Arterial Travel Time Characterization and Real-time Traffic Condition Identification Using GPS-equipped Probe Vehicles

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Outline

• Introduction
• Characterization of Arterial Travel Time
• Link Travel Time Distribution Estimation
• Mean Route Travel Time Estimation
• Real-time Traffic Condition Identification
• Conclusions
Introduction

• Travel time is a crucial variable both in traffic demand modeling and network performance measurement.

• Problem with Analytical models (eg. BPR function): only provide average travel time for all vehicles

• Travel time for individual Vehicle is needed
Introduction

• Monitoring system on arterials has lagged behind what is done on freeways, due to the size of urban arterial systems.

• Solution: using already-deployed sensors such as GPS equipped vehicles
Introduction

- NGSIM Program
- Peachtree St Dataset
- Section 2 – Section 5
- Two traffic conditions: Noon and PM
Characterization of Arterial Travel Time

The main factors that affect travel time:

• Geometric structure of the arterial
• Driving behaviors
• Signal control strategy
• Traffic demand
Characterization of Arterial Travel Time

- Travel time histograms of NGSIM data
- Section 2 Northbound at Noon

All vehicles

Through-through vehicles
Characterization of Arterial Travel Time
Characterization of Arterial Travel Time

Four states of travel time:

- State 1: non-stopped,
- State 2: non-stopped with delay,
- State 3: stopped,
- State 4: stopped with delay.
Travel time distribution Estimation

• Mixture normal density (State 1, 3)

\[ f(TT) = p \times f_n(TT) + (1 - p) \times f_s(TT) \]
\[ f_n(TT) \sim N(\mu_1, \sigma_1^2) \]
\[ f_s(TT) \sim N(\mu_2, \sigma_2^2) \]

• Parameters: \( \psi(p, \mu_1, \sigma_1^2, \mu_2, \sigma_2^2) \)
Construction of likelihood

- Group travel time into $m$ sub-intervals
  
  \[ m = \text{round}(TT_{\text{max}} - TT_{\text{min}}) + 1 \]

- Let $n_1 \ldots n_m$ be the number of travel time that falls into intervals $[a_0, a_1], \ldots, [a_{m-1}, a_m]$

- The probability that an individual vehicle travel time falls in the $j^{th}$ interval:

\[
P_j(\psi) = \int_{a_{j-1}}^{a_j} f(TT|\psi) \, dTT, \ j = 1, \ldots, m
\]
Construction of likelihood

• The grouped data follow a multinomial distribution:

\[ L(\psi) = \frac{n!}{n_1! \ldots n_m!} \{P_1(\psi)\}^{n_1} \ldots \{P_m(\psi)\}^{n_m} \]

• Log-likelihood:

\[ \log L(\psi) = \sum_{j=1}^{m} n_j \log(P_j(\psi)) + \log\left(\frac{n!}{n_1! \ldots n_m!}\right) \]

• Maximum likelihood estimation (R)
Travel time distribution Estimation

Noon

PM
Mean Route Travel Time Estimation

• Route travel time consists of successive link travel times
• Travel time state of each section is not independent to each other
• Markov property: travel time of the current section is only dependent on the immediate upstream section
• Markov Chain
Mean Route Travel Time Estimation

- **System States:**
  1: non-stop vehicles  
  2: non-stop vehicles with delay  
  3: stopped vehicles  
  4: stopped vehicles with delay

- **Transition matrix:**

  \[
  P = \begin{pmatrix}
  p_{11} & p_{12} & \cdots & p_{14} \\
  p_{21} & p_{22} & \cdots & p_{24} \\
  \vdots & \vdots & \ddots & \vdots \\
  p_{41} & p_{42} & \cdots & p_{44}
  \end{pmatrix}
  \]

- **Initial Distribution**
Mean Route Travel Time Estimation

- Joint probability of all steps is the product of the transit probability of each step:
  \[ P\{S_0 = i_0, S_1 = i_1, \ldots, S_n = i_n\} = \lambda_0 p_{i_0i_1} p_{i_1i_2} \ldots p_{i_{n-1}i_n} \]

