A wireless sensor network for traffic surveillance

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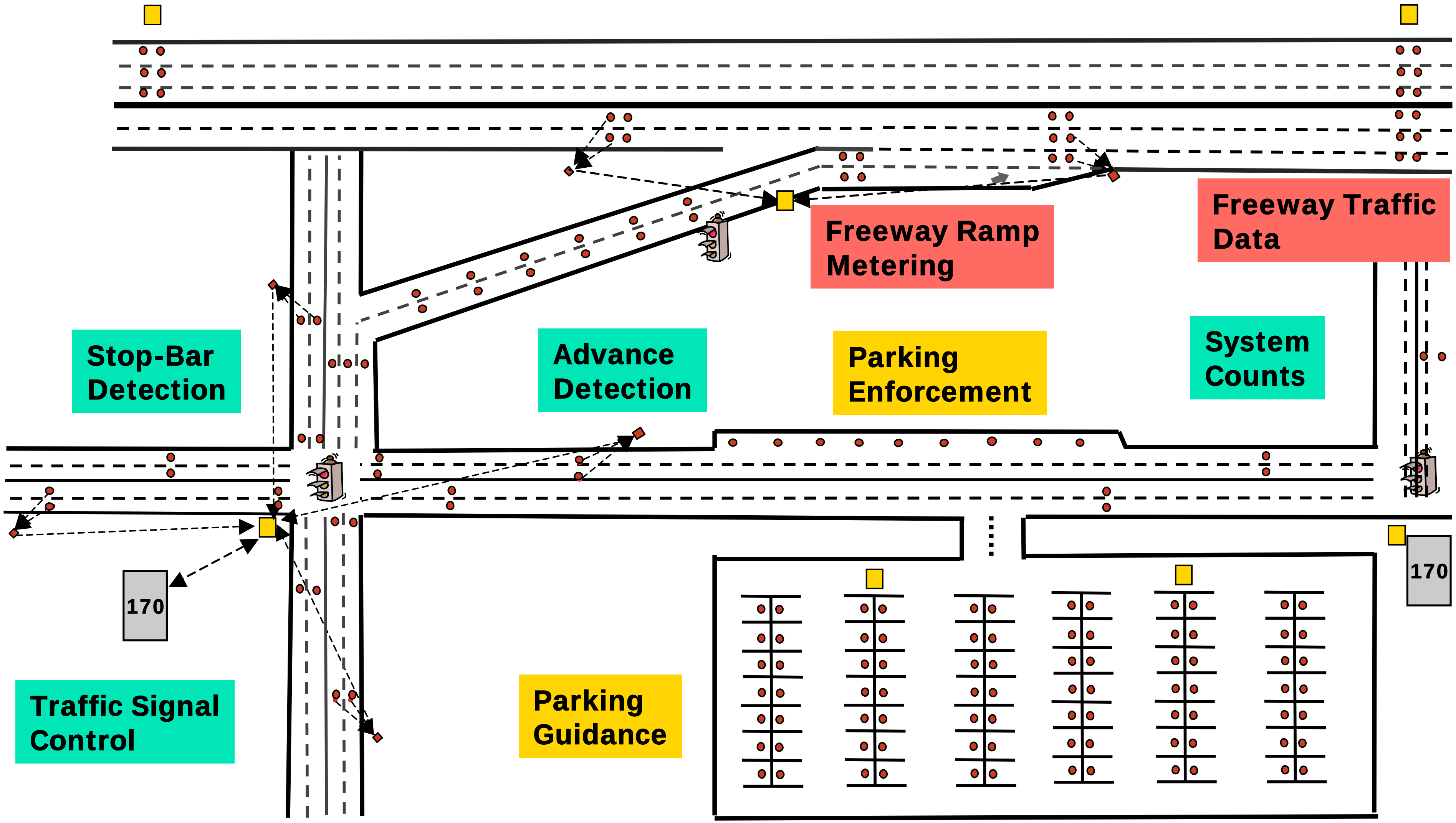
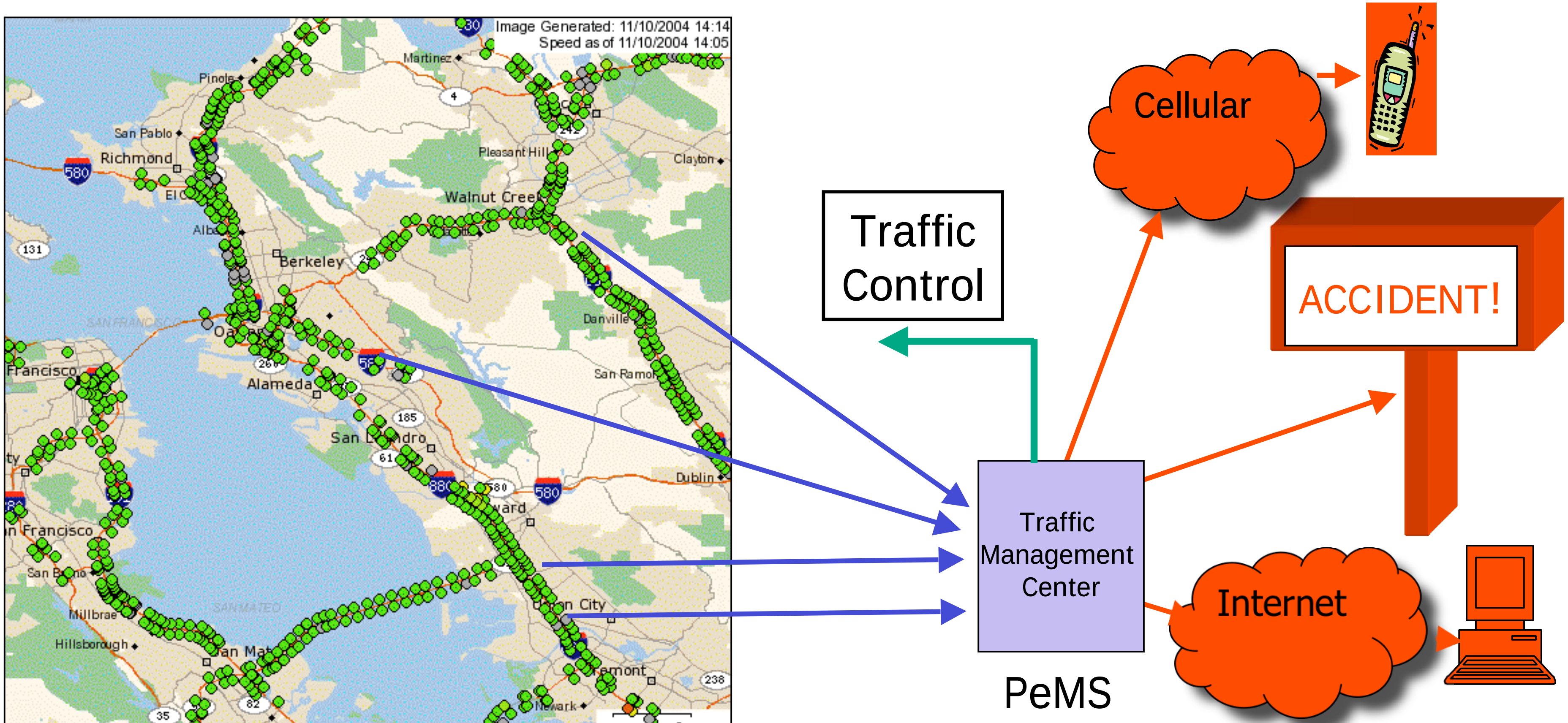
Outline

- Traffic measurement
- Wireless Sensor Networks
- Vehicle Count, Occupancy, Speed
- Vehicle Classification
- Vehicle Re-identification
- Communication protocol
- Future work

