Advanced Traffic Management on Arterial Corridors with Connected and Automated Vehicles

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Outline:

• arterial traffic measurement (for energy and emissions estimation)
• connected vehicles
• USDOT AERIS program efforts
• role of automation on arterial roadways
UCR’s Bourns College of Engineering
Center for Environmental Research and Technology
Transportation Systems Research Group
Research Areas of Interest:

• Environmental and Mobility Impacts of Intelligent Transportation Systems
• Applications of Integrated Transportation / Emissions Modeling: current (freight) and future applications (connected and automated vehicles)
• Innovative Navigation Systems, Mapping & Positioning, Digital Infrastructure
Traffic Activity

Freeway Traffic (uninterrupted flow)
- Speed (mph)
- Flow (veh/hr)
- Density (veh/mile)

Arterial Traffic (interrupted flow)
- (Link) Travel Time Distribution

PeMS (Inductive loop detector)

Fixed-location Sensors (re-identification)

Sparse Mobile Data
Energy/Emissions

Microscopic

Portable Emission Measurement System
- High variability
- Take space in trunk

OBD-II

Vehicle activity (e.g. speed trajectory)

Microscale Emissions Model (e.g. CMEM)

Energy/Emission
Energy/Emissions

Microscopic

Mesoscopic

Macroscopic

Vehicle activity (e.g. speed trajectory)

Microscale Emissions Model (e.g. CMEM)

Energy/Emission

Traffic Monitoring System

Traffic Activity (average speed)

Off-line

Real-time
Travel Time Measurement

After vehicle re-identification

\[ T T_{s1s2}, D_{fixed} \]

Sparse data

\[ t_{x1}, t_{x3}, (\text{lat, lon})_{x1}, (\text{lat, lon})_{x3} \]

After map matching

\[ T T_{x1x3}, Dist_{x1x3} \]
Travel Time Distribution (TTD)

Freeway (Single-Mode)

Arterial (Multi-Mode)
(Free flow travel time + Delay time)

Solution: Modified Gaussian Mixture Model to obtain distributions
Example Results: Emission and Fuel Consumption Evaluation (56 stop probe trajectories from intersection 6 at Telegraph Rd, Chula Vista)

vehicle type: sedan

CMEM

69% → 97%
**Connected Vehicles:** providing better interaction between vehicles and between vehicles and infrastructure

- increased **Safety**
- better **Mobility**
- lower **Environment impact**
## Connected Vehicle Applications (Phase 1)

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<th><strong>Environment</strong></th>
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<td>Incident Scene Work Zone Alerts for Drivers and Workers (INC-ZONE)</td>
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<td>Emergency Communications and Evacuation (EVAC)</td>
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<td>Do Not Pass Warning (DNPW)</td>
<td>Eco-Smart Parking</td>
<td>Connection Protection (T-CONNECT)</td>
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<td>Vehicle Turning Right in Front of Bus Warning (Transit)</td>
<td>Dynamic Eco-Routing (light vehicle, transit, freight)</td>
<td>Dynamic Transit Operations (T-DISP)</td>
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<td>Eco-ICM Decision Support System</td>
<td>Dynamic Ridesharing (D-RIDE)</td>
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<td>Probe-enabled Traffic Monitoring</td>
<td>Motorist Advisories and Warnings (MAW)</td>
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<td>Vehicle Classification-based Traffic Studies</td>
<td>Enhanced MDSS</td>
<td>Smart Roadside</td>
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<td>CV-enabled Turning Movement &amp; Intersection Analysis</td>
<td>Vehicle Data Translator (VDT)</td>
<td>Wireless Inspection</td>
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<td>CV-enabled Origin-Destination Studies</td>
<td>Weather Response Traffic Information (WxTINFO)</td>
<td>Smart Truck Parking</td>
</tr>
<tr>
<td>Work Zone Traveler Information</td>
<td><strong>Smart Roadside</strong></td>
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Vision – Cleaner Air Through Smarter Transportation
  
  • Encourage the development and deployment of technologies and applications that support a more sustainable relationship between surface transportation and the environment through fuel-use reductions and more efficient use of transportation services.

