

FREEWAY PERFORMANCE MEASUREMENT SYSTEM: MINING LOOP DETECTOR DATA

Chao Chen

Department of Electrical Engineering and Computer Science
University of California, Berkeley CA 94720
Tel: (510) 643-5886, Fax: (510) 642-6330
Chaos@eecs.berkeley.edu

Karl Petty

Department of Electrical Engineering and Computer Science
University of California, Berkeley CA 94720
Tel: (510) 649-6001, Fax: (510) 642-6330
pettyk@eecs.berkeley.edu

Alexander Skabardonis*

Institute of Transportation Studies
University of California, Berkeley CA 94720-
Tel: (510) 642-9166, Fax: (510) 642-1246
dromeas@uclink4.berkeley.edu

Pravin Varaiya

University of California, Berkeley CA 94720
Department of Electrical Engineering and Computer Science
Tel: (510) 642-5270, Fax: (510) 642-6330
varaiya@eecs.berkeley.edu

Zhanfeng Jia

Department of Electrical Engineering and Computer Science
University of California, Berkeley CA 94720
Tel: (510) 643-5886, Fax: (510) 642-6330
jia@eecs.berkeley.edu

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**Corresponding Author*

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.

PeMS is a low-cost system. It uses the Caltrans network for data acquisition. It is easy to deploy and maintain. It takes under six weeks to bring a Caltrans district online. Functionality can be added incrementally. PeMS applications are accessed over the World Wide Web. Custom applications can work directly with the PeMS database. PeMS has been in stable operation for 18 months. Built as a prototype, PeMS can be transitioned into a 7x24 production system. The paper describes the PeMS architecture and use.

INTRODUCTION

Caltrans (California Department of Transportation) needs a freeway performance measurement system that extracts information from real time and historical data. *PeMS* (*Performance Measurement System*) is such a system. It presents information in various forms to assist managers, traffic engineers, planners, freeway users, researchers, and value added resellers or VARs (VARs are businesses that package travel time information with other location-dependent services.)

PeMS obtains 30-second loop detector data in real time. Caltrans is divided into 12 districts; together they generate 2 gigabytes (GB) of data each day. District 7, Los Angeles, accounts for 1 GB. The PeMS database currently has 400 GB of data online.

PeMS is a low-cost system. It uses commercial-of-the-shelf products for communication and computation. Detector data are retrieved over the Caltrans ATM wide area network to which all districts are connected. The 45 Mbps link connecting PeMS to this network costs \$2000/month. The PeMS computer is a four-processor SUN 450 workstation with 1GB of RAM and 1 terabyte of disk. It uses a standard Oracle database for storage and retrieval.

The PeMS software architecture is modular and open. A new district can be added online with six person-weeks of effort, with no disruption of the district's TMC (Traffic Management Center). Data from new loops can be incorporated as they are deployed. New applications are added as need arises. PeMS has been in stable operation for 18 months. Although it is a prototype, it can serve as the blueprint for a 7x24 production system. A copy of PeMS would cost less than \$300,000. A part-time database administrator maintains PeMS.

PeMS is easy to use; built-in applications are accessed through a Web browser. Custom applications can work directly with the database. PeMS brings large benefits. 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 remainder of the paper is organized as follows. The next section summarizes the communication and software architecture. The following section describes PeMS applications. The last section collects some concluding observations.

PEMS ARCHITECTURE

Figure 1 shows the communication architecture. The PeMS computer, *transacct*, is located in the University of California at Berkeley. Users access PeMS over the Internet. *Transacct* also has a 45 Mbps link to the Caltrans ATM wide area network (WAN). The WAN is used to transfer data from districts to PeMS.

An individual Caltrans district is connected to PeMS over a permanent ATM virtual circuit. To establish such a circuit the routing tables at the two ends must be configured. The configuration is done remotely from Caltrans Headquarters in Sacramento.

A district TMC and PeMS collect data as follows. A “front end processor (FEP)” at the TMC receives data from freeway loops every 30 seconds. The FEP formats these data and writes them into the TMC database as well as into the PeMS database.

PeMS maintains a separate instance of the database for each district. Although the table formats vary slightly across districts, they are stored in PeMS in a uniform way, so the same software works for all districts.

The software is organized in three layers. At the bottom is database administration. The work is standard but highly specialized: disk management, crash recovery, table configuration. Many parameters must be tuned to improve database performance. A part-time Oracle database administrator is necessary.

The top layer comprises applications that are described in the next section. The middle layer comprises software that works on the data as they arrive in real time. It

- Aggregates 30-second values of flow 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. At this point, PeMS has flow, occupancy, speed, and travel time for each 5-minute interval for each detector station (one station typically serves the detectors in all the lanes at one location);
- Computes the basic performance measures.

Most detectors in California have single loops that report two numbers every 30 seconds: *flow* or the number of vehicles that crossed the loop, and *occupancy* or the average fraction of time a vehicle is present over the loop. The formula to calculate speed is

$$speed = g \times flow / occupancy.$$

The “*g*-factor” depends on both the actual vehicle length, which varies by lane and over the course of a day, and the loop’s electrical circuit, which varies randomly across loops.

