Freeway Data Collection, Storage, Processing, and Use

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ABSTRACT

The paper begins with a brief discussion of issues that must be resolved in building a freeway data management system. Following this is a description of the design choices that dealt with these issues in a functioning system for California freeways. The system is called PeMS. Some concrete uses of PeMS are presented next. These uses imposed the functional requirements that led to the design choices in PeMS. Any freeway data management system will have to meet similar functional requirements.

1. INTRODUCTION

The paper discusses the design, building, and maintenance of a freeway data management system. The system designer must address several issues: the purposes of such a system; the sources, storage, and diffusion of data; and the role of standards. We begin with a general discussion of these issues in section 2.

In section 3 we describe the design choices made in a functioning system for California freeways. The system is called PeMS (Freeway Performance Measurement System). This description clarifies some of the issues.

Section 4 describes some concrete applications of PeMS by transportation managers, engineers, planners, researchers and travelers. These applications elaborate the 'purposes' of a freeway data management system. The applications served as 'functional requirements' for PeMS. It is likely that other freeway data management system must meet the same requirements.

2. ISSUES IN FREEWAY DATA MANAGMENT

A freeway data management system is built to serve some purpose. The perspective adopted here is that the data are needed to produce information used by *suppliers* of transportation services to improve planning, investment, and operational decisions, and by *consumers* of these services to improve their travel choice.

2.1 Purpose

The transportation system produces one service: the movement of people and goods.[1] The output of the system is the people-miles or goods-miles traveled, and its input is the (variable) cost in time and money imposed on the consumers of the service, and the (relatively fixed) cost of capital and labor inputs used to support the infrastructure.[2] Thus the purpose of the data is the information they provide to improve the production and consumption of this service.

The most important determinant of production efficiency and consumer satisfaction is *congestion*.[3] In Los Angeles, freeway detectors typically record a maximum flow of 2,200 vehicles/lane/hour moving at 60 mph. During congestion the flow over one section may drop to (say) 1,800 and speed may drop to 35 mph, so this section's efficiency is reduced to (1800

[1] The transportation system has many economic outcomes. It changes the relative residential and commercial advantages of different location; it thereby affects the economic development of different regions. These outcomes, however, are not 'outputs' of the transportation system and are irrelevant in evaluating system performance.

[2] Damage to the environment should be included in a complete input-output account.

[3] The focus here is on operational or short-run efficiency. Evaluating the efficiency of major investments in transportation requires assessment of system performance over a time horizon of decades. It does not seem that freeway data can be reliably used to make these long-term assessments.

× 35)/(2200 × 60) or 48 percent (*1*). Congestion increases travel time, hence the cost of consumption. It dramatically increases the variability of travel time, leading to additional welfare loss. So the main use of freeway data is to help reduce congestion and its impact.

2.2 Sources

As will be seen in section 4, loop detector data can be processed to estimate congestion. They can also be used to reduce congestion through ramp metering, and to make reliable estimates of travel time to improve consumer well-being.

Congestion is affected by two other factors that cannot be estimated from loop detector data. The first is the occurrence of incidents. The second is trip data.

Because loop detectors are placed one-half mile apart, it is not possible to use these measurements to reliably and quickly detect incidents.[4] Incidents increase congestion by 20 to 50 percent, so rapid detection followed by quick response can reduce this additional congestion considerably (*3*).

Two data sources can improve incident detection. Video cameras can be used to detect incidents within their field of view. Video streams are typically manually inspected, which limits the number of cameras that can be deployed. Hence video coverage is limited. However, the data can be processed in real time to detect incidents (*4*). The bigger obstacle to widespread deployment of video cameras is the need for a relatively high-bandwidth communication link to transport video data.[5]

Drivers with cell phones frequently report incidents. These reports can provide a good description of the incident. Because cell phones are ubiquitous, they offer a large area of coverage. However, there are two difficulties. First, drivers often are unable to accurately locate where they witnessed the incident. Second, the reports are interpreted by a human operator, which seriously limits the number of reports that can be processed in a timely manner. If cell phones or vehicles are equipped with GPS devices, the inaccuracies in location can be reduced. But the voice processing ‘bottleneck’ remains.

Accidents, which cause the most congestion compared with other incidents, can be avoided if drivers are made aware of dangerous situations. For example, at intersections a driver may be alerted to the approach of cross traffic. Along a freeway, a driver may be warned if the vehicle is too close to the vehicle in front at the current relative speed, or if the vehicle is departing from its lane. The acquisition of these data from the vehicles and the roadside infrastructure, and processing the data to extract meaningful information poses challenging problems of sensing, communication, processing, and display. It is too early to assess the ongoing research in this area.

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[4] The false alarm rate of published algorithms is unacceptably high (*2*).

[5] Compression at the camera site can significantly reduce the required bandwidth. However, compression may remove features of the video scene, making computer processing more difficult.

Consumers choose their trip departure time and route. Information about the pattern of trip distributions is essential for planning and short-run investment decisions, and to operate a balanced multi-modal transportation system. Loop detector data cannot be used to estimate trip distributions because they measure the aggregate traffic at particular freeway locations, rather than the movement over space of individual vehicles. Limited experiments suggest that high scan rate loop detectors and video cameras can be used to extract 'signatures' that permit re-identification of vehicles at two nearby locations (*4*, *5*). But these results also suggest that these techniques may not accurately re-identify vehicles over a distance of several miles. Thus these techniques may not be useable to estimate trip distribution.

Machines that 'read' unique electronic tags placed in vehicles produce accurate records of those vehicles as they pass near the tag 'reader'.[6] In areas with electronic toll collection (ETC) many vehicles are equipped with such tags. Records from additional readers deployed along roads can be correlated to reconstruct vehicle trips over a long period of time, say 24 hours. The inferred trips provide much more information than origin-destination data. For example the 24-hour long record would tell us whether trips are single- or multi-purpose, and help characterize the difference between HoV and SoV trips. In turn, that information can be used to estimate the potential demand for transit. The information can also be used to estimate the transportation demand generated by 'special events'. The pattern of trip distribution can be used to mitigate the impact of lane closures, and to make emergency plans for re-routing traffic in the event of major incidents.[7]

In summary, loop detectors and their surrogates provide data for measuring congestion and controlling congestion mitigation field equipment. Video cameras seem most promising for incident detection. Tag readers seem well suited for generating information about trips.

