Utilizing MOVES for Evaluating Shared, Electric, Connected, and Automated Vehicles

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TRANSPORTATION IS UNDERGOING FOUR MAJOR REVOLUTIONS

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
- Drivers: advances in motors, controls, and batteries

Connectivity:

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

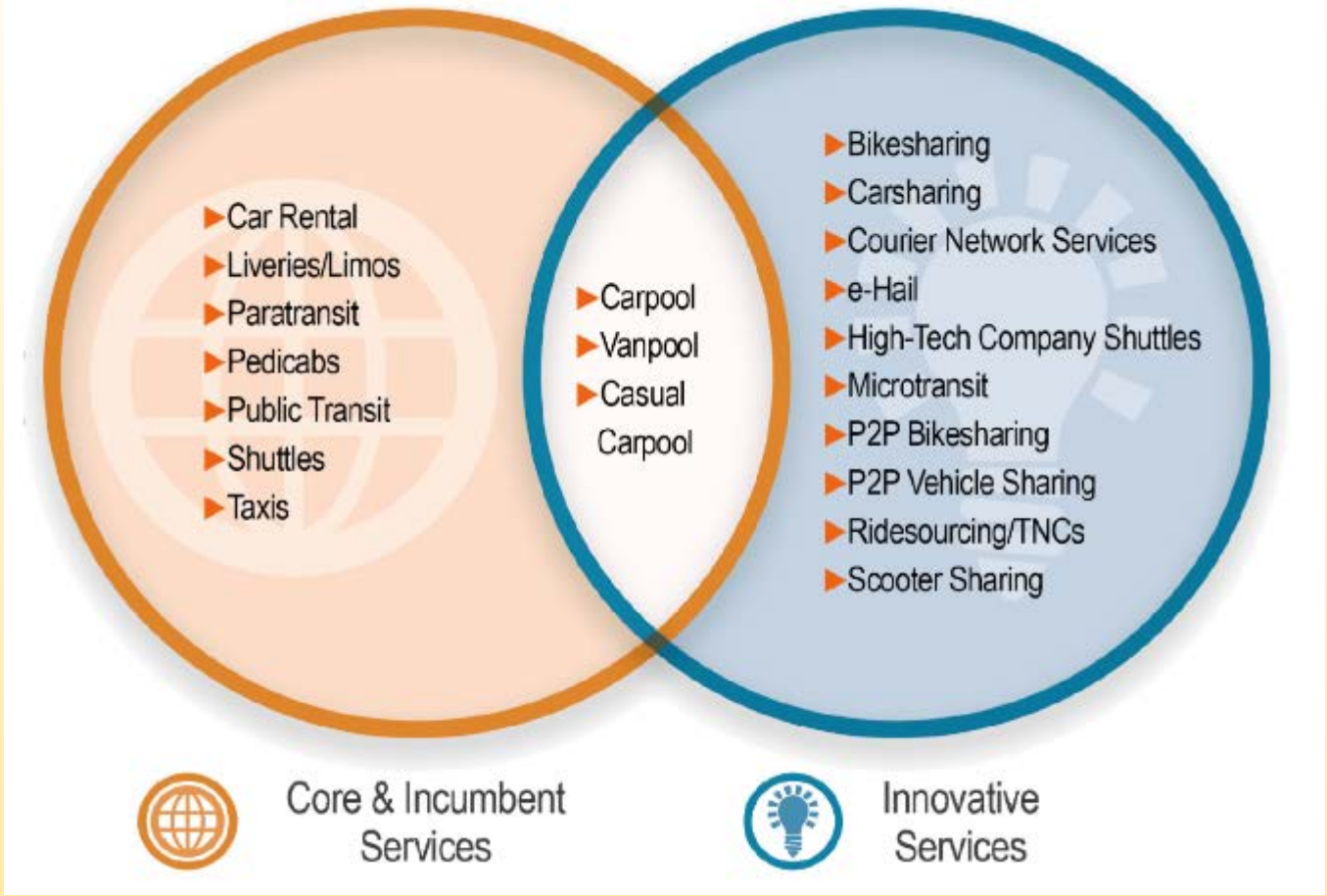
Automation:

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

THE NEED FOR SHARED ELECTRIC CONNECTED AUTOMATED VEHICLE RESEARCH

Shared Mobility:

- There are many forms of Shared Mobility
- Shared mobility can greatly improve land use and be used as a tool to manage excessive travel demand
- Shared trips tend to be more efficient, reducing energy use and producing less emissions



Shared Mobility Eco-System
(from Susan Shaheen, UC Berkeley)

UC Riverside's IntelliShare campus carsharing system

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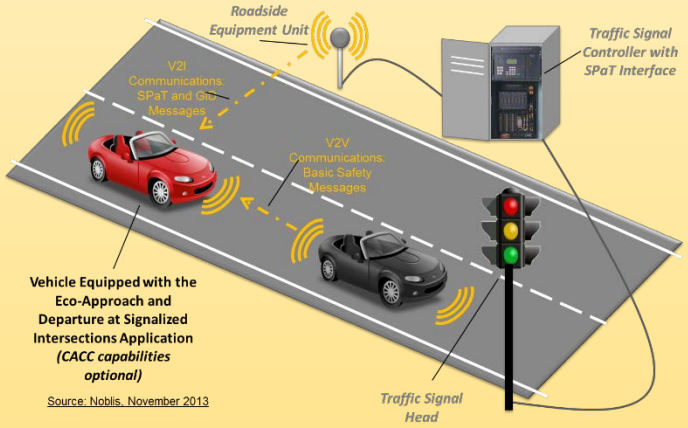
Electrification:

- Electric-drive vehicles have tremendous energy and air quality benefits
- Several traditional OEM companies entering electric-drive arena across modes
- Range and charge-time constraints can be managed when made part of a shared mobility option
- Vehicle Electrification must also consider infrastructure (necessity of microgrids)
- Need to consider in-direct emission sources

THE NEED FOR SHARED ELECTRIC CONNECTED AUTOMATED VEHICLE RESEARCH

Connectivity:

- Many forms of vehicle connectivity exist: cellular, short range radios, 5G
- Connectivity includes V2V, V2I, V2X
- Connectivity in vehicles is being mandated for safety reasons; there are many secondary benefits for mobility and energy
- Enables many more applications



THE NEED FOR SHARED ELECTRIC CONNECTED AUTOMATED VEHICLE RESEARCH

Automation:

- Automated and autonomous vehicles
- Level of automation:
  - Level 0: 100% human control
  - Level 1: Individual module is automated
  - Level 2: 2+ modules are automated in unison
  - Level 3: Conditional automation
  - Level 4: 100% automation
- Personalized automated vehicles can lead to a significant increase in traffic, worse air quality, and wasted fuel
- When matched with shared mobility and electric drive, automation benefits can fully be realized

THE NEED FOR SHARED ELECTRIC CONNECTED AUTOMATED VEHICLE RESEARCH

	Safety	Mobility	Vehicle Kilometers Traveled	Environmental Quality
Shared Mobility	↑	solo-passengers → multi-passengers ↑	solo-passengers → multi-passengers ↓	↑
Electrification	→	↓	↓	↑
Connectivity	↑	↑	→	↑
Automation	↑	autonomous → automated ↑	↑	↓ ↑

Potential Impacts if deployed separately,
Compared to Current Personalized Car Travel

THE NEED FOR SHARED ELECTRIC CONNECTED AUTOMATED VEHICLE RESEARCH

	Safety	Mobility	Vehicle Kilometers Traveled	Environmental Quality
Shared Mobility				
Electrification				

Potential Impacts of Shared and Electric

THE NEED FOR SHARED ELECTRIC CONNECTED AUTOMATED VEHICLE RESEARCH

	Safety	Mobility	Vehicle Kilometers Traveled	Environmental Quality
Shared Mobility				
Connectivity				
Automation				

Potential Impacts of Shared and Connected/Automated

THE NEED FOR SHARED ELECTRIC CONNECTED AUTOMATED VEHICLE RESEARCH

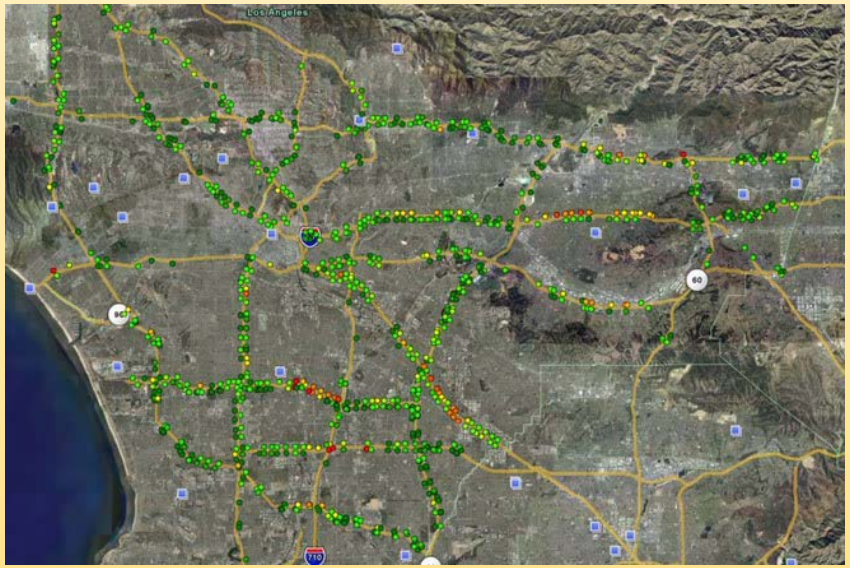
	Safety	Mobility	Vehicle Kilometers Traveled	Environmental Quality
Shared Mobility				
Electrification				
Connectivity				
Automation				

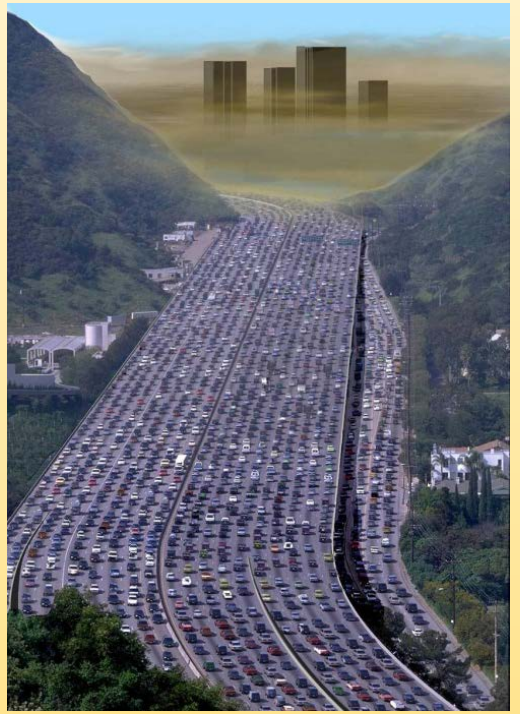
Potential Impacts of Coordinated Deployment