Districts typically assume a constant value of g . The assumption leads to errors in speed estimates of 100 percent or more. PeMS uses an adaptive algorithm that tracks the g -factor of each loop separately to provide accurate speed estimates.

The 5-minute averages concern individual links. A *link* is a section of freeway that holds a single loop detector. PeMS computes these performance measures for each link: delay, VMT, VHT, and travel time. *Delay* (d) over a link during a 5-minute interval is

$$d = \text{length} \times \text{flow} \times [1/\text{speed} - 1/V].^+$$

Here *length* is link length. (In California, detectors are placed one-third to one-half mile apart.) V is the target speed (35 mph in California). Speed below V is considered congestion, so delay is the additional vehicle-hours spent due to congestion. (In the formula above, $x^+ = \max(x, 0)$).

$$VMT = \text{flow} \times \text{length}, VHT = VMT/\text{speed}, \text{ and } Q = VMT/VHT.$$

VHT is the number of vehicle-hours spent by travelers (over a five-minute interval) on that link, and *VMT* is the number of vehicle-miles they have traversed. Thus *VHT* is the input of the link (vehicle-hours per 5 minutes) and *VMT* is the link output (vehicle-miles per 5 minutes). The ratio, $Q = VMT/VHT$, is the vehicle-miles-weighted speed or *productivity* of the link during a single 5-minute interval. (See Figure 2).

Observe that it makes sense to add up *VMT* and *VHT* over any set of links (for example, one freeway) and time periods (for example, one day). The ratio, Q , is the productivity of that freeway on that day. Comparing Q over different days, or on the same day in different weeks, gives a quick summary of changes in freeway performance. Lastly, the *Travel Time* over a link starting at the beginning of a 5-minute interval is

$$\text{Travel Time} = \text{length}/\text{speed}.$$

Here *length* is length of a link and *speed* is the estimated speed. The travel time over a route is estimated by adding the travel times over the links constituting the route. (More sophisticated estimates are being investigated.)

USES OF PEMS

Users run various applications through their Web browsers. Authorized users may directly query the database and develop custom applications. The following scenarios illustrate the use of PeMS by transportation managers, traffic engineers, travelers, VARs, and researchers.

Managers

It is a truism that “If you can’t tell how your system performed yesterday, you can’t expect to manage it today.” A manager pulls up PeMS on her Web browser to compare the performance of her district’s freeways with previous days. Figure 2 displays the daily productivity, Q , for the 23-mile northbound direction of I-405 freeway (405N) in District 12, Orange County, for the period 5/1/98 to 5/20/98. The manager observes that on 5/8/98 and 5/12/98, the average vehicle-mile-weighted speed or Q fell below 30 mph. She could initiate an inquiry whenever Q fell below, say, 30 mph. She also could compare the performance of other freeways in her district, and allocate resources towards improving the worst performers.

Engineer

In response to the manager’s inquiry, the engineer asks PeMS to display a contour plot of speed for the 24-hour period of 5/12/98 over the 23-miles of 405N. From that plot, which is too intricate to reproduce well here, the engineer observes four areas of congestion. Two of these occur in the morning and two in the evening commute hours. Figure 3 shows one of these, a 4-mile stretch from post mile 1 to 5, beginning at 6.30 am and ending at 9.30 am. Looking at plots of other days, the engineer verifies that all four are areas of recurrent congestion, although 5/12/98 is worse than usual. The plot of Figure 3 near post mile 1 is anomalous. Contour plots on other days at the same location reveals the same anomaly. The engineer uses PeMS to verify that the loop detectors at this location are not working properly. He sends a request to the loop maintenance crew to investigate the detector station.

PeMS creates a map of the entire freeway network for each 5-minute interval in which each link is colored according to speed or any of the other computed averages (see Figure 4). An “animation” application plays back these maps in sequence over any time interval. The engineer can use this application to visualize the behavior of the network on 5/12/98. The animation makes vivid how congestion starts and spreads. (New staff members can use the animation to quickly get a “feel” for the district’s traffic patterns.)

Traveler

TV and radio reports of freeway conditions are spotty (“there is a three-car accident on 405N at Edwards”). You can’t use the reports to estimate the shortest travel time and route for your trip. No one today provides such travel time estimates and shortest routes. PeMS provides these. You bring up the district freeway map on your Web browser, and select an origin and destination. PeMS decorates the map with two shortest routes, depending on whether or not you can use the High Occupancy Vehicle (HOV) lanes, and a caption containing the corresponding travel times. Figure 4 is an example. In this instance, the caption states that the HOV route in Figure 4 is 23.0 miles long and takes 22 minutes. The non-HOV route is also 23.0 miles long but it takes 59 minutes.

Often you want to know the travel time you would face, say, 30 minutes from now. The upper chart of Figure 5 is the empirical distribution of travel times over the 23-mile stretch of 405N for trips that started at 8:30 am on any Tuesday of 1998. This distribution says that with 90 percent probability you will reach your destination within 50 minutes. However, if you know that a trip that started at 8.00 took less than 27.5 minutes, you can reduce the

prediction to 40 minutes (middle chart). But, if you know that the earlier trip took more than 37.5 minutes, you should plan on taking 55 minutes (lower chart). Thus appropriately combining historical and current trip times reduces uncertainty in future trip time.