2.3 Storage and access

Virtually all applications of freeway data make use of historical as well as real time records. Thus it is essential to archive all data and make them available online. For all except video data, storage is extremely cheap. Video data may be processed and reduced to something manageable and storable.

Data archives will grow in time and to be useful they must be placed within a database management system that permits efficient insertion and retrieval of records in response to queries. Loop detector data records are conveniently stored within a relational database. Tag reader records could also be stored that way. It is less clear how video records should be archived.

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[6] Tag readers are much easier and cheaper to deploy than license plate readers, but their coverage is limited to vehicles with tags.
[7] Safeguards that insure that the tags uniquely associated with vehicles are stripped from the records can address legitimate concerns about privacy.

Even if one decides to use a relational database, many choices remain, which affect the performance of the database system. Critical choices include the choice of indexes, and the configuration of tables.

2.4 Standards

The National Transportation Communications for ITS Protocol (NTCIP) is a suite of communication protocols and data definitions designed to accommodate the needs of various subsystems and user services of the National ITS Architecture (*6*). NTCIP seeks to facilitate the transmission of relatively infrequent messages that carry data from and commands to intelligent field equipment. To achieve interchangeability and interoperability, NTCIP proposes a set of 'data models' based on DATEX and CORBA. Messages would be 'encapsulated' to conform to these data models.

The use of NTCIP to retrieve and transport loop detector data is problematic. First, loop detectors in the field are 'dumb' devices from which measurement records are retrieved by polling, typically every 30 seconds. Loop detectors themselves are incapable of providing data in a form that complies with NTCIP. Thus NTCIP can only be used at the TMC after loop data are received and stored. Second, the high overhead of NTCIP makes it unreasonable to transfer loop detector data from the TMC in real time. Third, NTCIP does not handle data streams like those generated by video cameras. Fourth, NTCIP is not suited to work with large amounts of historical data: NTCIP relies on SNMP for database management, which is too primitive compared with the transaction facilities provided by today's database management systems.

Much more useful would be the creation of 'meta data' relating to a traffic surveillance system. In the case of a loop detector system, such meta data might include items like the location of loop detectors in a variety of coordinate systems (lat-long, lane and postmile), their status (whether they are functioning or not), the loop's electrical characteristics. Additional meta data could describe freeway geometry, nominal mainline and ramp capacities. Such meta data are essential to the proper interpretation of the data themselves within useful applications. These meta data would also help to connect the database to a GIS system.

3. PeMS DESIGN CHOICES

Central to investments in ITS infrastructure is a surveillance system that gathers real time data from detectors and transmits the data to TMCs. The system should store the data and process them to produce useful information. PeMS is the freeway performance measurement system for all of California. It receives about 2 GB each day of 30-second loop detector data in real time from different Caltrans TMCs. Built-in applications combine these real time data with 2 TB of historical data to produce information of use by managers, transportation engineers, planners, researchers, and travelers. This section summarizes crucial design choices and draws some lessons from the experience of developing PeMS.

3.1 Architecture

The most important considerations in building a relatively large database system like PeMS are scalability and cost. Scalability means many things. The data should be in electronic form; its processing should require no human intervention. Thus, for example, raw video data feeds do not scale: It is impractical to install hundreds of video cameras whose outputs must be interpreted by human operators.

The system should be incrementally expandable to include new electronic data sources, without requiring that these data sources conform to some 'standard'. Different TMCs in California collect data in slightly different formats. However in PeMS, the data are organized to present a common view to application programs.

Scalability is facilitated if the system can work with distributed data sources, designed for different purposes. In the PeMS case, each district TMC maintains its own ATMIS database: PeMS merely receives a copy of the data as they enter the district database, with no interruptions in TMC operations.

Scalability requires modular application software. In PeMS, new applications are constantly being developed.

The most important way that PeMS has reduced cost is its use of off-the-shelf hardware and database software.[8] Its application software architecture is open, so anyone may develop new applications.

Because disk storage is very cheap, PeMS keeps all historical data online. This has proved to be an immense benefit. Every PeMS user analyzes data over several days or months. If the data were not online, those analyses would not have been conducted. Equally important, having the data online reduces system maintenance cost.

More than 99 percent of users access the PeMS database through their web browser, over the internet. In many TMCs, data are available only by logging on to the database machine, which severely limits access. The PeMS architecture separates the database from the web server that can be reached over the internet, dramatically increasing access to the database, without compromising the database itself.

3.2 Applications

PeMS calculates many link performance measures in real time and stores the results. Therefore most user requests are immediately served by a simple database transaction. This encourages experimentation, frees the user from time-consuming data processing tasks, and often challenges preconceived ideas that lack a sound empirical basis.

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[8] The cost to reproduce a copy of PeMS is under $300,000.

The most difficult challenge is integrating PeMS into daily use within Caltrans. Caltrans operations, planning, and investment processes were developed in an era when data were scarce and expensive to collect and analyze. As a result, these processes are not designed to make use of the massive amount of empirical data available in PeMS.

To take one example, Caltrans produces an annual congestion report, based on tach vehicle freeway runs during peak periods. PeMS data show that there is so much daily variation in congestion delay, that a single sample of congestion obtained from these vehicle runs is meaningless. What we need are congestion measures that recognize this random variation, and provide daily, weekly, monthly trends. Because travel time often varies by 300 percent, measuring average travel times is equally inadequate, unless accompanied by measures of variability.

Thus the availability of large amounts of historical data will encourage a change in performance measures that were designed during a period of data scarcity.

3.3 Sensor health and data integrity

The old adage "garbage in, garbage out" still holds. No amount of sophisticated processing can overcome the debilitating effect of a poorly maintained surveillance system. The quality of Caltrans' loop detector system is on the whole poor, and it varies widely from district to district. The PeMS loop diagnostic application provides a daily list of malfunctioning detectors. This application can be easily integrated into a detector health maintenance system.