- Mean route travel time:
  \[ TT_{route} = \sum_{i_1=1}^{4} \sum_{i_2=1}^{4} \ldots \sum_{i_n=1}^{4} \left( T^{(1)}_{i_1} + T^{(2)}_{i_2} + \ldots \right. \\
  \quad + T^{(n)}_{i_n} \left. \right) \times p_{i_0i_1} \times p_{i_1i_2} \times \ldots \times p_{i_{n-1}i_n} \]
**Mean Route Travel Time Estimation**

- Numerical Example: NGSIM Peachtree St Dataset at Noon
- Estimated mean travel times of different states in each link

<table>
<thead>
<tr>
<th></th>
<th>State 1</th>
<th>State 2</th>
<th>State 3</th>
<th>State 4</th>
</tr>
</thead>
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<tr>
<td>Link 2</td>
<td>11.29</td>
<td>38.12</td>
<td>68.87</td>
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<td>Link 3</td>
<td>10.49</td>
<td>26.02</td>
<td>45.47</td>
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<td>N/A</td>
<td>N/A</td>
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<tr>
<td>Link 5</td>
<td>9.58</td>
<td>23.47</td>
<td>51.76</td>
<td>84.88</td>
</tr>
</tbody>
</table>
Mean Route Travel Time Estimation

• **Case I: Given the vehicle is a non-stopped vehicle at the entrance**
  The mean travel time estimated by the model is 108.89s. The mean travel time from the data is 110.78s, and an approximate 95% confidence interval is (97.16s; 124.40s).

• **Case II: Given the vehicle is a stopped vehicle at the entrance**
  The mean travel time estimated by the model is 87.4s. The mean travel time from the data is 86.25s, with a approximate 95% confidence interval of (79.59s; 92.91s).
Traffic Condition Identification

Noon

PM
Traffic Condition Identification

- The probabilities that a travel time sequence belongs to each traffic condition can be calculated using Bayes Theorem.
- The joint probability of travel time states could be expressed by the following equation:

\[
P(S_1 = s_1, S_2 = s_2, \ldots, S_n = s_n) = P(S_n = s_n | S_{n-1} = s_{n-1}, \ldots, S_2 = s_2, S_1 = s_1) \times P(S_{n-1} = s_{n-1} | S_{n-2} = s_{n-2}, \ldots, S_2 = s_2, S_1 = s_1) \times \cdots \times P(S_2 = s_2 | S_1 = s_1) \times P(S_1 = s_1)
\]
Traffic Condition Identification

- Assuming the travel time of a single link is independent of travel time states in other links:
  \[ P(T_i = t_i | S_1 = s_1, S_2 = s_2, ..., S_i = s_i, ..., S_n = s_n) = P(T_i = t_i | S_i = s_i) \]

- The joint distribution of travel time and travel time states can be seen:
  \[ P(T_1 = t_1, ..., T_n = t_n, S_1 = s_1, ..., S_n = s_n) = \left( \prod_{i=1}^{n} P(T_i = t_i | S_i = s_i) \right) P(S_1 = s_1, ..., S_n = s_n) \]
Traffic Condition Identification

- So the marginal distribution for travel times becomes
  \[ P(T_1 = t_1, \ldots, T_n = t_n) = \sum_{s_1 = s_1, \ldots, s_n = s_n} \left( \prod_{i=1}^{n} P(T_i = t_i | S_i = s_i) \right) \ P(S_1 = s_1, \ldots, S_n = s_n) \]

- Assuming there are \( m \) different traffic conditions, the probability that a given travel time sequence belongs to traffic condition \( C_i \)
  \[ P(C_i | T_1 = t_1, \ldots, T_n = t_n) = \frac{P(T_1 = t_1, \ldots, T_n = t_n | C_i) \times P(C_i)}{\sum_{j=1}^{m} P(T_1 = t_1, \ldots, T_n = t_n | C_j) \times P(C_j)} \]
Traffic Condition Identification
Conclusions

- Four travel time states for through-through vehicles
- Fit travel time distribution with mixture normal densities (EM)
- Propose a Markov Chain model to estimate mean route travel time
- Identify real-time traffic condition (only GPS data from 1-2 vehicles)
Acknowledgement

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Thank you!
Questions?