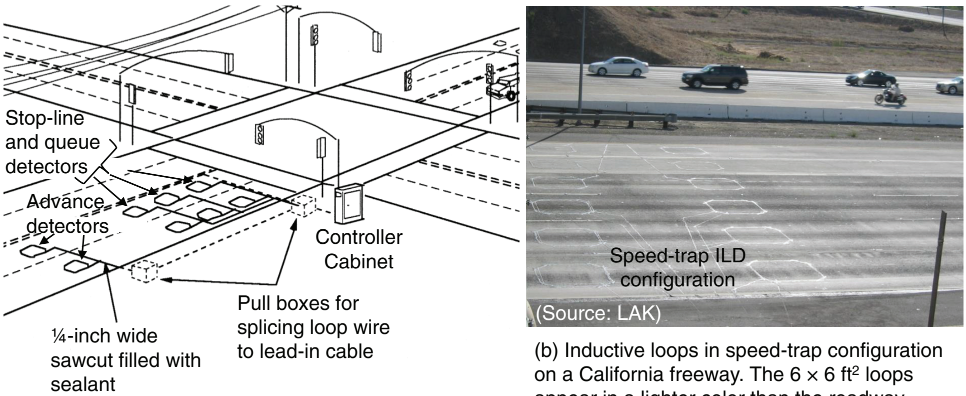
Table of Contents

1 Data Sources

Modern traffic and transportation management systems concern themselves with the safety of travelers, efficiency in moving travelers from one point to another (often referred to as mobility), and the environmental impacts of the transportation modes. Measures of effectiveness (MOEs) are utilized to quantify the success of the system in meeting these goals. The MOEs, in turn, require data for their evaluation. Historically, data were obtained from traffic flow sensors, such as inductive loop detectors (ILDs) in the roadway, which were installed by the traffic management agency. ILDs are able to provide vehicle counts, presence, passage, lane occupancy, and estimates of vehicle speed. As the variety of sensor technologies increased and matured, additional types of sensors became available. These include video detection systems (VDSs), microwave radar sensors, Doppler microwave sensors, acoustic sensors, ultrasonic sensors, magnetometers and magnetic sensors, passive infrared (PIR) sensors, LIDAR sensors, and sensors that employ combinations of these technologies. Many are capable of multilane coverage.

However, sensors that monitor traffic flow at a given point are often ineffective in supplying the data required by modern transportation management systems. For example, origin–destination (OD) pair data needed for planning purposes and vehicle density studies are not readily available from point sensors. Global positioning system (GPS) and other global navigation satellite systems' location devices, cell phone tracking through media access control address readers, probe vehicles, automatic license plate readers, toll-tag readers, and trucking industry transponders are increasingly supplementing the information provided by conventional traffic flow sensors. GPS and inertial navigation system information available on mobile devices provide travel route alternatives, travel time information, and can track commercial, transit, rural, traffic management agency, forestry, and emergency service provider vehicles to improve safety and operational efficiency.

More recently, initiatives such as the Connected Vehicle Program in the U.S., Cooperative Intelligent Transportation Systems (ITS) initiatives in Europe, and similar programs elsewhere are enabling vehicle-to-vehicle, vehicle-to-infrastructure, vehicle-to-pedestrian, and pedestrian-to-infrastructure communications that promise to further increase safety and mobility and reduce the environmental impacts of the automobile and other types of vehicles. These programs can utilize in-car sensors to monitor the status of vehicle systems and provide a variety of data, including braking severity, hazard warning light activation, time headways to vehicles surrounding the ego vehicle, and ego vehicle velocity, acceleration, steering wheel position, traction loss, lane departure warning, and windscreen wiper activation. However, this Spotlight Series monograph concerns itself only with traffic flow sensors that are installed in or above the roadway.



(a) Inductive loops installed for signal control.

(b) Inductive loops in speed-trap configuration on a California freeway. The 6 × 6 ft^2 loops appear in a lighter color than the roadway.

