Some Thoughts on Traffic Responsive and Adaptive Signal Control Systems and Traffic Detection Sensor Options

Presentation Prepared for
Faculty of Transport and Traffic Sciences
University of Zagreb
June 2, 2006

Presented by:

Lawrence A. Klein, Ph.D.

3 Via San Remo

Rancho Palos Verdes, CA 90275, USA

(Voice and fax: +1 310 541 2622)

Email: laklein@flash.net

Outline

1. Why coordinate traffic signals?
2. Effective coordination requires data!
3. Signal coordination issues
4. Considerations for traffic adaptive signal control
5. Specifying detection and sensor requirements
6. Sensor technologies
7. Summary

Competing Demands – We No Longer Just Move Cars!

Why Coordinate Traffic Signals?

- Coordination objectives
  - Reduce delay
  - Reduce stops
  - Increase speed
  - Avoid destructive queues
  - Accommodate special traffic flows
  - Reduce potential for accidents
  - Reduce gas consumption, air & noise pollution, motorist frustration

➢ **Increase capacity**

(Workshop on Best Practices for Signal Timing and Operations, Transportation Research Board, January 9, 2005, Washington, D. C.)

When to Coordinate

- Potential for destructive queues exists
- Spacing of signals is proper
- 0.95 > ICU* > 0.60 at critical intersections
- Or headways < 5 seconds
- Consistency of cycle lengths can be implemented
- Overall delay reduction and average speed increase is desired

* Intersection capacity utilization

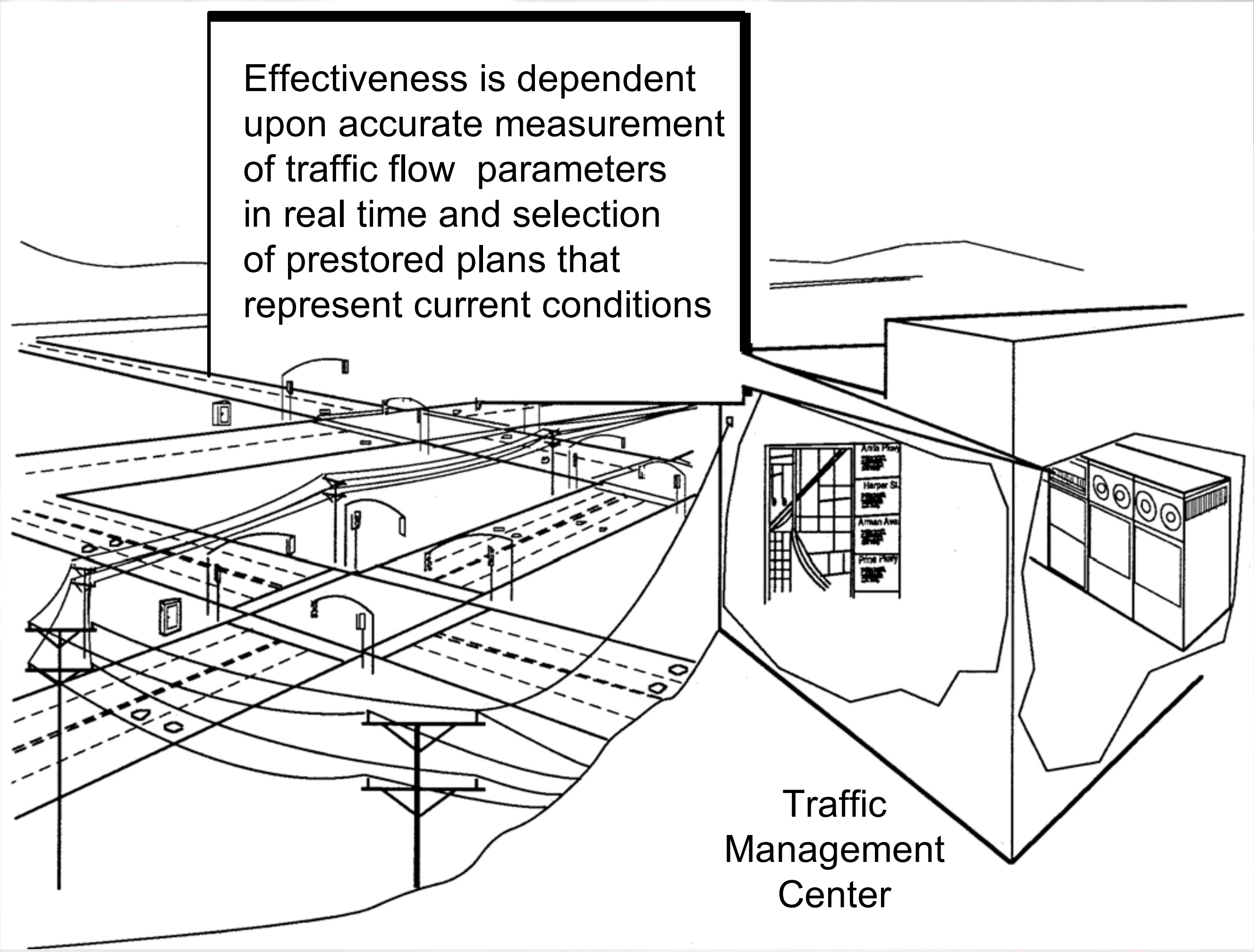
Good Signal Control Requires Descriptions of Road Configuration & Traffic Data

- Manual and machine volumes
- Intersection turning movements
- Speeds and delays
- Traffic characteristics (field checks)
- Lane geometry, aerial photos
- Bike and pedestrian requirements
- Distances between intersections
- Grade, alignment
- Accident history
- Engineering surveys of roads
- Signal timing cards

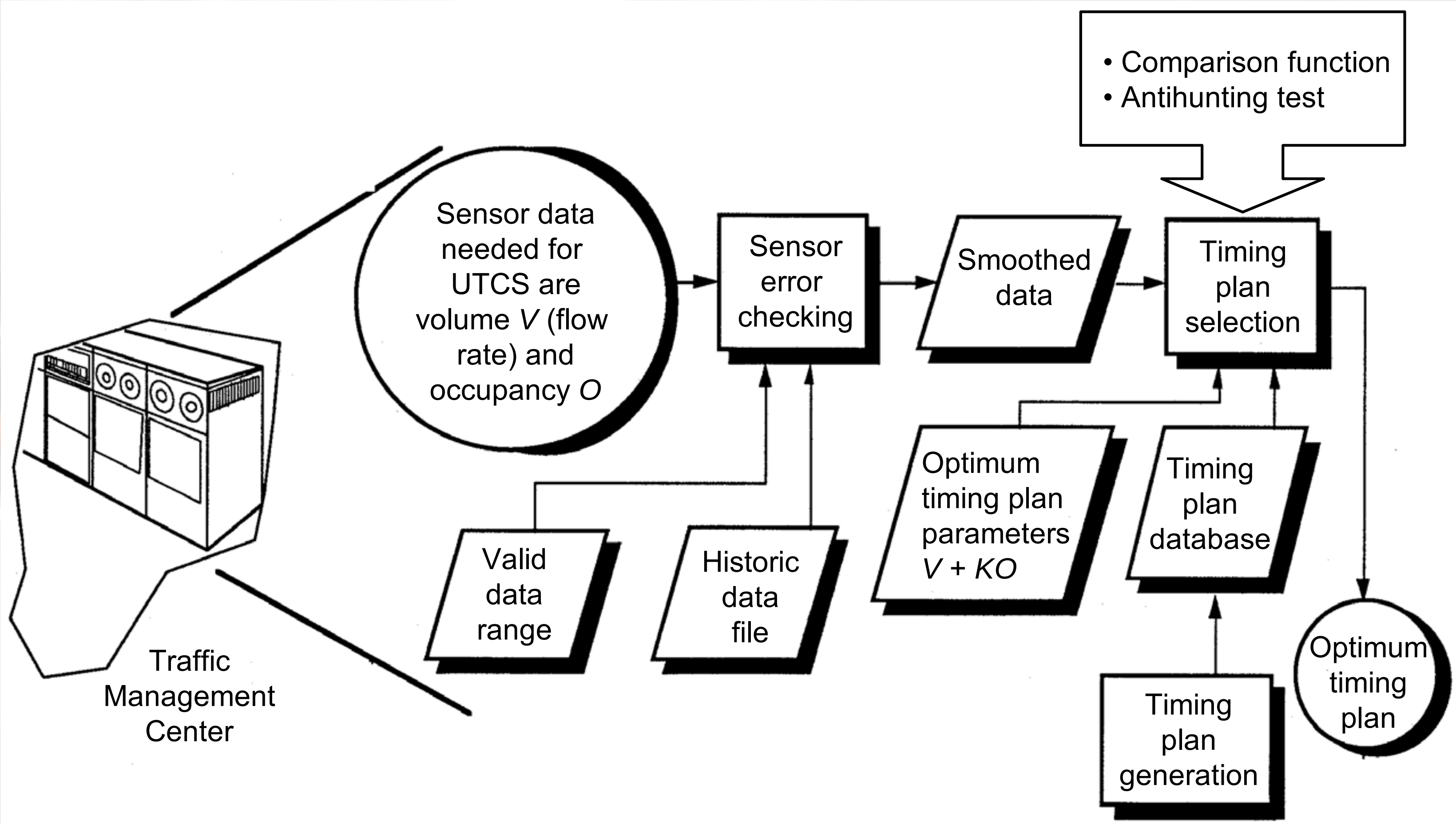
Traffic Responsive Signal Control

- Different plans needed for changes in:
  - Volume levels
  - Directional splits
  - Critical movements
- Plans must accommodate intra-day, day-of-week, seasonal, and preplanned special event and construction-induced variations in traffic flow rates
- One approach: Enable appropriate traffic responsive plan as needed …
  - When critical intersection likely to have ICU > 0.95
  - Near shopping centers on weekends
  - With preplanned special events or construction
  - When parallel expressway has incident
- Minimize number of plans – require 10% MOE change or greater to justify

Interconnected Intersection Control Using Urban Traffic Control System (UTCS)



Interconnected Intersection Control Using UTCS (continued)



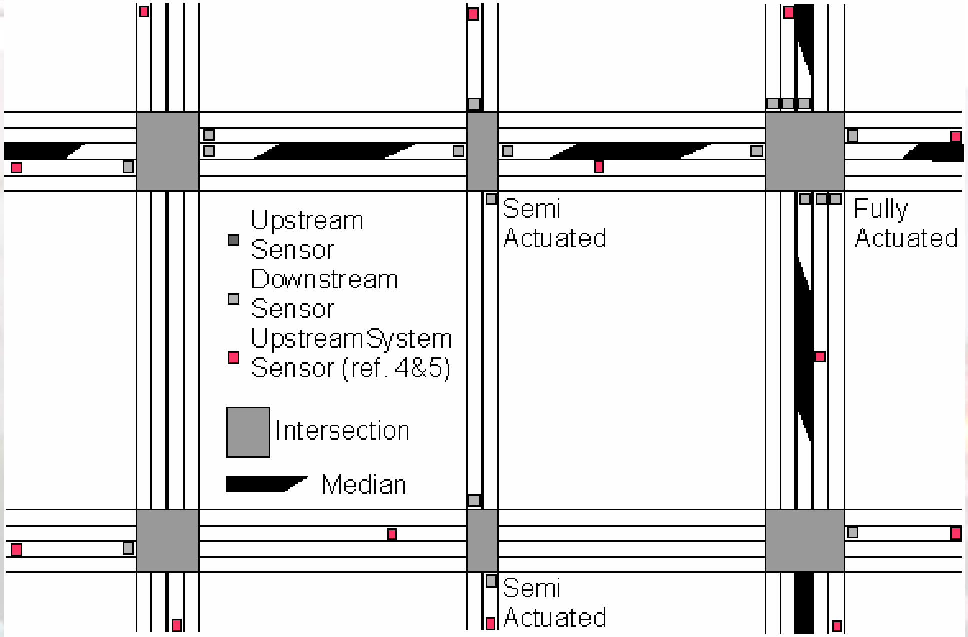


Figure L-4. Network sensor web density level 1.5. (UTCS 1.5, Closed Loop Systems with heavily actuated controller and several minor movements without detectors)

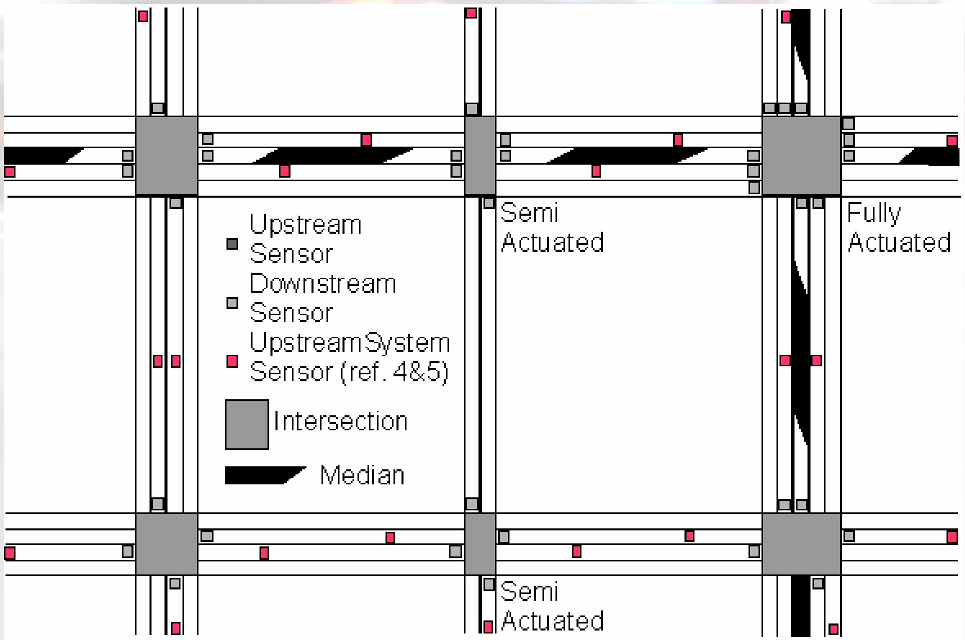


Figure L-5. Network sensor web density level 2.0 (Traffic Adjusted, UTCS 2 GC)

UTCS 2 GC requires instrumentation on all links between "major" intersections, which are defined as those intersections operating within the strategic optimization routine (p 84, ref 5)

[5] Henry, R.D.; J.M. Bruggeman; and S.A. Smith, "Locating Detectors for Advanced Traffic Control Strategies," Technical Report, FHWA-RD-75-92, Federal Highway Administration, Washington, D.C., 1975.

