# FREEWAY PERFORMANCE MEASUREMENT SYSTEM (PeMS): AN OPERATIONAL ANALYSIS TOOL

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## ABSTRACT

PeMS is a freeway performance measurement system for all of California. It processes 2 GB/day of 30-second loop detector data in real time to produce useful information. Managers at any time can have a uniform, and comprehensive assessment of freeway performance. Traffic engineers can base their operational decisions on knowledge of the current state of the freeway network. Planners can determine whether congestion bottlenecks can be alleviated by improving operations or by minor capital improvements. Travelers can obtain the current shortest route and travel time estimates. Researchers can validate their theory and calibrate simulation models.

The paper describes the use of PeMS in conducting operational analysis, planning and research studies. The advantages of PeMS over conventional study approaches is demonstrated from case studies on conducting freeway operational analyses, bottleneck identification, Level of Service determination, assessment of incident impacts, and evaluation of advanced control strategies

## INTRODUCTION

Caltrans (California Department of Transportation) needs a freeway performance measurement system that extracts information from real time and historical data. ***PeMS*** (***Pe***rformance ***M***easurement ***S***ystem) is such a system. It presents information in various forms to assist managers, traffic engineers, planners, freeway users, researchers, and traveler information service providers (value added resellers or VARs).

Caltrans managers can instantaneously obtain a uniform, and comprehensive assessment of the performance of their freeways. Traffic engineers can base their operational decisions on knowledge of the current state of the freeway network. Planners can determine whether congestion bottlenecks can be alleviated by improving operations or by minor capital improvements. Traffic control equipment (ramp-metering and changeable message signs) can be optimally placed and evaluated. Travelers can obtain the current shortest route and travel time estimates. PeMS can serve to guide and assess deployment of intelligent transportation systems (ITS).

The purpose of this paper is to present the use of the PeMS as a tool to perform operations studies. The PeMS database and built-in applications offer several advantages in understanding the system performance and analyzing options compared to traditional approaches that are based on limited data due to the high effort and cost involved in field data collection. The use of PeMS maximizes the utility of data from loop detector surveillance systems that often are archived off-line without any processing and analysis.

The paper first gives a brief overview of the PeMS system. The following sections present the process and the findings from the application of PeMS by practicing engineers and researchers in conducting freeway operational analyses, bottleneck identification, determining the Level of Service, assessment of incident impacts, and evaluation of advanced control strategies. The last section summarizes the major study findings, and discusses ongoing and future work.

## PeMS OVERVIEW

PeMS obtains 30 second loop detector data in real time from each Caltrans District Transportation Management Center (TMC). The data are transferred through the Caltrans wide area network (WAN) to which all districts are connected. Users can access PeMS over the Internet through a Web browser. The PeMS software architecture is modular and open. It uses commercial-of-the-shelf products for communication and computation. A brief overview of the system components is given below. These are described in detail elsewhere (*1*).

### Data Processing

The 30 second data received by PeMS consist of counts (number of vehicles crossing the loop), and occupancy (the average fraction of time a vehicle is present over the loop). The software processes the data in real time and

- Aggregates 30-second values of counts and occupancy to lane-by-lane, 5-minute values;
- Calculates the *g*-factor of each loop;
- Uses the g-factor to calculate the speed for each lane;
- Aggregates the lane-by-lane value of flow, occupancy, and speed across all lanes at each detector station (one station typically serves the detectors in all the lanes at one location);

Most detectors in California have single loops. The g-factor (effective vehicle length) is used to calculate the average vehicle speeds from the flow and occupancy data. Typically, a constant value for the g-factor is used which leads to inaccurate speeds because the g factor varies by lane, time-of-day, as well as the loop sensitivity. PeMS uses an adaptive algorithm to compute the g-factor per each loop to provide accurate speed estimates. The algorithm has been tested and validated against "ground truth" data from double loop detectors and floating cars (*2*).

**Calculation of Link Performance Measures**

A link is defined as a freeway segment that contains a single loop detector (typical detector spacing is one-third to one-half mile). PeMS uses the 5 minute average values of flow and speed to compute the following performance measures: VMT (vehicle-miles traveled), VHT (vehicle-hours traveled), delay and travel time. Details of the computations are presented elsewhere (*3*).

**Travel Time Estimation and Prediction**

PeMS provides trip travel time estimates and shortest routes. You bring up the district freeway map on your Web browser, and select an origin and destination. PeMS displays 15 shortest routes, along with the estimates of the corresponding travel times.

PeMS also provides travel time predictions, for example, what will be the travel time 30 minutes from now. The travel time prediction algorithm combines historical and real time data (*4*). In addition, PeMS displays on the freeway system map the location and details about accidents and other incidents based on information retrieved in real-time from the California Highway Patrol (CHP) website. The PeMS data also can be transmitted to VARs, who provide traveler information services.

## PEMS APPLICATION 1: FREEWAY OPERATIONAL ANALYSIS

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

Figure 2 shows the volume and average speed for the test section at 7:30 am. A major bottleneck exists at the I-10/I-710 interchange. Figure 3 shows a three dimensional contour plot of speeds showing that congestion begins at about 6:30 am lasting until 11:00 am and extends to most of the study area.

