PORTLAND STATE UNIVERSITY
DEPARTMENT OF CIVIL & ENVIRONMENTAL ENGINEERING
CENTER FOR TRANSPORTATION STUDIES

Using Archived Data to Measure Operational Benefits of ITS Investments: Ramp Meters

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EXECUTIVE SUMMARY

Introduction

The Oregon Department of Transportation (ODOT), the City of Portland, Tri-Met, Metro and other regional jurisdictions are partners in the advanced technology TRANSportation PORTland project—TransPort. This system is designed to provide traffic management, incident response and traveler information. Its goals are to reduce traffic congestion, stabilize travel times and prevent accidents on the highway system. It is hoped that this will be achieved by improving safety and efficiency of auto, truck, and transit modes, and by relaying real-time route and mode choice information to all travelers. TransPort also complements future improvements to the region's light rail, commuter rail, transit and highway system. This system is compatible with Metro's 2040 Framework Plan and enhances Portland's livability and quality of life while accommodating growth. As with other transportation management and information system implementations, the vision is that TransPort will provide long-term benefits without the need to add more travel lanes to the region's roadway system. TransPort is comprised of three main systems:

- Transportation management: traffic monitoring and surveillance equipment identifies incidents and accidents, thereby helping system operators manage traffic flows.
- Incident response: COMET (CORridor ManagEment Team) is dispatched to the incident and other appropriate emergency services are notified.
- Traveler information: drivers are notified by variable message signs or on the car radio of an incident ahead, enabling them to choose alternate routes to avoid congestion.

It is important to recognize that for state departments of transportation, Intelligent Transportation Systems (ITS) projects such as TransPort are conceptually new types of projects. The ITS projects that have been implemented rely on an unseen communications network, mostly invisible sensors, and software that is housed within the transportation management center. A relatively small number of individuals are required to operate the transportation management system, and in many cases users do not even know they are benefiting from the system. Therefore, it is important to develop an evaluation program so that benefits can be demonstrated and communicated. The results of such an evaluation program will be helpful for decision-making and also as part of a system feedback loop. As in any systems design process, lessons learned from evaluation should be fed back into the planning, operations and maintenance of the existing system and also into the planning, design and implementation of any expansions to the system.

In the Portland metro area ODOT currently operates an extensive advanced traffic management system (ATMS), including 75 CCTV cameras, 18 variable message signs, an extensive fiber optics communications system and 118 ramp meters, including approximately 436 inductive loop detectors.

This study, supported by TransNow, ODOT, and Portland State University, focuses primarily on the ramp meters in operation in the Portland metropolitan area. 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. 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.

Goals of Ramp Metering

Ramp meters are implemented to achieve two main goals:

1. Limit the amount of traffic entering a freeway, and;
2. Break up the platoons of vehicles discharged from a traffic signal upstream.

The underlying principle behind the first goal is to guarantee that the total incoming freeway traffic is less than its functional capacity. The reasoning behind the second goal is to supply a means for safe merge maneuvering at the entrance to the freeway.

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 eight 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 (*19*).

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. The benefits associated with ramp metering consist of improved traffic flow, reduction in travel time, improved safety, and improved air quality.

Research Objectives

The objective of this research is to use the existing data, surveillance and communications infrastructure (to the extent possible) to develop a case study ramp meter evaluation using the Portland, Oregon metropolitan area as the test bed. The existing ITS infrastructure is a rich data source, thus no dedicated data collection program is necessary. This case study will set a precedent for future evaluations of ITS programs.

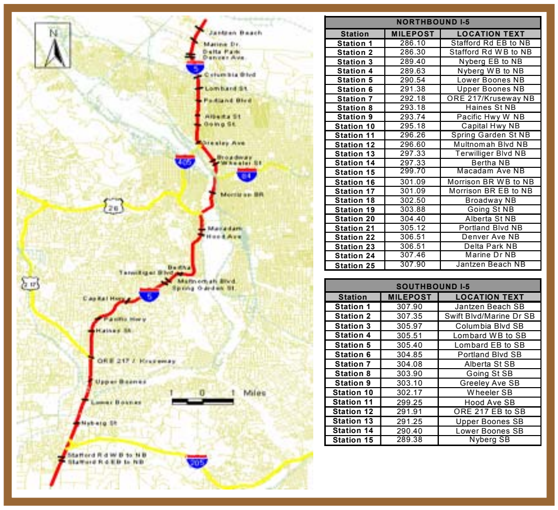
Data Sources

The inductive loop detectors and the CCTV cameras are the primary data sources for this evaluation.

Loop Detectors

These detectors collect vehicle count, occupancy and average speed at 20-second intervals. The ODOT Traffic Management Operations Center (TMOC) currently archives all of its loop detector data at a 15-minute level of aggregation, but makes the more detailed 20-second data available upon request for research purposes.

This study has involved collection of loop detector and video data from the Interstate 5/Barbur Blvd. corridor, as shown in Figure 1, which provides access into downtown Portland from the south with aparallel arterial, complicated freeway geometry and major transit lines.



NORTHBOUND I-5		
Station	**MILEPOST**	**LOCATION TEXT**
Station 1	286.10	Stafford Rd EB to NB
Station 2	286.30	Stafford Rd WB to NB
Station 3	289.40	Nyberg EB to NB
Station 4	289.63	Nyberg WB to NB
Station 5	290.54	Lower Boones NB
Station 6	291.38	Upper Boones NB
Station 7	292.18	ORE 217/Kruseway NB
Station 8	293.18	Haines St NB
Station 9	293.74	Pacific Hwy W NB
Station 10	295.18	Capital Hwy NB
Station 11	296.26	Spring Garden St NB
Station 12	296.60	Multnomah Blvd NB
Station 13	297.33	Terwilliger Blvd NB
Station 14	297.33	Bertha NB
Station 15	299.70	Macadam Ave NB
Station 16	301.09	Morrison BR WB to NB
Station 17	301.09	Morrison BR EB to NB
Station 18	302.50	Broadway NB
Station 19	303.88	Going St NB
Station 20	304.40	Alberta St NB
Station 21	305.12	Portland Blvd NB
Station 22	306.51	Denver Ave NB
Station 23	306.51	Delta Park NB
Station 24	307.46	Marine Dr NB
Station 25	307.90	Jantzen Beach NB

SOUTHBOUND I-5		
Station	**MILEPOST**	**LOCATION TEXT**
Station 1	307.90	Jantzen Beach SB
Station 2	307.35	Swift Blvd/Marine Dr SB
Station 3	305.97	Columbia Blvd SB
Station 4	305.51	Lombard WB to SB
Station 5	305.40	Lombard EB to SB
Station 6	304.85	Portland Blvd SB
Station 7	304.08	Alberta St SB
Station 8	303.90	Going St SB
Station 9	303.10	Greeley Ave SB
Station 10	302.17	Wheeler SB
Station 11	299.25	Hood Ave SB
Station 12	291.91	ORE 217 EB to SB
Station 13	291.25	Upper Boones SB
Station 14	290.40	Lower Boones SB
Station 15	289.38	Nyberg SB

Figure 1 - Study Area

CCTV Video Data

To validate the loop data, vehicles were manually counted using video data by establishing a reference point on the video monitor. The arrival time of each vehicle to the reference point was recorded using a simple computer program that records the time when a computer key is pressed. This method was used to record the number of cars traveling in each lane and on the ramp.

Data Validation

This study has pursued the validation of inductive loop detector data for the Portland metropolitan area. This has been an important step toward developing a system for automatically generating mobility measures for the transportation network.

It was determined graphically and statistically that the loop detectors report a negative error code when there was a zero count. This is an important consideration when developing automated methods for processing loop detector data, since any algorithm will need to handle all sources of error. It is still not possible to differentiate between a "-999" error code and a "-1" error code, and thus requires additional research.

The inductive loop detector data analyzed here also appeared to over count by an average of 8.3%. According to the video processing, 8.1% of the total vehicles observed were trucks with five axles. The assumption we make in here is that the detectors counts the vehicles with three axles as one vehicle while it counts the vehicles with five axles as two vehicles. This is further borne out by Figure 2, which is an adjusted cumulative count curve for loop 1106. For this figure, when a truck was observed on the video, a single vehicle was subtracted from the loop detector curve. As shown, the cumulative count curves appear to be superimposed after the truck over count was manually corrected.

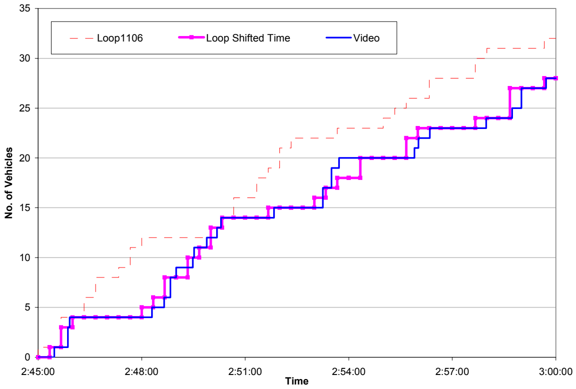


Figure 2 - N(x,t) Channel 27 and Loop1106 [2:45-3:00AM]

Ramp Meter Evaluation

Figure 3 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 pre-timed ramp metering system.

In addition to the use of the 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

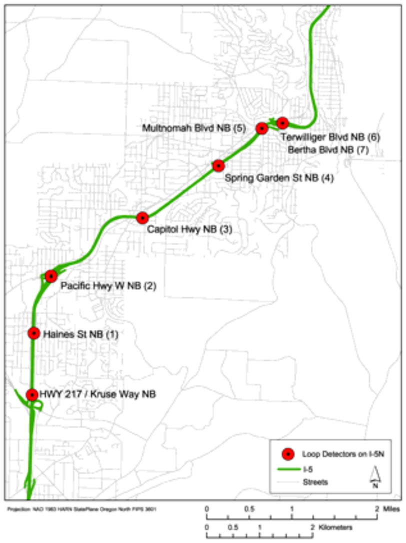


Figure 3 - Interstate 5 with Loop Detector Locations

of the freeway. AVL may use a variety of techniques to determine the location of the vehicle. The most common system is the use of global positioning systems (GPS), a satellite-based positioning system. The GPS system creates a log file with time, latitude and longitude where the data are collected.

A first step in the process of measuring the performance of the ramp metering system 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 (*23*). 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 used GPS technology and recorded 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 ramp metering 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 concentrated on the northbound morning peak period when the ramp metering system was in operation on the freeway on-ramps. A bottleneck occurred 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. 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 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.

Manual Traffic Simulation

Manual traffic simulation using the information obtained from the previously presented analytical methods can help in tuning the ramp metering system. Knowing the ideal level of service will help in evaluating the performance of the ramp metering system. 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 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.

From	To	Flow veh/hr	Occupancy Percent	Velocity mi/h
6:00:00	6:10:00	2990	3.17	55.12
6:10:20	6:14:00	2880	8.06	32.47
6:14:20	6:20:00	3250	6.31	37.26
6:20:20	6:26:00	3660	9.52	32.43
6:26:20	6:30:00	3345	6.03	39.31
6:30:20	6:43:00	4703	9.96	35.32
6:43:20	6:49:20	5949	8.21	42.65
6:49:40	7:07:00	5896	6.83	48.64
7:07:20	7:20:00	5709	9.58	40.51
7:20:20	7:28:00	6480	9.19	42.68
7:28:20	7:48:00	6513	7.36	40.92
7:48:20	8:02:00	5229	5.76	20.63
8:02:20	8:15:00	5982	7.01	31.98
8:15:20	8:34:00	6224	7.62	34.30
8:34:20	8:46:00	5755	8.62	27.08
8:46:20	9:11:00	4963	7.02	25.17
9:11:20	10:00:00	4582	4.87	52.16

Table 1 Traffic Parameter Changes Upstream of Station 6

Summary of Ramp Meter 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 study through analyzing 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.

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.

Several points were considered when modifying the hypothetical ramp metering system 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 be informed in advance about expected ramp delays and suggestions for possible alternate routes with the estimated travel time savings.

Case Study: Ramp Metering in Portland, Oregon

Ramp meters were first implemented in the Portland metropolitan area by ODOT in January 1981, along a 6-mile stretch of Interstate 5 from the Broadway Bridge to the Interstate Bridge. ODOT currently maintains 118 ramp meters in the Portland metropolitan area, and all the meters are operated in a fixed-timed operation, activated and deactivated at the same times every weekday. In order for the entire system to work, all ramps must be metered, even those with relatively low flows. When ramps are left unmetered, drivers will switch to them instead of using metered ramps, resulting in traffic problems on and off the freeways. The meters also deter motorists from making short trips on the freeways during peak periods when the freeway capacity is most needed for commuters making longer trips. One of ODOT's goals of ramp metering is the preservation of mobility in the Portland metropolitan area during peak hours. With so much of Portland's recent growth centered around freeway interchanges, there is naturally a significant demand for immediate freeway access. Without meters, the freeway system would break down at lower volumes caused by less stable flow. Although metering might result in queuing on arterial streets in a few areas, it is significantly less than without meters. ODOT's goal is to maximize the capacity of the freeway while minimizing the effects on the arterial street system.

Weekend Ramp Meter Shutdown on U.S. Highway 26

In 2001, ODOT performed studies, collected data, and compiled traffic flows for a typical Saturday and a typical Sunday for each month of the entire year. The results showed that during the periods of congestion, speeds were reduced to considerably less than 30 mph. In response to frequent weekend congestion on the eastbound lanes of Highway 26, ODOT implemented weekend ramp metering along an 11-mile corridor, between Helvetia Road and Skyline Road, as shown in Figure 4.

Weekend ramp metering of these ramps began on Saturday, August 25, 2001, and will be in effect each year from May through December, between the hours of 12:00 noon and 6:00 p.m. Studies performed after activation of the weekend meters revealed that traffic was functioning in free flow conditions through the entire corridor.

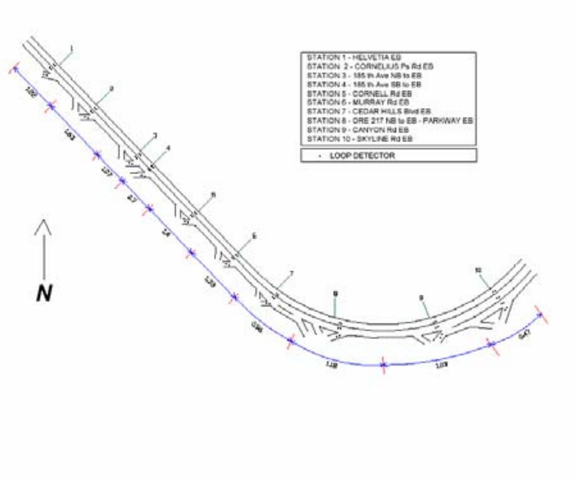


Figure 4 Site Map of 11-Mile Corridor Analyzed

As an example of ODOT's continued monitoring of this corridor, the agency recently deactivated the weekend ramp meters to ensure that the weekend metering operation was beneficial. Ramp meters were turned off during the weekend of October 11 and 12, 2003 along all the eastbound ramps of this 11-mile corridor. The following weekend (October 18 and 19, 2003), the ramp meters were turned back on.

It is possible to determine the percent of time (between the hours of 12:00 noon and 6:00 pm on all four days) that traffic conditions fell into a particular freeway level of service (LOS) category. As shown in Table 2, VMT is tabulated by LOS for the entire metering period for each day. The Saturday data indicate that the proportion of time spent by drivers in LOS D, E and F dropped from 42% to 39% and the Sunday data indicate that the percentage dropped from 37% to 32%. Taking into account variations in total volumes, this indicates that the ramp metering led to more travel at better quality of service through the corridor.

Analysis Time Period = 12 P.M. to 6 P.M.