EVALUATION OF THE BELLEVUE UTCS 1.5 SIGNAL CONTROL SYSTEM
WA-RD 188.1
Published: February, 1990
Author(s): Rutherford GS, Schroeder M, Jacobson LN, Hallenbeck ME
Organization(s): University of Washington
Report available from: Office of Research and Library Services
Washington State Department of Transportation
PO Box 47372
Olympia WA 98504-7372

The Bellevue UTCS 1.5 signal system has improved traffic flow on Bellevue's arterial network (volumes increased 17 percent with no significant changes in travel time)

Why Coordination Isn't Easy

- **Beware of coordination killers!**
  - Unnecessary signals
  - Non-optimal signal spacing
  - Unneeded protected left turns
  - Geometrical constraints
  - Going "Cheap" on signal and sensor design
  - Congestion
  - Multi-jurisdictional systems
  - Changing conditions
  - Lack of expertise

(Rick Denney, Iteris)

Developing Traffic Adaptive Signal Control

- **The motorists are the ultimate judges of the success of a signal timing project**
- **Before designing the new timing, be sure to understand the timing strategy that's currently in effect**

(Wayne Kurfees, Kimley-Horn and Associates, Inc.)

Understand the Client's Preferences and Limitations

- Minimum split times
  - Coordinated phases
  - Other through phases
  - Left-turn phases
    - Protected or protected/permissive
- Signal sequences
  - Are lead-lag sequences allowed?
  - Is it okay to use phasing that avoids the yellow trap if the leading side has protected-permissive left turns?
  - Is it okay for the sequence to change as a function of the timing plan?

Motorist Considerations

- Are the progression speeds realistic?
  - What if the actual platoon speeds are greater than the posted speed limit?
- Whenever a major flow has to stop …
  - A short stop is better than a long one
  - Try not to have the stop occur at an insignificant minor street
  - For safety, the platoon should arrive on red (rather than encounter an unexpected yellow)

Pedestrian Considerations

- Some locations require full accommodation of pedestrian intervals
  - CBD intersections (and other locations with significant pedestrian volumes)
  - School crossings (at least during times when school is in session)
  - Coordinated phases
  - Pretimed intersections
  - Guidelines from national or local disability legislation
  - Other locations without push buttons (if pedestrian movements regularly occur)

Pedestrian Considerations (cont)

- Otherwise, the minor-phase split will generally not accommodate the walk and pedestrian clear intervals (and a resynchronization will have to occur after the pedestrian call is served)

Who Wins?

- Different modes have different optimal signal timing parameters
- Pedestrians want the shortest waiting time possible (short cycle lengths)
  - Long wait times at intersections with school pedestrians may result in voluntary crossing on red phase
- Protected left turn phases require longer cycle lengths
- Transit vehicles move more slowly between signalized intersections than general traffic

Traffic Adaptive Algorithm Performance

TABLE 2: SCOOT Field Evaluation Results

Location of SCOOT Installation	Previous Control Method	Year	% Benefit over previous control method	
			Delay	Travel Time
São Paulo, Brazil (ver. 2.4)	Fixed-time (TRANSYT)	1997	0 – 40	-
São Paulo, Brazil (ver. 3.1)	Fixed-time (TRANSYT)	1997	0 – 53	-
Nijmegen, The Netherlands (ver. 2.4)	Fixed-time	1997	25	11
Toronto, Canada (ver. 2.4)	Fixed-time	1993	17	8
Beijing, China (ver. 2.3)	Fixed-time (Uncoordinated)	1989	15 - 41	2 - 16
Worcester, UK (ver. N/A)	Fixed-time (TRANSYT)	1986	3 - 11	7 - 18
Worcester, UK (ver. N/A)	Isolated Vehicle Actuation	1986	7 - 18	15 - 32
London, UK (ver. N/A)	Fixed-time	1985	19	6 - 8
Southampton, UK (ver. N/A)	Fixed-time	1985	39 - 48	18 - 26
Coventry, UK - Foleshill Road (ver. N/A)	Fixed-time (TRANSYT)	1981	22 - 33	4 - 8
Coventry, UK - Spon End (ver. N/A)	Fixed-time (TRANSYT)	1981	0 - 8	0 - 3

(Effectiveness of SCOOT Adaptive Control on Networks and Corridors, Chintan S. Jhaveri, Joseph Perrin, Jr., Peter T. Martin, TRB, January 2004)

2004 Survey of US Traffic Adaptive Systems

Agency	System	Intersections
City of Anaheim, CA	SCOOT	22
Orange County, FL	SCOOT	13
City of Minneapolis, MN	SCOOT	56
City of Toronto	SCOOT	300
Oakland County, MI	SCATS	575
Minnesota DOT	SCATS	71
City of Tucson, AZ	RHODES	–
City of Tempe, AZ	RHODES	1
New Jersey DOT	OPAC	12

(Peter T. Martin, Associate Professor, University of Utah)

General Observations

- Most agencies are satisfied with ATCSs because
  - They adapt to varying traffic conditions caused by daily traffic fluctuations and special events
- Agencies agree that successfully operating and maintaining the system is a substantial time investment
- To gain proficiency, a person must spend at least one year with the system
- Acquiring signal timing expertise is the most difficult skill to master in traffic engineering

Specifying Detection and Sensor Requirements

- Problem Statement
- Operational Assessment

(Peter Koonce, Kittelson and Associates, & L.A. Klein)

Problem Statement: Sensor Layout and Location (Design)

- Briefly explain and provide (using standard drawings, graphs, or spreadsheets) the approach utilized to design the sensor layout
- Discuss methodology used to determine the number of required sensors; what criteria are used?

Sensor Location Depends on Traffic Adaptive Algorithm

- **SCOOT sensors are located upstream from the signal stopline, approximately 15 meters downstream of the adjacent upstream intersection**
- **SCATS sensors are installed in each lane immediately in advance of the stopline to collect volume and occupancy data during the green of the approach**

Detection Requirements

Application	Strategy	Typical Data Collection Interval	Parameter and Generalized Accuracy
Local Isolated Intersection Control	Intervehicle gap detection on intersection approach	Sampled every 0.1 s	Detect intervehicle gaps ≤ 3 to 4 s duration to an accuracy of ± 0.05 s
	Stopline presence and passage detection	Sampled every 0.1 s	100% vehicle detection
Interconnected Intersection Control	Timing plan selection	5 min or signal cycle	Flow rate within ± 2.5% at 600 vplph*; Occupancy within ± 2.5% at 25% occupancy
	System performance measure of effectiveness	5 or 15 min	Flow rate, average vehicle length, occupancy within ± 10%; Average speed within ±5%
	Critical intersection control where goal is to set signal timing to nearest second	Signal cycle	Flow rate to ± 1 vehicle per lane at 600 vplph*; Occupancy within ± 2.5% at 25% occupancy
Traffic Adaptive Intersection Control	SCOOT split optimization that requires generation of traffic flow cyclic profiles	Signal cycle	Vehicle detection within ± 2 veh/cycle for 90% of the signal cycles
Freeway Incident Management	Incident management and decision support	5 min	Vehicle detection within ± 1 vehicle for 90% of the 5-min intervals
	Incident detection algorithms	20 or 30 s	Occupancy within ± 1% at 25% occupancy; Flow rate within ± 1 veh/min at 2000 veh/h
Freeway Ramp Metering	Ramp metering based on mainline traffic flow	1 min	Downstream occupancy within ± 2% at 25% occupancy; Upstream flow rate within ± 2 veh/min at 2000 veh/h; Upstream occupancy within ± 2% at 25% occupancy

* vplph = vehicles per lane per hour

Input Data Required by Popular Incident Detection Algorithms

	← Traffic Variables →			Data Collection Interval		← Number of Stations →	
Algorithm	Flow Rate	Occ.	Speed	1 s	30-60 s	Single	Adjacent
Comparative		X			X		X
McMaster	X	X	X		X	X	X
Time series	X	X			X	X	X
HIOCC		X		X		X	

(*From*: Stephanedes, Y.J., A.P. Chassiakos, and P.G. Michalopoulos, "Comparative Performance Evaluation of Incident Detection Algorithms," *Transportation Research Record* 1360, Transportation Research Board, Washington, D.C., 1993, pp. 50-57)

VIP Camera Mounting for Four-Way Intersection Control

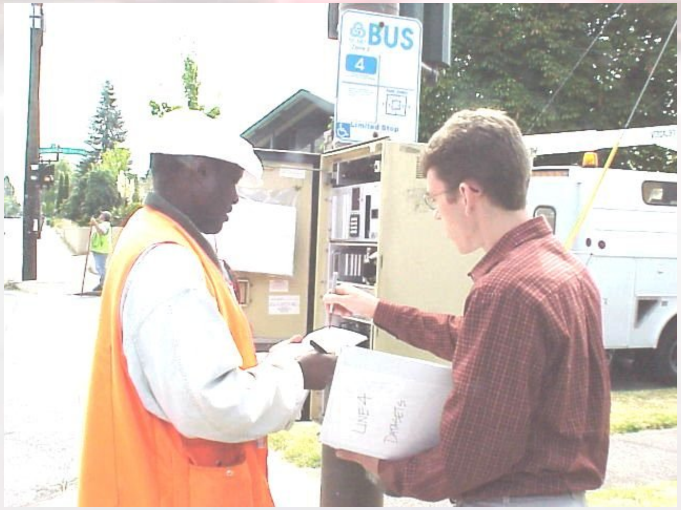
Intersection Control with VIP Camera Mounted Over Center of Monitored Lanes

(Caution: Beware of sun glint from shallow camera angles)

Microwave Presence-Detecting Radar Sensor Side Mounted for Multiple Lane Monitoring

Problem Statement: Detection Timing (Operations)

- Briefly explain your approach to detection timing
- Discuss the timing functions used
  - What are the basic parameters used for detection timing and what is their purpose? (e.g., volume density functions, minimum green, passage)



Problem Statement: Define Detection Purpose

- **Design for Safety and/or Efficiency**
- **Any consideration of Timing Functions in Design Phase or vice versa?**

	Safety	Efficiency	Both
Minimum Green			x
Detection Switching			x
Volume-Density Function		x	
Dilemma Zone Protection	x		
Clearance Intervals	x		

Detection Functions and Timing (Operations)

- **Consider the following questions:**
  - **Does the choice of sensor technology change what you do?**
  - **What effects do speed changes have on your approach?**
  - **Do you change parameters depending on the operation of the intersection (isolated and coordinated or by time of day)?**
  - **How do additional through lanes (2 or more) affect your approach to timing (e.g., gap settings, dilemma zone)?**
  - **How much does the public affect what you do and what effects exist?**
  - **Do you use detection timing features? Contrast these with controller timing features (e.g., vehicle extension interval).**

Are Detection Needs Affected By ...?

- Types of conditions
  - Urban: pedestrians, mass transit, schools, CBD
  - Rural: high speed, mostly uncoordinated/fully actuated
  - Road alignment
- Time of day, season
  - P.M. peak vs. late night travel
  - Harvesting of crops (e.g., use of roadways on a seasonal basis)
- Preplanned or known special events (e.g., additional turning movements and volume) or construction activities (e.g., lane closures, work zone safety issues)
- Coordinated vs. uncoordinated operation
- High-speed (>35 mph) conditions
- High-speed coordinated operation

No consensus

Questions Raised by Practitioners

- Are safety benefits possible with sensor and timing design?
- What is the importance of lane-by-lane detection?
- Is emphasizing dilemma zone safety over multiple lane efficiency a good idea?
- What maintenance issues need to be addressed?
- How do we communicate these issues to the practitioner?

