Sensor Network Design for Multimodal Freight Traffic Surveillance

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(Joint work with Xiaopeng Li and Yanfeng Ouyang)
Motivation

- **Challenge: Real-Time Traffic Information Surveillance and Estimation**
  - e.g., travel time estimation, traffic volume estimation
  - Traffic is unstable in congestion (Li et al, 2009), e.g., which increases the difficulty of estimation
  - Congestion is common at intermodal traffic connections
- **Helper: Sensor Technologies**
  - Accurately sample real-time traffic information
  - Increase the accuracy of estimation at the network level.
Background

- **Sensor Technologies**
  - Loop Detector
  - Video Camera
  - **RFID**: widely used vehicle detection method
    - *e.g.*, *I-Pass in Chicago*
    - **Identification of vehicles**
    - *30~100 ft typical detection range*
    - **Installation & operating costs** ($70,000+ per installation)

- **Problem: Where to Deploy Sensors?**
  - Maximize surveillance benefit for any installation budget
  - Consider potential sensor failures
    (Rajagopal and Varaiya, 2007; Carbunar, 2005)
Related Literature

• Sensor Location for Traffic Surveillance
  – Flow volume estimation in highway networks
  – Flow coverage in railroad networks (Ouyang et al. 2009)
  – Corridor travel time estimation (Ban et al. 2009)

• Facility Location
  – Discrete models (Daskin 1995; Drezner 1995)
  – Continuum models
    (Newell 1971, 1973; Daganzo and Newell 1986; Daganzo 1991)
  – Reliable models allowing for facility failure
    (Daskin 1983; Snyder and Daskin 2005; Cui et al. 2009; Li and Ouyang 2009)
Objective of Current Study

- Develop a Sensor Location Framework for Traffic Surveillance
  - General benefit measure
    - flow coverage
    - path coverage (Origin-Destination travel time estimation)
  - Suitable for general transportation network topology
  - Consider expected benefit under probabilistic sensor failures
Major Tasks

Team Work

- Mathematical model
- Solution techniques
- Case studies

My Focus

- Data Preparation for Chicago Case Study
  - Intermodal Transportation Network
  - Freight Traffic
- Analysis and Insights
Model and Solution Algorithm

- **Linear Integer Program**
  - Maximize expected flow coverage and path coverage
  - Probabilistic iid sensor failures
  - NP-hard

- **CPLEX**
  - Fails even for moderate-size instances

- **Greedy Heuristic**
  - Simple and intuitive
  - No optimality guarantee
  - May yield sub-optimal solution

- **Lagrangian Relaxation (LR)**
  - Works efficiently
  - Provides optimality gap (solution quality)
  - Embedded in a Branch & Bound framework to eliminate possible residual gaps

\[
\max_{h,e} \sum_{i \in \mathcal{I}} \sum_{j \in \mathcal{J}_i} \sum_{r=0}^{R_i-1} q^r (1-q) f_i \left[ -\beta_i m_{ij} h_{ijr} + (\beta_i m_{ij} + \beta_e) e_{ijr} \right]
\]

subject to

\[
\sum_{j \in \mathcal{J}_i} x_j \leq N,
\]

\[
\sum_{r=0}^{R_i-1} h_{ijr} = x_j, \forall i \in \mathcal{I}, \forall j \in \mathcal{J}_i,
\]

\[
\sum_{r=0}^{R_i-1} e_{ijr} = x_j, \forall i \in \mathcal{I}, \forall j \in \mathcal{J}_i,
\]

\[
\sum_{j \in \mathcal{J}_i} h_{ijr} \leq \begin{cases} 1, & r = 0, \forall i \in \mathcal{I}, \forall r = 0, 1, \ldots, R_i - 1, \\ \sum_{j \in \mathcal{J}_i} h_{ij(r-1)}, & \text{otherwise}, \forall i \in \mathcal{I}, \forall r = 0, 1, \ldots, R_i - 1. \end{cases}
\]

\[
\sum_{j \in \mathcal{J}_i} e_{ijr} \leq \sum_{j \in \mathcal{J}_i} h_{ijr}, \forall i \in \mathcal{I}, \forall r = 0, 1, \ldots, R_i - 1,
\]

\[
x_j, h_{ijr}, e_{ijr} \in \{0, 1\}, \forall i \in \mathcal{I}, \forall j \in \mathcal{J}_i, \forall r = 0, 1, \ldots, R_i - 1.
\]
Test Case: Sioux-Falls Network