		11-Oct		18-Oct			12-Oct		19-Oct		
LOS	Occupancy	VMT	% Total	VMT	% Total	% Diff	VMT	% Total	VMT	% Total	% Diff
		(i)		(ii)		(ii) - (i)	(iii)		(iv)		(iv) - (iii)
A	0 < 5	34,866	19%	33,405	18%	-4.4	31,656	16%	34,353	17%	7.9
B	5 < 8	33,736	18%	33,851	18%	0.3	44,893	22%	50,993	25%	12.0
C	8 < 12	40,144	21%	47,552	25%	15.6	52,302	26%	52,973	26%	1.3
D	12 < 17	49,296	26%	45,275	24%	-8.9	47,632	24%	42,620	21%	-11.8
E	17 < 28	24,879	13%	26,818	14%	7.2	23,300	12%	20,536	10%	-13.5
F	28 and above	5,378	3%	2,699	1%	-99.3	2,616	1%	2,926	1%	10.6
	Total VMT	188,300	100%	189,600	100%		202,400	100%	204,400	100%	

Table 2 VMT by Level of Service

Conclusion

Transportation agencies around the world have experienced success with their ramp metering programs. Some have even seen freeway capacity above 2,000 vph per lane. Unfortunately, ramp meters are not a cure-all. While they can generate significant improvements in some areas, they cannot eliminate all congestion or every accident. The true measure of their effectiveness, however, is the continued increase in ramp metering implementations such as those demonstrated in cities such as Portland, Oregon.

Discussion

This research project represented the first use of ODOT's 20-second loop detector data, and presented some initial challenges with its interpretation and validation. Initially the data were reporting erroneous speed and occupancy values (off by a factor of 256), and subsequently we examined the -999 and -1 reports, now attributed to communications failures and zero count readings coupled with a divide by zero error. This study has been valuable in that it revealed these issues and has led to improvements in ODOT's data collection and archiving algorithms.

The second main benefit of this study is that it has established that the ramp metering system that is currently in place is performing reasonably well given its own limitations. It was shown that many times the preprogrammed metering rates do not match the actual ramp flows measured in the field. The reasons for this are not completely clear, but can be attributed to meter violations and uncounted vehicles on the on-ramps. We recommend that better ramp detection be installed in future implementations of ramp metering. In addition, we recommend that off-ramp detection be included in future implementations to facilitate preservation of vehicle conservation when analyzing mainline count data between merges and diverges.

A third benefit is that we have established a baseline for a "before" and "after" evaluation of the new SWARM system that is being readied for deployment. This coupled with the new data archive being established at Portland State University will facilitate a more comprehensive analysis of the performance of the new metering system. ODOT should consider a transition period prior to the start-up of the new SWARM system where the current meters along selected segments are shut down during particular periods in order to collect better traffic demand data.

Finally, a small study was conducted both with and without ramp metering in one corridor, resulting in a unique level of analysis for the eastbound Route 26 corridor on two weekends. The results confirm that the metering is most definitely not leading to deteriorated conditions and appears to improve traffic operations in the corridor.

1.0 INTRODUCTION

1.1 Background

The Oregon Department of Transportation (ODOT), the City of Portland, Tri-Met, Metro and other regional jurisdictions are partners in the advanced technology TRANSportation PORTland project—TransPort. This system is designed to provide traffic management, incident response and traveler information. Its goals are to reduce traffic congestion, stabilize travel times and prevent accidents on the highway system. It is hoped that this will be achieved by improving safety and efficiency of auto, truck, and transit modes, and by relaying real-time route and mode choice information to all travelers. TransPort also complements future improvements to the region's light rail, commuter rail, transit and highway system. This system is compatible with Metro's 2040 Framework Plan and enhances Portland's livability and quality of life while accommodating growth. As with other transportation management and information system implementations, the vision is that TransPort will provide long-term benefits without the need to add more travel lanes to the region's roadway system. TransPort is comprised of three main systems:

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ITS include the application of information and communication technologies to increase safety and enhance mobility on the existing transportation system. Current 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 (*14, 15, 16*). The potential to archive ITS data has begun to make a revolutionary difference in traffic and transportation management. 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 planners and operators are working 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 more efficient, effective, equitable and sustainable.

1.2 Problem Statement

The objective of this research is to use the existing data, surveillance and communications infrastructure (to the extent possible) to develop two case study evaluations using the Portland, Oregon metropolitan area as the testbed. These will include an evaluation of the COMET incident management program and the Portland ramp metering system. Existing data sources are the ITS infrastructure and the statewide crash database, thus no dedicated data collection program is necessary. These two case studies will set a precedent for future evaluations of ITS programs. These evaluations are immediately feasible using existing data sources.

1.3 Ramp Metering System Background

Mobility and transportation have long been a high priority for human beings. However, the latter part of the twentieth century has brought with it the phenomenon of traffic congestion, resulting from the rapid rise in the number of vehicles using transportation facilities. Congestion occurs when the number of vehicles using a common transportation infrastructure exceeds the system's capacity. The phenomenon of congestion has become common in all developed countries, and it generally results in delay and a reduction in traffic safety and air quality *(2).* It is also not uncommon for the flow of traffic to reach a stop-and-go conditions, particularly during rush hour periods. More often than not, these stop-and-go states continue for several hours and can compromise the safety of the drivers in addition to the extraordinary price, as it relates to lost time, delay, increased fuel consumption and emissions as well as vehicle wear and tear *(3).*

There are generally two types of congestion: recurrent and non-recurrent. Recurrent congestion results from demand exceeding capacity during peak periods of usage, such as rush-hour. Non-recurrent congestion results from unusual incidents temporarily reducing the system's capacity, such as crashes, breakdowns and other random events *(2).*

Studies have shown that congestion is growing in three increasingly visible ways:

- Greater time penalty for traveling during rush-hour.
- Longer duration of time that drivers may encounter congestion (peak spreading).
- Higher percentage of roads and highways that are congested *(4).*

On freeways throughout the world, traffic management systems have been proposed and applied as a means of reducing congestion without adding capacity to existing systems. Adding capacity is not only very expensive, but it could also result in undesirable side effects on a region's social and economic environments *(2).*

With the evolution of Intelligent Transportation Systems (ITS), ramp metering has proven to be one of the most effective methods of traffic management. This tool is the most direct and efficient method of controlling and upgrading congested freeways. In the context of ITS, ramp metering provides multiple operational characteristics for improvement of traffic flow, traffic safety, and air quality *(5).* In addition, the double gain of both decreased travel time and higher traffic flow greatly exceeds any benefits that may result by adding more freeway lanes *(6).*

Ramp metering is a common freeway management technique and has been implemented in many cities around the world. It is one of ten key strategies recently identified for mitigating freeway congestion with advanced technologies (*18*). At their most basic level, ramp meters are traffic signals located at on-ramps to control and/or regulate the flow of vehicles from the ramp onto the freeway (*19*). 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 (*17*). Figure 1 is a map with the number of ramp meters in operation in the U.S. (1999).

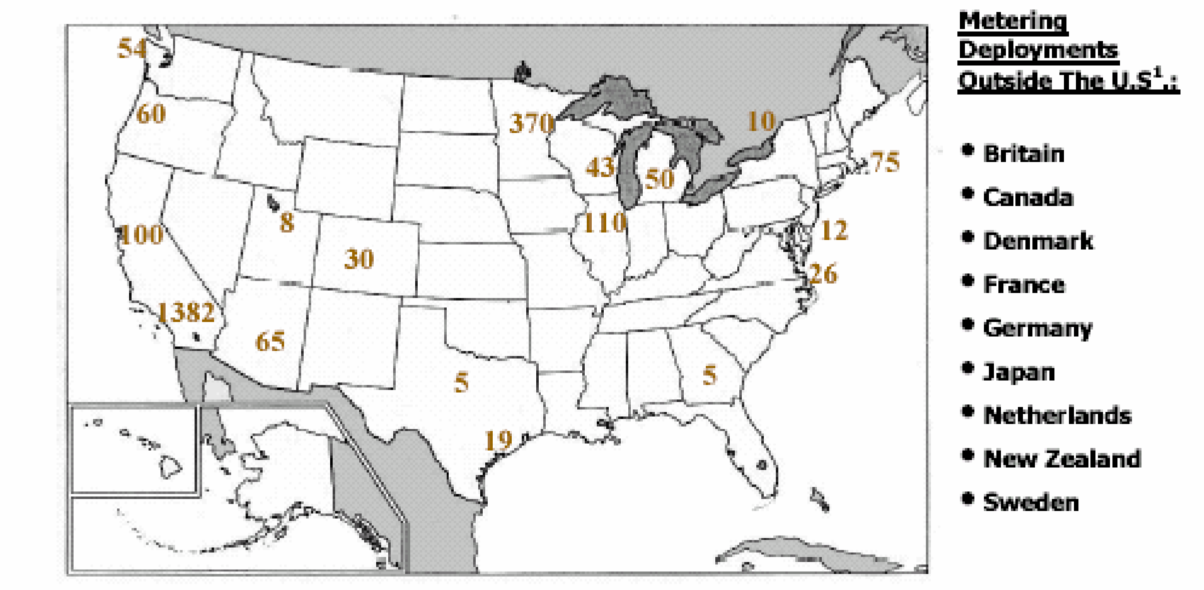


Figure 1 Ramp Metering Deployments

Ramp 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.

1.4 Goals of Ramp Metering

Ramp meters are usually implemented to achieve two main goals:

3. Limit the amount of traffic entering a freeway, and
4. Break up the platoons of vehicles discharged from a traffic signal upstream.

The underlying principle behind the first goal is to guarantee that the total incoming freeway traffic is less than its functional capacity. The reasoning behind the second goal is to supply a means for safe merge maneuvering at the entrance to the freeway.

Using this framework, transportation agencies typically implement a policy that falls somewhere within the following extremes:

1. Give the highest priority to vehicles already on the highway, or
2. Give the highest priority to vehicles on the ramp.

The goal of the first policy, currently used by the State of Minnesota, is to keep the flow of freeway traffic moving at all times, including those times when an incident occurs. This policy is utilized by operating the meter controller in a traffic-responsive mode. In a traffic-responsive mode (described in greater detail below), loop detectors measure freeway conditions, and the metering rates are modified such that only the number of vehicles that can be accommodated while maintaining a certain level of service are allowed to enter the freeway.

The goal of the second policy, currently used by the State of Texas, is to guarantee that upstream traffic signals are kept free of any queues, at all costs. This policy uses queue detectors at the entrance to the ramps and delays ramp metering when a queue is identified and for the duration that it persists.

The remaining 48 states in America have implemented policies that produce a compromise between the above two extremes, typically closer to the first extreme *(3)*. Also, as a result of a recent ramp meter shutdown study (19), the state of Minnesota has modified its ramp meter control strategy to balance delays between on-ramp vehicles and mainline vehicles.

1.5 History of Ramp Metering In America

The first ramp meter, as we recognize it today, was implemented in Chicago on the Eisenhower Expressway in 1963. However, this first installation was preceded by successful experiments on the efficiency of metering the traffic entering New York tunnels and ramp closure research in Detroit. Interestingly enough, the original experiment in Chicago consisted of a police officer positioned on the entrance ramp, stopping vehicles and releasing them one at a time at a rate pre-determined from a pilot detection study.

Ramp metering began in Los Angeles in 1968 and has gradually expanded. There are now over 1,300 meters operating in Los Angeles County, the most of any system in the world. Ramp metering implementations can vary in size from a fixed-time process at one ramp to computer control of each ramp along several miles of a freeway. Since their inception in

Chicago in 1963, the use of ramp meters in North American cities has steadily increased from one in 1963 to 23 in 1989 to 33 in 2000 *(5)*.

Due to the available level of technology at the time, early ramp meters were limited to simple fixed-time operations supplied by data collected locally. At first historical data provided the basis of the metering rate, later enhanced to a real-time basis. Enhanced communication technology over the last 30 years has resulted in an increase in the complexity of ramp metering hardware and control algorithms. The objective of these more advanced ramp metering plans is to use information gathered from several ramps, and to use that information to assist in the prevention of mainline flow breakdowns, queue spillbacks past the off-ramps (resulting in a reduction of outflow from the system), and queue spillbacks from entrance ramps onto secondary road systems *(2)*.

1.6 Types of Ramp Metering Strategies

There are generally three types of ramp metering configurations: single-lane one vehicle per green, single-lane multiple cars per green, and dual-lane metering.

1.6.1 Single-Lane One Vehicle per Green Metering

This approach permits one vehicle to enter the highway through each signal cycle. Signal cycles vary across the country from green, yellow, and red to only green and red indicators. The lengths of the green/yellow interval are established to provide sufficient time for each vehicle to clear the stop bar. The length of the red indication is established to allow the following car to completely stop before continuing. From a practical standpoint, the minimum cycle is four seconds with one second green, one second yellow, and two seconds red for the green/yellow/red cycle, and two seconds green and 2 seconds red for the green/red cycle. The resulting meter capacity is approximately 900 vehicles per hour (vph). However, field studies have revealed that a four-second cycle is not long enough for each vehicle to completely stop prior to continuing. In addition, any indecision on the part of the driver could result in the use of two cycles per vehicle. Field studies have shown that 4.5 seconds is a more realistic cycle, achieved by raising the duration of the red signal to 2.5 seconds. The resulting meter capacity is approximately 800 vph.

1.6.2 Single-Lane Multiple Vehicles per Green Metering

This approach is also known as bulk metering and permits two or more vehicles to enter the highway throughout each green cycle. The most frequent method of using this approach is to permit two vehicles per green. Three or more could be allowed, but this would sacrifice the second objective of ramp metering, which is breaking up vehicle platoons. In addition, contrary to conventional thinking, this approach does not result in a major improvement of capacity over a single-lane one car per green strategy. This is because this approach demands more green and yellow times as ramp speed rises, producing a longer cycle length. Therefore, there are fewer cycles in each hour. As an example, the two vehicles per green approach demands cycle lengths ranging from 6 to 6.5 seconds and produces a metering capacity of 1,100 to 1,200 vph. This result indicates that this strategy does not double the advantages.

1.6.3 Dual-Lane Metering

This approach requires two lanes near the metered ramp. In this strategy, the cycles are alternated for each of the two lanes, typically synchronized (but not always) such that the green cycle never happens in both lanes simultaneously. The green cycles are typically timed to permit a constant headway between vehicles from both lanes. Metering capacities using this strategy can be 1,600 to 1,700 vph. The drawback to this strategy is that many existing single-lane ramps do not have physical space to expand to a dual-lane operation *(3)*.

1.7 Types of Ramp Metering Control

There are generally two types of ramp metering control: local ramp metering and coordinated ramp metering.

1.7.1 Local Ramp Metering

Local Fixed-Time Control is the least complicated method of ramp metering and uses local, pre-timed control. Metering rates are initially set based on methods presented in the Highway Capacity Manual. The rates are then fine-tuned based on local field conditions. Fixed-time 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 (defined as accidents, breakdowns or other random events occurring on the freeway) (*17*).

Local Traffic-Responsive Control utilizes traffic-responsive metering rates that are based on locally determined traffic flow. As opposed to fixed-time control, this method uses loop detectors in the mainline and the on-ramp to determine the metering rate. With a local traffic responsive ramp control system, traffic flow conditions are obtained in real time 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 of local traffic responsive systems is that they are 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.

1.7.2 Coordinated Ramp Metering

Coordinated ramp metering uses information from a series of on-ramps in conditions where a single meter cannot take up the excess mainline demand. This control system utilizes demand-capacity for the entire system rather than each individual ramp. The coordinated traffic responsive metering system is often 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. There are two types of coordinated ramp metering: coordinated fixed-time control and coordinated traffic-responsive control.

1.7.2.1 Coordinated Fixed-Time Control

This method of control is based on constant historical demand, without using real-time data. The advantages of this method are its simple formulation and its methodical style for determining the best solution for a given set of constraints.

