Optimization, Modeling and Assessment of Smart City Transportation Systems

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Introduction

• The world has seen significant advances in wireless communication that have made it possible for vehicles, travelers, and infrastructure to be connected
  – Connected Vehicles (CVs), Connected Travelers (CTs), and Connected Infrastructure (CI)
• In addition vehicle automation has added a dimension of vehicle control that did not exist before
  – Connected Automated Vehicles (CAVs)
• Global warming is a challenge that we collectively have to address
• This presentation describes research attempts to use CAVs and CTs to reduce the transportation system carbon footprint


Collaborative Optimization and Planning for Transportation Energy Reduction (COPTER)

- Decision-theoretic, Multi-agent, Multi-provider Trip Planning
- Dynamic Ride Request Pooling
- Departure Time Optimization
- Personality-based Predictive User Modeling
- Multi-modal Transportation and Energy Simulation

**Demonstrated:** Providing the information to 10% of the travelers results in a 5.5% participation producing a 4% reduction in energy usage and 20% reduction in delay.
Multi-Modal Agent-based Simulation Model

Simulation Coordinator
Tracks traveler through simulations

INTEGRATION
Simulates arterials and highways

MesoSim
Simulates local roads

RailSim
Simulates LA Metro Rail lines

BPSim
Simulates walking and biking
Modeling of Road Network

- The proposed model attempts to achieve high fidelity modeling of highly traveled roadways and low fidelity on other roadways
  - Computationally efficient modeling of large networks
- A hybrid simulation approach is used
  - Microscopic:
    - Enables the highest possible accuracy.
    - Models freeways, major arterials, and minor arterials
  - Mesoscopic:
    - Computationally efficient modeling of large networks
    - Used for local roads
Modeling of Road Network
Modeling of Rail Systems

• Objective:
  – Develop a longitudinal train dynamics model that captures realistic train longitudinal motion and can be calibrated without any mechanical engine data, making it ideal for implementation in microscopic transportation simulation models

• Model developed using empirical data:
  – Data from the Tri-County Metropolitan Transportation District of Oregon (TriMet).
    • Information for the Metropolitan Area Express (MAX) Blue Line where the train trajectories were collected

Modeling of Rail Systems

- Virginia Tech Comprehensive Power-based Energy Model (VT-CPEM)
  - Energy consumption:
    \[ P(t) = \left( \frac{R(t) + (1+\lambda)ma(t)}{3600\eta_d} \right) v(t) \]
  - Energy regeneration:
    \[ \eta_{rb}(t) = \begin{cases} \left[ e^{\alpha/t} \right]^{-1} & \forall P(t) < 0 \\ 0 & \forall P(t) \geq 0 \end{cases} \]
    \[ P_B(t) = \begin{cases} \frac{P_W(t)}{\eta_D \cdot \eta_{EM} \cdot \eta_B} + P_A & \forall P_W(t) \geq 0 \\ P_W(t) \cdot \eta_D \cdot \eta_{EM} \cdot \eta_B \cdot \eta_{rb}(t) + P_A & \forall P_W(t) < 0 \end{cases} \]
    \[ P_W(t) = \left( ma(t) + R(t) \right) \cdot v(t) \]


Modeling Bicyclists

- Developed a dynamics-based cycling longitudinal motion model that captures cyclist training, pavement condition, gender, and grade effects.
Modeling Results

- Baseline: Driving routes planned for influenced population
- Best Case: Influenced population stays home
- CASM_1: Driving, carpooling, walking, biking, and transit routes are planned for influenced population using an assumed PQoS cost function
- CASM_2_ECO: Same as CASM_1, but all influenced driving trips are controlled by INTEGRATION’s eco-routing algorithm
- CASM_1_INF: Driving, walking, biking, and transit routes are planned for the influenced population and the actual route is determined by a stated preference influence model.
# Modeling Results