General Components of a Transportation-based Emissions/Energy Inventory:

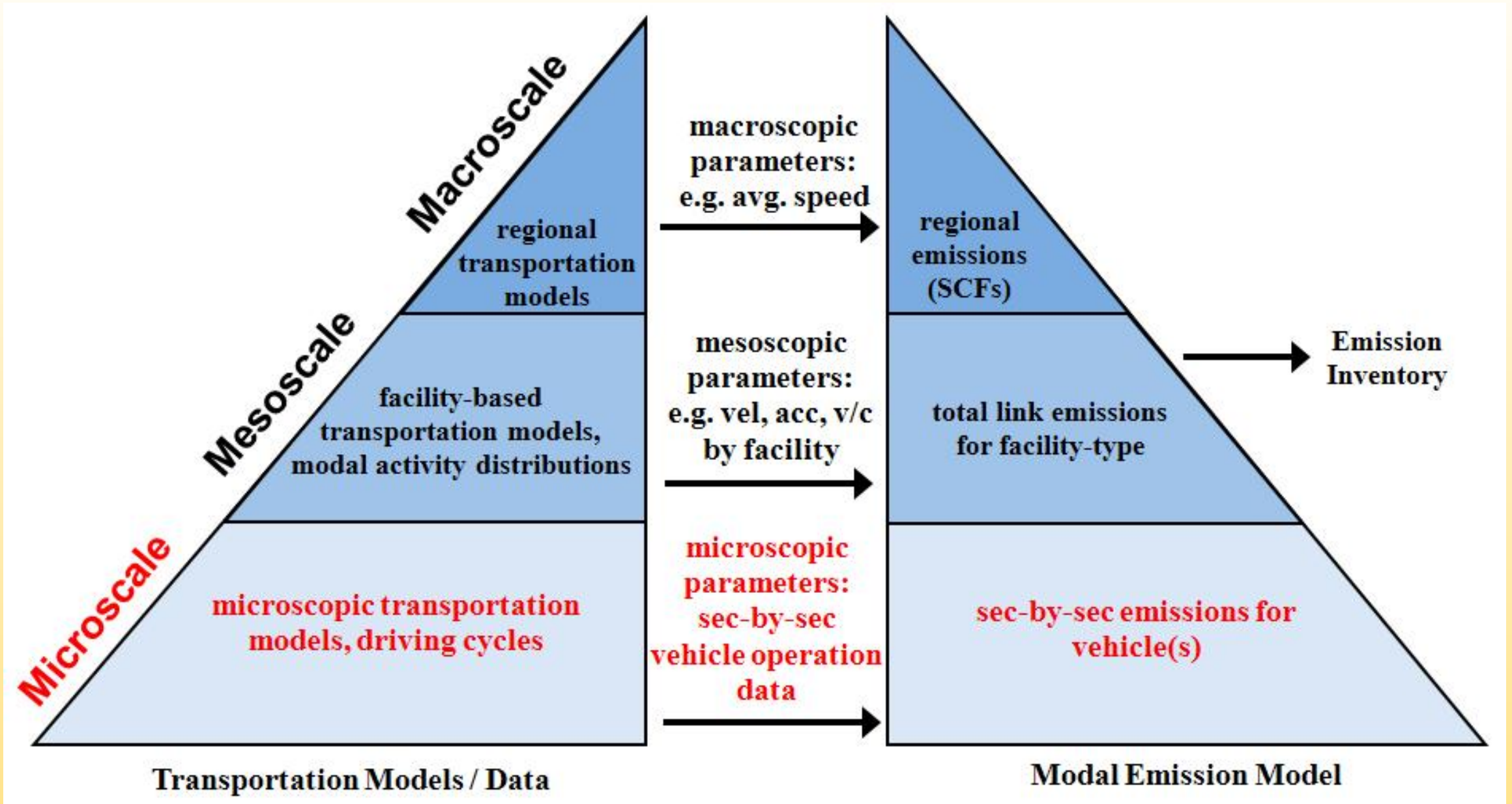
- *emissions/energy factors*
- *vehicle activity*
- *fleet composition*

environmental inventory





Transportation/Emissions Modeling Framework

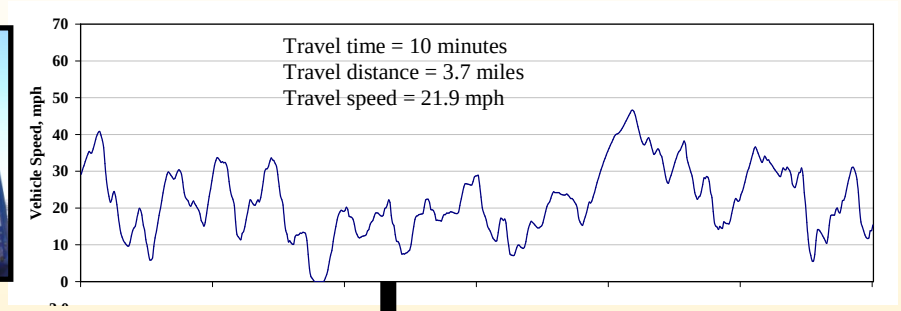


Alternative Vehicle Emission Modeling Approaches

Array of new modeling techniques developed since the late 1990's:

- **Fuel-Based Emission Inventories**
  - **normalizes vehicle emissions to fuel consumption, not VMT**
  - **requires estimates of fuel use, e.g., from fuel tax**
  - **generates reasonable emission inventories for large databases**
- **Modal and instantaneous vehicle emission models:**
  - **concerned with estimating emissions as a function of vehicle operating mode, (e.g., idle, acceleration, cruise, deceleration)**
  - **predicts emissions second-by-second**
- **Integrated Transportation and Emission Models:**
  - **microscale and mesoscale**

Microscale Emission Modeling



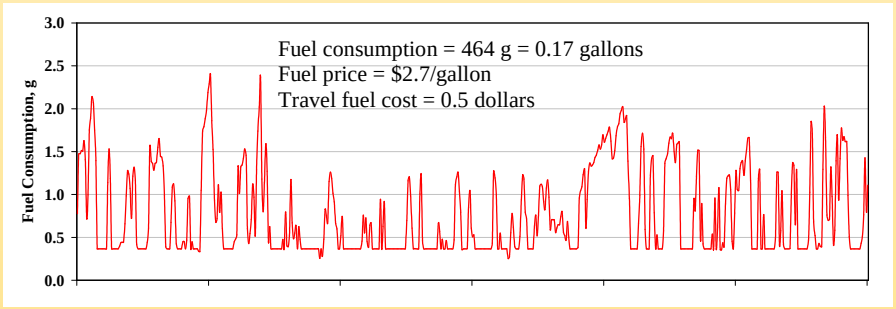
vehicle activity (velocity trajectory and grade if available)

or:

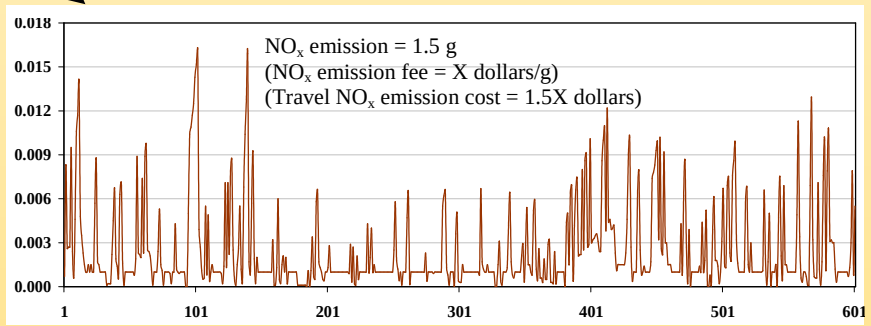
traffic simulation

Emissions Modeling

vehicle calibration parameters and emissions factors



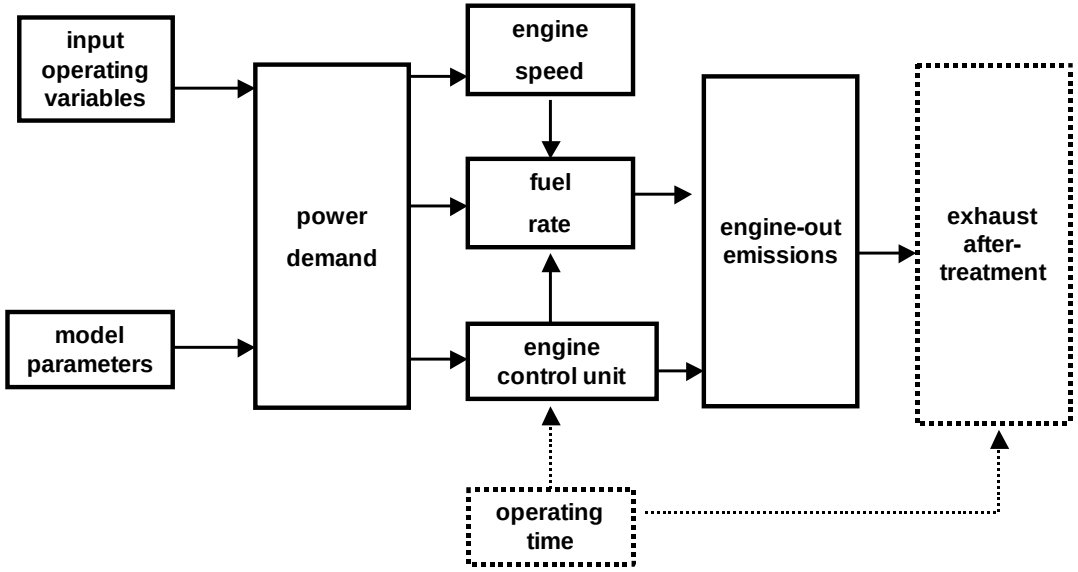
fuel consumption



emissions

Comprehensive Modal Emissions Model (CMEM):

- predicts second-by-second emissions and fuel consumption given arbitrary vehicle activity (speed, grade)
- 28 vehicle/technology categories including light- and heavy-duty vehicles
- can be used with measured vehicle activity data or easily integrated with transportation simulation models
- Also has short term “history effects” built in to the model