Various Sensor Technologies and What They Can Do For You

References for this section:

1. ***Traffic Detector Handbook*, FHWA-HRT-06-108, Klein, L.A., Gibson, D., and Mills, M.K., Federal Highway Administration, US Department of Transportation, Washington, DC, 2006.**
2. ***Sensor Technologies and Data Requirements for ITS*, Klein, L.A., Artech House, Norwood, MA, 675 pp. (including pages on CD), June 2001.**

(Lawrence A. Klein)

Traffic Parameters

- Sensors may provide:
  - Flow rate (volume), occupancy, and density
  - Count, presence, and passage
  - Speed of individual vehicles and platoons of vehicles
  - Queue lengths
  - Approach flow profile
  - Approach stops
  - Link travel time
  - Origin-destination pairs

•
•
•

A given sensor generally does not output all traffic parameter types

Overhead Sensor Technology Applications to Traffic Management

Application	Assumptions	Overhead Sensor Technologies
• Signalized intersection control	• Detect stopped vehicles • Weather not a major factor	• Microwave presence-detecting radar • Passive infrared • Laser radar • Video image processor (with adequate lighting)
• Signalized intersection control	• Detect stopped vehicles • Inclement weather	• Microwave presence-detecting radar
• Signalized intersection control	• Detection of stopped vehicles not required • Inclement weather	• Microwave presence-detecting radar • Doppler microwave radar
• Real-time adaptive signal control (e.g., SCOOT)	• Desirable for sensor footprint to emulate a 6-ft × 6-ft inductive loop	• Video image processor • Microwave presence-detecting radar • Passive infrared (with suitable aperture beamwidth)

Overhead Sensor Technology Applications to Traffic Management (continued)

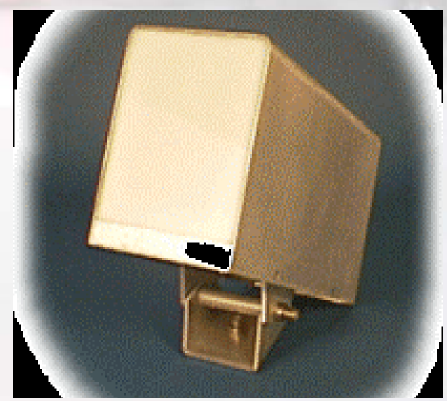
Application	Assumptions	Overhead Sensor Technologies
• Vehicle counting (surface street or freeway)	• Detect and count vehicles traveling at speeds > 3 to 5 mi/h (4.8 to 8.0 km/h)	• Microwave presence-detecting radar • Doppler microwave radar • Passive infrared • Ultrasound • Video image processor
• Vehicle speed measurement	• Detect and count vehicles traveling at speeds > 3 to 5 mi/h (4.8 to 8.0 km/h)	• Microwave presence-detecting radar • Doppler microwave radar • Laser radar • Video image processor
• Vehicle classification	• By length	• Video image processor • Laser radar • Microwave presence-detecting radar
• Vehicle classification	• By profile	• Laser radar • Inductive loop with high frequency excitation and special signal processing software

Microwave Presence-Detecting Radar Sensors

RTMS multizone presence-detecting microwave radar. (Photograph courtesy of Lawrence A. Klein)

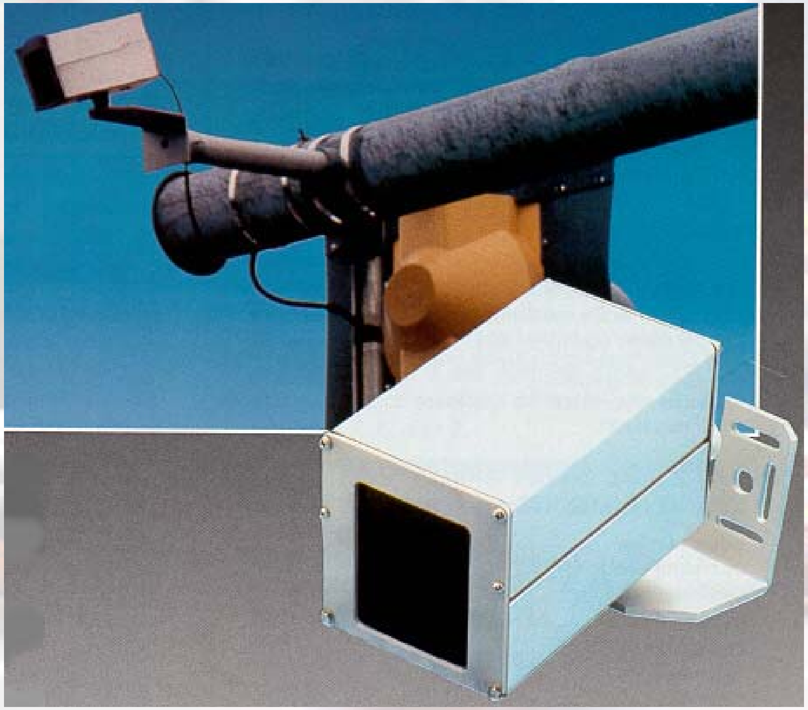
SmartSensor multizone presence-detecting microwave radar. (Photograph courtesy of Wavetronix, Provo, UT)

Loren multizone presence-detecting microwave radar. (Photograph courtesy of Electronic Control Measurement Inc, Manor, TX)

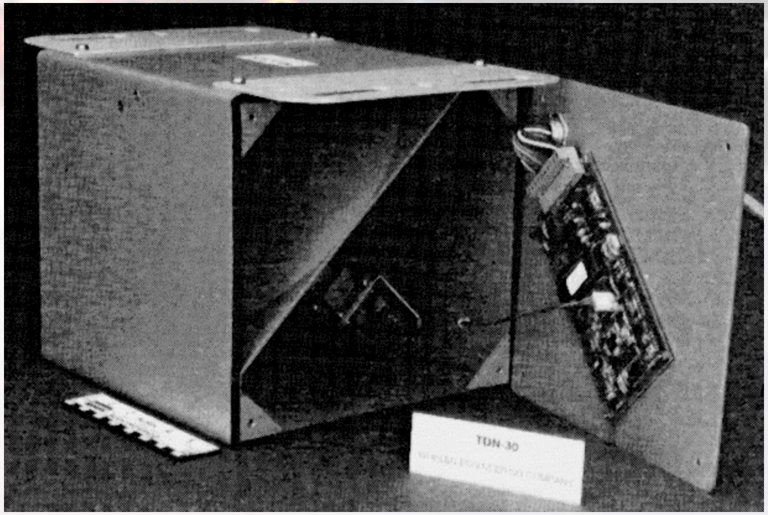


150LX single zone presence-detecting microwave radar. (Photograph courtesy of Naztec, Inc., Sugar Land, TX)