1.7.2.2 Coordinated Traffic-Responsive Control

This control method applies traffic-responsive metering to a series of on-ramps *(2).*

1.7.3 Summary of Ramp Meter Control

When the demand of mainline freeway flow itself exceeds the capacity of a bottleneck downstream, local ramp metering of a single on-ramp cannot typically alleviate the problem, because the demand at any one on-ramp is typically a small fraction of the total freeway demand. Even when freeway flow approaches capacity, the mainline can typically handle incoming vehicles one or two at a time. However, when vehicle platoons merge into the freeway, turbulence results, which can create a breakdown in mainline flow and an increase in the frequency of sideswipe and rear-end crashes.

1.8 Assessing the Costs and Benefits of Ramp Metering

The costs associated with ramp metering are capital/maintenance costs related to the hardware and its installation, user costs, and other costs in the form of congestion, pollution, and safety. The benefits include improvements in overall traffic flow, safety, and air quality.

1.8.1 Costs of Ramp Metering

The costs associated with ramp metering consist of installation and maintenance, ramp delay and spillback, and air quality costs.

1.8.1.1 Installation and Maintenance Costs

Installation and maintenance costs will vary, depending on the chosen level of technology and the number of meters installed. Depending on the ramp layout and the size of the overall system, these costs can be substantial. The majority of these costs is associated with the communications mode connecting the ramps to the ramp control center.

1.8.1.2 Ramp Delay and Spillback Costs

Because of the metered ramps, the ramps may develop queues that back up onto nearby surface streets. This results in a negative effect on the surface streets.

1.8.1.3 Air Quality Costs

Metering requires vehicles on the ramp to accelerate and decelerate, which results in increased fuel consumption and more air pollution.

1.8.2 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 eight weeks and a true 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 (*19*).

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.

The benefits associated with ramp metering consist of improved traffic flow, reduction in travel time, improved safety, and higher air quality.

1.8.2.1 Improved Traffic Flow

In theory, ramp metering is supposed to decrease congestion by reducing the duration of congestion and improving the overall mainline traffic flow. Studies have shown that metering increases throughput, with many metered freeways maintaining peak flows exceeding 2,100 VPH per lane. In some cases, flows have been recorded at 2,450 VPH per lane. By removing the stop-and-go characteristics related to congestion, metering also produces increased travel speeds and a decrease in the number of incidents.

1.8.2.2 Reduction in Travel Time

Studies have shown that metering, if well implemented, can result in a substantial increase in peak speeds and a reduction in travel time. Ramp delays may increase, but the system as a whole benefits from significantly lower delays.

1.8.2.3 Improved Safety

Ramp metering produces improved safety of the merging process by restricting vehicle platoons from entering the highway. The stop-and-go conditions on the freeway are eliminated, and traffic flow becomes safer with a more uniform speed distribution.

1.8.2.4 Improved Air Quality

More uniform traffic flow on the highway has been shown to result in a significant reduction in fuel consumption and vehicle emissions.

1.8.3 Equity Issues

Applying a cost-benefit analysis to ramp metering concentrates on the notion of achieving net increases in economic efficiency. However, the process of execution can be of substantial importance. The issues of equity and public support fall within the process element. Due to the fact that ramp metering places an emphasis on maintaining through traffic, metering has a tendency to benefit longer trips at the expense of local trips. Local trips may be redirected to local surface streets, and motorists who live near the affected ramps may be denied access given to suburban residents *(7)*. In the fall of 2000, for example, ramp meters in the Twin Cities, MN area were turned off for eight weeks to assess the effectiveness of the meters. While the State of Minnesota (the State) study focused on the system's overall efficiency, an equity analysis of the delay distribution across space was performed by an independent private party using the data obtained by the State. The private study confirmed the findings of the State, that is, that ramp meters increase the mobility of the freeway system. However, the private study also found that the system becomes more fair, in terms of travel time per mile, travel speed, and travel delay per mile, when the meters are removed. This study found that the shortest trips actually are hurt in mobility terms by ramp metering, but the longest trips receive the most benefit *(8)*. In

Milwaukee, Wisconsin, equity has proven to be a delicate subject. Here, metering rates are adjusted such that average delay is the same on close-in ramps and on outlying ramps *(7)*.

1.9 Past Ramp Metering Evaluations

Numerous evaluation studies have been performed on ramp metering systems around the world. There are difficulties in constructing ideal ramp meter evaluations since it is often impossible to conduct a true "before" and "after" study. Depending on the goals and objectives of each program, the performance measures used can be different. Table 1 summarizes common measures that have been used, along with the impacts resulting from the implementation of ramp metering.

Table 1 Changes in Performance Measures Resulting from Ramp Metering

Performance Measure	Change
Freeway mainline speed	Increases
Accident rate/frequency	Decreases
Overall travel time/delay time	Decreases
Freeway mainline volume/flow/stability of flow	Increases and stabilizes
Fuel savings	Increases
Benefit/cost (B/C) ratio	4:1 to 62:1
Ramp delays	Increases
Arterial vehicle volume	Increases, but insignificant

The recent benchmark comparison conducted in Minnesota, where ramp meters were turned off for an eight week period in 2000. This provided a rare opportunity to examine true "with" and "without" traffic characteristics. The following is a brief summary of the finding of the Minnesota study.

- Mainline speed, travel time savings, safety (crashes), and vehicle volume (throughput) are the most commonly used measures of effectiveness in ramp metering evaluations.
- The Minnesota study's finding of 22 percent savings in freeway travel time was well within the seven percent to 91 percent range observed in other areas (average of 25 percent travel time savings for 13 observations). The 22 percent travel time savings was

also within the range of prior studies conducted on ramp metering within the Twin Cities (14 to 26 percent).

- It appeared that system wide crashes for the Twin Cities increased by 26 percent without ramp metering. The average across eight other ramp meter evaluation studies reviewed by the Minnesota evaluation team was a 32 percent reduction in crashes. The range of values for reductions in crashes due to ramp metering was from five percent to 50 percent. In areas with more than 50 meters, the average crash reduction was 29 percent.
- The Minnesota evaluation showed that there was a 14 percent increase in freeway throughput with ramp metering. The average for the 12 other studies reviewed by the evaluation team was 18 percent, with a range from zero percent to 86 percent. Long Island, Phoenix, Portland, and Seattle (cities with more than 50 meters) showed an average of 38 percent increase in freeway throughput.
- Other evaluation studies have limited information related to emissions impacts of ramp metering. Three other metropolitan areas (Denver, Detroit, Long Island), which evaluated emissions as part of their ramp meter studies, showed improvements in overall emissions due to ramp metering. Long Island showed a 6.7 percent increase in NOx, and the improvements in CO and HC of 17.4 and 13.1 percent, respectively.
- Four areas which evaluated fuel consumption impacts of ramp metering showed savings due to ramp metering ranging from about six percent to 13 percent.
- There is limited information on benefit/cost ratios of ramp metering evaluations. The Minnesota evaluation's benefit/cost ratio of 5:1 for the entire congestion management system and 15:1 for the ramp metering costs only were within the ranges seen for other areas. For five areas (Abilene, Atlanta, Phoenix, Seattle, and previous Minneapolis/St. Paul evaluation efforts), the range of benefit/cost ratios was from 4:1 to 62:1, with an average of 20:1.

2.0 DATA VALIDATION

2.1 Introduction

With the implementation of intelligent transportation systems (ITS), there are new surveillance systems that can serve as data sources for developing mobility-related measures. These measures can be useful for transportation planning, management and operations. Often the data recorded with ITS surveillance systems can be exploited beyond their original purpose. For example, there are thousands of inductive loop detectors present on the streets and highways of America with the potential to provide valuable information for transportation managers if the data they collect are archived and processed carefully.

Perhaps the most common traffic sensor used in traffic management applications, inductive loop detectors are comprised of copper wire loops carrying an electrical current embedded in a shallow saw cut in the road surface. An electromagnetic field is thus established that is interrupted when a vehicle passes over the loop. The action of interrupting the field induces a change in the electrical current passing through the loop which is measured and used to determine the presence of, and to count, vehicles. Sequences of loops can also be configured to measure the speed of vehicles passing across them. The detectors are typically connected to a transportation management center (TMC) via telephone lines or a fiber optic system in order to report the collected data at predefined time intervals. Detectors are capable of measuring individual vehicle arrival times, but most systems are preprogrammed to report data at 20-, 30- or 60-second intervals. Most systems are programmed to report vehicle count, occupancy (the percent time a detector is occupied by a vehicle) and average speed. Some TMCs archive the reported detector data, while others aggregate them to 15-minute intervals and archive them after a filtering process (*20, 21, 22*).

As part of the deployment of a regional ITS program in the Portland, Oregon metropolitan region, we are developing a system to automate the generation of mobility measures using the inductive loop detector data available from the freeway system. Before embarking upon such a program, it is important to understand the accuracy of the data sources. Fortunately, the Portland ITS program includes both inductive loop detectors and closed-circuit television (CCTV) cameras, so it is possible to compare data from two distinct sources. In this section, we describe a rigorous, microscopic validation process that has been developed to validate the inductive loop detector data using ground truth video. In addition, we present several methods for converting the validated data to useful visualizations which are helpful for transportation management and operations. Because we were the first research team to use the 20-second data, a larger portion of this study was consumed with data validation than originally intended.

2.2 Loop Detector Data

The Oregon Department of Transportation (ODOT) currently operates an advanced traffic management system (ATMS) that includes 75 CCTV cameras, 18 variable message signs, an extensive fiber optics communications system and 118 ramp meters, including approximately 436 inductive loop detectors. These detectors collect vehicle count, occupancy and average speed at 20-second intervals. Table 2 shows a sample of the data from one loop detector on the freeway.

Table 2 Archived Data Sample

Station ID	Date/Time	Count	Speed (mph)	Occupancy (%)
1129	4/16/2002 8:00:00 AM	9	40	3
1129	4/16/2002 8:00:20 AM	7	23	6
1129	4/16/2002 8:00:40 AM	8	22	8
1129	4/16/2002 8:01:00 AM	9	33	8
1129	4/16/2002 8:01:20 AM	9	18	6
1129	4/16/2002 8:01:40 AM	6	19	3
1129	4/16/2002 8:02:00 AM	7	29	7
1129	4/16/2002 8:02:20 AM	7	18	5
1129	4/16/2002 8:02:40 AM	8	25	9
1129	4/16/2002 8:03:00 AM	5	30	7
1129	4/16/2002 8:03:20 AM	5	16	1

In addition to a number of system expansion and integration projects, the existing pre-timed ramp metering system is undergoing major improvements with the incorporation of the System Wide Area Ramp Metering (SWARM) system. The ODOT Traffic Management Operations Center (TMOC) currently archives all of its loop detector data at a 15-minute level of aggregation, but makes the more detailed 20-second data available upon request for research purposes. Further, as part of the development of the Portland metropolitan region's archived data user service (ADUS), ODOT is collaborating with the Intelligent Transportation Systems laboratory at Portland State University (PSU) to begin archiving the 20-second loop detector data on a permanent basis.

This study has involved collection of loop detector and video data from the Interstate 5/Barbur Blvd. corridor, as shown in Figure 2, which provides access into downtown Portland from the south with a parallel arterial, complicated freeway geometry and major transit lines.

NORTHBOUND I-5		
Station	**MILEPOST**	**LOCATION TEXT**
Station 1	286.10	Stafford Rd EB to NB
Station 2	286.30	Stafford Rd WB to NB
Station 3	289.40	Nyberg EB to NB
Station 4	289.63	Nyberg WB to NB
Station 5	290.54	Lower Boones NB
Station 6	291.38	Upper Boones NB
Station 7	292.18	ORE 217/Kruseway NB
Station 8	293.18	Haines St NB
Station 9	293.74	Pacific Hwy W NB
Station 10	295.18	Capital Hwy NB
Station 11	296.26	Spring Garden St NB
Station 12	296.60	Multnomah Blvd NB
Station 13	297.33	Terwilliger Blvd NB
Station 14	297.33	Bertha NB
Station 15	299.70	Macadam Ave NB
Station 16	301.09	Morrison BR WB to NB
Station 17	301.09	Morrison BR EB to NB
Station 18	302.50	Broadway NB
Station 19	303.88	Going St NB
Station 20	304.40	Alberta St NB
Station 21	305.12	Portland Blvd NB
Station 22	306.51	Denver Ave NB
Station 23	306.51	Delta Park NB
Station 24	307.46	Marine Dr NB
Station 25	307.90	Jantzen Beach NB

SOUTHBOUND I-5		
Station	**MILEPOST**	**LOCATION TEXT**
Station 1	307.90	Jantzen Beach SB
Station 2	307.35	Swift Blvd/Marine Dr SB
Station 3	305.97	Columbia Blvd SB
Station 4	305.51	Lombard WB to SB
Station 5	305.40	Lombard EB to SB
Station 6	304.85	Portland Blvd SB
Station 7	304.08	Alberta St SB
Station 8	303.90	Going St SB
Station 9	303.10	Greeley Ave SB
Station 10	302.17	Wheeler SB
Station 11	299.25	Hood Ave SB
Station 12	291.91	ORE 217 EB to SB
Station 13	291.25	Upper Boones SB
Station 14	290.40	Lower Boones SB
Station 15	289.38	Nyberg SB

Figure 2 Interstate 5 Location Map

2.3 Loop Detector Count Validation

The aim of this analysis was to compare loop detector counts with "ground truth" counts obtained from video data in order to determine the level of loop accuracy. Video data from camera 48 on southbound I-5, MP 299.25, was recorded between 4:00 p.m. and 6:45 p.m. on Thursday, January 25, 2001. The loop detector data were requested from ODOT for the same location and the same period of time to be used in the validation process. Figure 3 shows the location and the view of the study segment.

○ Camera # 48, Southbound I-5 MP 299.25.
Hood River Ave

Figure 3 View From Camera #48

2.3.1 Video Data

The vehicles were manually counted using video data by establishing a reference point on the video monitor. The arrival time of each vehicle to the reference point was recorded using a simple computer program that records the time when a computer key is pressed. This method was used to record the number of cars traveling in each lane and on the ramp. Table 3 shows an example of the raw data obtained from the video.

Table 3 Sample Video Data

Vehicle Arrival Time			Count
Hours	Minutes	Seconds	
16	14	1.16	1
16	14	2.09	2
16	14	3.25	3
16	14	4.40	4
16	14	6.49	5

2.3.2 Loop Detector Data

The loop detector data used were recorded every 20 seconds from loop detectors located at Hood River Ave. on southbound I-5, MP 299.25. Table 4 shows an example of the data where the first column corresponds to the loop detector identification number. Note that the speed and occupancy data needed to be multiplied by 256 in order to obtain the correct values(this is due to a system error that has been since been corrected as a result of this study).

