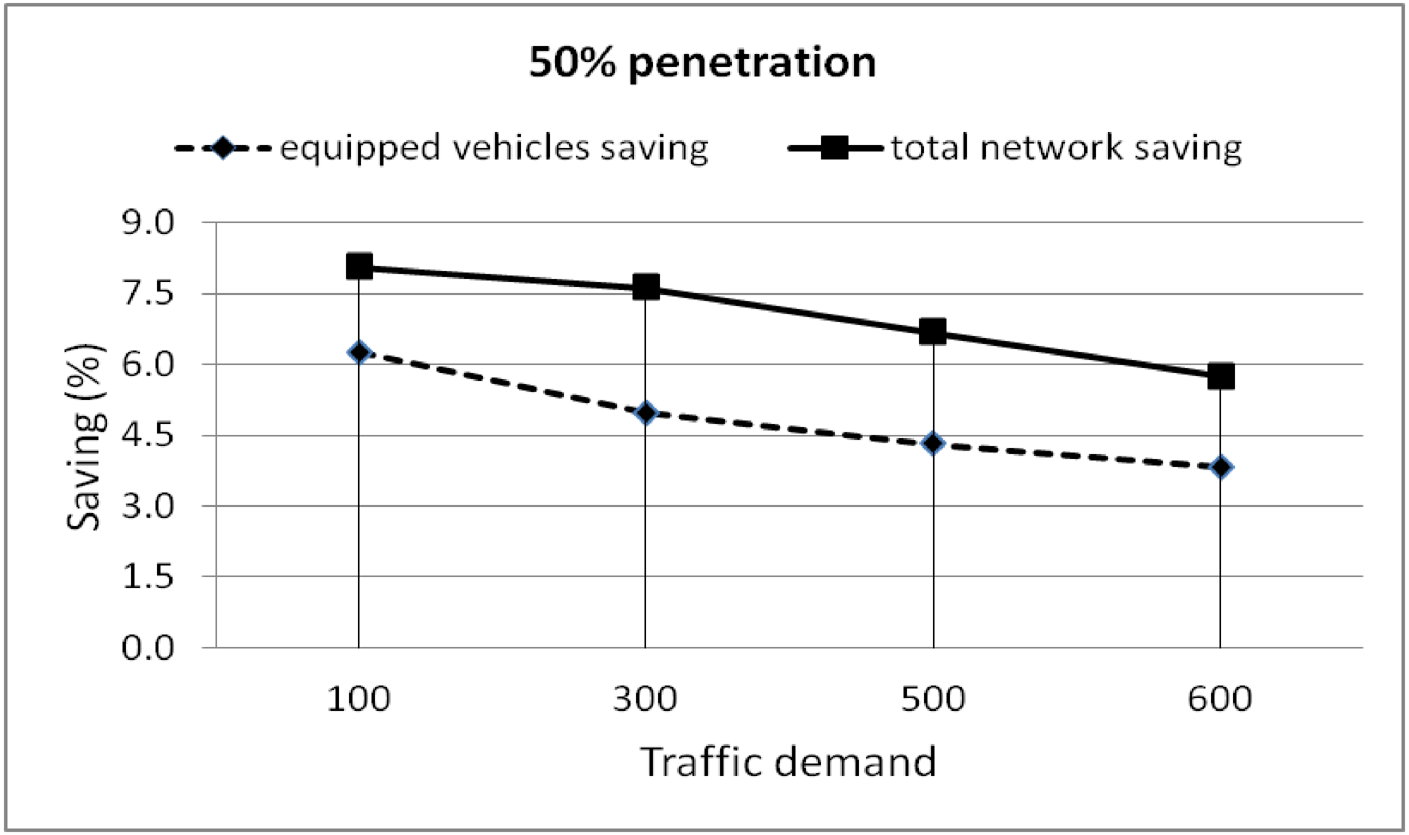
Uncoordinated Signal Control

Coordinated Signal Control



Modeling Results: Individual vs. Network Benefits

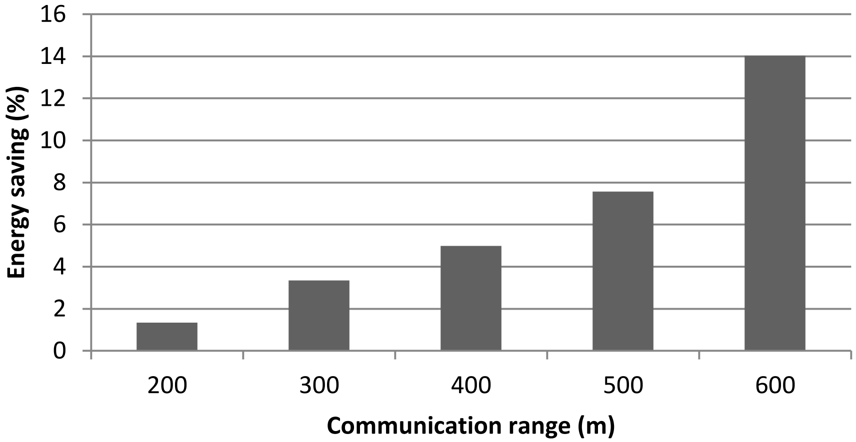
Total network savings is slightly higher than sum of equipped vehicle savings



reference:

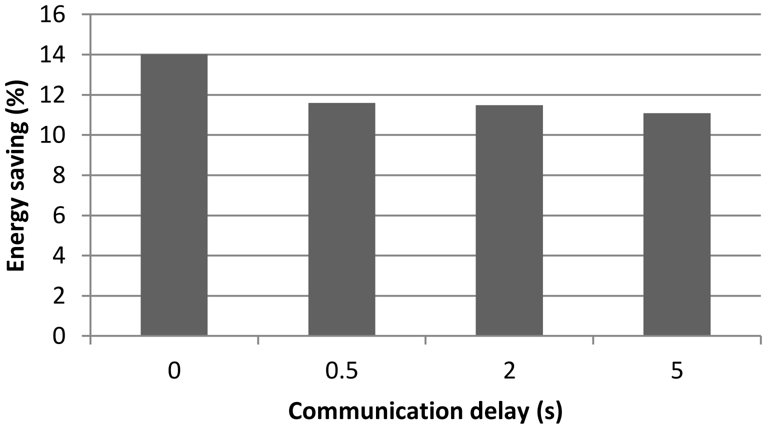
H. Xia, et al.,"Dynamic ECO-Driving for Signalized Arterial Corridors and its Indirect Network-Wide-Energy/Emissions Benefits", *Journal of ITS*, V. 17, No. 1, pp. 31-41, 2013.

Modeling Results: Communications



Communication Range Analysis

Communication Delay Analysis



Simulation Modeling Conclusions (1 of 2)