VARs—Value Added Resellers (Travel Information Service Providers)

If you were stuck on a freeway, you would want to know how long your trip will take, whether you should call in late for your appointment, or cancel it altogether. You could one day access PeMS with your cell phone to find out. A VAR that provides this service could also send you alerts during your trip if the traffic situation changed so that your trip will take, say, 20 minutes longer than was estimated when you began your trip. PeMS has developed such a prototype for a Web-enabled cell phone.

Planner/Researcher

Congestion imposes a burden on many Californians. Reliable estimates are not available, but the monetary value of time wasted in congestion is surely in the millions of dollars each day. The state cannot afford to build additional freeways to relieve congestion. It must improve the productivity of its freeways through the use of Information Technology (IT). The most important question to answer is: By how much can IT reduce congestion? PeMS can help answer this question.

Congestion may be measured by Caltrans' definition of *Delay*, or by using VHT and VMT. For a particular freeway call this *Delay_total*. Traffic theory allows us to decompose the delay in two parts:

$$Delay_total = Delay_congestion + Delay_demand.$$

The first component, *Delay_congestion*, is the result of congestion that reduces freeway throughput to less than capacity. In principle, this delay can be completely eliminated by ramp-metering that maintains throughput at the freeway capacity. Assume this is done. There remains the second component, *Delay_demand*. This is caused by travel demand in excess of freeway capacity. Only demand shifting can reduce that delay. 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 origination time (or travel mode) would then do so.

We can use PeMS to analyze delay for any section of freeway. Figures 6 and 7 summarize the analysis of a 6.3-mile stretch of 405N from 5.00 to 10.00 am on 6/1/98. Figure 6 plots VMT vs. VHT. Each point is a pair of numbers (VHT, VMT) corresponding to a five-minute interval. VHT is the number of vehicle-hours spent per five minutes during a particular 5-minute interval and VMT is the vehicle-miles traveled per five minutes in the same interval. In the figure VHT is expressed in vehicle-hours per hour and VMT in vehicle-miles per hour. There are 60 points in all for the five-hour interval; the points corresponding to 7.15, 7.30, 8.00, 8.30 and 9.00 are marked. At 5.00 am VHT= 160 and VMT = 10000, corresponding to an average speed of 62.5 mph. Average speed remains constant while the throughput measured in VMT increases until 7.15 am when the VMT reaches its maximum value of 58000. (This arguably should be called the capacity of this stretch of freeway.)

From 7.15 to 7.30, VMT remains at capacity but VHT increases by 20 percent from 1000 to 1200. So the density on the freeway has increased and the speed has dropped by 20 percent: queues are building up on the freeway. Between 7.30 and 8.00 flow has collapsed; VMT is 48000 (16 percent below capacity), and VHT has increased to 1550, giving an average speed of 30 mph. The situation recovers one hour later at 9.00 am. At that time VMT is well below capacity indicating that demand has to drop significantly below capacity before speed recovers.

With PeMS you could observe this congestion develop in real time. Appropriate ramp-metering strategy would throttle the inflow at the beginning of the congestion period (when throughput reaches capacity, at 7.15 am in this case). In principle, the reduction in throughput, and the corresponding *Delay_congestion* could be eliminated.

The uppermost plot in Figure 7 is the actual VHT per 5 minutes on this section from 5 am to 10 am. The middle plot gives the VHT the *same* vehicles would spend if perfect metering maintained throughput at capacity. The lowest plot is the VHT that would result if demand-shift eliminated queues at ramps. The area between the topmost and middle curves is the first component, *Delay_congestion*; the area between the middle and lowest curve is *Delay_demand*. So the area between the topmost and lowest curves is *Delay_total*. An inspection of Figure 6 suggests that for this example *Delay_congestion* \approx 500 vehicle-hours and *Delay_demand* \approx 200 vehicle-hours.

CONCLUSIONS

California's citizens and businesses face increased freeway congestion. The cost in time, money, stress, and pollution is large. Caltrans is planning to deploy ITS technology to relieve congestion. But these plans are debated, revised, and launched in analytical darkness. No one knows how well the freeways are operated, what targets for operations improvement are realistic, and how those targets might be achieved.

For example, Caltrans publishes congestion measures of daily vehicle-hours of delay. To estimate this delay, cars equipped with computers that record speed and distance are driven along each section of congested freeways, during commute periods, twice a year. A glance at Figure 2 shows there is a huge daily variation in delay, so that congestion measured this way is a random number. It is unsurprising that Caltrans does not use these estimates to formulate congestion reduction goals or to guide capital improvements.

Caltrans is evolving a strategy for ITS deployment, founded on a performance evaluation system. This system would help managers, planners, and engineers accurately estimate current performance; discover locations where improvements are likely to be most effective; evaluate in advance the benefits of suggested investments (ramp-metering, changeable message signs, freeway service polls, etc); and, after those investments are made, measure the resulting benefits. Such a system should be part of the daily operations, just as production, cost, sales and revenue figures are essential in the daily operations of a private corporation. PeMS can be a key element of the Caltrans performance evaluation system.

ACKNOWLEDGEMENTS

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The contents of this paper reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views of or policy of the California Department of Transportation. This paper does not constitute a standard, specification or regulation.