## Results for AM Peak/Off peak

<table>
<thead>
<tr>
<th></th>
<th>BASE</th>
<th>BEST</th>
<th>Mean Savings</th>
<th>Upper Bound</th>
<th>Lower Bound</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Fuel (L)</td>
<td>3,195,637</td>
<td>2,905,967</td>
<td>9%</td>
<td>10%</td>
<td>8%</td>
</tr>
<tr>
<td>Total Delay (s)</td>
<td>897,198,320</td>
<td>619,162,732</td>
<td>30%</td>
<td>37.2%</td>
<td>24.2%</td>
</tr>
</tbody>
</table>

## Results for PM Peak/Off peak

<table>
<thead>
<tr>
<th></th>
<th>BASE</th>
<th>BEST</th>
<th>Mean Savings</th>
<th>Upper Bound</th>
<th>Lower Bound</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Fuel (L)</td>
<td>3,487,982</td>
<td>3,162,249</td>
<td>9.3%</td>
<td>10%</td>
<td>8.3%</td>
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<tr>
<td>Total Delay (s)</td>
<td>1,350,493,856</td>
<td>961,607,536</td>
<td>28.8%</td>
<td>32.9%</td>
<td>24.7%</td>
</tr>
</tbody>
</table>
Modeling Results

• Upper bound benefits (remove 10% of the trips):
  – 9% reduction in energy and 30% reduction in delay
• Support for a 2-4% reduction in system-wide energy through messaging 10% (5% accept the recommendations) of the population without any monetary incentives
  – Eco-routed vehicles saved 17% in energy consumption
• Eco-driving (optimizing throttle based on traffic signals and grades) does not produce benefits in highly congested areas
INTEGRATED TRANSPORTATION AND COMMUNICATION SYSTEM MODELING


Integrating Transportation and Direct C-V2X Communication Modeling

• Current communication tools are slow and not scalable
  – Auto manufacturer modeled around 2000 vehicles traveling along a highway
    • Traffic mobility and communication modeling were decoupled
      – The simulation took several days to model 20 to 50 seconds of vehicle trajectories
  – There is an urgent need to develop a scalable and integrated (coupled) traffic and communication modeling tool

• The proposed effort addresses this urgent need
  – We developed an integrated traffic and communication modeling tool
    • Simulated an hour of the calibrated AM peak demand in downtown LA (145,000 vehicles with up to 30,000 concurrent vehicles)
      – The simulation took 1.5 actual hours to simulate 1.86 simulated hours coupling every 1 to 30s while capturing millisecond packet and deci-second vehicle interactions
Integrating Transportation and Direct C-V2X Communication Modeling

• The key contributions of this effort are:
  – Developed a scalable analytical communication model that captures packet movement at the milli-second level
    • Existing model could not model LA peak hour demand
  – Coupled the communication and traffic simulation models in real-time to develop a fully-integrated dynamic modeling tool
    • Each model runs at a different modeling frequency
      – Communication model abstraction runs at 1000Hz and simulation runs at 10Hz
  – Model coupling time step is dependent on the number of concurrent vehicles on the network
    • Ranges from 1 to 30s
Integrating Transportation and Direct C-V2X Communication Modeling

- The model computes the spatiotemporal PDR
  - Can identify communication holes and hotspots
Eco-routing Application Considering DSRC Communication to RSUs

• For the ideal communication assumption, increasing the market penetration resulted in improvements in the network-wide fuel consumption levels.
  – Market penetration levels between 20% and 30% resulted in acceptable performance.

• Using realistic communication modeling showed a trade-off when increasing the market penetration of CVs.
  – At low penetration rates, the performance is acceptable because of the low packet drop rates.
  – Increasing the market penetration level results in increasing the fuel consumption because of routing errors caused by delayed and dropped data packets.