Microwave Doppler Sensors

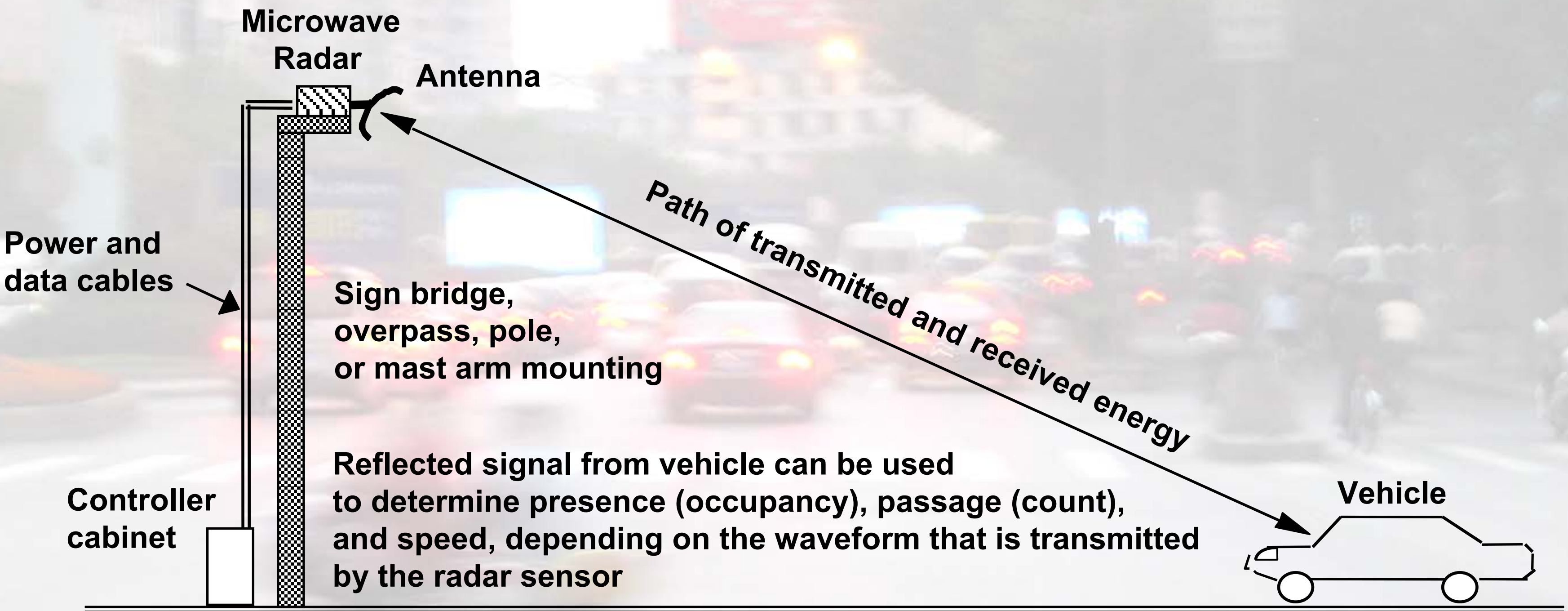


Microwave Sensors TC-20

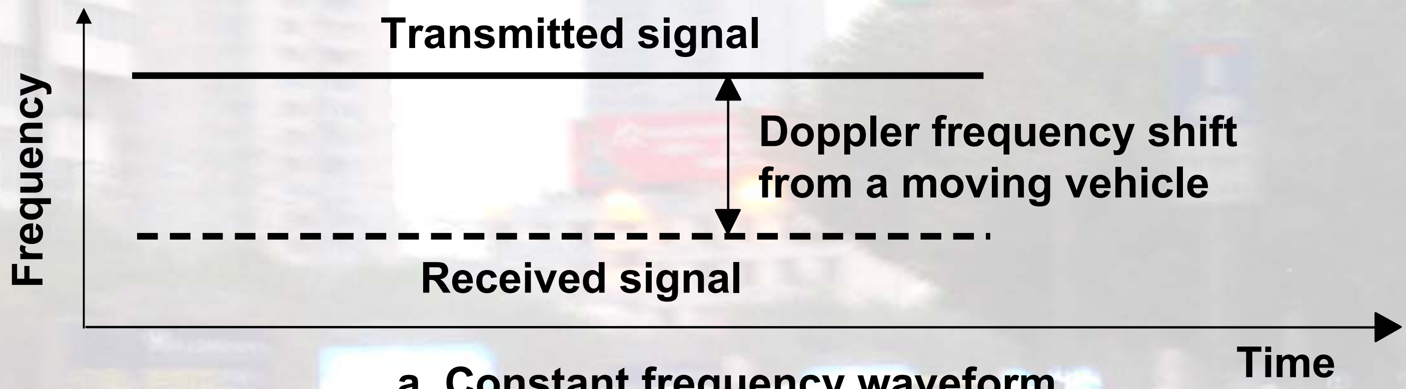


Whelen TDN-30

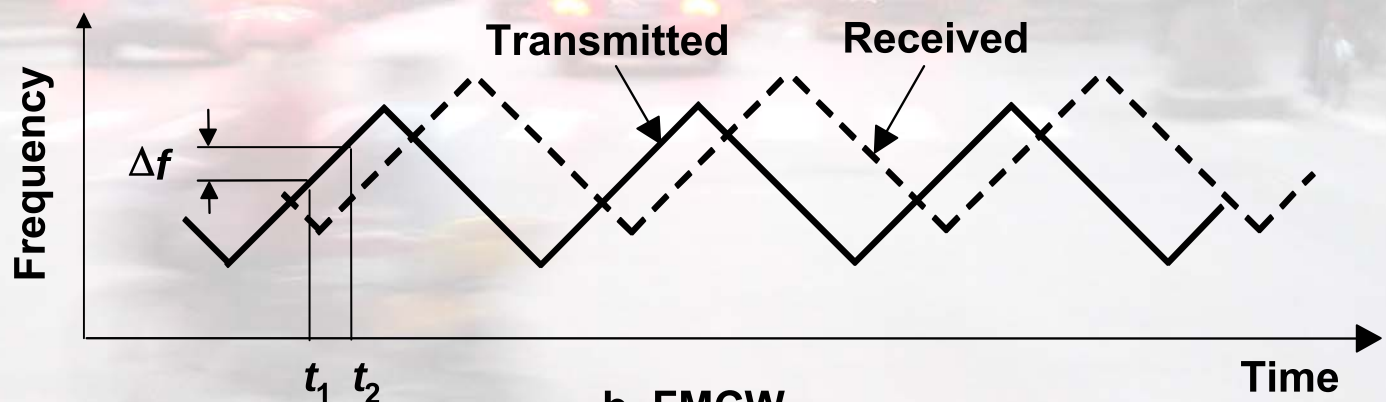
Microwave Radar Operation



Microwave Radar Waveforms



a. Constant frequency waveform



b. FMCW

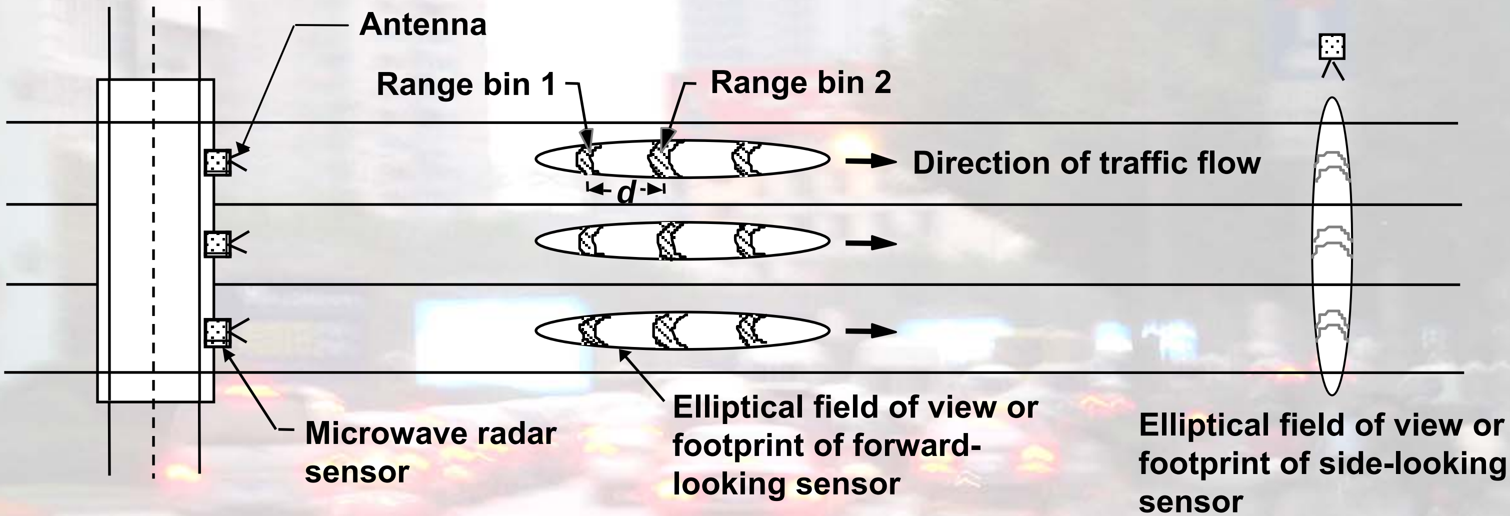
Presence Detection

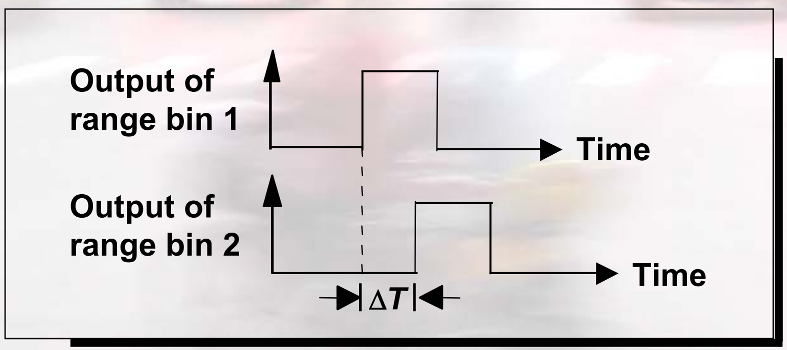
- Presence is detected by the change in distance to the energy reflecting surface measured by the radar when a vehicle appears

  - Range R is proportional to Δf or equivalently the time difference $t_2 - t_1$

  - $R = c(t_2 - t_1)/2$

Range Bins for Improved Spatial Resolution and Speed Measurement





$v = d/\Delta T$

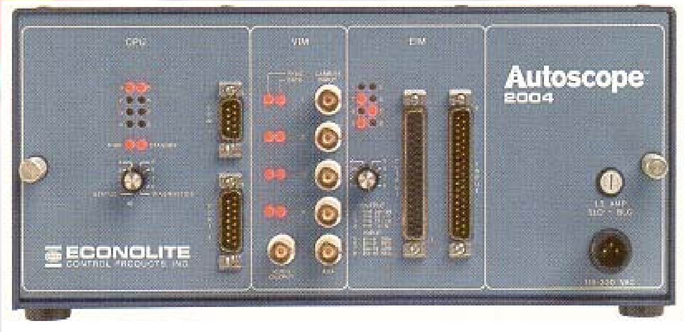
where

v = vehicle speed

d = distance between range bins

ΔT = time difference between pulse returns

Video Image Processors



Autoscope 2004

Autoscope Solo

(Photographs courtesy of Econolite Control Products, Anaheim, CA)

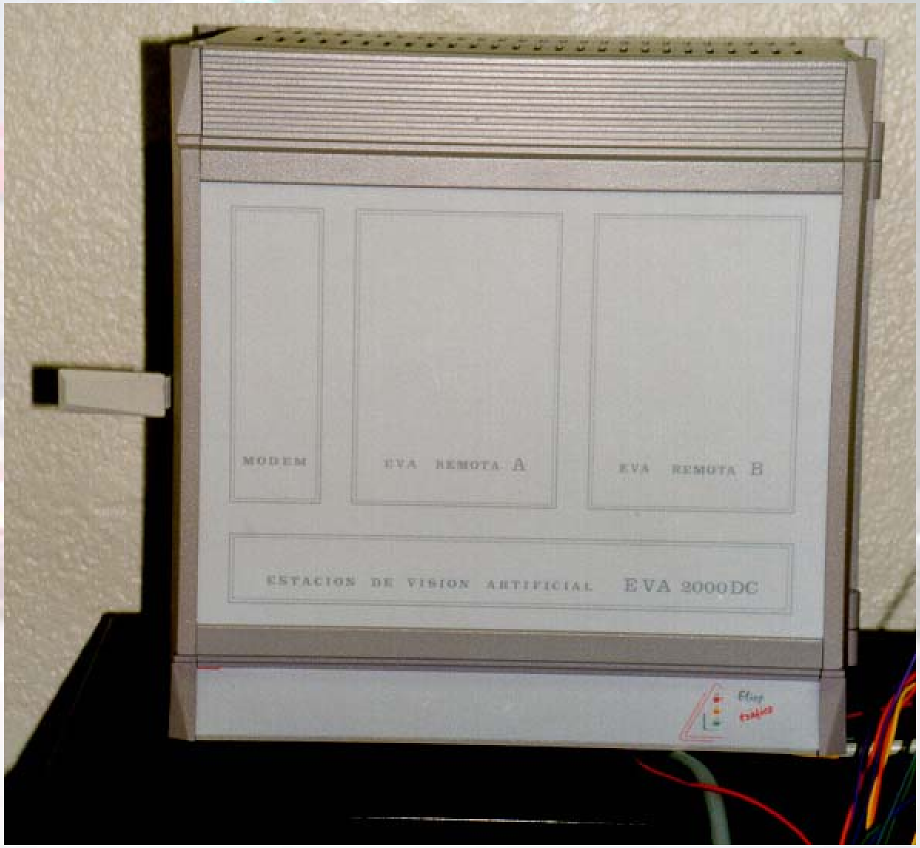
Traficon VIP 3 (Photograph courtesy of Traficon, Heule, Belgium)

Iteris Vantage processors
(Photograph courtesy of Iteris, Anaheim, CA)

Peek 910
VIP

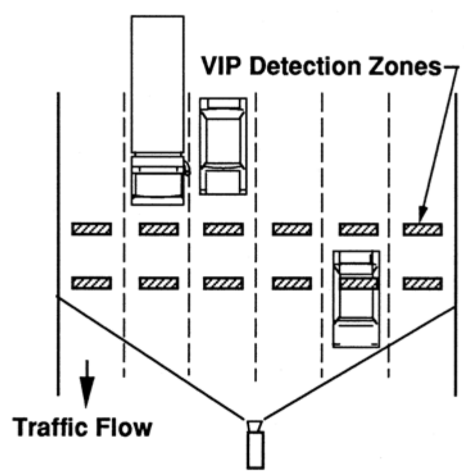
Video Image Processors (cont)

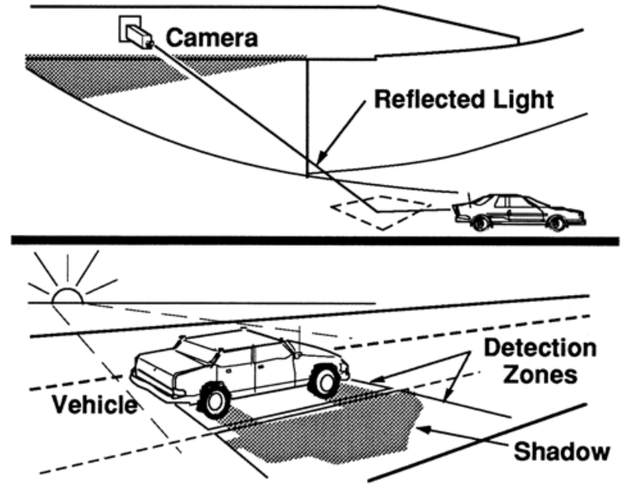
Computer Recognition Systems
Traffic Analysis System VIP



EVA 2000 VIP

Video Image Processor (VIP) Operation



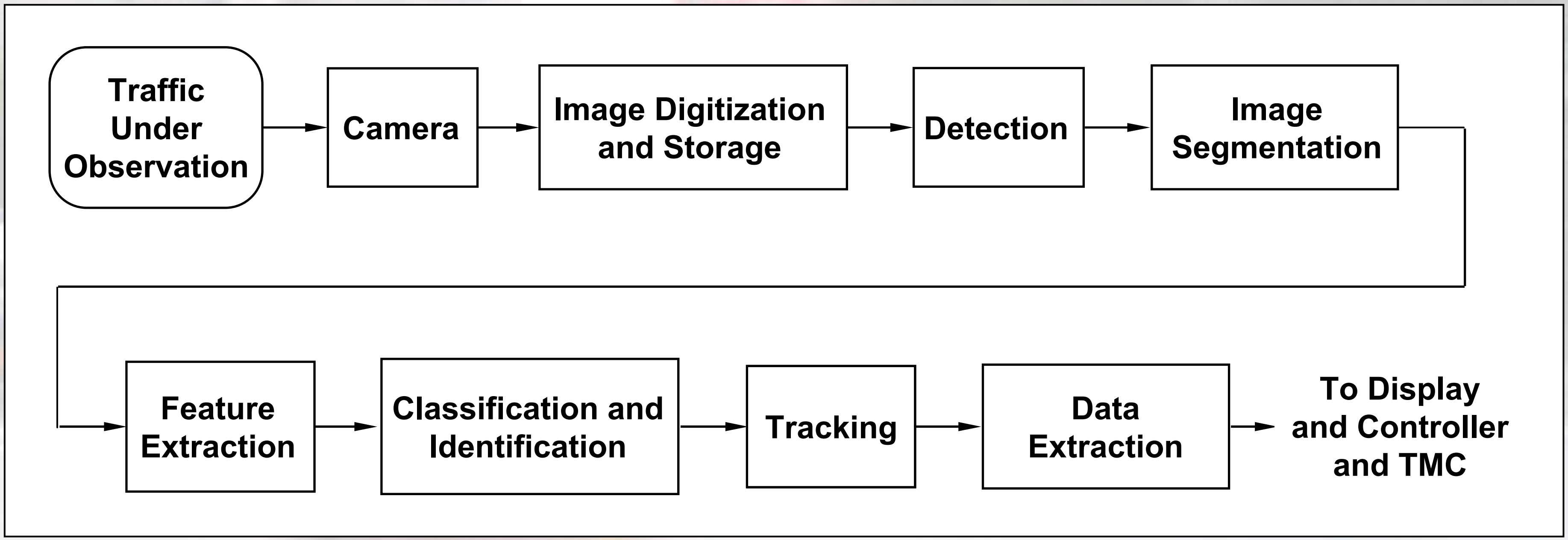


Reflected light from wet pavement and shadows caused false detections in some early VIPs

- Video image processor field of view determined by focal length of lens, camera mounting height, and camera tilt.
- Some VIPs insert vehicle detection zones into the camera's field of view based on traffic management and data collection requirements; others track vehicles through the entire field of view.

- **VIPs digitize the input video imagery and identify preselected features using hardware and software typically hosted in a PC. They utilize a variety of signal processing algorithms to compute traffic parameters.**

Conceptual Image Detection, Classification, and Tracking Algorithm



Types of Machine Vision Systems

- Tripline
  - Functional equivalent of inductive loops
  - Defines some number of detection zones within the field of view of the video camera
  - Measures changes in the pixel characteristics between successive frames
  - Changes are attributed to the presence of a vehicle
- Closed-loop tracking
  - Extension of tripline approach where detection is performed along longer roadway sections
  - Vehicle detection is associated with multiple detections of the same vehicle along a track
- Data association tracking
  - Identifies and tracks separate distinguishable objects, represented by connected pixels, in the field of view of the camera
  - Vehicles are identified by the motion of the connected pixels as derived from comparisons with known background pixels

Vehicle Tracking Methods

- Blob or region based
  - Generates a background model for the scene
  - For each input image frame, processes the absolute difference between the input image and the background image to extract foreground blobs that correspond to the vehicles
  - Vehicle tracking possible at region level and vehicle level
  - Difficulties reported handling shadows, occlusions, and large vehicles, all of which cause multiple vehicles to appear as a single vehicle
- Active contour based
  - Tracks the outside contour or boundary of an object
  - Contour initialized using a background difference image and tracked using intensity and motion boundaries
  - Occlusions are detected using depth-ordered regions associated with the objects

Vehicle Tracking Methods (cont)