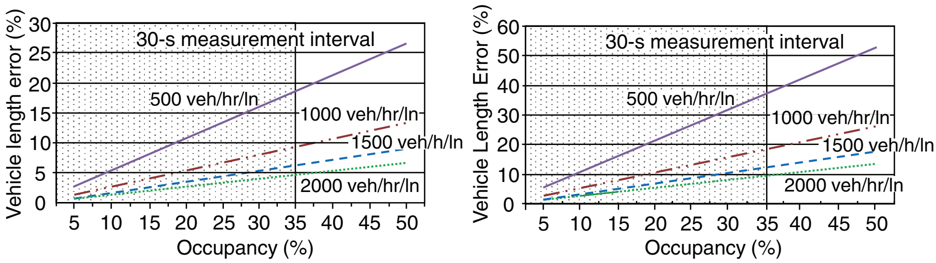
Figure 1 Inductive loop configurations at a signalized intersection and a limited-access highway (typical).

Quadrupole loop configurations, which divide the cross-lane loop dimension in half, are utilized to enhance motorcycle and bicycle detection (by increasing the electromagnetic field strength in the center of the lane) and to eliminate adjacent lane detection in high-sensitivity inductive loop systems. The increased field strength of the quadrupole loop is due to the doubling of the number of windings at the lane center. Diamond-shaped loops also enhance motorcycle detection by extending the field to the lane edges where motorcycles sometimes drive to avoid oil spots that are more prevalent at the lane center. *The Traffic Detector Handbook*[12] discusses other loop configurations, such as those that extend the detection area to full lane widths or increase the sensitivity for motorcycle and bicycle detection.

The popularity of the ILD is due, in part, to its mature technology and low unit cost. Reliability of the wire loop has been improved through better packaging and installation techniques. These include delivery of loops already encased by the manufacturer in protective materials, more thorough cleaning of debris from the sawcut, and the use of improved sealant in the installation process. The loop detector system, however, may still suffer from poor reliability. Contributing factors are poor splice connections in the pull box between the loop wire and the lead-in cable, failure to twist wire pairs properly leading to cross talk, and faulty sawcut cleaning and sealant application procedures. These problems are accentuated when loops are installed in poor pavement or in areas where utilities frequently dig up the roadbed.[12]

The major steps for installing an ILD system are as follows:

1. Preparing plans and specifications.
2. Securing the work zone.



(a) Tolerable vehicle length error for estimating speed within *5%* over a 30-s measurement interval.

(b) Tolerable vehicle length error for estimating speed within *10%* over a 30-s measurement interval.

Figure 2. Allowable error in vehicle length estimate as a function of lane occupancy, flow rate, and desired speed measurement accuracies of 5% and 10%.

I-Loop Duo Card

Sampling frequency	100 Hz to 5000 Hz
Signal bandwidth	15 kHz–150 kHz (loop signals)
Loop operating modes	Presence or pulse, providing count, speed, and class
Classification categories	FHWA 13 vehicle classes
Controller data output rate	300–921.6 kbps (Serial & Bluetooth®), 100 Mbps (Ethernet),12 Mbps (SPI/USB), 100–2500 Hz (digital control lines)
Controller compatibility	170/2070 or NEMA TS-1/TS-2
Frequency selections	16 (software controllable)
Sensitivity selections	8 for conventional loop detectors and an optional 16 settings for the intelligent card standard
Frequency and sensitivity selection method	Front panel by user or one of five communication methods: USB, Bluetooth®, SPI, UART, or Ethernet
Communication speeds	USB 2.0, Ethernet 10/100, Bluetooth® to 921.6 kbps, SPI to 12 Mbit, UART to 921.6 Kbps
Concurrent communications	Yes
Onboard flash data storage	2 Gbit (128 Mb) to 16 Gbit (2 Gb)
Firmware upgradable	Via USB, Bluetooth®, or Ethernet
Performance Monitoring System compatible	Yes
Customization	Yes. On-board real-time data processing for vehicle signature and parameter calculations via dual-core ARM Cortex 32-bit safety-core processor operating at 220 MHz.

(Photograph courtesy of CLR Analytics and Diamond Traffic Products)

Figure 3 I-loop duo card for classifying and reidentifying vehicles.

The 13 classes are based on whether the vehicle carries passengers or commodities. Non-passenger vehicles are further sub-divided by the number of axles and the number of units, including both power and trailer units. The addition of a trailer to vehicle classes 1 to 5 does not change the classification of the vehicle.