Traffic Applications



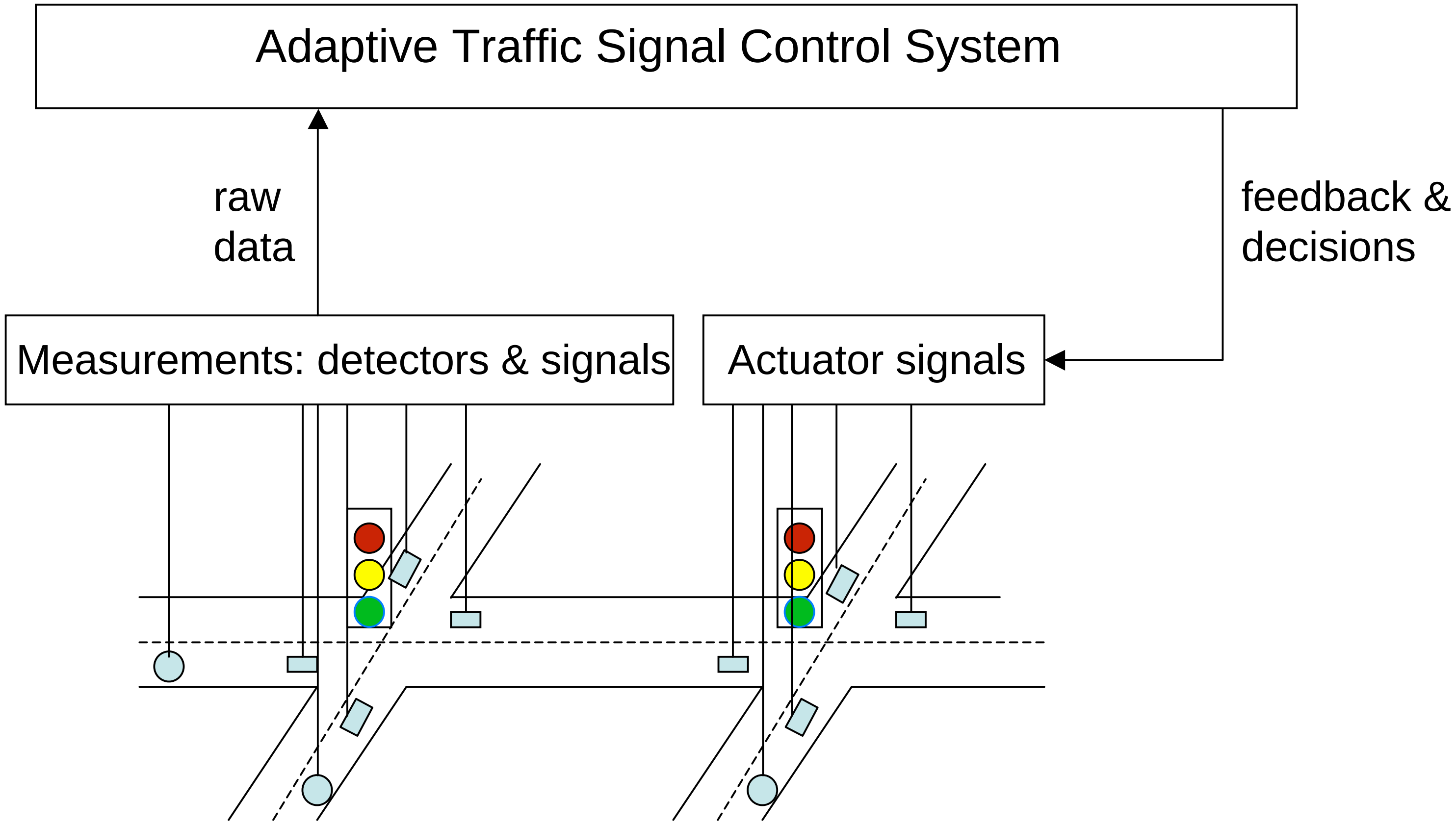
Freeway Traffic Management



http://pems.eecs.berkeley.edu

Measurement **Backhaul** **Processing** **Control & Info**

Intersection Signal Control

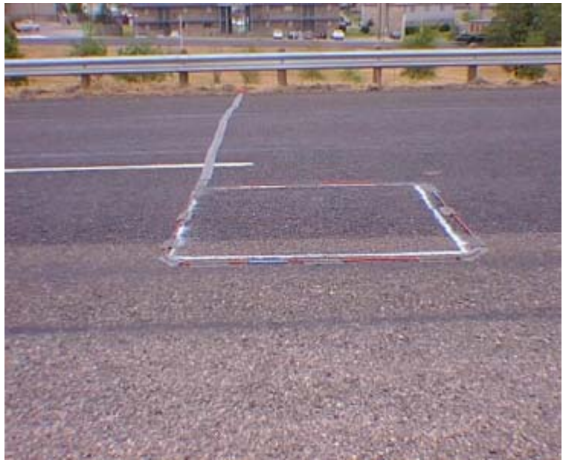


Source: Mirchandani, P. and L. Head, ‘Rhodes’ Traffic-adaptive control system, TRB 2001

Data Requirements

- Freeway detectors must report count, occupancy, speed every 30 s, 95% accuracy
- Intersection detectors must report vehicle presence at intersection within 0.1 s, 99% accuracy
- Parking detectors must report events within one minute, 90-99% accuracy

Current Traffic Measurement Technologies



Inductive loop

Video

Microwave radar

- Loop detector is the standard; lasts years but unreliable; closing lane to cut loops in pavement is disruptive; alternatives are microwave radar, video
- Can wireless sensor networks compete?

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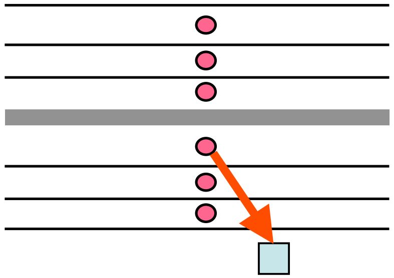
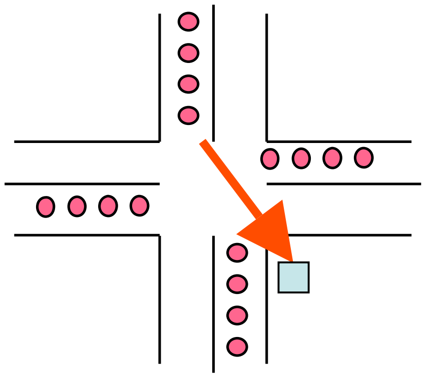
Wireless Magnetic Sensor Networks



Freeway



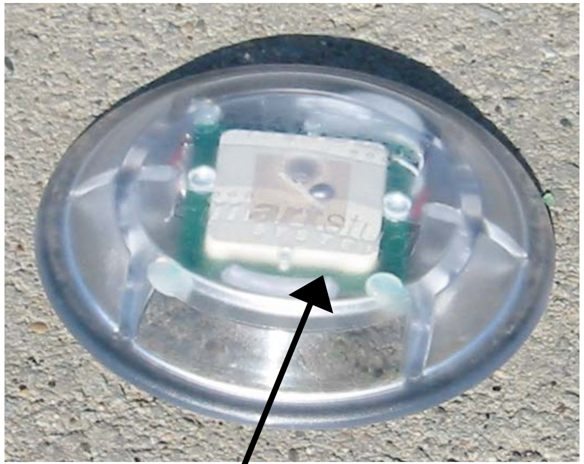
Intersection

Sensor node

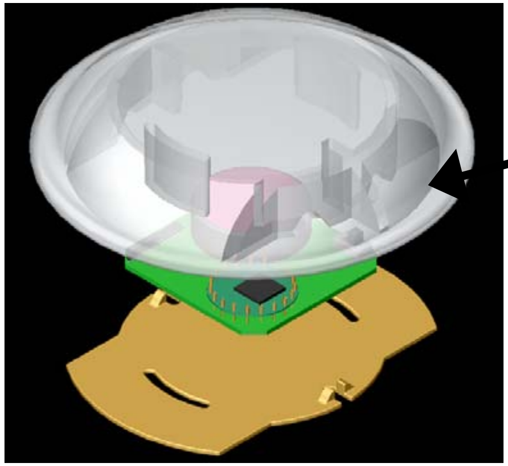
Access point

- Sensor nodes
  - Detect vehicles by change in earth's magnetic field
  - Transmit data to access point via radio
- Access point reports to signal controller or TMC
- Low cost, non-intrusive, flexible, easy to install

Prototype sensor Node



3-axis magnetometer,
microprocessor,
radio transceiver,
antenna, battery



Protective cover
can withstand
9000kg

Sensys Vehicle Detector Station

Hardened plastic mounted flush with pavement surface, 10 year battery life

GPS receiver, GPRS/CDMA interface, poE, or power over RS485

Note: Varaiya is a director of Sensys Networks, Inc

Advantages of Wireless Sensing

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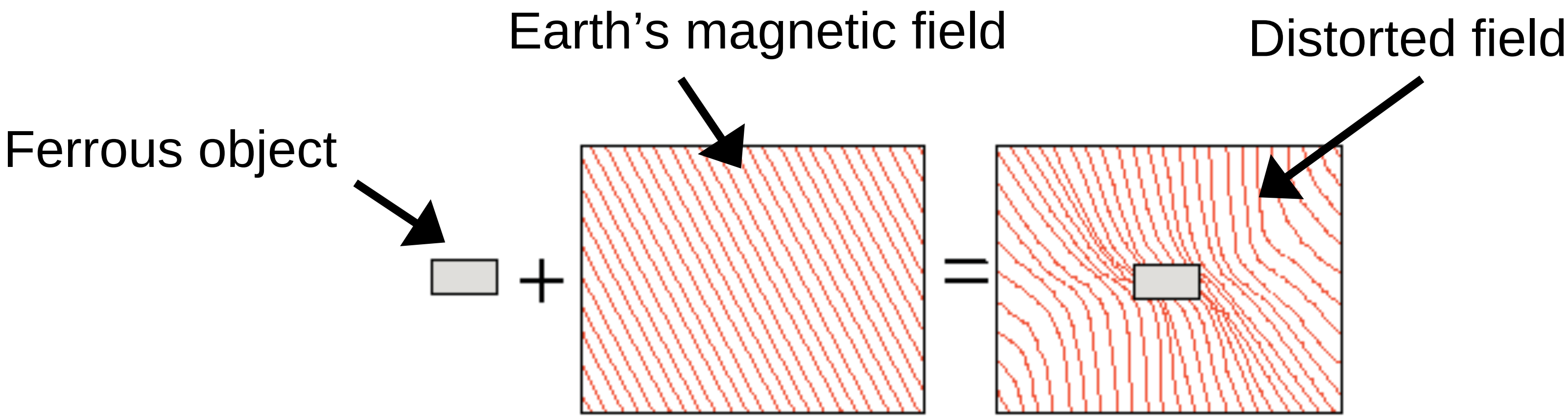
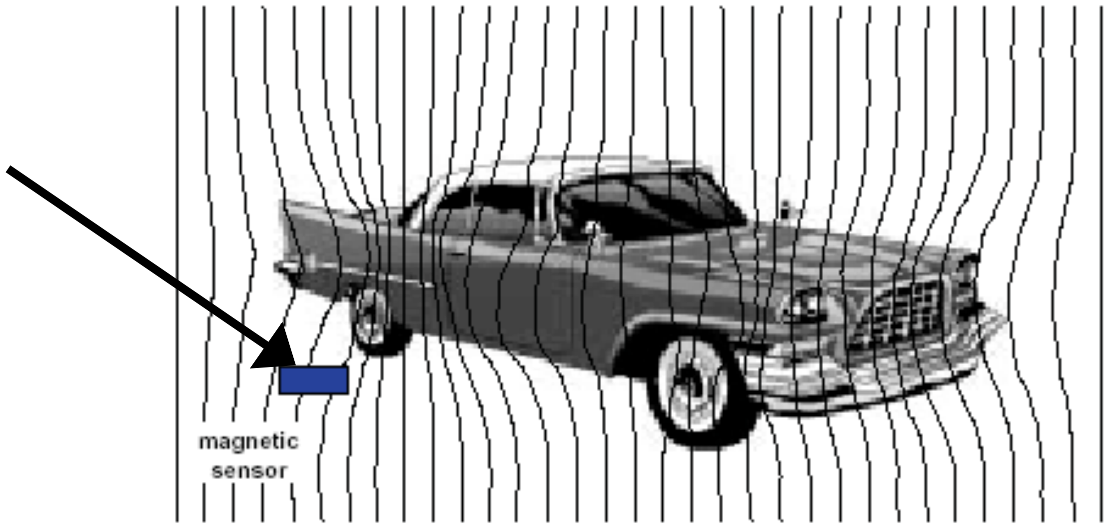
Magnetometer: Basic principle