Data from even a healthy system cannot be fully trusted. It is essential to put in place a real time automatic data integrity check. It is also necessary to have a method that replaces suspect data with more reliable statistical estimates. That way, a complete data set is available and applications, which often assume a complete time series, will run correctly.

Thus a data management system must make provisions for the fact that sensor data are frequently missing or erroneous.

3.4 Data coverage

PeMS only includes freeway data. There are plans to extend its coverage—first to arterials, later to transit. A 'multi-modal' PeMS will provide the means to more fully assess system performance and evaluate options.

4. PeMS APPLICATIONS

We describe some applications to demonstrate how PeMS is used, and compare this use with traditional approaches. These applications originally served as the 'functional requirements' for the design of PeMS. Any freeway data management system must meet similar requirements.

4.1 Freeway Operations Analysis

Caltrans staff analyzed existing operating conditions in the westbound direction of I-10 freeway during the am peak period using PeMS. Figure 1 shows the study area. It extends for 30 miles from the Los Angeles/San Bernardino County line to Downtown Los Angeles.

Figure 2 shows the volume and speed (averaged across all lanes) for the test section at 7:30 am. A major bottleneck exists at the I-10/I-710 interchange. Figure 3 is a three-dimensional contour plot of speeds: Congestion begins at 6:30 am and lasts until 11:00 am, extending to most of the study area.

The traditional approach uses 'floating car' studies to measure speed and delay. This requires a minimum of two days field data collection with four-person teams per segment driving instrumented vehicles in three 10-mile segments, which translate into 120 person-hours of effort. Additional field data collection to obtain statistically valid results is prohibitively expensive.

PeMS provides both input (volumes) and performance data (speed, delay, VMT, VHT) for the study area. Contour and across-space plots assist in determining problem locations and their impacts. More importantly, the data can be analyzed over several typical days. The entire analysis requires less than one person-day of effort.

4.2 Bottleneck identification and analysis

This example involves direct interaction with the PeMS database for a custom application. The objective is to identify where freeway bottlenecks are located, and assess their impacts. Another objective is to determine if the effectiveness of traffic control measures, such as ramp metering.

The northbound direction of I-5 freeway in Los Angeles was analyzed. PeMS built-in speed and occupancy contour plots are first used to pinpoint bottleneck locations along the study section. Observations for several weekdays are inspected. This preliminary analysis indicates a potential bottleneck at postmile 29 (a weaving section). Figure 4 shows the average 5-minute freeway occupancy at three loop detector locations for a four-hour period (2:00 to 6:00 pm). The loop occupancy at the bottleneck location (loop 716974) is about 11 percent. The downstream loop occupancy (loop 716978) is about 7 percent indicating free flow conditions. By contrast, the occupancy at the upstream loop (loop 716973) increases with time to about 25 percent from 4:00 to 6:00 pm, indicating congested conditions due to the presence of a downstream bottleneck.

Next, the 30-second count and occupancy data for each detector were downloaded from the PeMS database and the results were analyzed in detail using cumulative count and occupancy plots (*5*). Figure 5 shows the plots for loops upstream and downstream of the bottleneck. The values of counts and occupancy are appropriately scaled to remove stochastic fluctuations and reveal changes in traffic states. The plot for the downstream detector shows that the cumulative counts and occupancy track each other throughout the analysis period indicating free flow conditions. The opposite is the case for the upstream loop. At about 2:30 pm, the cumulative occupancy increases and the cumulative count decreases, indicating congested conditions.

An alternative way to study bottleneck locations is by analyzing the speed contour maps. From Figure 2, we can easily identify potential bottleneck locations at postmiles 22 and 32 along the westbound I-10 corridor as the speeds there are reduced from free flow conditions to stop and go. Looking at a time slice between 7:30 am to 9:30 am, the second bottleneck at postmile 32 might have been missed, “buried” amongst the contour of congestion. With the speed contour maps, we can see the lengths of peak hours, formation and duration of bottlenecks, and indications of hidden bottlenecks. A key benefit of PeMS is that this speed contour map is available for any time period, for any length of corridor, 24 hours a day, 365 days a year. This allows engineers to study mid-day congestion periods, weekend peaks, holiday congestion, and alterations in traffic flow patterns due to lane closures.

4.3 Incident impact

PeMS was used to analyze the impact of a major incident in the eastbound direction of I-210 freeway (Figure 6). PeMS plots of speeds and volumes across space make it possible to determine the spatial and temporal impact of the freeway incident, and the time for recovery to normal operating conditions.

Figure 6 shows the average speed vs. distance of 10 miles of freeway at various time slices. At 11:00 am traffic is free flowing at 60 mph. There are five through lanes on the freeway mainline until postmile 29, where they are reduced to four lanes. The traffic volume is about 6,000 vph (or 1500 vph/lane through the four-lane section).

At 11:20 am a multi-vehicle collision blocked three out of four travel lanes on the freeway. The average speed drops to about 5 mph at the incident location. The incident lasted 2.5 hours. The figure shows vehicle speeds at 2:00 pm, shortly after the incident was cleared. Congestion reached five miles upstream of the incident location. Normal operating conditions on the freeway resumed at 3:10 pm, 1.5 hours following incident removal. Further analysis of the PeMS data provided additional insights:

Remaining capacity. The discharge rate of vehicles past the incident location on the single travel lane was very low (about 300 vph) for the first 10 minutes of the incident. The rate then increased to about 1,400 vph for the rest of the incident duration. Assuming a typical capacity range of 8,000-8400 vph for the four-lane section, the remaining capacity due to the incident is 17 percent of the capacity under normal conditions. This is higher than the suggested value of 13 percent reported in the HCM2000 (Chapter 25: Freeway Systems).

Discharge ("getaway" flow). Following the incident clearance, the queued vehicles discharged past the incident location at a rate of 7,400 vph—lower than the nominal capacity of the freeway section (8,000-8,400 vph).