The traditional approach to obtain performance data involves conducting floating car studies to obtain speed and delay data. This requires a minimum of two days field data collection with four person teams/segment driving instrumented vehicles in three 10-mile segments. This translates into 120 person hours. Additional field data collection to obtain statistically valid results is prohibitive due to the time and cost requirements. Further, several additional data need to be assembled including geometrics (aerial photos, as built plans), and traffic volumes (manual counts, historical data).

The use of PeMS brings several benefits. PeMS provides both the 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 can be performed in less than one person day.

## PEMS APPLICATION 2: BOTTLENECK IDENTIFICATION AND ANALYSIS

This example application involves the direct interaction with the PeMS database for customized applications. The objective is to identify where freeway bottlenecks are located, and assess their impacts. An important objective of this analysis is to determine if the bottleneck capacity could be preserved through traffic control measures (ramp metering).

The northbound direction of I-5 freeway in Los Angeles was analyzed. First, the PeMS built-in speed and occupancy contour plots were used to pinpoint bottleneck locations along the study section. Observations were performed for several weekdays. This preliminary analyses indicated that a potential bottleneck exists at postmile 29 (a weaving section). Figure 4 shows the average five-minute freeway occupancy at three loop detector locations for a four hour time 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. In contrast, the occupancy at the upstream loop (loop 71673) 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 sec 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 the upstream and downstream loop from 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 true for the upstream loop.

At about 15:30 pm, the cumulative occupancy increases and the cumulative count decreases indicating congested conditions.

A broad based approach, another way to study bottleneck locations is by analyzing the speed contour maps. From Figure 3, we can easily identify potential bottleneck locations at postmiles 22 and 32 along the westbound I-10 corridor as the speeds are reduced from free flow conditions to virtually stop and go. Looking at a time slice between 7:30 am to 9:30 am, the second bottleneck at postmile 32 might not have been identified as it would be "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 the 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 of traffic flow patterns due to extended construction road closures.

## PeMS APPLICATION 3: LEVEL OF SERVICE (LOS) CHARACTERIZATION

The objective of this PeMS application was to determine the Level of Service (LOS) at several freeway segments per the Highway Capacity Manual--HCM2000 (*6*). Caltrans and the California Air Resources Board (ARB) are conducting chase car studies to derive speed correction factors to be incorporated into their emission factors for air quality analysis. This process involves recording vehicle speeds at selected freeway segments along with the prevailing operating conditions (LOS) as perceived by the observers. However, it is required to obtain LOS designations based on the actual operating conditions at each test segment.

The database included over 37 hours of chase car speed data collected in 250 segments in Los Angeles. The determination of the segments LOS using PeMS was done as follows:

- Match test segments with PeMS database
- Extract loop data (counts, speed, occupancies) from the loop detectors per segment
- Aggregate the data per segment per 15 minutes and compute the segment density (vpm/l)
- Determine the segment LOS per HCM2000 (basic freeway sections)

Currently, the effort is continuing using PeMS to identify and select test freeway sections with specific LOS to collect additional chase car data.

## PeMS APPLICATION 4: INCIDENT IMPACTS

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

Figure 6A shows the average speed vs. distance of 10 miles of freeway at 11:00 am. Traffic is free flowing at an average speed of about 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 occurred blocking three out of four travel lanes on the freeway. Figure 6B shows that the average speed drops to about 5 mph at the incident location. The incident lasted about 2.5 hours. Figure 6C shows the vehicle speeds at 2:00 pm shortly after the incident was cleared. The congestion has reached five miles upstream of the incident location. Normal operating conditions on the freeway resumed at 3:10 pm, 1.5 hrs following the incident removal (Figure 6D).

Further analysis of the PeMS data revealed the following regarding the incident impacts:

> **Remaining capacity**: The discharge rate of vehicles past the incident location on the single travel lane was very low (about 300 vph) the first 10 minutes of the incident. The discharge rate then increased to about 1,400 vph 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, it was observed that the queued vehicles discharged past the incident location at a rate of 7,400 vph, which is lower than the nominal capacity of the freeway section (8,000-8,400 vph).

## PeMS APPLICATION 5: ASSESSMENT OF ATMIS STRATEGIES

Caltrans and other agencies nationwide have started to deploy Advanced Traffic Management and Information Systems (ATMIS) to manage freeway congestion. Examples include ramp metering, changeable message signs, and incident detection. The most important question to answer is: By how much can ATMIS reduce congestion? PeMS can help answer this question.

Congestion may be measured by Caltrans' definition of *delay (when freeway speeds fall below 35 mph)*, or 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-405 from 5.00 to 10.00 am on 6/1/98.

The top curve in Figure 7 shows the actual VHT per 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 demand-shift eliminated queues at ramps. 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 is then the area between the topmost and lowest curves. The delay due to the excess demand can only be reduced through temporal, spatial or modal demand-shifting. 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.

## DISCUSSION

Significant investments in ITS infrastructure are underway in California and in most metropolitan areas in the US to manage traffic congestion. Central to this infrastructure is a surveillance system that gathers real-time information from detectors on the state of the system and transmits to TMCs. However, in many cases the surveillance data are simply being archived and they are not analyzed to assist in operational analyses or calculate performance measures. PeMS is a unique data archival, processing and analysis system that allows access to the data and calculates performance measures.