Table 4 Sample Loop Detector Data

DetectorId	SampleStart	Volume	TimeAveSpeed	TimeOccupancy
1616	4:00:00 PM	3	0.253906	0.015625
1616	4:00:20 PM	2	0.226562	0.003906
1616	4:00:40 PM	5	0.246094	0.027344
1616	4:01:00 PM	2	0.265625	0.003906
1616	4:01:20 PM	1	0.234375	0.003906
1616	4:01:40 PM	5	0.246094	0.007813
1616	4:02:00 PM	3	0.265625	0.019531
1616	4:02:20 PM	3	0.246094	0.003906

2.3.3 Observations

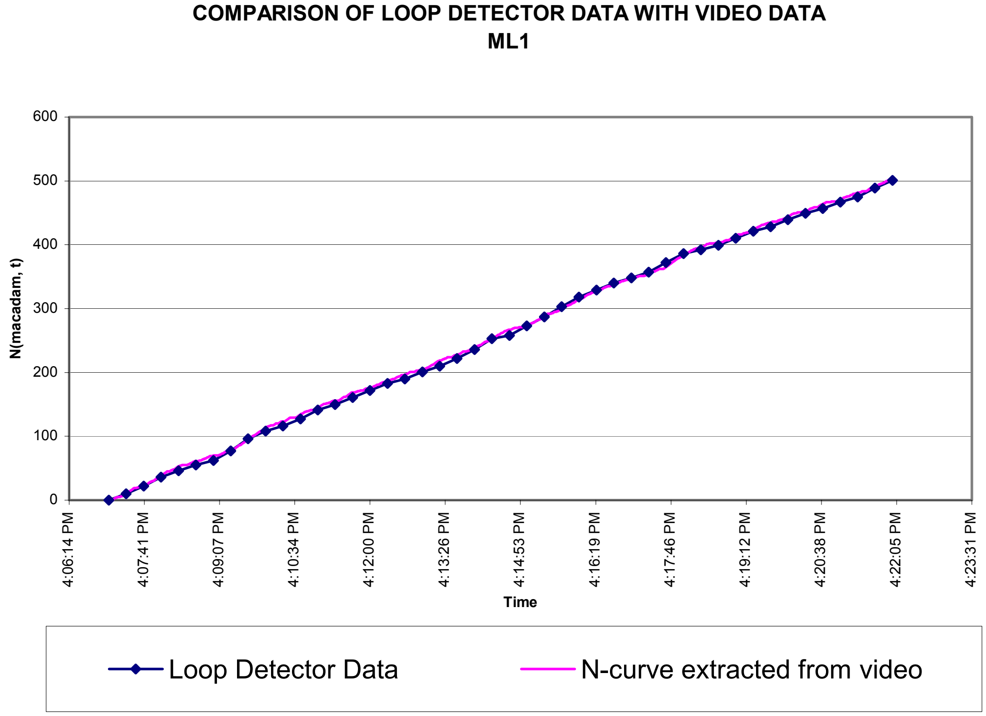
The total number of vehicles reported from the loop detectors and the video data between 4:00 p.m. and 4:30 p.m. were established. The final counts for the mainline and the ramp was very similar using both loop detector and video data. However, they show some differences in the total number of vehicles, as shown in Table 5. Lane 1 corresponds to the median lane and Lane 3 corresponds to the shoulder lane. It is possible that the differences are due to lane changing or human error.

Table 5 Loop Detector and Video Count Comparison

Total Vehicle Counts			
	Loop Detector	Video	Difference
Lane 1	501	504	3
Lane 2	479	480	1
Lane 3	325	324	1
Ramp	146	145	1

Figure 4 shows a comparison of loop detector and data with vehicle arrival times plotted cumulatively. In order to compare video data with loop data both data sources must be sampled in the same time period. ODOT's Region 1 TMOC provided confirmation that the clocks for the video cameras and the loop station controller are synchronized using an internet-based clock system. As shown in the upper figure, the cumulative vehicle arrival curves are aligned almost perfectly. The lower curve uses an oblique axis to magnify the details of the vehicle arrival patterns. As shown, these patterns are also aligned remarkably well, though the individual vehicle level data extracted from the video archive reveals more about the fluctuations in the vehicle arrivals (and headways) than does the loop detector data. Figures 5, 6 and 7 show the comparisons for lanes 2, 3 and the ramp with similar results.

Figure 4 Lane 1 Comparison



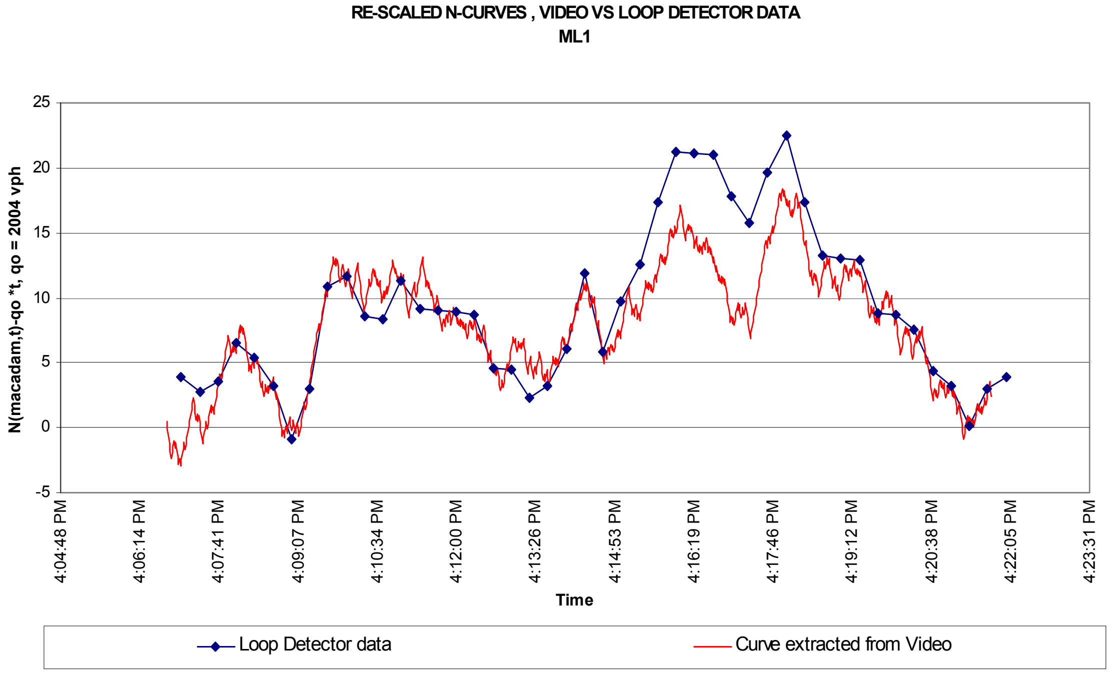
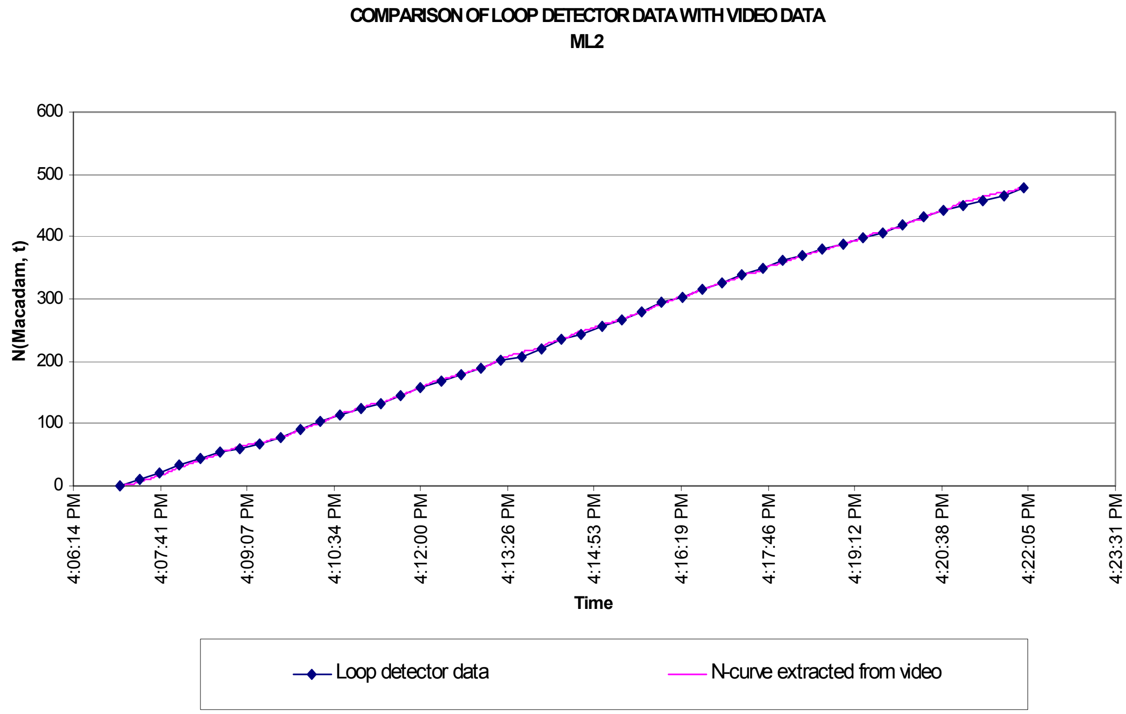


Figure 5 Lane 2 Comparison



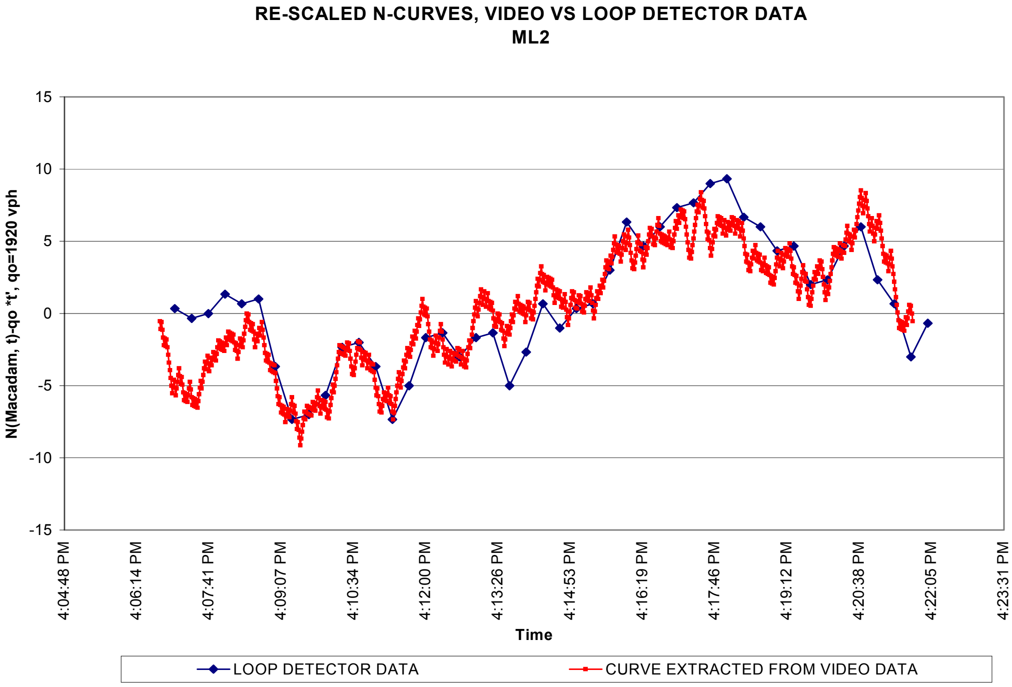
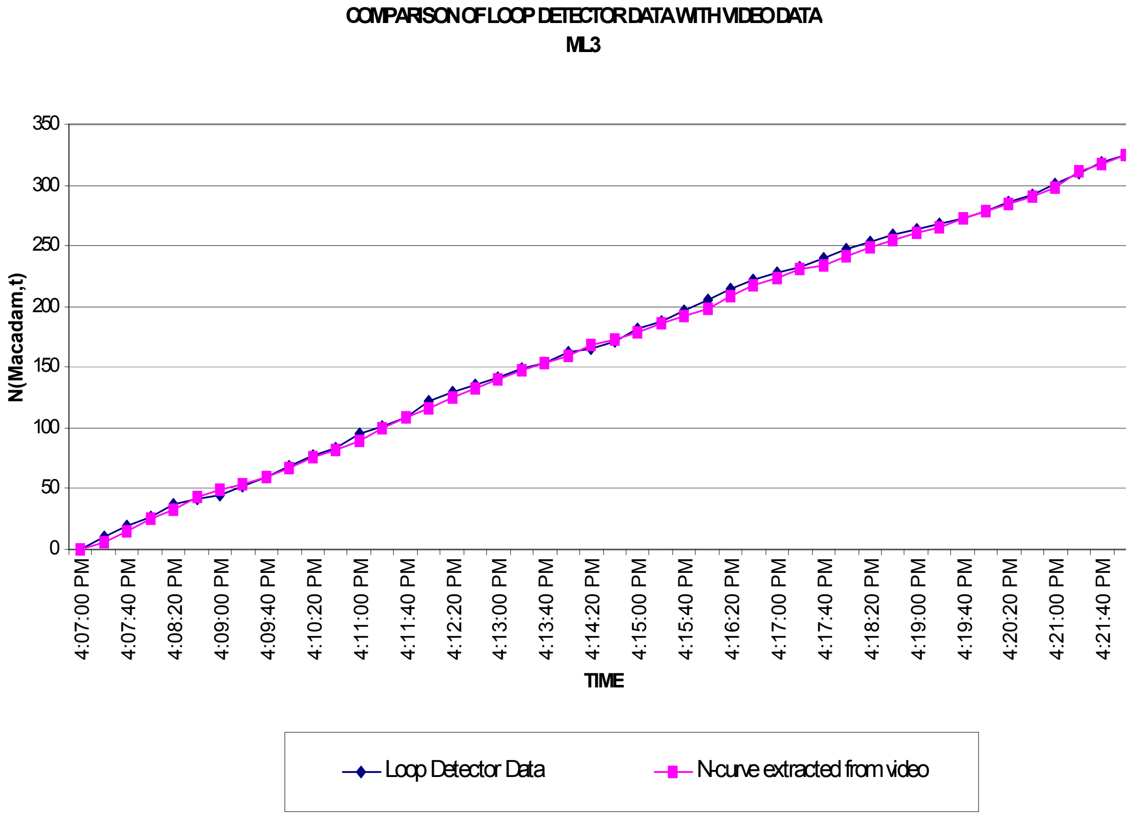


