CHAPTER 1

Traffic Sensing Technologies

Safe and efficient operations of transportation systems rely heavily on applications of advanced technologies. As a result, recent decades have witnessed wide applications of communication, sensing, and computing technologies in traffic surveillance, incident detection, emergency response, fleet management, and travel assistance. Figure 1.1 illustrates an example of these technologies at an intersection.

"Intelligent transportation systems" (ITS) refers to efforts that apply information, communication, and sensor technologies to vehicles and transportation infrastructure in order to provide real-time information for road users and transportation system operators to make better decisions. ITS aim to improve traffic safety, relieve traffic congestion, reduce air pollution, increase energy efficiency, and improve homeland security. ITS encompass a suite of measures that address the above objectives: advanced traffic management systems, advanced traveler information systems, advanced public transportation systems, the intelligent vehicle initiative, the commercial vehicle operations program, etc. The recent development of ITS emphasizes the application of dedicated short-range communications in vehicle-to-vehicle and vehicle-to-roadside wireless communications—that is, connected vehicle technology according to the US Department of Transportation.

1.1 TRAFFIC SENSORS

This section describes a few types of traffic sensors that are often employed in ITS and other traffic surveillance and data collection systems. The discussion of each type of sensor focuses on how it works, what traffic data it is capable of collecting, its advantages, and its disadvantages.

1.1.1 Inductive-Loop Detector

Inductive-loop detectors are widely used at intersections with traffic-actuated signals, freeway entrances with automatic ramp metering, highway segments monitored by traffic counting programs, and entrances of gated parking facilities.

Traffic Flow Theory
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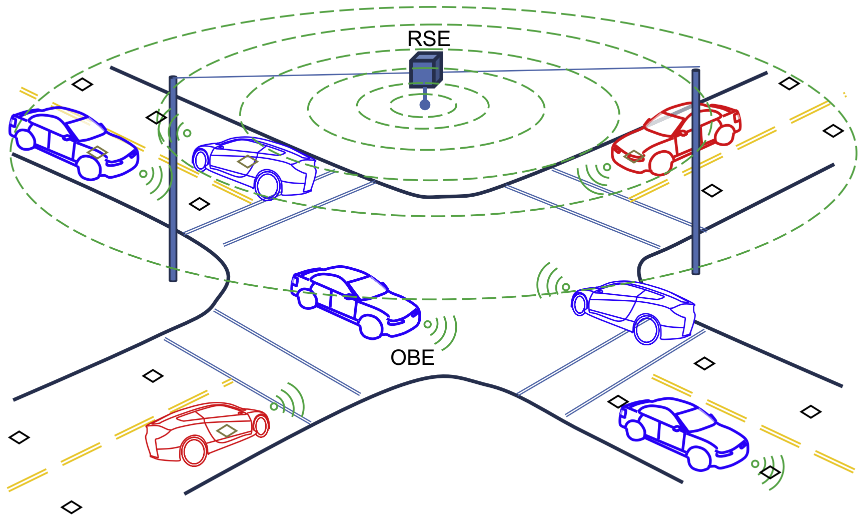

Figure 1.1 An example application of connected vehicles at an intersection.

How It Works

As illustrated in Figure 1.2, an inductive-loop detection system consists of an inductive loop, which is simply a coil of wire embedded in the road's pavement, and a detector, which typically sits in a signal cabinet and links the signal controller to the inductive loop. The detector drives an alternating flow of current through the loop at or below the resonant frequency. All wire conductors carrying an electrical current produce a magnetic field, and the magnetic flux induces the electrical property called inductance. Note that the metal body and frame provide a conductive path for the magnetic field. Therefore, when a vehicle enters the detection zone or crosses the loop, this produces a loading effect, which in turn causes the loop inductance to decrease. The decreased inductance causes the resonant frequency to increase from its nominal value. If the frequency change exceeds the threshold set by the sensitivity setting, the detector module will output a detect signal—that is, an "on" state. Otherwise, the detector does not output a signal—that is, an "off" state.

