Delay Pattern and Queue Length Estimation for Signalized Intersections Using Mobile Sensors

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What are Mobile Sensors (MS)?

- Traffic sensors that move with the flow they are monitoring and can provide detailed movement of individual vehicles
- A special form of probe vehicles
  - Global Positioning Systems (GPS) based devices
  - Cellular phones (if sufficient location accuracy can be achieved)
  - ETC readers or blue tooth MAC matching (if sufficient density of readers are available)
  - IntelliDrive
- What MS can bring to us?
  - New form of data (i.e. potentially traces of individual vehicles)
  - Tracking capability that enables new traffic network management schemes (mileage fee, path-based pricing, etc.)
MS Data vs. Fixed Location Sensor Data

- Fixed location sensor data: spatially discrete aggregated or disaggregated volume, speed, occupancy for the *entire* traffic flow
- MS data: spatially continuous traces of a *sample* of the traffic flow
- Observations:
  - Standard intersection traffic modeling methods that require volume, speed, occupancy as the input may not be directly used for MS data
  - It is more beneficial to fuse MS data and fixed location data to obtain a more complete picture of the traffic flow
MS Data under Relatively High Penetration

• Current practice: very low penetration

• Relatively high penetration (>=30%) is possible in the future
  – GPS cellular phones: cell phone penetration is nearly 100% in developed countries and 50% in developing countries (ITU, 2009)
  – IntelliDrive: may convert hundreds of thousands of vehicles into mobile sensors

• Opportunities
  – Provide new ways to obtain knowledge of the traffic system and to manage the system

• Challenges
  – New traffic modeling and system modeling techniques
  – Privacy protection
Arterial Modeling Using MS

- Signal performance evaluation
- Arterial traffic estimation and prediction
- Vehicle classification
- Emission modeling
- ...

Signal Performance Evaluation Using MS

• What mobile data to collect/use?
  – Modeling needs
  – Privacy protection (simply removing the IDs would not work!)
  – Cost of collecting the data

• Intersection travel times
  – Collected through Virtual Trip Lines (VTL)
  – Similar to the “Monument” concept (He, et al. 2002; Demers et al, 2006)
  – Preserve privacy (Hoh et al., 2008; Herrera et al., 2010)
I. Intersection Delay Pattern Estimation

• What is intersection delay pattern?
  – The delay an *imaginary* vehicle would have experienced if it had arrived at the intersection at a given time
  – A continuous approximation of the (discrete) measured vehicle delays
  – Helpful to answer questions like (e.g. at 3:00 pm):
    • What was the vehicle delay at 8:00 am at this intersection (*estimation*)?
    • What will the vehicle delay be at 8:00 pm (*prediction*)?
Delay Pattern Estimation Method

• Travel time / delay pattern reflects signal and traffic state changes
• Queue forming and discharging process at a traffic signal
  – Shockwave theory
  – Uniform arrival assumption
  – Linear approximation
  – Well known: Liu et al. (2009)
    Skabardonis and Geroliminis (2005); Lighthill and Whitham (1955); Richards (1956)
• Characteristics of signalized intersection delay patterns
  – Discontinuities: start of red
  – Non-smoothness: change of traffic states such as clear of the queue
• Delay estimation method
  – Reconstruct the piece-wise linear delay pattern from measured delays
Delay Pattern Estimation Method

- Geometry of the triangles
- Signal timing information
- Fundamental diagram

\[ s = \frac{u_f (w - u_w)}{w (u_f + u_w)} = \frac{v}{k_j} \left( \frac{1}{u_f} + \frac{1}{w} \right) - 1 \]

- Volume
- Shock wave speed
- Jam density
- Free flow speed

Slope of delay pattern curve
Role of Mobile Sensor Data

- Mobile sensors can directly provide discrete, sampled travel time (or delay) information
- The key is to estimate the (almost continuous) signal delay pattern using discrete sampled travel times
Delay Pattern Estimation Algorithm

• A curve fitting/estimation problem
  ➢ **Cycle breaking.** Detect the start of a new cycle.
  ➢ **Pattern matching.** Fitting the piecewise delay pattern curve using measured delay samples within a cycle by solving an estimation / optimization problem.
  ➢ **Cycle length adjustment** (for pre-timed signals). Calculate the average cycle length; adjust the lengths of neighboring cycles to make each cycle length is close to the average.
Naïve Cycle Breaking

• A threshold can be defined
• If the travel time increase exceeds this threshold, a new cycle starts
• Ideally, this threshold should equal to the red time of the new cycle
• In practice, we multiply a factor $0 < \alpha \leq 1$ to the red time to account for the fact that the exact discontinuity point may not be sampled directly.
Robust Cycle Breaking

- Apply Support Vector Machines (SVM) to travel time data set measured by MS
- Use change in arrival time ($dT$) and change in delay ($dD$) between two consecutive samples as the measures
- SVM can be formulated and solved as a quadratic optimization problem
- Test on some field test data
  - Training set: 15 minutes GPS data
  - Test set: 1 hour GPS data
- The penetration rate is 30%.
Experimental Data (C = 60 s)

Training set: magenta and cyan asterisks
Test set: red and blue dots

Error rate: 0.6%

Cycle breaking points

Non-cycle breaking points

\( w \cdot x = b - 1 \)
\( w \cdot x = b \)
\( w \cdot x = b + 1 \)
Pattern Matching Method