Figure 6 Lane 3 Comparison



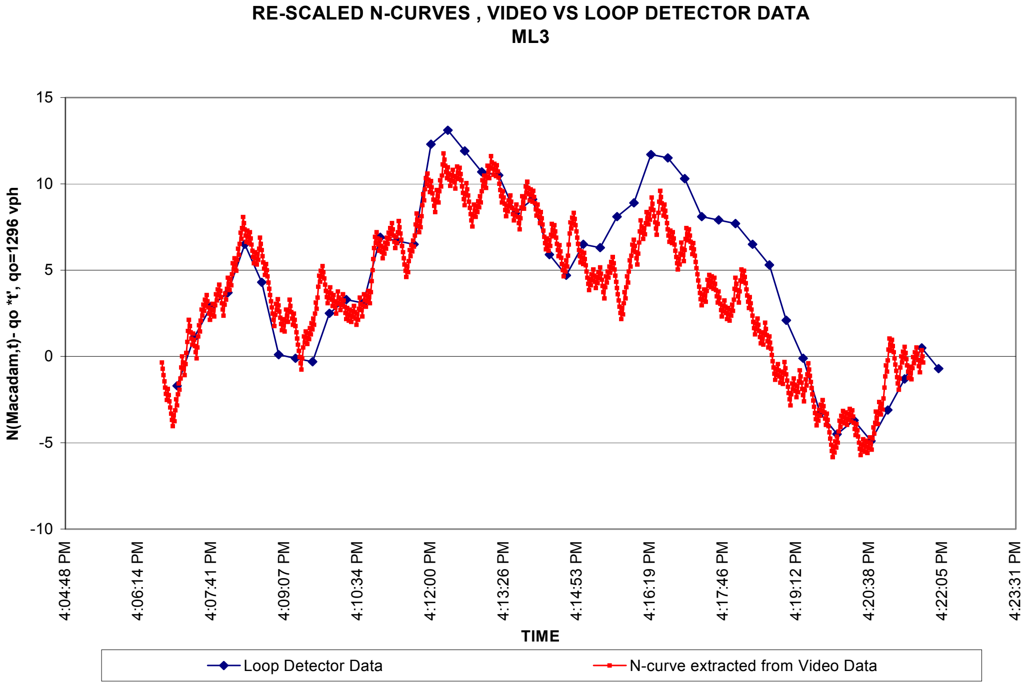
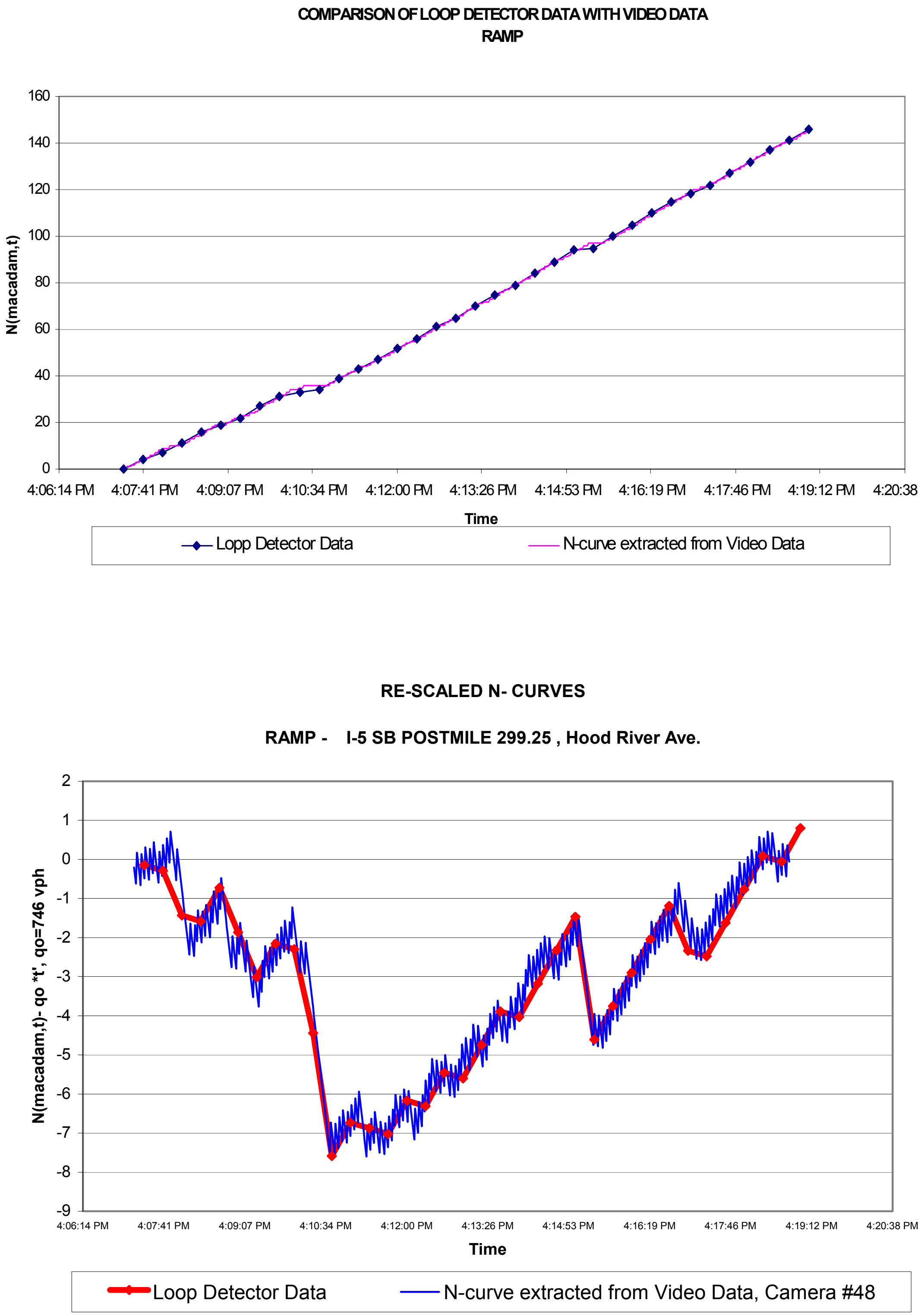


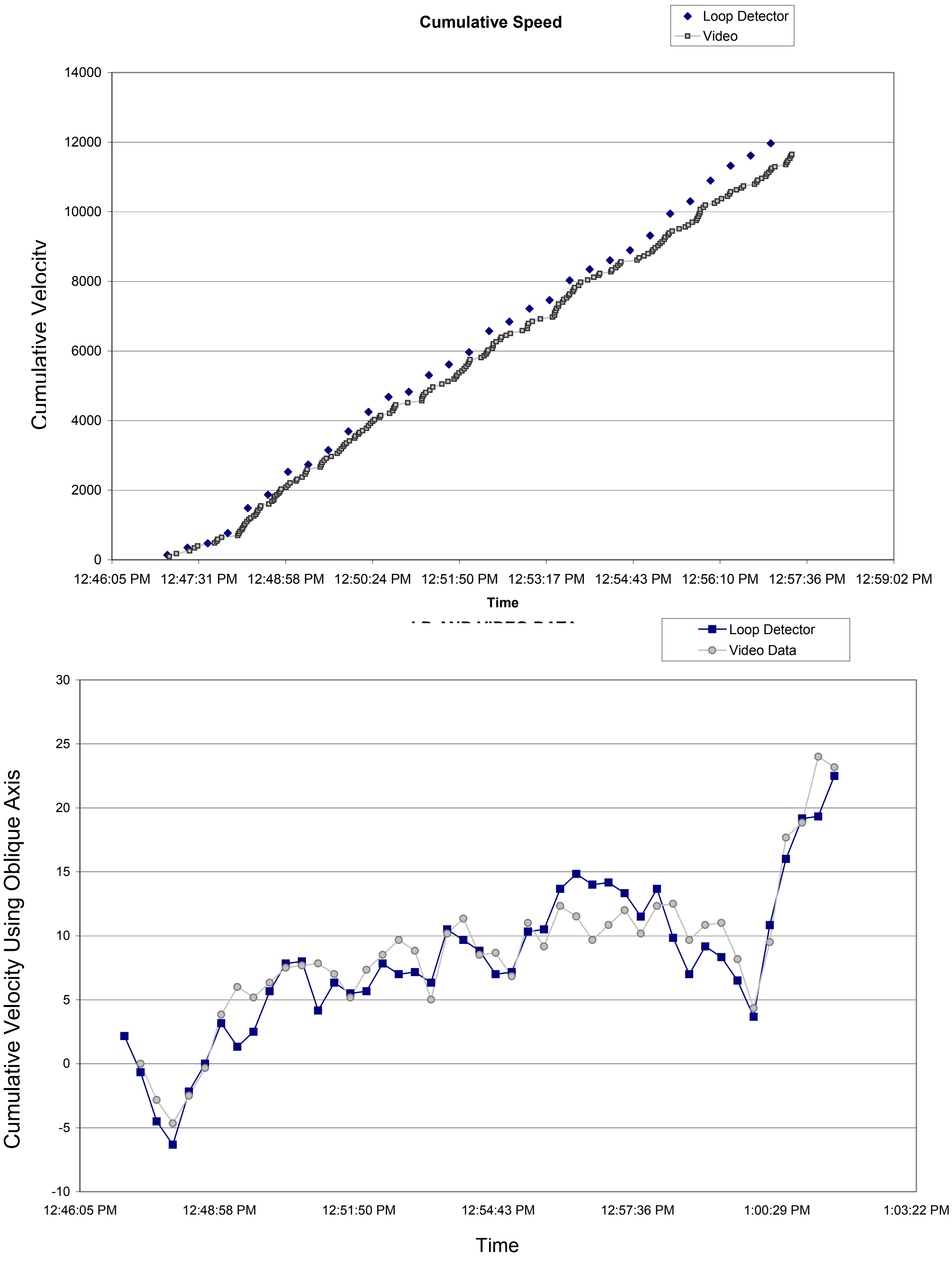
Figure 7 Ramp Comparison



2.4 Loop Detector Speed Validation

Some preliminary analysis of the speed data recorded by the loop detectors is shown in Figure 8. Speeds were recorded manually from video data (arrival and departure times of each vehicle were recorded over a short fixed distance). As shown, the speeds were plotted cumulatively, with similar total values over a ten-minute period. Using an oblique y-axis (lower figure) to magnify the details of the fluctuations in speed, the two curves appear well-aligned. This indicates that the speed data reported by the detectors are valid.

Figure 8 Speed Validation



2.5 Loop Detector Error Analysis

Data from detectors throughout the Portland metropolitan region have been systematically analyzed in order to develop mobility measures such as vehicle miles traveled, vehicle hours traveled, average speed, travel time, delay and other nationally accepted parameters that measure transportation system performance. We are collaborating with regional, state and national agencies to develop these measures on an on-going basis. As a case study to be described here, data from a randomly chosen day (Wednesday, December 19, 2001) will be described and analyzed. This analysis included the observation of data from 71 loop detectors on the northbound I-5 freeway mainline (data are analyzed from individual lanes) and from 25 loop detectors on the northbound on-ramps. In addition, the analysis considered 42 loop detectors on the southbound I-5 mainline and 15 loop detectors on the southbound on-ramps. The traffic management software inserts a code into the archived data file when conditions do not result in a valid data point or when communications are lost. The two codes reported in the data are “-999” and “-1.”

Toward determining the validity of these data, several plotting techniques were used to assist in visualizing the data, including the speed contour diagram shown in Figure 9 for the northbound direction and Figure 10 for the southbound corridor. In these figures, the horizontal axis is time, the vertical axis is distance (indicated by detector station numbers) and the color scale represents average vehicle speed. As shown, any negative value error codes are shown in blue. The –999 and –1 were kept in the analysis, as an experiment. To improve visualization in Figure 9 data reported as “–999” or “–1” were temporarily replaced by “–10”, this improved the color map in the figure. On this particular day, one southbound station (Wheeler, Milepost 302.17) reported values of 0. As shown, negative error codes were observed predominantly during the overnight hours.

In order to further clarify the visualizations, a filter was applied to remove the negative values, as shown in Figure 11 and 12. The filter used simple averaging techniques to account for a negative value in one lane. If there was a negative reading in one of the lanes, the average speed was calculated using the other lanes. Locations where all lanes included –1, -999 or 0 readings were given the color blue and marked as “No information.”