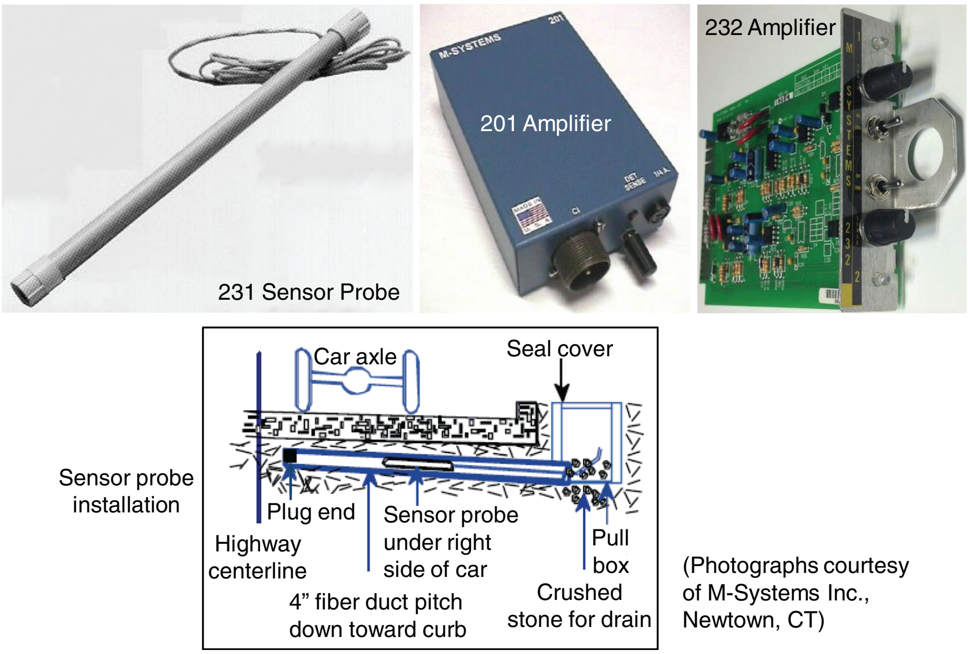


Figure 8 Model 231 magnetic detector.

(a) Model 701 Microloop Sensor

(b) Model 702 Microloop Sensor detects stopped vehicles using application-specific software and an array of sensors.

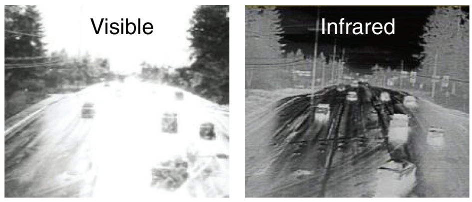
(Photographs courtesy of Global Traffic Technologies, LLC, St. Paul, MN)

Figure 9 Model 701 and 702 magnetic detectors.

Table 4 summarizes the prominent attributes of magnetic sensors as used for traffic management. Now that we have discussed sensors that are mounted in or under the roadway bed, let us explore sensors that are mounted above or to the side of the roadway.

Thermal imaging cameras see in total darkness and show more scene detail.

Thermal imaging cameras can see into shadows.

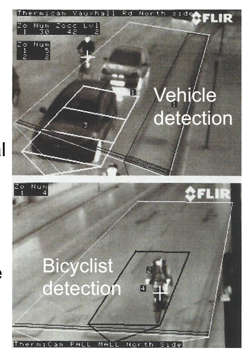


Thermal imaging cameras see through glare and backlighting, improving signal control.

(Photographs courtesy of FLIR Systems, Meer, Belgium)

Figure 14 Visible and thermal image comparison.

- FLIR ThermiCam™ senses long wavelength (7 to 14 m) thermal energy emitted from objects in its field-of-view. It provides vehicle, bicycle, and pedestrian presence detection; vehicle, bicycle, and pedestrian counting; traffic data collection; traffic flow monitoring; and wrong-way driver detection.
- Detects vehicles and bicycles at and nearby the stop bar for control of traffic signals. Typical intersection applications are green on demand and green time extension.
- Vehicle and bicycle counting occurs simultaneously with presence detection.
- 24 vehicle presence zones, 8 bicycle presence regions, 8 pedestrian zones, 6 traffic data zones, 6 wrong way driver zones.
- Detection range: 0 to 90m, depending on focal length of lens.
- Frame rate: 30 fps.



[https://www.flir.co.uk/products/thermicam2/?model=10-7432 (accessed Mar. 18, 2020)]

Figure 15 Long-wavelength (thermal) infrared camera detection system. (Photographs courtesy of FLIR Systems, Meer, Belgium.)

and close a pair of isolated contacts in the controller cabinet in response to a vehicle, bicycle, or pedestrian detection. The contact closure thus provides information concerning the number of vehicles passing the sensor per hour or the presence of a vehicle, bicycle, or pedestrian in the detection area of the sensor.