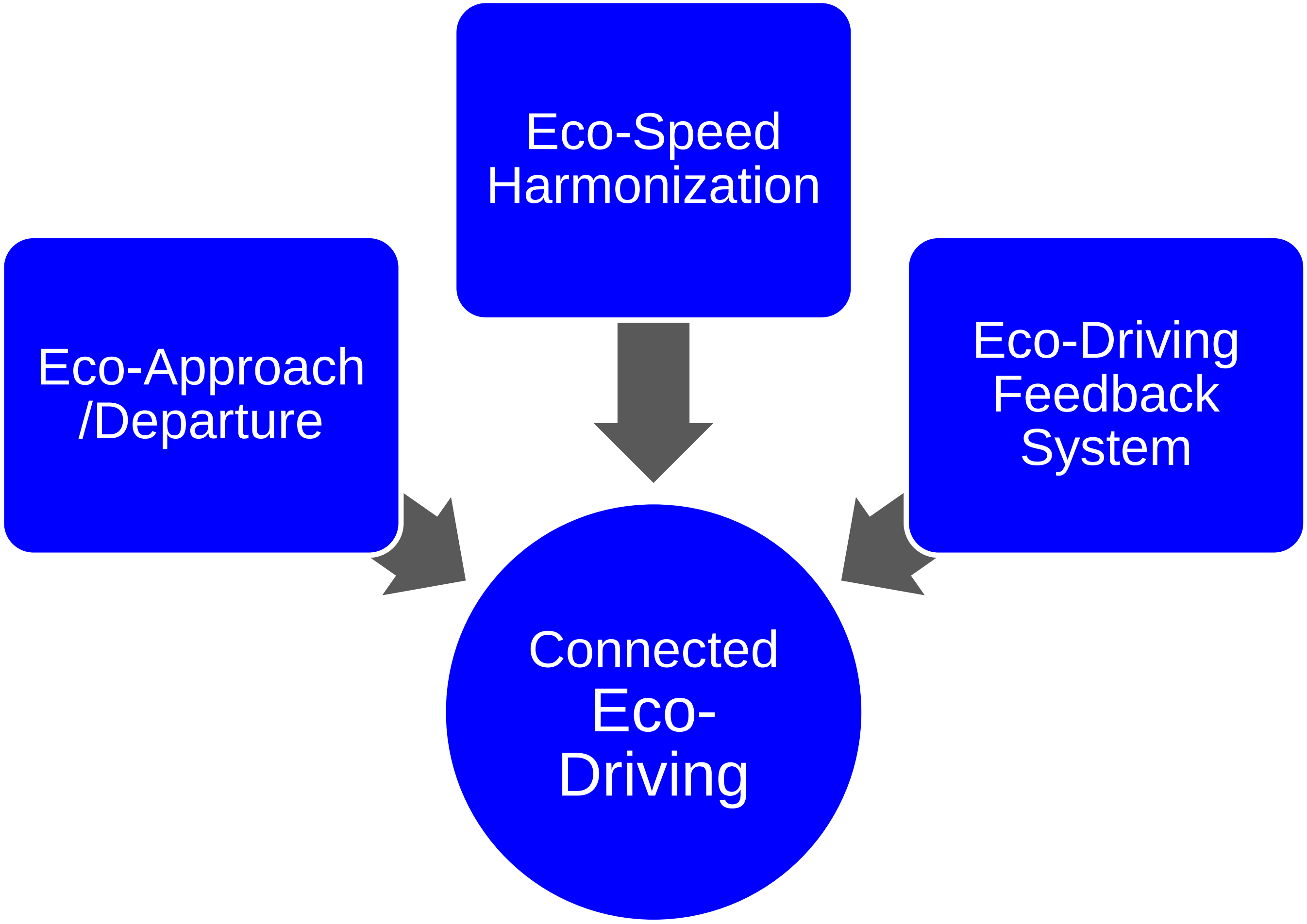
- In general, 5%- 10% fuel savings can be achieved with 100% penetration rate of technology
- Eco-approach and departure technology provides an additional 4% - 5% improvement on top of a coordinated corridor
- Coordinated signal control by itself results in approximately 8% fuel/emissions reduction over uncoordinated
- Smaller penetration rate of technology still has a positive network effect (non-equipped vehicles also have a slight benefit)
- Eco-approach and departure is less effective with increased congestion

Simulation Modeling Conclusions (2 of 2)