- Sample travel times: \( \{d_r, r \in R\} \)
- Timestamps: \( \{t_r, r \in R\} \)
- \( m: 3 \leq m \leq |R|-1 \), dividing all travel times into two groups
- A line needs to be fitted for each group of travel times – equivalent to solve the following quadratic program based on least square

\[
\min_{a_1, b_1, a_2, b_2} \sum_{1 \leq i \leq m-1} (a_1 t_i + b_1 - d_i)^2 + \sum_{m \leq i \leq |R|} (a_2 t_i + b_2 - d_i)^2
\]

s.t. \( a_1[(1-\theta)t_{m-1} + \theta t_m] + b_1 = a_2[(1-\theta)t_{m-1} + \theta t_m] + b_2 \)

Why 30%?
- 2 samples for each line segment
- 2 line segments for one normal cycle
- 3 line segments for one over-saturated cycle
- Assume cycle length = 60 seconds (60 cycles/hour), and 20% cycles are over-saturated
- Total number of required samples: \( 2 \times 60 \times (2 \times 0.8 + 3 \times 0.2) = 264 \)
- Assume volume = 900 vph
- Penetration rate = 30%
Results - Albany, CA

• Test site: the intersection of San Pablo Ave and Solano Ave in Albany, CA;
• Intersection is actuated/coordinated with a cycle length 108 s;
• Two sets of wireless traffic sensors installed upstream and downstream of the intersection
• Travel times of 140 vehicles for a 30 minute period (1:00- 1:30 pm) were generated via a vehicle re-identification algorithm, 50% - 60% of all vehicles
Estimated Delay Pattern

- Results: 88% of estimated delays are within 15% of the observed delays
Results - Albany, NY

- A Field test conducted in the Albany, NY area during a PM rush hour in November, 2009.
- 9 Drivers equipped with GPS loggers repeatedly drove over the intersection of Route-4 vs. Jordan Rd by making a left turn onto Route-4 NB.
- Totally 126 travel time measurements were collected. The penetration rate of the equipped vehicles is about 30%.
- Video cameras were located at the upstream and downstream of the intersection to record travel times of all vehicles (ground truth).
RPI Tech Park

Jordan 105/145/165 Parking Lot (Staging Area)

Alexis Dinner Parking Lot

Experimental Site
Results – Albany, NY (30%)

Success rate: 50%
Error: 4.6%; 97.5% under 15%
Evaluated using all samples:
Error: 7.2%; 86.8% under 15%
Results – Albany NY (100%)

Success rate: 80%
Error: 6.7%; 85.6% under 15%
Penetration Rate

Error

Success Rate
II. Queue Length Estimation

• The intersection delay pattern also describes how the queue length varies over time (approximately linearly)
• Also based on the \textit{uniform arrival} assumption
• \textbf{Delay-based} definition of queued vehicles
  – Queued vehicles are usually identified manually by visual assessment
  – Moving queue is hard to define
  – Queued vehicles are associated delays
  – Measure the minimum travel time of all vehicles passing the intersection
  – Use a threshold $\Delta T$ to distinguish queued and non-queued vehicles
Queue Length (30%)
Queue Length (100%)
### Characteristics of arrival patterns within a cycle:
- **SO**: Spread Out
- **NAB**: No Arrival at the Beginning of the cycle
- **NAM**: No Arrival in the Middle of the cycle
- **NAR**: No Arrival in the Rear of the cycle

### Observations:
- Uniform arrival can approximate SO well, but not NAB/NAM/NAR

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<th>ID</th>
<th>Estimated Queue Length</th>
<th>Observed Queue Length</th>
<th>Relative Percentage Error (%)</th>
<th>Arrival Pattern</th>
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<td>NAM/NAR</td>
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Results - NGSIM

• Provided by Federal Highway Administration (FHWA)
• Trajectories were transcribed from video data on a segment of Peachtree Street in Atlanta, Georgia
• Analysis on one intersection for one time period (12:45pm-1:00pm)
Results

30%

100%
Issues and Limitations

• **Uniform arrival** assumption is the most problematic
• A more robust way is to focus on the discharging process
• A new method is under-development to estimate the *position* of a vehicle in the queue based on its delay information – this can provide a lower-bound of the maximum queue size
• **Success Rate**: Under a given penetration rate, the numbers of samples for different cycles may vary. The performance of the algorithm for a cycle depends on the number of samples in that cycle
Conclusions

• Under certain (restrictive) assumptions, intersection delay pattern and queue length can be estimated based on measured travel times from mobile sensors
• Using travel times only can ensure privacy
• The modeling approaches are a combination of basic traffic flow theory (e.g. shockwave theory) and estimation/optimization methods, which in certain sense represent an inverse process of standard intersection modeling approaches using data from fixed location sensors
• Model assumptions need to be relaxed
Future Research

• Relax uniform arrival assumption: study the queue discharging process and the platoon forming/dispersion process (*challenge* is how to model these processes using MS data)
• Estimate signal timing information from MS data
• Additional forms of MS data? Short vehicle traces (for vehicle classification and emission modeling)
• Data fusion
• *Privacy protection vs. data requirements for modeling?*

• Extend the models to arterial traffic modeling and prediction
• *Integrate the models with dynamic network control and guidance models*
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Publications


Thanks You!

• Questions?