Eco-Approach and Departure at Signalized Intersections: Field Study and Modeling Results

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

Fall/Winter Webinar Series
March 13, 2013
Research Team

- **University of California-Riverside:**
  - Matthew Barth (principal investigator)
  - Kanok Boriboonsomsin (research faculty)
  - Guoyuan Wu (research faculty)
  - Haitao Xia, Apple Jin (graduate students)

- **Booz Allen Hamilton:**
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- **Many others have contributed:**
  - AERIS research team partners
  - UC Berkeley California PATH
  - BMW (part of FHWA EAR project on Advanced Signalization)
  - etc.
Presentation Overview

- Eco-Approach and Departure Concept
- Field Study Setup
- Experimentation and Results
- Field Study Summary Findings and Recommendations
- Simulation Modeling Setup and Results
- Simulation Modeling Summary Findings
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.

**Example scenarios:**

1) Coast down earlier to a red light;
2) Modestly speed up to make it (safely) through the intersection on green.
Signal Phase and Timing (SPaT)

- Data are broadcast from traffic signal controller (infrastructure) 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) or cellular communications
Variations of Analysis

- **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
- **Analysis Approach**: increasing incremental complexity and using previous results as “building blocks”
- **Initial Field Study**: single vehicle, no traffic, fixed-timed intersection
- **Simulation Modeling**: multiple vehicles, examining the sensitivity of other variables
Field-Study
Field Study Objectives

1) To provide quantitative data on the performance of this initial AERIS eco-approach and departure application

2) To allow us to assess the practicality of implementation

3) To gain a better understanding of potential user experience

4) To provide data that can later be used to both calibrate and validate AERIS computer modeling efforts
Eco-Approach Scenario Diagram

Intersection of interest

Analysis Boundary

DSRC Range

Vehicle 2

Vehicle 1

Vehicle 3

Vehicle 4

Intersection of Interest

Phase 1 Accelerating

Phase 2 Cruising

Phase 3 Decelerating

Phase 4 Idling

Phase 5 Accelerating

Speed

Distance
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
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
- Objective is to: minimize $|a|$

subject to: (i) $v_0 t_1 + \frac{1}{2} a t_1^2 + (v_0 + at_1)(t - t_1) = D$

(ii) $t_1 \leq t$

(iii) $t_g \leq t < t_r$

(iv) $\frac{P_{\text{tractive}}}{\eta_{tf}} + P_{\text{accessories}} \leq P_{\text{engine}}$

(v) $v_0 + at_1 \leq v_{\text{limit}}$

$v_0 = $ velocity of the vehicle at the instant it enters the DSRC range
$t = $ total time taken to reach the intersection
$t_1 = $ the portion of time spent accelerating or decelerating with an acceleration rate $a$
$(t-t_1) = $ portion of time spent traveling at uniform velocity before reaching the intersection

Previous Studies & Results with Algorithm

Initial Simulation:

<table>
<thead>
<tr>
<th>LDV24</th>
<th>Without</th>
<th>With</th>
<th>% Diff. in Avg</th>
<th>p-value of t-test</th>
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<td></td>
<td>Avg.</td>
<td>S.D.</td>
<td>Avg.</td>
<td>S.D.</td>
</tr>
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<td>103.8</td>
<td>9.3</td>
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<td>41.2</td>
<td>318.8</td>
<td>25.3</td>
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<td>TT (sec)</td>
<td>456.7</td>
<td>60.7</td>
<td>451.9</td>
<td>56.9</td>
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references:


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

<table>
<thead>
<tr>
<th></th>
<th>uninformed</th>
<th>informed</th>
<th>Improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel (l/100km)</td>
<td>10.23</td>
<td>8.84</td>
<td>-13.59%</td>
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<tr>
<td>Travel time (sec/trip)</td>
<td>40.69</td>
<td>40.3</td>
<td>-0.96%</td>
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</table>

reference:

SPaT Communication Setup at Riverside

Traffic Signal Controller

SPaT processor

Road-side DSRC
Vehicle Setup at Riverside

Driver display advising driver
Vehicle computer interprets data, performs velocity planning
Vehicle OBD-II data
On-board DSRC
Riverside Testing
SPaT Communication Setup at TFHRC