The output of the detector can be used for many applications. For example, an actuated signal controller relies on the detector output to decide whether a green indication is granted to the approach that is monitored by the detector. As another example, when a vehicle exits a gated parking garage, an inductive loop is able to detect the vehicle in advance so that the

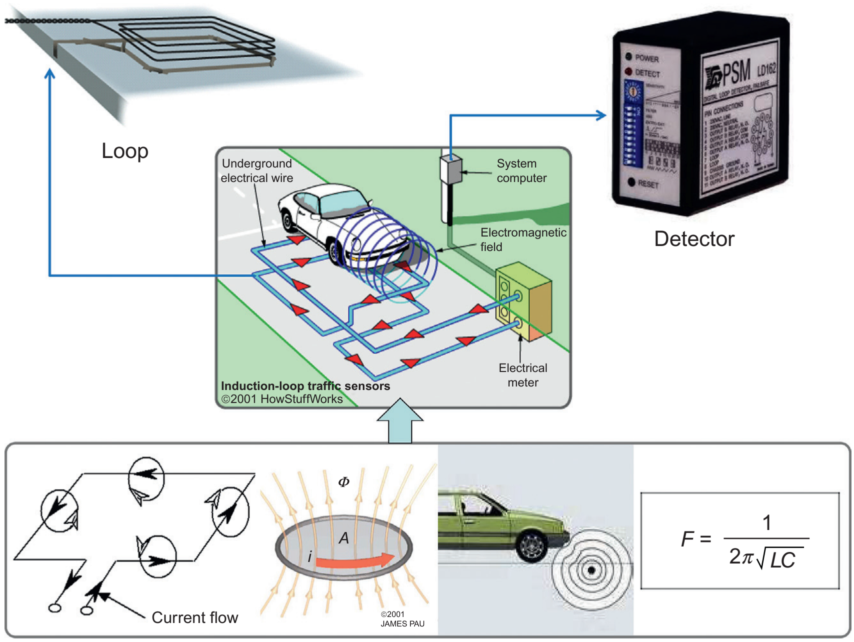

Figure 1.2 An inductive-loop detection system.

gate automatically opens for the vehicle. Yet another innovative application is a red-light-running camera. An intersection with such a system has the detector connected to the signal controller and an overhead camera. As a result, when a vehicle is running a red light, the camera will be triggered and a picture of the vehicle will be taken as evidence of red light violation.

Data Collected

An inductive-loop detector monitors a point of the roadway and is able to collect time-stamped traffic counts with vehicle classification, vehicle instantaneous speed, headway (temporal separation between two consecutive vehicles), on time (time during which the detector outputs an "on" state), etc.

Advantages

An inductive-loop detector is able to monitor traffic on a regular basis (i.e., day-round and year-round) under all weather and lighting conditions.

Disadvantages

Installation of inductive-loop detectors is intrusive to traffic (i.e, the traffic must be interrupted in order to put the loop in the pavement). In addition, setup and maintenance costs of inductive-loop detectors are high. Inductive-loop detectors can fail under some weather conditions, especially snow and ice.

1.1.2 Video Image Processing System

A video image processing system (VIPS) is widely used for traffic surveillance and hence is an essential component of ITS.

How It Works

A VIPS comprises (1) an image capturing system (e.g., a video camera mounted above the roadway that captures real-time images/video streams of the traffic under surveillance), (2) a telecommunication system (e.g., a modem and a telephone line that transmit images/video streams to the image processing system), and (3) an image processing system (e.g., a computer that processes frames of a video clip to extract traffic data).

The left panel in Figure 1.3 illustrates a video camera which is monitoring traffic. The right panel shows an image of roadway traffic (not necessarily a match of the view of the video camera in the left panel) with detection zones set up on the screen. When a vehicle enters a detection zone, the VIPS outputs an "on" signal, which remains until the vehicle exits the detection zone, at which time the VIPS switches to an "off" signal. Multiple detection zones can be set up—for example, one for each lane. Hence, these detection zones constitute a detection station.