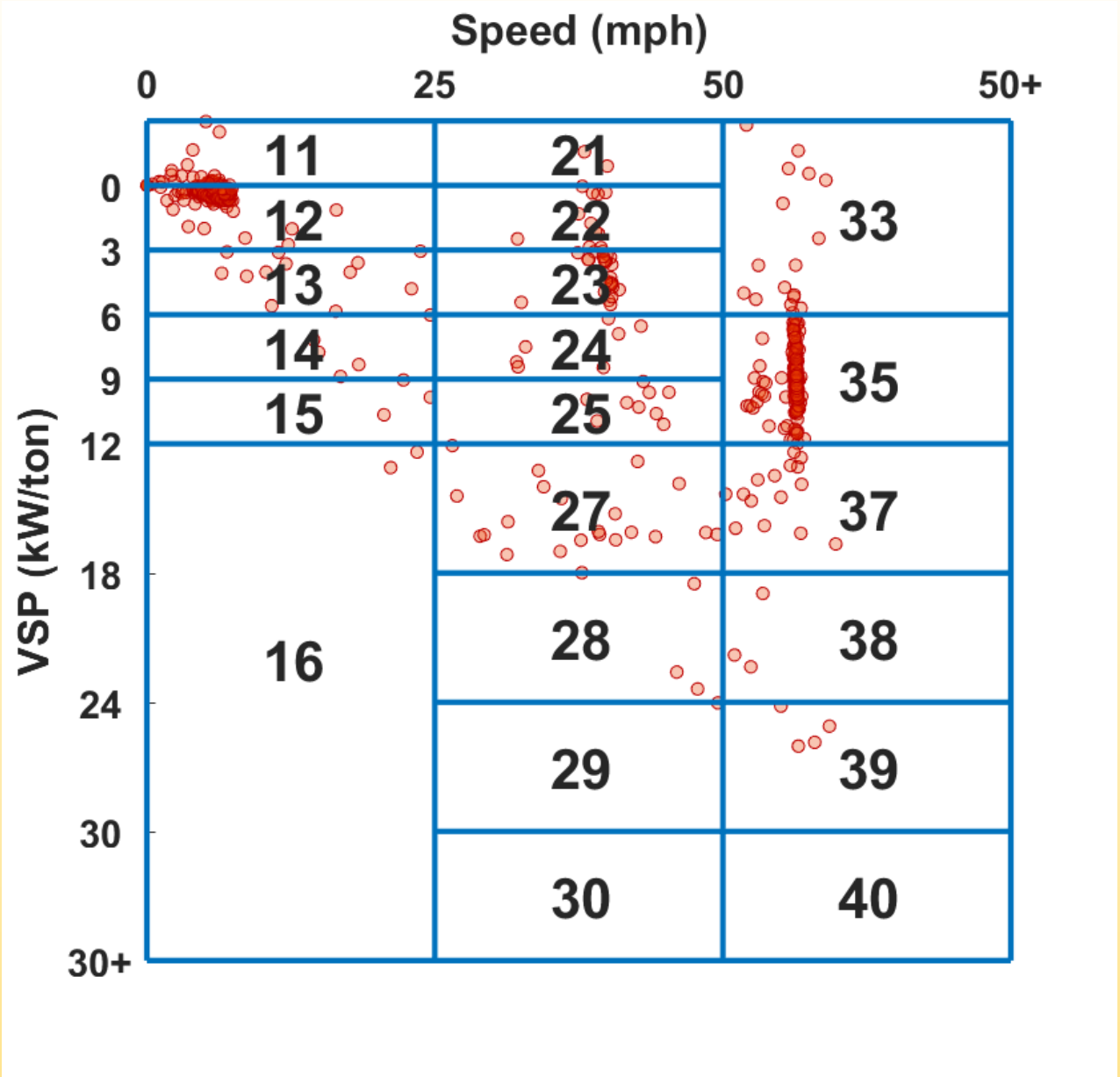
$$tailpipe\,emissions = FR \bullet \left(\frac{g_{emissions}}{g_{fuel}} \right) \bullet after\,treatment\,pass\,fraction$$

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
50	LEV PC
51	ULEV PC
52	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)
41	Pre 1991, 2-stroke HDDT
42	Pre 1991, 4-stroke HDDT
43	1991 to 1993, 4-stroke, Mech. FI HDDT
44	1991 to 1993, 4-stroke, Elect. FI HDDT
45	1994 to 1997, 4-stroke, Elect. FI HDDT
46	1998, 4-stroke, Elect. FI HDDT
47	1999 to 2002, 4-stroke, Elect. FI HDDT
	High Emitting Light Duty Vehicles
19	Runs lean
20	Runs rich
21	Misfire
22	Bad catalyst
23	Runs very rich