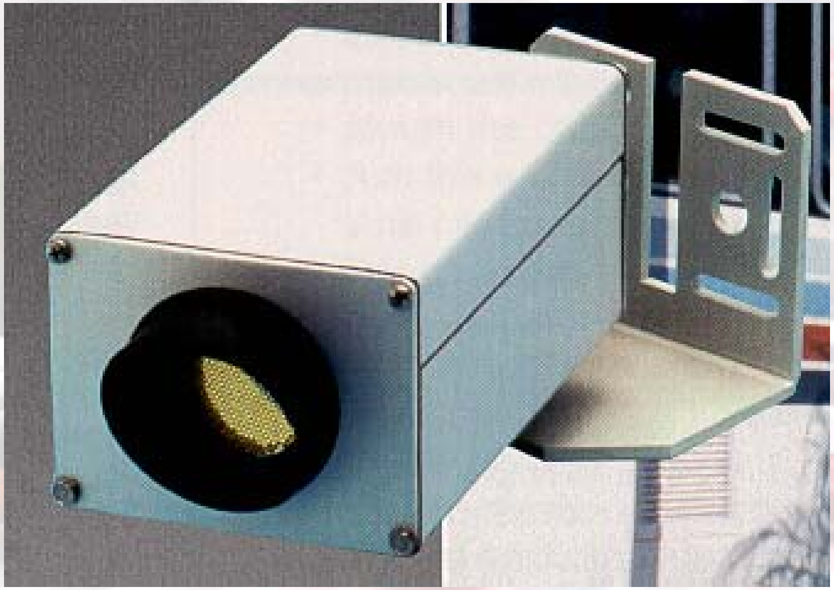
- Model based
  - Matches detected objects with preidentified 3-D vehicle models
  - Emphasizes recovery of trajectories for a small number of vehicles with high accuracy
  - Some model-based approaches assume an aerial view of the scene, virtually eliminating all occlusions, and match wire-frame models of vehicles to edges detected in the image
- Feature based
  - Tracks subfeatures in the object, represented as points, rather than tracking the entire object
  - Useful when vehicles are partially occluded
  - Tracks multiple objects by identifying groups of features based on similarity criteria, which are tracked over time

Vehicle Tracking Methods (cont)

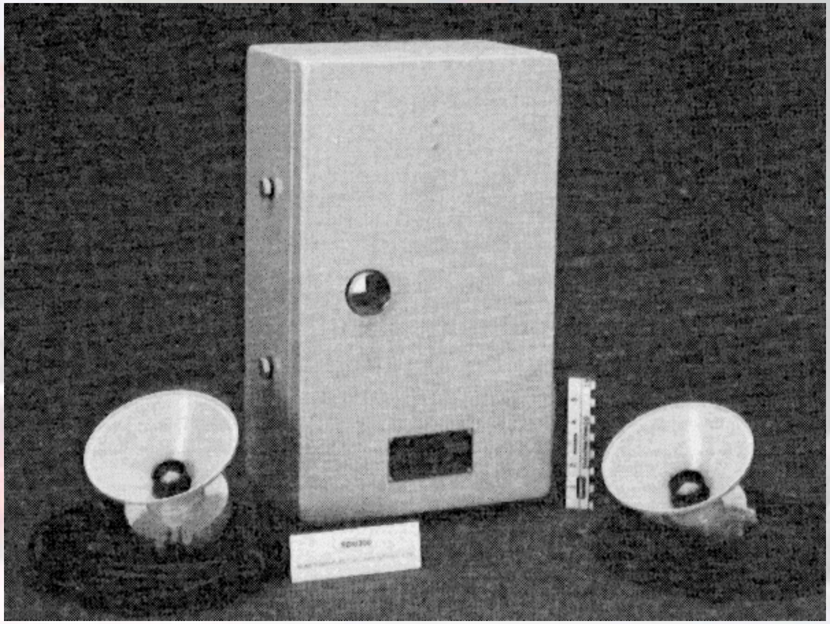
- Color based
  - Color signatures (chromatic information) are used to identify and track objects
  - Vehicle detections are associated with each other by combining chromatic information with driver behavior characteristics and arrival likelihood
- Pattern based
  - Vehicle detection treated as a classical pattern classification problem using support vector machines

(Kanhere, N.K., S.T. Birchfield, W.A. Sarasua, “Vehicle Segmentation and Tracking in the Presence of Occlusions,” 85th Annual TRB Meeting, Washington, DC, 2006)

Ultrasonic Sensors

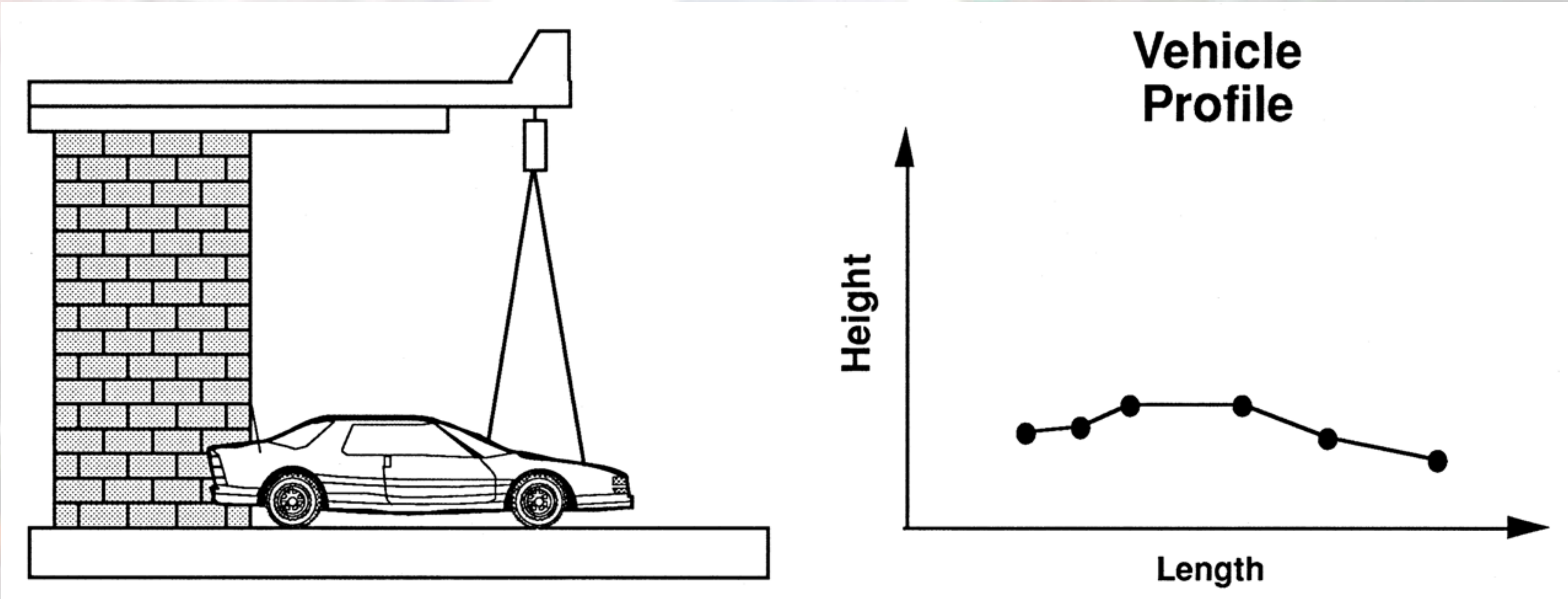


Microwave Sensors TC-30C



Sumitomo SDU-300

Ultrasonic Pulse Sensor Operation



- Ultrasonic sensors transmit and receive high frequency sound waves (25 kHz to >50 kHz)
- Vehicle range is determined using range gates, analogous to processing found in some microwave radars

Passive Infrared (IR) Sensors

Eltec 842 passive infrared vehicle presence sensor. [*Source*: L.A. Klein, *Sensor Technologies and Data Requirements for ITS* (Norwood, MA: Artech House, 2001)]

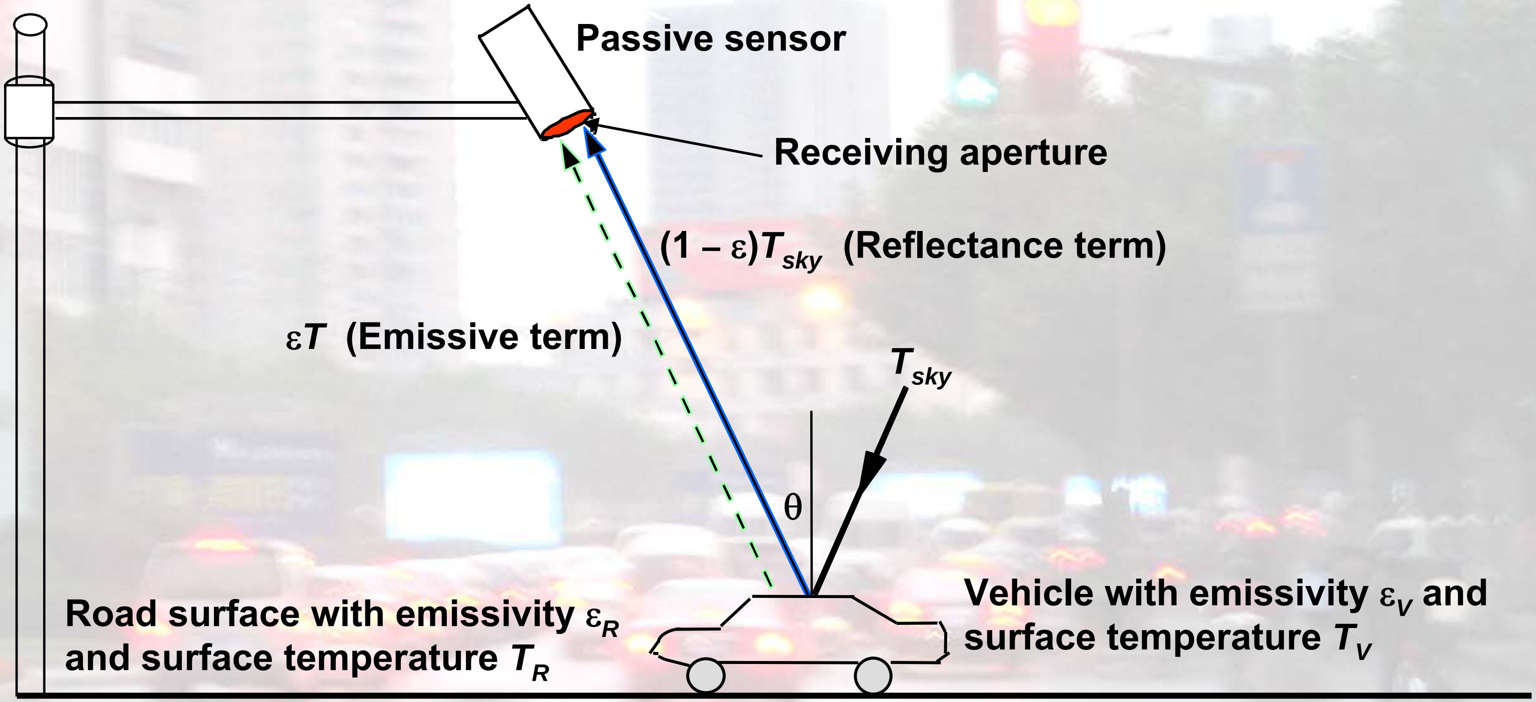
ASIM IR 250 series passive infrared sensor. This multizone sensor performs vehicle counting, speed measurement, classification by length, and presence detection. (Photograph courtesy of ASIM Technologies, Uznach, Switzerland)

Siemens Eagle PIR-1 sensor. Performs vehicle counting, stop line presence detection, occupancy detection, and queue detection. (Photograph courtesy of Siemens ITS, Austin, TX)

Passive Infrared Sensor Operation

- All objects emit energy based on their absolute surface temperature and emissivity at all wavelengths in the electromagnetic spectrum (Planck radiation law)
- Energy at infrared (IR) wavelengths can be collected by optics transmissive in the wavelength band of interest and focused on a photon detector
- A reference or background temperature emitted from the road surface is established
- The sensor's electronics detect a change in energy when a vehicle emitting an energy different from that of the background passes within the sensor's field of view. The change in energy signifies a vehicle detection.
- This thermal energy contrast is analogous to the visible contrast of a CCD camera in the visible spectrum

Passive Infrared Sensor Operation (cont)



- **For emission from the vehicle:**

  $T_{BV}(\theta, \phi) = \varepsilon_V T_V + (1 - \varepsilon_V)T_{sky}$

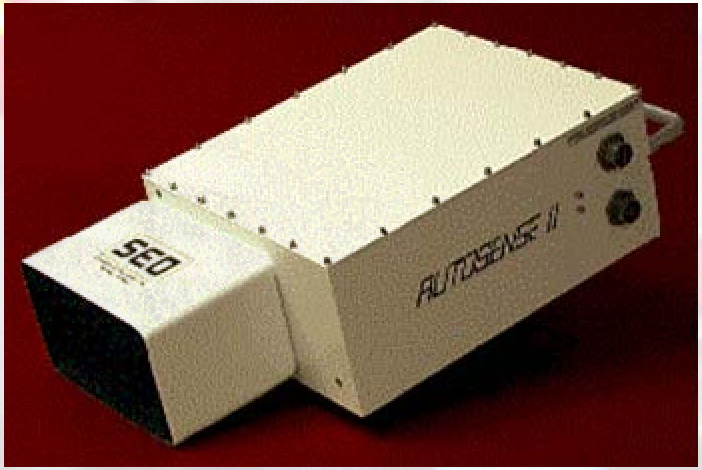
  T_{sky} **is a function of atmospheric, galactic, and cosmic emission**