PeMS is based on a modular and open software architecture. Currently, it stores data from over 4500 loop detectors in California. All the data are available on line. Users access PeMS through the Internet. PeMS is easy to use; built-in applications are accessed through a Web browser. Custom applications can work directly with the database. There is no need for special access to the agency's TMC data storage, writing scripts to access the database, or requesting off-site archived historical data.

The paper presented a number of case studies to demonstrate how PeMS can be used in operations, planning and research studies. PeMS brings large benefits. It maximizes the utility of the information from surveillance systems, and minimizes the effort and costs of performing studies through traditional data collection methods. Managers can instantaneously obtain a uniform, and comprehensive assessment of the performance of their freeways. Traffic engineers can base their operational decisions on knowledge of the current state of the freeway network, and determine whether bottlenecks can be alleviated by design or operational improvements. PeMS can serve to guide and assess deployment of ITS.

Caltrans engineers using PeMS are performing several other operations studies. These include analysis of peaking characteristics (midday and weekend peak), traffic patterns during special events, historical comparisons, planned lane closures, and CHP special programs on congestion management. Some of the ongoing collaborative work between Caltrans and the research team on PeMS includes:

**Recurrent vs. non-recurrent congestion:** Previous widely cited studies suggest that over 50 percent of freeway congestion is incident related (*7,8*). These studies are based on limited empirical data on freeway operating conditions and several simplifying assumptions on incident frequency, severity and impacts. Previous extensive field studies by the research team (*9,10*) developed a comprehensive data base on incident characteristics, and showed that only a fraction of the reported incidents causes delay. The example PeMS application described in the previous section demonstrated on how to evaluate the incident impacts based on real life data. Work is underway to estimate the amount of incident related vs. recurring congestion using the PeMS database and the incident data collected from the CHP.

**Simulation models application, calibration and validation:** simulation models are increasingly being used to analyze existing operations and evaluate the effectiveness of alternative scenarios. The critical questions regarding the practical application of simulation models are:

- Does the model accurately predict the existing bottleneck location(s) and impacts in the study section?
- Are the benefits from the simulated design/control improvements significant?

First, accurate input data are needed on design, demand and control characteristics, and proper calibration of the model parameters. The PeMS database provides the input data (traffic volumes, link lengths, number of lanes, detector locations) and the performance measures to assess the model accuracy in replicating existing conditions. Contour plots of speed and occupancy can be compared with the model results to verify that the model correctly identifies bottleneck locations. The PeMS flow/occupancy or speed/flow plots at selected locations can be used to adjust the model parameters (free flow speed, capacity or minimum headways) to better match field conditions. Other performance measures produced by PeMS (average speeds, delays, VMT or VHT) can be compared with the simulation outputs to assess the models' accuracy in replicating observed operating conditions.

The second question relates on how the variability in operating conditions affects the confidence of the predicted benefits from the testing of alternative scenarios (e.g., is the predicted 2 percent improvement significant?). This has not been investigated in past simulation studies, because the data were collected during a single day. PeMS can be used to readily assess the variability in the input data and performance measures for the study section over a long period of time. Figure 8 shows the distribution of travel times for a 22 mile section of I-405 in Orange County, California, during the am peak for a typical incident-free weekday during 1998. In this example, it would be really hard to determine that small predicted improvements are significant.

Currently, we are analyzing a section of a 10 mile section of I-210 freeway using the FREQ macroscopic simulation model (*11*), and a 15 mile section of I-10 freeway using the PARAMICS microscopic simulator (*12*). A key objective of this work is to automate the input/output data between PeMS and simulation models in order to minimize the effort for the models' application.

**Performance Measures:** It is widely recognized that planning and operational decisions should be based on the transportation system performance measures. PeMS' premise has been to produce performance measures that are based on real data that can be easily understood by the system manager (VMT, VHT) and the system user (travel time). PeMS also provides travel time reliability measures (Figure 8) which is perceived to be of high importance by travelers. Work is continuing to expand the built-in PeMS applications to produce performance measures for planning applications including areawide performance indicators and growth trends.

The usefulness of the PeMS system depends on the loop detector data accuracy. Detector failures result in lost and unreliable data. PeMS includes a set of diagnostics to check the incoming loop data for accuracy and reliability. It also provides information on the number of data samples received daily and spatial/temporal data dropouts. In addition, PeMS includes procedures to "fix" data holes at a location based on information from adjacent detector stations as appropriate. However, there is no substitute for accurate data and any agency installing and operating freeway surveillance systems which are primarily designed for real-time operating strategies must have a plan for intensive maintenance of the field and communications equipment.