4.4 Assessment of ATMIS strategies

Caltrans has started to deploy Advanced Traffic Management and Information Systems (ATMIS) to manage freeway congestion. Example applications include ramp metering, changeable message signs, and incident detection. The most important question is: How much congestion can ATMIS reduce? A PeMS application can help answer this.

Congestion may be measured by Caltrans' definition of delay (when speeds fall below 35 mph), or directly by using VHT and VMT. We can use PeMS to analyze delay for any section of freeway, and the effectiveness of ramp metering. Figure 7 shows the results for a 6.3-mile section of I-405N from 5.00 to 10.00 am on 6/1/98.

The top curve in Figure 7 gives the actual VHT every 5 minutes on the study section from 5 to 10 am. The middle curve is the estimated VHT the *same* vehicles would spend if ideal ramp metering maintained throughput at capacity. This implies that a certain number of vehicles have to be stored at the freeway entrance ramps (excess demand). The lowest curve is the VHT that would result if the same vehicles were to travel at free flow speeds (60 mph), without waiting at a ramp.

The area between the top and middle curves is the delay that can be eliminated with ideal ramp metering (about 500 veh-hrs in this study section). The area between the middle and lowest curve is the delay due to the excess demand (about 200 veh-hrs). The total delay (with respect to a reference speed of 60 mph) is the area between the topmost and lowest curves. The delay due to the excess demand can only be reduced through temporal, spatial or modal shift in demand. One way to shift demand is to use PeMS to inform travelers that they will face this delay. Travelers that are better off changing their trip departure time, route or travel mode would then do so.

4.5 Traveler information

The left of Figure 8 is a screen capture of the PeMS freeway real time speed map for District 7 (Los Angeles). The map also shows incidents. A description of an incident pops up when its icon is clicked.[9] More interesting is the screen shot on the right. A user can click the origin and destination points on the map, specify departure (or arrival times). PeMS provides an estimate of the travel time for 15 shortest routes, together with directions.

[9] The incident descriptions are obtained from the California Highway Patrol website. These maps are now quite common. Many value added resellers (VARs) obtain 5-minute data free from PeMS through its ftp server for which PeMS provides client download software.

A recently started pilot project will display travel time estimates on ‘changeable message signs’. The aim is to study how drivers react to such signs, as well as how to conveniently implement them, given that PeMS routinely makes these estimates.

PeMS can easily extend the availability of traveler information. Users can register preferred routes on the website, and download the results on a desktop machine or a mobile web-enabled cell phone or other hand-held device. Freeway information can be integrated with transit information.

More interestingly, PeMS provides a real time ‘traffic report’. It contains daily and hourly summaries of freeway performance, aggregated by district, county, city, or freeway; the slowest freeway sections, and those with the largest flows; and a health indicator of the detector system. The traffic report will soon include incidents (or accidents) per million VMT, by freeway.

5. CONCLUSIONS

The view adopted in this paper is that a system to collect, archive, and process freeway data is built to provide information that reduces congestion and mitigates its impact on the traveler. This view serves to evaluate what sources of data are likely to be useful, how they should be processed and disseminated. The design of the system requires additional choices: its architecture, communication network, database management system, and application software. These choices were elaborated in the context of a concrete system, PeMS, which was designed for California’s freeway system.

California freeways are currently managed using processes and practices that need little help from real time or historical data. These processes and practices will need to change to make effective use of these data and to achieve the potentially large efficiency gains that seem available.

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views of or policy of the California Department of Transportation. This paper does not constitute a standard, specification or regulation.

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Figure 1. The Test Section (WB I-10)