Figure 1.3 Video image processing system. *(Photos from http://www.imagesensing.com/)*

Data Collected

Similarly to inductive-loop detectors, the VIPS monitors a point of the roadway and is able to collect time-stamped traffic counts with vehicle classification, vehicle instantaneous speed, headway, on time, etc.

Advantages

The VIPS is an automatic system and is able to collect traffic data on a regular basis. Its overhead installation makes this technology nonintrusive to traffic flow. It is flexible in the setting up of detection zones and aggregation intervals. It provides video footage in addition to traffic monitoring.

Disadvantages

The VIPS is expensive and its setup cost is high. It is vulnerable to visual obstruction—for example, inclement weather, shadows, poor-lighting conditions, and strong winds.

1.1.3 Pneumatic Tubes

Pneumatic tubes are portable traffic data collection devices and are ideal for short-term traffic engineering studies.

How It Works

A rubber tube with a diameter of about 1 cm is placed on the surface of a road. When a vehicle passes, the wheel presses the tube and the air inside the tube is pushed away. One end of the tube is connected to a box that contains a membrane and an electrical switch. The air pressure moves the membrane and engages the switch. The other end of the tube has a small opening, to prevent reflection of the air wave. The box counts axles that travel over the tubes and stores the data for later analysis.

Figure 1.4 illustrates how pneumatic tubes are installed: from left to right, a technician is nailing tubes on the road; the technician is programming the data recorder with a laptop computer to collect the desired information; the technician is connecting the pneumatic tubes to the data collector; the installation is complete and the system is collecting traffic data.

Figure 1.4 Installation of pneumatic tubes. (*Photos from http://www.arlingtonva.us.*)

Data Collected

Rather than collecting traffic counts as in the previous two types of sensors, pneumatic tubes are able to collect time-stamped axle counts, from which vehicle classification, direction of flow, traffic counts, flow, vehicle instantaneous speed, headway, and on time can be inferred.

Advantages

Pneumatic tubes are portable devices for automatic traffic data collection. The cost is moderate, and the system can be reused at other locations. Installation can be done by one or two persons.

Disadvantages

The system has a limited lane coverage and is not intended for use on a regular basis (year-round). The system can be damaged by vehicles or roadway maintenance, causing inaccurate data collection. The system may be intrusive to traffic and nearby properties.

1.1.4 Global Positioning System Receiver

The global positioning system (GPS) is widely used in automotive navigation and traffic engineering studies such as traffic time studies. Many cell phones are equipped with positioning functions, and hence they are considered in the same category as the GPS.

How It Works

The GPS is a satellite-based navigation system made up of a network of 24 satellites placed in orbit by the US Department of Defense. GPS satellites circle Earth twice a day in a very precise orbit and transmit signal information to Earth. GPS receivers take this information and use triangulation to calculate the user's exact location (see Figure 1.5 for an illustration). Essentially, the GPS receiver compares the time when a signal was transmitted by a satellite with the time when it was received. The

Figure 1.5 The global positioning system. *(Photos from https://en.wikipedia.org/wiki/Global_Positioning_System.)*

time difference tells the GPS receiver how far away the satellite is. Now, with distance measurements from a few more satellites, the receiver can determine the user's position and display it on the unit's electronic map.

If a vehicle carries a GPS receiver on board and it is set up to log GPS signals, it is possible to record the positions of the vehicle and the time when a location is passed as the vehicle moves along the road. Therefore, the vehicle would leave a trace of spatial-temporal points in the time-space diagram, and a curve that connects these points depicts the vehicle's spatial-temporal trajectory. From this trajectory, the motion of this vehicle can be understood.

Data Collected

Vehicle-specific motion data such as instantaneous speed, average running speed, distance traveled, and travel time are collected.

Advantages

GPS has become an affordable technology since one only needs a GPS receiver to receive positioning signals. GPS receivers are simple to install and operate. They work under all weather and lighting conditions.

Disadvantages

GPS receivers provide only vehicle-specific data. Traffic information has to be obtained from all vehicles in the traffic stream. In addition, GPS signals can be obstructed by tall buildings and trees.

1.1.5 Acoustic/Ultrasonic Sensor

Acoustic/ultrasonic sensors can be used for vehicle detection, automotive radar, and assisting vehicle parking.