Traffic Signal Controller

Vehicle OBD-II data

wireless

On-board DSRC

Driver display advising driver

Vehicle computer performs velocity planning

SPaT processor

Road-side DSRC

U.S. Department of Transportation
Signal Phase and Timing System Setup at TFHRC

Roadside equipment (DSRC)

Traffic signal controller

DSRC-enabled vehicle
Vehicle Setup at TFHRC

**Test vehicle**
(Jeep Grand Cherokee)

**On-board DSRC transceiver**

**Pseudo-dashboard (driver interface)**

**On-board computer**

**Vehicle OBD-II data**
Graphical User Interface for Testing

- Speedometer
- SPaT (Signal Phase and Timing)
- Tachometer
- Advisory speed
- Real-time MPG
- Distance to intersection
- Vehicle location indicator
- Intersection location indicator
Graphical User Interface for Demonstration

- Speedometer
- Tachometer

Advisory speed
Map of Test Site (TFHRC)
STOL Intersection at TFHRC

1) Signal set up for fixed timed signal phasing (26-seconds green, 4-seconds yellow, then 30-seconds red)
2) SPaT message sent from intersection controller at 10 Hz
## Test Matrix

<table>
<thead>
<tr>
<th>Speed \ Time</th>
<th>0 sec</th>
<th>5 sec</th>
<th>10 sec</th>
<th>15 sec</th>
<th>...</th>
<th>55 sec</th>
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<tr>
<td>15 mph</td>
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<td>35 mph</td>
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</table>

- Minimum three data runs per cell (more if high variability)
- “uninformed” driving performed for each cell, then “informed” driving performed for each cell
- Data collected in each cell: velocity trajectory, fuel economy, driver “score”
## Scenario Mapping in Test Matrix

### Riverside Test Matrix

<table>
<thead>
<tr>
<th>V/T</th>
<th>0</th>
<th>5</th>
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<td>Scenario 3</td>
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<tr>
<td>25  mph</td>
<td>S 3</td>
<td>Scenario 4</td>
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<td>Scenario 1</td>
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<tr>
<td>30  mph</td>
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<td>Scenario 1</td>
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<tr>
<td>35  mph</td>
<td>Scenario 3</td>
<td>Scenario 4</td>
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<td></td>
<td>Scenario 1</td>
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<tr>
<td>40  mph</td>
<td>Scenario 3</td>
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<td>Scenario 1</td>
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### TFHRC Test Matrix

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<td>Scenario 3</td>
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<tr>
<td>30  mph</td>
<td>Scenario 4</td>
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<td>35  mph</td>
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<td>S 4</td>
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<td>40  mph</td>
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</tbody>
</table>
Example Scenario 1 (cruise)

Testing GUI

validation camera
Example Scenario 2 (speed up)
Example Scenario 3 (coast then stop)
Example Scenario 4 (coast, no stop)
### Field Study Results: Fuel Savings (% improvement)

<table>
<thead>
<tr>
<th>Vel\Time</th>
<th>0 s</th>
<th>5 s</th>
<th>10 s</th>
<th>15 s</th>
<th>20 s</th>
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<th>30 s</th>
<th>35 s</th>
<th>40 s</th>
<th>45 s</th>
<th>50 s</th>
<th>55 s</th>
<th>saving %</th>
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<tr>
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<td>-2.7</td>
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<td>6.0</td>
<td>16.4</td>
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<tr>
<td>25 mph</td>
<td>3.3</td>
<td>13.8</td>
<td>19.6</td>
<td>15.3</td>
<td>0.7</td>
<td>2.0</td>
<td>0.4</td>
<td>0.5</td>
<td>-1.5</td>
<td>3.3</td>
<td>6.8</td>
<td>2.4</td>
<td>17.7</td>
</tr>
<tr>
<td>30 mph</td>
<td>-1.9</td>
<td>9.5</td>
<td>16.0</td>
<td>13.0</td>
<td>0.8</td>
<td>0.6</td>
<td>2.2</td>
<td>3.3</td>
<td>3.5</td>
<td>19.6</td>
<td>11.0</td>
<td>10.1</td>
<td>25.6</td>
</tr>
<tr>
<td>35 mph</td>
<td>7.1</td>
<td>9.3</td>
<td>7.2</td>
<td>25.1</td>
<td>29.3</td>
<td>1.0</td>
<td>0.2</td>
<td>-1.3</td>
<td>1.3</td>
<td>-1.1</td>
<td>2.3</td>
<td>6.6</td>
<td>28.4</td>
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<tr>
<td>40 mph</td>
<td>-3.5</td>
<td>3.9</td>
<td>-1.6</td>
<td>12.8</td>
<td>5.8</td>
<td>1.0</td>
<td>1.6</td>
<td>3.4</td>
<td>0.6</td>
<td>0.7</td>
<td>4.5</td>
<td>4.8</td>
<td>11.0</td>
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</table>