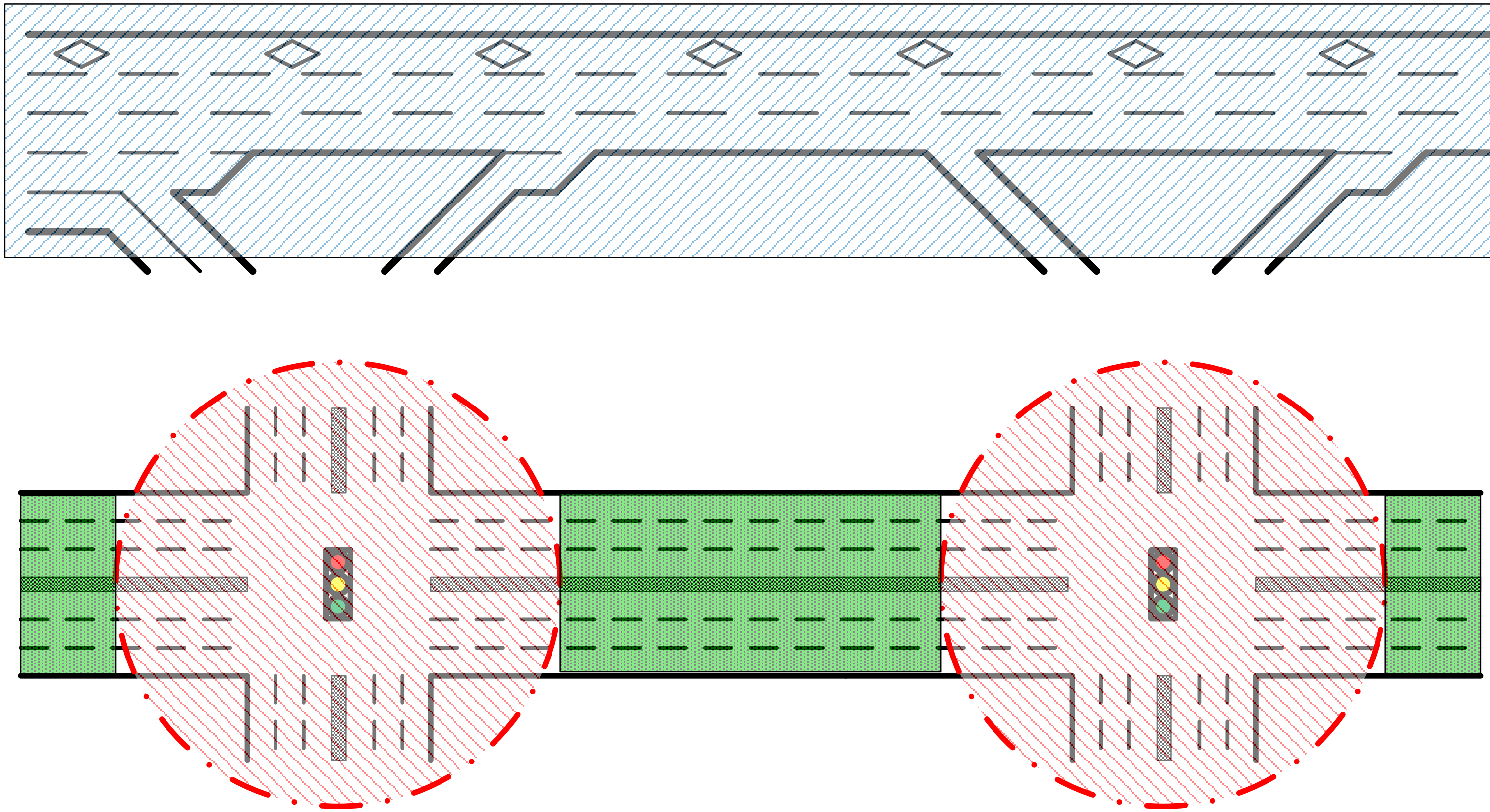
- Application benefits are sensitive to communications range (when is the information received by the vehicle)
- Application benefits are not very sensitive to communications delay
- General Eco-Approach and Departure Application could be accomplished without DSRC, instead using a cellular communications network
- Enhanced Application (with CACC, etc.) would likely require DSRC or a hybrid communication strategy

Enhanced Simulation Modeling

Inserting Eco-Approach and Departure into Connected Eco-Driving Application



Connected Eco-Driving Application



Eco-speed harmonization for freeways

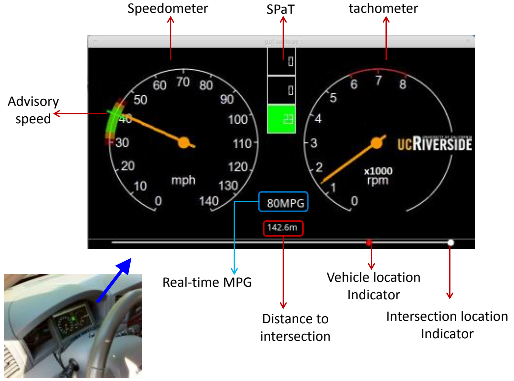
Eco-approach and departure (inside V2I communication range)

