Wireless sensors for managing traffic

If you don’t know what’s happening on your roads, don’t expect to manage the traffic well

Pravin Varaiya

EECS, University of California, Berkeley
Sensys Networks, Inc., Berkeley

Work with Ronnie Bajwa, Christopher Flores, Wenteng Ma, Ajith Muralidharan, Ram Rajagopal, Rene Sanchez, Ben Wild
Traffic management objectives

- Increase efficiency and safety
  - Reduce congestion (veh-hrs of delay) and travel time variability (median, 90\textsuperscript{th} percentile)
  - Reduce risk of accidents

- Using
  - Direct control: arterial signal settings, freeway ramp meters, rules, and enforcement
  - Indirect control: traveler information, tolls, parking fees, other incentives

- Direct control affects ‘supply’ of transportation services; indirect control shapes ‘demand’
Control

- Control is feedback function of network state estimate
- Estimate obtained by processing traffic sensor signals
- Estimate quality depends on sensor spatial coverage, accuracy, and informativeness of measurements
Outline

- Typical deployments

- Magnetic sensors for
  - Vehicle detection: volume, occupancy, speed
  - Re-identification: ramp queues, travel time
  - Turn ratios, speed and red-light enforcement
  - Vehicle classification

- Micro-radar sensors for pedestrians, bicycles, parking

- Accelerometer sensors for Weigh-in-Motion
Outline

- Typical deployments
  - Magnetic sensors for
    - Vehicle detection: volume, occupancy, speed
    - Re-identification: ramp queues, travel time
    - Turn ratios, speed and red-light enforcement
    - Vehicle classification
  - Micro-radar sensors for pedestrians, bicycles, parking
  - Accelerometer sensors for Weigh-in-Motion
Full deployment

- Truck weight
- Stop-Bar Detection
- Advance Detection
- Parking Enforcement
- Ramp Metering
- System Counts
- Traffic count
- Tolls
- Peds Detection
- Parking Guidance
- Signal Controller
- 170
Arterial roads
Outline

- Typical deployments

- Magnetic sensors for
  - Vehicle detection: volume, occupancy, speed
  - Re-identification: ramp queues, travel time
  - Turn ratios, speed and red-light enforcement
  - Vehicle classification

- Micro-radar sensors for pedestrians, bicycles, parking

- Accelerometer sensors for Weigh-in-Motion
Wireless sensor platform (Sensys Networks)

- Magnetic sensors for
  - Vehicle detection: volume, occupancy, speed
  - Re-id: ramp queues, travel time
  - Turn ratios, speed and red-light violation
  - Vehicle classification
- Micro-radar sensors for pedestrians, bicycles, parking
- Vibration sensors for Weigh-in-Motion
- 10+ year battery life (for magnetic sensors)
- Installs in minutes
- Remote management, configuration and diagnostics

3”
Sensor installation

Place sensor in 4” diameter, 2 ½” deep hole; cover with epoxy; dry in 10 minutes

Access point (base station) 15’ high, with GPS receiver, GPRS interface, poE, or power over RS485. About 50% battery power used by radio
Vehicle magnetic signature

Ferrous object + Earth’s magnetic field = Distorted field

HMC1051Z
Vehicle detection

Sensor z axis measurement

vehicle signal

detection signal

seconds
Count station (volume, occupancy, speed)

A. Haoui, et al., Wireless magnetic sensors for traffic surveillance, TRC 16(3): 294-306
**Outline**

- Typical deployments

- Magnetic sensors for
  - Vehicle detection: volume, occupancy, speed
  - Re-identification: ramp queues, travel time
  - Turn ratios, speed and red-light enforcement
  - Vehicle classification

- Micro-radar sensors for pedestrians, bicycles, parking

- Accelerometer sensors for Weigh-in-Motion
Queue length and travel time estimates

Ramp queue between A and D = ?

I-80S, Hegenberger Rd

Time from A to D = ?

San Pablo Av, Albany CA

Vehicle re-identified at A, D

\( T = \text{travel time from A to D} \)

\( N = \# \text{ vehicles between A, D} \)
Matching signatures at A, D

Signature at A

Signature at D

Raw signal

Compressed
Matching signatures

\[(X_A, Y_B) \rightarrow \text{signature distance extraction} \rightarrow d(X_A, Y_B)\]

Queue at Hegenberger Rd ramp

Queue Length vs Time of Day

- Queue Length (Ground Truth)
- Queue Length (Veh Re-ID)
- Matched Vehicles (392/536)
- Mismatched Vehicles (24/392)

TT distribution on San Pablo Ave

23 May 2008, 1-1:30PM

K. Kwong et al. “Arterial travel time estimation based on vehicle re-identification using wireless magnetic sensors.” TRC 17(6): 586–606
Outline

- Typical deployments

- Magnetic sensors for
  - Vehicle detection: volume, occupancy, speed
  - Re-identification: ramp queues, travel time
  - Turn ratios, speed and red-light enforcement
  - Vehicle classification