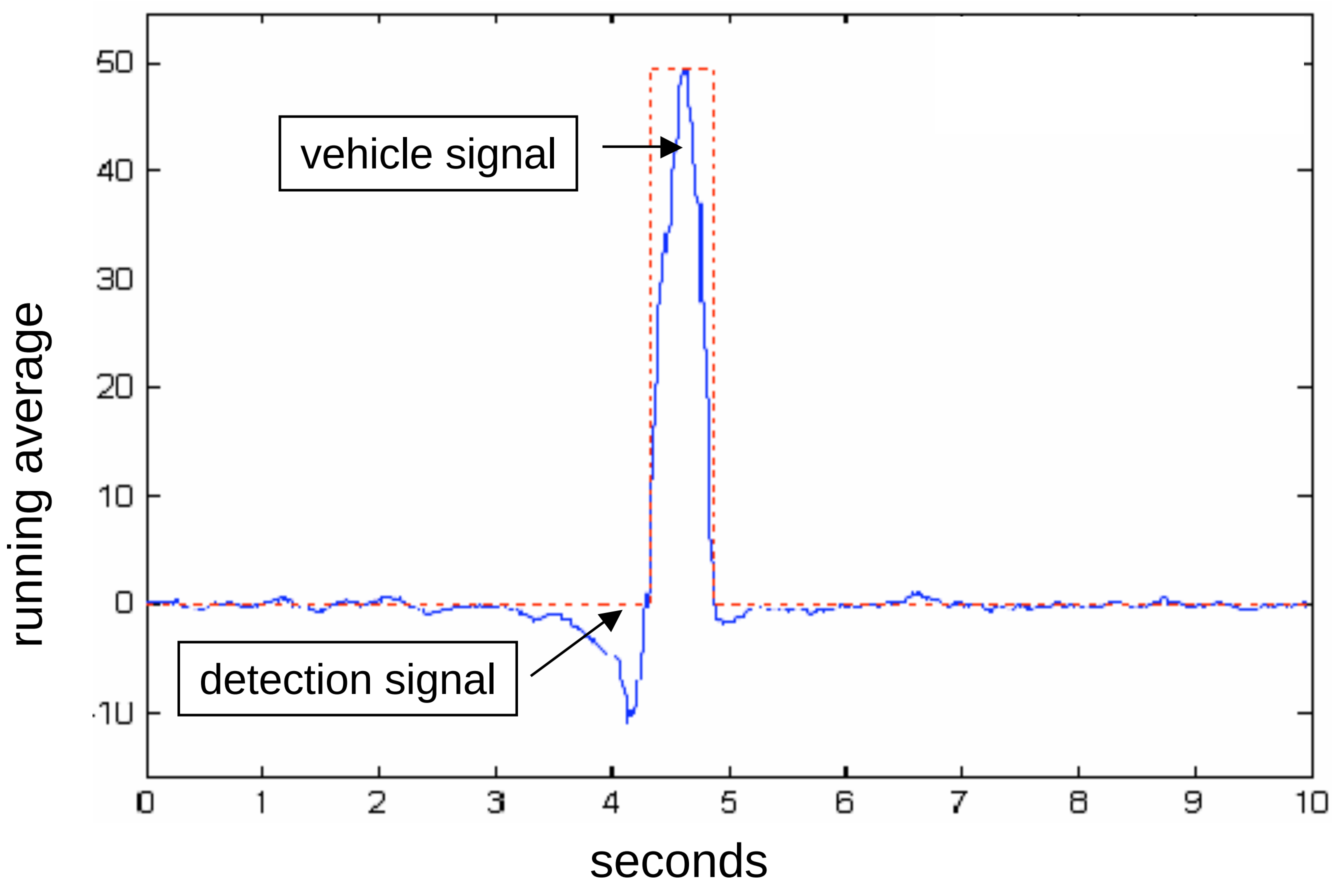


HMC1051Z



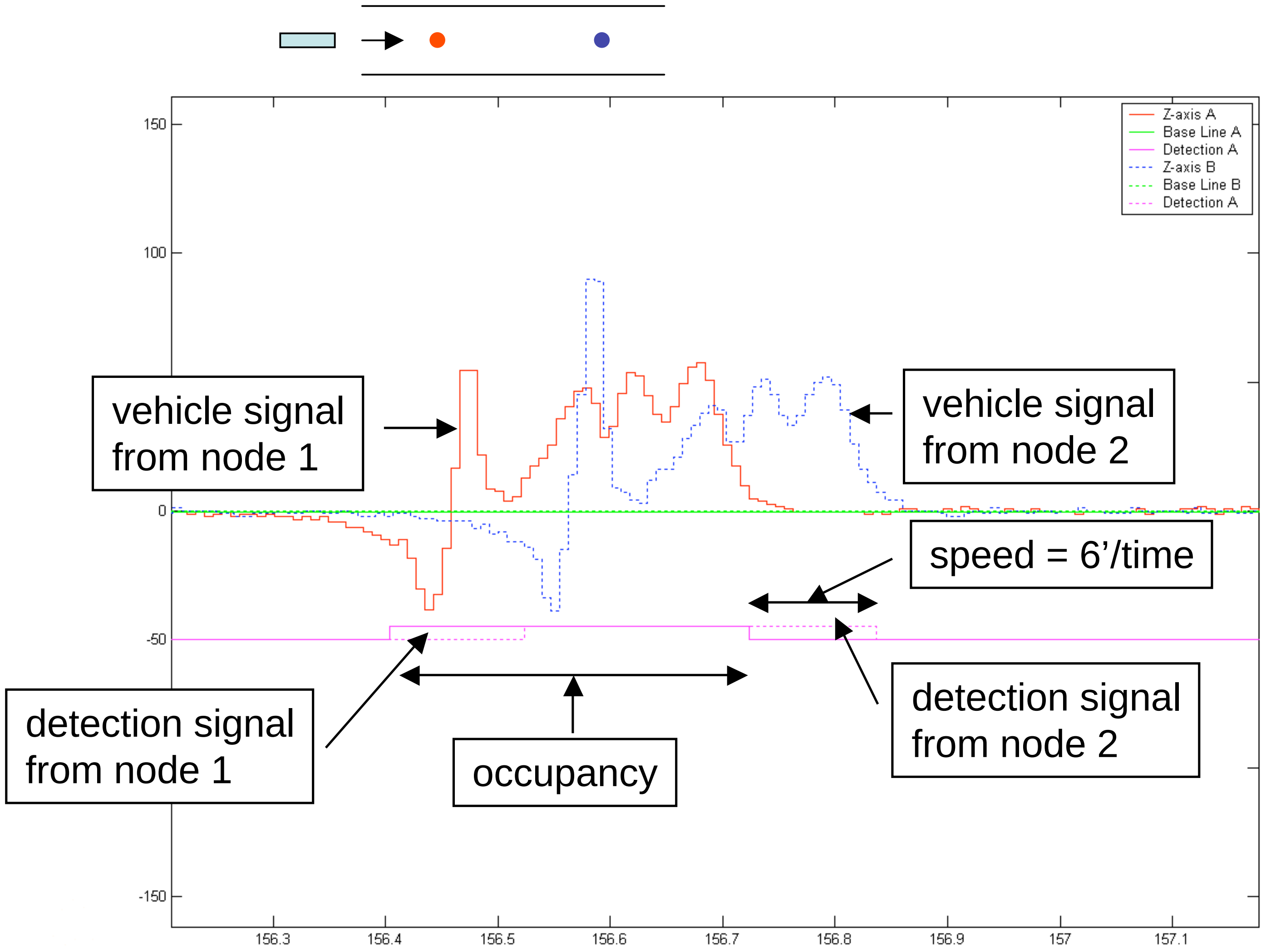
Vehicle Detection (count)

z axis measurement as vehicle goes over node



- Note sharp, localized threshold crossing

Occupancy and speed by Node Pair



CCIT test results on I-80 (1/3)

Table 5.6 - Accuracy - Reference to Loops for 30-sec Samples

Measurement	Range	Loop - Loop			Sensor - Sensor			Loop - Sensor		
		Bias[1]	**StdDev**[2]	**CC**[3]	**Bias**[1]	**StdDev**[2]	**CC**[3]	**Bias**[1]	**StdDev**[2]	**CC**[3]
Occupancy (%)	1 - 24	0.06 - 0.28	1.04 - 1.30	1.00	0.06 - 0.07	0.72 - 1.13	1.00	0.14 - 0.32	1.10 - 1.74	0.98 - 0.99
Volume (counts)	3 - 16	0.01 - 0.14	0.31 - 0.55	1.00	0.00 - 0.01	0.37 - 0.50	1.00	0.10 - 0.24	0.99 - 1.22	0.96 - 0.98
Speed (mph)	19 - 77	–	–	–	–	–	–	0.35 - 0.98	2.25 - 2.33	0.99