Objectives – Investigate whether it is possible and feasible to:
  
  • Identify connected vehicle applications that could provide environmental impact reduction benefits via reduced fuel use, improved vehicle efficiency, 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 a prototype for one of the applications to test its efficacy and usefulness.
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
Vehicle Equipped with the Eco-Approach and Departure at Signalized Intersections Application (CACC capabilities optional)

Source: Noblis, November 2013
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
Eco-Approach and Departure Scenario Diagram

Intersection of interest

Analysis Boundary

DSRC Range

Vehicle 2
Vehicle 1
Vehicle 3
Vehicle 4

Phase 1
Accelerating

Phase 2
Cruising

Phase 3
Decelerating

Phase 4
Idling

Phase 5
Accelerating
Scenario 1: Maintain speed to pass through green

- The vehicle passes through the intersection on the green phase without having to slow down or speed up
- Environmental benefits result from maintaining speed and reducing unnecessary accelerations
Scenario 2: Speed Up to pass through green

- The vehicle needs to safely speed up to pass through the intersection on a green phase.
- Energy savings result from the vehicle avoiding a stop and idling at the intersection.
Scenario 3: Coast to stop at Intersection

- The vehicle cannot make the green light and needs to slow down to stop at the signalized intersection
- Energy savings result from slowing down sooner and coasting to the stop bar
- Once stopped, the vehicle could engage engine start-stop capabilities
Scenario 4: Slow Down to pass through Intersection

- The vehicle needs to slow down to pass through the intersection on a green phase
- Energy savings result from the vehicle avoiding stopping and idling at the intersection
Simulation Modeling…

baseline

eo eco approach & departure
Major Research Efforts in EAD:

- FHWA Exploratory Advanced Research Program (EAR) in Advanced Traffic Signalization (2012 – present)
  - Phase 1: simulation and fixed time signal trials with BMW
  - Phase 2: simulation and actuated signal trials
- USDOT University Transportation Research Program supported several similar efforts
- USDOT AERIS: Applications for the Environment: Real-Time Information Synthesis
  - Phase 1: demonstration at TFHRC
  - Phase 2: extensive simulation modeling in traffic, sensitivity analyses
- FHWA GlidePath Project: applying partial automation
- Europe: GLOSA (Green Light Optimal Speed Advisory)
  - Compass4D
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
- **Level of Automation**: driver vehicle interface or some degree of automation
- **Field Studies**: typically limited to a few instrumented single vehicles, constrained infrastructure
- **Simulation Modeling**: multiple vehicles, examining the sensitivity of other variables
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

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

EAD Algorithm for Actuated Signal

AERIS Modeling Overview

- A traffic simulation model (e.g., Paramics) was combined with an emissions model (e.g., EPA’s MOVES model) to estimate the potential environmental benefits.

- Application algorithms were developed by the AERIS team and implemented as new software components in the traffic simulation models.

- Modeling results indicate a possible outcome – results may vary depending on the baseline conditions, geographic characteristics of the corridor, etc.
AERIS Modeling Network

- **El Camino Real Network**
  - Signalized, urban arterial (27 intersections) in northern California
  - 6.5 mile segment between Churchill Avenue in Palo Alto and Grant Road in Mountain View
  - For the majority of the corridor, there are three lanes in each direction
  - Intersection spacing varies between 650 feet to 1,600 feet
  - 40 mph speed limit
  - Vehicle demands and OD patterns were calibrated for a typical weekday in summer 2005 (high volumes on the mainline)
  - Vehicle mix (98.8% light vehicles; 1.2% heavy vehicles)
Eco-Approach and Departure at Signalized Intersections Application: **Modeling Results**