• The VANET communication network performance (packet drop and delay) can have significant effects on a dynamic eco-routing system performance, especially in highly congested networks.
  – In some cases, resulting in network-gridlock.
DEVELOPING AN ECO-COOPERATIVE AUTOMATED CONTROL SYSTEM (ECO-CAC)

Proposed Eco-CAC System

Upper Level Strategic Controller

- Real-time Data Fusion
  - Strategic Speed Controller
    - Eco-router

Lower Level Controller

Local Controller (Interrupted Flow): Eco-CACC-I
- 1. SPaT Data
- 2. MAP Data
- 3. Topographical Data
  - Vehicle Dynamics Optimization

Local Controller (Uninterrupted Flow): Eco-CACC-U
- 1. User Input
  - Vehicle Dynamics Optimization
- 2. Topographical Data

Data Sources:
- 1. User Input
- 2. Topographical Data
- 3. Topographical Data

Vehicle Dynamics Optimization

Optimization

Real-time Data Fusion

SPaT Data

MAP Data

Topographical Data
CAV Eco-routing Algorithm

- Developed a vehicle-agnostic approach to collect transient vehicle data in real-time
  - Entire vehicle trajectory captured using 8 link-specific variables
- Data are sent to the cloud to be fused with existing data and then sent back to CAVs
  - Vehicle-specific link cost computed using the combination of vehicle parameters and the 8 link-specific variables
- Algorithm was implemented in INTEGRATION to generate
  - A dynamic, stochastic, incremental, multi-class, and user-equilibrium traffic assignment
    - Minimum paths computed using the Dijkstra algorithm

CAV Eco-routing Algorithm

- BEV eco-routing conflicts with TT-optimum routing
CAV Eco-routing Algorithm

- We introduced a multi-objective router that combines travel time and energy consumption
  
  \[ C_l = (1 - \alpha) \times TT_l + \alpha \times E_l \times \frac{\text{cost}\_\text{factor}}{\text{value}\_\text{time}} \]

- Considered: \( \alpha = 0.01 \) (MO1) and 0.05 (MO2), \( \text{value}\_\text{time} \) $10/h, \( \text{cost}\_\text{factor} \) $0.1319/kWh
Strategic Speed Controller Field Testing

- Developed SPD-HARM algorithm
- I-66 test bed proof of concept and field testing
  - Supported Leidos and FHWA run three vehicles across all three lanes of I-66
- Conducted simulation testing considering different levels of market penetration
Strategic Speed Controller Testing

• The SH algorithm increases the discharge rate of the bottleneck.
  – Increases by up to 2% with reductions in vehicular delay by approximately 20%;

• The algorithm reduces vehicle emissions and fuel consumption levels.
  – At MPR=100%, CO₂ and fuel consumption can be reduced by approximately 3.5%;

• When CAV MPR is very low, benefits of the SH algorithm cannot be observed, as non-CAV vehicles do not follow the control algorithm;
  – An MPR=10% is sufficient for the SH algorithm to work successfully.

• For the study section, a CAV flow of 400 veh/h (167 veh/h/lane) is sufficient to obtain significant savings in trip delays, emissions and fuel consumption levels.
Strategic Speed Controller

- Based on network gating control using the NFD
  - Use CV data to construct NFDs
  - Identify congested regions in real-time
  - Identify gating points to control CAV speeds
  - Traffic gating using SPD-HARM
  - Integrating traffic control with dynamic routing to develop fully-integrated network controllers


An arterial strategic speed controller was developed that regulates the traffic stream speed upstream of traffic signals entering a protected region

- Gating of traffic entering the protected region
- Computation of gating rate requires an estimate of the traffic signal timings

<table>
<thead>
<tr>
<th>Network-wide Performance</th>
<th>No SH</th>
<th>SMC-SH</th>
<th>Improvement (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg. Travel Time (s/veh)</td>
<td>757.44</td>
<td>626.65</td>
<td>17.27</td>
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<tr>
<td>Avg. Total Delay (s/veh)</td>
<td>299.42</td>
<td>24.97</td>
<td>18.18</td>
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<tr>
<td>Avg. Stopped Delay (s/veh)</td>
<td>144.85</td>
<td>126.38</td>
<td>12.76</td>
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<tr>
<td>Avg. Accel/Decal delay (s/veh)</td>
<td>154.57</td>
<td>118.60</td>
<td>23.27</td>
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<tr>
<td>Avg. Fuel (L/veh)</td>
<td>0.45</td>
<td>0.42</td>
<td>5.91</td>
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<tr>
<td>Avg. CO₂ (g/veh)</td>
<td>1029.38</td>
<td>956.89</td>
<td>7.04</td>
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</table>