1. Mean difference between matched samples
2. Standard deviation of the difference between matched samples
3. Correlation coefficient between matched samples

CCIT test results on I-80 (2/3)

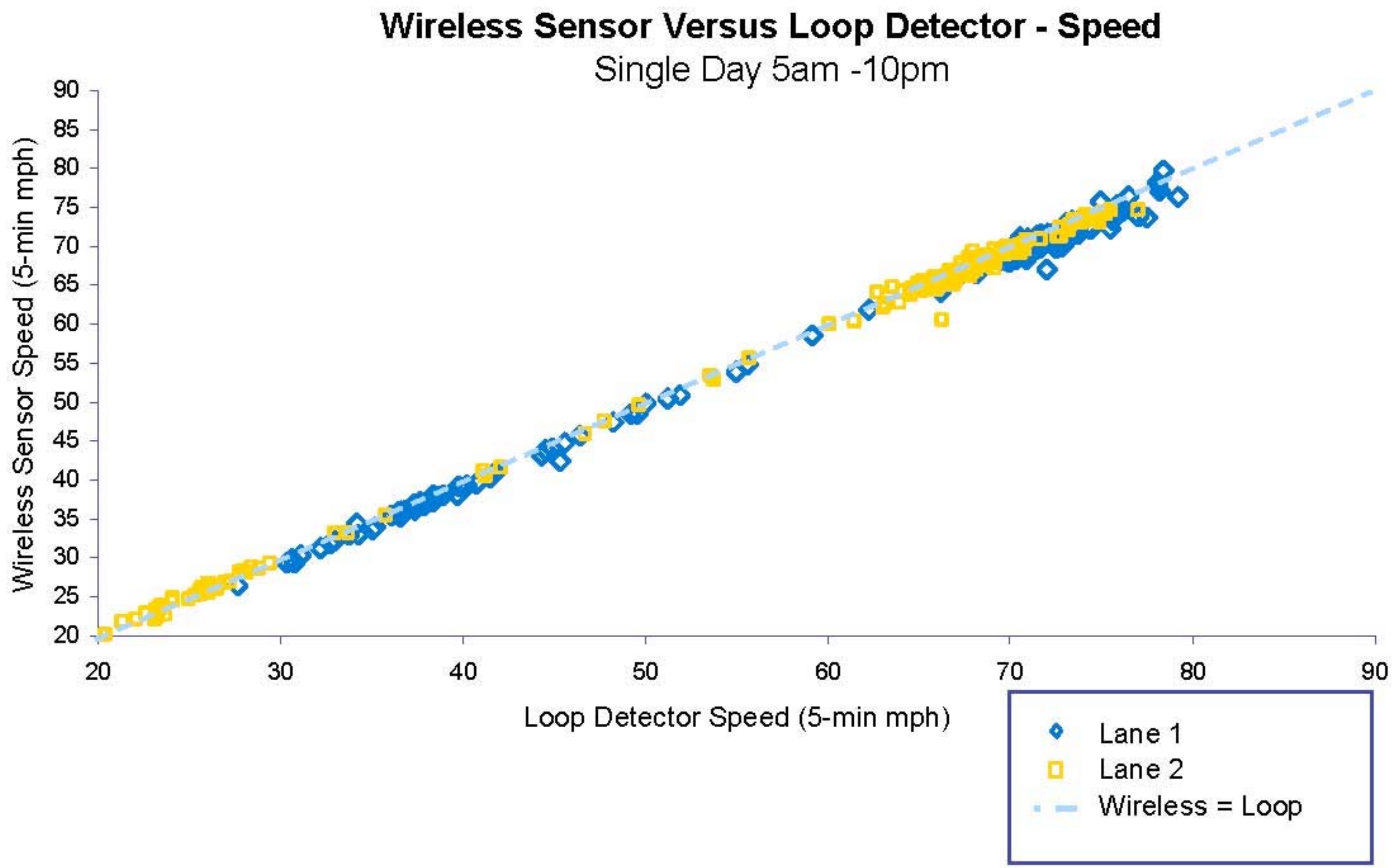


Figure 5.2 - Wireless sensor vs. loop speed measurements for a single day 5am - 10pm (scatter)

CCIT test results on I-80(3/3)

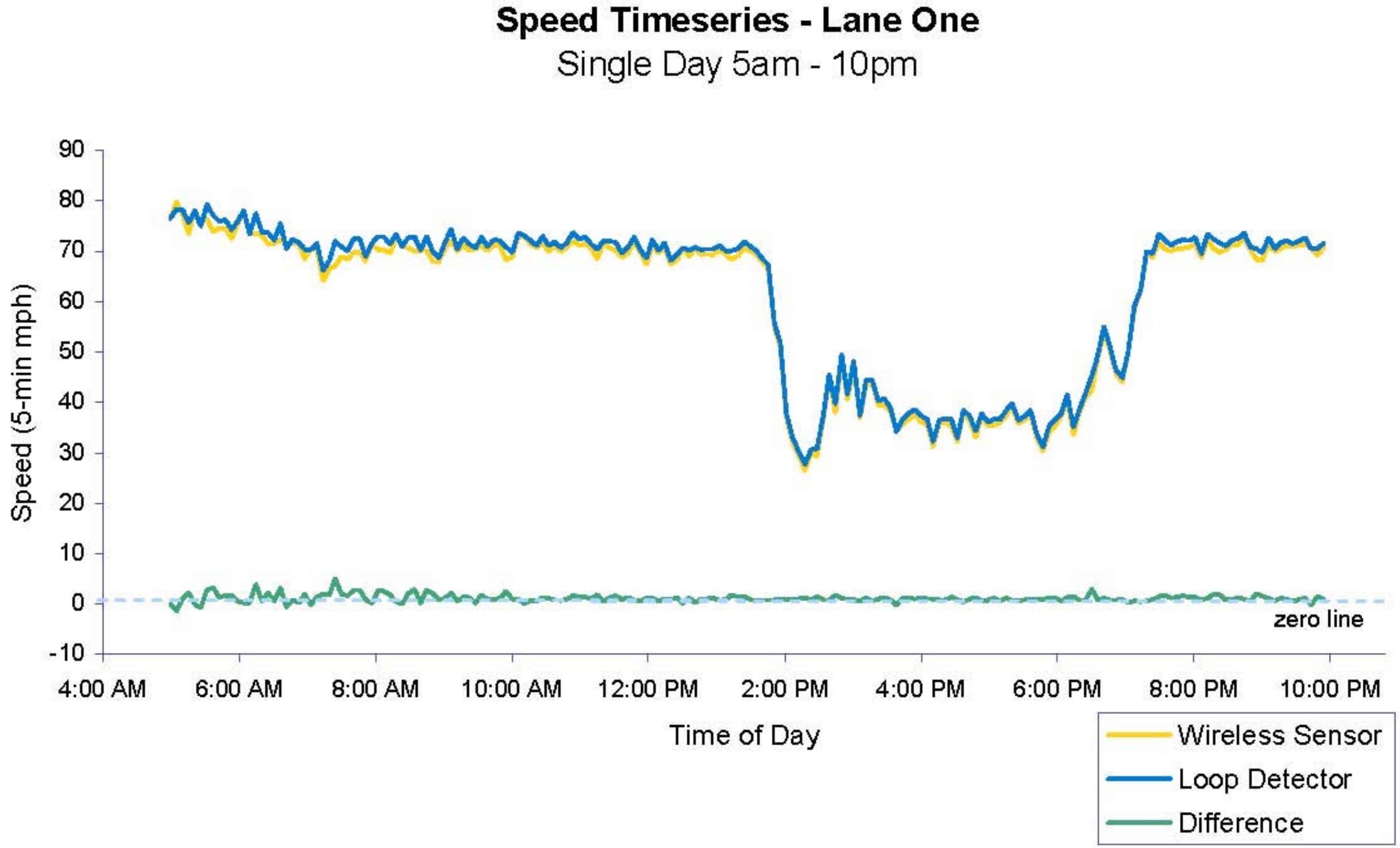


Figure 5.3 – Wireless sensor vs. loop speed measurements for a single day 5am - 10pm (time series))

