Connected Vehicles Based Eco-Intelligent Transportation Systems

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Objectives of Eco-ITS

- Identify connected vehicle applications that could provide environmental impact reduction benefits via reduced fuel use, more efficient vehicles, and reduced emissions.

- Facilitate and incentivize “green choices” by transportation service consumers (i.e., system users, system operators, policy decision makers, etc.).

- Identify vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), and vehicle-to-grid (V2G) data (and other) exchanges via wireless technologies of various types.

- Model and analyze connected vehicle applications to estimate the potential environmental impact reduction benefits.

- Develop prototypes and conduct demonstrations to validate the efficacy and usefulness of proposed applications.
AERIS Connected Vehicle Research

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)

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

Applications for the Environment: Real-Time Information Synthesis (AERIS)
Eco-Signal Operations Simulation Modeling

Traffic Simulation Model Inputs
- Origin-Destination (OD) Data
- Roadway Geometry
- Traffic Signal Timing Plans
- Driver Behavior Parameters

Traffic Simulation Model Outputs
- Vehicle Type
- Vehicle Position
- Vehicle Speed
- Traffic Signal Data
- Traffic Conditions

Assumptions for Sensitivity Analysis
- Connected Vehicle Technology Penetration Rates
  - On-Board Equipment (OBE)
  - Roadside Equipment (RSE)
- Driver Compliance Rate
- Volume-to-Capacity (V/C) Ratio
- Vehicle Fleet Mix
  - Percentage of Alternative Fuel Vehicles
  - Percentage Trucks
  - Percentage Transit

AERIS Algorithm API Outputs
- Updates to Traffic Signal Timing
  - Cycle Lengths
  - Green Splits
  - Offsets
  - Green Extension or Truncation (for traffic signal priority)
- Recommended Speeds

AERIS Algorithm APIs
- Eco-Approach and Departure at Signalized Intersections
- Eco-Traffic Signal Timing
- Eco-Traffic Signal Priority
  - Eco-Transit Signal Priority
  - Eco-Freight Signal Priority
- Connected Eco-Driving

MOVES API

MOVES Emissions Model

MOVES Outputs
- Fuel Consumption
- Emissions
EAD at Signalized Intersections

- Collects signal phase and timing (SPaT) and Geographic Information Description (GID) messages using vehicle-to-infrastructure (V2I) communications
- Collects basic safety messages (BSMs) from nearby vehicles using vehicle-to-vehicle (V2V) communications
- Receives V2I and V2V messages, the application performs calculations to determine the vehicle’s optimal speed to pass the next traffic signal on a green light or to decelerate to a stop in the most eco-friendly manner
- Provides speed recommendations to the driver using a human-machine interface or sent directly to the vehicle’s longitudinal control system to support partial automation
EAD for Fixed Time Signals

- **10-15%** fuel reduction benefit for an equipped vehicle
- **5-10%** fuel reduction benefits for traffic along an uncoordinated corridor

A field study was carried out at the Turner Fairbanks Highway Research Center (TFHRC) in McLean, Virginia, in August, 2012.

Evaluate the benefits of enhancing the application with partial automation: GlidePath
EAD for Actuated Signals

- Estimate Distance to Intersection
- Map Information
- Map Matching
- Vehicle Location from GPS

- Real Time SPaT
- Green Window Estimator
- Historical Database

- Vehicle Trajectory Planning Algorithm (VTPA)
- State Machine to Turn on/off the Display of Target Speed

- Human-Machine Interface (HMI)

- Car-Following Speed Estimator
- Estimate Preceding Vehicle Related Parameters
- Activity Data of Preceding Vehicle from Radar
- Time-to-Collision Estimator

- Instantaneous Speed, RPM and MPG
- Activity Data of Subject Vehicle from OBD

- Instantaneous Speed and Acceleration

- Extract Subject Vehicle Dynamics
EAD in Real-World Traffic

- BSM message from Connected vehicles
- Sensor information (e.g. radar)
- SPAT and MAP message from signal controller
- Signal timing update
- Vehicle dynamics
  - Vehicle emissions
- Actuated signals
- Road-side DSRC
EAD Guidelines for Actuated Signals

The primary objectives of the proposed algorithm:

- Safety: keep safe headway while not exceeding the speed limit and not crossing on red
- Avoid (possibly) unnecessary acceleration and deceleration.
- Avoid or minimize idling at the intersection
- Avoid crawling for a long distance

Source: Barth and Boriboonsomsin (2008)
EAD Strategies for Actuated Signals

(a) Three strategies for EAD

(b) Case I: Minimum time-to-change

(c) Case II: Maximum time-to-change

1. Unnecessary deceleration
2. Unnecessary acceleration
3. Idling

(a) Approaching in green time

- In Green Time
  - Enough time for a guaranteed pass?
  - $d > d_i$:
    - No
      - $t_{min} < g_{min}$
        - No Stop with prescribed profile
        - Yes Accelerating to or keep speed at $v_m$
    - Yes
      - $t_{min} < g_{min}$
        - No Stop with prescribed profile
        - Yes Accelerating to or keep speed at $v_m$