### Riverside Testing Results

**delay into cycle (sec)**

<table>
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<tr>
<th>V/T</th>
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<th>50</th>
<th>55</th>
<th>% savings</th>
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<tbody>
<tr>
<td>20</td>
<td>8.6</td>
<td>-11.3</td>
<td>-10.2</td>
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<td>7.1</td>
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<td>12.5</td>
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<tr>
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<td>17.8</td>
<td>22.5</td>
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<td>0.9</td>
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### TFHRC Testing Results
Typical Velocity Trajectories

- **Actual Spd**
- **Target Spd**

![Graph showing typical velocity trajectories with labels for actual and target speeds.](image-url)
Driver “Score”

• Measure of how well the driver follows the recommended speed
• Useful for testing phase, can eliminate bad runs
• Score definition:

\[
SCORE = 100 \left( 1 - \sum_{n=1}^{\infty} \frac{1}{n} \left| \frac{A - T}{A + T} \right| \right)
\]

A: actual speed; T: target speed.

• highest possible score: 100; lowest possible score: 0

Experienced Driver Scores:

Driver 1: 87.9  Driver 2: 90.0  Driver 3: 89.0
Model-Based Estimation

Velocity trajectories from testing

Vehicle Type selected to be Composite 2012 Light-Duty Vehicle

Estimated Energy and Emissions for composite Light-Duty Vehicle

<table>
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<tr>
<th>V/T</th>
<th>0</th>
<th>5</th>
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</table>

Velocity trajectories from testing

Comprehensive Modal Emissions Model (CMEM)

Vehicle Type selected to be Composite 2012 Light-Duty Vehicle

Estimated Energy and Emissions for composite Light-Duty Vehicle

<table>
<thead>
<tr>
<th>V/T</th>
<th>0</th>
<th>5</th>
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</tbody>
</table>
## Composite Vehicle Fuel and Emissions Savings

### Vel\Time | 0 s | 5 s | 10 s | 15 s | 20 s | 25 s | 30 s | 35 s | 40 s | 45 s | 50 s | 55 s | %
<table>
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<td>19.23</td>
<td>18.59</td>
<td>19.75</td>
<td>4.86</td>
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<td>9.59</td>
<td>12.80</td>
<td>16.14</td>
<td>21.42</td>
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<td>23.02</td>
<td>12.23</td>
<td>1.87</td>
<td>-0.77</td>
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<td>15.62</td>
<td>-0.97</td>
<td>6.55</td>
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<td>4.56</td>
<td>11.58</td>
<td>10.24</td>
<td>3.21</td>
<td>0.03</td>
<td>5.31</td>
<td>3.40</td>
<td>2.70</td>
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### Fuel and CO\(_2\) Savings for Composite Vehicle

### Vel\Time | 0 s | 5 s | 10 s | 15 s | 20 s | 25 s | 30 s | 35 s | 40 s | 45 s | 50 s | 55 s | %
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<td>47.6</td>
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<tr>
<td>25 mph</td>
<td>1.3</td>
<td>2.5</td>
<td>1.8</td>
<td>1.1</td>
<td>0.3</td>
<td>0.1</td>
<td>0.1</td>
<td>0.2</td>
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<td>2.4</td>
<td>7.5</td>
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<td>0.1</td>
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<td>-0.1</td>
<td>0.1</td>
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### CO Savings for Composite Vehicle

### Vel\Time | 0 s | 5 s | 10 s | 15 s | 20 s | 25 s | 30 s | 35 s | 40 s | 45 s | 50 s | 55 s | %
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<td>0.05</td>
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</table>