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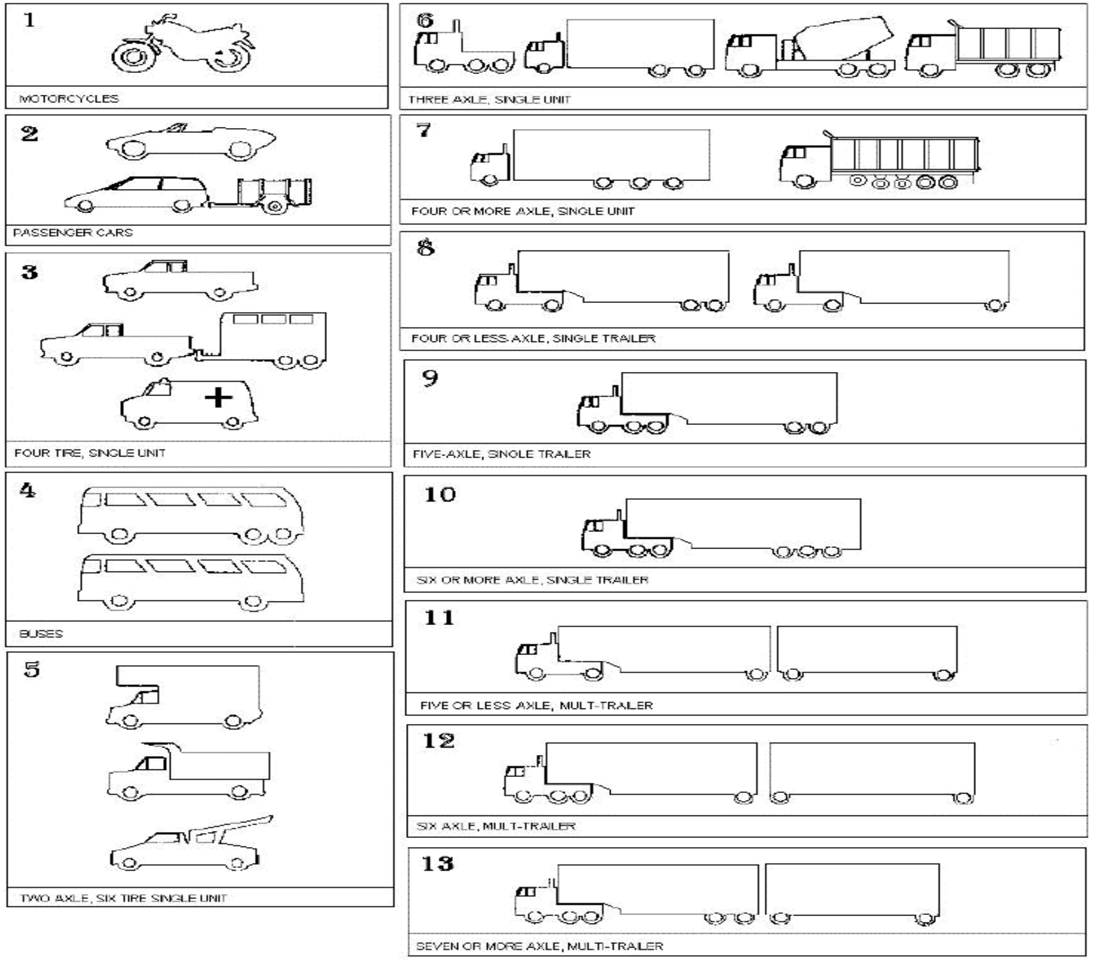
FHWA 13 Classes



- Classify detected vehicle from signal

Classification approach

- Collect labeled samples, (x_1,y_1), …, (x_N,y_N), $x_i \in R^{n(i)}$, class of $x_i = y_i \in \{1, \dots, 13\}$
- Train good classifier, $f: x_i \rightarrow y_i$
- Classify new sample x as f(x)

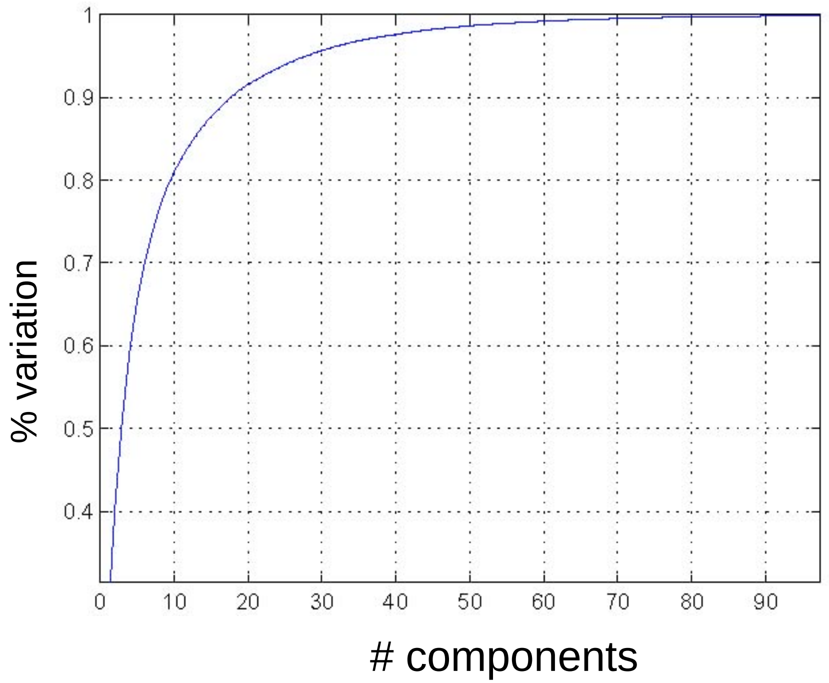
Difficulties

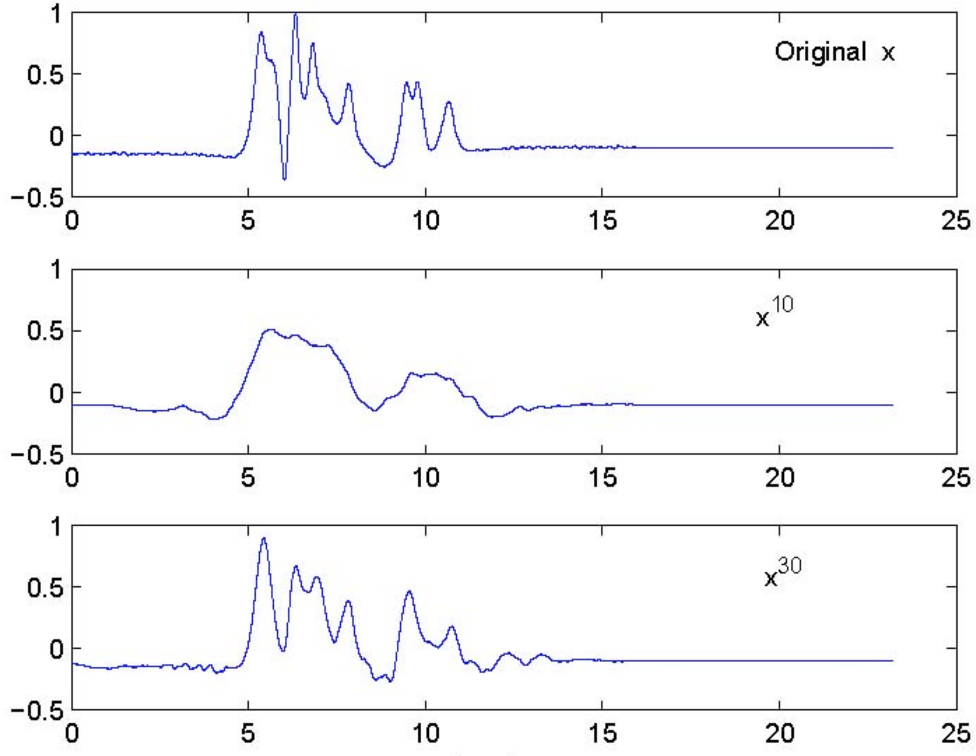
- Large and unequal sample vector size:
  - Vehicle length 5-20 m, speed 2-25 m/s, so duration is 0.2-10s, f_s = 128/256 Hz, 3-axes, so size n(i) is 75-7680 samples; inter-vehicle spacing 2-4 s
- Approach: Convert to fixed vector size n
  - Preprocessing: h: $x_i \in R^{n(i)} \rightarrow R^n$ all i
  - Extract features (compress): f: $R^n \rightarrow R^k$, k << n
- Train classifier: g: $R^k \rightarrow \{1, \ldots, 13\}$
- Overall: f = $g \circ h$: $R^{n(i)} \rightarrow \{1, \ldots, 13\}$

Preprocessing + compression A

1. Normalize sample vector to zero mean, [-1,1] and fixed sample size n: if n(i) > n downsample; if n(i) < n upsample
2. Extract features by principal components: If X is M × n matrix of M test sample vectors $\{x_i\}$ with SVD $X = USV^T$, $X^TX = VS^2V$, project x_i onto subspace of k eigenvectors with 90-99% of variation
3. Computationally expensive steps

Example A (n=2971)