How It Works

The sensor shoot a beam of sound, like radar, which travels until it hits an object. The sound wave then bounces back and returns to the sensor. The sensor then measures the time it takes the sound wave to travel. Knowing the speed of sound, the sensor outputs the distance between the sensor and the object. In traffic applications, these sensors can be used to count pedestrians and vehicles by knowing the distance between a pedestrian/vehicle and the sensor. In mechanical applications, these sensors can be used to measure fluid levels. The photo in Figure 1.6 shows them installed in the rear of a vehicle as a parking sensor. The sensors measure the distance between the vehicle and an object behind the vehicle, and then

Figure 1.6 Acoustic/ultrasonic sensors. *(Photo from http://autoteksheffield.co.uk/security/parking-sensors/.)*

display a color corresponding to the distance on the dashboard panel. When the display turns red, the driver can stop and is perfectly parked.

Data Collected

The sensor collects the time of sound wave travel, and then converts it to distance.

Advantages

The sensor is inexpensive in general and involves relatively simple hardware.

Disadvantages

The sensor covers only a short range and has slow response times. Accuracy is limited by the surface of the objects. Sound waves may bounce off various surfaces differently, which may throw off readings on the sensor.

1.1.6 Aerial/Satellite Imaging

How It Works

This technology usually requires the use of either manned or unmanned helicopters in the sky to monitor and observe traffic on the ground for data collection purposes. Illustrated in Figure 1.7, the helicopter can be used to capture images of the ground, and the images are stored or transmitted to a workstation for analysis. The information obtained includes vehicle counts, vehicle speeds, and traffic density.

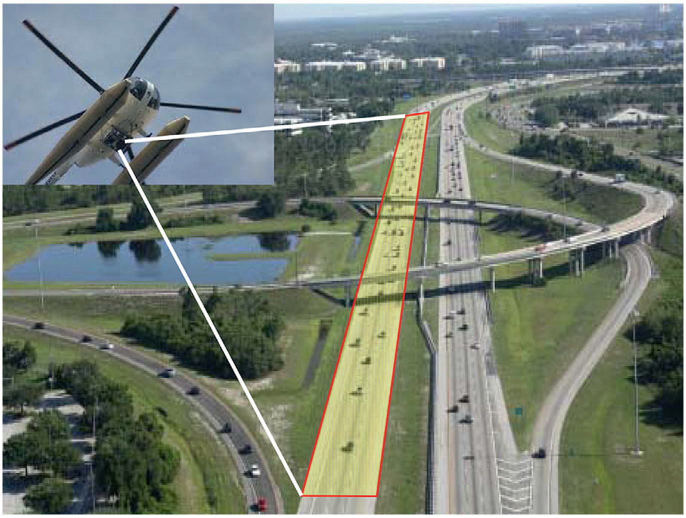

Figure 1.7 Unmanned helicopter as a traffic sensor.

Data Collected

The captured aerial photos contain snapshots of traffic on roadways, from which spatial traffic data such as spacing (i.e., spatial separation between two consecutive vehicles), vehicle counts over a segment of roadway, and traffic density can be obtained. In addition, analysis of consecutive aerial photos may yield information about vehicle speeds and mean traffic speed.

Advantages

Traffic surveillance can be done at high accuracy. There is no need for hardware installation on or near roadways—that is, it is a nonintrusive and noninterruptive technology. It can provide a bird's eye view of system-wide traffic conditions.

Disadvantages

Helicopters are expensive and may require pilots to operate them. It is time-consuming and resource-consuming to collect traffic data. Analysis of aerial photos is complicated—for example aligning aerial photos captured from different angles and extracting traffic data from these photos.

1.1.7 Radio-Frequency Identification Technology

Radio-frequency identification (RFID) is the core technology of many traffic sensors known as transponders (e.g., E-ZPass tags), and is used for automatic vehicle identification, etc.