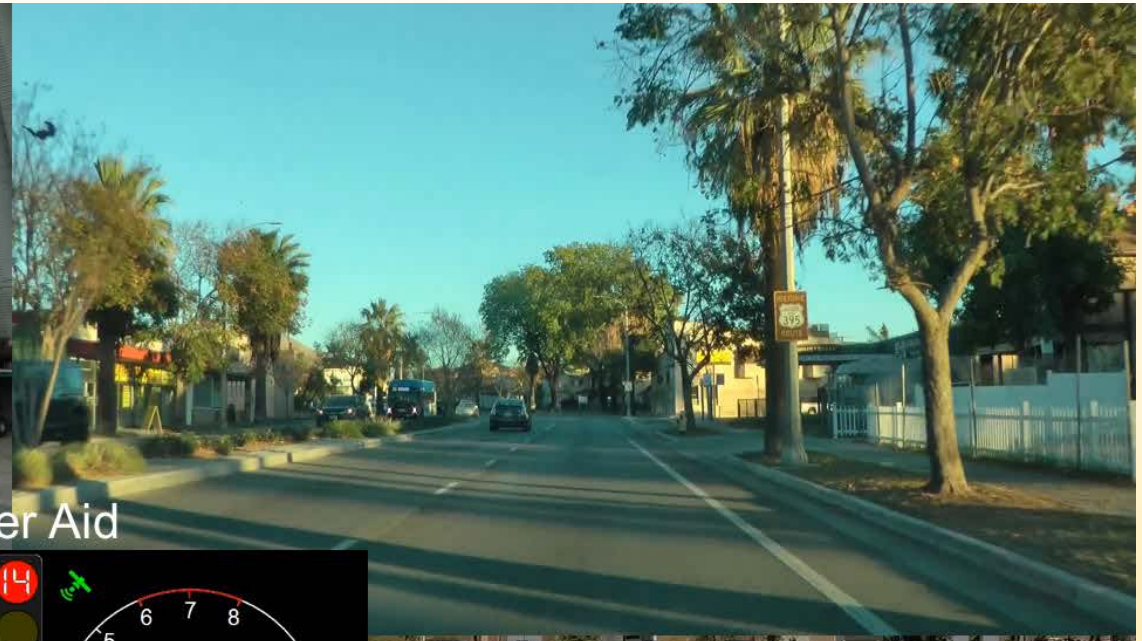
http://www.cert.ucr.edu/cmem

US EPA MOVES Model using an OpMode binning approach

- Bins are based on two dimensions: VSP and speed



Sources of Activity Data: Traffic Simulation, On-Road

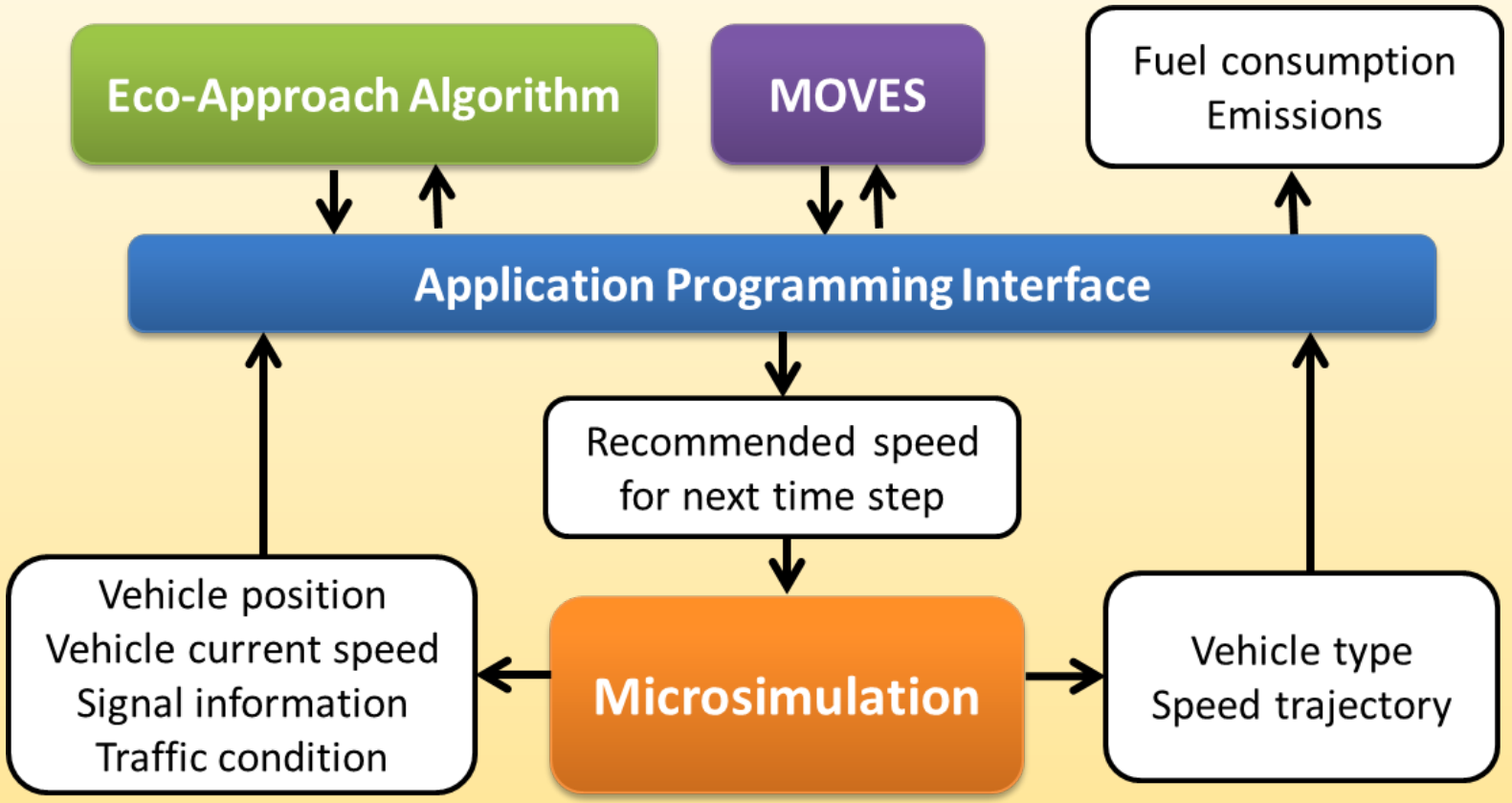


Driver Aid

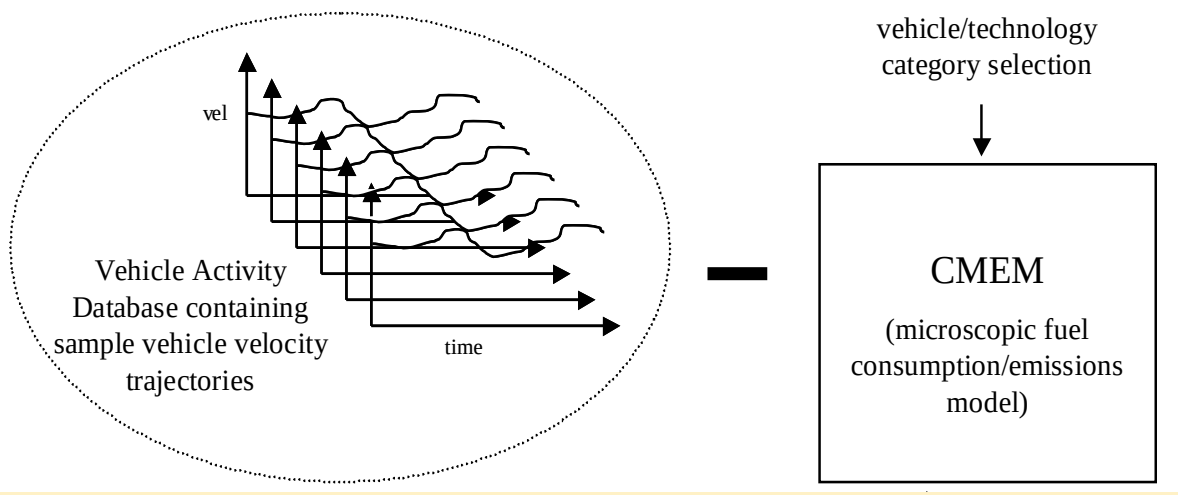
Dyno-In-The-Loop

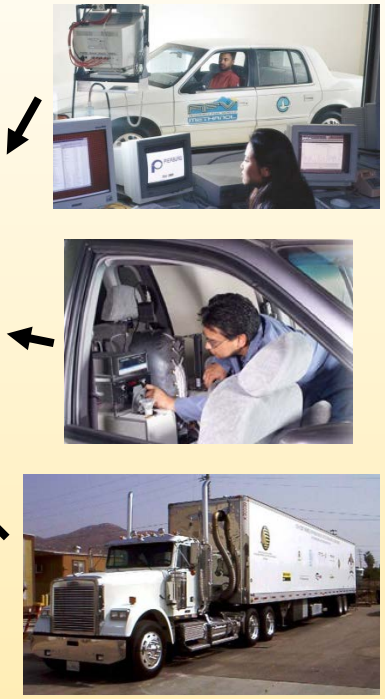
Driver's Perspective

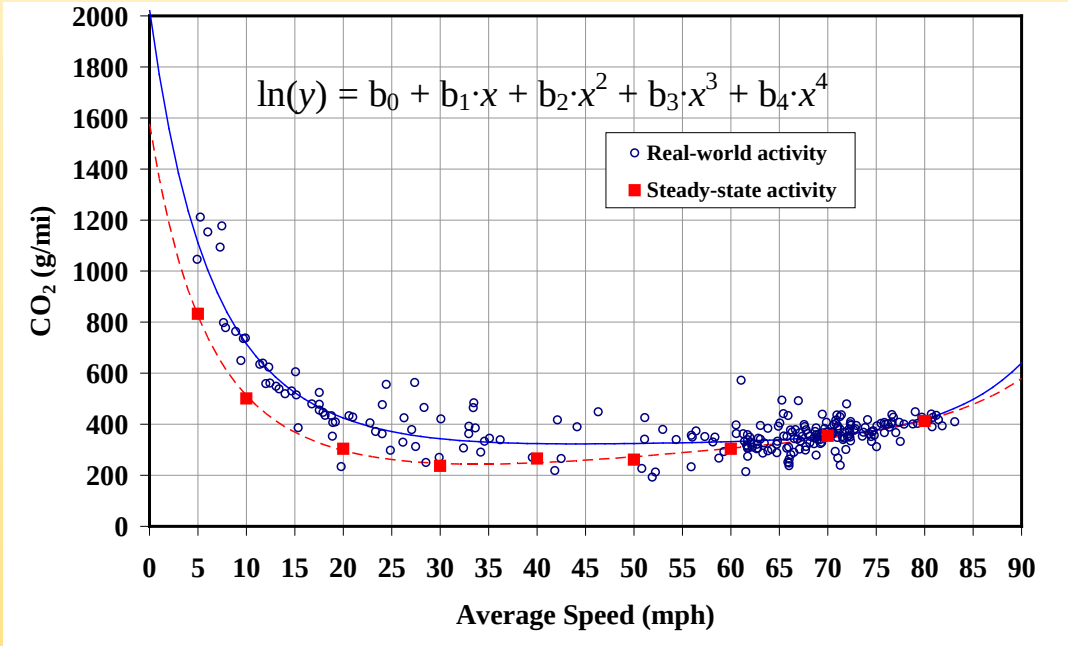
Energy and Emissions Modeling Architecture using Traffic Microsimulation



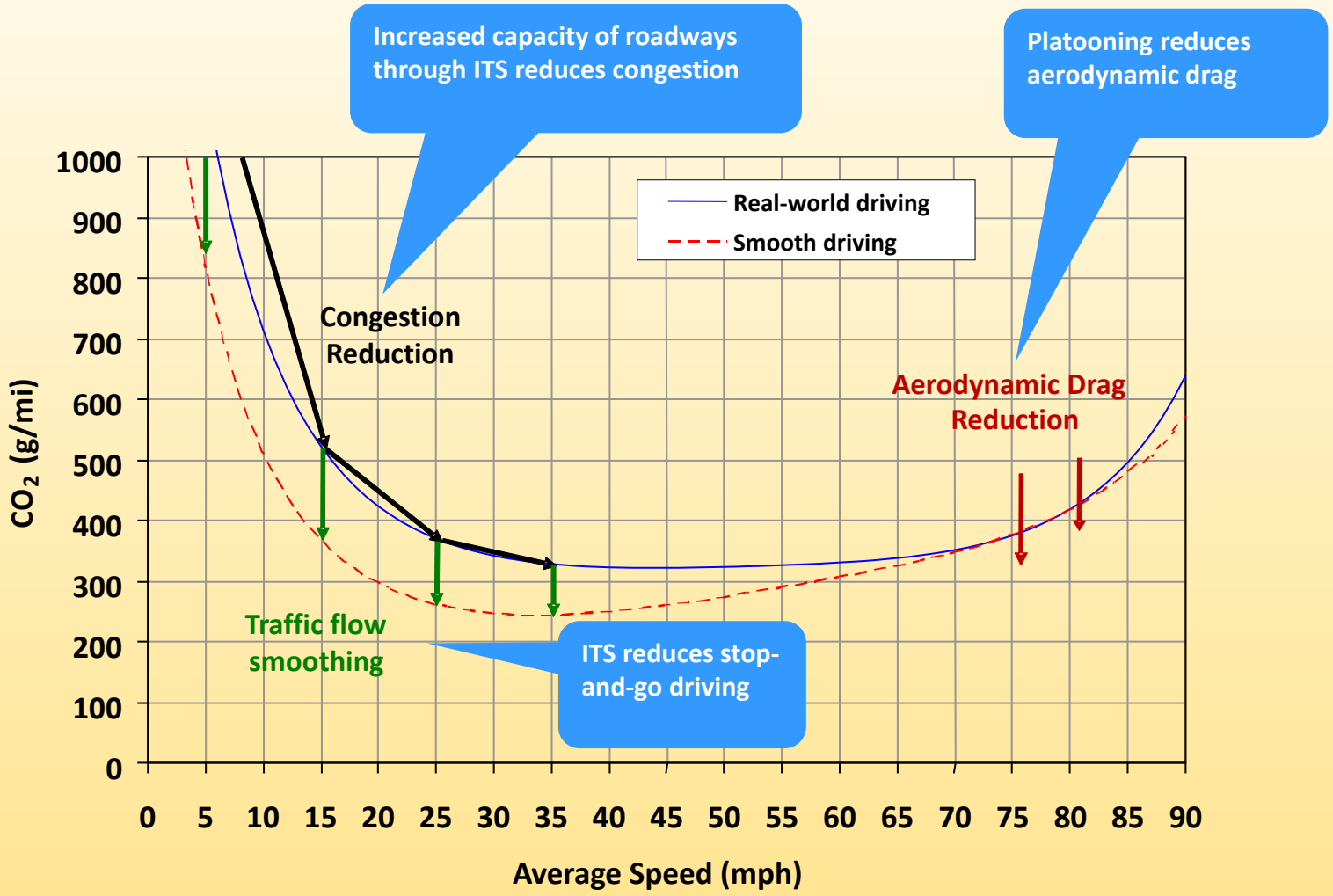
Mesoscopic Model: Emissions as a Function of Average *Traffic* Speed







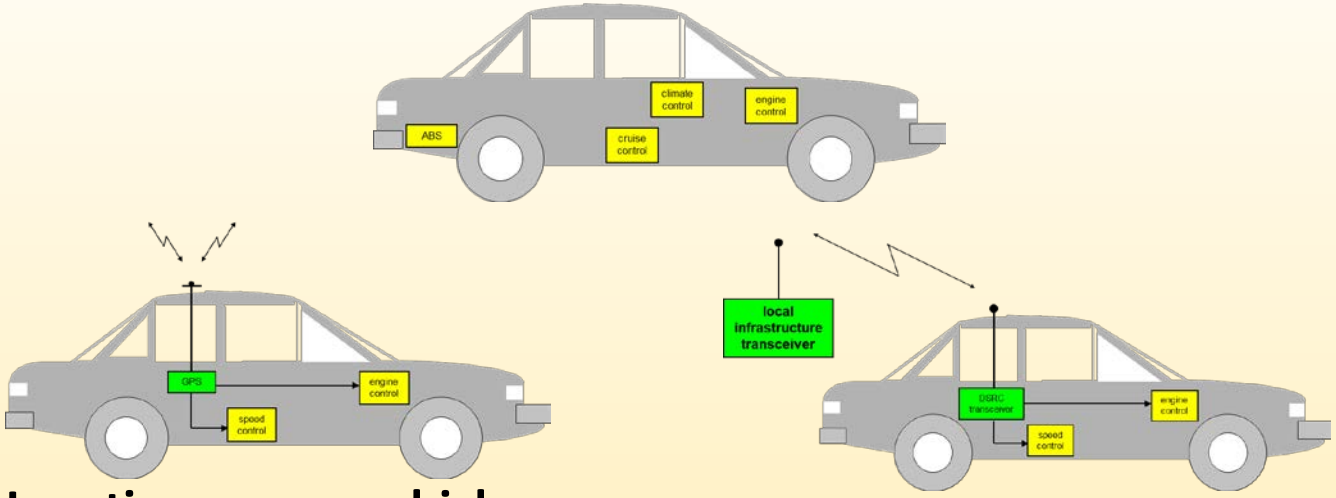
Three regimes on how Intelligent Transportation Systems (shared, connected, automated vehicles) can reduce on-road energy and emissions



Source: Barth, M. and Boriboonsomsin, K. (2008). Real-world carbon dioxide impacts of traffic congestion. *Transportation Research Record*, 2058, 163-171.