### Summary of Preliminary 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
### EAD Dimensions of Analysis

<table>
<thead>
<tr>
<th>Single Vehicle</th>
<th>Fixed-time Signals</th>
<th>Actuated Signals</th>
</tr>
</thead>
</table>
| **Vehicle in Traffic** | **Field study 2012** *(FHWA EAR P1, AERIS)*  
**Simulation modeling 2012** *(AERIS)*  
**GlidePath** | **Field studies 2014/15** *(FHWA-EAR-P2 @PATH FHWA-EAR-P2 @UCR)*  
**Limited simulation modeling 2014** *(FHWA-EAR-P2)* |
| | **Vehicle Control:** | |
| Driver with DVI | **longitudinal control**  
*(GlidePath project, 2014/15)* | **longitudinal control**  
*with V2V* |
Merging of Connected Vehicles and Automation

**Autonomous Vehicle**
Operates in isolation from other vehicles using internal sensors

Traffic operations with **autonomous vehicles** will not likely change much
- Mobility and Environmental impacts will remain the same or could even get worse
- Partial Automation Example: automated cruise control (ACC) has been shown to have negative traffic mobility impacts

**Connected Automated Vehicle**
Leverages autonomous and connected vehicle capabilities

Traffic operations with **connected automated vehicles** will have a improved mobility and environmental impacts

**Connected Vehicle**
Communicates with nearby vehicles and infrastructure
GlidePath Prototype Application

Objectives and Period of Performance

▪ Project Objectives
  • Develop a working prototype GlidePath application with automated longitudinal control for demonstration and future research;
  • Evaluate the performance of the algorithm and automated prototype (specifically, the energy savings and environmental benefits);
  • Conduct testing and demonstrations of the application at TFHRC

▪ Period of Performance:
  • May 2014 through December 2015
GlidePath Prototype Application
High-Level System Architecture

- Component Systems
  - Roadside Infrastructure
    - Signal Controller
    - SPaT Black Box
    - DSRC RSU
  - Automated Vehicle
    - Existing Capabilities
    - Additional Functionality
  - Algorithm
    - Objective
    - Input
    - Output
GlidePath Prototype Application
Components – Architecture

1. Traffic Signal Controller
2. SPaT Black Box
3. Roadside Unit
4. Onboard Unit
5. Onboard Computer with Automated Longitudinal Control Capabilities
6. Driver-Vehicle Interface
7. Evaluation: Data post-processed by UC-Riverside using EPA’s MOVES Model

Evaluation:
Data post-processed by UC-Riverside using EPA’s MOVES Model

Backhaul:
Communications back to TFHRC

The roadside unit transmits SPaT and MAP messages using DSRC

Onboard Computer with Automated Longitudinal Control Capabilities

U.S. Department of Transportation
Notes:
1. Primary RSU is installed on the mast arm on the west side of the intersection and connected to Cabinet 6 of the Saxton roadside infrastructure.
2. Secondary RSU is installed on a pole and connected to Cabinet 1 of the Saxton roadside infrastructure along the entrance road from GW Parkway.
3. Econolite signal controller and SPaT blackbox location.

Note: Secondary RSU added to extend communications range caused by line of sight issues.
GlidePath Prototype Application

Components – Automated Vehicle

- Ford Escape Hybrid developed by TORC with ByWire XGV System
  - Existing Capabilities
    - Full-Range Longitudinal Speed Control
    - Emergency Stop and Manual Override
  - Additional Functionality
    - Computing Platform with EAD Algorithm
    - DSRC OBU
    - High-Accuracy Positioning Solution
    - Driver Indicators/Information Display
    - User-Activated System Resume
    - Data Logging
The field experimentation will be organized into three stages