**ACKNOWLEDGEMENTS**

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## LIST OF FIGURES


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

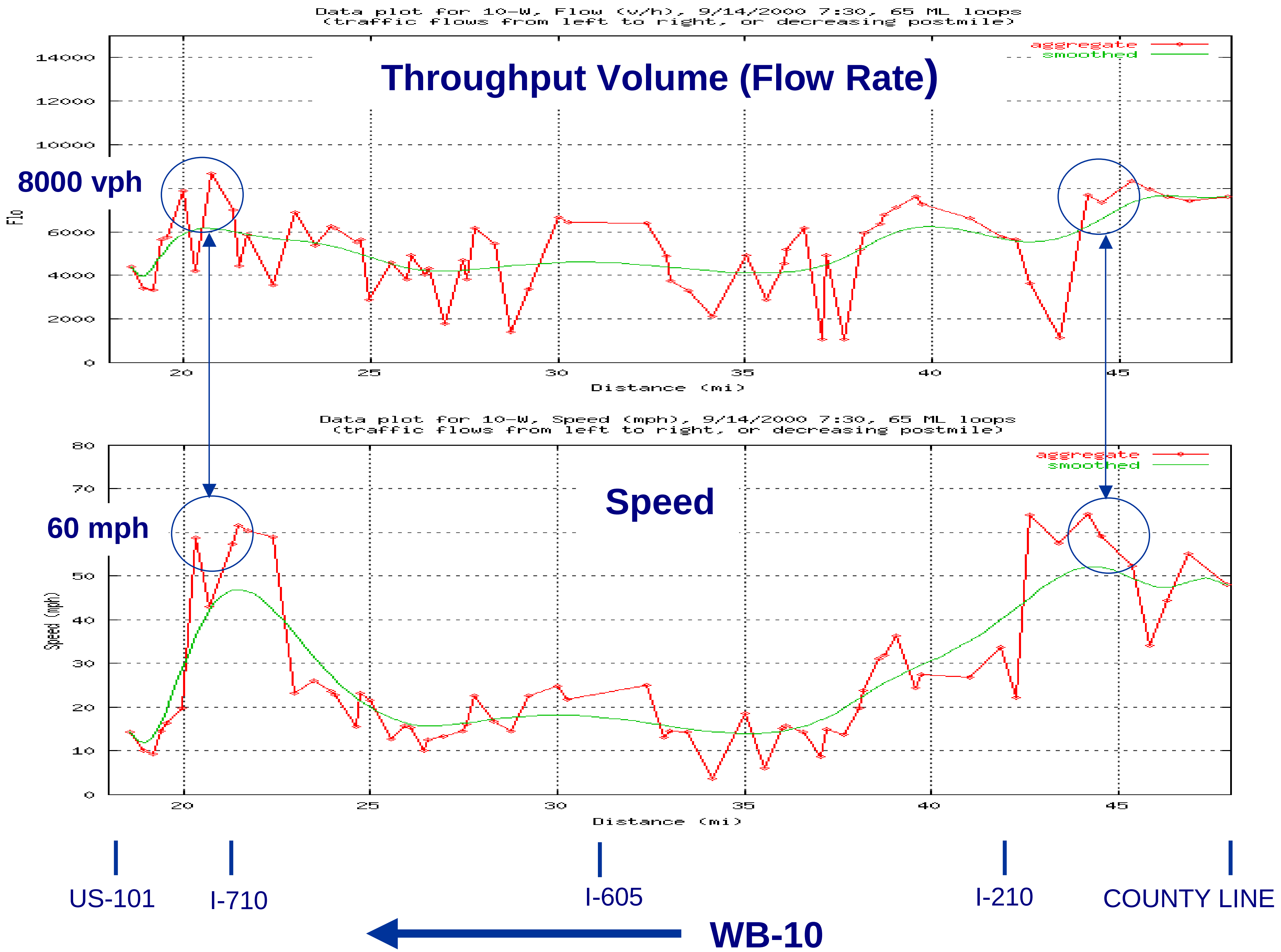



**Figure 2. Flow and Speed along WB I-10, 7:30 am, 9/14/2000**

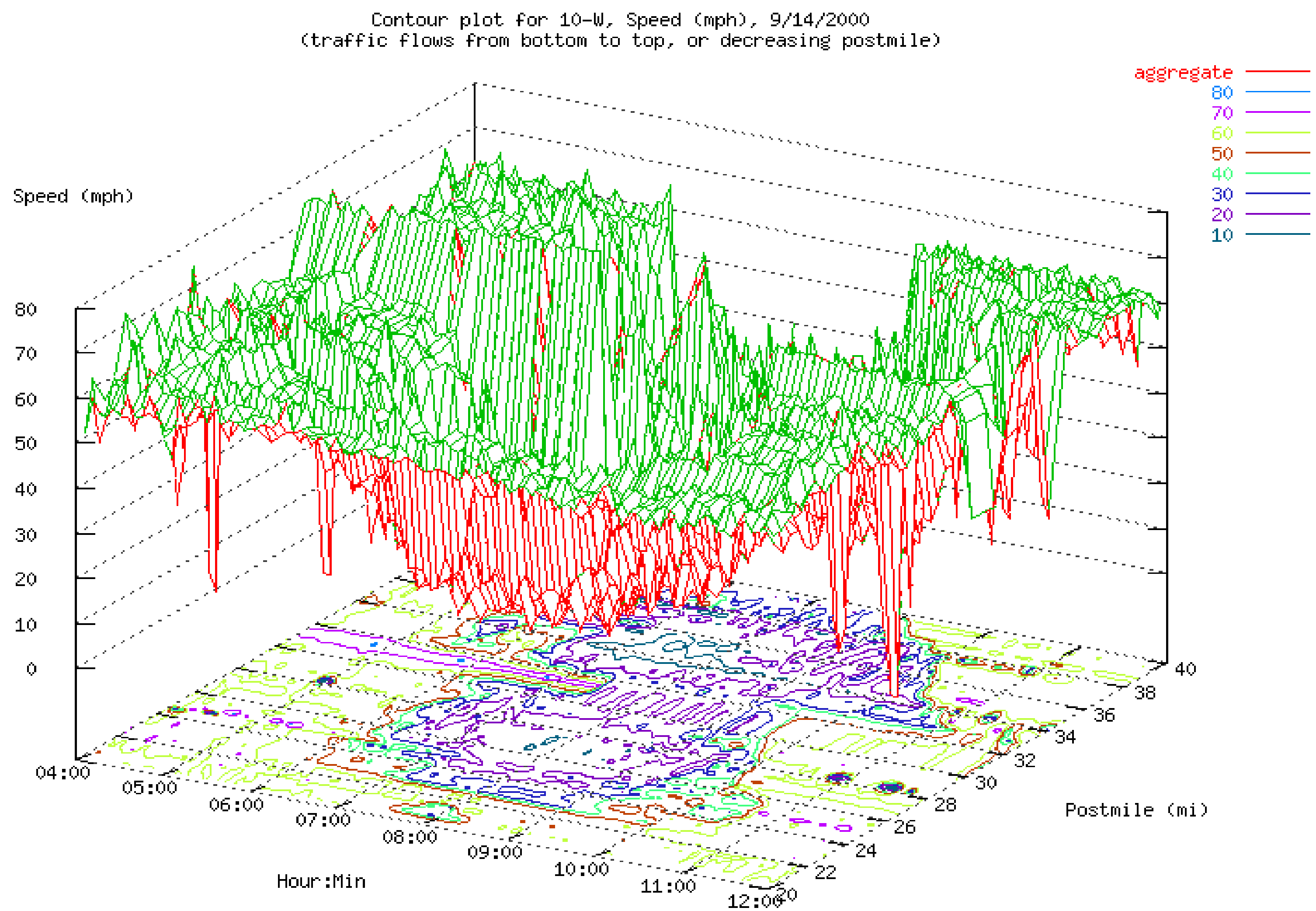