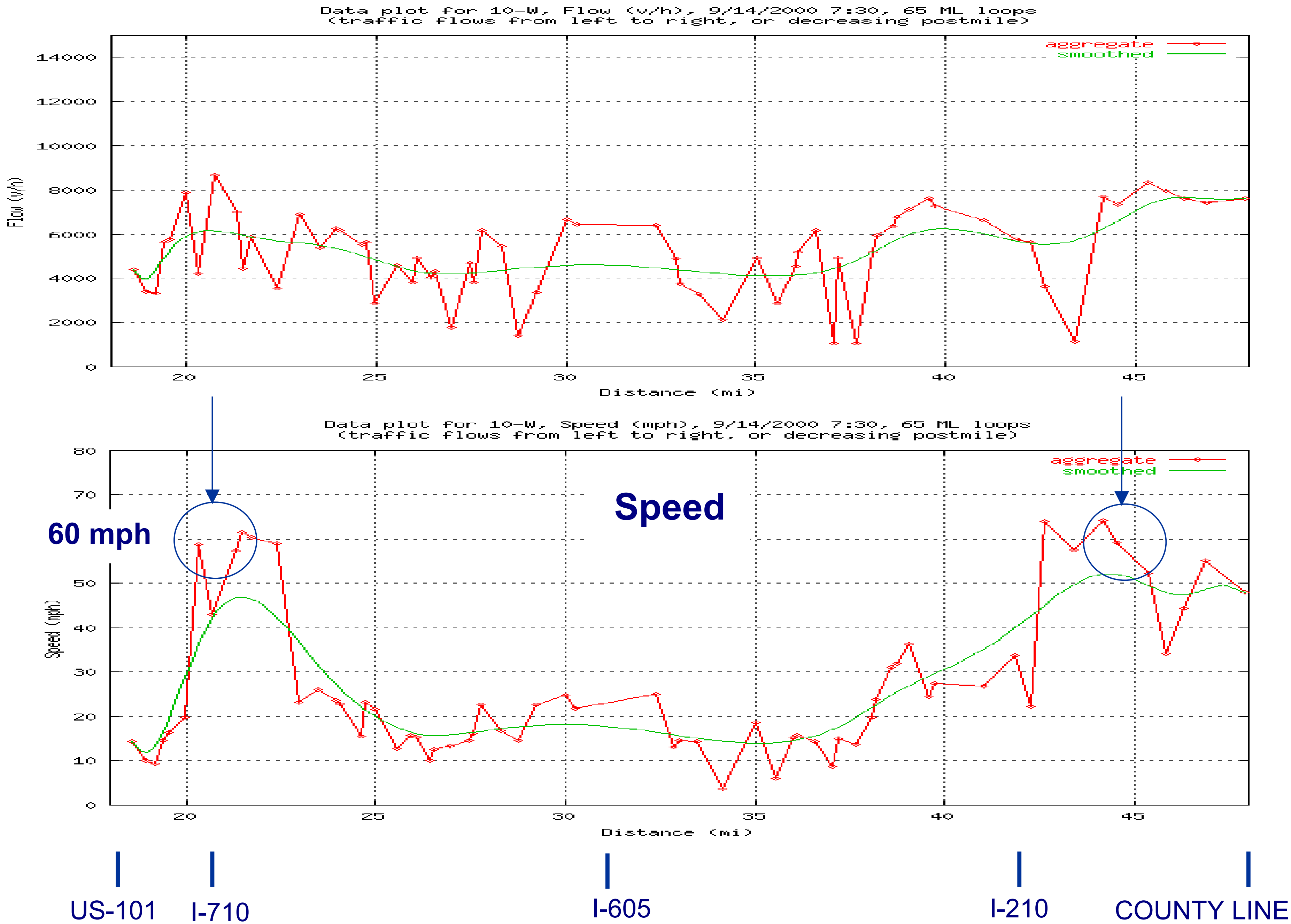

Figure 2. Flow and Speed along WB I-10, 7:30 am, 9/14/2000

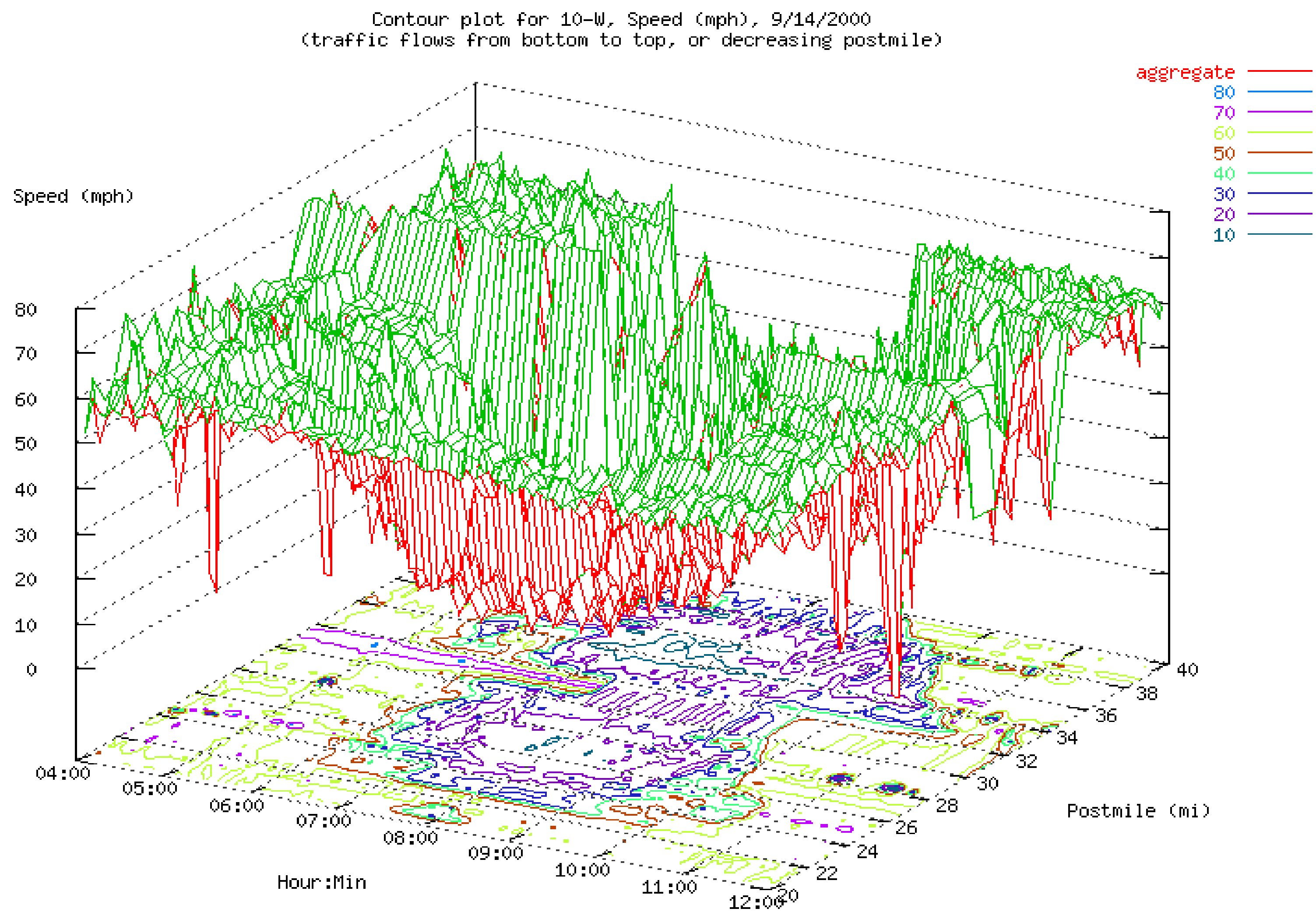

Figure 3. Speed Contour Plot (WB I-10)