Eco-speed harmonization for arterials (outside V2I communication range)

Eco-Driving feedback for the whole network

CACC-assist and Eco-Approach and Departure

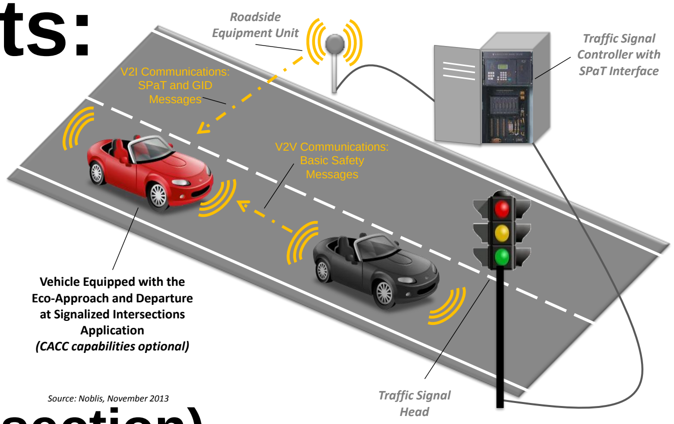
- **Note that we have been modeling vehicles in the eco-approach and departure scenarios such that the vehicles follow the speed profiles exactly as specified**
- **TFHRC demonstration: when a driver followed the "speed-advice" speedometer, it was often difficult to follow the recommended speed**



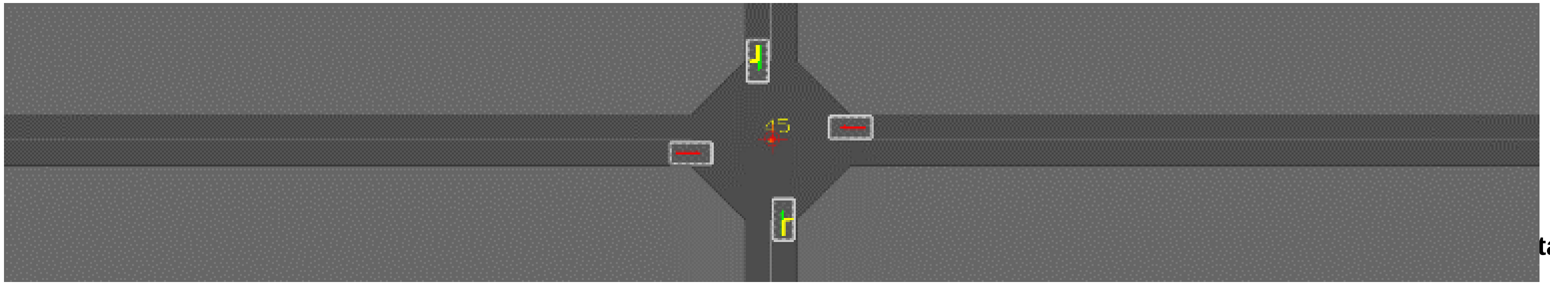
- **Results: typical drivers can't follow the planned trajectories exactly. Comparing typical driver following speed advice with exact trajectory following, following exact trajectories results in a 5% improvement in fuel savings. (2014 TRB paper)**
- **Consider having CACC-assistance when following trajectories**