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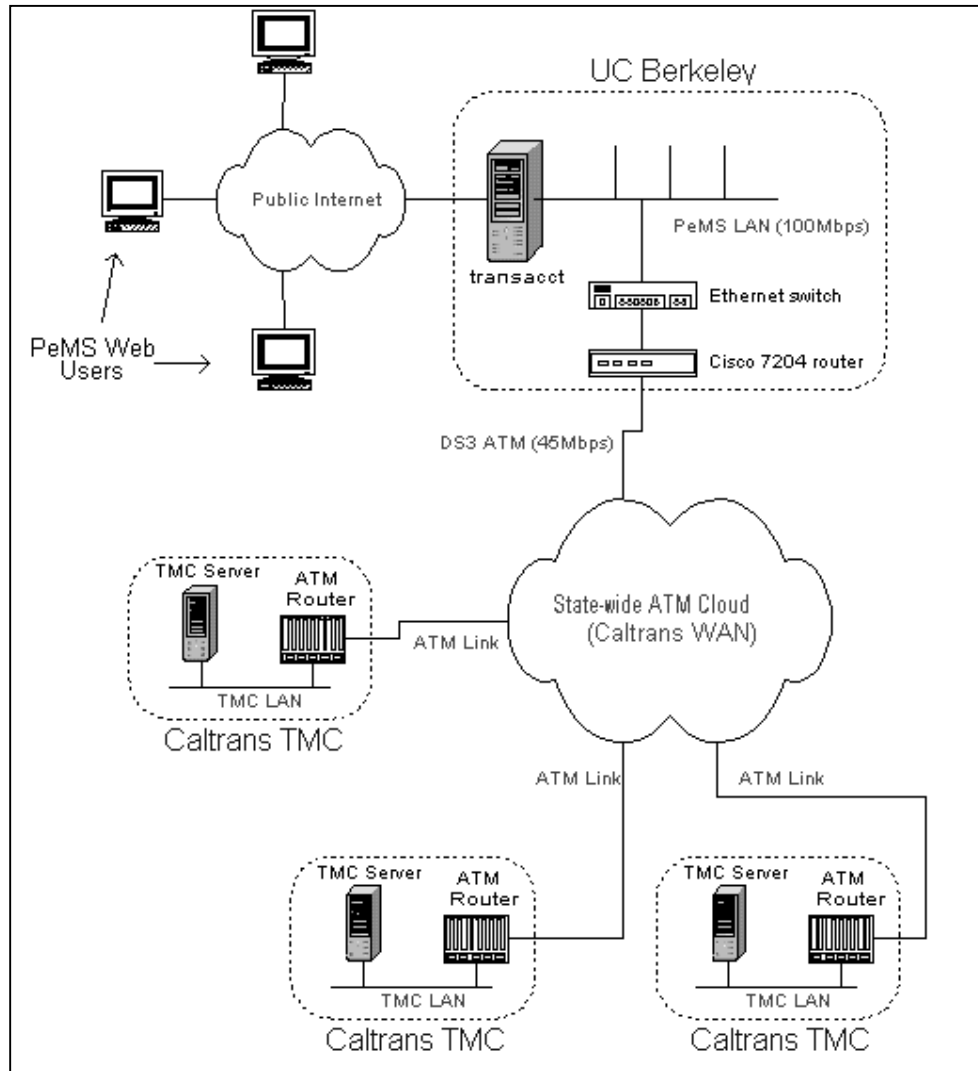


