TECHNIQUES FOR EVALUATING THE PERFORMANCE OF PRE-TIMED RAMP METERS USING ARCHIVED ITS DATA

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ABSTRACT

Pre-Timed Ramp Metering (PRM) is a traffic management technique. The Oregon Department of Transportation (ODOT) currently operates a comprehensive Advanced Traffic Management System (ATMS). ATMS collects data from various sources and archives it for later usage. In this paper we demonstrate several techniques for measuring and assessing the performance of Portland, Oregon's existing PRM system. These techniques can help departments of transportation (DOTs) in locations where PRM has been applied to measure the performance of their systems. This type of analysis uses data that are already being collected as part of an overall Intelligent Transportation System (ITS) deployment.

INTRODUCTION

Intelligent transportation systems (ITS) include the application of information and communication technologies to increase safety and enhance mobility on the existing transportation system. Current ITS deployments include concepts that have existed for many years, but that are now enhanced by the existence of increased computing power and more ubiquitous high speed communication networks (*1, 2, 3*). Increasing ITS deployments have made a revolutionary difference in traffic and transportation management due to the ability to archive transportation data. These data, if carefully managed and extracted, can be used to evaluate the implementation of new and existing operational and planning strategies at relatively low cost. In recognition of the need to provide feedback to decision-makers, transportation operators, and planners, efforts are underway to provide rigorous documentation of ITS benefits and costs. This can be done through the evaluation of the performance of the existing system to ensure that future actions will make the system efficient, effective, equitable and sustainable.

Pre-Timed Ramp Metering (PRM) is a traffic management techniques that was implemented in the 1960's (*4*). In this paper we will demonstrate several techniques for measuring and assessing the performance of an existing PRM system using archived ITS data obtained from several sources. Through this type of analysis, using data that are already being collected as part of an overall ITS traffic management system, DOTs can test different operational strategies in order to improve performance along the corridors where PRM is implemented.

DATA

The Oregon Department of Transportation (ODOT) currently operates a comprehensive Advanced Traffic Management System (ATMS), including 60 closed circuit television (CCTV) cameras, 16 variable message signs, an extensive fiber optics communications system and 90 PRMs, including approximately 400 inductive loop detectors on freeway mainlines and on-ramps. These detectors collect vehicle count, occupancy and average speed at 20-second intervals. In addition to a number of system expansion and integration projects, the PRM system in particular is undergoing a major renaissance with the incorporation of the System Wide Area Ramp Metering (SWARM) system over the next several years. ODOT currently archives their loop detector data at a 15-minute level of aggregation.

To date, this study has involved collection of loop detector and video data from the Interstate 5/Barbur Blvd. corridor, which provides access into downtown Portland from the south. With a parallel arterial, complicated freeway geometry and major transit lines, this corridor provides an opportunity to analyze the existing performance of the ramp metering system before the planned SWARM improvements are made. Figure 1 is a map of the study corridor, showing detector stations 1 (Haines St.) through 6 (Terwilliger/Bertha Blvd.) on northbound I-5. We will use this corridor as a case study to demonstrate the techniques used for evaluating the PRM system. Further, Figure 2 shows a functional diagram of the study corridor, depicting the lane geometry and on- and off-ramp locations along the freeway. In addition to high-resolution loop detector data, probe vehicles equipped with automated vehicle location (AVL) systems were dispatched along the same corridor to collect information regarding the characteristics of the freeway.

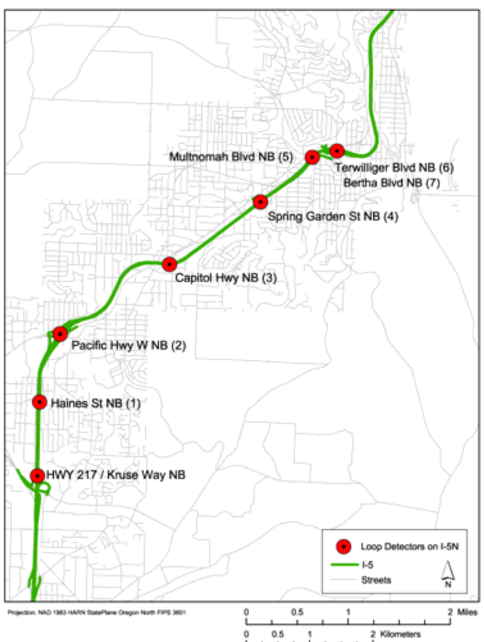


Figure 1. Interstate 5 with Loop Detectors Locations

Figure 2. Schematic Diagram of the Study Corridor

RAMP METERING

Ramp metering is a common freeway management technique and has been implemented in many cities around the world. It is not controversy in some locations but is one of ten key strategies recently identified for mitigating freeway congestion with advanced technologies (*5*). At their most basic level, ramp meters are traffic signals located at on-ramps to control the flow of vehicles from the ramp onto the freeway (*6*). Based on a pre-defined or variable signal cycle, vehicles are allowed to enter the freeway at a rate of one vehicle per green. The definition of the rate is determined through the knowledge of the freeway capacity and the demand of the on-ramps. Ramp meters are currently present in more than thirty cities worldwide with more than 3,000 ramps being metered every day (*4*). Metering strategies are often debated, but one primary premise behind the deployment of ramp meters is to regulate the flow of vehicles onto the freeway since vehicles often arrive at an on-ramp in platoons after being discharged from traffic signals on the local street. In addition, ramp meters are often employed in an attempt to prevent freeway flows from reaching capacity or breakdown levels, with the notion that it is "better" to maintain freeways flowing freely while asking entering vehicles to wait their turn. If the demand exceeds capacity on a freeway, congestion occurs, with its negative effect on the environment, energy consumption and vehicle delay.