<table>
<thead>
<tr>
<th>Protected Network Performance</th>
<th>Improvement (%)</th>
</tr>
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<tbody>
<tr>
<td>Avg. Travel Time (s)</td>
<td>15.17</td>
</tr>
<tr>
<td>Avg. queued vehicles (veh)</td>
<td>18.22</td>
</tr>
<tr>
<td>Total CO₂ (g)</td>
<td>6.68</td>
</tr>
<tr>
<td>Total Fuel (I)</td>
<td>6.71</td>
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</tbody>
</table>
Strategic Speed Controller: Freeways

- A freeway strategic speed controller was developed for use on freeways
  - Automatically identifies the onset of congestion on a roadway segment
  - Starts regulating the speed on the link upstream of the congested link
  - SPD-HARM is activated and de-activated dynamically and at different locations along the freeway

### Network-wide Performance

<table>
<thead>
<tr>
<th></th>
<th>No SH</th>
<th>F-SMC-SH</th>
<th>Improvement (%)</th>
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</thead>
<tbody>
<tr>
<td>Avg. Travel Time (s/veh)</td>
<td>1034.27</td>
<td>908.37</td>
<td>12.17</td>
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<tr>
<td>Avg. Total Delay (s/veh)</td>
<td>557.46</td>
<td>442.25</td>
<td>20.67</td>
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<tr>
<td>Avg. Stopped Delay (s/veh)</td>
<td>256.77</td>
<td>155.13</td>
<td>39.58</td>
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<tr>
<td>Avg. Fuel (L/veh)</td>
<td>1.16</td>
<td>1.12</td>
<td>2.60</td>
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<tr>
<td>Avg. CO₂ (g/veh)</td>
<td>2482.13</td>
<td>2400.16</td>
<td>3.30</td>
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### Freeway Network Performance

<table>
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<tr>
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<th>Improvement (%)</th>
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<tbody>
<tr>
<td>Avg. Travel Time (s/veh)</td>
<td>20.48</td>
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<tr>
<td>Avg. queued vehicles (veh/link)</td>
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<tr>
<td>Avg. CO₂ (g/link)</td>
<td>3.75</td>
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<tr>
<td>Avg. Fuel (L/link)</td>
<td>2.56</td>
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## Eco-CACC-U Controller
### Potential Benefits

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<tr>
<th></th>
<th>HC</th>
<th>CO</th>
<th>NO\textsubscript{x}</th>
<th>CO\textsubscript{2}</th>
<th>Fuel</th>
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<tr>
<td><strong>VT-Micro Hwy</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Top 1 %</td>
<td>16 %</td>
<td>19 %</td>
<td>4 %</td>
<td>3 %</td>
<td>4 %</td>
</tr>
<tr>
<td>Top 2 %</td>
<td>24 %</td>
<td>30 %</td>
<td>7 %</td>
<td>6 %</td>
<td>7 %</td>
</tr>
<tr>
<td>Top 5 %</td>
<td>39 %</td>
<td>47 %</td>
<td>17 %</td>
<td>13 %</td>
<td>14 %</td>
</tr>
<tr>
<td>Top 10 %</td>
<td>54 %</td>
<td>64 %</td>
<td>32 %</td>
<td>23 %</td>
<td>25 %</td>
</tr>
<tr>
<td><strong>CMEM24 Hwy</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Top 1 %</td>
<td>20 %</td>
<td>38 %</td>
<td>30 %</td>
<td>3 %</td>
<td>5 %</td>
</tr>
<tr>
<td>Top 2 %</td>
<td>32 %</td>
<td>63 %</td>
<td>50 %</td>
<td>6 %</td>
<td>9 %</td>
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<tr>
<td>Top 5 %</td>
<td>52 %</td>
<td>80 %</td>
<td>73 %</td>
<td>14 %</td>
<td>17 %</td>
</tr>
<tr>
<td>Top 10 %</td>
<td>81 %</td>
<td>84 %</td>
<td>90 %</td>
<td>25 %</td>
<td>28 %</td>
</tr>
</tbody>
</table>

5/17/2021
Advancing Transportation Through Innovation
The behavior of ICEVs and BEVs in platoons is very different

- Optimum speed for ICEVs is much higher than that for BEVs

ICEVs (Opt. Speed 88 km/h)  
BEVs (Opt. Speed 27 km/h)
Eco-CACC-U Controller
Simulation Testing

- We developed a platooning controller that attempts to maintain relatively small time gaps between CAVs
- We assumed that a vehicle attempting to join a platoon can
  - increase its velocity by up to 7% beyond the speed limit (i.e., platooning speed) for a maximum duration of 6.5 s.


