A Data-Driven Paradigm for Arterial Traffic Flow Monitoring, Modeling, and Control

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Ideally, for an Intelligent System

If you cannot tell the system performance yesterday, you cannot hope to manage your system today.
State-of-the-Practice in Traveler Info.

- Usually traveler information is available for freeways, so far NO arterial travel information is available.
- New wireless sensing technologies that can re-identify vehicles is promising.
State-of-the-Practice in Signal Operations

- The majority of transportation agencies DO NOT monitor or archive traffic signal data.
- Benefit/Cost ratio of signal re-timing is about 40:1; but usually traffic signal systems will be re-timed every 2 ~ 5 years.
- Adaptive signal control is implemented sporadically because most of them can only deal with lightly-congested situations.
Research Roadmap(I)

1. High-Resolution Data Collection
2. Performance Measurement
3. Operational Improvement
4. Real-time Adaptive Signal Control
Research Roadmap (II)

Stochastic Traffic Flow Theory

Prediction and Est. Algorithms

V2X Communication

Driver Advisory

Powertrain Opt.
The SMART Signal System Architecture

Field

- Signal Detectors
- Local Data Collection Unit

TMC

- Data Server
  - Raw Data
  - Performance Measures
- Firewall
- Web Server

Users

- Traffic Engineers
  - Monitor, Performance report, Diagnosis
- Road Users
  - Travel Time, Delay, …
1st Gen. Data Collection

- Off-the-shelf
- Windows based

(TH 55 & Bonne)
2nd Gen. Data Collection

- Plug-and-play
- Linux based

(TH 13 & Lynn Ave)
Event-Based Data

Detector #8 on at 08:09:15.012; Vacant time is 7.902s

Green Phase #3 off at 08:09:16.761; Green duration time is 29.389s

Detector #9 off at 08:09:18.307; Occupy time is 0.687s

Yellow Phase #3 off at 08:09:20.244; Yellow duration time is 3.482s

Green Phase #1 on at 08:09:23.242; Red duration time is 172.806s
Research Implementation Sites

- 11 intersections on France Ave. in Bloomington (March 07 – June 09)
- 6 intersections on TH55 in Golden Valley (Feb. 08 – Sept. 09)
- 3 intersections on PCD in Eden Prairie (Current)
- 6 intersections in Pasadena, CA (Iteris, Current)
- 13 intersections on TH13 (Dec. 2011, Current)
- 10 intersections on TH55 and 5 loop detector stations for I-394 (December 2012, Expected)
Performance Measurement Algorithms

- Queue length estimation
  - Delay, Level of Services, number of stops

- Identification of oversaturated conditions
  - Oversaturation Severity Index (OSI)

- Travel time estimation
  - Personal trip delay, number of stops, carbon footprint on travel
Queue Length Estimation

- Instead of traditional input-output approach, we estimate queue length by taking advantage of queue discharge process
- Based on LWR shockwave theory
Queue Length Estimation

- Utilize the data collected by advance detector
- Identify Critical Points: A, B, C
Traffic State Identification

(a) Detector Occupancy Time

(b) Time Gap Between Consecutive Vehicles

Pattern I: Capacity condition \((q_m, k_m)\)
Pattern II: Free flow arrival \((q'_m, k'_m)\)

Break Point C
Travel Time Estimation

- Track a virtual probe vehicle
  - Signal delay
  - Queuing delay
  - Acceleration/deceleration/no-speed-change
Virtual Probe Decision Tree

Safe Space Headway?

Yes

Queue Ahead?

No

Signal Status

Yellow

Able to Cross?