There are three primary approaches to ramp metering: pre-timed (PRM), local traffic responsive and coordinated traffic responsive. PRM systems are designed based on an analysis of historical traffic flow patterns along the corridor and a quantification of the demand for the use of the freeway. The major disadvantage of this metering system is that it does not respond to changing conditions on the freeway due to daily and seasonal dynamics in traffic flow or due to incidents (*4*). The local traffic responsive ramp control is the second system. Traffic flow conditions are obtained online from detectors in the vicinity of an individual ramp. Based on this information a particular timing plan is applied to the ramp. The primary advantage to local traffic responsive systems is that it is simple. However, these systems do not allow for coordination between adjacent ramps along a corridor. This can cause problems during incidents because timing decisions are based on the flow measured at one isolated location and not on optimizing the flow of the overall system. The coordinated traffic responsive metering system can be considered the best choice, while also being the most expensive and sophisticated. Metering plans are developed and altered based on real-time traffic conditions along the corridor with the idea of attempting to avoid reaching some capacity threshold. The traffic flow data are usually transmitted to the transportation management center (TMC) where an algorithm is applied in order to develop optimal meter timing based on simple objective functions. The hope is that the dynamic metering strategy can be responsive to incidents and day to day variations in traffic flow. If drivers sense that traffic control is being applied rationally, they will be less likely to violate the control system and are more likely to be supportive of the traffic management system as a whole.

BENEFITS OF RAMP METERING

A recent study was conducted in Minneapolis, Minnesota to evaluate the benefits of their ramp metering system. The meters were shut down for several weeks and a before and after analysis was performed. The study found that during the peak periods, freeway mainline throughput declined by an average of 14% without the ramp meters and travel time increased by more than 25,000 (annualized) hours. In addition, it was determined that crash frequency increased by 26% after the meters were shut off (*6*).

It would be difficult to apply a similar study in other cities due to the undesirable side effects that would accompany the shut down and re-deployment of the ramp meters. However, to perform a pure "before and after" evaluation, to estimate the actual benefits of a ramp metering system, would require collecting data both with and without the ramp metering system in operation. A major public complaint about ramp meters occurs when drivers find themselves waiting in queues to access a freely flowing freeway; this will be discussed later.

ANALYSIS TECHNIQUES

In this section we will discuss the process used to quantify the existing conditions of the freeway corridor using several sources of ITS data. Next, we will demonstrate how to assess the performance of the Portland PRM system based on an understanding of traffic conditions and how the freeway system is operating. Finally, we will demonstrate several techniques for examining how we can test potential changes to the existing PRM timing plans in order to improve overall corridor performance.

UNDERSTANDING FREEWAY OPERATIONS

A first step in the process of measuring the performance of the PRM is to understand the characteristics of the freeway which is being studied, knowing where the bottlenecks are and understanding the causes of delay. It is well-known that a freeway bottleneck is a location upstream of which there is queued traffic and downstream of which there is freely-flowing traffic (*7*). Common examples of bottlenecks are busy on-ramps and merge sections, busy off-ramps that may back up onto the mainline, weaving areas, and geometric changes such as horizontal and vertical curves or tunnel entrances.

There are several ways to identify freeway bottlenecks—including the use of probe vehicles equipped with an AVL system and the use of inductive loop detectors installed on the freeway mainline. During the morning peak period of July, 9 2002, a probe vehicle was dispatched along the study corridor while ODOT was simultaneously archiving high resolution loop detector data. The probe vehicle's AVL system uses GPS technology and records time, longitude, and latitude every 3 seconds. The distance traveled and speed dynamics can be determined from the AVL data at a high degree of accuracy. The probe vehicle's run time was between 6:00 and 9:00 am, and the vehicle traversed 6 northbound runs during this period. On this day the PRM system in the corridor began operating at 6:45 am and concluded its operation at approximately 8:30 am. Each ramp has its own timing plan that was defined by ODOT traffic management center staff.