Eco-CACC-I Overview

• We developed an Eco-CACC system to compute the optimum vehicle trajectory
  – Using I2V and V2V communication
  – Explicitly optimizing vehicle fuel consumption
Eco-CACC-I Queue Prediction

- The model predicts the time at which the queue will be dissipated using kinematic wave theory
Eco-CACC-I Modeling Evaluation

- Benefits increase with increased market penetration
- Multi-lane approaches more challenging to deal with
Eco-CACC-I Field Implementation and Testing

- The system was implemented in an ACC-equipped vehicle and tested on the VDOT Smart Road
  - A total of 32 subjects were recruited
    - Equal male and female participants
  - Four scenarios:
    - S1: Uninformed driver
    - S2: In-vehicle indication count-down display
    - S3: In-vehicle audio speed recommendation every 2 seconds
    - S4: L2 automation from 250m upstream of the intersection to 180m downstream
Eco-CACC-I Field Results

- The automated Eco-CACC system reduced fuel consumption levels and travel time by up to 39 and 9 percent, respectively.
- The manual Eco-CACC system reduced fuel consumption levels and travel time by nearly 13 and 9 percent, respectively.
https://doi.org/10.1109/TITS.2020.2978184.


De-centralized Traffic Signal Control

- Developed a novel acyclic Nash Bargaining traffic signal control system
  - Objective is to control the queues on the various traffic signal approaches
  - Abandons the concept of a fixed cycle length
    - Extends or ends various phases using the NB technique
    - Jumps directly to phases that are needed
- The utilities for each player (phase) can be defined as the estimated sum of the queue lengths in each phase after applying a specific action.

\[
\tilde{q}_P(t + \Delta t) = \sum_{l \in P} (q_i^t + Q_{inl}\Delta t - Q_{outl}\Delta t)
\]
De-centralized Cycle-free Traffic Signal Controller

- System tested on numerous networks:
  - Main St., Blacksburg
  - Blacksburg
  - Downtown LA

<table>
<thead>
<tr>
<th>MOE</th>
<th>System</th>
<th>PSC</th>
<th>NB</th>
<th>NB Imp. (%)</th>
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<tbody>
<tr>
<td>Average Total Delay (s/veh)</td>
<td>557.463</td>
<td>476.346</td>
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<td>14.55</td>
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<td>Average Stopped Delay (s/veh)</td>
<td>256.766</td>
<td>192.116</td>
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<td>25.178</td>
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<tr>
<td>Average Travel Time (s)</td>
<td>1034.27</td>
<td>952.732</td>
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<td>7.89</td>
</tr>
<tr>
<td>Average Number of Stops</td>
<td>7.406</td>
<td>6.487</td>
<td></td>
<td>12.4</td>
</tr>
<tr>
<td>Average Fuel (L)</td>
<td>1.155</td>
<td>1.109</td>
<td></td>
<td>4.0</td>
</tr>
<tr>
<td>Average CO₂ (grams)</td>
<td>2482.13</td>
<td>2376.59</td>
<td></td>
<td>4.25</td>
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</table>

<table>
<thead>
<tr>
<th>MOEs</th>
<th>Travel time</th>
<th>Queue</th>
<th>Num. of Stops</th>
<th>CO₂</th>
<th>Fuel</th>
<th>Nox</th>
</tr>
</thead>
<tbody>
<tr>
<td>Int. #</td>
<td>Overall 457 Int. (%)</td>
<td>35.156</td>
<td>54.669</td>
<td>44.031</td>
<td>9.966</td>
<td>9.919</td>
</tr>
</tbody>
</table>
Thank you!

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540-231-1505