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

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

AERIS Concept of Operations and Modeling Workshop
March 26 - 27, 2013
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 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

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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) $(v_0 t_1 + \frac{1}{2} a t_1^2) + (v_0 + a t_1)(t - t_1) = D$

(ii) $t_1 \leq t$

(iii) $t_g \leq t < t_r$

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

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

$v_0$ = 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:

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<tr>
<th>LDV24</th>
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references:


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

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reference:

Vehicle Setup

Vehicle computer interprets data, performs velocity planning.

Driver display advising driver.

Vehicle OBD-II data.

On-board DSRC.

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SPaT Communication Setup

- Traffic Signal Controller
- SPaT processor
- Road-side DSRC
- On-board DSRC
- Vehicle OBD-II data
- wireless

Driver display advising driver
Vehicle computer performs velocity planning

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Signal Phase and Timing System Setup at TFHRC

Roadside equipment (DSRC)

Traffic signal controller

DSRC-enabled vehicle
Graphical User Interface for Testing

- Speedometer
- SPaT
- Tachometer
- Advisory speed
- Real-time MPG
- Distance to intersection
- Vehicle location indicator
- Intersection location indicator
Map of Test Site (TFHRC)
### Scenario Mapping in Test Matrix

#### Riverside Test Matrix

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Example Scenario 1 (cruise)

Testing GUI  ➔validation camera

\[
\begin{align*}
v(t) & = \text{constant} \\ d(t) & = \frac{1}{2} a t^2
\end{align*}
\]
Example Scenario 2 (speed up)
Example Scenario 3 (coast then stop)
Example Scenario 4 (coast, no stop)
## Field Study Results: Fuel Savings (% improvement)

### Riverside Testing Results

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### TFHRC Testing Results

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<th>% savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 mph</td>
<td>8.6</td>
<td>-11.3</td>
<td>-10.2</td>
<td>-5.2</td>
<td>-9.3</td>
<td>-13.1</td>
<td>13.8</td>
<td>7.1</td>
<td>9.4</td>
<td>-13.2</td>
<td>12.5</td>
<td>24.0</td>
<td>2.5%</td>
</tr>
<tr>
<td>25 mph</td>
<td>17.8</td>
<td>22.5*</td>
<td>7.0</td>
<td>0.9</td>
<td>6.4</td>
<td>-9.4</td>
<td>-11.1</td>
<td>16.0</td>
<td>12.2</td>
<td>18.9</td>
<td>14.7</td>
<td>14.8</td>
<td>18.1%</td>
</tr>
<tr>
<td>30 mph</td>
<td>-1.2</td>
<td>4.3</td>
<td>1.5</td>
<td>2.3</td>
<td>-1.2</td>
<td>6.7</td>
<td>-4.4</td>
<td>8.8</td>
<td>16.3</td>
<td>10.3</td>
<td>21.9</td>
<td>10.6</td>
<td>11.2%</td>
</tr>
</tbody>
</table>
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)
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 Fuel (g/mi)</th>
<th>CO2 (g/mi)</th>
<th>stops/veh</th>
<th>TT/veh</th>
<th>100% penetration Fuel (g/mi)</th>
<th>CO2 (g/mi)</th>
<th>stops/veh</th>
<th>TT/veh</th>
<th>Fuel %</th>
<th>stops/veh</th>
<th>TT/veh</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.00</td>
<td>474.17</td>
<td>1034.42</td>
<td>3.94</td>
<td>99.63</td>
<td>453.52</td>
<td>1008.34</td>
<td>4.58</td>
<td>104.92</td>
<td>4.36</td>
<td>-0.64</td>
<td>-5.29</td>
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<tr>
<td>0.77</td>
<td>444.34</td>
<td>951.92</td>
<td>2.84</td>
<td>86.88</td>
<td>406.45</td>
<td>885.94</td>
<td>3.27</td>
<td>87.13</td>
<td>8.53</td>
<td>-0.44</td>
<td>-0.25</td>
</tr>
<tr>
<td>0.38</td>
<td>432.58</td>
<td>901.97</td>
<td>2.14</td>
<td>77.70</td>
<td>389.42</td>
<td>824.76</td>
<td>2.25</td>
<td>77.54</td>
<td>9.98</td>
<td>-0.11</td>
<td>0.16</td>
</tr>
</tbody>
</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%
- Increased savings with increased penetration rate