(b) Approaching in yellow time

- In Yellow Time
  - $t_{min} > y$:
    - Yes Stop with prescribed profile
    - No Accelerating to or keep speed at $v_m$

(c) Approaching in red time

- In Red Time
  - Possibly cross on red if speed up?
    - No
      - $d > d_i$
        - Yes $d/v_{max} < v_c$
          - Yes Accelerating to or keep speed at $v_m$
          - No Need acceleration?
            - Yes Accelerating/Decelerating to uniform speed $d/v_{max}$
            - No Keep current speed $v_c$
    - Yes $d/v_{max} < v_c$
      - No Stop with prescribed profile
      - Yes $d/v_{max} < v_c$
State Machine for Target Speed Display

Condition Set 1 – $A \cup B \cup C \cup D$
- A. Vehicle is out of the target corridor
- B. DSRC or GPS signal is lost
- C. Estimated time-to-collision (TTC) is less than $T_2$ seconds
- D. Measured distance is less than $d_1$ meters

"Opt-in" mode (display recommended speed)

Condition Set 1 is satisfied

"Opt-out" mode (not display recommended speed)

Condition Set 2 is satisfied

Condition Set 2 -- $A \cap B \cap C \cap D$
- A. Vehicle is traveling along the target corridor with good DSRC and GPS signals
- B. Estimated time-to-collision (TTC) is greater than $T_3$ seconds
- C. Measured distance is greater than $d_2$ meters
- D. Last transition (from "opt-in") occurred more than $T_1$ (e.g., $T_1=2$) seconds ago
Field Testing in Riverside, CA

Field study location in Palmyrita Ave, Riverside CA

Test platform

Roadside and on-board components

Signal controller
Road-side computer and DSRC
On-board DSRC
Vehicle computer
Driver display

OBD data  Radar data
Evaluation Methodology

To comprehensively evaluate possible signal and traffic conditions for eco-approach and departure at an actuated-signalized intersection, we defined four typical scenarios in the test.

<table>
<thead>
<tr>
<th></th>
<th>Cross street</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>Mild traffic</strong></td>
</tr>
<tr>
<td><strong>Main street</strong></td>
<td><strong>Mild traffic</strong></td>
</tr>
<tr>
<td></td>
<td>① Minimum green Minimum red</td>
</tr>
<tr>
<td></td>
<td>Likely to be leading vehicle Target speed display: On</td>
</tr>
<tr>
<td><strong>Heavy traffic</strong></td>
<td>③ Maximum green Minimum red</td>
</tr>
<tr>
<td></td>
<td>Likely to be following vehicle Target speed display: Off</td>
</tr>
</tbody>
</table>
Results: Trajectories for Scenario 1

- : informed drivers, 35 mph as the entry speed
- : informed drivers, 25 mph
- : uninformed drivers, 35 mph
- : uninformed drivers, 25 mph
Results: Trajectories for Scenario 4

- Informed drivers, 35 mph
- Informed drivers, 25 mph
- Uninformed drivers, 35 mph
- Uninformed drivers, 25 mph
# Results: Percentage Savings of Fuels

<table>
<thead>
<tr>
<th>Main street</th>
<th>Cross street</th>
<th>Mild traffic</th>
<th>Heavy traffic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mild traffic</td>
<td></td>
<td>G5</td>
<td>G15</td>
</tr>
<tr>
<td>35\text{mph}</td>
<td></td>
<td>43.4</td>
<td>13.0</td>
</tr>
<tr>
<td>25\text{mph}</td>
<td></td>
<td>19.5</td>
<td>8.3</td>
</tr>
<tr>
<td>Heavy traffic</td>
<td></td>
<td>G25</td>
<td>G35</td>
</tr>
<tr>
<td>35\text{mph}</td>
<td></td>
<td>11.6</td>
<td>8.5</td>
</tr>
<tr>
<td>25\text{mph}</td>
<td></td>
<td>15.3</td>
<td>37.3</td>
</tr>
</tbody>
</table>
Field Testing in Palo Alto, CA
Human-Machine Interface (HMI) Design

Case 1: No preceding vehicle. Target speed displayed.