Figure 9 **I-5 Speed Contour**

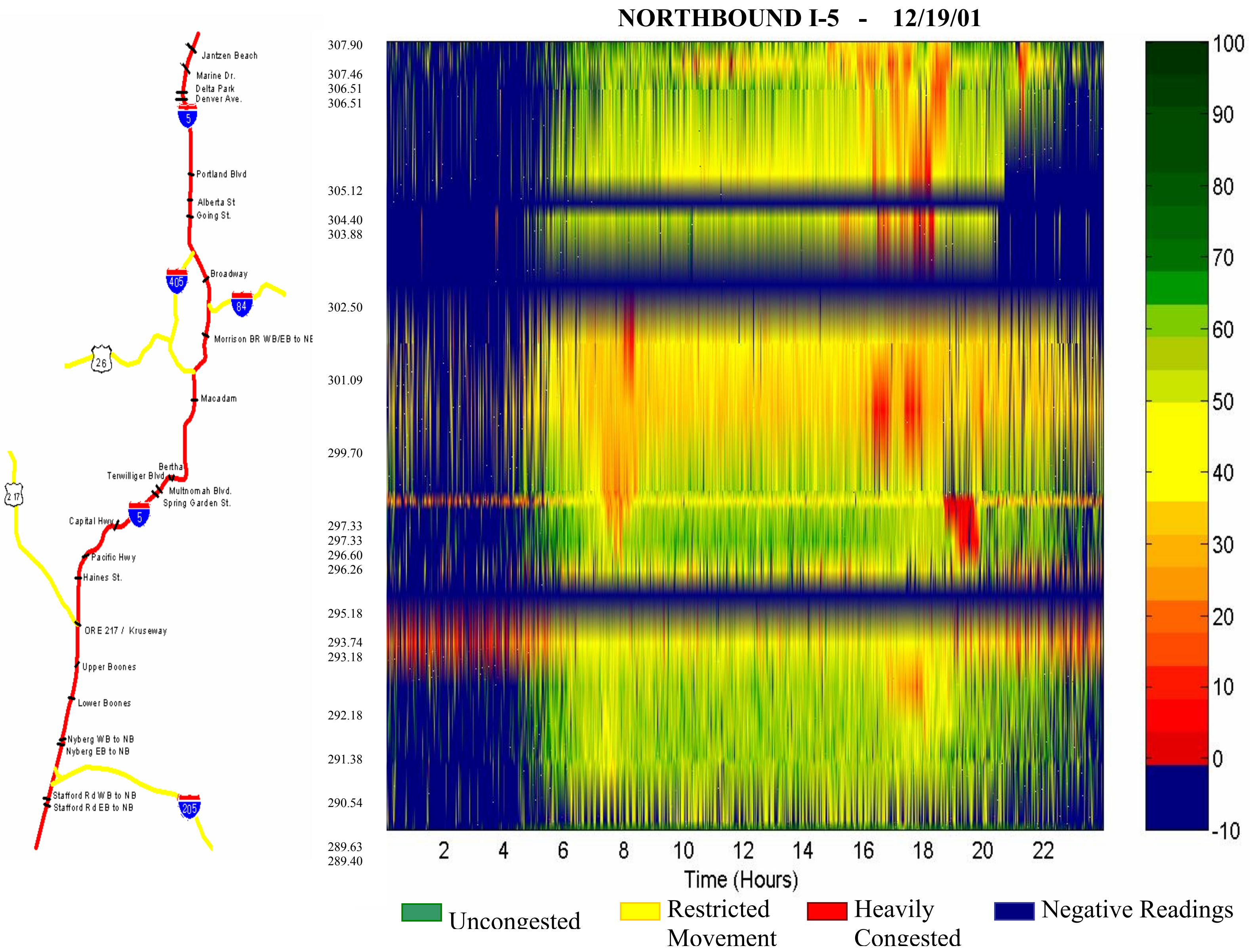


Figure 10 I-5 Speed Contour

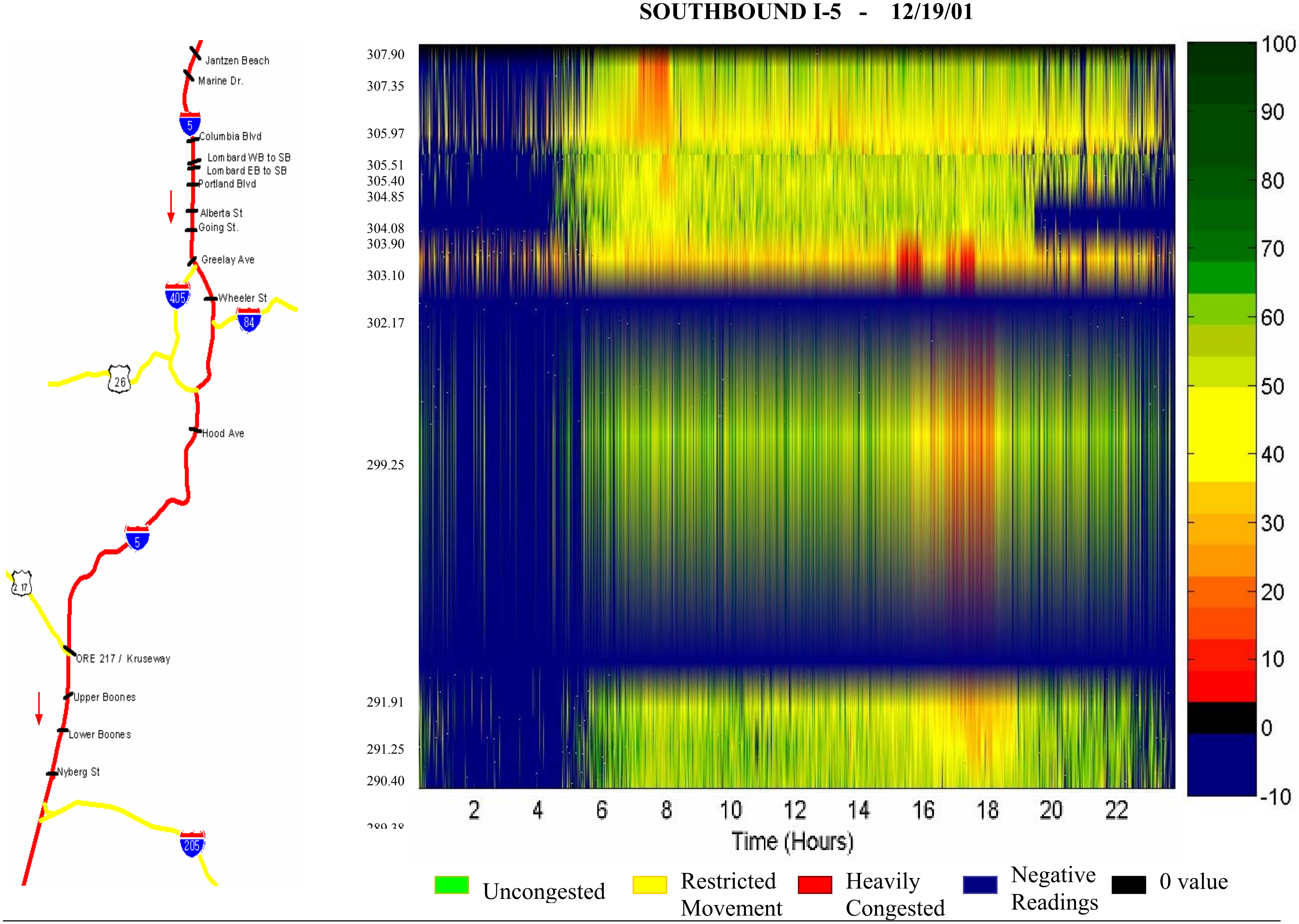


Figure 11 **I-5 Speed Contour Filtered** **NORTHBOUND I-5 - 12/19/01**

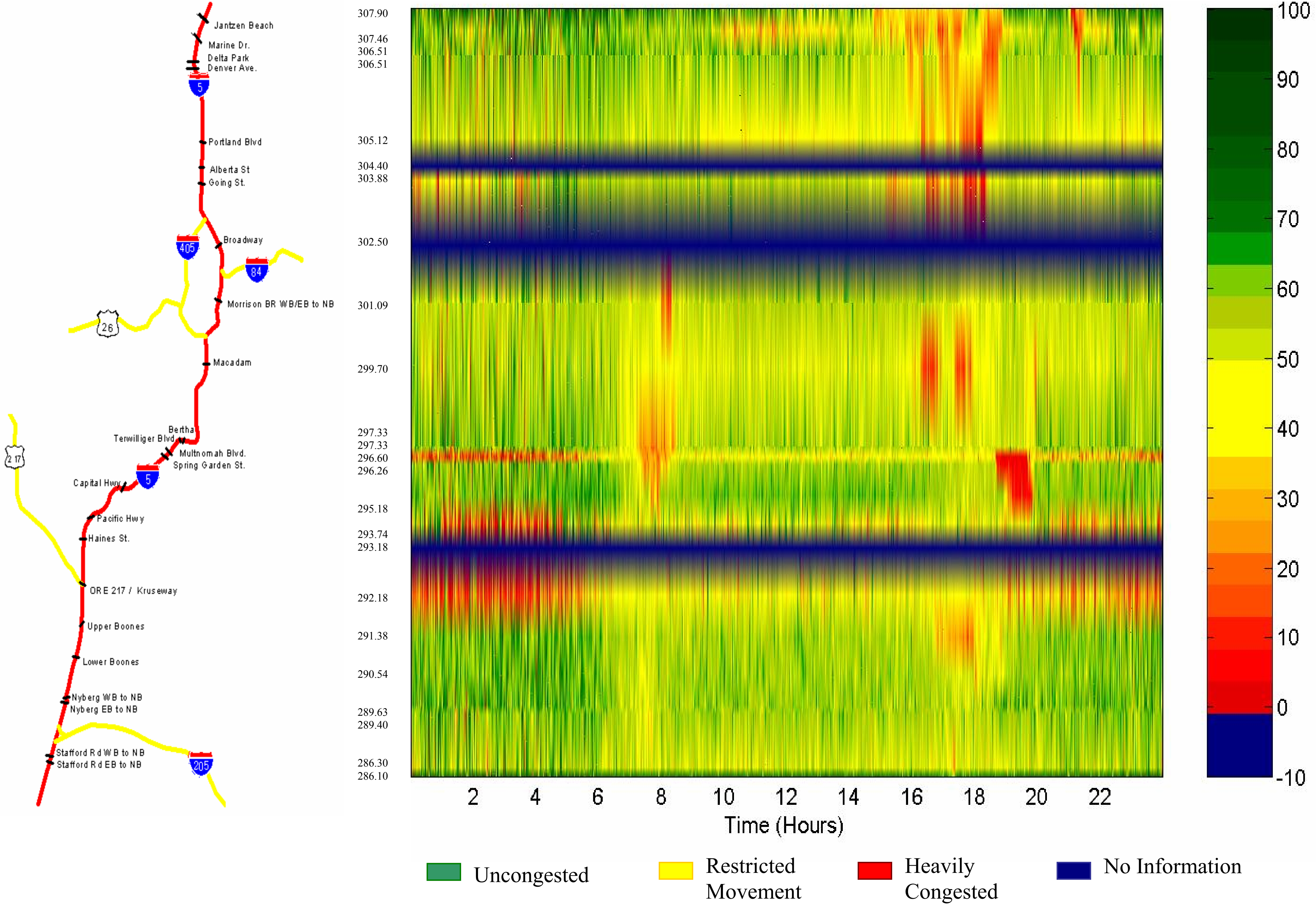
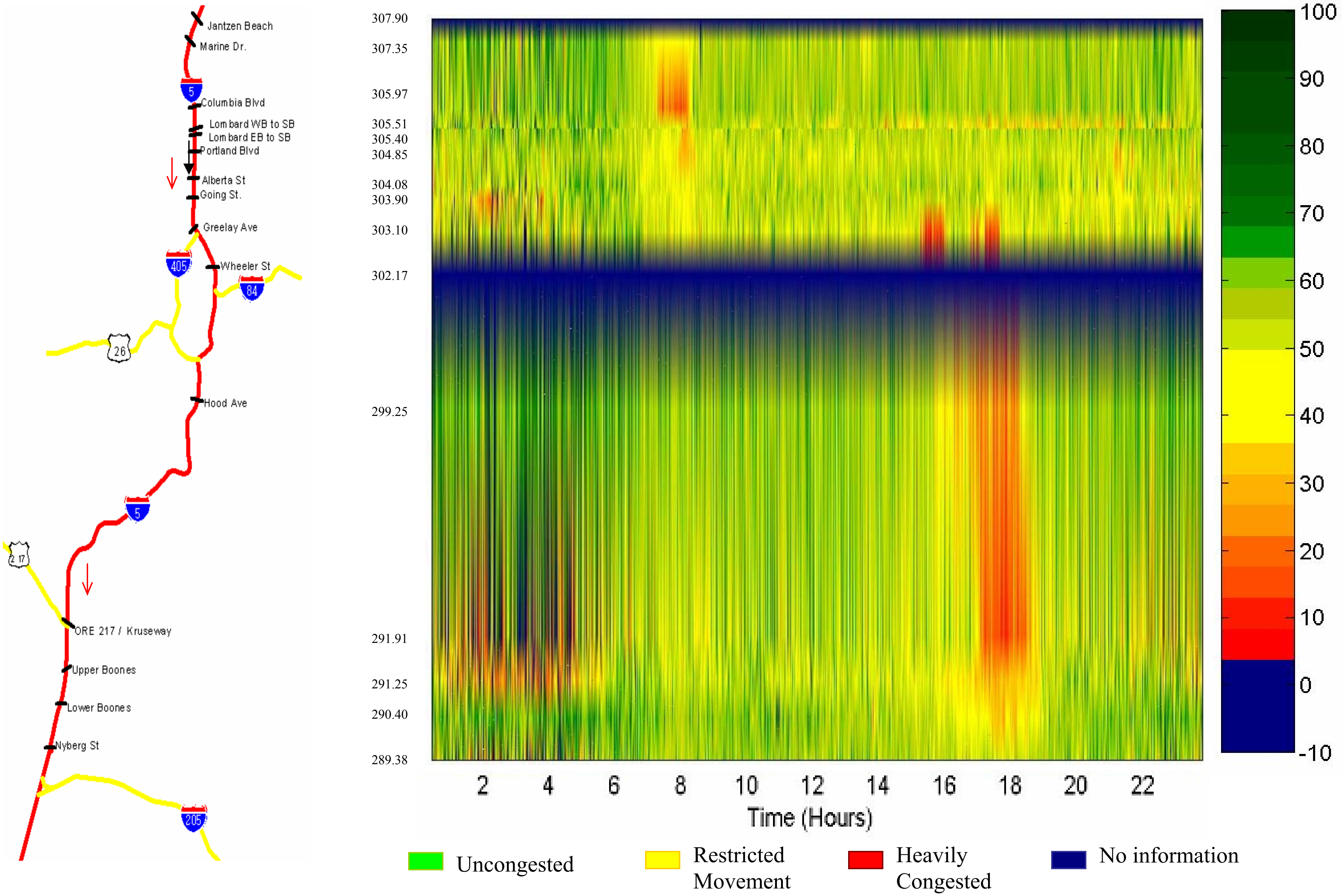


Figure 12 **I-5 Speed Contour Filtered**



In order to understand the sources and impacts of loop detector negative readings, a detailed analysis was performed for one day. Figures 13 and 14 show the total percentage of negative readings on I-5 on the day studied.

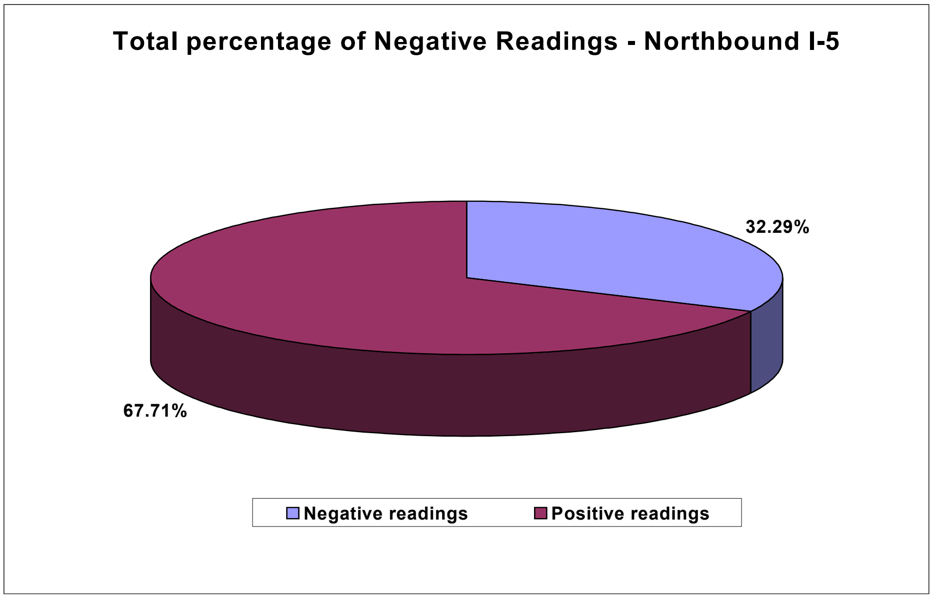


Figure 13 Northbound I-5 Negative Readings

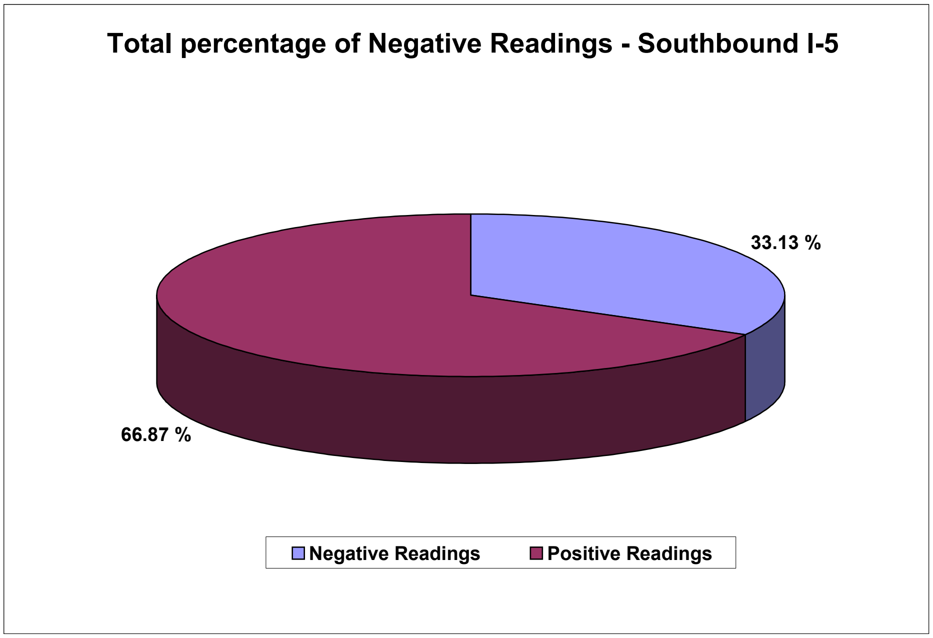


Figure 14 Southbound I-5 Negative Readings

Because the ramp detectors only are designed to measure vehicle counts, there was a great difference in the percentage of negative count values for the ramps and the mainline. Figures 15 and 16 show the distribution of negative readings versus positive readings. For the ramps it can be observed that the negative counts are more that 50% of the total number of counts.

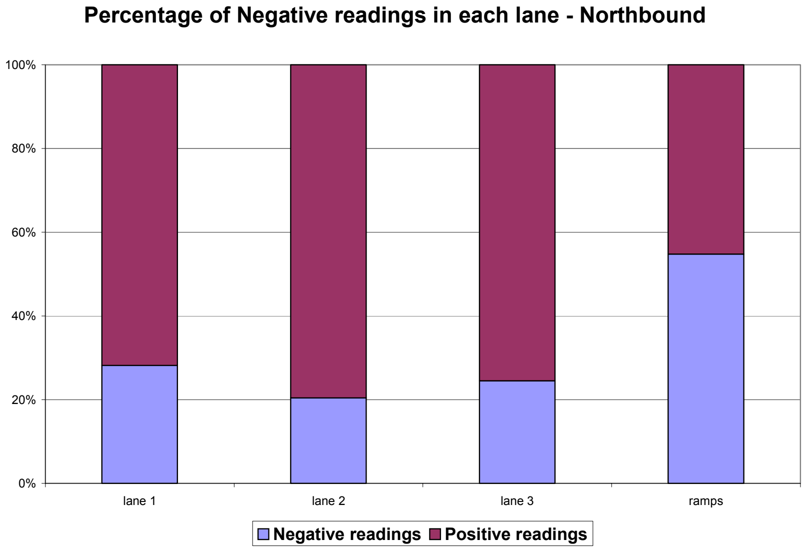


Figure 15 **Northbound I-5 Negative Readings by Lane**

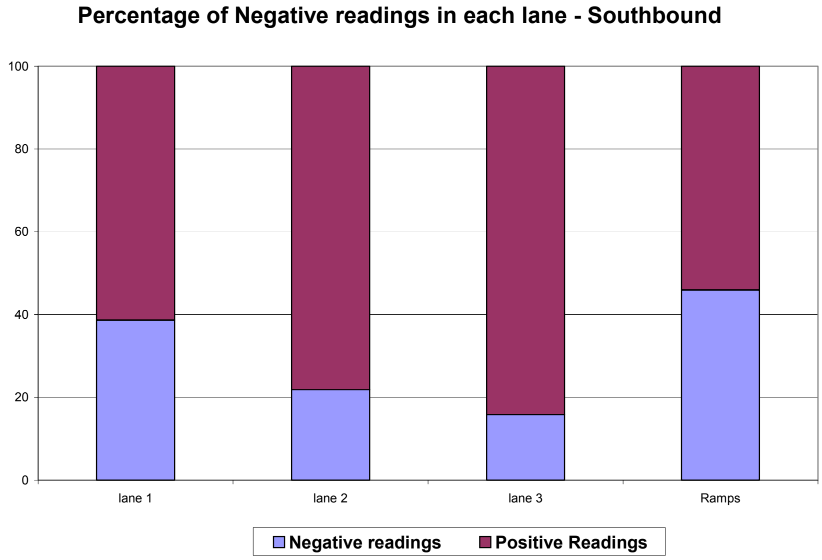


Figure 16 **Southbound I-5 Negative Readings by Lane**

A detailed report of negative readings for each detector is included in Tables 6 and 7 (northbound and southbound respectively). These tables include the loop identification number, the milepost, and the location name in addition to the percentage of negative values.