Modeling Energy and Emissions from Shared Electric Connected and Automated Vehicles

Location-Aware and Connected Vehicles

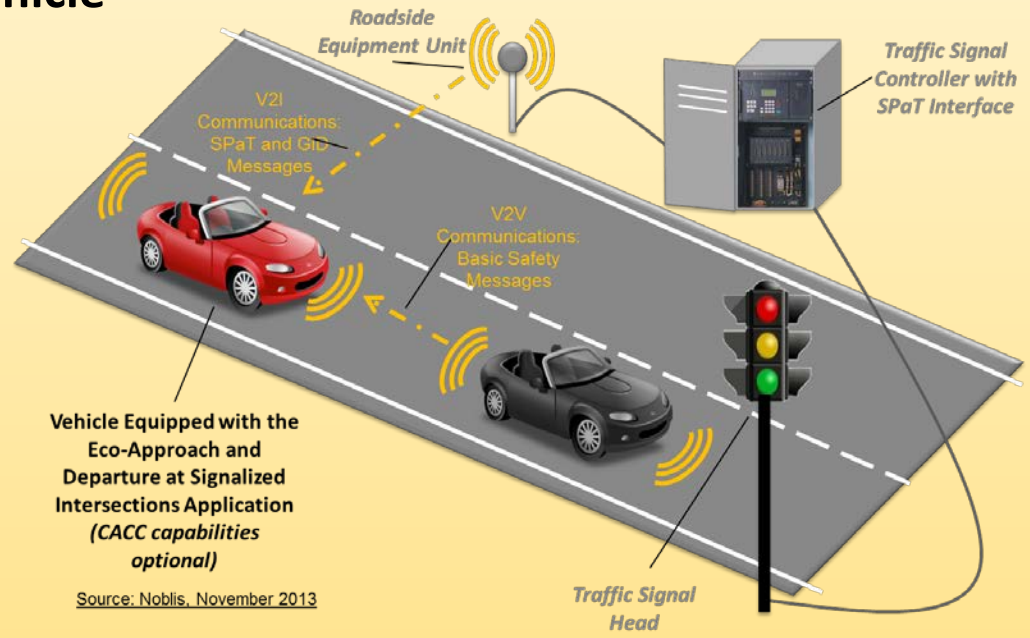


Location-aware vehicle

Connected vehicle

Platooning

Connected Environment



USDOT's Connected Vehicle Program

CV Technology Pilot Programs

- Safety: Connected vehicle safety pilot
- Mobility: Dynamic mobility applications (DMA)
- Environment: Applications for the environment – real-time information synthesis (AERIS)
- Road Weather: Road Weather Connected Vehicle Applications

SAFETYPILOT

CV Pilot Deployment Program (Wave 1)

- I-80 in Wyoming (truck safety and efficiency)
- New York City (vehicle and pedestrian)
- Tampa, Florida (traffic around reversible freeway lanes)

US DOT Research Data Exchange (RDE)

http://www.its-rde.net/

Connected Vehicle Applications:

V2I Safety

- Red Light Violation Warning
- Curve Speed Warning
- Stop Sign Gap Assist
- Spot Weather Impact Warning
- Reduced Speed/Work Zone Warning
- Pedestrian in Signalized Crosswalk Warning (Transit)

V2V Safety

- Emergency Electronic Brake Lights (EEBL)
- Forward Collision Warning (FCW)
- Intersection Movement Assist (IMA)
- Left Turn Assist (LTA)
- Blind Spot/Lane Change Warning (BSW/LCW)
- Do Not Pass Warning (DNPW)
- Vehicle Turning Right in Front of Bus Warning (Transit)

Agency Data

- Probe-based Pavement Maintenance
- Probe-enabled Traffic Monitoring
- Vehicle Classification-based Traffic Studies
- CV-enabled Turning Movement & Intersection Analysis
- CV-enabled Origin-Destination Studies
- Work Zone Traveler Information

Environment

- Eco-Approach and Departure at Signalized Intersections
- Eco-Traffic Signal Timing
- Eco-Traffic Signal Priority
- Connected Eco-Driving
- Wireless Inductive/Resonance Charging
- Eco-Lanes Management
- Eco-Speed Harmonization
- Eco-Cooperative Adaptive Cruise Control
- Eco-Traveler Information
- Eco-Ramp Metering
- Low Emissions Zone Management
- AFV Charging / Fueling Information
- Eco-Smart Parking
- Dynamic Eco-Routing (light vehicle, transit, freight)
- Eco-ICM Decision Support System

Road Weather

- Motorist Advisories and Warnings (MAW)
- Enhanced MDSS
- Vehicle Data Translator (VDT)
- Weather Response Traffic Information (WxTINFO)

Mobility

- Advanced Traveler Information System
- Intelligent Traffic Signal System (I-SIG)
- Signal Priority (transit, freight)
- Mobile Accessible Pedestrian Signal System (PED-SIG)
- Emergency Vehicle Preemption (PREEMPT)
- Dynamic Speed Harmonization (SPD-HARM)
- Queue Warning (Q-WARN)
- Cooperative Adaptive Cruise Control (CACC)
- Incident Scene Pre-Arrival Staging Guidance for Emergency Responders (RESP-STG)
- Incident Scene Work Zone Alerts for Drivers and Workers (INC-ZONE)
- Emergency Communications and Evacuation (EVAC)
- Connection Protection (T-CONNECT)
- Dynamic Transit Operations (T-DISP)
- Dynamic Ridesharing (D-RIDE)
- Freight-Specific Dynamic Travel Planning and Performance
- Drayage Optimization

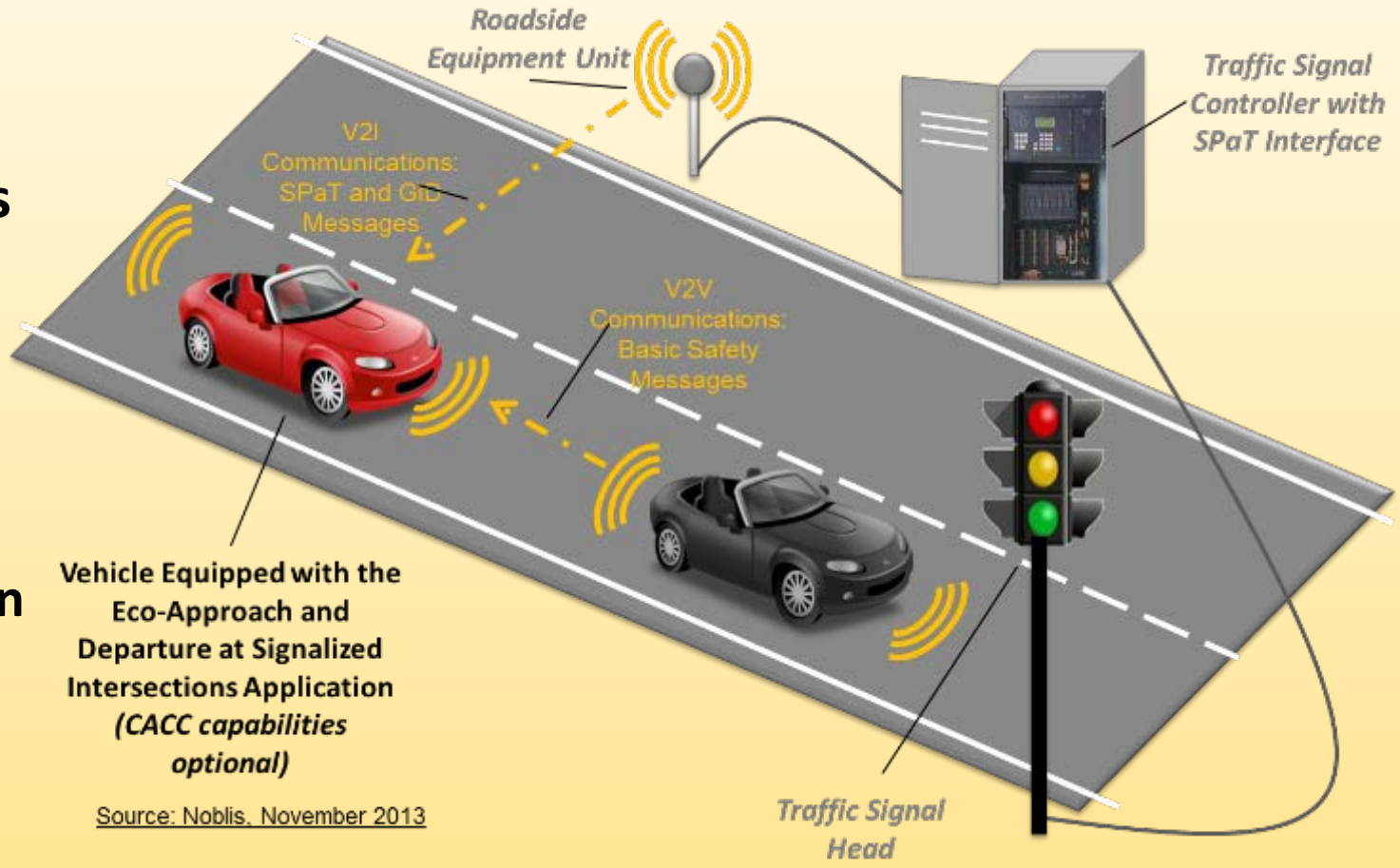
Smart Roadside

- Wireless Inspection
- Smart Truck Parking

UC RIVERSIDE CE-CERT RESEARCH

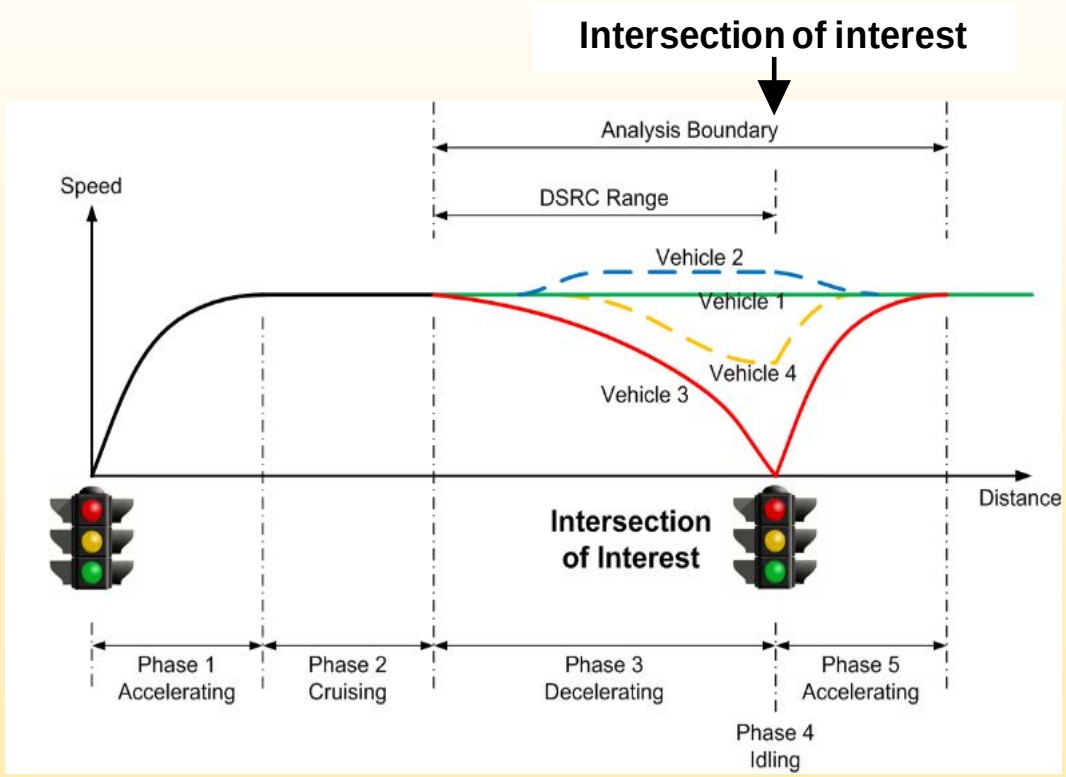
Connected: Environmentally-Friendly Intelligent Transportation Systems