The study concentrates on the northbound morning peak period when the PRM is in operation on the freeway on-ramps. The probe vehicle also collected data on southbound runs, which was archived for future research. The probe vehicle analysis is shown in Figure 3, where the trajectories of the probe vehicle's six runs are plotted geographically on the freeway with speed illustrated according to the legend shown in grayscale. As shown, the darker the color of the point indicates the slower that the vehicle was traveling on the freeway. As indicated by the dark cluster, a bottleneck appeared to occur near the Terwilliger/Bertha Blvd. on-ramps (milepost 297.33). This bottleneck impacted the rest of the corridor, as a queue formed and propagated upstream as shown in the figure. During the first two runs a small decrease in speed was noticed around the curve. The traffic slowed more dramatically during the third run but still was in a free flow mode. During the 4th and 5th runs the queue had formed and the bottleneck was active. The queue had propagated upstream to the Pacific Hwy on-ramp (milepost 293.74) and a second slowdown occurred at Capitol Hwy (milepost 295.18). Finally, during the 6th run the queue had begun to dissipate, as shown in the figure, and the second slowdown was now visible upstream of the Capitol Hwy on- ramp. The secondary slowdown occurred when the queue from the Terwilliger/Bertha Blvd. bottleneck reached the lane drop from 6 lanes at the on-ramp of Pacific Hwy to 3 lanes approximately 0.86 miles north of the on-ramp. Based on this analysis, the traffic flow in the study corridor appears to depend on the capacity of the freeway at the Terwilliger/Bertha Blvd. curve.

Magnifying the location around the Terwilliger/Bertha Blvd on-ramps to display where the vehicle speed dropped and where it increased will enable us to more closely identify the location of the freeway bottleneck and determine whether the bottleneck occurred upstream or downstream of the on-ramp. Figure 4 shows the locations where the probe vehicle speed dropped during each run and where the probe vehicle began to accelerate. As shown in the range between milepost 297.25 to milepost 297.80. The bottleneck may have moved slightly figure, the locations differ from run to run, indicating that the bottleneck is located in the

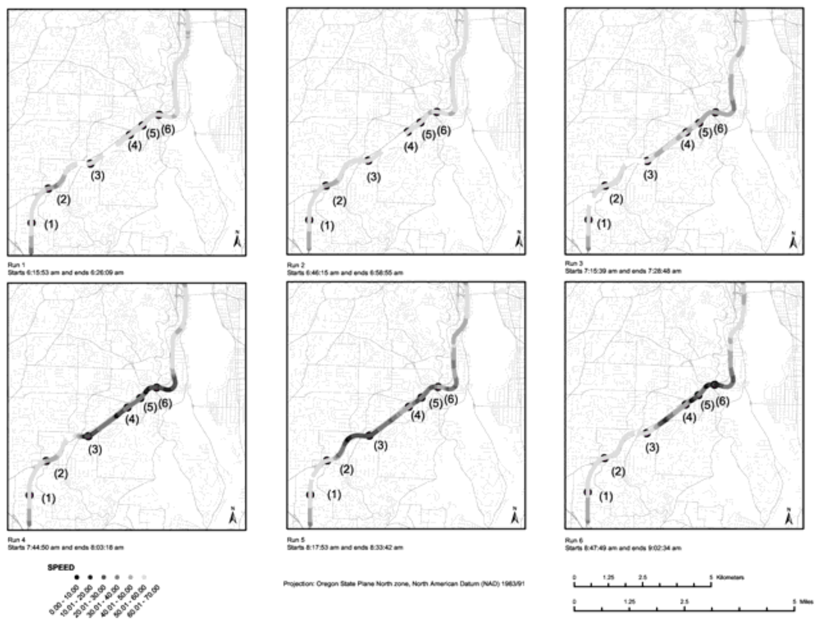


Figure 3. Runs Represented Geographically with the Speed Displayed in Grayscale

vicinity of the Terwilliger/Bertha Blvd. curve but appeared to remain downstream of the on-ramp. The probe vehicle consistently began its acceleration after it passed the horizontal curve (note that there are vertical grade changes in this area also). This confirms that the ramp meter design for upstream on-ramps will be based upon the mainline flow measured downstream of the Terwilleger Blvd. on-ramp. Since the bottleneck's location was tentatively identified from the probe vehicle data, the next step is to determine the time at which this bottleneck became active and to measure its discharge flow. This can be done using the archived loop detector data for the same site on the same day. In order to promote the visual identification of time-dependant features of the traffic stream, oblique curves of cumulative vehicle count (*N(x,t)*), curves of cumulative time-mean velocity (*V(x,t)*) and curves of cumulative occupancy (*T(x,t)*) were constructed using the archived loop detector data. These cumulative curves provide the measurement resolution necessary to observe the transitions from freely-flowing to queued conditions and to identify a number of notable time-dependant traffic features in and around the bottleneck (*8, 9, 10, 11*).

Figure 5 shows oblique *V(x,t)* for stations 3, 4, 5, and 6. As shown in Figure 3, the queue did not propagate to stations 1 and 2 during the morning peak period. The speed decreased at station 6 at 7:11 am, and at station 5, the speed reduction is visible a short time later, at 7:12 am. Further, the queue reached station 4 at 7:24 am. The effects of queueing upstream of the bottleneck ended at approximately 8:44 as recorded at station 3. The queue then dissipated over the next 27 minutes, when the impacts diminished at station 6 at approximately 9:11:20 am. The oblique *V(x,t)* highlight the time during which the bottleneck was active.