Individual lanes were also analyzed. Figures 17, 18, 19 and 20 describe the lane-by-lane analysis for northbound I-5 and Figures 21, 22, 23 and 24 describe the lane-by-lane analysis of southbound I-5. There were some loop detectors that reported negative values all day for the northbound and southbound stations; we assumed that these were not functioning during the studied day due to construction or maintenance.

The presence of negative values in the archived 20-second data was quantified in Figure 25, indicating the distribution of positive readings and negative error codes reported for northbound I-5 on the mainline. Similarly, Figure 26 shows the distribution of readings for southbound I-5 on both the mainline and the on-ramps. It can be observed that the majority of negative values occur during the off-peak, overnight hours, approximately between 10:00 p.m. and 5:00 a.m.

Figures 25 and 26 lead one to conclude that the negative error codes indicated either a lack of data or a communication problem. One possibility is that during overnight hours when no vehicles are counted during a 20-second period, the system could be reporting an error code rather than a zero count.

Figures 27 and 28 show the distributions of positive and negative readings for northbound I-5 on the ramps and for the southbound I-5 ramps. It can be observed that the majority of negative values occur during the off-peak hours, approximately from 10:00 p.m. to 6:00 am.

Table 6 Summary of Northbound Readings

NB I-5 -12-19-01					
Station	DETECTOR ID	MILEPOST	LOCATION TEXT	DETECTOR TITLE	Percentage Negative Readings
Station 1	1001	286.1	Stafford Rd EB to NB	I5N286.10-ML1	21.65
	1002	286.1	Stafford Rd EB to NB	I5N286.10-ML2	10.51
	1003	286.1	Stafford Rd EB to NB	I5N286.10-ML3	11.07
	1006	286.1	Stafford Rd EB to NB	I5N286.10-ENTD1	47.07
Station 2	1009	286.3	Stafford Rd WB to NB	I5N286.30-ML1	10.07
	1010	286.3	Stafford Rd WB to NB	I5N286.30-ML2	9.45
	1011	286.3	Stafford Rd WB to NB	I5N286.30-ML3	63.56
	1014	286.3	Stafford Rd WB to NB	I5N286.30-ENTD1	45.87
Station 3	1017	289.4	Nyberg EB to NB	I5N289.40-ML1	25.75
	1018	289.4	Nyberg EB to NB	I5N289.40-ML2	12.29
	1019	289.4	Nyberg EB to NB	I5N289.40-ML3	9.15
	1022	289.4	Nyberg EB to NB	I5N289.40-ENTD1	42.97
Station 4	1025	289.63	Nyberg WB to NB	I5N289.63-ML1	25.01
	1026	289.63	Nyberg WB to NB	I5N289.63-ML2	11.65
	1027	289.63	Nyberg WB to NB	I5N289.63-ML3	8.22
	1030	289.63	Nyberg WB to NB	I5N289.63-ENTD1	34.27
Station 5	1041	290.54	Lower Boones NB	I5N290.54-ML1	25.31
	1042	290.54	Lower Boones NB	I5N290.54-ML2	12.43
	1043	290.54	Lower Boones NB	I5N290.54-ML3	6.09
	1046	290.54	Lower Boones NB	I5N290.54-ENTD1	30.96
Station 6	1057	291.38	Upper Boones NB	I5N291.38-ML1	14.49
	1058	291.38	Upper Boones NB	I5N291.38-ML2	10.07
	1059	291.38	Upper Boones NB	I5N291.38-ML3	14.82
	1062	291.38	Upper Boones NB	I5N291.38-ENTD1	54.46
Station 7	1073	292.18	ORE 217/Kruseway NB	I5N292.18-ML1	1.02
	1074	292.18	ORE 217/Kruseway NB	I5N292.18-ML2	2.50
	1075	292.18	ORE 217/Kruseway NB	I5N292.18-ML3	6.02
	1078	292.18	ORE 217/Kruseway NB	I5N292.18-ENTD1	30.91
Station 8	1089	293.18	Haines St NB	I5N293.18-ML1	100.00
	1090	293.18	Haines St NB	I5N293.18-ML2	100.00
	1091	293.18	Haines St NB	I5N293.18-ML3	100.00
	1094	293.18	Haines St NB	I5N293.18-ENTD1	100.00
Station 9	1097	293.74	Pacific Hwy W NB	I5N293.74-ML1	7.66
	1098	293.74	Pacific Hwy W NB	I5N293.74-ML2	12.99
	1099	293.74	Pacific Hwy W NB	I5N293.74-ML3	27.30
	1102	293.74	Pacific Hwy W NB	I5N293.74-ENTD1	100.00
Station 10	1105	295.18	Capital Hwy NB	I5N295.18-ML1	23.96
	1106	295.18	Capital Hwy NB	I5N295.18-ML2	9.56
	1107	295.18	Capital Hwy NB	I5N295.18-ML3	8.59
	1110	295.18	Capital Hwy NB	I5N295.18-ENTD1	39.55
Station 11	1113	296.26	Spring Garden St NB	I5N296.26-ML1	23.20
	1114	296.26	Spring Garden St NB	I5N296.26-ML2	9.61
	1115	296.26	Spring Garden St NB	I5N296.26-ML3	8.10
	1118	296.26	Spring Garden St NB	I5N296.26-ENTD1	63.16
Station 12	1121	296.6	Multnomah Blvd NB	I5N296.60-ML1	0.39
	1122	296.6	Multnomah Blvd NB	I5N296.60-ML2	0.97
	1123	296.6	Multnomah Blvd NB	I5N296.60-ML3	10.05
	1126	296.6	Multnomah Blvd NB	I5N296.60-ENTD1	34.36

NB I-5 -12-19-01					
Station	DETECTOR ID	MILEPOST	LOCATION TEXT	DETECTOR TITLE	Percentage Negative Readings
Station 13	1129	297.33	Terwilliger Blvd NB	I5N297.33-ML1	8.13
	1130	297.33	Terwilliger Blvd NB	I5N297.33-ML2	8.10
	1131	297.33	Terwilliger Blvd NB	I5N297.33-ML3	24.38
	1134	297.33	Terwilliger Blvd NB	I5N297.33-ENTD1	54.16
Station 14	1137	297.33	Bertha NB	I5N297.33-ML1	8.08
	1138	297.33	Bertha NB	I5N297.33-ML2	8.10
	1139	297.33	Bertha NB	I5N297.33-ML3	24.36
	1142	297.33	Bertha NB	I5N297.33-ENTD1	49.83
Station 15	1145	299.7	Macadam Ave NB	I5N299.70-ML1	15.37
	1146	299.7	Macadam Ave NB	I5N299.70-ML2	8.24
	1149	299.7	Macadam Ave NB	I5N299.70-ENTD1	32.58
Station 16	1152	301.09	Morrison BR WB to NB	I5N301.09-ML1	21.72
	1153	301.09	Morrison BR WB to NB	I5N301.09-ML2	11.81
	1156	301.09	Morrison BR WB to NB	I5N301.09-ENTD1	30.33
Station 17	1159	301.09	Morrison BR EB to NB	I5N301.09-ML1	21.58
	1160	301.09	Morrison BR EB to NB	I5N301.09-ML2	11.83
	1163	301.09	Morrison BR EB to NB	I5N301.09-ENTD1	44.85
Station 18	1173	302.5	Broadway NB	I5N302.50-ML1	100.00
	1174	302.5	Broadway NB	I5N302.50-ML2	100.00
	1177	302.5	Broadway NB	I5N302.50-ENTD1	100.00
Station 19	1180	303.88	Going St NB	I5N303.88-HOV1	33.06
	1181	303.88	Going St NB	I5N303.88-ML2	19.36
	1182	303.88	Going St NB	I5N303.88-ML3	3.50
	1185	303.88	Going St NB	I5N303.88-ENTD1	42.97
Station 20	1188	304.4	Alberta St NB	I5N304.40-ML2	100.00
	1189	304.4	Alberta St NB	I5N304.40-ML3	100.00
	1190	304.4	Alberta St NB	I5N304.40-HOV1	100.00
	1193	304.4	Alberta St NB	I5N304.40-ENTD1	100.00
Station 21	1196	305.12	Portland Blvd NB	I5N305.12-ML2	13.31
	1197	305.12	Portland Blvd NB	I5N305.12-ML3	4.82
	1198	305.12	Portland Blvd NB	I5N305.12-HOV1	34.11
	1201	305.12	Portland Blvd NB	I5N305.12-ENTD1	77.54
Station 22	1204	306.51	Denver Ave NB	I5N306.51-ML2	28.78
	1205	306.51	Denver Ave NB	I5N306.51-ML3	9.52
	1206	306.51	Denver Ave NB	I5N306.51-HOV1	17.30
	1209	306.51	Denver Ave NB	I5N306.51-ENTD1	43.81
Station 23	1212	306.51	Delta Park NB	I5N306.51-ML2	28.59
	1213	306.51	Delta Park NB	I5N306.51-ML3	9.66
	1214	306.51	Delta Park NB	I5N306.51-HOV1	17.43
	1217	306.51	Delta Park NB	I5N306.51-ENTD1	51.19
Station 24	1220	307.46	Marine Dr NB	I5N307.46-ML1	23.82
	1221	307.46	Marine Dr NB	I5N307.46-ML2	8.71
	1222	307.46	Marine Dr NB	I5N307.46-ML3	11.97
	1225	307.46	Marine Dr NB	I5N307.46-ENTD1	19.40
Station 25	1228	307.9	Jantzen Beach NB	I5N307.90-ML1	23.64
	1229	307.9	Jantzen Beach NB	I5N307.90-ML2	8.38
	1230	307.9	Jantzen Beach NB	I5N307.90-ML3	8.91
	1233	307.9	Jantzen Beach NB	I5N307.90-ENTD1	100.00

Table 7 Summary of Southbound Readings

SB I-5 -12-19-01					
	DETECTOR ID	**MILEPOST**	**LOCATION TEXT**	**DETECTOR TITLE**	**Percentage Negative Readings**
Station 1	1233	307.9	Jantzen Beach NB	I5N307.90-ENTD1	100.00
	1237	307.9	Jantzen Beach SB	I5S307.90-ML2	100.00
	1238	307.9	Jantzen Beach SB	I5S307.90-ML3	100.00
	1241	307.9	Jantzen Beach SB	I5S307.90-ENTD1	100.00
Station 2	1244	307.35	Swift Blvd/Marine Dr SB	I5S307.35-ML1	18.38
	1245	307.35	Swift Blvd/Marine Dr SB	I5S307.35-ML2	6.30
	1246	307.35	Swift Blvd/Marine Dr SB	I5S307.35-ML3	20.74
	1249	307.35	Swift Blvd/Marine Dr SB	I5S307.35-ENTD1	48.29
Station 3	1252	305.97	Columbia Blvd SB	I5S305.97-ML1	15.88
	1253	305.97	Columbia Blvd SB	I5S305.97-ML2	3.80
	1256	305.97	Columbia Blvd SB	I5S305.97-ENTD1	38.08
Station 4	1259	305.51	Lombard WB to SB	I5S305.51-ML1	19.95
	1260	305.51	Lombard WB to SB	I5S305.51-ML2	4.98
	1261	305.51	Lombard WB to SB	I5S305.51-ML3	13.98
	1264	305.51	Lombard WB to SB	I5S305.51-ENTD1	61.13
Station 5	1267	305.4	Lombard EB to SB	I5S305.40-ML1	20.46
	1268	305.4	Lombard EB to SB	I5S305.40-ML2	5.63
	1269	305.4	Lombard EB to SB	I5S305.40-ML3	11.60
	1272	305.4	Lombard EB to SB	I5S305.40-ENTD1	45.42
Station 6	1275	304.85	Portland Blvd SB	I5S304.85-ML1	26.30
	1276	304.85	Portland Blvd SB	I5S304.85-ML2	5.76
	1277	304.85	Portland Blvd SB	I5S304.85-ML3	7.73
	1280	304.85	Portland Blvd SB	I5S304.85-ENTD1	45.25
Station 7	1283	304.08	Alberta St SB	I5S304.08-ML1	38.68
	1284	304.08	Alberta St SB	I5S304.08-ML2	19.07
	1285	304.08	Alberta St SB	I5S304.08-ML3	3.66
	1288	304.08	Alberta St SB	I5S304.08-ENTD1	38.01
Station 8	1291	303.9	Going St SB	I5S303.90-ML1	34.07
	1292	303.9	Going St SB	I5S303.90-ML2	22.43
	1293	303.9	Going St SB	I5S303.90-ML3	3.06
	1296	303.9	Going St SB	I5S303.90-ENTD1	33.56
Station 9	1299	303.1	Greeley Ave SB	I5S303.10-ML1	14.63
	1300	303.1	Greeley Ave SB	I5S303.10-ML2	4.84
	1303	303.1	Greeley Ave SB	I5S303.10-ENTD1	99.75
Station 10	1166	302.17	Wheeler SB	I5N302.17-ML1	100.00
	1167	302.17	Wheeler SB	I5N302.17-ML2	100.00
	1170	302.17	Wheeler SB	I5N302.17-ENTD1	100.00
Station 11	1306	299.25	Hood Ave SB	I5S299.25-ML1	19.35
	1307	299.25	Hood Ave SB	I5S299.25-ML2	6.97
	1308	299.25	Hood Ave SB	I5S299.25-ML3	7.22
	1311	299.25	Hood Ave SB	I5S299.25-ENTD1	28.63
Station 12	1081	291.91	ORE 217 EB to SB	I5N291.91-ML1	99.68
	1082	291.91	ORE 217 EB to SB	I5N291.91-ML2	12.18
	1083	291.91	ORE 217 EB to SB	I5N291.91-ML3	7.04
	1086	291.91	ORE 217 EB to SB	I5N291.91-ENTD1	52.82
Station 13	1065	291.25	Upper Boones SB	I5N291.25-ML1	24.91
	1066	291.25	Upper Boones SB	I5N291.25-ML2	11.97
	1067	291.25	Upper Boones SB	I5N291.25-ML3	4.44
Station 14	1049	290.4	Lower Boones SB	I5N290.40-ML1	23.63
	1050	290.4	Lower Boones SB	I5N290.40-ML2	11.83
	1051	290.4	Lower Boones SB	I5N290.40-ML3	5.39
	1054	290.4	Lower Boones SB	I5N290.40-ENTD1	34.84
Station 15	1033	289.38	Nyberg SB	I5N289.38-ML1	24.26
	1034	289.38	Nyberg SB	I5N289.38-ML2	12.34
	1035	289.38	Nyberg SB	I5N289.38-ML3	5.72
	1038	289.38	Nyberg SB	I5N289.38-ENTD1	26.76