### HC Savings for Composite Vehicle

### Vel\Time | 0 s | 5 s | 10 s | 15 s | 20 s | 25 s | 30 s | 35 s | 40 s | 45 s | 50 s | 55 s | %
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<td>0.3</td>
<td>0.3</td>
<td>0.2</td>
<td>0.1</td>
<td>1.1</td>
<td>0.1</td>
<td>0.2</td>
<td>0.0</td>
<td>0.1</td>
<td>0.2</td>
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<td>0.3</td>
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<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
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<td>0.0</td>
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<td>0.1</td>
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<td>0.2</td>
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### NOx Savings for Composite Vehicle
Field Study Summary

- On average, significant fuel savings achieved
- High degree of variability between runs; multiple runs in each cell are needed
- Sensitive to driver variability
- Sensitive to terrain variability
- With increased DSRC range, the earlier the maneuver can be planned and executed
- Traveling at slower speeds allows for higher chance of passing on green
- Sensitivity analysis is being carried out in simulation
Field Study Recommendations

• SPaT enhancements:
  – Broadcast of next-next-phase information
  – Broadcast of intersection GPS-WAAS latitude & longitude for better range estimation

• Need to extend to Actuated Signals

• Better HMI (human-machine interface) development, OR

• Should consider semi-automated driving through intersection (e.g., interface to ACC)
Simulation Modeling
Modeling Objectives

• Expand the field study results by conducting detailed simulation modeling and test benefits under different traffic conditions, network conditions, vehicle type, 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
Modeling Setup

• **Paramics traffic simulation model** with API plug-ins (eco-approach method, energy/emissions models)
Modeling Results: congestion and penetration

- Single generic intersection, fixed-timed signal
- Less effectiveness with increased congestion
- Higher effectiveness with increased penetration of technology
- Total network savings is slightly higher than sum of equipped vehicle savings

reference:

Modeling Results: multiple intersections

- El Camino Real in Palo Alto, California (part of ITS testbed in Northern California)
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
- Moderate Savings: 5% - 10% overall

<table>
<thead>
<tr>
<th>Vol/Cap</th>
<th>baseline</th>
<th>100% penetration</th>
<th>baseline - Eco Approach</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fuel (g/mi)</td>
<td>CO2 (g/mi)</td>
<td>stops/veh</td>
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<tr>
<td>0.38</td>
<td>432.58</td>
<td>901.97</td>
<td>2.14</td>
</tr>
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</table>
Modeling Results: multiple intersections

Coordinated Signal Control:

- Signal timing is set to be coordinated between intersections (real-world)
- Coordinated signal control results in ~18% fuel reduction over uncoordinated
- Eco-approach algorithm applied on all three intersections, cross traffic included in analysis
- Moderate Savings on total traffic: 5% - 10% overall
- Minimum Savings on coordinated mainline flow: 1% - 3%

<table>
<thead>
<tr>
<th>Vol/Cap</th>
<th>baseline</th>
<th>100% penetration</th>
<th>baseline - Eco Approach</th>
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Total traffic

Mainline flow
Simulation Modeling Summary (to date)

- Eco-approach and departure is less effective with increased congestion
- In general, 5%-10% fuel savings can be achieved with 100% penetration rate
- Smaller penetration rate of technology still has a positive network effect (non-equipped vehicles also have a slight benefit)
- Eco-approach and departure technology only provides a slight improvement (1% - 3%) to mainline flow in a coordinated traffic corridor
Contact Information

Eco-Approach and Departure at Signalized Intersection:
• Matthew Barth, UC-Riverside, barth@cert.ucr.edu

AERIS Program:
• Marcia Pincus, Program Manager, Environment (AERIS) and ITS Evaluation, US DOT RITA, marcia.pincus@dot.gov
AERIS IdeaScale Site

https://aeris.ideascale.com
AERIS ConOps and Modeling Workshop

- **Purpose:**
  - Validate the content of three (3) Draft Concept of Operations documents:
    - Eco-Signal Operations
    - Dynamic Low Emissions Zones
    - Dynamic Eco-Lanes
  - Begin detailed discussions on the plans for modeling and analysis of the AERIS Transformative Concepts.

- **When:**
  - March 26th and 27th, 2013

- **Location:**
  - Hyatt Regency Washington on Capitol Hill
    - 400 New Jersey Ave NW
    - Washington, DC 20001

- **Registration:**
  - Persons planning to attend any part of the workshop or participate in the webcast should register online at [www.itsta.org/aeris2013](http://www.itsta.org/aeris2013).