Yes

Red

No

Desired Speed

Speed of Last Queued Vehicle

< = > = < = > = < =

A N D N A N D N A N D
Field Tests on TH55 in Minneapolis


TH 55  2635 ft  842 ft  1777 ft

Advanced detectors  Stopbar detectors  Additional detectors

Independent Evaluation of Performance Measures on TH55

- By Alliant Engr. Inc
- Queue length
  - Manually count the vehicles (Two persons per approach)
  - Four peak hours (July 22\textsuperscript{nd} and 23\textsuperscript{rd}, 2009)
- Travel time
  - Floating car method with GPS
  - Four peak hours (July 22\textsuperscript{nd} and 23\textsuperscript{rd}, 2009)
  - More than 70 runs
Results – Maximum Queue Length

July 22nd for TH55WB at Rhode Island Intersection (AM)

July 23rd for TH55WB at Rhode Island Intersection (AM)
Results – Maximum Queue Length

MaxQL-Estimation vs. MaxQL-Observation (AM & PM)

Observation (ft)

Estimation (ft)
Results – Travel Time

Travel Time Estimation vs. Observation (July 22 & 23)
Performance Measurements
(http://dotapp4.dot.state.mn.us/smartsignal/)

<table>
<thead>
<tr>
<th>Level of Service</th>
<th>Queue Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>A (&lt;10 sec)</td>
<td>&lt; 400 ft</td>
</tr>
<tr>
<td>B (10~20 sec)</td>
<td>400 ~ 800 ft</td>
</tr>
<tr>
<td>C (20~35 sec)</td>
<td>&gt;800 ft</td>
</tr>
<tr>
<td>D (35~55 sec)</td>
<td></td>
</tr>
<tr>
<td>E (55~80 sec)</td>
<td></td>
</tr>
<tr>
<td>F (&gt;80 sec)</td>
<td>Spillover</td>
</tr>
</tbody>
</table>
Operational Improvement

- Problem Diagnosis
  - Functional diagnosis
  - Performance diagnosis
- Parameter Fine-tuning
  - Correctable offset
  - Correctable split
- Automatic Retiming
  - Pseudo-adaptive
Offset Fine-tuning

- Traditional offset optimization is deterministic, using MIPs
- Intersection queue is either ignored or exogenous
- Our approach is data-driven, scenario-based, and intersection queue is endogenously considered
- Formulated as a stochastic program
Delay Formulation

Intersection i

Intersection i+1

\[ o_{i+1} \]

\[ r_{i+1} \]

\[ q_i^s \times h \]

\[ d_i^c \]

\[ o_i \]

\[ r_i \]

\[ d_i^g \]

\[ t_i^q \]

\[ A' \]

\[ B' \]

\[ C' \]

\[ A \]

\[ B \]

\[ C \]
## Results – Queue Reduction

Field Offsets: \{0, -24.9, -21.6, 4.6, -20.5, -11.9\}

Optimized Offsets: \{0, -21.4, -21, -20.9, -21.1, -21.2\}

<table>
<thead>
<tr>
<th></th>
<th>9/3/2009 (Field)</th>
<th>9/14/2009 (Optimized)</th>
<th>Change Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eastbound Average Delay (Sec)</td>
<td>11.98</td>
<td>10.14</td>
<td>-15.3%</td>
</tr>
<tr>
<td>Westbound Average Delay (Sec)</td>
<td>78.48</td>
<td>70.84</td>
<td>-9.7%</td>
</tr>
</tbody>
</table>
Results – Delay Reduction

**Intersection 4 EB**
- Original offset
- Optimized offset

**Intersection 6 EB**
- Original offset
- Optimized offset
On-going research

- V2X and Smart-phone applications
  - Driver speed advisory
  - Driver routing advisor in a signalized network
Driver Speed Advisory

Distance

Int. j+1

Queue

Vehicle trajectory without advisory

Int. j

Vehicle trajectory with speed advisory

Time
Vehicle Routing in Traffic Signal Network
Concluding Remarks

- Although traffic is traditionally modeled as “continuous flow”, traffic, after all, is discrete.
- Measuring traffic flow parameters using the data collected at the individual vehicle level
- Technological advances support such data collection at affordable prices
- A number of applications can be developed based on the availability of such data
Acknowledgements
THANK YOU!

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SMART-Signal Web Site:
http://signal.umn.edu