How It Works

RFID is a technology that uses radio waves to exchange data between a reader and an electronic tag attached to an object for the purpose of identification and tracking. Figure 1.8 illustrates an electronic toll collection system which consists of (1) a transponder on the vehicle, (2) a tag reader antenna at each plaza toll lane, (3) lane controllers that control the lane equipment and track vehicles passing through, and (4) a host computer system. All of the toll plaza controllers are connected to a central database. When a vehicle comes to the toll booth, the tag reader detects the transponder and records its unique ID, the time instant, and other account-related information such as balance and toll paid.

Data Collected

RFID technology is able to record the IDs of equipped vehicles and time-stamp the arrival of these vehicles.

Advantages

RFID technology is inexpensive. It does not interrupt traffic.

Disadvantages

RFID only detects equipped vehicles at a point of roadway.

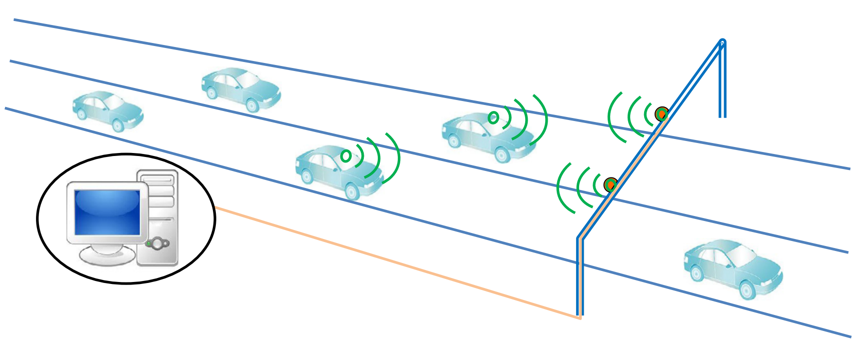

Figure 1.8 Electronic toll collection system.

1.2 TRAFFIC SENSOR CLASSIFICATION

Traffic sensors can be classified in many ways. For example, according to its working principle, a traffic sensor can be a

- *mobile sensor* if it resides in a vehicle and collects data only specific to this vehicle. GPS receivers, acoustic/ultrasonic sensors, and cell phones are examples of mobile sensors.
- *point sensor* if it is mounted at a fixed location along the roadway and observes traffic only at this particular location. Inductive-loop detectors, VIPS, pneumatic tubes, and RFID technology (e.g., transponder-reader system) are examples of point sensors.
- *space sensor* if it is up in the air and is able to take a snapshot of traffic on a stretch of road. Helicopters and satellites are examples of space sensors.

According to the extent to which a sensor intrudes into the roadway and traffic, the sensor can be

- *intrusive* if installation of the sensing system requires pavement work and interruption of traffic. Inductive-loop detectors and pneumatic tubes are examples of intrusive sensors.
- *nonintrusive* if installation of the sensing system does not require pavement work and interruption of traffic. VIPS and RFID technology are example of intrusive sensors.
- *off-roadway* if the sensor is not fixed to a location on the roadway—that is, the sensor can move with vehicles or float in the sky. GPS receivers, acoustic/ultrasonic sensors, cell phones, helicopters, and satellites are examples of space sensors.

1.3 DATA SOURCES

As example products of traffic sensors, two sets of data are presented below—Georgia State Route 400 (GA400) data and Next Generation Simulation (NGSIM) data. These data sets will be used in later chapters.

1.3.1 GA400 Data

GA400 is a toll road in Atlanta (Georgia, USA). Part of the road is freeway by design and is monitored by the NaviGAtor system-the—Georgia Department of Transportation's intelligent transportation system. NaviGAtor's video detection system (VDS) is the primary source of real-time information about current travel conditions. Approximately 1645 VDS stations are installed approximately every third of a mile along most major interstate highways in the Atlanta Metropolitan Area. These VDS cameras provide continuous speed and volume data to the traffic management center and allow the system to generate travel times for the changeable message signs. NaviGAtor also uses about 500 full-color closed-circuit television cameras, positioned about every 1 mile on most major interstate highways in Atlanta. The closed-circuit television cameras have tilt, pan, and zoom capabilities, and serve as traffic cameras sending real-time footage to the operators at the traffic management center for enhanced situational awareness. The information collected from these cameras allows the operators to confirm incident details, dispatch rescue units, and request appropriate emergency resources.