The next step is to estimate the capacity of the freeway section at station 6. This can be determined by a more detailed analysis of loop detector data archived for station 6. Figure 6 shows the oblique *N(x,t)* and *T(x,t)* for station 6. As shown, the speed dropped from 42 mph (71 km/h) at 7:20 am with a flow of 5,925 veh/hr to 20 mph (34 km/h) at 7:48 am with a flow of 4556 veh/hr. After comparing Figure 5 with Figure 6 it is clear that the origin of the congestion was observed at station 6 during the period between 7:07 am and 7:20 am. The

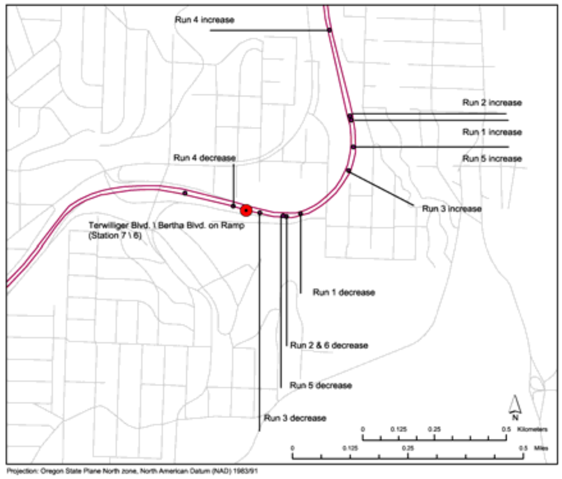


Figure 4. Bottleneck Characteristics

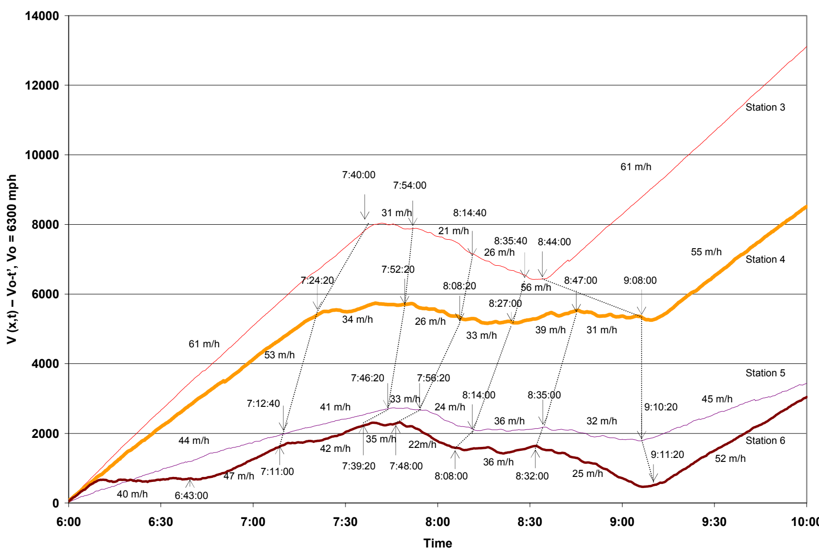


Figure 5. Oblique V(x,t) Upstream of the Bottleneck

volume during this period was 5709 vph and the speed was 40.5 mph (67 km/h). Figure 6 shows that the highest speed and flow levels for this location occurred during the period between 9:11 am and 10:00 am. The measured flow was 4582 vph and the reported speed was 52 mph (87 km/h). To maintain freely flowing traffic on the freeway, and to minimize delay for freeway mainline vehicles, we hypothesize that we would need to maintain the speed at 52 mph and the volume at 4582 vph. To achieve this level of service, more delay will be imparted to the vehicles entering the freeway via the on-ramps. Accordingly, the best choice for avoiding congestion is the level of flow that was present during the period between 6:43 am and 6:49 am, which was 5896 vph with an accompanying speed of approximately 42 mph (71 km/h). The magnitude of the delay resulting from traffic flowing in this state might be reduced for entering ramp vehicles. In order to test either of these possibilities, the ramp metering system would need to be adjusted to provide this level of service at station 6.

The loop detector data indicated the presence of a bottleneck downstream of station 6 while the AVL helped to narrow the problem down and to focus on a smaller segment. It appears that the bottleneck arose due to a combination of the horizontal curve on the freeway and the merge of 2 on-ramps at the same location. From the oblique cumulative *N(x,t)* and *T(x,t)*, it