- Micro-radar sensors for pedestrians, bicycles, parking

- Accelerometer sensors for Weigh-in-Motion
Intersection sensors
**Turn movements**

- For each vehicle obtain departure lane and time $t_d$ and arrival lane and time $t_a$. Match departures and arrivals under constraint
  \[ \tau < t_a - t_d < \bar{\tau} \]

- For protected turn lanes are there is no ambiguity

- For permissive turns there is ambiguity (underdetermined)
Turn movement Diablo & Green Valley

Green Valley

new detectors

vehicle detectors

Diablo

Access Point

Controller

crosswalk
## Turn ratios (%) 2011-11-17: 16:12-16:40

<table>
<thead>
<tr>
<th>Dir/ Turn</th>
<th>LT</th>
<th>T</th>
<th>RT</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>36</td>
<td>2.9</td>
<td>61</td>
</tr>
<tr>
<td>E</td>
<td>0.5</td>
<td>60</td>
<td>40</td>
</tr>
<tr>
<td>S</td>
<td>64</td>
<td>18</td>
<td>18</td>
</tr>
<tr>
<td>W</td>
<td>47</td>
<td>44</td>
<td>8.9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Dir/ Turn</th>
<th>LT</th>
<th>T</th>
<th>RT</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>35</td>
<td>2.2</td>
<td>62</td>
</tr>
<tr>
<td>E</td>
<td>0.5</td>
<td>60</td>
<td>40</td>
</tr>
<tr>
<td>S</td>
<td>66</td>
<td>20</td>
<td>14</td>
</tr>
<tr>
<td>W</td>
<td>48</td>
<td>44</td>
<td>8.4</td>
</tr>
</tbody>
</table>

Error = E - A

<table>
<thead>
<tr>
<th>Dir/ Turn</th>
<th>LT</th>
<th>T</th>
<th>RT</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>1</td>
<td>0.7</td>
<td>-1</td>
</tr>
<tr>
<td>E</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>S</td>
<td>-2</td>
<td>-2</td>
<td>4</td>
</tr>
<tr>
<td>W</td>
<td>-1</td>
<td>0</td>
<td>0.5</td>
</tr>
</tbody>
</table>
Outline

- Typical deployments

- Magnetic sensors for
  - Vehicle detection: volume, occupancy, speed
  - Re-identification: ramp queues, travel time
  - Turn ratios, speed and red-light enforcement
  - Vehicle classification

- Micro-radar sensors for pedestrians, bicycles, parking

- Accelerometer sensors for Weigh-in-Motion
Speed, red-light violations 2011-11-17

Right turns

Direction - E Lane - 1. Time: 13hr to 17hr
No. Red Light Violations - 63

Direction - N Lane - 1. Time: 13hr to 17hr
No. Red Light Violations - 148

Data over many cycles. T=0 after start of green (top) or after end of green (bottom)
Speed, red-light violations 2011-11-17

Through movement

Direction - E Lane - 3. Time: 13hr to 17hr

Data over many cycles. T=0 after start of green (top) or after end of green (bottom)
Outline

- Typical deployments

- Magnetic sensors for
  - Vehicle detection: volume, occupancy, speed
  - Re-identification: ramp queues, travel time
  - Turn ratios, speed and red-light enforcement
  - Vehicle classification

- Micro-radar sensors for pedestrians, bicycles, parking

- Accelerometer sensors for Weigh-in-Motion
Pedestrian detection

Micro-radar sensor sends 4ns pulses, gates recd signal for 4ns for delay of 4-24ns, corresponding to distance of 2’ to 10’. Size of recd signal grows with area of reflection.
Pedestrian dynamic 10 to 8 ft

threshold

actual

holdover

ignore
Pedestrian dynamic 8 to 6 ft

- threshold
- actual
- holdover

ignore
Pedestrian dynamic 2 to 0 ft

threshold
actual
holdover

ignore
Pedestrian detection zone

Pedestrian Detection Zone. Sensor at origin pointing at 90 deg. Pedestrian facing sensor.
Outline

- Typical deployments

- Magnetic sensors for
  - Vehicle detection: volume, occupancy, speed
  - Re-identification: ramp queues, travel time
  - Turn ratios, speed and red-light enforcement
  - Vehicle classification

- Micro-radar sensors for pedestrians, bicycles, parking

- Accelerometer sensors for Weigh-in-Motion
Weigh station functions

- Monitor load on roads (and bridges); enforce weight limits; charge fees based on truck class and weight

- Early pavement damage diagnosis corrected by ‘preservation’ vs ‘rehabilitation’. In 2007 Caltrans preservation cost $90K/mile vs. rehabilitation cost $442K/mile, and contracted preservation of 2,700 miles of pavement and 696 bridges
Principle of operation

- Current stations, like bathroom scales, measure displacement of plate as axle moves over it; plate isolated from pavement, and axle load estimated from displacement of plate.