FIGURE 1. PeMS Communication Architecture

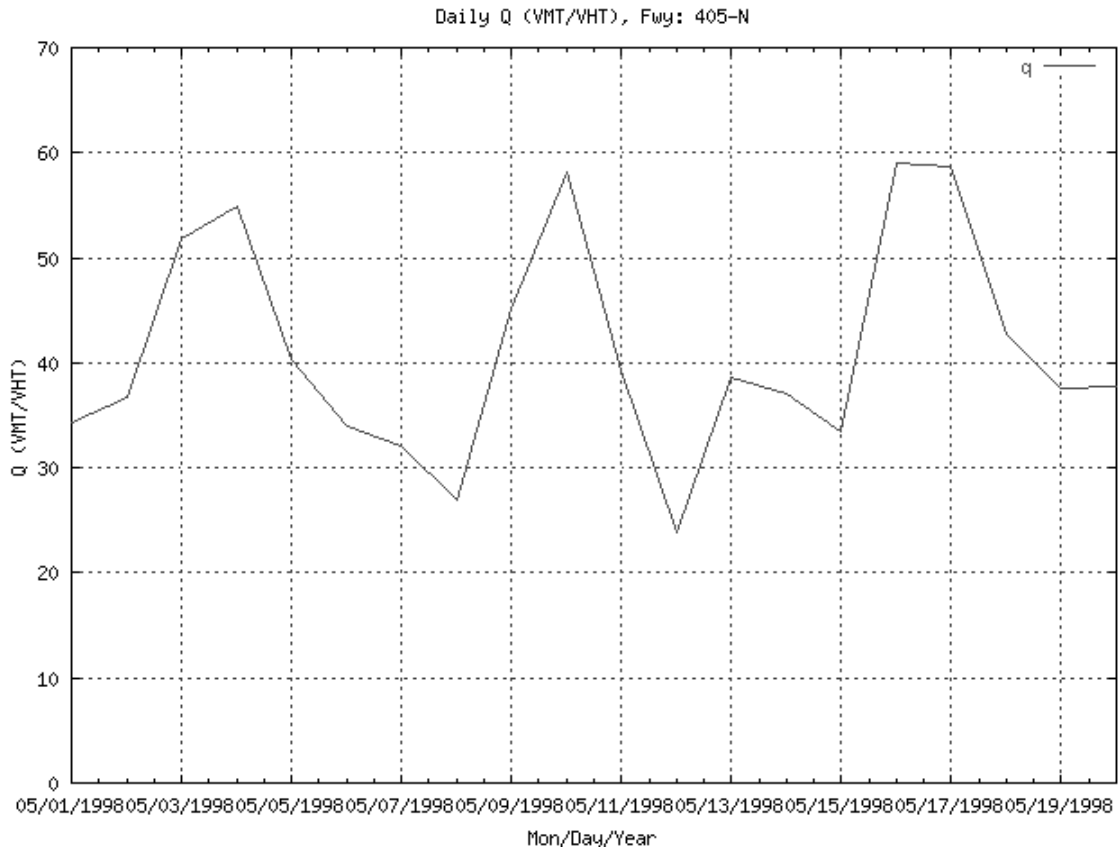


FIGURE 2. Daily Q for I-405N from 5/1/98 to 5/20/98

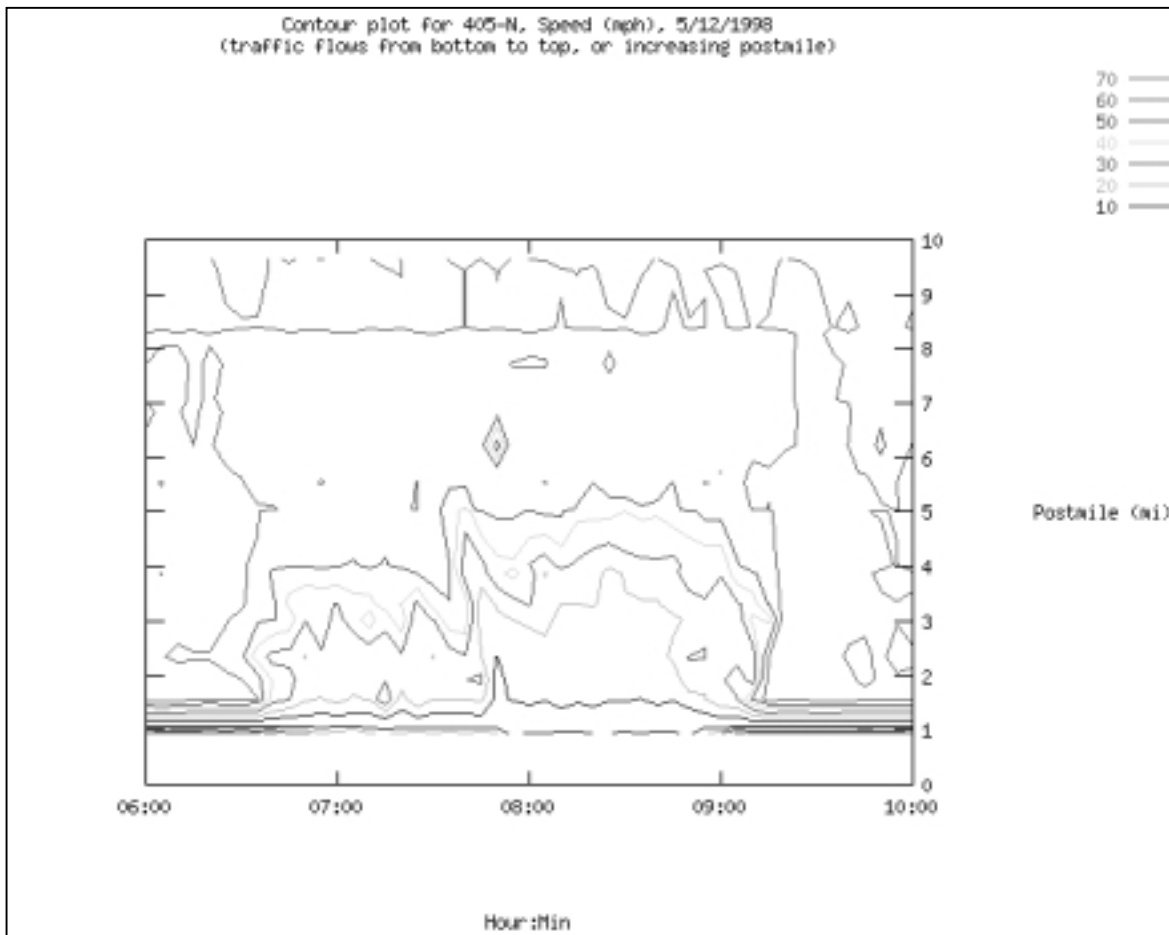