Figure 1.9 shows a real-time traffic map of NaviGAtor in the Atlanta Metropolitan Area. On this map, roadway links are color-coded to highlight the level of congestion. In addition, the locations of some of the video cameras and changeable message signs are labeled on the map. A sample image from a video camera on GA400 is illustrated in the top left corner of the figure.

The data collected by the automated surveillance systems on GA400 were archived every day in the form of a single compressed file. This archived file contains observations at each station during the day. Each data entry represents 20 s of aggregation of classified vehicle counts, time

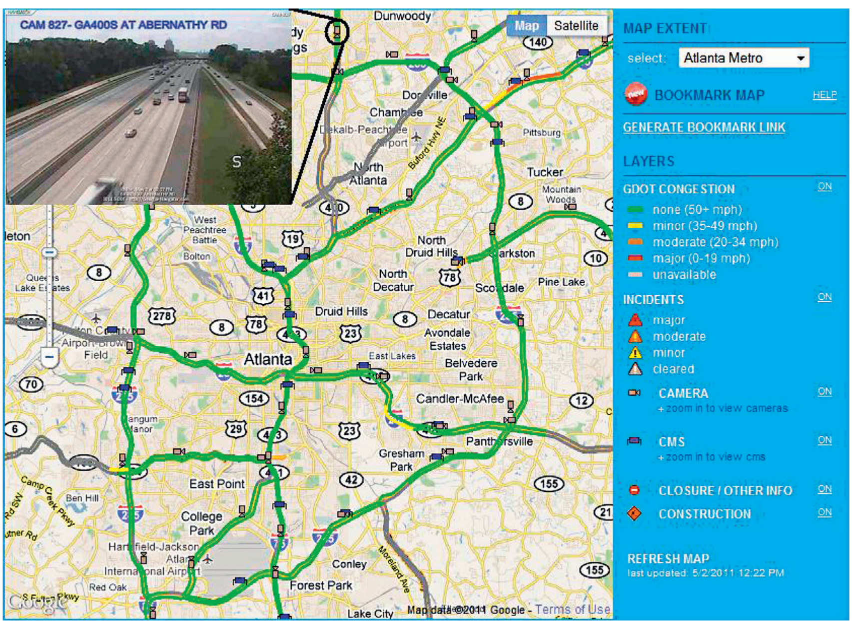

Figure 1.9 Georgia NaviGAtor. *(Photo from http://www.511ga.org/)*

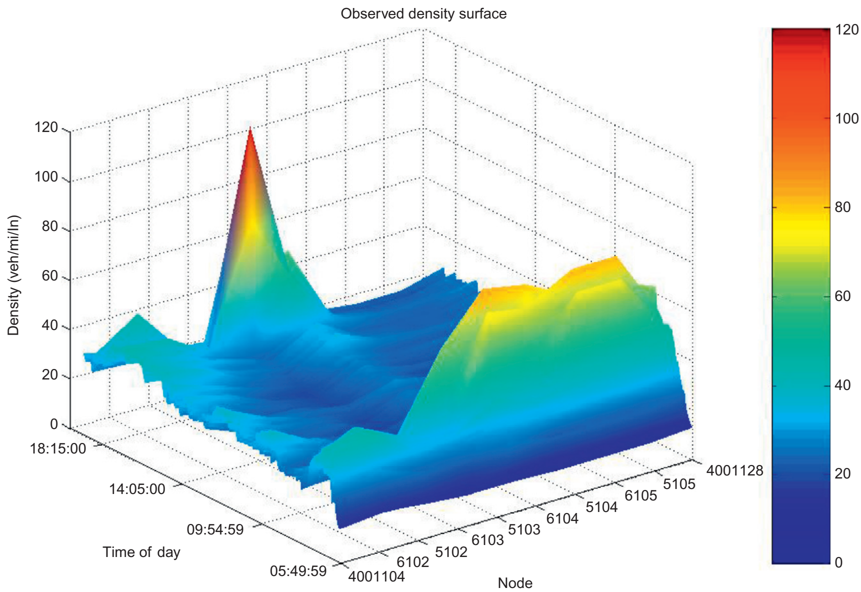

Figure 1.10 GA400 data sample.

mean speed, occupancy, etc. Figure 1.10 illustrates three-dimensional traffic density (converted from field data collected on Friday, October 11, 2002) over time and space.