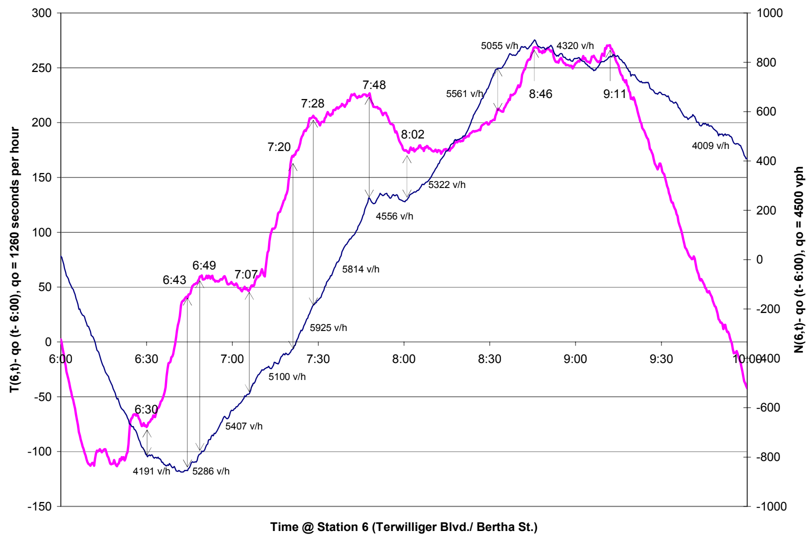


Figure 6. Oblique N(x,t) and T(x,t) at Station 6

appears that the prevailing flow at this location was 5896 vph with a speed of 40 mph (67 km/h). So the freeway bottleneck capacity that appears to dictate the upstream on-ramp and mainline flows is approximately 5900 vph. This observation is the first step toward adjusting the ramp metering on I-5 in order to avoid a certain flow threshold, which may help to avoid severe congestion on this freeway segment during the am peak.

PRE-TIMED AND ACTUAL METERING RATES

The objective of this section is to compare the ODOT ramp metering timing design with what is actually occurring on the freeway corridor. This will be accomplished by demonstrating a technique for comparing the performance of the PRM system to the actual traffic flows recorded on the ramps. Figures 7 and 8 show comparisons between the flow based on the PRM system and the actual flow measured by the loop detectors installed on the on-ramps. The PRM were activated at 6:45 a; some of the meters were deactivated at 8:30 am and others stopped metering at 8:45 am. Note that Station 7 (Bertha St.) records entering vehicles separately from those crossing detector Station 6 (Terwilliger Blvd). These entering vehicles merge onto one on-ramp before entering the freeway. As shown in Figure 2, this on-ramp shares the same mainline detectors with station 6. The PRM system studied here has a special characteristic when the queue behind the meter reaches the capacity of the on-ramp. Specifically, when ramp vehicles begin to backup onto city streets and arterials, the PRM is turned off automatically to flush the ramp. In these situations, higher flows of platooned vehicles enter the freeway. This clarifies why at station 3, 5, 6, and 7 at some points there were more vehicles passing at a higher rate than it was planned in the PRM. At stations 1, 2, and 4 the PRM was over-metering vehicles. Plotting the traffic flow at the on-ramps using an oblique cumulative curve makes it easy to visualize the time when the meter was functioning. A straight line should be present during the period where the PRM was functioning while based on the figures these straight lines were not present at all times while the meters were functioning. This method has shown how the PRM system is performing compared to the actual demand arriving at the on-ramps. The next step is to compare the relationship between the flow on the on-ramp and the flow on the freeway mainline.

USE OF VOLUME AND CAPACITY

The flow changes observed on the freeway mainline were also compared to the changes in flow measured on the on-ramps as an additional means of evaluating the performance of the PRM. This comparison used the loop detector data to construct oblique cumulative curves. Table 1 shows the characteristics of the freeway flow and speed for station 4. The time intervals were recorded based on observations of the marked changes in the oblique *N(x,t)* and *T(x,t)* measured at station 4. The PRM were activated at 6:45 am and remained operational until 8:30 am. It is clear that the ramp meters were not sensitive to the changes in mainline flow. It is observed that such sensitivity is important for attempting to avoid congestion and to achieve the goals of PRM.

From	To	Speed mi/hr	Occupancy percent	Mainline Flow veh/hr	Ramp Flow veh/hr
6:00:00	6:29:00	58.78	3.99	3355	82
6:29:20	6:40:00	56.86	6.58	4947	180
6:40:20	6:49:00	56.49	7.64	5400	207
6:49:20	6:52:00	50.00	6.78	5060	80
6:52:20	6:54:00	58.33	7.06	5340	300
6:54:20	7:19:00	56.40	7.86	5650	173
7:19:20	7:32:00	40.16	12.68	5825	249
7:32:20	7:53:00	37.29	13.40	5474	320
7:53:20	8:14:00	27.76	16.63	4643	217
8:14:20	8:37:00	38.94	12.65	5507	175
8:37:20	8:56:00	34.02	13.49	4866	202
8:56:20	9:15:00	36.55	12.74	4588	117
9:15:20	9:50:00	57.57	5.04	4125	177
9:26:20	10:00:00	56.52	5.07	4146	96

Table 1. Traffic Parameter Changes at Station 4

MANUAL TRAFFIC SIMULATION

Manual traffic simulation using the information obtained from the previously presented analytical methods can help in tuning the PRM. Knowing the ideal level of service will help in evaluating the performance in PRM. The study segment was 4.23 miles (7.06 km) in length. If a vehicle traversed this section of the freeway at an average speed of 40 mph (67 km/h), the travel time would be 6.3 minutes. The free flow travel time for this segment at the speed limit of 55 mph (90 km/hr) would be 4.6 minutes. The total delay resulting from the suggested level of service would be approximately 1.7 minutes. As observed from the probe vehicle runs shown in Figure 3, the actual delay before any modified strategy was implemented was approximately 10 minutes. To achieve this level of service the total volume upstream of station 6 should never reach 6500 vph. During the period between 7:07 am and 7:20 am the volume was 5709 vph as shown in Table 1 and speed was maintained at approximately 40 mph (67 km/hr). Another stationary period was observed between 6:43 and 6:49 with a flow of 6000 vph and a speed of 42 mph (71 km/hr). The best choice for this section of the freeway is to maintain flow less than 6000 vph at speed of 40 mph (68 km/hr) to avoid delays and congestion from occurring.