FIGURE 3. Speed Contour Plot along 10 miles of I-405N—6:00 to 10:00 am, 5/12/98

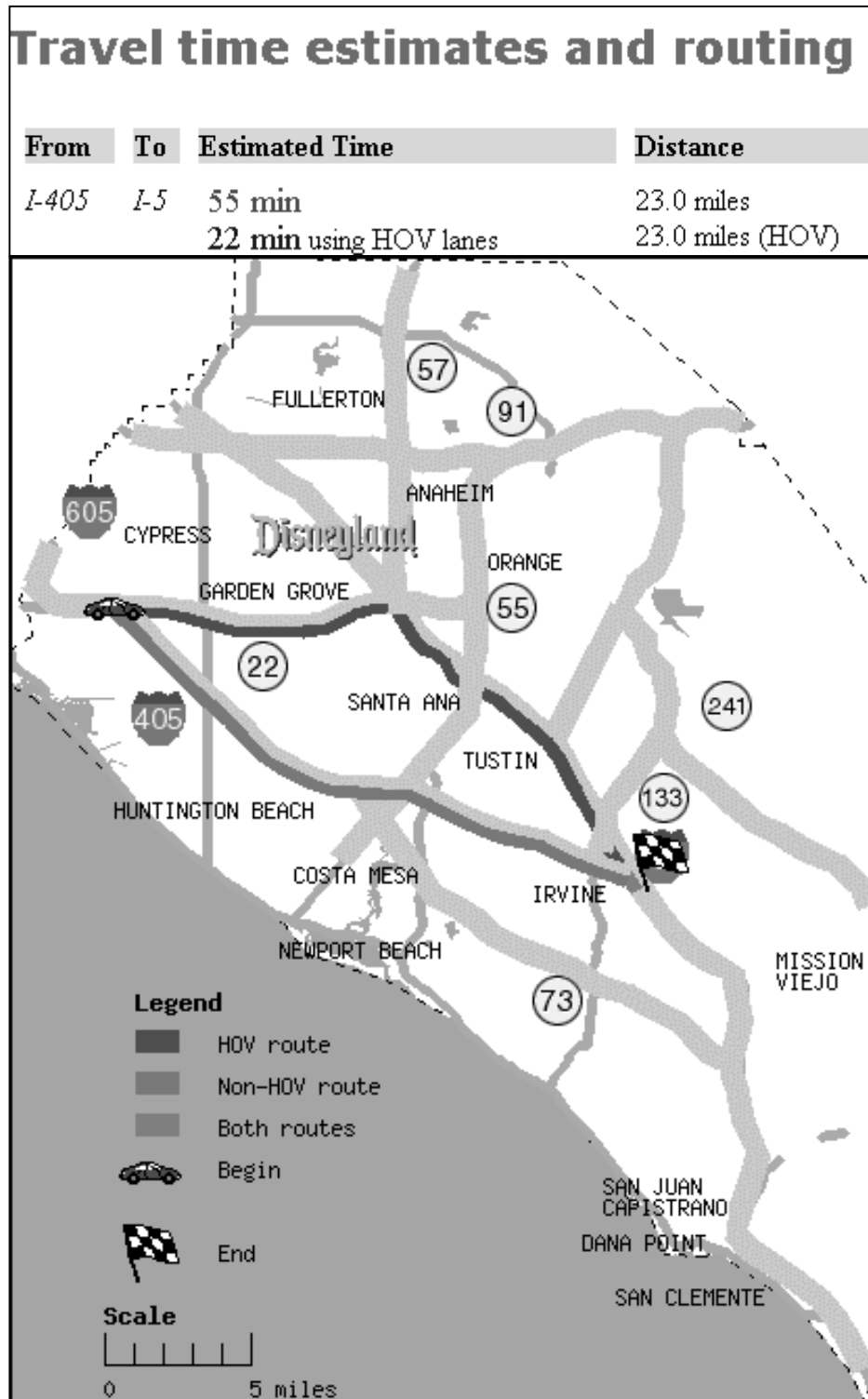