1.3.2 NGSIM Data

The NGSIM program was initiated by the Federal Highway Administration of the US Department of Transportation around 2000. The program developed a core of open behavioral algorithms in support of traffic simulation with a primary focus on microscopic modeling. To support the research and testing of the new algorithms, high-quality primary traffic and trajectory data were collected at multiple locations nationwide. The NGSIM program also actively engaged traffic simulation vendors to accelerate the inclusion of advanced or improved algorithms in the commercial models used across the world.

NGSIM vehicle trajectory data were collected for a set of sites including freeways, arterial roadways, and urban streets. Figure 1.11 illustrates one of the sites on Interstate 80 in California. The left panel shows an aerial photo of the site where seven video cameras were set up on top of a 30-story building with each camera covering part of the study area. The right panel visualizes a camera and its perspective. These cameras shot the site

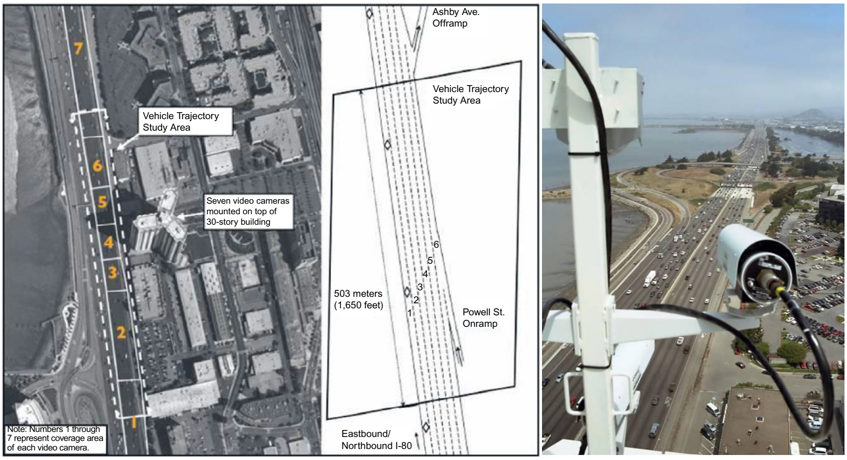

Figure 1.11 NGSIM data collection site. *(Photos from http://www.fhwa.dot.gov/.)*

Figure 1.12 NGSIM data sample.

at different angles such that a vehicle entering from upstream is monitored continuously and consecutively by these cameras until it exits the study area.

Videos captured by these cameras were then processed by a customized software application which identifies, tracks, and records every vehicle's temporal-spatial positions as the vehicle traverses the study areas. The resultant vehicle trajectory data provided the precise location of each vehicle within the study areas every 0.1 s, resulting in detailed lane positions and locations relative to other vehicles. Figure 1.12 illustrates a sample result of such vehicle trajectory data. The y-axis (not shown) is the highway running from south to north and the x-axis (not shown either) is time. Vehicle trajectories are so fine and dense that disturbances of traffic flow and its propagation are clearly visible like ripples in water.

PROBLEMS

1. Explain what an ITS is. What are the components of an ITS? Name a direction of recent development of ITS in the United States.
2. According to their working principle, traffic sensors can be classified into three types, what are they?

3. Provide an example of a mobile sensor. With a sketch, explain how it works, what kind of traffic data it is capable of collecting, and what advantages and disadvantages it has.
4. Provide an example of a point sensor. With a sketch, explain how it works, what kind of traffic data it is capable of collecting, and what advantages and disadvantages it has.
5. Provide an example of a space sensor. With a sketch, explain how it works, what kind of traffic data it is capable of collecting, and what advantages and disadvantages it has.