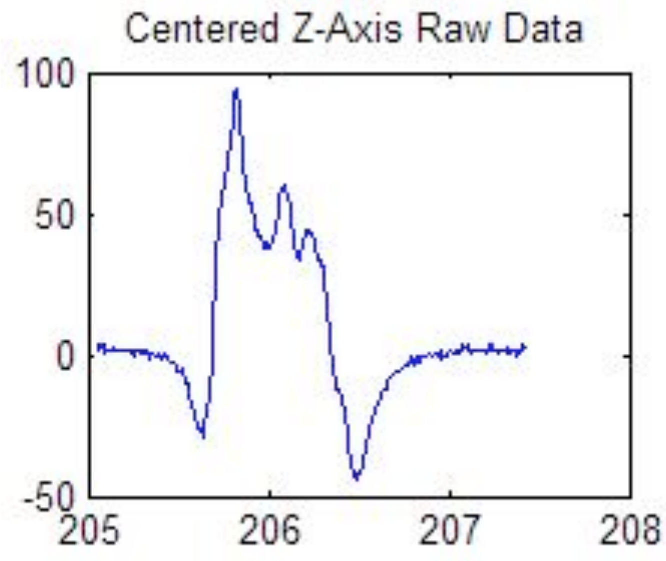


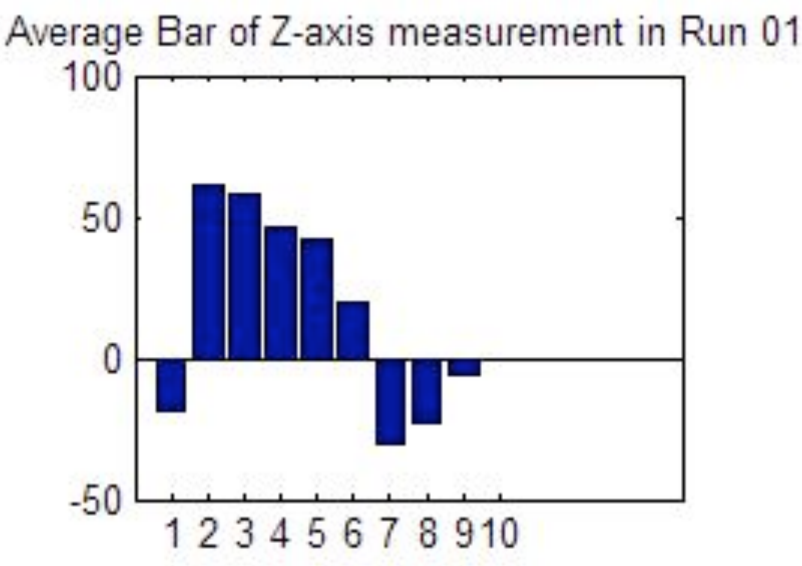


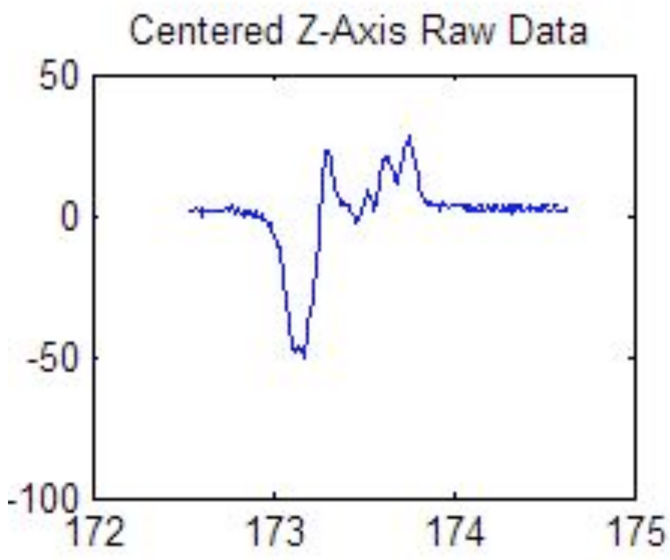
Preprocessing + compression B

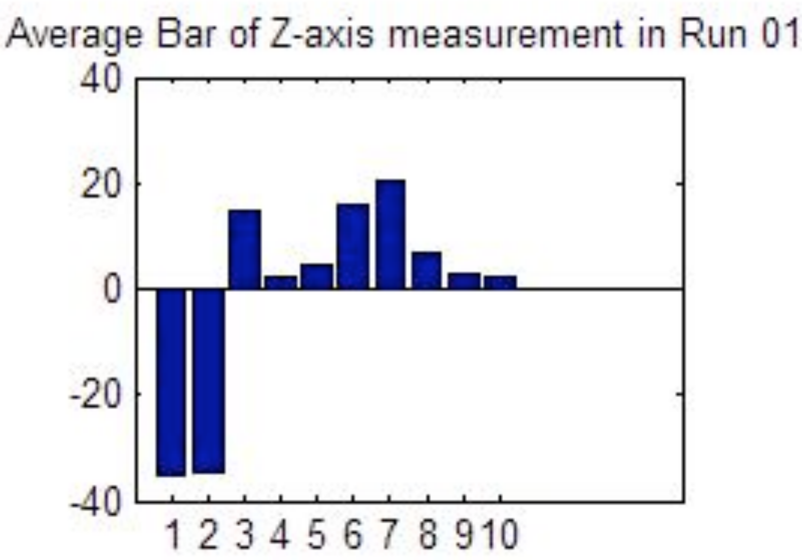
1. Replace sample vector x_i of size n(i) by vector of fixed size k (k=10, 20) with components = average value of x_i in bins of size n(i)/k
2. Extract principal components if necessary
3. Eliminates speed variation, but also length

Example B (k=10)





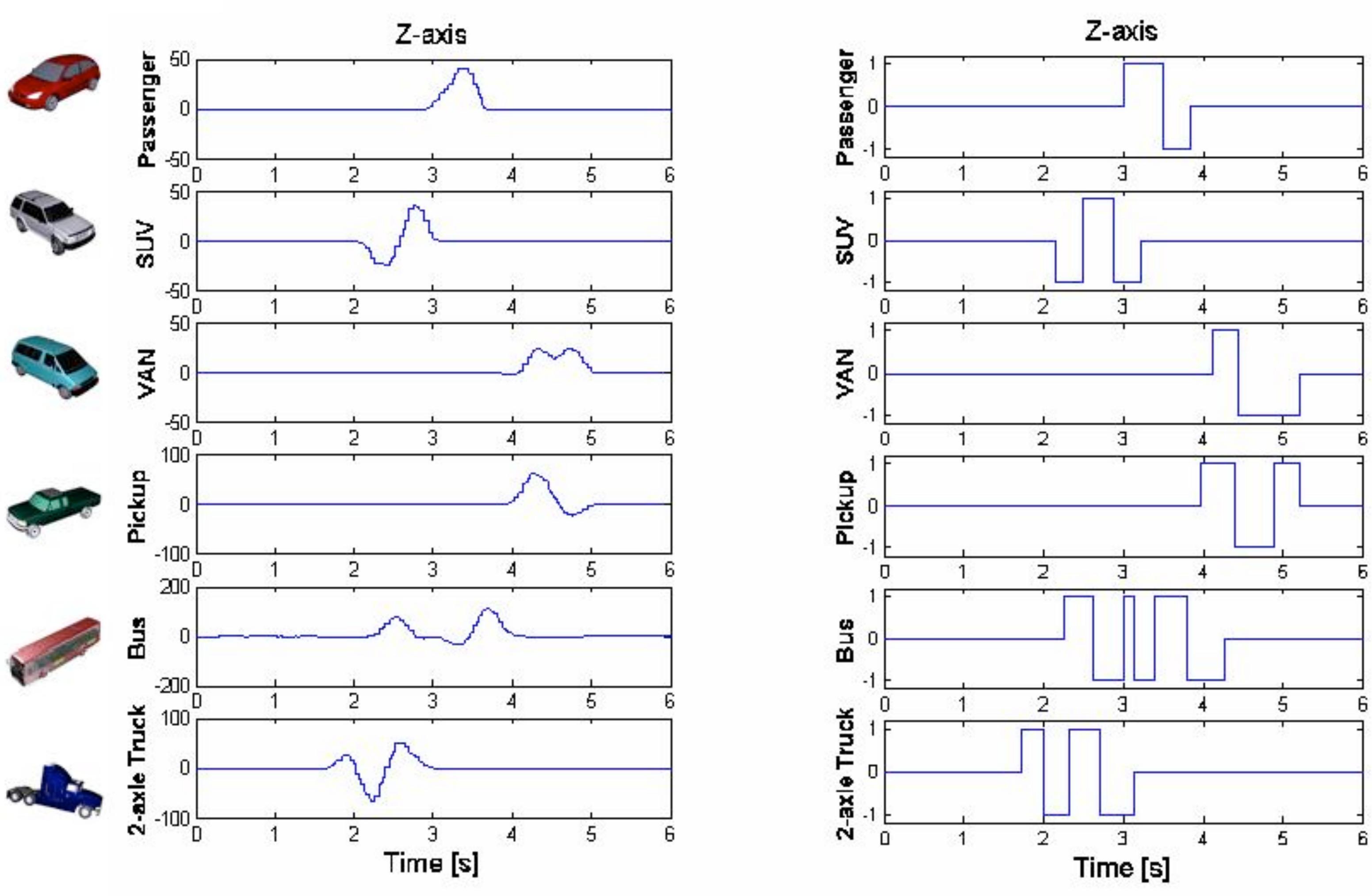




Preprocessing + compression C

1. Extract (-1,0,1) ‘hill pattern’
2. Add zero padding to obtain (-1,0,1) vector of fixed size k

Example C



- Very high compression

Classification Schemes

1. Support vector machines (SVM) using radial basis function kernel

$$k(u,v) = \exp(-\gamma\ |u-v|^2)$$

2. K-Nearest-Neighbor (KNN) scheme
   - Several variants depending on distance and 'voting' schemes

KNN results (1/4)

- 839 vehicles

Class	2	5	6	8	9	11
#	85	359	45	83	194	73

Trucks

- 50% from each class are randomly selected for training; 50% left for testing
- Correct rate is average from 10 trials
- Length information is not used

KNN results (2/4)

Passenger vehicles vs Trucks: FHWA 2 vs (5,6,8,9,11)

	Classification rate (%)	
	Test	Training
Hill pattern	91.2	91.4
Ave. bars	97.9	97.6

2-axle vs 3+ axle trucks FHWA 5 vs (6,8,9,11)

	Classification rate (%)	
	Test	Training
Hill pattern	78.9	82
Ave. bars	81.3	87.1

FHWA 9 vs (6,8,11)

	Classification rate (%)	
	Test	Training
Hill pattern	61.2	72.8
Ave. bars	71.2	80.8