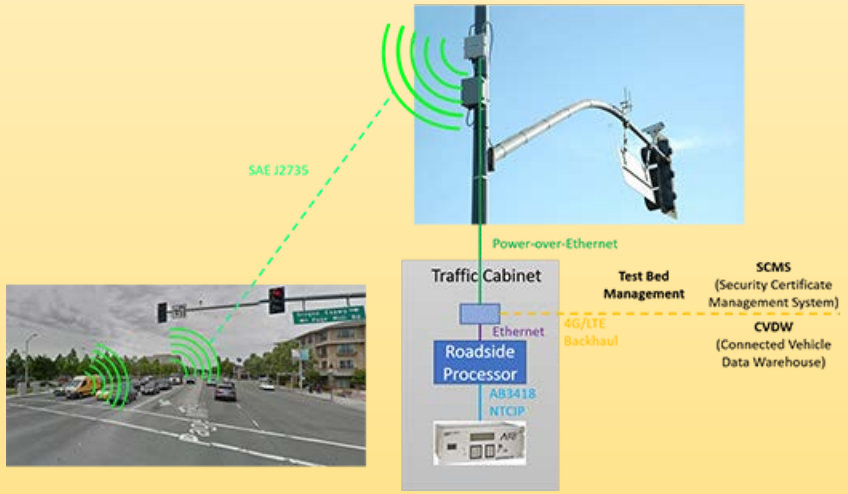
- Application utilizes traffic signal phase and timing (SPaT) data to provide driver recommendations that encourage "green" approaches to signalized intersections
- Example scenarios:
  - Coast down earlier to a red light;
  - Modestly speed up to make it (safely) through the intersection on green
-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



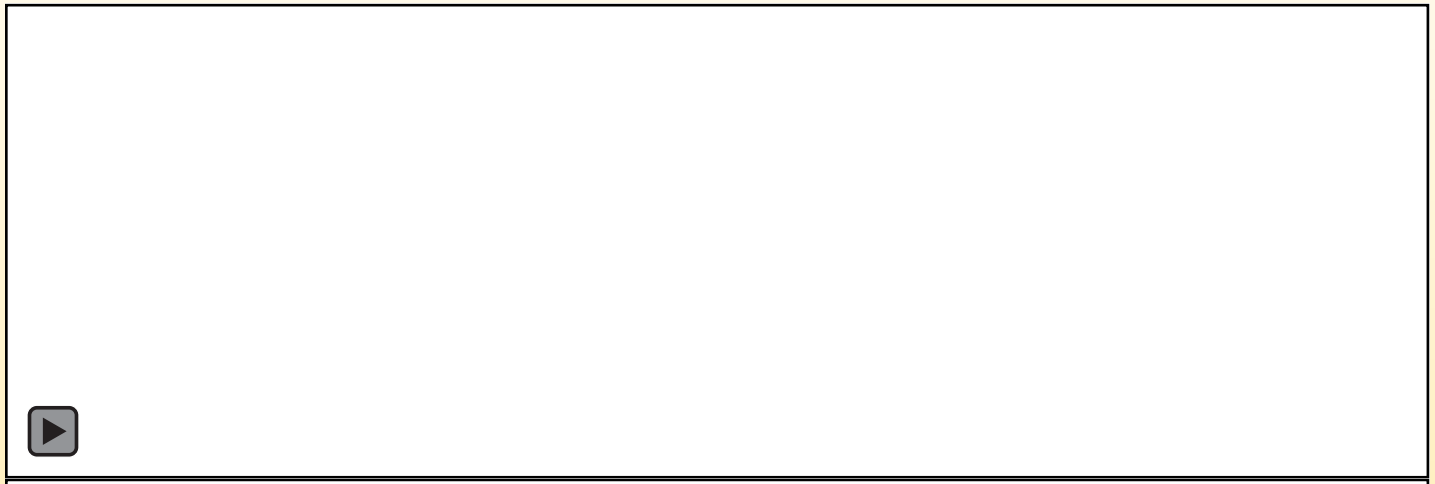
Source: Noblis, November 2013

Signalized Intersections: Eco-Approach and Departure





Simulation Modeling…



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

- **Summary of Modeling Results**
  - **10-15%** fuel reduction benefit for an equipped vehicle;
  - **5-10%** fuel reduction benefits for traffic along an uncoordinated corridor
  - Up to 13% fuel reduction benefits for a coordinated corridor
    - 8% of the benefit is attributable to signal coordination
    - 5% attributable to the application
- **Key Findings and Takeaways**
  - The application is less effective with increased congestion
  - Close spacing of intersections resulted in spillback at intersections. As a result, fuel reduction benefits were decreased somewhat dramatically
  - Preliminary analysis indicates significant improvements with partial automation
  - Results showed that non-equipped vehicles also receive a benefit – a vehicle can only travel as fast as the car in front of it
- **Opportunities for Additional Research**
  - Evaluate the benefits of enhancing the application with partial automation:

→ **GlidePath**

FHWA GlidePath Prototype Application

GlidePath Results:

Table 1. Fuel consumption (g/mi) for different entry time (speed limit is 35 mph)

Phase	Green						Red					
Time in Phase (s)	2	7	12	17	22	27	2	7	12	17	22	27
Uninformed (U)	57.61	60.69	142.68	136.31	127.44	135.84	126.48	114.85	54.60	70.50	64.26	69.51
DVI (D)	64.41	67.82	131.86	129.22	117.80	119.48	94.77	71.43	64.62	55.19	64.61	60.11
Automatic (A)	54.92	56.11	92.39	107.76	101.59	92.77	85.19	59.83	56.76	51.83	51.38	53.60

Scenario 1 Scenario 2 Scenario 3 Scenario 4

Table 2. Relative savings in fuel consumption (%) between different driving modes

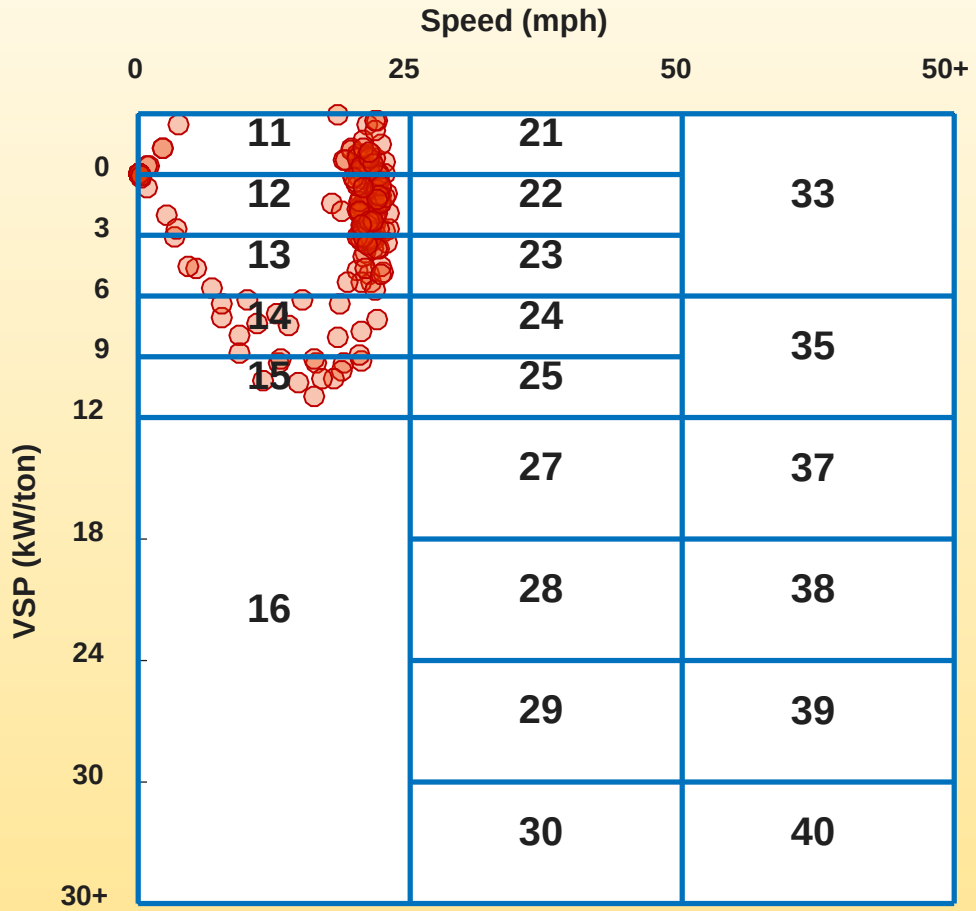
Phase	Green						Red						On
Time in Phase (s)	2	7	12	17	22	27	2	7	12	17	22	27	Average
D vs. U	-11.80	-11.75	7.59	5.20	7.56	12.05	25.08	37.80	-18.34	21.71	-0.55	13.53	7.34
A vs. U	4.67	7.55	35.25	20.94	20.28	31.71	32.65	47.91	-3.95	26.48	20.05	22.89	22.20
A vs. D	14.73	17.27	29.93	16.60	13.76	22.36	10.11	16.25	12.16	6.10	20.48	10.83	15.88

Summary of Results:

