Vehicular Cyber-Physical Systems
(Or, Improving Your Commute)

Hari Balakrishnan
M.I.T.
CarTel project (cartel.csail.mit.edu)
The Challenge

- Road transportation presents an array of hard problems worldwide
- Accidents & hazards, congestion (routing & tolling), emissions & pollution, degrading infrastructure, telematics

Traffic Problems

Rush “Hour”

<table>
<thead>
<tr>
<th></th>
<th>1982</th>
<th>2005</th>
</tr>
</thead>
<tbody>
<tr>
<td>Morning Commute</td>
<td><img src="image1.png" alt="Graph" /></td>
<td><img src="image2.png" alt="Graph" /></td>
</tr>
<tr>
<td>Evening Commute</td>
<td><img src="image3.png" alt="Graph" /></td>
<td><img src="image4.png" alt="Graph" /></td>
</tr>
</tbody>
</table>

80% of world’s population is in places where automobile growth is occurring at >20% per year

Highway congestion costs $128 billion annually
Avg commuter travels 100 minutes a day
33% commuters stuck in very heavy traffic at least once/week

Source: Texas Transportation Institute; ABC News Survey.
Phones as Probes

- Gather <time, position, other data> samples from phone
- Map sequence of positions to a trajectory
- Estimate delays & other data for individual road segments
- Use in prediction, combining historic and current information

Phones as Probes: Challenges

Accuracy
- Errors & outages

Energy
- GPS is an energy hog: 400 mW for continuous monitoring
- Effective radiative power only $2 \times 10^{-11}$ W/m$^2$
  (Cf. cellular radio: 10 mW/m$^2$ – 117 dB difference!)

Location privacy

A. Thiagarajan, L. Sivalingam, K. LaCurts, S. Toledo, J. Eriksson, S. Madden, HB, Sensys, 2009
Idea: Trade-off Accuracy for Longer Battery Life

Energy consumption

GPS

GPS has outages and errors in urban canyons

Wi-Fi

Cellular all the time, WiFi some of the time, and GPS infrequently

Augment with accel & compass for turn hints

Accuracy of position samples

5-10m 75m 200m

Input: Radio Fingerprint Sequence

Base station / Access point | Signal strength

d8:30:62:5f:be:da | RSSI -94
00:0f:b5:3d:43:20 | RSSI -58
00:18:0a:30:00:a3 | RSSI -51

...
Current RF Localization Produces Poor Trajectories

- State-of-the-art: localize each RF fingerprint to best static location [PlaceLab]
- Ok for point localization – poor for tracks

CTrack: Accurate Trajectory Mapping with Cellular Signals

- Maximum-likelihood trajectory estimate
- Operates directly with fingerprints using a 2-stage hidden Markov model (“soft decision decoding”)
- 75% as accurate as 1 Hz GPS
- Energy comparable to GPS every 240 seconds (on Android G1)

A. Thiagarajan, L. Sivalingam, HB, S. Madden, NSDI 2011
Delays are Inherently Probabilistic

Speed (Delay/Length)

Traffic-Aware Stochastic Routing

• You need to reach the airport by 6 pm. You leave at 4.45 pm. What route should you take?
  – Want max probability route
  – Or, for a given probability of arrival, minimize time for arrival with at least that probability
• Goal: Credible routes & accurate estimates

• Practical solution for single-user planning
• Challenges: fast online re-routing, multi-user routing, multi-mode routing

Stochastic Routing Isn’t Easy

• Optimal substructure property doesn’t hold

PDFs of path delays A→B

<table>
<thead>
<tr>
<th>Path</th>
<th>Mean</th>
<th>St.dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>A→B</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>A→C</td>
<td>7</td>
<td>1</td>
</tr>
</tbody>
</table>

deadline time
Stochastic Routing Isn’t Easy

• Optimal substructure property \textit{doesn’t hold}

- Mean 5
- St. dev. 3

- Mean 7
- St. dev. 1

• Non-convex objective

Key Insights

\textit{Insight 1:} \text{min \ \text{Prob}(late)} \\
for \text{Gaussian is equivalent to:}

\text{minimize} \ \left \{ \text{paths} \right \} \quad \frac{\text{path mean} - t}{\sqrt{\text{path var.}}}

\textit{Insight 2:} \text{Visualize on mean-variance plane}

\textit{Insight 3:} \text{Solution is on bottom-left quadrant boundary}

Evdokia Nikolova, “Strategic Algorithms” (stochastic shortestpaths via quasi-convex maximization)
Practice: Pruned Parametric Optimization

- Set edge weight = $m_e + \lambda \cdot v_e$
- Search over $\lambda$ by running deterministic shortest paths with above weights
- Prune search space efficiently: $O(N^2 \text{ polylog } N)$ avg time
  - ~2-10 shortest path computations (~1-3 seconds)

Lim, HB, Madden, Rus, Stochastic Motion Planning and Applications to Traffic, IJRR 2010

Example: 4 pm MIT to Alewife

Google: “take Mass Av”
21% probability arriving in 20 min

CarTel: >95% probability arriving in 20 min

Google: Mean = 22 mins, stddev = 3 mins
CarTel: Mean = 15 mins (30% better), stddev = 1.5 mins
Conclusion

- Transportation is a “grand challenge” problem
- Vehicular cyber-physical systems combining mobile sensing, wireless networking, and mobile/cloud computing can help
- Many interesting problems
  - whose solutions have to be embedded in a complex social and physical context
- cartel.csail.mit.edu