Evaluating benefits of CACC-assist

- **Initial Simulation Experiments:**

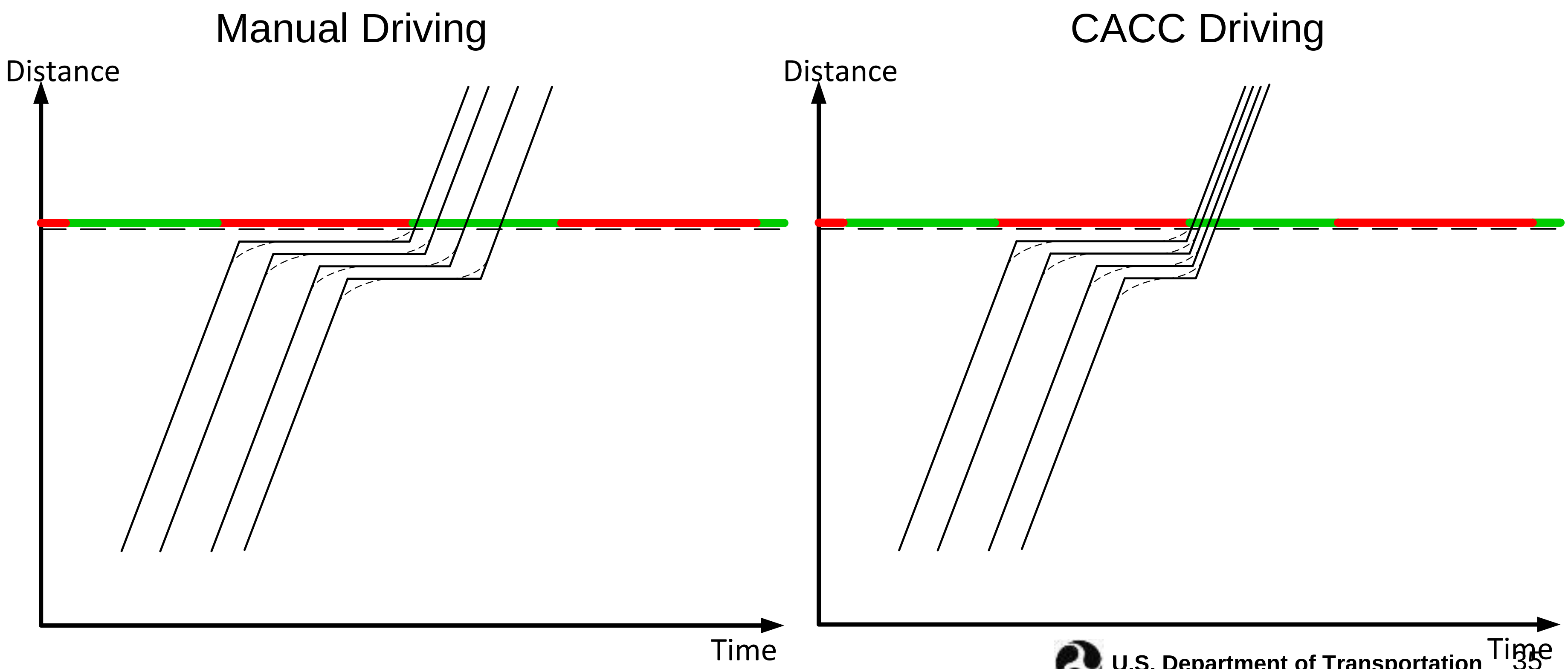


  - Isolated intersection
  - One lane in each direction
  - Link lengths 680m (before and after intersection)
  - Speed limit 40mph
  - Mainline through signal: green 30s, red 60s
  - Traffic demand: 1200 veh/lane/hour
  - Typical queues at red lights: ~10 vehicles
  - We varied reaction time and headway



CACC-Based Eco-Approach and Departure

- For isolated intersection
  - Approach: platoon-based eco-approach
  - Departure: platoon discharges with minimum headway



Results: Comparing driver HMI and CACC-assist

VMT(mi)		target headway (s)				
		0.20	0.40	0.60	0.80	1.00
reaction time(s)	0.00	0.91	0.91	0.91	0.91	0.91
	0.25	0.91	0.91	0.91	0.91	0.91
	0.50	0.91	0.91	0.91	0.91	0.91
	0.75	0.91	0.91	0.91	0.91	0.91
	1.00	0.91	0.91	0.91	0.91	0.91