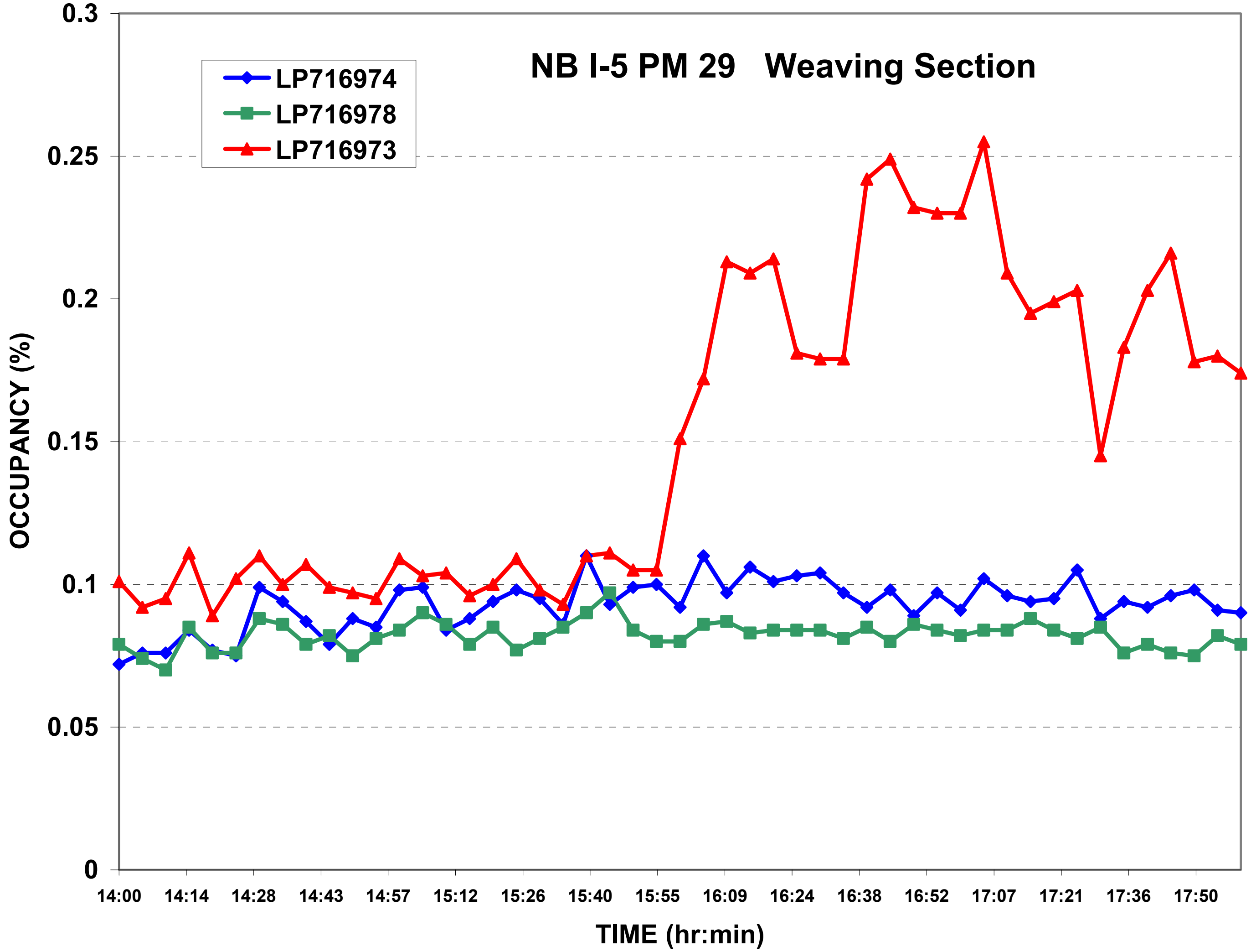

Figure 4. Detector Occupancy vs. Time

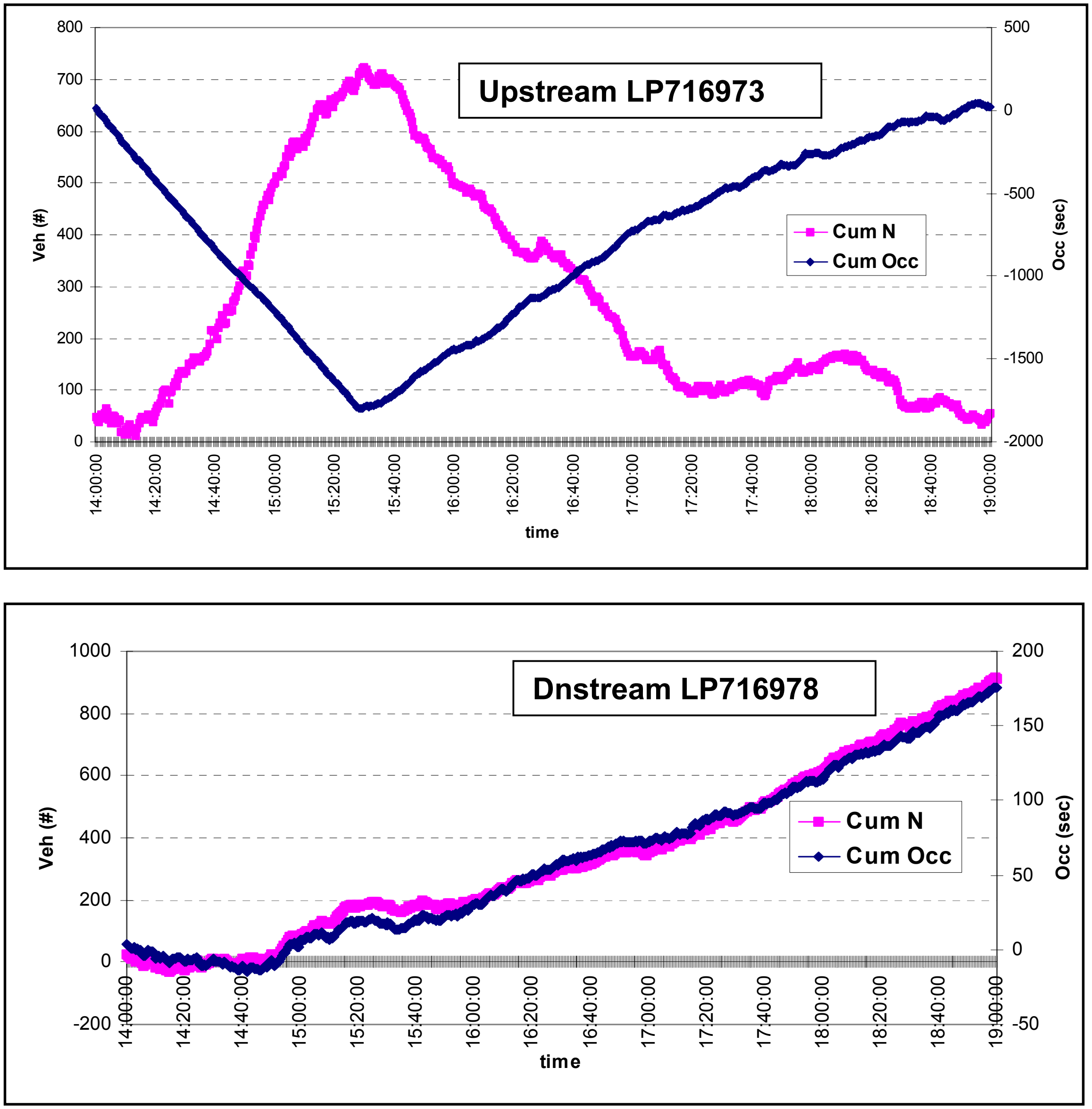

Figure 5. Cumulative Count