- 24 candidate locations for potential sensor installations
- 528 O-D paths (obtained with shortest path algorithm)
- LR algorithm vs. CPLEX over 36 instances, within 1800 CPU seconds
  - LR beats CPLEX on almost all instances
  - LR yields optimal solution for 35 instances
  - CPLEX failed to yield optimal solution for 21 instances
  - CPLEX failed to yield a feasible solution for 4 instances
Chicago Case: Data Preparation

- Highway network & rail terminals
- Consider conjunctions as origin/destination of Chicago traffic
  - Ignore “through” traffic
  - Destination volume based on nearby population
  - Freight takes the shortest path (distance)
  - All rail freights are transferred at Terminals
Data Preparation – Freight Movement

- Macroscopic Freight Traffic Statistics
  - Traffic from other states -> Traffic Assignment
  - Traffic distribution
    - Terminal Capacity
    - Chicago Area Population

<table>
<thead>
<tr>
<th>(unit: thousand tons)</th>
<th>Inbound</th>
<th>Outbound</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Modes</td>
<td>384,554</td>
<td>398,993</td>
</tr>
<tr>
<td>Single Mode</td>
<td>371,023</td>
<td>381,750</td>
</tr>
<tr>
<td>Truck</td>
<td>312,279</td>
<td>294,611</td>
</tr>
<tr>
<td>Truck: Outer States</td>
<td>117,289</td>
<td>87,778</td>
</tr>
<tr>
<td>Rail</td>
<td>34,343</td>
<td>43,957</td>
</tr>
<tr>
<td>Multi Modes</td>
<td>5,926</td>
<td>9,864</td>
</tr>
</tbody>
</table>

(Source: Bureau of Transportation Statistics www.bts.gov/)
Network Representation

→ 89 total nodes
→ 363 total links
→ 1046 O-D flows

Figure 1.5 Network representation of the intersection in Figure 1.4: (a) representing the intersection as a node; (b) a detailed intersection representation.

(Sheffi, 1985)

21 Conjunctions
17 Terminals
8 Access Points
Analysis Scenarios

- Number of sensors (10, 20)
- Sensor Failure Probability (0%, 20%)
- Coverage Type (flow, path)
Results

Flow Coverage – 10 sensors

0% Failure
96.8% Coverage

20% Failure
89.4% Coverage
Results

Flow vs. Path Coverage – 0% failure

Flow
96.8% Coverage

Path
67.8% Coverage
Results
Flow vs. Path Coverage – 20% failure

Flow
89.4% Coverage

Path
48.5% Coverage
Results

Path Coverage – 10 vs. 20 sensors

0% Failure
67.8% Coverage

0% Failure
92.3% Coverage
Results

- **Net Benefit** vs **Failure Probability**
  - Path Coverage: Blue line
  - Flow Coverage: Red line

- **Net Benefit** vs **# of Installations**
  - Path Coverage: Blue line
  - Flow Coverage: Red line
Conclusions

• A new reliable sensor location model to improve intermodal freight traffic surveillance in Chicago
• Customized algorithms to solve the problem efficiently
• Insights on optimal sensor network deployment
• Potential Societal Benefits
  – Increase the visibility of freight movement
  – Traffic management based on congestion points
  – Network and infrastructure planning
Thank You

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Future Research

- Uncertainty in traffic flow and routing
- Site-dependent failure probability
- Develop continuous models
Challenges

- **Obtaining Sufficient Freight Data**
  - Difficult to portray more realistic illustration
  - Better understanding of freight movements is required
- **Uncertainty at much larger network**
  - Much more complex work is required
  - Higher chance of error at solving process
RFID

- Range around 31 ft.
  - Possible to increase the range by boosting the power up, but much higher cost
  - http://www.businesswire.com/portal/site/transcore/?ndmViewId=news_view&newsId=20041020005274&newsLang=en

- Failure Probability <3%

- Installing RFID sensor system
  - ~$70,000 per location
  - Plus maintenance cost
  - IGA Reader, Fusion Redundant Reader
  - http://www.tollroadsnews.com/node/3280