- using length may improve accuracy

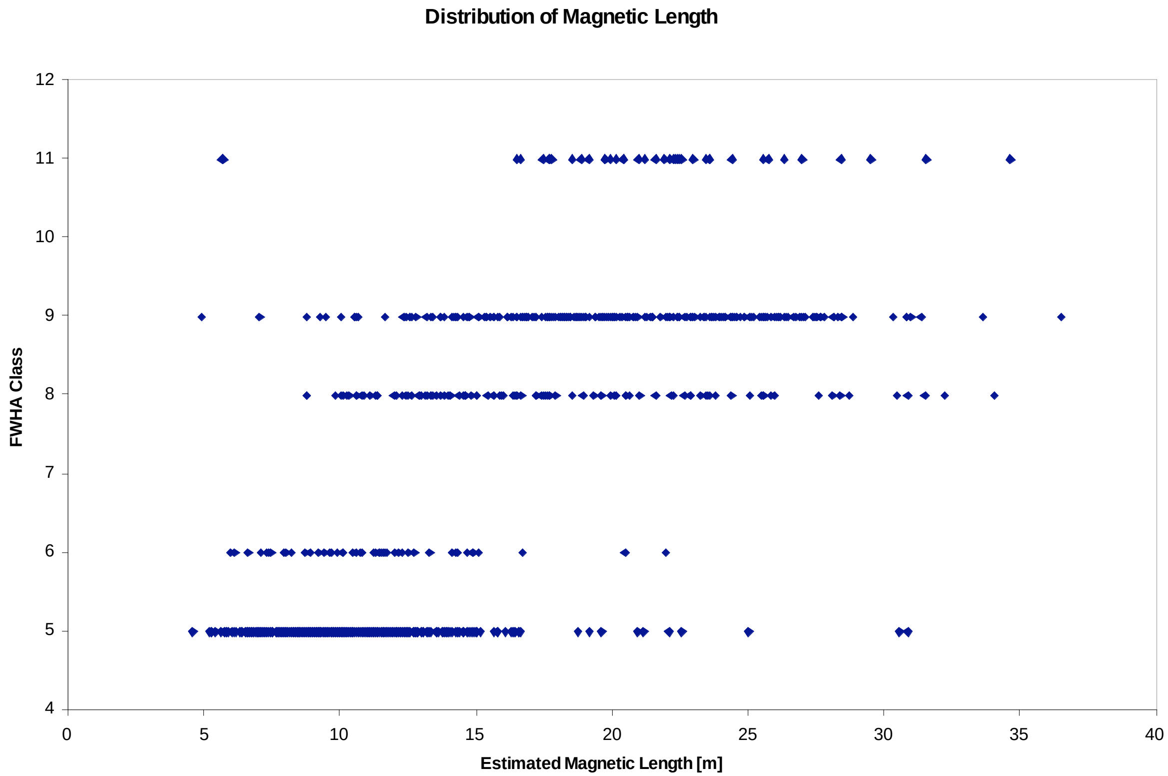
KNN results (3/4)

[%]		Classified as						Counts
Observed Class		***5***	***6***	***8***	***9***	***11***		
5		0.84	0.07	0.05	0.03	0.01		217
6		0.60	0.23	0.06	0.11	0.00		23
8		0.42	0.03	0.22	0.29	0.04		53
9		0.18	0.03	0.17	0.55	0.08		118
11		0.07	0.02	0.07	0.36	0.49		20
Avg. Counts		241.6	24.7	44.5	97.6	22.6		

FWHA Class		**5**	**6**	**8**	**9**	**11**	**Total**
#		435	47	106	236	40	864

- Average correct rate is 64%

KNN results (4/4)



	FHWA Classes				
Magnetic Length [m]	***5***	***6***	***8***	***9***	***11***
Mean	10.35	11.22	17.89	20.79	21.43
Std Dev	3.21	3.36	6.31	6.11	5.41

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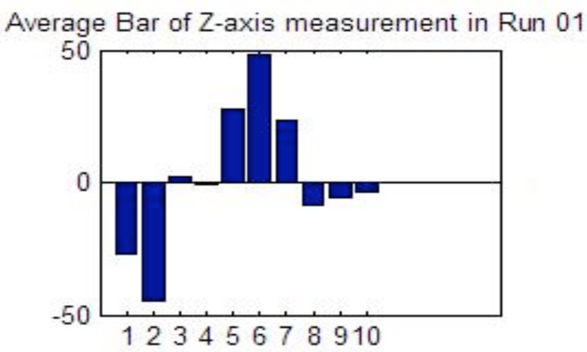
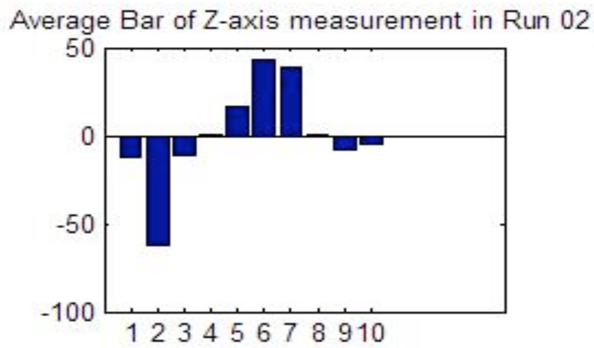
Vehicle re-identification

- Use an array of nodes to compensate for offset
- Experiment conducted with 7 test vehicles
  - Buick Le Sabre 97 (x 2)
  - Toyota Corolla 89
  - LandRover Range Rover 96
  - Ford Taurus 96
  - Ford Taurus 2000
  - Ford WindStar (Van)
- Each vehicle driven over SN array 5 times: Note 2 vehicles are the same model

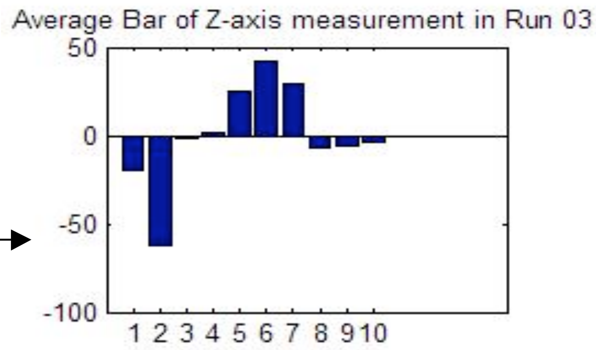
Compress with 10 ave bar

- No length or speed information
- Compare correlation of the Average-Bar from all three axes
- 100% correct re-identification among all 7 test vehicles





Compressed data from same vehicle



Summary

- Wireless magnetic sensor network has better detection properties than alternatives
- What about lifetime?
- Depends on energy consumption

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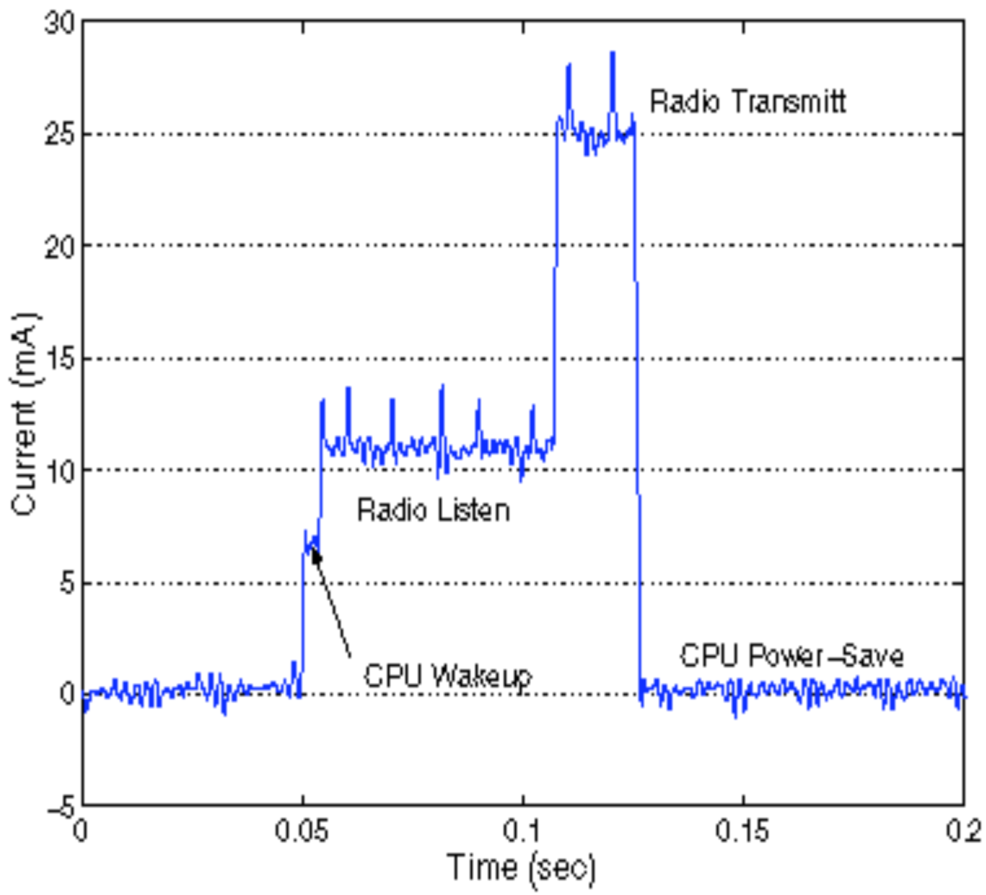
Energy Calculations

- Focus on radio energy
- Suppose battery rating is 2 Amp-hr @ 3V
- In 1 year = 8700 hours, average power budget is
  - 230 μA for 1 year lifetime
  - 23 μA for 10 year lifetime
- What kind of protocol and data rate can be supported with this power budget?