**Figure 3. Speed Contour Plot (WB I-10)**

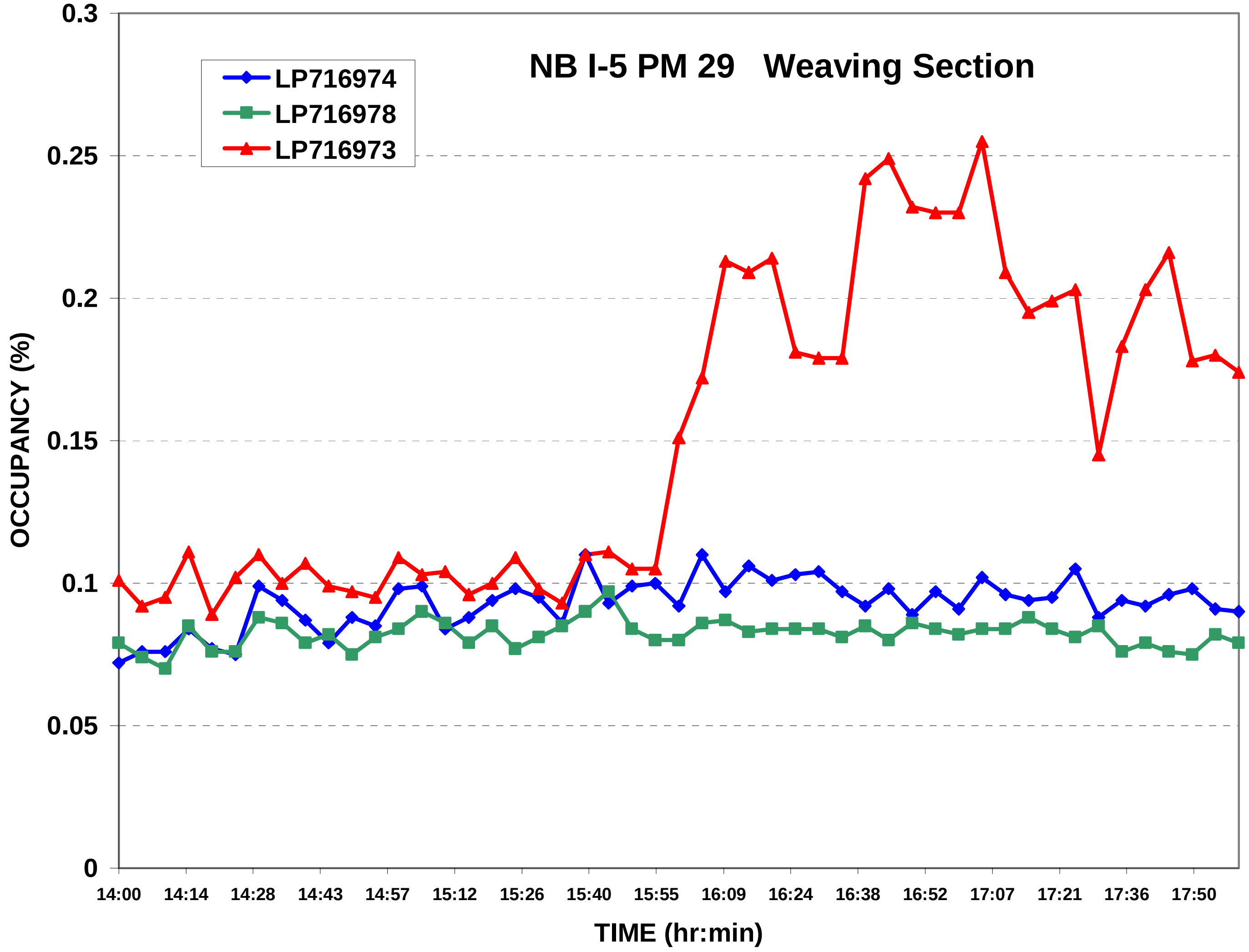
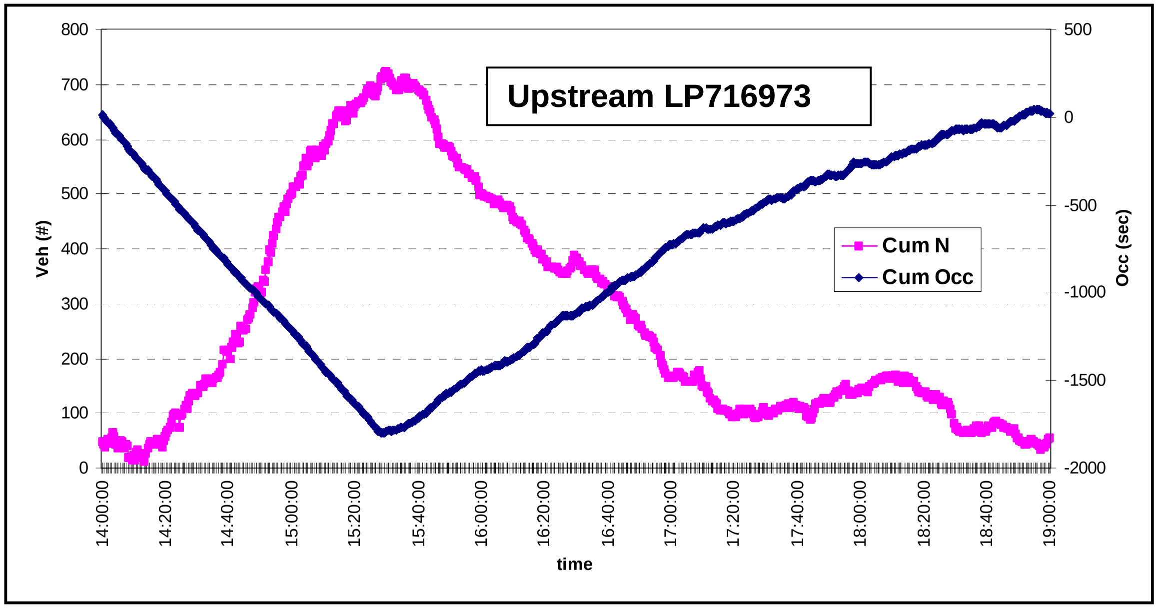