The next step is to attempt to understand the demand for the entry to the freeway. From Figures 7 and 8 it is clear that stations 3, 5, and 6 are functioning at capacity, station 7 is functioning over capacity, and stations 1, 2, and 4 are under capacity. Figure 9 shows the results of a manual simulation based on a straight forward demand and supply analysis (*12*).

The time interval for analysis was defined as 15 minutes in this simulation for simplicity of the calculations. For further analyses, the oblique *N(x,t)* and *T(x,t)* curves would be the best way to define the PRM temporal resolution. Knowing that the on-ramp queues are exceeding the ramp's capacity at station 7, changes can be applied to the cycle to avoid situations when vehicles back up onto the city street, which in turn triggers an over-ride of the PRM system by flushing the ramp. The metering rate at station 7 should be increase from 257 vph to 360 vph. As a result, the flow downstream of stations 6 and 7 will be 6168 vph. According to the previous section, the freeway mainline flow should be maintained below 6000 vph downstream of these stations. An flow of 168 vph will need to be metered at the upstream stations. Knowing the volumes and capacities at the upstream stations a decision is to be made which on-ramps will delay the 168 vph to avoid reaching congestion levels downstream of stations 6 and 7. From Figures 7 and 9, it was clear that stations 1, 2 and 4 were functioning below their metered capacities. Therefore, the 168 vph were distributed among these three stations based on the ratios of their existing flows. Station 4 will need to drop from 164 vph to 130 vph, resulting in further delays of 34 vph.

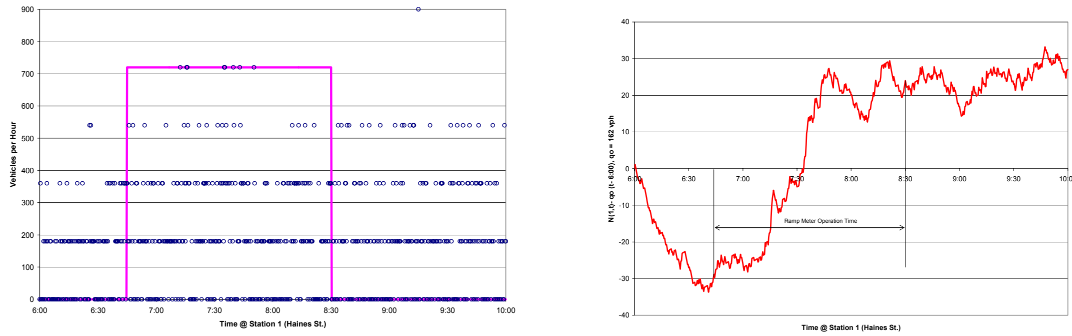
The queue length at this station will be 8 vehicles during the 15 minute period with an added delay of 3.6 minutes per vehicle for the existing queue. Knowing the number of vehicles that will be delayed is important so that it can be compared to the existing capacity of the on-ramp which was 19 vehicles at station 4 as measured in the field. If the queue reached capacity at this location and the number of proposed vehicles was not satisfied, the remaining vehicles should be delayed at stations further downstream. It is better to keep the on-ramp slightly below capacity because having it at capacity will cause the ramp to be flushed, eliminating the positive effects of the PRM system. The remaining 134 vph that needed to be delayed to avoid congestion upstream of stations 6 and 7 were distributed among stations 1 and 2. The ramp queue at station 2 increased by 25 vehicles every 15 minutes and the additional delay was 3.8 minutes per vehicle using this on-ramp.

Similarly, the queue at station 1 was increased by 8 vehicles every 15 minutes causing an increase in the delay at the on-ramp of 3.3 minutes. The maximum number of vehicles added to the previously existing delay at the on-ramps was 168 vph with approximately 3.6 minutes per vehicle. This additional ramp delay will be compensated by a hypothetical savings of 10 minutes of delay by 6000 vehicles passing the mainline upstream of stations 6 and 7. Thus over one hour on one day, the savings could add up to 990 veh-hr. Similar analysis can be conducted for the other time periods and other days. Macroscopic or microscopic simulation tools can also be used to quantify and test other simple PRM timing plans.