- **For emission from the road surface:**

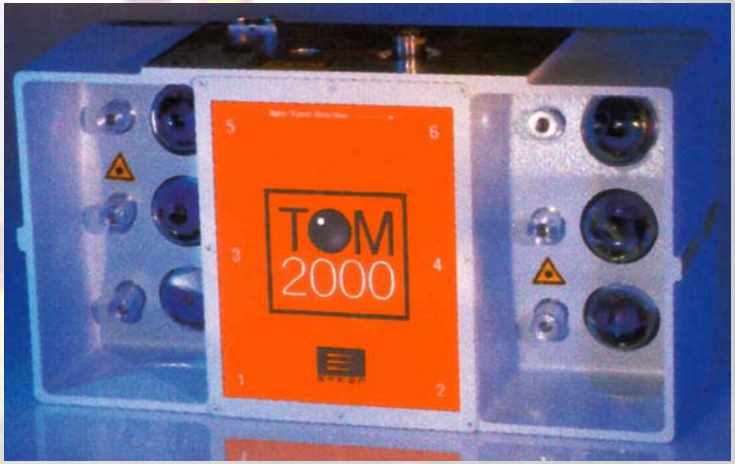
  $T_{BR}(\theta, \phi) = \varepsilon_R T_R + (1 - \varepsilon_R)T_{sky}$

- **Finally,** $\Delta T_B(\theta, \phi) = (\varepsilon_R - \varepsilon_V)(T_R - T_{sky})$ **when** $T_R = T_V$

Laser Radar Sensors



OSI Laserscan
Autosense II – US (7.6 m range)



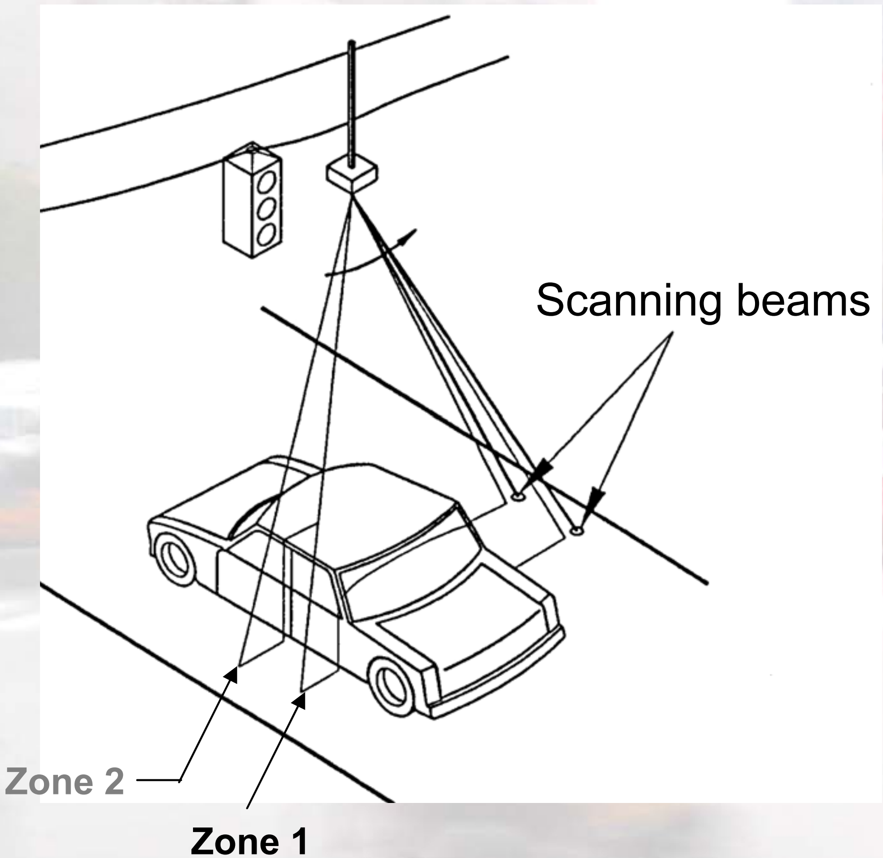
EFKON TOM – Austria
(7 m range)

MDL LaserAce® IM 300 – UK
(300 m range)

Noptel CMP2-30 – Finland
(30 m range)

Laser Rangefinders

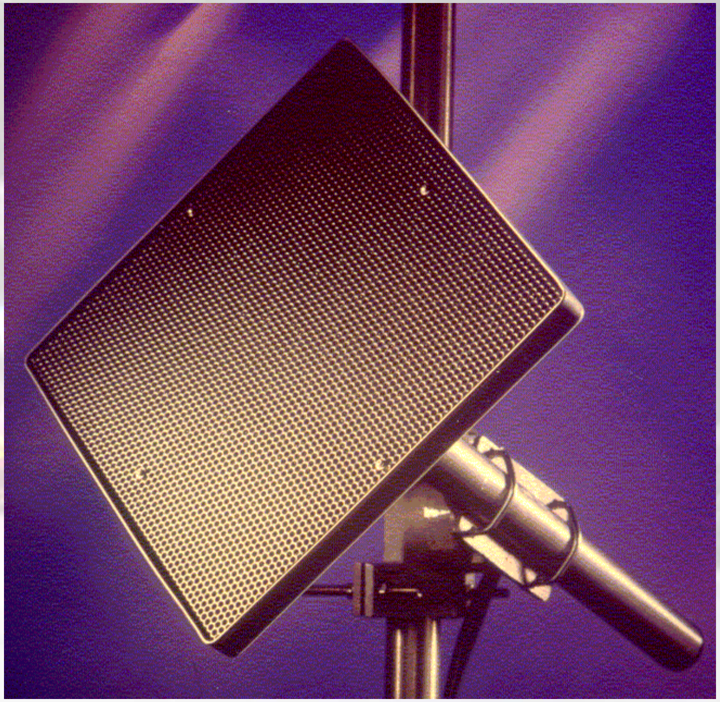
Laser Radar Sensor Operation



- Detection zones are illuminated with IR energy transmitted by laser diodes
- One model uses a scanning mirror, another a series of diodes to illuminate the travel lane
- IR energy reflected from the vehicle is focused by an optical system onto a detector array mounted at the focal plane of the optics
- Real-time signal processing is used to analyze the received signals and to determine count, presence, speed, and vehicle class

Passive Acoustic Array Sensors

SmarTek Multiple Lane

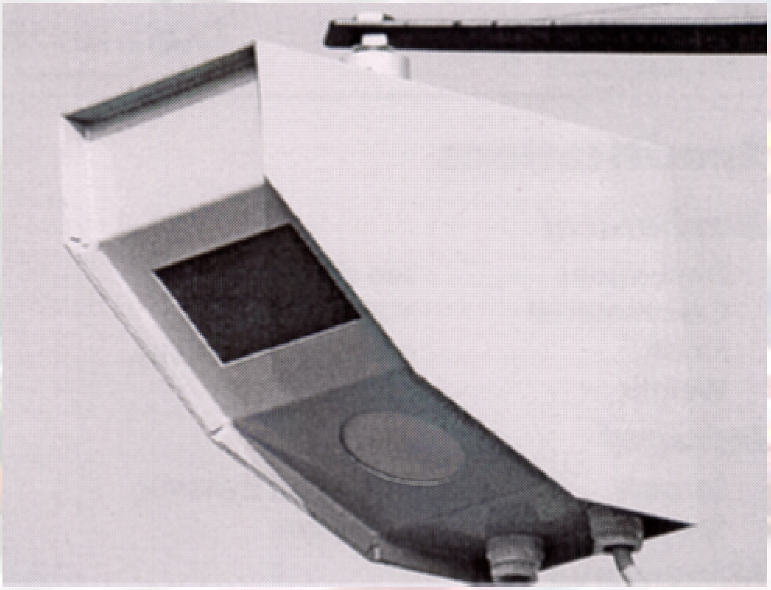


IRD Single Lane

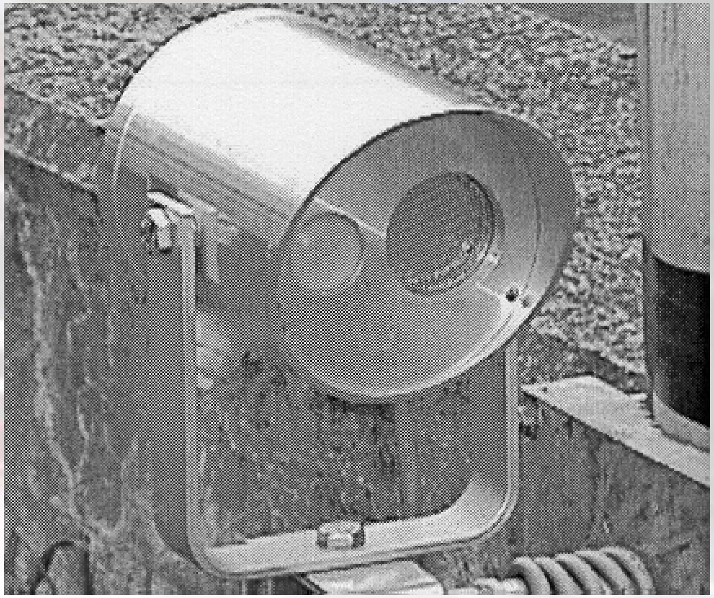
Passive Acoustic Array Sensor Operation

- Vehicular traffic produces acoustic energy from a variety of sources such as the interaction of the vehicle's tires with the road surface and engine noise
- An array of microphones provides spatial directivity from which sounds are continuously detected and processed from specific locations along the roadway
- Signal processing algorithms confirm or reject the source of acoustic energy as a vehicle

ASIM Technologies Sensor Combinations



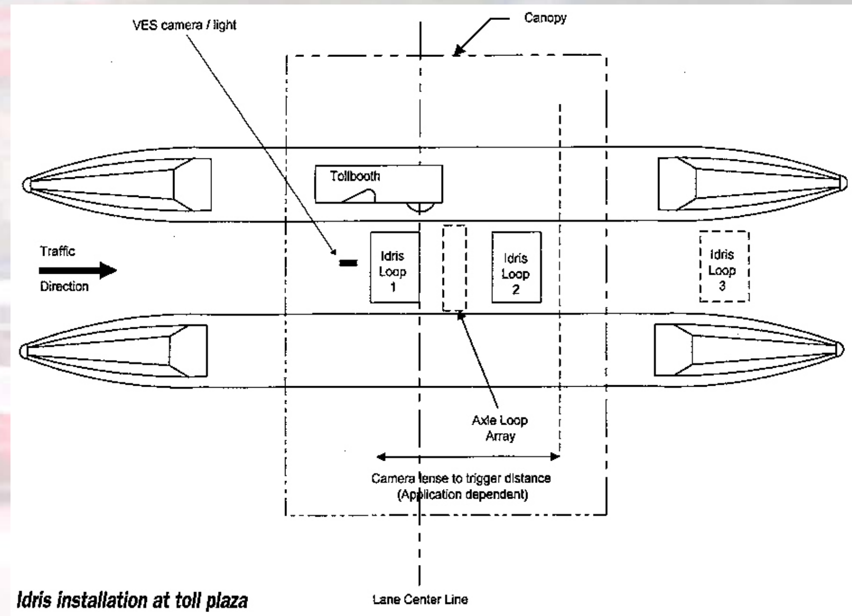
DT 281 Infrared-Doppler radar sensor



DT 272 Infrared-ultrasonic sensor

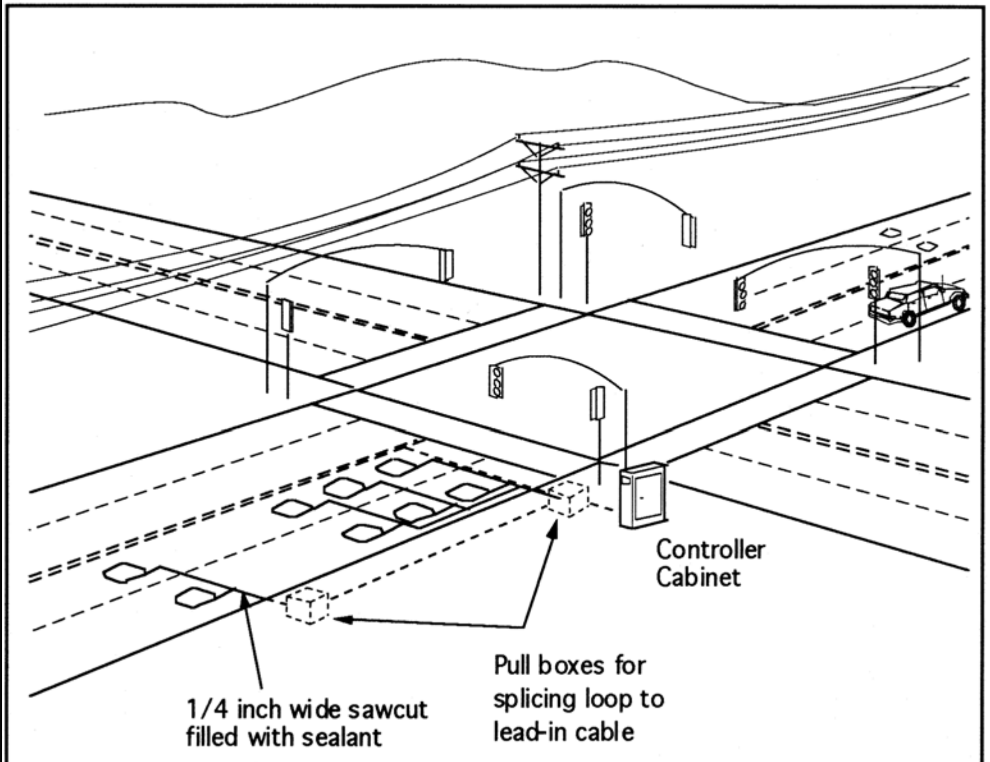
Inductive Loop Detector Vehicle Classifiers