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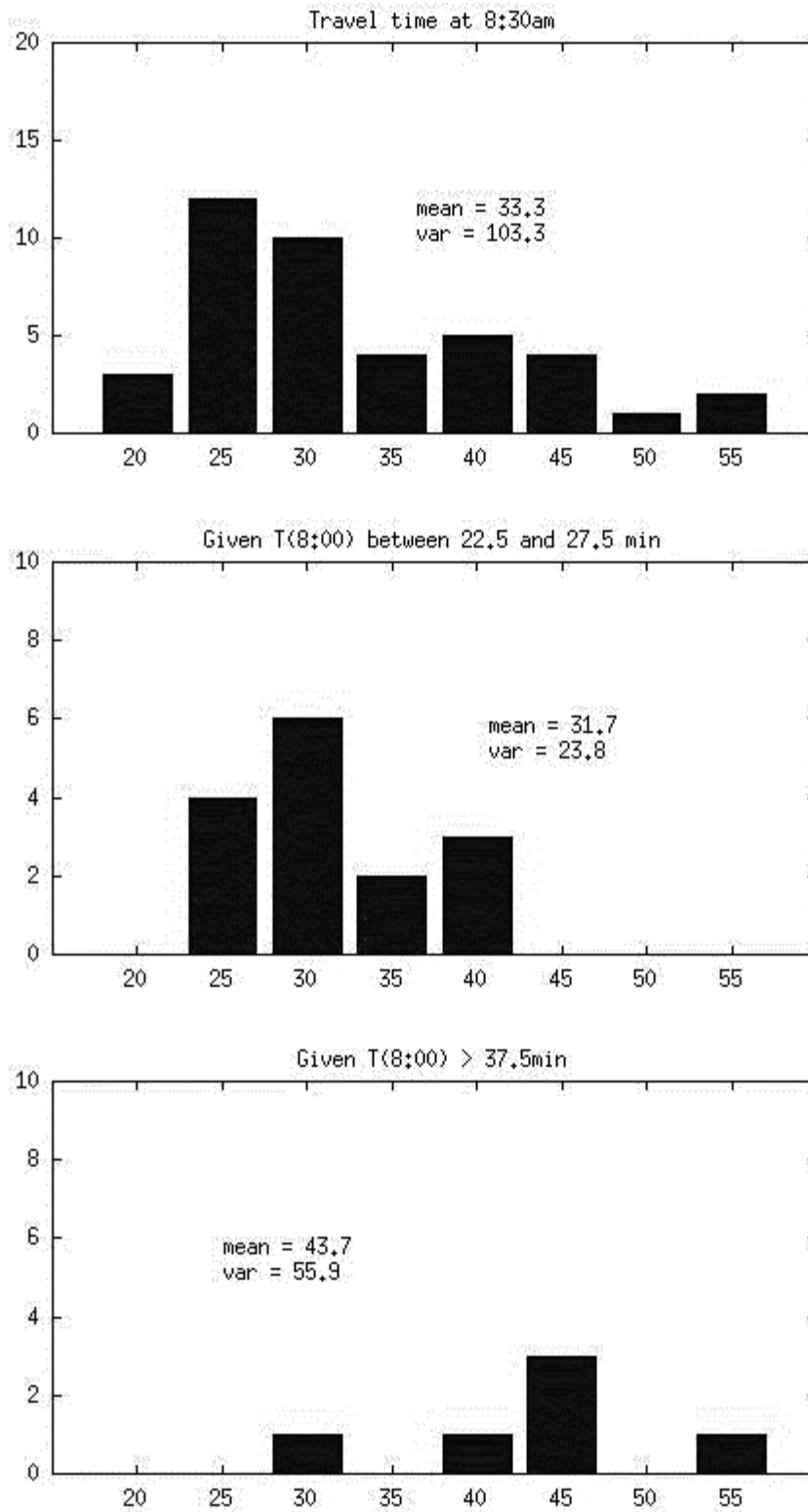


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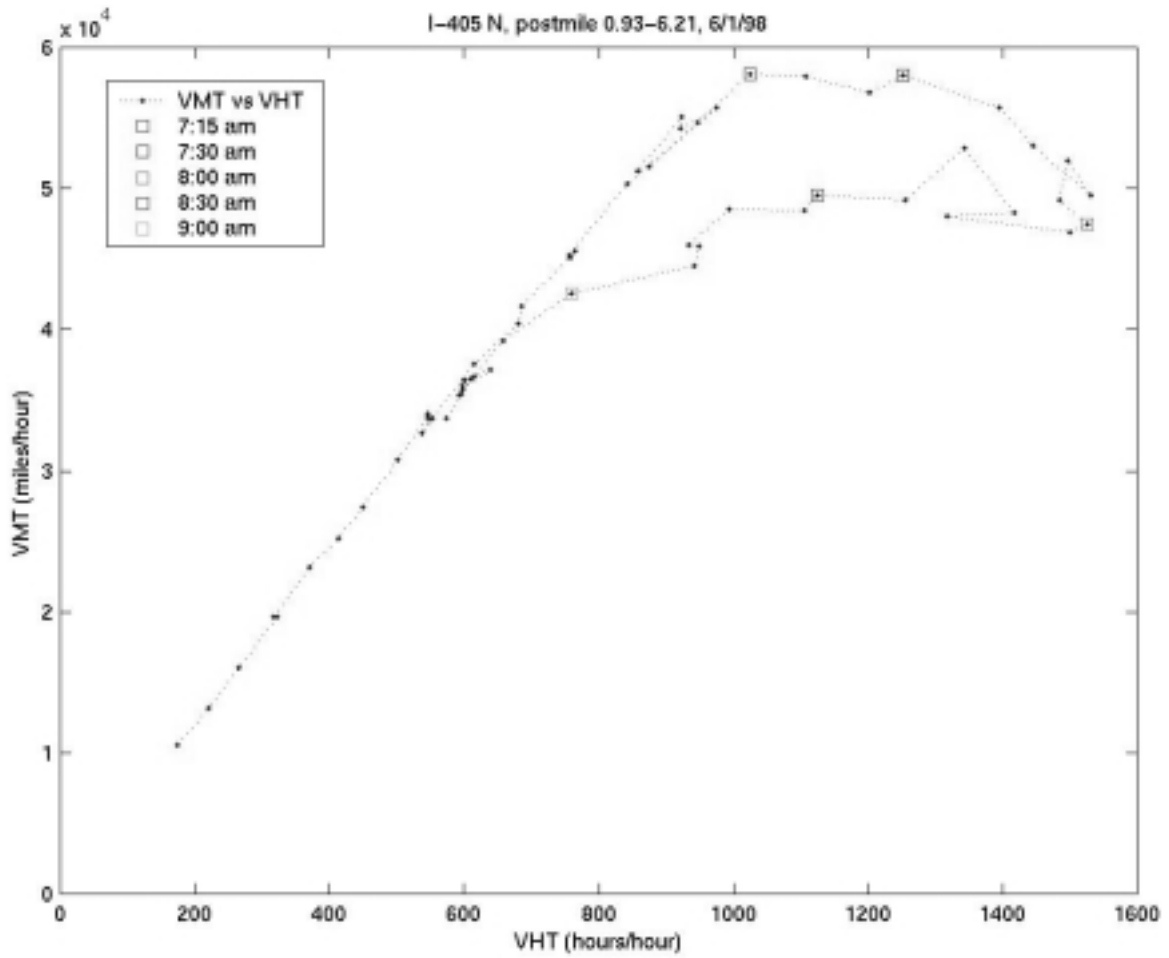