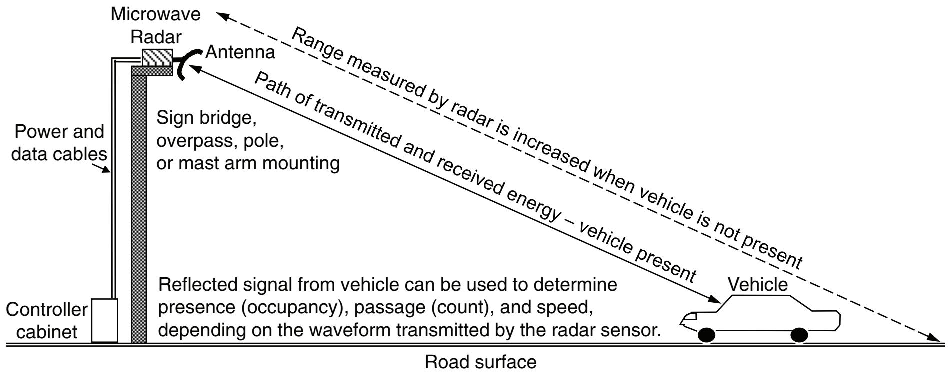


Figure 20 Vehicle detection by a presence-detecting microwave radar sensor.

Forward-looking radars with large antenna beamwidths acquire data representative of the composite traffic flow in one direction over multiple lanes. Forward-looking radars with narrow antenna beamwidths can monitor a single lane or several individual lanes of traffic flowing in one direction, depending on the model. Side-mounted, multiple detection zone radars project their detection area (i.e., footprint) perpendicular to the traffic flow direction and provide traffic data from several lanes.

7.4 Types of transmitted waveforms

Figure 21(a) describes the constant frequency waveform transmitted by a continuous wave Doppler microwave sensor. The constant frequency signal (with respect to time) allows vehicle speed to be measured using the Doppler principle. Vehicle speed S is proportional to the frequency change f_D between the transmitted and received signals given by

$$f_D = \frac{2\, Sf \cos\theta}{c}, \tag{4}$$

where S is the vehicle speed, f is the transmitted frequency, f_D is the Doppler frequency, c is the speed of light, and θ is the angle between the direction of propagation of the sensor energy and the direction of travel of the vehicle.

The frequency of the received signal is given by $f \pm f_D$, where $\pm$ denotes whether the vehicle is moving toward or away from the sensor. Accordingly, the frequency of the received signal is increased by a vehicle moving toward the sensor and decreased by a vehicle moving away from the sensor. Vehicle passage or count is denoted by the presence of the frequency shift. Vehicle presence cannot be measured with the constant frequency waveform as only moving vehicles are detected by most sensors of this type.

Figure 21(b) shows the waveform transmitted by many presence-detecting microwave radars. This frequency-modulated continuous-wave (FMCW) signal reflection of energy from surfaces whose emissivity is not unity) as they view objects through the atmosphere. Application of radiative transfer theory allows the determination of the brightness temperature change caused by a vehicle passing through a sensor's field-of-view.

8.2 Radiative transfer theory

When a vehicle enters a PIR sensor's field-of-view, the detected energy is modified due to the presence of the vehicle.[34] Radiative transfer theory describes the contributions of cosmic, galactic, atmospheric, and ground-based emission sources to the passive signature of the detected objects. As shown in Fig. 25, the cosmic, galactic, and atmospheric emission sources can be combined into a term denoted as T_{sky}, while the ground-based radiation sources derive from emission from the road and vehicle surfaces and the reflection of the cosmic, galactic, and atmospheric sources into the sensor's aperture.

In Fig. 25, ε_V and ε_R denote the emissivities of the vehicle and road surface in the wavelength region of interest, while T_V and T_R represent their surface temperatures in degrees Kelvin, respectively. Emission from the vehicle contributes a brightness temperature T_{BV} given by

$$T_{\text{BV}}(\theta, \phi) = \varepsilon_V T_V + (1 - \varepsilon_V) T_{\text{sky}}, \tag{12}$$

where θ and ϕ are the nadir and azimuth angles, respectfully, and T_{sky} is a function of the cosmic, galactic, and atmospheric emission.