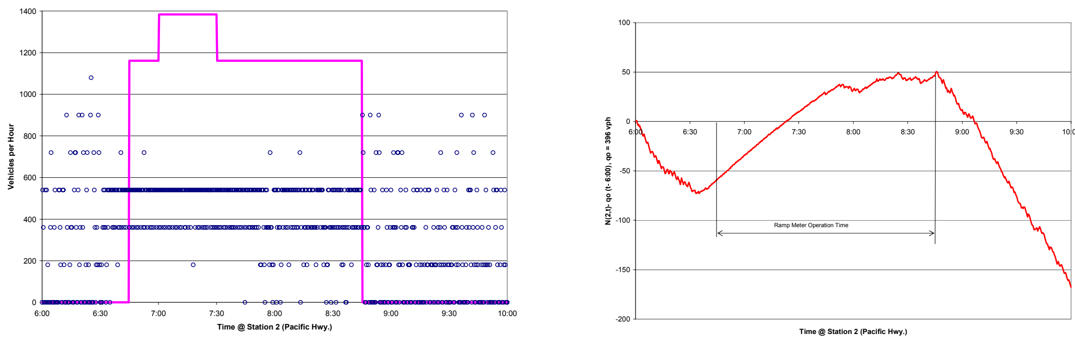
CONCLUSIONS

The capacity of the freeway bottleneck was determined based on the study of one day. More research is needed to validate the findings of this paper through studying different days throughout the year. Seasonal changes might have effects on the ramp metering system so studying different days around the year will help in answering this question.

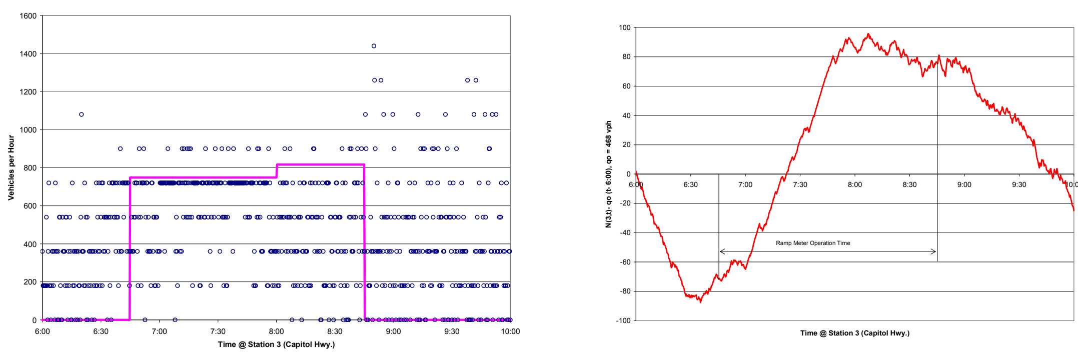
This paper has demonstrated different techniques for understanding the characteristics of a freeway corridor and how to evaluate the performance of a PRM system and tune it to a better level of service. This has been an experiment in order to attempt to relieve congestion on the freeway. The methods described in this paper used a combination of inductive loop detector data and AVL technology. In the future, additional data sources can be used to achieve a better understanding of the freeway system and to relieve congestion. The methods implemented in this paper can be applied to more than one day on regular bases for best timing plans. For simplicity the paper used only one day worth of data.