Reno A&E S-1500 Series
Vehicle Classifier and Speed Sensor



Peek Traffic Axle Location and
Vehicle Classification System

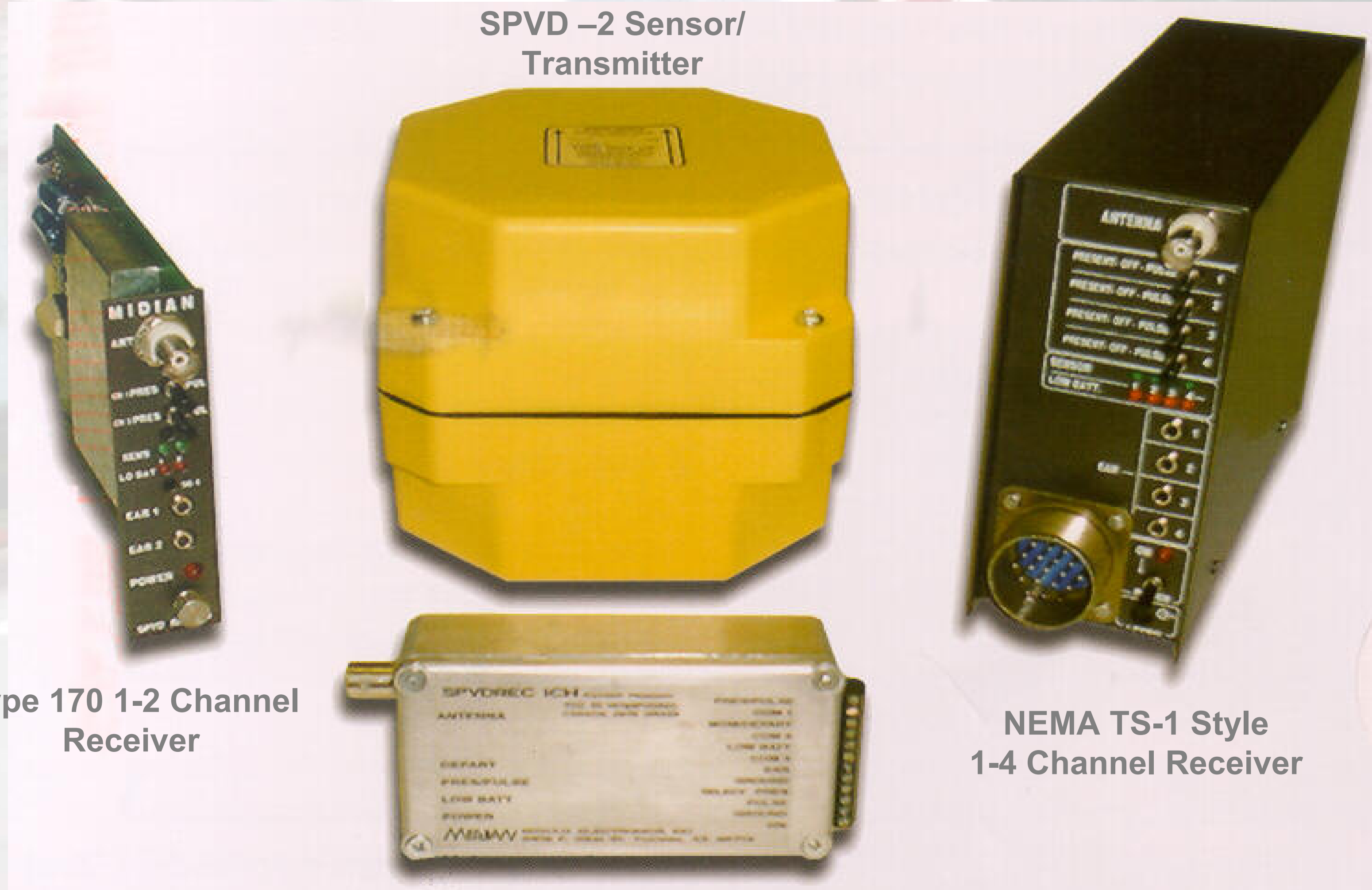
Inductive Loop Detector (ILD) Operation



Surface Street Installation Example for Inductive Loop Detectors

- **Passage of a vehicle over an inductive loop detector induces a current that decreases the inductance of the wire loop. The change in inductance is sensed by the electronics circuitry in the controller cabinet.**
- **The detector electronics output is typically a relay or semiconductor closure signifying the presence, passage, or absence of a vehicle.**
- **Loops produce accurate vehicle counts and presence indication when properly installed in good pavement.**

Midian Electronics SPVD-2 Magnetometer Sensor



One-Channel Receiver

(This is an example of a two-axis fluxgate magnetometer)

Nu-Metrics Groundhog Magnetometer Sensors

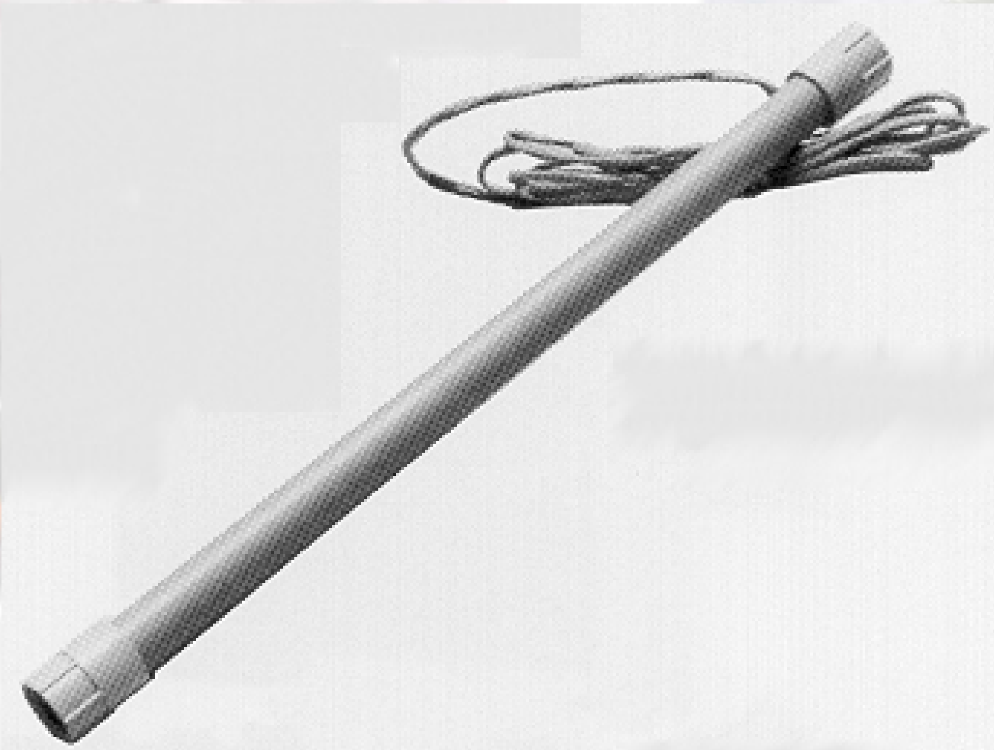
G-1

G-2 and G-2wx

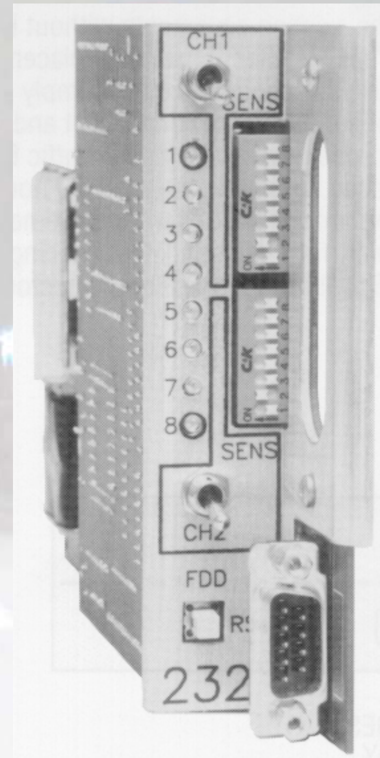
G-1 and G-2 sensors transmit data over the 908 to 922 MHz spread spectrum band to a local base unit located within 200 m (656 ft) of the sensor. The G-4 series sensors transmit data using the 2.45 GHz spread spectrum band.

(This is an example of a two-axis fluxgate magnetometer)

Safetran Magnetic Sensor



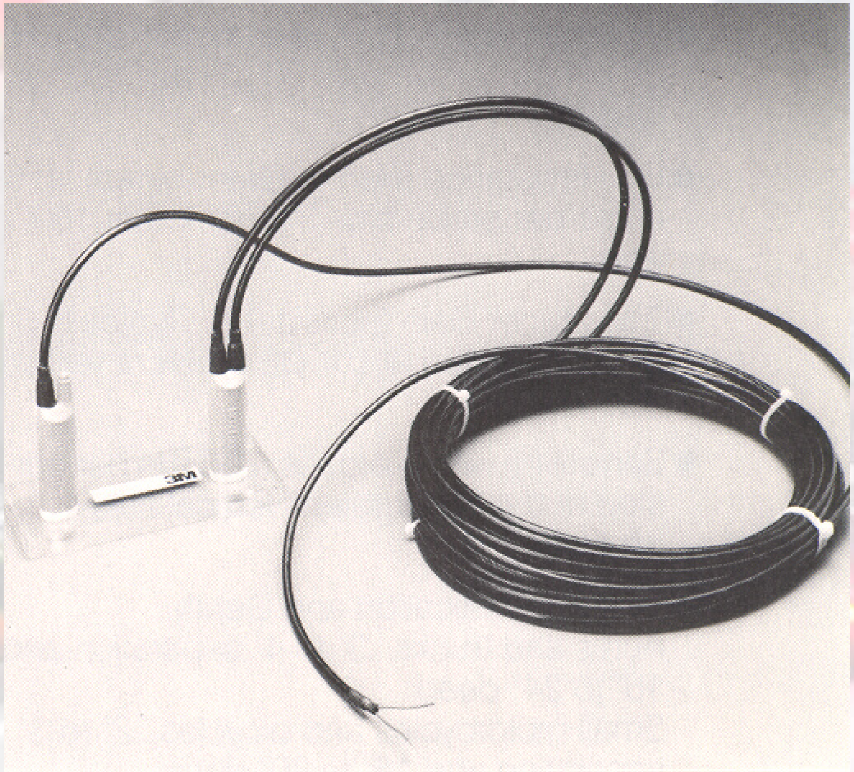
231E Sensor Probe



232E Sensor Electronics

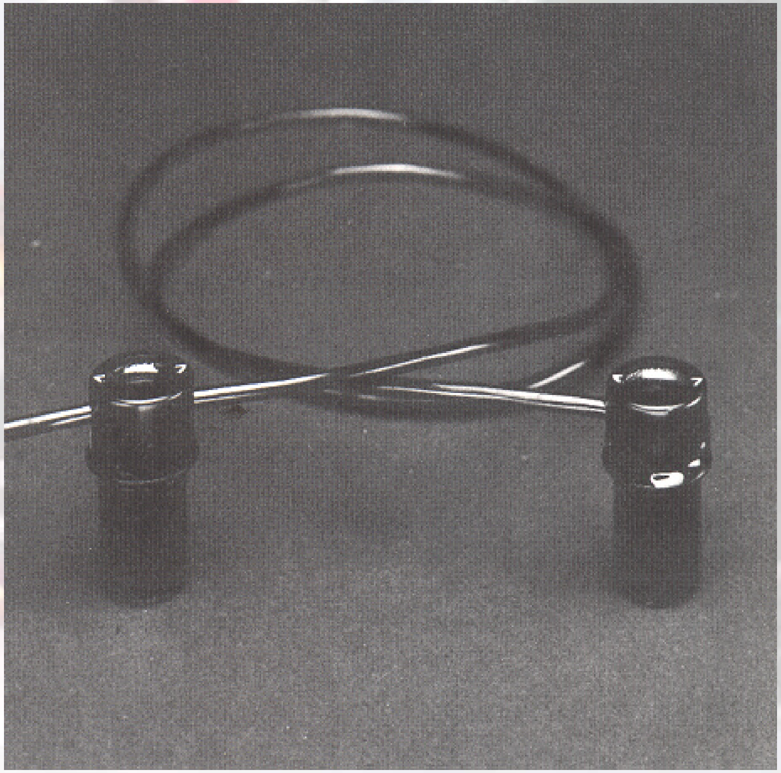
(This is an example of an induction or search coil magnetometer that typically detects only moving vehicles)

3M Microloop Probes (Magnetic Sensors)



Model 701

[Inserted into 1-in (25-mm) diameter holes bored to a depth of 16 to 24 in (406 to 610 mm)]