Emission from the road surface contributes a brightness temperature T_{BR} as follows:

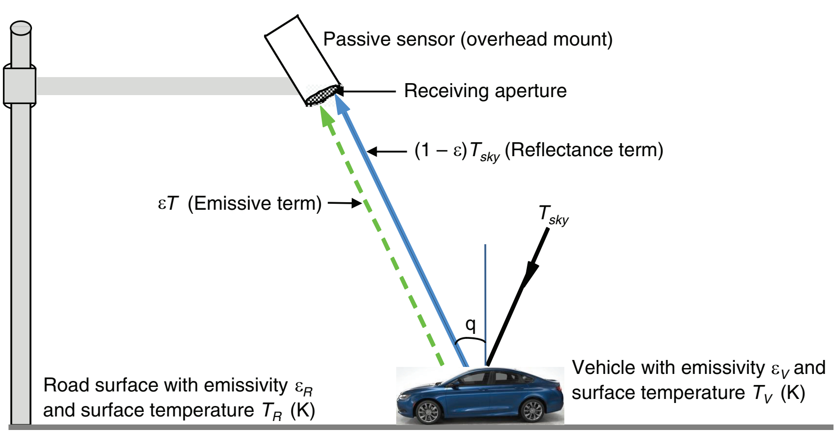


Figure 25 Radiative transfer theory is used to calculate the change in apparent temperature sensed by a PIR sensor when a vehicle enters its field-of-view.

TDC2-PIRUS infrared, ultrasound sensor provides true-presence vehicle detection at stop bar and pedestrian detection in waiting zones for objects 0.5–10 m (1.7–33 ft) away. Applications include vehicle count, traffic signal control, green signal request, vehicle direction detection, vehicle discrimination by height, i.e., cars from trucks and buses.
Ultrasonic frequency: 40 kHz
Ultrasonic pulse rate: 13–30 pulses/s
PIR spectral response: 8–14 µm
Mounting: gantries, overpasses or bridges or otherwise on a pole at the roadside.

TDC3 series infrared, Doppler, ultrasound sensor provides vehicle counts, individual vehicle speed (Doppler), vehicle class (ultrasound and PIR), presence, queue and wrong-way driver detection, occupancy, headway, and time gap.
K-band Doppler: 24.05–24.25 GHz
Ultrasonic frequency: 40 kHz
Ultrasonic pulse rate: 10–30 pulses/s
PIR spectral response: 6.5–14 µm
Mounting: Gantries or other overhead structures above the lane center.

TDC4 series infrared, Doppler, ultrasound, video sensor provides vehicle counts, individual vehicle speed, vehicle class, presence, queue and wrong-way driver detection, occupancy, headway, time gap, and visual verification of traffic flow anomalies.
VGA color video: 640 x 480 max. (Provides snapshot pictures transmitted over 9K6 bps RS 485 for visual verification of wrong-way drivers and queues, and for outstation command.)
K-band Doppler: 24.05–24.25 GHz
Ultrasonic frequency: 40 kHz
Ultrasonic pulse rate: 10–30 pulses/s
PIR spectral response: 6.5–14 µm
Mounting: Same as for TDC3.

(Photographs courtesy of ADEC Technologies, Eschenbach, CH)

Figure 32 Multiple technology sensors.

transmitted at 30 frames/s. The transmission rate is also affected by the numbers of sensors, roadside information devices such as changeable message signs and highway advisory radio, and frequency of signal timing plan updates needed to implement traffic management strategies.

The range of purchase costs for a particular sensor technology reflects cost differences among specific sensor models and capabilities. If multiple lanes are to be monitored on a lane-by-lane basis and a sensor is capable of only single detection zone operation, then the sensor cost must be multiplied by the number of monitored lanes. Installation and life-cycle maintenance costs also contribute to the true cost of any sensor selection.

13.1 Life-cycle cost considerations

Direct hardware and software purchase costs are only one portion of the expense associated with choosing a sensor. Installation, maintenance, and repair should also be factored into the sensor selection decision. Installation costs include fully burdened costs for technicians to prepare and perhaps upgrade the road surface or sub-surface (for inductive loops or other surface or sub-surface sensors), install the sensor and mounting structure (if one is required), provide power if none is available at the site, close traffic lanes, divert traffic, implement safety measures