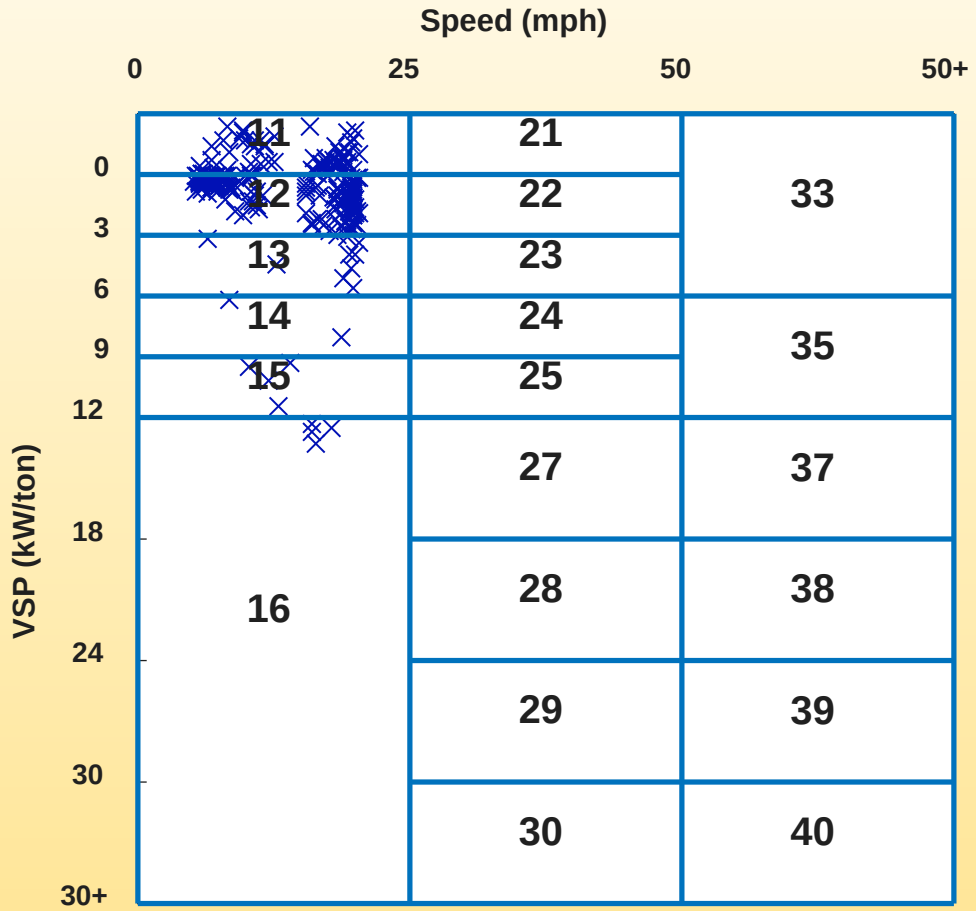
- DVI-based driving provided variable fuel economy benefit over an "uninformed" driver (-5% up to 9%)
- Partially automated driving provided a 16% to 22% benefit over an "uninformed" driver

MOVES Model OpMode Distribution

- Typical driving scenario through traffic light, with and without EAD
- Measured fuel reduction is approximately 15%
- MOVES fuel reduction is approximately 7%



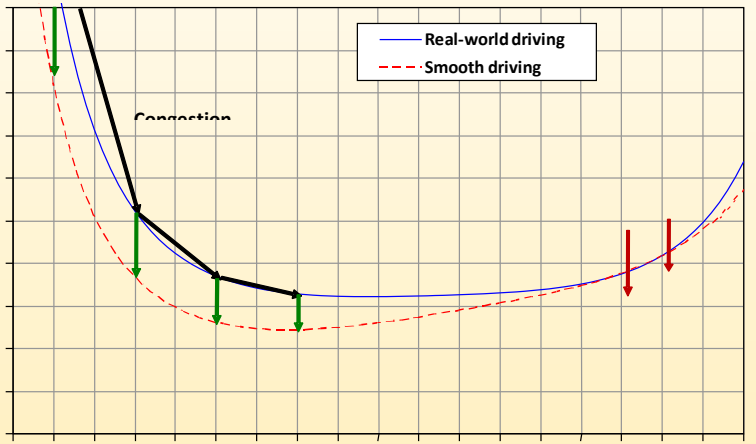
EAD OpMode distribution for manual driving



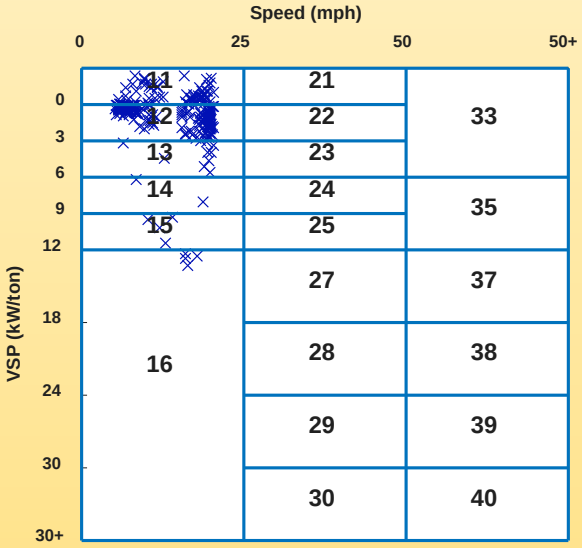
EAD OpMode distribution under partially automation

Eco-Approach and Departure
MOVES Model OpMode Distribution Method

Summary of Results:



- **Measured** fuel consumption reductions can range anywhere from **5% to 22%** benefit over an "uninformed" driver
- Modal Emissions Models (CMEM, VT-Micro) generally match the real-world measurements
- MOVES OpMode distribution modeling approach typically **under-estimates** fuel consumption benefits by approximately half; this is due to size of OpMode bins



AERIS OPERATIONAL SCENARIOS & APPLICATIONS

ECO-SIGNAL OPERATIONS

- Eco-Approach and Departure at Signalized Intersections *(similar to SPaT)*
- Eco-Traffic Signal Timing *(similar to adaptive traffic signal systems)*
- Eco-Traffic Signal Priority *(similar to traffic signal priority)*
- Connected Eco-Driving *(similar to eco-driving strategies)*
- Wireless Inductive/Resonance Charging

ECO-LANES

- Eco-Lanes Management ***(similar to HOV Lanes)***
- Eco-Speed Harmonization ***(similar to variable speed limits)***
- Eco-Cooperative Adaptive Cruise Control *(similar to adaptive cruise control)*
- Eco-Ramp Metering *(similar to ramp metering)*
- Connected Eco-Driving *(similar to eco-driving)*
- Wireless Inductive/Resonance Charging
- Eco-Traveler Information Applications *(similar to ATIS)*

LOW EMISSIONS ZONES

- Low Emissions Zone Management *(similar to Low Emissions Zones)*
- Connected Eco-Driving *(similar to eco-driving strategies)*
- Eco-Traveler Information Applications *(similar to ATIS)*

ECO-TRAVELER INFORMATION

- AFV Charging/Fueling Information *(similar to navigation systems providing information on gas station locations)*
- Eco-Smart Parking *(similar to parking applications)*
- Dynamic Eco-Routing *(similar to navigation systems)*
- Dynamic Eco-Transit Routing *(similar to AVL routing)*
- Dynamic Eco-Freight Routing *(similar to AVL routing)*
- Multi-Modal Traveler Information *(similar to ATIS)*
- Connected Eco-Driving *(similar to eco-driving strategies)*

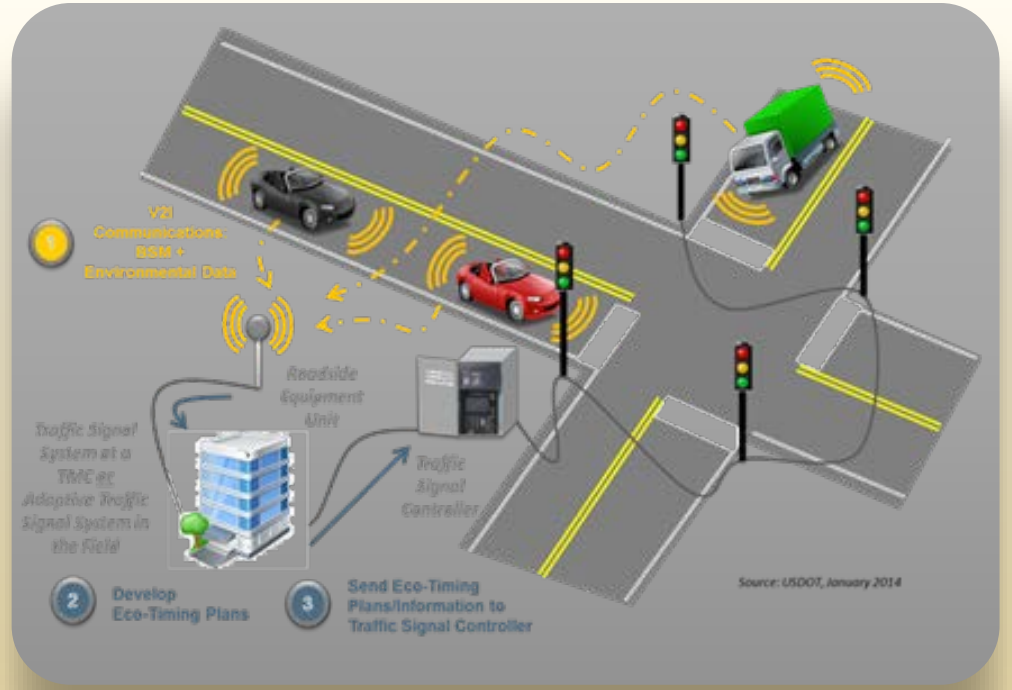
ECO-INTEGRATED CORRIDOR MANAGEMENT

- Eco-ICM Decision Support System *(similar to ICM)*
- Eco-Signal Operations Applications
- Eco-Lanes Applications
- Low Emissions Zone s Applications
- Eco-Traveler Information Applications
- Incident Management Applications

ECO-TRAFFIC SIGNAL TIMING APPLICATION

Application Overview

- Similar to current traffic signal systems; however the application's objective is to optimize the performance of traffic signals for the environment
- Collects data from vehicles, such as vehicle location, speed, vehicle type, and emissions data using connected vehicle technologies