VHT(s)		target headway (s)				
		0.20	0.40	0.60	0.80	1.00
reaction time(s)	0.00	106.10	106.70	107.49	108.35	109.11
	0.25	106.25	107.00	107.57	108.60	109.55
	0.50	106.87	107.76	108.81	110.29	112.34
	0.75	107.68	108.68	110.97	115.05	121.74
	1.00	108.80	110.28	114.57	125.34	180.08

fuel rate (kJ/mi)		target headway (s)				
		0.20	0.40	0.60	0.80	1.00
reaction time(s)	0.00	5182.47	5213.35	5250.33	5292.15	5303.93
	0.25	5187.43	5218.96	5256.44	5284.40	5322.03
	0.50	5201.99	5232.51	5264.80	5318.77	5388.72
	0.75	5217.89	5248.50	5316.99	5415.67	5569.58
	1.00	5240.09	5293.02	5396.92	5619.35	6630.72

CACC

21.84%

HMI

Improvements due to smoothness, less idle time, better throughput

Lessons Learned:

- **The Eco-Approach and Departure Application is very promising, showing fuel and CO_2 reductions in the range of 5% to 10%, depending on conditions**

- **The application has the potential to be a near-term deployable connected vehicle application:**
  - **low cost**
  - **doesn’t require high penetration rates**
  - **doesn’t require new communication infrastructure at every intersection**

Future Work:

- Integrate modeling of the Eco- Approach and Departure Application with other Eco-Traffic Signal Applications to determine composite benefits
- Continue to evaluate the benefits of enhancing Eco-Approach and Departure with partial automation (CACC)
- Place research results in context with other research programs, e.g., domestic and international
- Demonstrate the concept with an AERIS Prototype

Future Work: Analyzing other Dimensions

	Fixed-time Signals	Actuated Signals
Single Vehicle	*Field study 2012* *(FHWA EAR P1, AERIS)* *Simulation modeling 2012* *(AERIS)*	*Field study 2014* *(FHWA-EAR-P2 @PATH)* *Simulation modeling Fall 2013* *(FHWA-EAR-P2)*
Vehicle in Traffic	*Simulation modeling 2013* *(AERIS sensitivity analysis)*	*Field study 2014* *(FHWA-EAR-P2 ECR)* *Simulation modeling 2014* *(FHWA-EAR-P2)*

Vehicle Control:

Driver with HMI

⇩

ACC-assist

⇩

CACC-assist

Research Team

- ***University of California-Riverside:***
  - **Matthew Barth (principal investigator)**
  - **Kanok Boriboonsomsin (research faculty)**
  - **Guoyuan Wu (research faculty)**
  - **Haitao Xia (graduate student)**
- ***Booz Allen Hamilton:***
  - **Balaji Yelchuru**
  - **Sean Fitzgerel**
  - **Sudeeksha Murari**
  - ***Many others have contributed:***
  - **AERIS research team partners**

Contact Information

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AERIS Program:

- **Marcia Pincus, Program Manager, Environment (AERIS) and ITS Evaluation, US DOT RITA, marcia.pincus@dot.gov**

AERIS

Upcoming AERIS Webinars

Webinar #2: Incorporation of Stakeholder Input Into the AERIS Program

Wednesday, December 4th, 2013 at 1:00 pm ET

Webinar #3: Preliminary Eco-Traffic Signal Timing Modeling Results

Wednesday, January 29th, 2013 at 1:00 pm ET

Webinar #4: Preliminary Eco-Traffic Signal Priority (for Transit and Freight) and Connected Eco-Driving Modeling Results

Wednesday, February 12th, 2014 at 1:00 pm ET

Webinar #5: A Comparison of US and EU Connected Vehicle Environmental Research Activities

Wednesday, March 12th, 2014 at 1:00 pm ET

Registration

Persons planning to participate in the webinar should register online at www.itsa.org/aerisfall2013