Case 2: With preceding vehicle, Target speed not displayed.
Impact of EAD

- Percentage of low-speed mode (i.e. speed between 0~15 mph) drops significantly
- Percentage of relatively high speed cases is reduced
- The EAD system is activated for 22% of the entire trips, saving 6% energy and reducing 6% of CO₂, 32% of CO, 30% of HC and 24% of NOx.
- For all trips, the proposed system also reduced 2% of fuel and CO₂, 7% of CO, 18% of HC and 13% of NOx.
GlidePath

- EAD with Partial Automation (Tested in TFHRC in McLean, VA)

Ford Escape Hybrid developed by TORC with ByWire XGV System
## Summary of Connected EAD Studies

<table>
<thead>
<tr>
<th>Technology</th>
<th>Approach</th>
<th>Description</th>
<th>Energy Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Corridors</strong></td>
<td>Numerical Simulation</td>
<td>Arterial velocity planning based on traffic signal information under light traffic conditions</td>
<td>12-14%</td>
</tr>
<tr>
<td></td>
<td>Numerical Simulation</td>
<td>Dynamic eco-driving for signalized arterial corridors</td>
<td>12%</td>
</tr>
<tr>
<td></td>
<td>Micro-Simulation</td>
<td>Dynamic eco-driving for corridors and its indirect network-wide energy/emissions benefits</td>
<td>4%</td>
</tr>
<tr>
<td><strong>Connected Vehicles</strong></td>
<td>Micro-Simulation</td>
<td>Simulation of an enhanced eco-approach traffic signal application for Connected Vehicles</td>
<td>7%-11%</td>
</tr>
<tr>
<td><strong>Fixed Signals</strong></td>
<td>Field Test in McLean, VA</td>
<td>Manually following speed advice to pass through an intersection with fixed-time signal control in a controlled environment with no traffic</td>
<td>10-20%</td>
</tr>
<tr>
<td><strong>Actuated Signals</strong></td>
<td>Numerical Simulation</td>
<td>Framework development of EAD application for actuated signal control</td>
<td>3%-11%</td>
</tr>
<tr>
<td></td>
<td>Field Test in Riverside, CA</td>
<td>Manually following speed advice to pass through an intersection with actuated signal control in a controlled environment with no traffic</td>
<td>5-25%</td>
</tr>
<tr>
<td></td>
<td>Field Test in Palo Alto, CA</td>
<td>Manually following speed advice to pass through a corridor with actuated signal control in the real world traffic in El Camino Real testbed</td>
<td>7%</td>
</tr>
<tr>
<td><strong>Partial Vehicle Automation</strong></td>
<td>Numerical Simulation</td>
<td>Comparison between the trajectories of HMI-based manual driving and partially automated driving</td>
<td>5%-7%</td>
</tr>
<tr>
<td></td>
<td>Field Test in McLean, VA</td>
<td>Automatically following of speed advice to pass through an intersection with fixed-time signal control in a controlled environment with no traffic</td>
<td>10-20%</td>
</tr>
<tr>
<td><strong>EAD in Traffic</strong></td>
<td>Numerical Simulation</td>
<td>Prediction based EAD trajectory design considering preceding traffic</td>
<td>4.5%</td>
</tr>
</tbody>
</table>
Eco-FRATIS

- Eco-friendly Freight Advanced Traveler Information System
  - Integration of operational and environmental improvement technologies
  - 1-year demonstration at the Port of Los Angeles
Eco-FRATIS

Truck Eco-Drive

Drayage Trucks

On-Board Radar
  Preceding Vehicle’s Activity

On-Board Diagnostics
  Speed/Acceleration

City TMC

Real-time SPaT

Green Band

4G Network

Truck Eco-Drive Planner

Eco-Approach and Departure
Eco-Drive in Green Band
Display State Machine

Driver-Vehicle Interface

Speed Recommendation
Green Band Visualization

Onboard Digital Map

Distance-to-Intersection

GPS
Connected Eco-Bus

- An Innovative Vehicle-Powertrain Eco-Operation System for Efficient Plug-In Hybrid Electric Buses
  - Co-optimization of vehicle dynamics and powertrain control
  - 20% energy consumption reduction target
Eco-Traffic Signal Timing Application

- 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

- 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 from vehicles approaching the intersection, such as a transit vehicle’s adherence to its schedule, the passenger number on the transit vehicle, or weight of a truck is also 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
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 calculates 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.

~4.5% Energy Benefit
Eco-Cooperative Adaptive Cruise Control (CACC) Application

- 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.
- Up to 19% fuel savings on a real-world freeway corridor.
Lessons Learned (Eco-Signal Operations)

ECO-SIGNAL OPERATIONS

Free Flow Traffic Conditions

- Eco-Approach & Departure
- Connected Eco-Driving
- Arterial Speed Harmonization (partially modeled)
- Eco-Traffic Signal Priority
- Eco-Traffic Signal Timing
- Wireless Inductive / Resonance Charging (not modeled)

Congested Traffic Conditions

When traffic conditions are severely congested, there are limited opportunities for Connected Vehicle Applications of all types to provide mobility or environmental benefits.
Lessons Learned (Eco-Lanes)

When traffic conditions are severely congested, there are excellent opportunities for Eco-CACC to provide mobility & environmental benefits.

- Eco-Speed Harmonization
- Eco-Cooperative Adaptive Cruise Control
- Combined Application of ESH + Eco-CACC
Thank you
Questions or Comments?