|------------------------------------------|--------|

**Stage II:** Manual-DVI Driver  
(2012 AERIS experiment)

**Stage III:** Automated Driver
Expected Scenario Outcome for Test Runs

<table>
<thead>
<tr>
<th>Current Phase</th>
<th>Red</th>
<th>Y</th>
<th>Green</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \begin{array}{c} V \ t \end{array} )</td>
<td>0</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>20 mph</td>
<td>15</td>
<td>20</td>
<td>25</td>
</tr>
<tr>
<td>25 mph</td>
<td>30</td>
<td>35</td>
<td>40</td>
</tr>
<tr>
<td>30 mph</td>
<td>45</td>
<td>50</td>
<td>55</td>
</tr>
<tr>
<td>(trials)</td>
<td>Scenario 1</td>
<td>Scenario 2</td>
<td>Scenario 4</td>
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**Scenarios will be run in each of the three (3) stages:**
- **Stage I:** Manual-uninformed driver
- **Stage II:** Manual-DVI driver
- **Stage III:** Automated driver
GlidePath Prototype Application
Preliminary Results

Table 1. Example driver’s fuel consumption (g/mi) for different entry time (speed 20 mph)

<table>
<thead>
<tr>
<th>Phase</th>
<th>Green</th>
<th>Red</th>
<th>Avg.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time (s)</td>
<td>2</td>
<td>7</td>
<td>12</td>
</tr>
<tr>
<td>Stage 2 vs. Stage 1</td>
<td>-11.80</td>
<td>-11.75</td>
<td>7.59</td>
</tr>
<tr>
<td>(DVI vs. Uninformed Driver)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stage 3 vs. Stage 1</td>
<td>4.67</td>
<td>7.55</td>
<td>35.25</td>
</tr>
<tr>
<td>(Automated vs. Uninformed Driver)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stage 3 vs. Stage 2</td>
<td>14.73</td>
<td>17.27</td>
<td>29.93</td>
</tr>
<tr>
<td>(Automated vs. DVI)</td>
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</table>

- Four different drivers were part of the experimentation, each conducting Stage I, II, and III at two different speeds (20 mph and 25 mph)

- General Results thus far:
  - DVI (Stage II) improved fuel economy over uninformed driving (Stage I) by only 5% on average, with a wide range of responses (18% standard deviation)
  - Some drivers with the DVI (Stage II) performed worse than uninformed driving (Stage I)
  - Automation (Stage III) improved fuel economy over uninformed driving (Stage I) by 20% on average, within a narrow range of responses (6% standard deviation)
GlidePath Prototype Application
Lessons Learned

- Minimizing controller lag on the vehicle is important.
- The Eco-Approach and Departure at Signalized Intersections algorithm and vehicle control perform well with 2-meter positioning accuracy; however, precise positioning is more important near the intersection stop bar.
- “Creep” towards the intersection can feel very un-natural (under scenario 4).
### 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)*
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- 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

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

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.
CACC Applied to a General Freeway Segment

Baseline

Upstream Segment with CACC Platoon Formation

Downstream Segment with CACC Platoons
Eco-Cooperative Adaptive Cruise Control (CACC) Application: Modeling Results

- **Summary of Key Modeling Results**
  - Up to 19% fuel savings on a real-world freeway corridor
  - Up to an additional 7% fuel savings when using a dedicated “eco-lane” instead of general purpose lane on the freeway corridor
  - Up to 42% travel time savings on a real-world freeway corridor

- **Key Findings and Takeaways**
  - The presence of a single dedicated “eco-lane” leads to significant increases in overall network capacity
  - Drivers may maximize their energy and mobility savings by choosing to the dedicated “eco-lane”

- **Opportunities for Additional Research**
  - Increasing the number of dedicated lanes will likely further improve results
  - Quantifying relationship between platoon headway and increased network capacity is also of interest
Cooperative Adaptive Cruise Control applied to Intersections

Baseline: typical queuing

Arterial CACC Baseline
High Volume (800 vphpl)

CACC: ~17% less energy & emissions

Arterial CACC
High Volume (800 vphpl)
Cooperative Adaptive Cruise Control with Eco-Approach and Departure

• For isolated intersection:
  – Approach: platoon-based eco-approach
  – Departure: platoon discharges with minimum headway
AERIS OPERATIONAL SCENARIOS & APPLICATIONS

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- Connected Eco-Driver (similar to eco-driving strategies)
- Wireless Inductive/Resonance Charging