FIGURE 6. VMT vs. VHT on a 6.3- mile section of I-405N—5:00 to 10:00 am

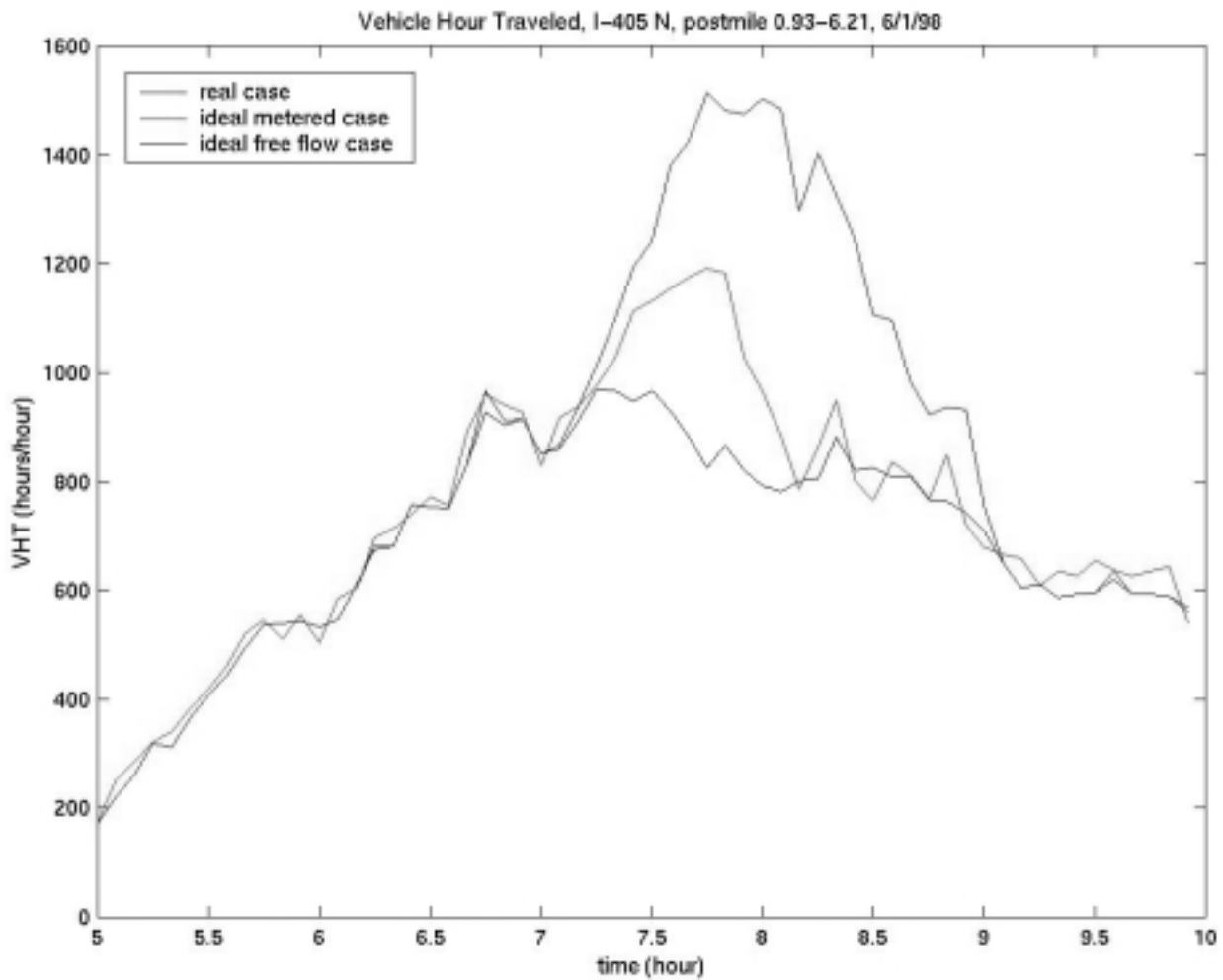


FIGURE 7. Vehicles-hours (VHT) actually traveled (upper plot), the VHT under ideal ramp metering (middle plot), and the VHT under ideal ramp metering and demand shift.