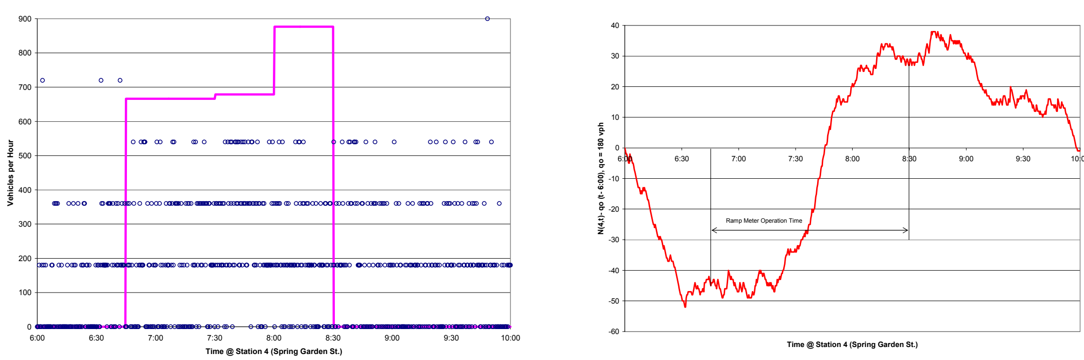
Station 1



Station 2

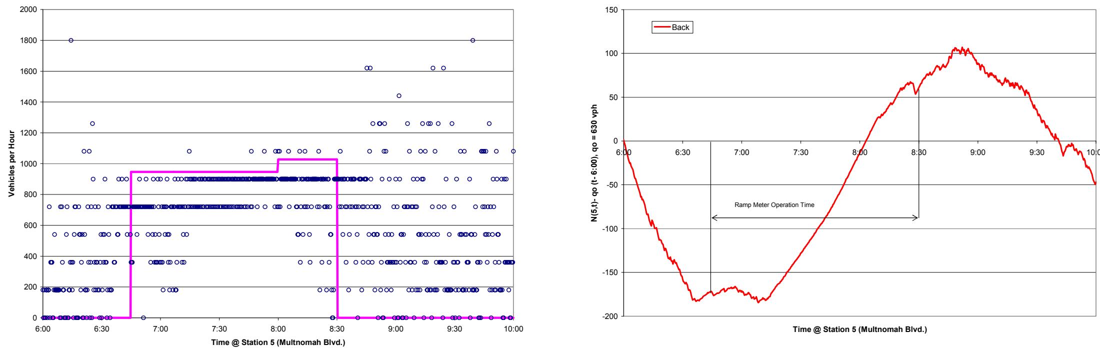


Station 3

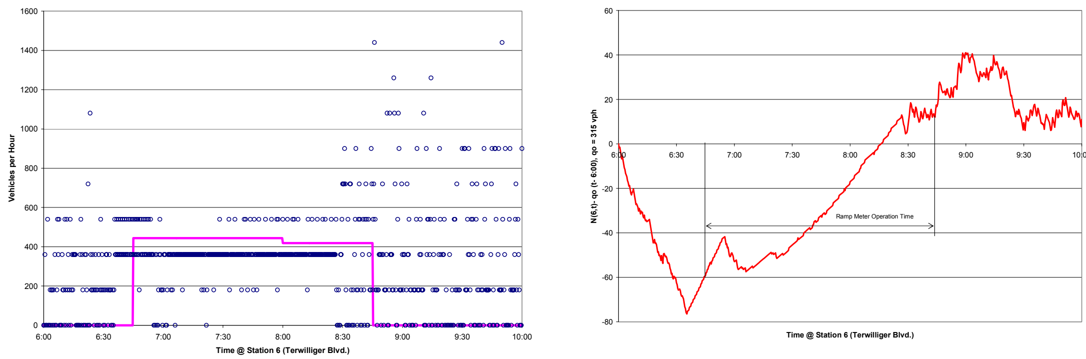


Station 4

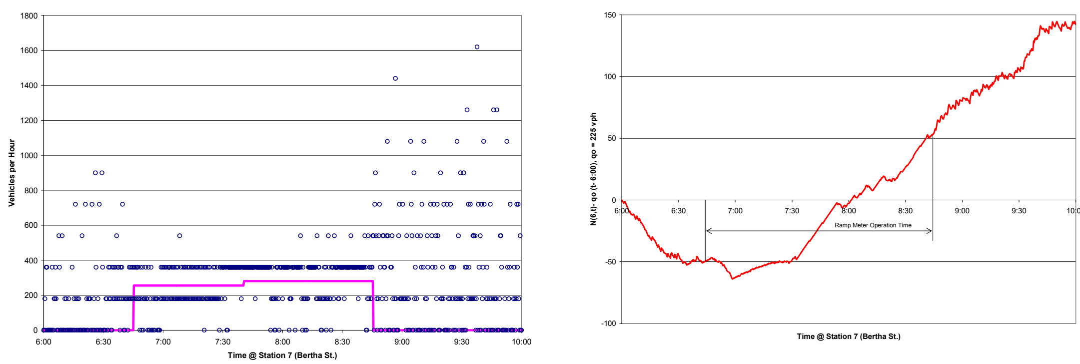
Figure 7. Actual and Planned PRM Timing



Station 5



Station 6

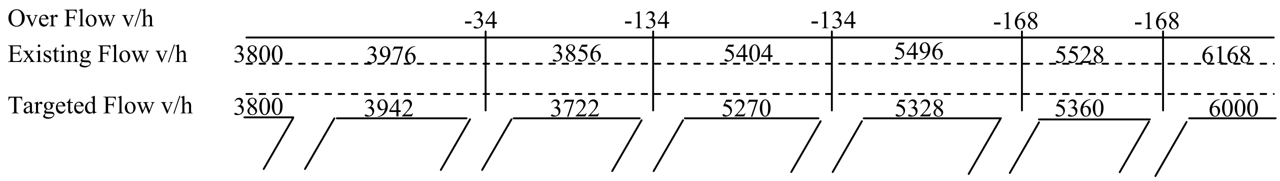


Station 7

Figure 8. Actual and Planned PRM

Using existing technologies to better inform drivers of travel time and delay and savings will be helpful in improving transportation system efficiency. The manual simulation described led to substantial delay savings on the freeway mainline yet added delay to the vehicles on the on-ramps. The system wide total savings were great; the presence of variable message signs will help the drivers understand the expected amount of delay at on-ramps before a decision is made and the amount of savings if they took an alternate route.

In summary, several points were considered when modifying the hypothetical PRM timing plans. First, we avoided reaching capacity on the freeway mainline. Second, we avoided reaching the spatial capacity of the on-ramps. Finally, we recommend that drivers are informed in advance about expected ramp delays and suggestions about possible alternate routes with the estimated travel time savings.



	Station 1	Station 2	Station 3	Station 4	Station 5	Station 6 and 7
Existing Flow	176 v/h	492 v/h	492 v/h	164 v/h	628 v/h	344 v/h (St6) 172 v/h (St7)
Proposed Flow	142 v/h	391 v/h	492 v/h	130 v/h	628 v/h	344 v/h (St6) 380 v/h (St 7)
Additional Queue	34 v/h 8 v/15 min	101 v/h 25 v/15 min		34 v/h 8 v/15 min		
Additional Delay	3.3 min	3.8 min		3.6 min		
On Ramp Capacity	19 vehicles	55 vehicles	16 vehicles	19 vehicles	40 vehicles	34 vehicles (St 6) 18 vehicles (St 7)
Distribution Factor	0.2	0.6		0.2		

Figure 9. Manual Simulation from 6:45 to 7:00

ACKNOWLEDGEMENTS

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