**Figure 4. Detector Occupancy vs. Time**



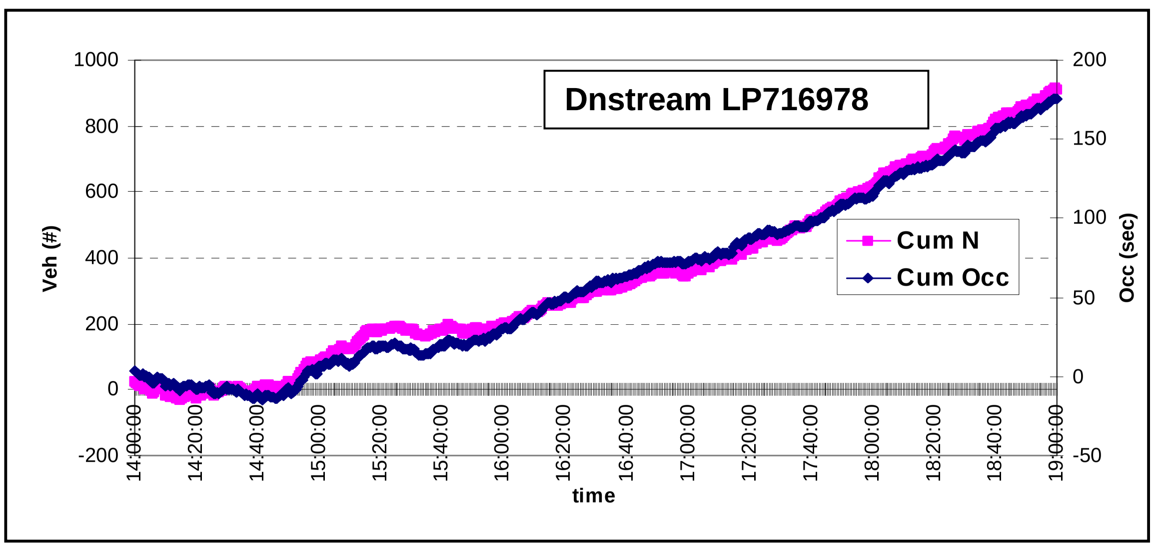




**Figure 5. Cumulative Count and Occupancy Plots**

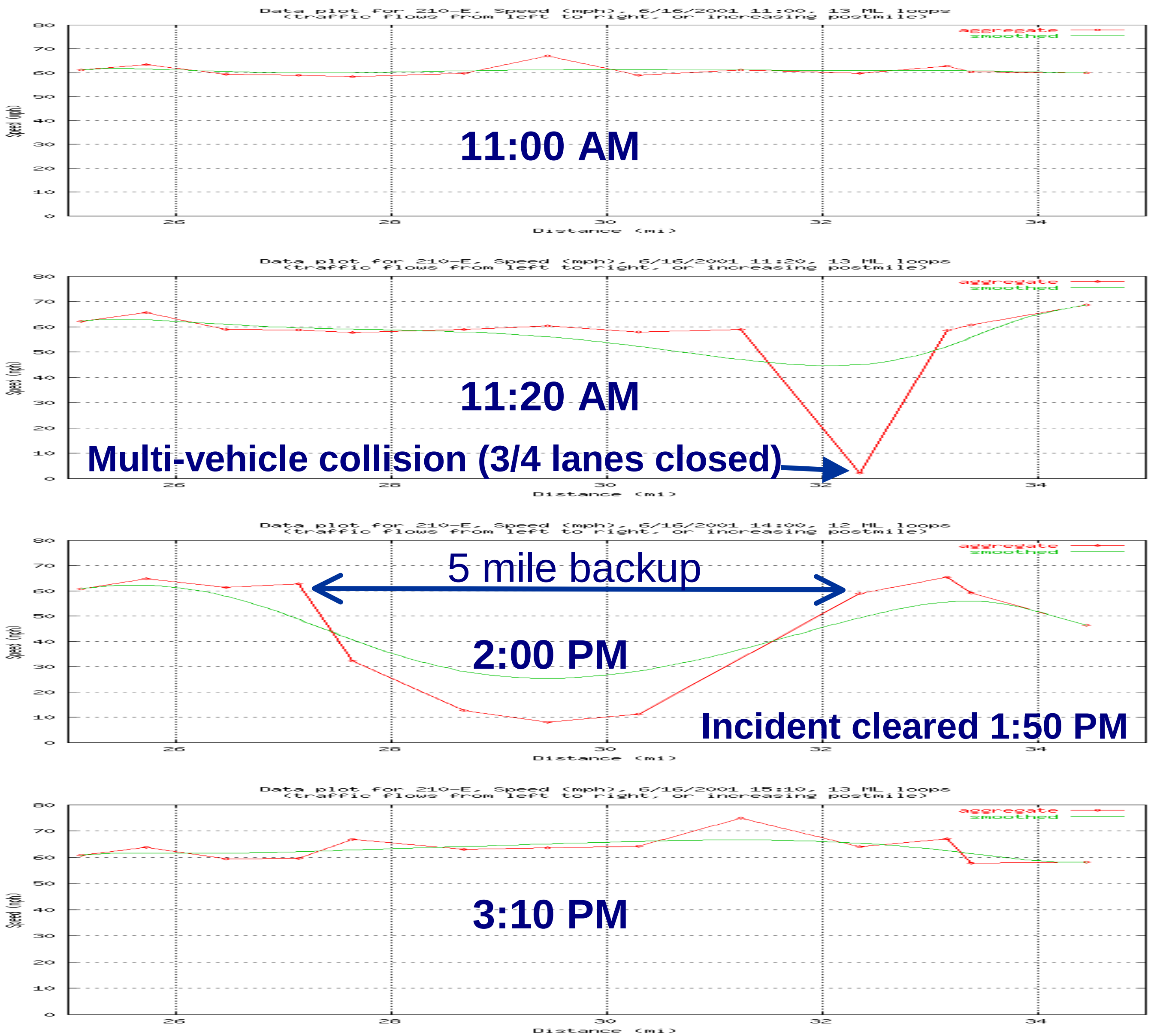



**Figure 6. Incident Impacts: EB I-210 Saturday 6/16/2001**

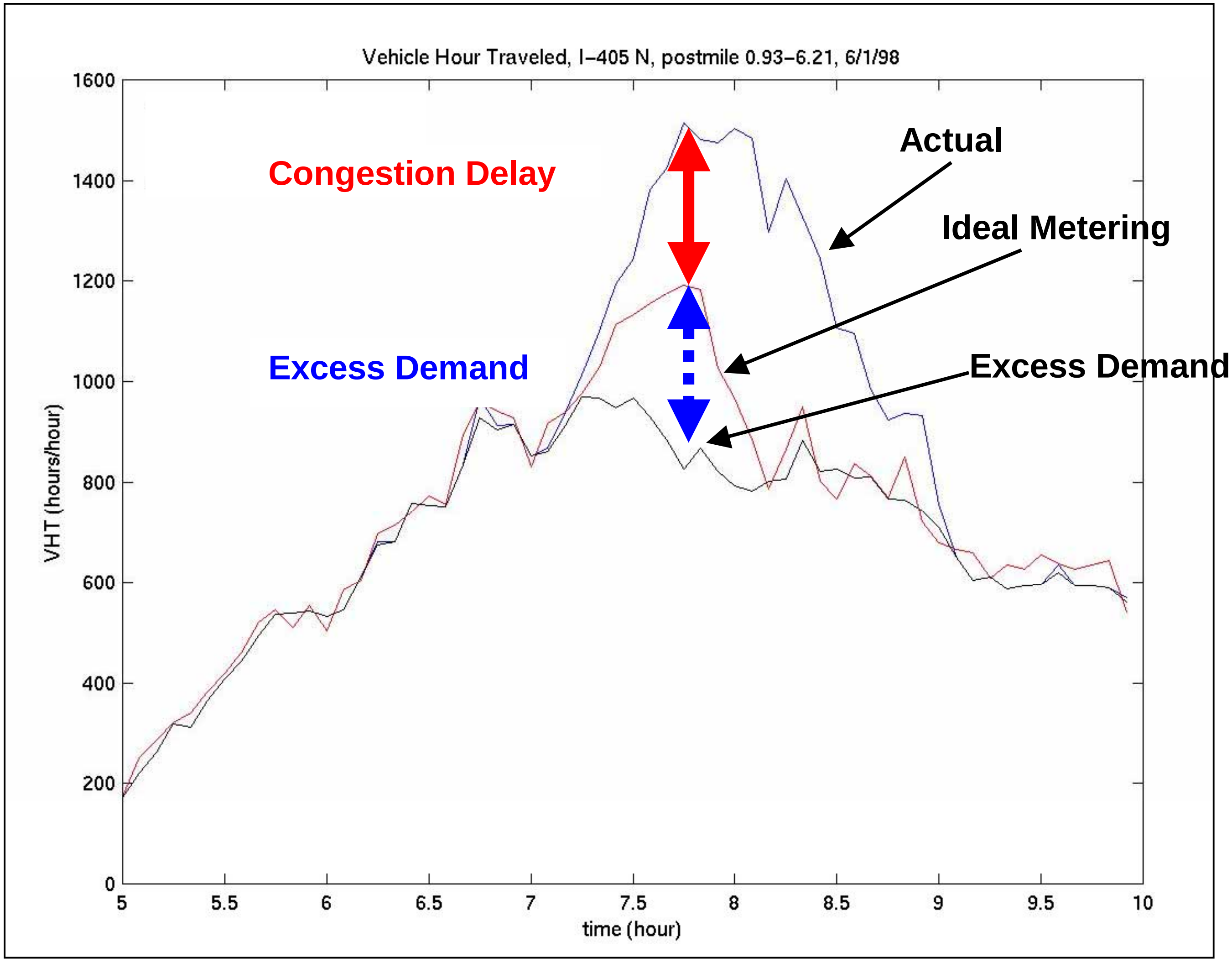