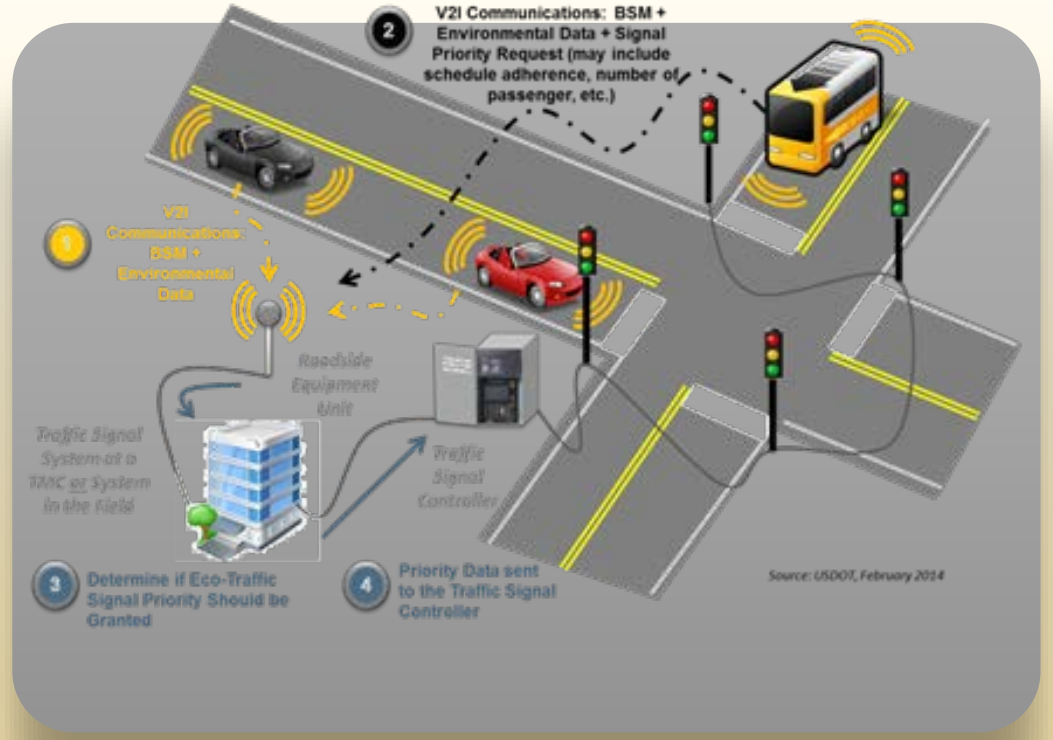
- Processes these data to develop signal timing strategies focused on reducing fuel consumption and overall emissions at the intersection, along a corridor, or for a region
- Evaluates traffic and environmental parameters at each intersection in real-time and adapts the timing plans accordingly

- **5% Energy Benefit**

ECO-TRAFFIC SIGNAL PRIORITY APPLICATION

Application Overview

- Allows either transit or freight vehicles approaching a signalized intersection to request signal priority
- Considers the vehicle's location, speed, vehicle type (e.g., alternative fuel vehicles), and associated emissions to determine whether priority should be granted

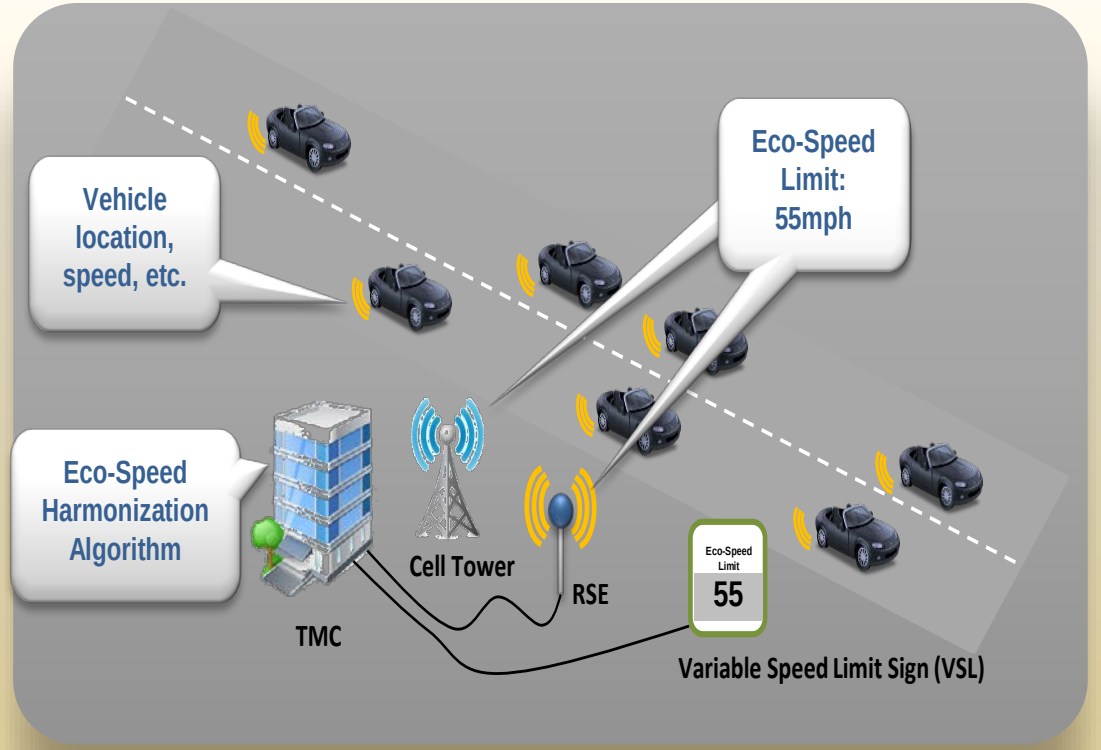


- Information collected from vehicles approaching the intersection, such as a transit vehicle's adherence to its schedule, the number of passengers on the transit vehicle, or weight of a truck may also be considered in granting priority
- If priority is granted, the traffic signal would hold the green on the approach until the transit or freight vehicle clears the intersection
- **~4% Energy Benefit for freight; ~6% for all vehicles**

ECO-SPEED HARMONIZATION APPLICATION

Application Overview

- Collects traffic information and pollutant information using connected vehicle-to-infrastructure (V2I) communications
- The application assists in maintaining flow, reducing unnecessary stops and starts, and maintaining consistent speeds near bottleneck and other disturbance areas



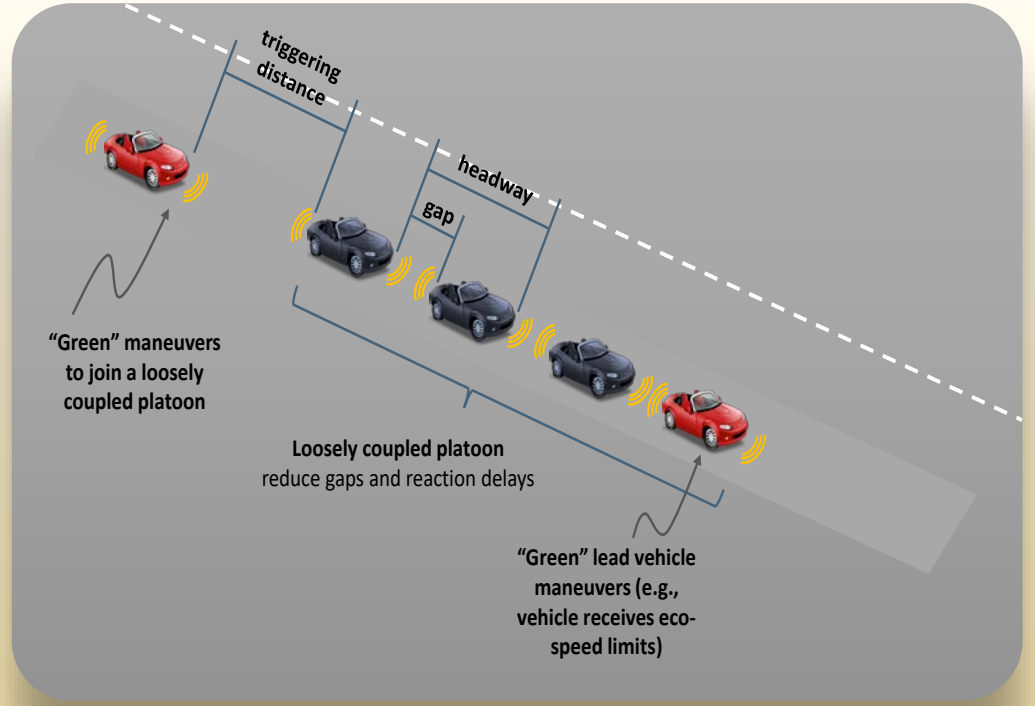
- Receives V2I messages, the application performs calculations to determine the optimal speed for the segment of freeway where the bottleneck, lane drop, or disturbance is occurring
- The optimal “eco-speed” is broadcasted by V2I messages from roadside RSE equipment to all connected vehicles along the roadway

- **~5% Energy Benefit**

ECO-COOPERATIVE ADAPTIVE CRUISE CONTROL (CACC)

Application Overview

- Eco-CACC includes longitudinal automated vehicle control while considering eco-driving strategies.
- Connected vehicle technologies can be used to collect the vehicle's speed, acceleration, and location and feed these data into the vehicle's ACC.



- Receives V2V messages between leading and following vehicles, the application performs calculations to determine how and if a platoon can be formed to improve environmental conditions
- Provides speed and lane information of surrounding vehicles in order to efficiently and safely form or decouple platoons of vehicles

- **~20% Energy Benefit**

AERIS OPERATIONAL SCENARIOS & APPLICATIONS

ECO-SIGNAL OPERATIONS

Traffic Energy Benefits (modeling)

- **Eco-Approach and Departure at Signalized Intersections** *(similar to SPaT)* → **10% energy savings**
- **Eco-Traffic Signal Timing** *(similar to adaptive traffic signal systems)* → **5% energy savings**
- **Eco-Traffic Signal Priority** *(similar to traffic signal priority)* → **6% energy savings**
- **Connected Eco-Driving** *(similar to eco-driving strategies)*
- **Wireless Inductive/Resonance Charging**

ECO-LANES

- **Eco-Lanes Management** ***(similar to HOV Lanes)***
- **Eco-Speed Harmonization** ***(similar to variable speed limits)*** → **5% energy savings**
- **Eco-Cooperative Adaptive Cruise Control** *(similar to adaptive cruise control)* → **20% energy savings**
- **Eco-Ramp Metering** *(similar to ramp metering)*
- **Connected Eco-Driving** *(similar to eco-driving)*
- **Wireless Inductive/Resonance Charging**
- **Eco-Traveler Information Applications** *(similar to ATIS)*

LOW EMISSIONS ZONES

- **Low Emissions Zone Management** *(similar to Low Emissions Zones)*
- **Connected Eco-Driving** *(similar to eco-driving strategies)*
- **Eco-Traveler Information Applications** *(similar to ATIS)*

Conclusions and Recommendations

- **MOVES Modeling Approach** tends to under-estimate traffic smoothing effects due to connected and automated applications
- **All Modeling Approaches** tends to miss effects of aerodynamic drag reduction effects
- Consider adopting a **physical modal or instantaneous emissions model** for connected and automated vehicle scenarios, as well as other traffic smoothing effects
- Dust off PERE emissions generator model that was previously used for MOVES

THANK YOU!