and Occupancy Plots

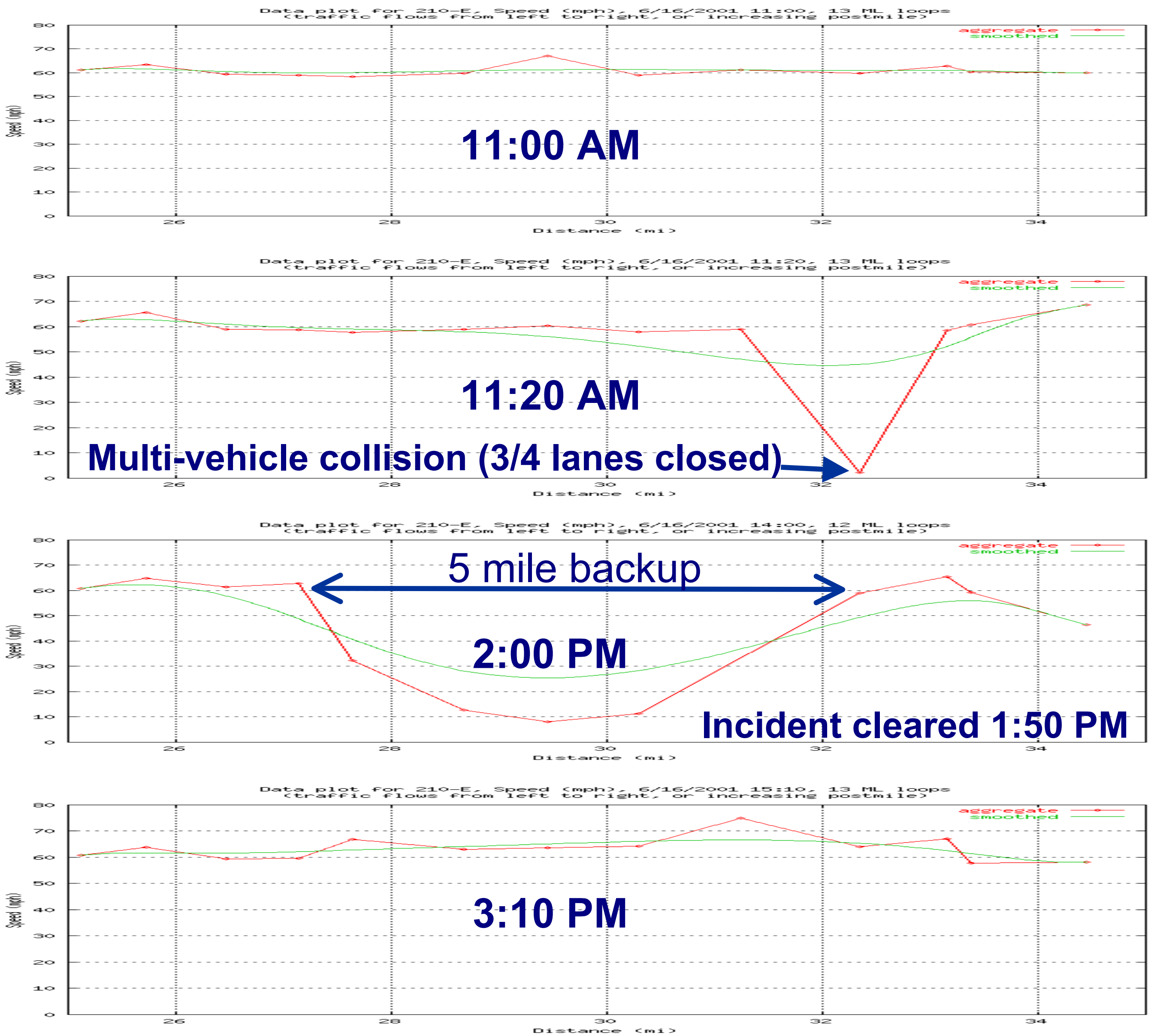

Figure 6. Incident impact: EB I-210 Saturday 6/16/2001

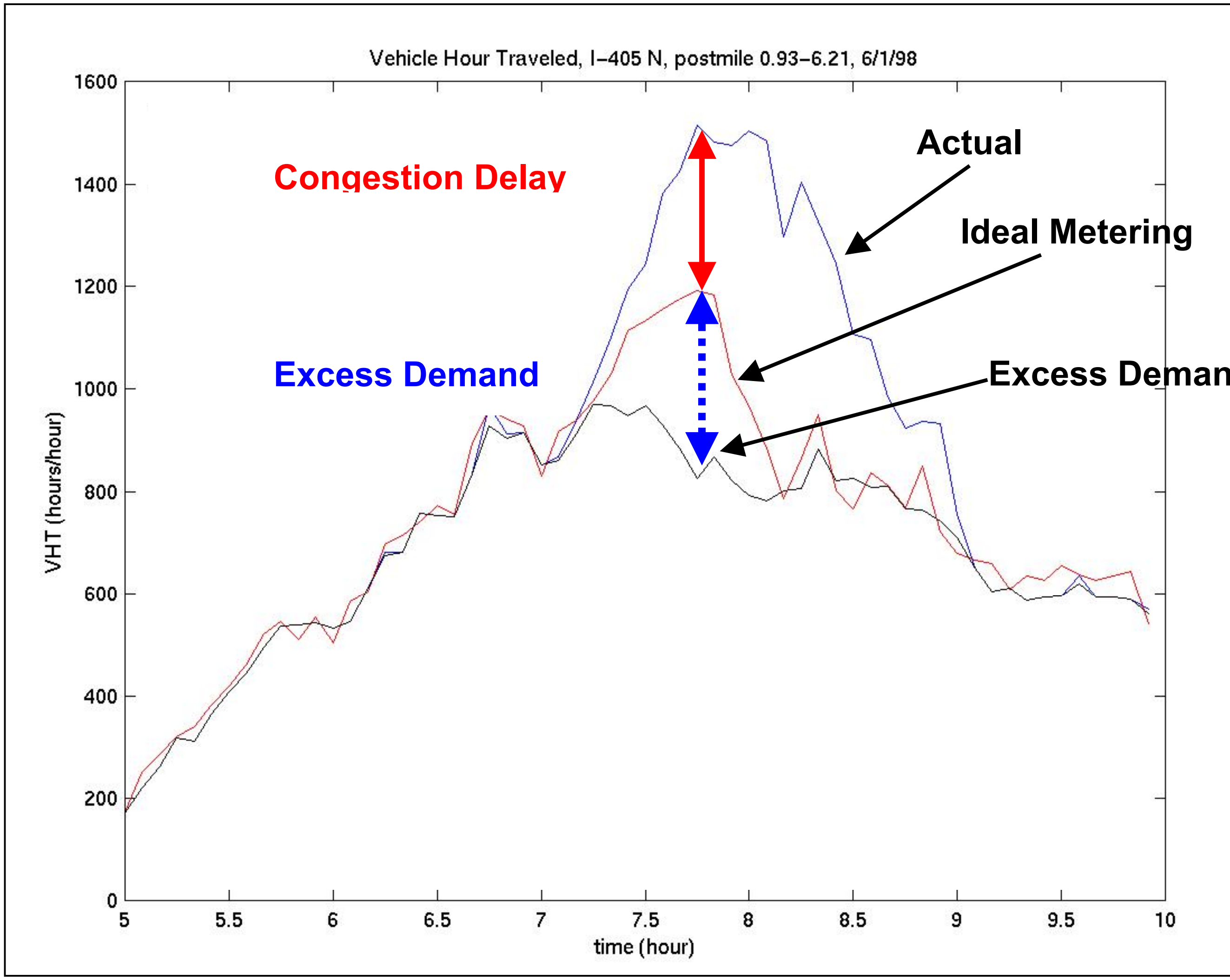