**Figure 7. Veh-Hours Traveled (VHT) Under Different Scenarios**

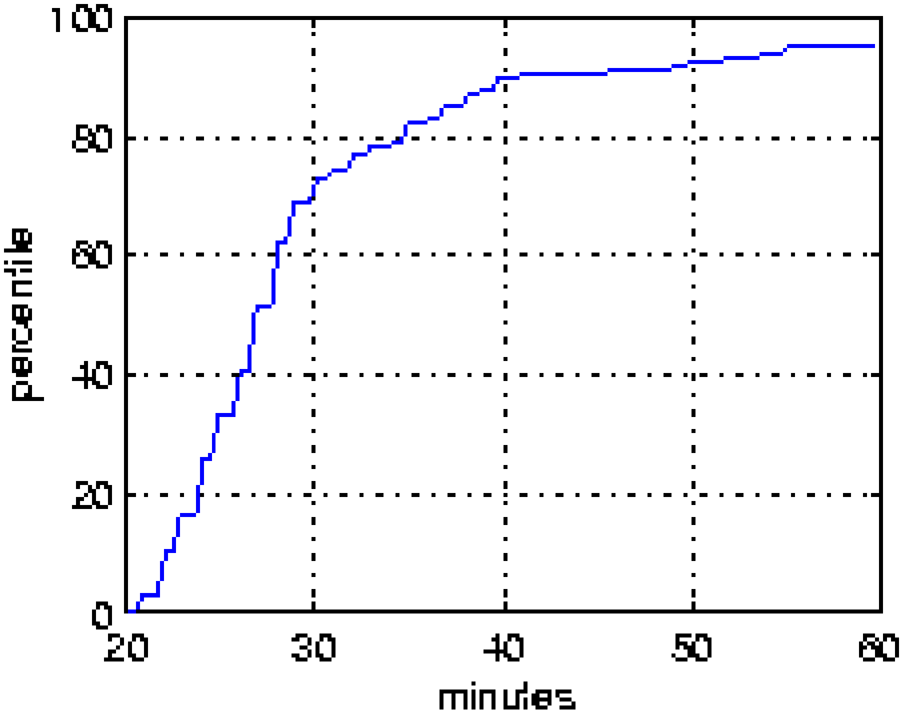



**Figure 8. Distribution of travel times on I-405N in Orange County, CA. 8-9 am on Tuesdays in 1998. Mean Travel Time=31.5 min.**