Traffic Energy Benefits
- 10% energy savings
- 5% energy savings
- 6% energy savings

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-Driver (similar to eco-driving)
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- Eco-Traveler Information Applications (similar to ATIS)

Traffic Energy Benefits
- 4.5% energy savings
- 19% energy savings

LOW EMISSIONS ZONES
- Low Emissions Zone Management (similar to Low Emissions Zones)
- Connected Eco-Driver (similar to eco-driving strategies)
- Eco-Traveler Information Applications (similar to ATIS)
Stages of Connected and Automated Vehicle Applications

**Phase 1:**
- Deploy DSRC radios in cars for safety, take advantage with compatible mobility and environmental applications (homogenous multi-agent systems, decentralized control)

**Phase 2:**
- Develop specifically designed mobility and environmental applications for greater benefits (heterogeneous multi-agent systems, decentralized and centralized control schemes, new message sets)

**Phase 3:**
- Phase 2, but also integrate connected and automated vehicle operations and applications with new infrastructure designs
Different Intersection Management Systems

- Stop Signs: 3 lanes, Speed: 2X
- Traffic Light: 3 lanes
- AIM: 3 lanes, Light Traffic, Speed: 2X

Intersection reservation system with automated connected vehicles

Source: David Kari, UCR, 2014
System architecture of multi-agent based dynamic reservation management

- Interaction between Multi-agents:
  - Car following
  - Reservation request
  - Accept (with arrival time assistance) or Reject
  - preplanned arrival information

Schedule vehicle agents arrival times based on:
- Priority-based policy (level 1): vehicle’s priorities
- Lane-based policy (level 2): vehicle’s lane position
- FCFS (first come, first serve) policy (level 3): based on vehicle’s requesting time
Simulation Analysis and Results

➢ Travel Time Improvement
  • Two direction traffic flow: Travel time reduction ranges from 45% to 87% depending on traffic volume.
  • Travel time has 2% reduction when communication range changes from 100 meters to 300 meters.

➢ Fuel consumption and Emissions Improvement
  Two direction traffic flow compared to traditional signal control system:
  • 41% to 71% reductions for CO
  • 65% to 75% for CO₂ and fuel consumption
  • 55% to 78% for HC
  • 63% to 74% for NOx

Round-about Merge Assist (RMA)

- Human drivers entering a round-about typically slow down to look for hazards such as other vehicles, bicyclists, and pedestrians
  - Slowing down reduces intersection throughput and increases vehicle emissions/energy

- Automation of round-about merging via automated merging and lateral maneuvers
  - Improves intersection throughput
  - Reduces vehicle emissions/energy consumption
  - Is a natural stepping stone to true continuous flow intersections
Why Automate Round-abouts?

Round-abouts are an excellent choice for incorporating lane merging maneuvers.

2. Automating round-abouts is less complex than automating traditional 4-way intersections (Automated Merging Maneuvers vs. Autonomous Intersection Management)

Automating traditional 4-way intersections requires reservation-based AIM (infrastructure calculates and broadcasts specific vehicle trajectories)

Automating round-abouts requires only automating lane merge maneuvers (infrastructure support is not strictly required)
Ultimate Arterial Lane Merge Scenario is with Continuous Flow Intersections
Key Take Away Points:

• Partial and full automation can provide better energy & emission results compared to human-machine interfaces, depending on design of control system.

• With automation, system design trade-offs will exist between safety, mobility, and the environment (e.g., automated maneuvers).

• Connected automated vehicles will likely have greater improvements in mobility and environment compared to autonomous vehicles.

• Basic Safety Messages can be used for energy and emissions estimates.

• Advanced Connected and Automated Vehicle operation will have a greater benefit with changes to the infrastructure.
Future Work: Synergies and Tradeoffs of Safety, Mobility, and Environment

Safety & Mobility:
- Collision avoidance
- Increased spacings

Safety & Energy:
- Electronic Brake Lights
- Conservative automated maneuvers

Mobility & Energy:
- CACC
- Higher speeds