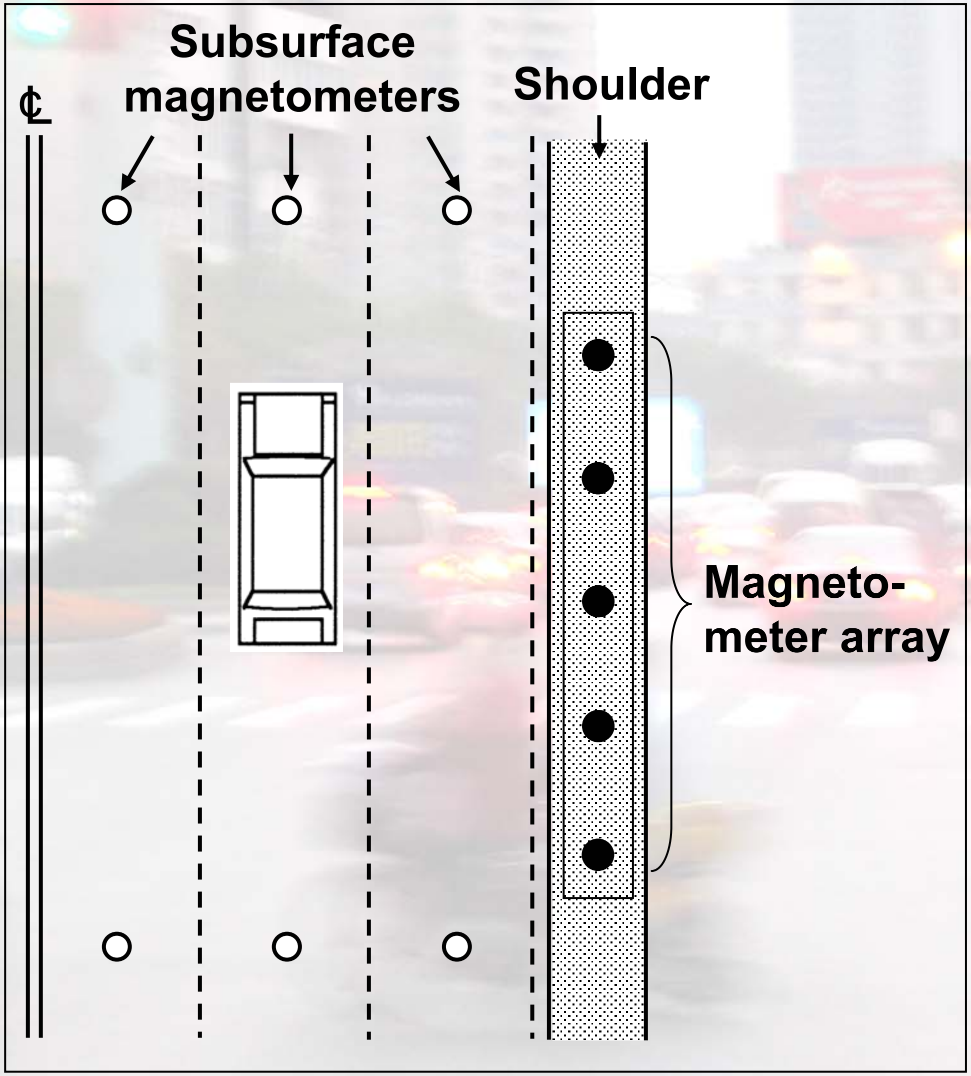


Model 702

[Inserted into 3-in (76-mm) Schedule 80 PVC 18 to 24 in (457 to 610 mm) below the road surface using horizontal drilling from the side of the road]. Detects stopped vehicles using special 3M software.

(This is an example of an induction or search coil magnetometer that typically detects only moving vehicles)

Magnetometer Operation



- Magnetometers consist of one or more turns of wire wound around a magnetic core material
- Magnetometers sense the presence of a ferrous metal object by the perturbation it causes in the Earth's quiescent magnetic field
- Magnetometers can be used on bridge decks where ILDs may be affected by the steel support structure or simply cannot be installed
- Three-axis fluxgate magneto-meters can be arrayed to give vehicle signatures in support of vehicle classification

Traffic Sensor Output Data, Bandwidth, and Cost

Technology	Output Data					Multiple Lane, Multiple Detection Zone Data	Communi-cation Bandwidth	Sensor Purchase Cost[1]
	Count	Presence	Speed	Occu-pancy	Classifi-cation			(each in 1999 $)
Inductive loop	X	X	X[2]	X	X[3]		Low to moderate	Low[9] ($500 to $800)
Magnetometer (Two-axis fluxgate)	X	X	X[2]	X			Low	Moderate[9] ($900 to $6,300)
Magnetic (Induction coil)	X	X[4]	X[2]	X			Low	Low to moderate[9] ($385 to $2,000)
Microwave radar	X	X[5]	X	X[5]	X[5]	X[5]	Moderate	Low to moderate ($700 to $3,300)
Active infrared	X	X	X[6]	X	X	X	Low to moderate	Moderate to high ($6,500 to $14,000)
Passive infrared	X	X	X[6]	X			Low to moderate	Low to moderate ($700 to $1,200)
Ultrasonic	X	X		X			Low	Low to moderate (Pulse model: $600 to $1,900)
Acoustic array	X	X	X	X		X[7]	Low to moderate	Moderate ($3,100 to 8,100)
Video image processor	X	X	X	X	X	X	Low to high[8]	Moderate to high ($5,000 to $26,000)

1. Installation, maintenance, and repair costs must also be included to arrive at the true cost of a sensor solution.
2. Speed can be measured by using two sensors a known distance apart or by knowing or assuming the length of the detection zone and the vehicle.
3. With specialized electronics unit containing embedded firmware that classifies vehicles.
4. With special sensor layouts and signal processing software.
5. From microwave radar sensors that transmit the proper waveform and have appropriate signal processing.
6. With multi-detection zone passive or active mode infrared sensors.
7. With models that contain appropriate beamforming and signal processing.
8. Depends on whether higher-bandwidth raw data, lower-bandwidth processed data, or video imagery is transmitted to the traffic management center.
9. Includes underground sensor and local receiver electronics. Electronics options are available for multiple sensor, multiple lane coverage.

Advantages and Disadvantages of Traffic Flow Sensor Technologies

Technology	Advantages	Disadvantages
Microwave Doppler	• Good performance in inclement weather • Direct measurement of speed	• Cannot detect stopped or very slow-moving vehicles
Microwave True Presence	• Good performance in inclement weather • Detects stopped vehicles • Can operate in side-looking mode to service multiple lanes	• Some vehicle occlusion may occur with side-looking, multiple lane sensor
Passive Infrared	• Provides day and night operation • Multizone passive sensors measure speed	• Performance possibly degraded by heavy rain, fog, overcast skies, or snow
Active Infrared (Laser Radar)	• Direct measurement of speed • Provides vehicle classification data	• Performance degradation by heavy fog [visibility < ≈20 ft (6 m)] and blowing snow • Installation and maintenance require lane closure
Ultrasonic	• Compact size, ease of installation	• Performance may be degraded by variations in temperature and extreme air turbulence • Low PRF may degrade occupancy measurement on freeways with moderate to high speeds
Visible VIP	• Single camera and processor can service multiple lanes and multiple zones/lane • Rich array of traffic data available • Easy to add and modify detection zones	• Large vehicles can mask smaller vehicles, leading to undercounting • Tall vehicles can project their image into adjacent lanes, leading to overcounting • Shadows, reflections from wet pavement, vehicle/road contrast, headlight projection into adjacent lanes on curved road sections, day/night transitions, camera vibration, and debris on camera lens can affect performance • Side viewing requires high, stable camera mounting platform • Over-roadway camera mounting requires lane closure for installation and maintenance • Reliable nighttime signal actuation requires street lighting

Advantages and Disadvantages of Traffic Flow Sensor Technologies (continued)

Technology	Advantages	Disadvantages
Infrared VIP	• Possibility of using same algorithms for day and night operation • Rich array of traffic data available	• Low-cost technology not yet available, but being developed
Acoustic	• Insensitive to precipitation • One model services multiple lanes	• Cold temperature has been reported as affecting data accuracy • Specific models not recommended to detect slow moving vehicles in stop-and-go traffic
Magnetometer	• Less susceptible than loops to stresses of traffic • Detects stopped and moving vehicles • Some models transmit data over wireless RF link	• Installation requires pavement cut • Installation and maintenance require lane closure • Decreases pavement life
Magnetic Sensors	• Can be used where loops are not feasible (e.g., bridge decks) • Some models installed under roadway without need for pavement cuts • Less susceptible than loops to stresses of traffic	• Small detection zone • Installation requires pavement cut or boring under roadway • Cannot detect stopped vehicles (exception for 1 model using multiple sensors and application specific software from vendor)
Inductive Loop Detector	• Standardization of loop electronics units • Excellent counting accuracy • Mature, well understood technology • Some models provide classification data	• Reliability and useful life are dependent on installation procedures • Installation and maintenance require lane closure • Decreases life of pavement • Susceptible to damage by heavy vehicles, road repair, and utilities • Multiple detectors usually required at a site

Traffic Sensor Technology Matrix

Type	Observable	Installation	Location	Advantages	Disadvantages	Reliability
Inductive Loop Detector (ILD)	•Count •Presence •Occupancy •Average vehicle speed (with data processing algorithm or two ILDs) •Queue length using multiple detectors	Embedded in roadway	Freeways and surface streets	•Low per unit cost •Large experience base •Mature, well under-stood technology •High frequency models provide vehicle classification data	•Not suitable for bridges, over passes, viaducts, poor roadbeds •Traffic interrupted for repair and installation •Susceptible to damage by heavy vehicles, road repair, and utilities •Decreases pavement life •Multiple detectors usually required to instrument a site	• Moderate to high for wire loop itself (0.12 to 0.29 failures per detector per year) • Most failures occur in connections of ILD to pull box or pull box to controller
Magnetic (Magnetome-ters and magnetic sensors)	•Count •Presence (mag-netometer) •Occupancy •Speed with multiple sensors or knowledge of detection zone length and vehicle length	• Magnetometers are buried in cylindrical holes • Magnetic sensors are surface or subsurface mounted	Bridges, viaducts, freeways, surface streets	•Small vehicle or obstacle detection (bicycles) •Arrays of magneto-meters provide vehicle classification	•Traffic interruption for installation and repair of magnetometers •Magnetic sensors require vehicle to be moving unless special layouts and software are used	•Unknown
Piezoelectric	•Count •Axle weight •Wheel weight •Speed	Road surface mounted or embedded in roadway	Freeways and surface streets	•Low per unit cost •Easy to install and repair •All weather, multilane capable	•Traffic interrupted for repair and replacement •No presence output •Special sensor and smooth roadbed needed for high accuracy WIM	•1 million activations (may be limited by snow, plowing, salt) •Axle counters typically replaced once per year

Traffic Sensor Technology Matrix (continued)

Type	Observable	Installation	Location	Advantages	Disadvantages	Reliability
Radar (Microwave and millimeter-wave)	•Count •Presence •Occupancy •Speed •Range •Instantaneous traffic density •Classification by vehicle length	Overhead or to side of roadway	Freeways and surface streets	• Install and repair do not disrupt traffic • All weather, day/night operation • Direct measurement of speed • Multi-lane data • Compact size	•May have vehicle masking in multilane application primarily if individual vehicle data are needed •Doppler type cannot detect stopped or slow moving vehicles	•Some presence models designed to 90,000 h MTBF •RTMS: Of 624 units shipped to NYC, 10 returned for repair from Apr. 1994-Jun 2002, or 1.6%.
Passive IR (Non-imaging)	• Count • Presence • Occupancy • Speed with multi-zone sensor	Overhead	Freeways and surface streets	• Day/night operation • Easy to install • Install and repair do not disrupt traffic • Compact size	• Performance possibly degraded by heavy rain, fog, or snow • One per lane required • Some models not for presence detection	•Unknown
Active IR (Imaging and non-imaging)	• Count • Presence • Occupancy • Range • Speed • Classification	Overhead or to side of roadway	Freeways and surface streets	• Same as for Passive IR	• Performance degraded by heavy fog (visibility <≈20 ft) or blowing snow	•Some laser radar models exhibit 64,000 h MTBF. Others designed to 50,000 h MTBF
Acoustic (Audible frequency range)	• Count • Presence • Occupancy • Speed with multiple detection zones or data processing algorithm	Overhead or to side of roadway	Freeways and surface streets	• Easy to install and maintain • Passive detection • Provides day and night operation • Multi-lane data (some models)	• Cold temperature reported to affect data accuracy • Specific models not recommended with slow moving vehicles in stop-and-go traffic	• Unknown

Traffic Sensor Technology Matrix (continued)

Type	Observable	Installation	Location	Advantages	Disadvantages	Reliability
Ultrasonic	• Count • Presence • Occupancy • Speed with Doppler sensor • Queue length with multiple detectors	Overhead	Freeways and surface streets	• Compact size • No traffic interruption for installation and repair • Large experience base in Japan	• Accuracy affected by variations in air temperature and by air turbulence • One per lane required, except for one model • Low PRF may degrade occup measm't on fwys with mod to high speeds	• Unknown
Video Image Processor (Machine vision sensor)	• Count • Presence • Occupancy • Speed • Instantaneous traffic density • Incident evaluation • Queue length • Turning move-ments	Overhead or to side of roadway	Freeways and surface streets	• Roadside processing allows low data rate transmission • Imagery available for incident management • Monitors multiple lanes and zones/lane • No traffic interruption for installation and repair when camera is side mounted • Rich array of data available • Easy to add or modify detection zones	• Inclement weather, shadows, vehicle projection into adjacent lanes, occlusion, day-to-night transition, vehicle/road contrast, headlight beams in adjacent lanes can affect performance • Reliable nighttime signal actuation requires lighting • Requires 30- to 50-ft camera mounting height (when side-mounted) for optimum presence and speed measurement • Some models affected by camera motion caused by high winds • Generally cost-effective only if application requires many detection zones	• Unknown

Summary

- Why coordinate signals?
  - Increase safety and vehicle flow
  - Reduce stops and delays
- Conditions needed to apply signal coordination
  - Long queues, headways > 5 seconds
  - Same cycle lengths on controlled segment
  - Proper signal spacing
- Must gather before and after data
  - Leads to good design
  - Can better explain benefits to public

Summary (cont)

- Account for known contingencies when developing timing plan
  - Transit and emergency vehicles
  - Pedestrians
  - Bicycles
  - Time-of-day and seasonal variations in traffic flow
- Detectors (sensors)
  - Understand advantages and limitations of each technology
  - Understand life-cycle costs
  - Beware of over-aggressive sales people

Questions