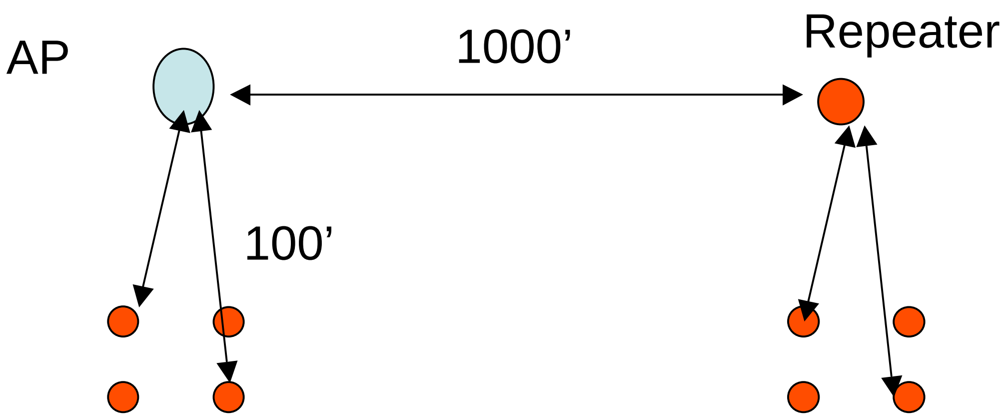
Mica2 CSMA protocol

- Mica2 CSMA protocol requires ‘listen’ before ‘transmit’ and constant ‘listen’ at 10mA current
- Gives lifetime < 10 days with no transmission



Source: Shnayder, V et al. SenSys 2004

Sensys network architecture



- All links are one-hop
- AP uses one channel; Repeater uses a different channel

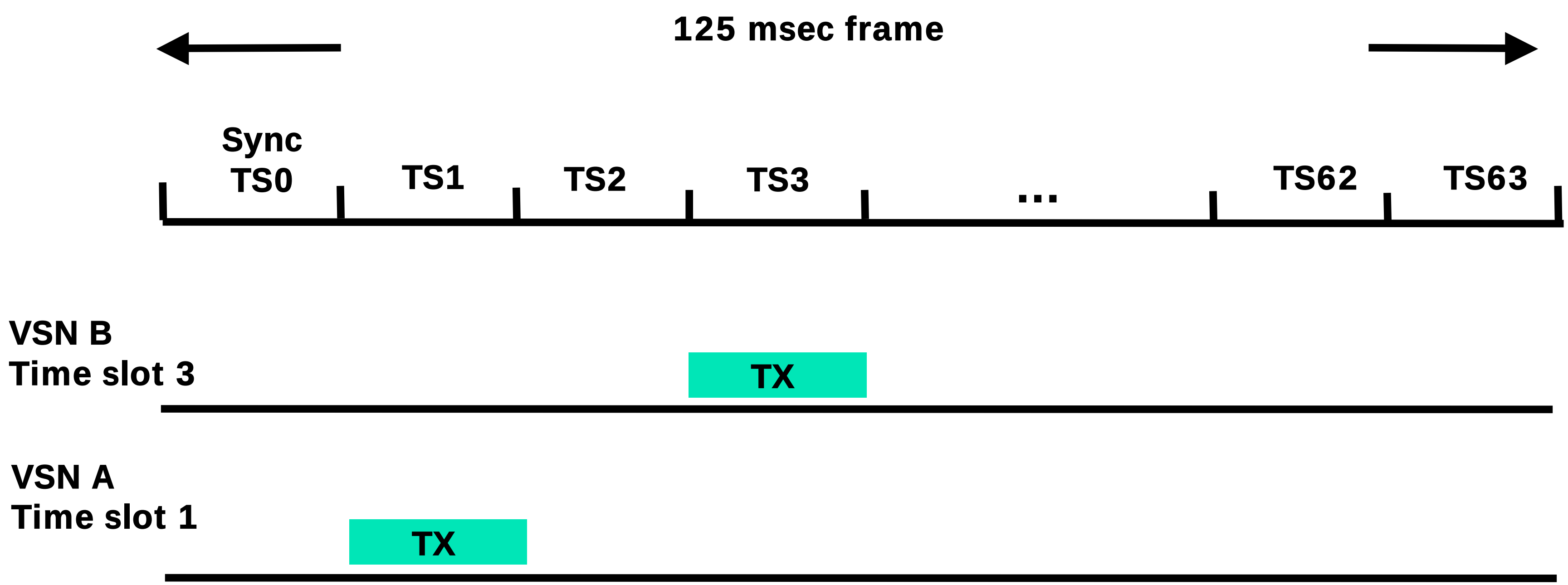
Sensys TDMA Protocol (1/2)

125 msec frame divided into 64 time slots

Each sensor in the network gets to transmit in one time slot each frame

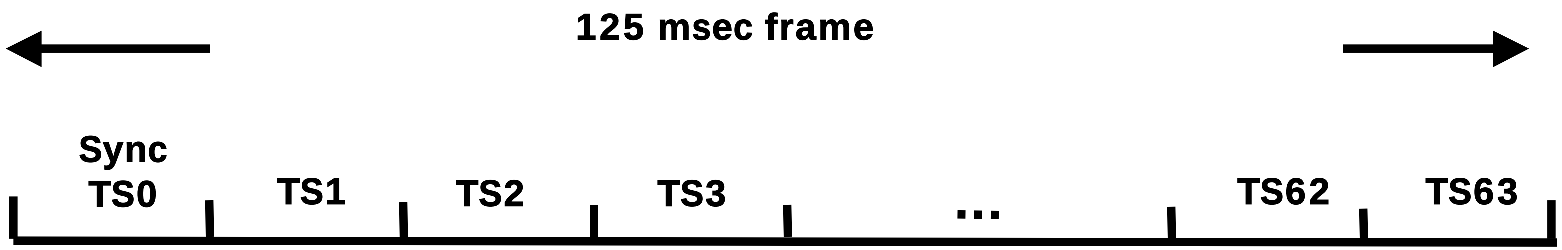
So latency is less than 125msec

Timeslots permit 50 bytes of data



Sensys TDMA Protocol (2/2)

- Time-slot 0 is the sync timeslot sent from the AP to the sensors; this timeslot also contains global parameters such as the detection parameters, the transmit interval, etc.
- Time-slot 2 is used for software download
- Time-slots 4 and 34 are used for ACK packets from the AP to the sensors
- Remaining time-slots can be used by sensors



Conclusion

Wireless sensor networks for traffic measurement are promising and pose interesting problems of

- Signal processing
- Power consumption
- Engineering design

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Future work

- Use accelerometers to estimate truck weight

Equations of motion

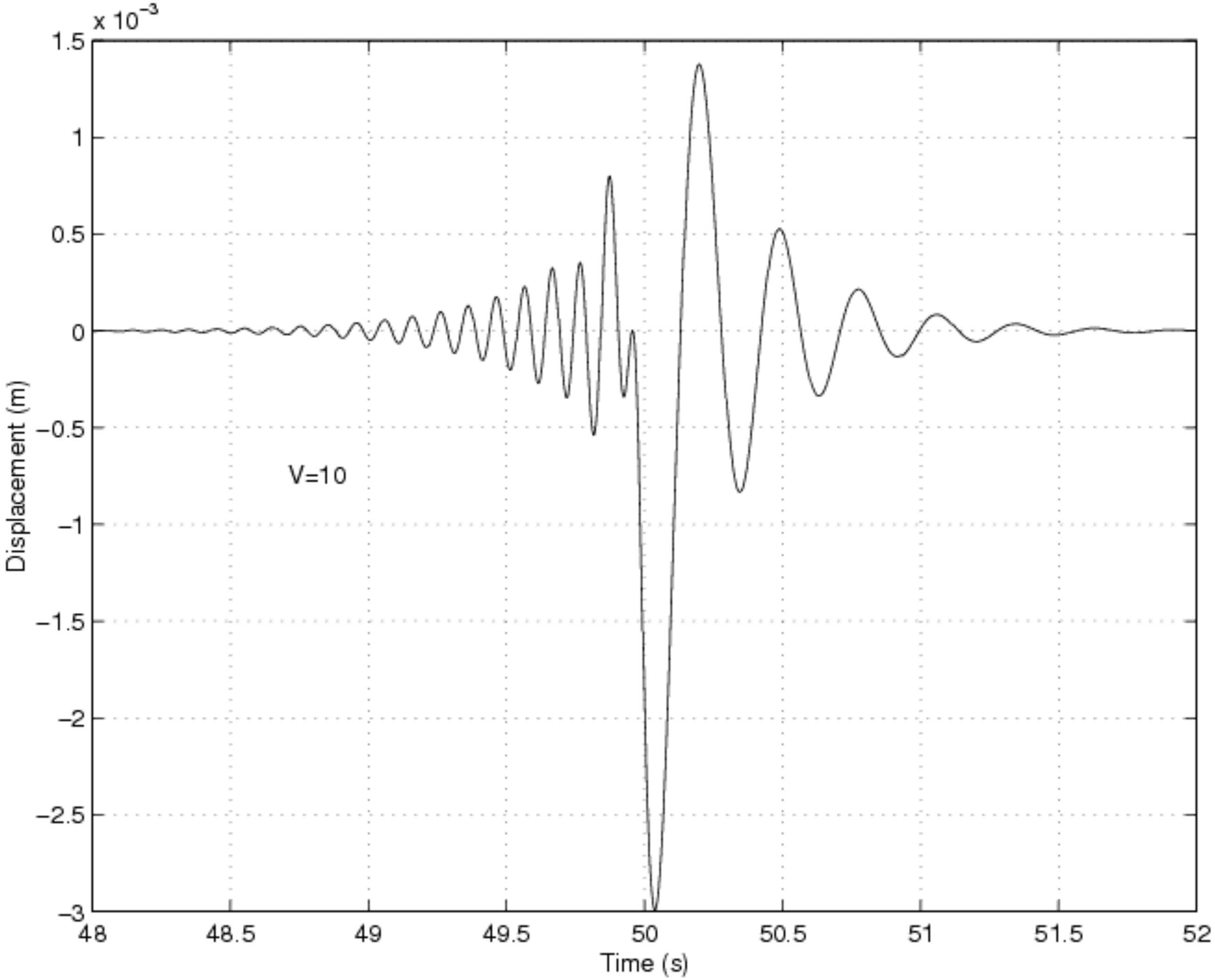
- Model pavement as Euler beam with elastic foundation with a moving load:

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

$$\begin{aligned} y(x,t) &= \text{displacement} \\ F(x,t) &= F\cos(\omega_0 t) \times \delta(x - Vt) \\ &= \text{force from truck} \end{aligned}$$

Estimate F, ω_0 from $\ddot{y}(0,t)$

A simulation: L=1km, $\omega_0/2\pi$ = 1.23Hz



- Acceleration peak ~ 0.5-1.0 mg

Conclusions

- Most research in sensor networks is generic: platform, protocols
- Applications require specific designs and great deal of engineering
- TDMA-based protocols offer great advantages over random access protocols
- Need to combine sensing with control