Figure 7. Veh-Hours Traveled (VHT) Under Different Scenarios

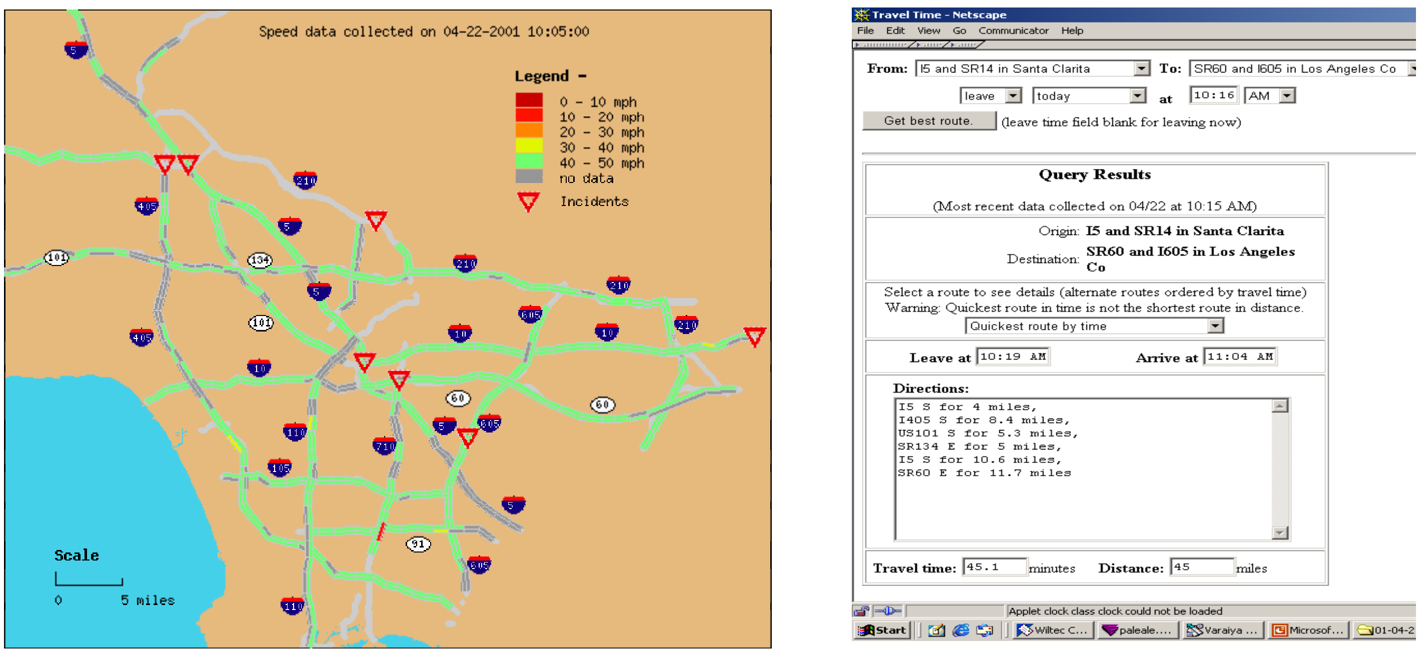

Figure 8. Traveler information