Optimal Sensor Requirements for Traffic Management and Traveler Information Applications

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Outline

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Objectives of this Research

- Focusing on loop or other point sensors: continuous in time but discrete in space
- Optimal sensor requirements for traffic management and traveler information applications (sensor density)
- Two main factors for Caltrans to install sensors
  - Sensor location
  - Sensor density
- More sensor more accurate ➔ higher density
- To minimize cost ➔ lower density
- To satisfy application requirement with optimal trade-off between sensor density and traffic parameter estimation error
Previously Proposed Approach: Traffic Data Sensitivity Analysis

• Empirical approach: Through traffic data sensitivity analysis for the application required traffic parameters with respect to
  – Sensor error
  – Sensor density
  – Estimation methods (proposed to search for a method independent approach)

• Main Tasks:
  – Identify the control or decision algorithms with Caltrans
  – Establish the frequency, severity and impact of measurement errors through data (from BHL and PeMS) analysis
  – Establish the Sensitivity of required traffic parameters to measurement errors
  – Establish the impacts of measurement errors on application
  – Document the methodology
Performance of application determines error tolerance:
(a) Ramp metering
(b) Congestion on-set detection
(c) Travel information

From Required Tolerance to Key Factors Affecting Traffic Parameter Estimation

Tolerance in:
(1) Update rate
(2) Time delay
(3) Parameter error

Traffic parameters estimation error

Sensor density

Sensor features

Data aggregation method

Parameter estimation methods

Time delay

Updated rate
Optimization philosophy:

• Identify optimal locations
• For fixed sensor feature
• Choosing appropriate methods in
  – Preprocessing
  – Cleaning
  – Correction
• Choosing appropriate method for data aggregation
  – Time interval
  – Distance interval
  – or both
• Then consider the effect of sensor density on traffic parameter estimation error under the constraint of tolerance required by application performance
Two Approaches for Traffic Parameter Estimation Error Analysis

1. Analytic approach:
   Sensor measurement error propagation in traffic parameter estimation

   Basic parameter data error directly from sensor measurement → Pre-processed data error → Error of aggregated basic parameter data in the sense of statistics

   Deduced parameter estimation error: absolute, relative or statistical distribution

2. Empirical approach for error analysis: Direct data comparison with ground truth

   Basic parameter data error directly from sensor measurement → Direct data analysis → Deduced parameter estimation error: absolute, relative or statistical distribution
Dependent Factors: Data Pre-processing

- Filtering process to reduce error
  - Low pass/high pass/bad pass
  - Data cleaning/correction
  - Kalman filtering
Dependent Factors: Data Aggregation Method

- Aggregation over time
- Aggregation over space
- Aggregation over time and space
- Methods for aggregation:
  - Mean value
  - Median
  - Harmonic mean
  - Bayesian weighting
  - Optimal weighting: To achieve even lower variance for weighted signal
Dependent Factors: Estimation Method: Analytic Approach

- The proposed approach must be an empirical since analytic approach will involve error propagation and sensitivity. As an example, suppose that \((x_1, x_2)\) is measured with error vector \((\Delta x_1, \Delta x_2)\). Then

  \[
  \hat{x}_1 = x_1 + \Delta x_1 \\
  \hat{x}_2 = x_2 + \Delta x_2 \\
  \hat{y} = \hat{x}_1 + \hat{x}_2
  \]

- If \(y = x_1 + x_2\) then it has an estimation as

  \[
  \hat{y} = \hat{x}_1 + \hat{x}_2 = (x_1 + \Delta x_1) + (x_2 + \Delta x_2) = (x_1 + x_2) + (\Delta x_1 + \Delta x_2) \\
  \hat{y} = \hat{y}_0 + \Delta y \\
  \Delta y = (\Delta x_1 + \Delta x_2)
  \]

where \(\hat{y}_0\) is the nominal value of \(y\).
Dependent Factors: Estimation Method: Analytic Approach

- From analytic approach, we might be able to establish some relationships (with unknown parameters) between sensor measurement errors and deduced traffic parameter estimation errors. Then traffic data can be used to identify those parameters. Again, this approach will be method dependent.

- Besides, such relationship could be conservative.
Sensor Station Location

- **Location: Depending on information requirement for application**
  - **Traffic management**
    - Bottlenecks
    - Locations with higher probability of accident/incident
    - On-ramp merging point
  - **Traffic control: such as ramp-metering**
    - Immediate upstream
    - On-ramp
    - Off ramp
  - **Information**
    - Less stringent
Sensor Station Density and Estimation Error

- **Section: Link between two sensor stations**
- **Assuming known measurement error on the two terminal sensor stations**
- **Sensor density effects**: How the distance between two sensor stations would affect the traffic parameters estimation between the two stations
- **Current methods for traffic parameter estimation from discrete points to continuous space**
  - Smoothing methods such as linear or nonlinear Interpolation
  - Kalman filtering
  - Other prediction methods
Sensor Station Density and Estimation Error (cont.)

- **Proposed future approach:** To investigate the traffic flow dynamics between the two terminal sensor station

- **Main idea:** If the sensors are dense enough to capture the traffic flow dynamics between the two terminal sensors, then traffic parameters along the stretch of the freeway can be satisfactorily estimated. *Mean speed* is the most important traffic parameter to consider.
Sensor Station Density and Estimation Error (cont.)

• What traffic flow dynamics between two sensor stations?
  – Free flow, Sustainable; speed estimation at the terminal sensor stations can determine the speed between the two
  – Congestion on-set towards congestion: Shockwave is one candidate; Speed changes between two terminal sensor stations are reflected as shockwave propagation. Detection delay time of upper stream sensor station is also depend on the propagation speed.
  – Congestion in steady state: Mean speed below certain level, unsustainable
  – Traffic recover phase speed pattern: Characterized by speed increasing and occupancy dropping
Look at Speed Estimation only Using NGSIM data

- To work out a mathematical form of speed estimation error with respect to measurement error then use NGSIM data for identification and verification
- 45 min data over I-80 over afternoon peak period
- Hoping to use sub-second data and use different method for aggregation and speed estimation
- With vehicle tracking using video camera as ground truth
- We can drop some intermediate loops to see how the estimation error changes (density dropping)
- BHL has similar data set with Sensys inserted between loop station and with video image coverage; Need to confirm vehicle trajectories from video image available (density increasing) as ground truth
Concluding Remarks

• Traffic parameter estimation error depends on several factors
  – Sensor measurement error
  – Data Pre-processing method and error resulted
  – Data aggregation method and statistical error resulted
  – Parameter estimation method
• We can use the empirical method to investigate the parameter estimation error w. r. t. the loop density for specific methods.
• Proposed new approaches
  – To establish a relationship between measurement error and traffic parameter (such as mean speed) estimation error based on analytic method and then identify the unknown parameters with traffic data and ground truth (to be conducted)
  – To investigate the traffic dynamics in different phases between two terminal sensor stations to determine the relationship between sensor density and traffic parameter estimation error (future)