- W-WIM measures pavement acceleration; signal processed to estimate axle load; pavement serves as transducer.

R. Bajwa et al. An experimental wireless accelerometer-based sensor system for applications to WIM and vehicle classification. ICWIM 6, JUNE 2012.
Types of station

- Static weigh station—classify stationary trucks, measure axle load and enforce rules

- WIM stations weigh axles and classify trucks at normal speed (cost $400K/lane); not used for enforcement

- W-WIM wireless WIM will cost a fraction of current WIM
Static, WIM, and W-WIM
Pavement as transducer

- Vehicle-pavement interaction
  \[ F(x, t) = F \cos(\omega_0 t) \times \delta(x - Vt) \]

\[
\alpha \frac{\partial^4 y}{\partial x^4} + \gamma \frac{\partial^2 y}{\partial t^2} + \kappa \frac{\partial y}{\partial t} + \beta y = F(x, t)
\]

- In long roads, it's a traveling wave [Theorem]
  \[ y(x, t) \approx F \gamma^{-1} \text{Re}[\psi^*(Vt - x)e^{i\omega_0 t}] \]

  \[
  \psi^*(t) = \frac{1}{2\pi i} \int_{-\infty}^{\infty} \Omega(s)^{-1} e^{st} ds,
  \]

  \[
  \Omega(s) = \alpha/\gamma s^4 + V^2 s^2 + (2\omega_0 V i + 2kV)s + (\beta/\gamma - \omega_0^2 + 2k\omega_0 i)
  \]

- Simulations indicate BW of 50Hz, resolution 500 \(\mu g\)
W-WIM test site I-80S Pinole, CA
W-WIM experimental system

Accel. arrays

Mag sensors

Sensor data and video

$\zeta^{i,k}(t)$

12 feet

15 feet

45 feet

TOPBox

SP: Radio
APCC: Access Point
HD: Hard Disk

Data Port

AC Power

WiFi Bridge
Raven 3G Modem
Temp Controller
PS and Controller
Installation

- Installation team; procedure, 40 sensors (top)

- Mounting top box; checking data. Total time 4 hours.
Signal processing

\[ \zeta_{i,k}(t) = \text{signal of sensor } i \text{ from truck } k \]

\[ \hat{\zeta}_k(t) = \text{av signal of truck } k \]
Raw acceleration signal

\[ \zeta^i_k(t) \]

- Graph showing a raw acceleration signal with time (s) on the x-axis and measured acceleration (mg) on the y-axis.
Filtered vs fitted response

\[ \hat{\zeta}^k(t) \]

fitted
## Results (calibrated truck, 16 runs)

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>SWWIM Axle 1 error (%)</td>
<td>-0.39</td>
<td>6.45</td>
</tr>
<tr>
<td>SWWIM Axle 2 error</td>
<td>-0.12</td>
<td>3.61</td>
</tr>
<tr>
<td>SWWIM Axle 3 error</td>
<td>-0.17</td>
<td>4.31</td>
</tr>
<tr>
<td>WIM Axle 1 error</td>
<td>-4.31</td>
<td>2.51</td>
</tr>
<tr>
<td>WIM Axle 2 error</td>
<td>-1.84</td>
<td>4.13</td>
</tr>
<tr>
<td>WIM Axle 3 error</td>
<td>5.02</td>
<td>2.98</td>
</tr>
</tbody>
</table>
300 class9 trucks, GT=WIM, Axle 1

- Std = 7.7 after omitting last 2 outliers
300 class9 trucks, GT=WIM, Axle 2+3

- Std = 8.1 after omitting last 3 outliers
300 class9 trucks, GT=WIM, Axle 4+5

- Std = 14.17 after omitting last 2 outliers
Dynamic loading

- Load varies by array because of roughness and pavement-suspension interaction

- Variation of weight estimate in different sensor arrays gives estimate of dynamic load

- Average of array estimates gives static load

Dynamic load for U-haul truck

Response of 4 rows, 15’ apart

20%

Fit coefficients:
Row 1: 7.4, 8.3
Row 2: 7.7, 9.0
Row 3: 6.3, 8.0
Row 4: 7.7, 10
Dynamic load variation of 19 class 9 trucks

min, av, max
Future work

- Larger set of calibrated trucks
- Better compensation for wander, variable axle width, speed, and temperature
- Relationship between error and dynamic variation
Conclusions

- Wireless sensor networks can be economically deployed over a wide area with several sensing modalities
  - Magnetometers give detection, flow, speed & occupancy; queue length & travel time distribution; with signal phase, give intersection performance, violations
  - Accelerometers give per axle weight and per truck classification
  - Radar sensors detect pedestrians, bicycles, parked cars; could be used to warn drivers at pedestrian crossings & red-light enforcement

- A complete deployment gives data that can be processed to achieve large improvements in network performance

- If you don’t know what’s happening on your roads, don’t expect to manage the traffic well