<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>
</tr>
<tr>
<td>1.00</td>
<td>380.97</td>
<td>788.32</td>
<td>2.42</td>
</tr>
<tr>
<td>0.77</td>
<td>359.64</td>
<td>725.33</td>
<td>1.61</td>
</tr>
<tr>
<td>0.38</td>
<td>355.75</td>
<td>698.19</td>
<td>1.24</td>
</tr>
</tbody>
</table>

**Total traffic**

<table>
<thead>
<tr>
<th>Vol/Cap</th>
<th>baseline</th>
<th>100% penetration</th>
<th>improvement (baseline - Eco Approach)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fuel(g/mi)</td>
<td>CO2 (g/mi)</td>
<td>stops/veh</td>
</tr>
<tr>
<td>1.00</td>
<td>331.43</td>
<td>678.14</td>
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<tr>
<td>0.77</td>
<td>298.33</td>
<td>592.10</td>
<td>1.73</td>
</tr>
<tr>
<td>0.38</td>
<td>286.25</td>
<td>559.74</td>
<td>1.27</td>
</tr>
</tbody>
</table>

**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
- Modeling Challenges: different traffic simulators have different features (Paramics, VISSIM, SUMO, TransModeler, etc.)
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:**
  - Balaji Yelchuru
  - Steve Brady

- **Many others have contributed:**
  - AERIS research team partners
  - UC Berkeley California PATH
  - BMW (part of FHWA EAR project on Advanced Signalization)
  - etc.
Extra Slides
SPaT Communication Setup at Riverside

Traffic Signal Controller

SPaT processor

Road-side DSRC

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Riverside Testing
Graphical User Interface for Demonstration

- Speedometer
- Tachometer
- Advisory speed
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</th>
<th>0 sec</th>
<th>5 sec</th>
<th>10 sec</th>
<th>15 sec</th>
<th>…</th>
<th>55 sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>15 mph</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20 mph</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25 mph</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30 mph</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>35 mph</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</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”
Typical Velocity Trajectories
Driver “Score”

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

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

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

U.S. Department of Transportation
## Composite Vehicle Fuel and Emissions Savings

<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>
<th>25 s</th>
<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>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 mph</td>
<td>19.23</td>
<td>18.59</td>
<td>19.75</td>
<td>4.86</td>
<td>3.24</td>
<td>2.12</td>
<td>1.00</td>
<td>4.36</td>
<td>-2.73</td>
<td>9.59</td>
<td>12.80</td>
<td>16.14</td>
<td>21.42</td>
</tr>
<tr>
<td>25 mph</td>
<td>15.34</td>
<td>21.14</td>
<td>23.02</td>
<td>12.23</td>
<td>1.87</td>
<td>-0.77</td>
<td>0.56</td>
<td>0.94</td>
<td>0.73</td>
<td>7.20</td>
<td>13.72</td>
<td>11.79</td>
<td>22.24</td>
</tr>
<tr>
<td>30 mph</td>
<td>15.62</td>
<td>-0.97</td>
<td>6.55</td>
<td>7.09</td>
<td>-1.96</td>
<td>0.16</td>
<td>0.35</td>
<td>-0.62</td>
<td>-0.11</td>
<td>29.70</td>
<td>11.45</td>
<td>11.99</td>
<td>18.42</td>
</tr>
<tr>
<td>35 mph</td>
<td>7.77</td>
<td>18.75</td>
<td>13.74</td>
<td>19.42</td>
<td>10.70</td>
<td>1.12</td>
<td>-1.02</td>
<td>-0.36</td>
<td>-0.13</td>
<td>4.68</td>
<td>6.61</td>
<td>9.86</td>
<td>25.45</td>
</tr>
<tr>
<td>40 mph</td>
<td>-4.24</td>
<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>
<td>0.14</td>
<td>0.29</td>
<td>7.64</td>
<td>15.82</td>
</tr>
</tbody>
</table>

### Fuel and CO₂ Savings for Composite Vehicle

### CO Savings for Composite Vehicle

### HC Savings for Composite Vehicle

### NOx Savings for Composite Vehicle

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U.S. Department of Transportation
Algorithm for Actuated Signals