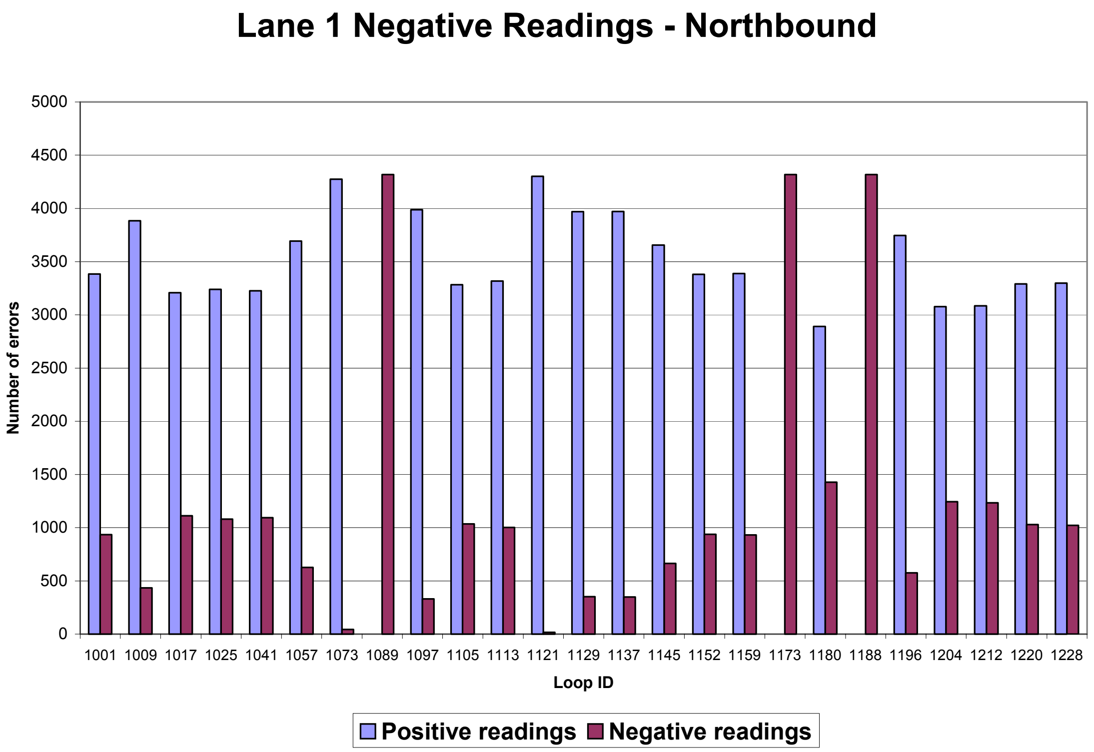


Figure 17 Northbound I-5 Negative Readings - Lane 1

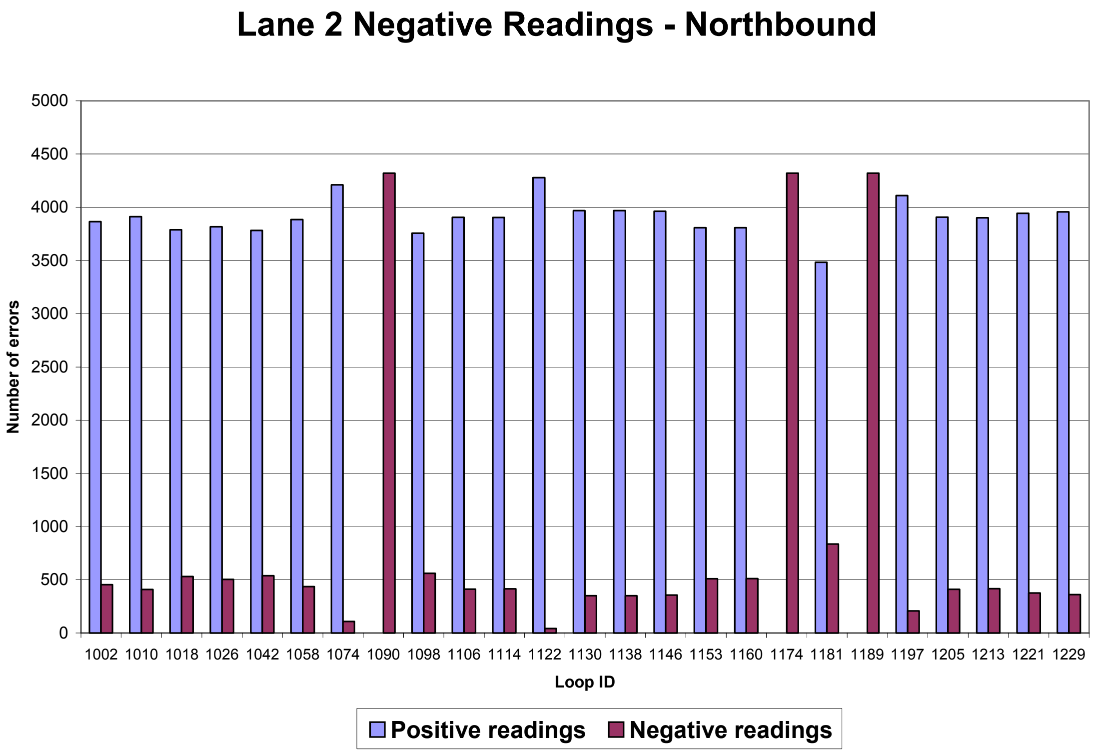


Figure 18 Northbound I-5 Negative Readings - Lane 2

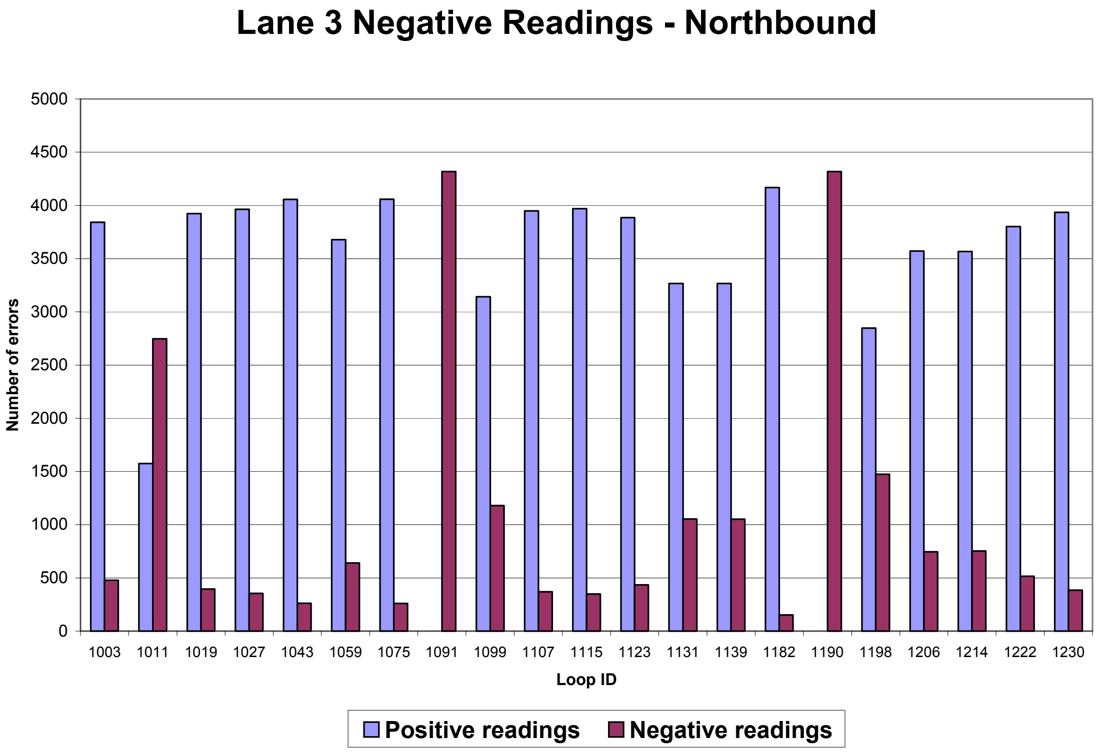


Figure 19 Northbound I-5 Negative Readings - Lane 3

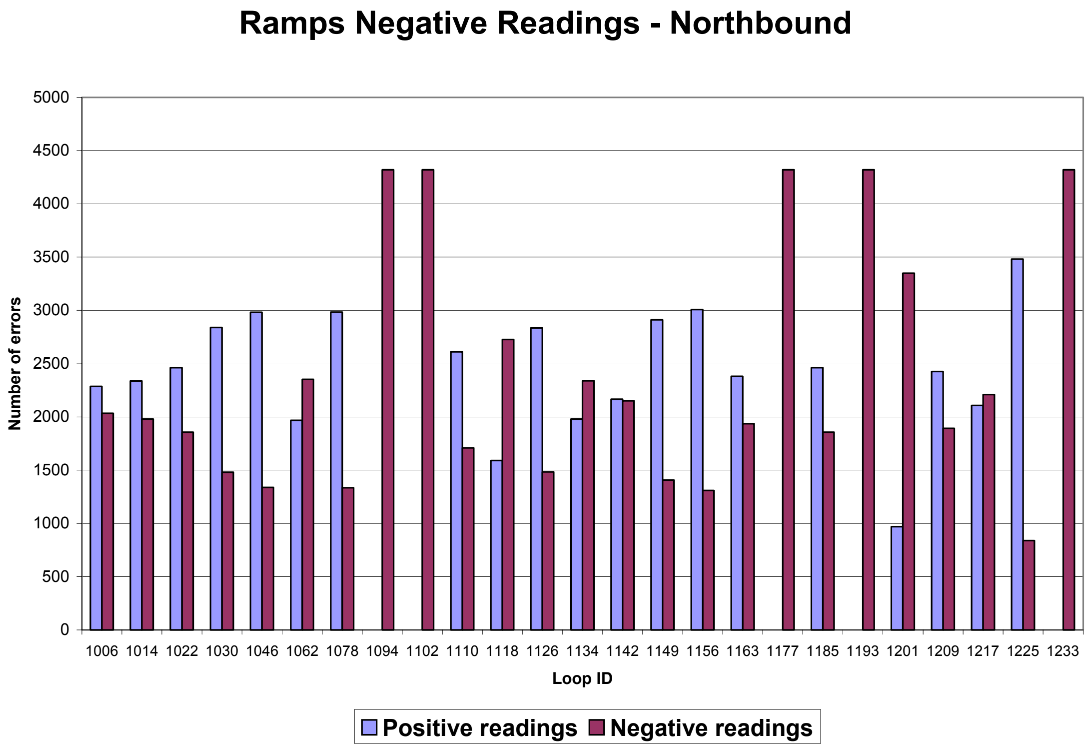


Figure 20 Northbound I-5 Negative Readings - Ramps

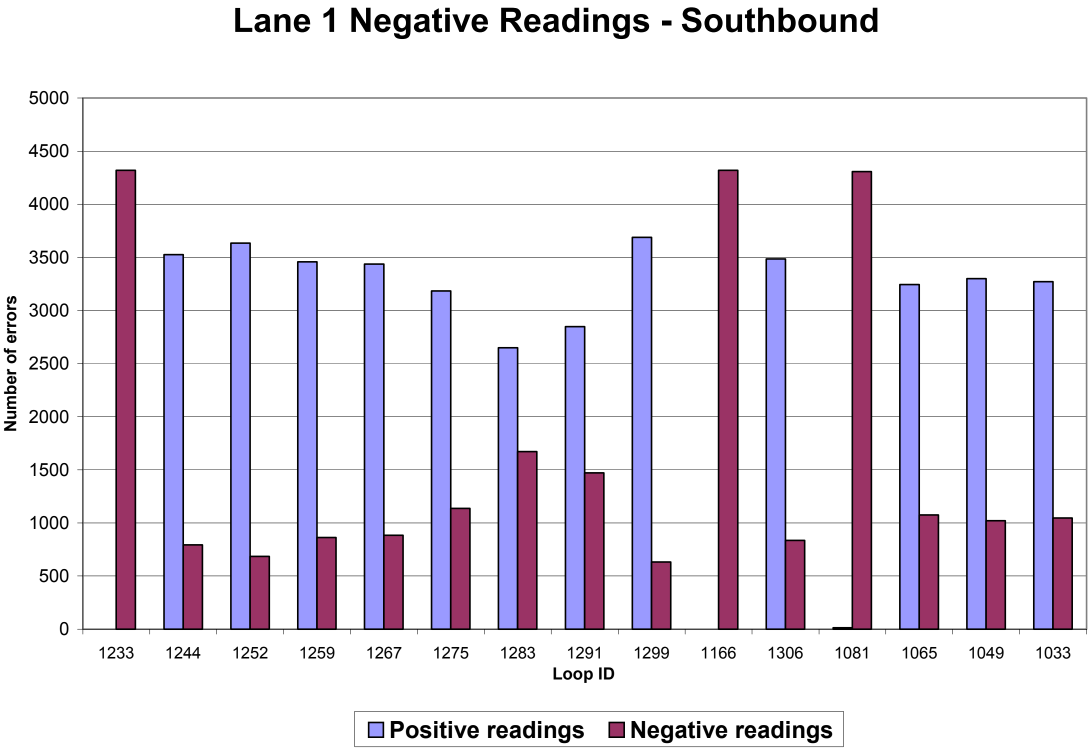


Figure 21 **Southbound I-5 Negative Readings - Lane 1**

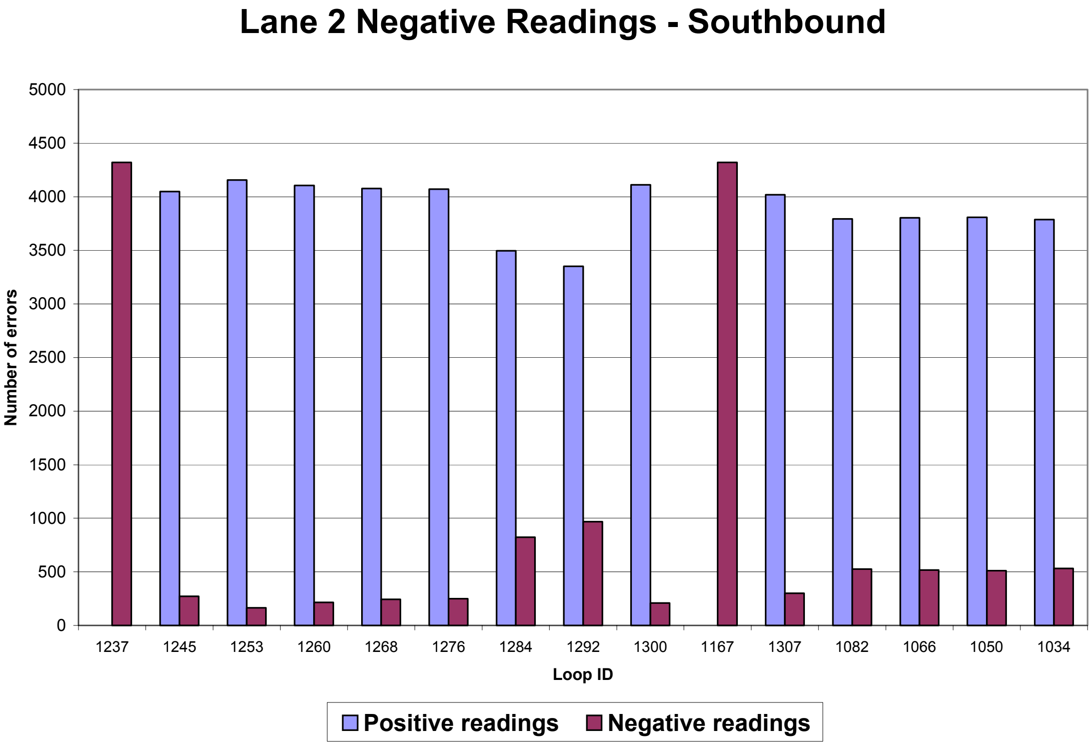


Figure 22 **Southbound I-5 Negative Readings - Lane 2**

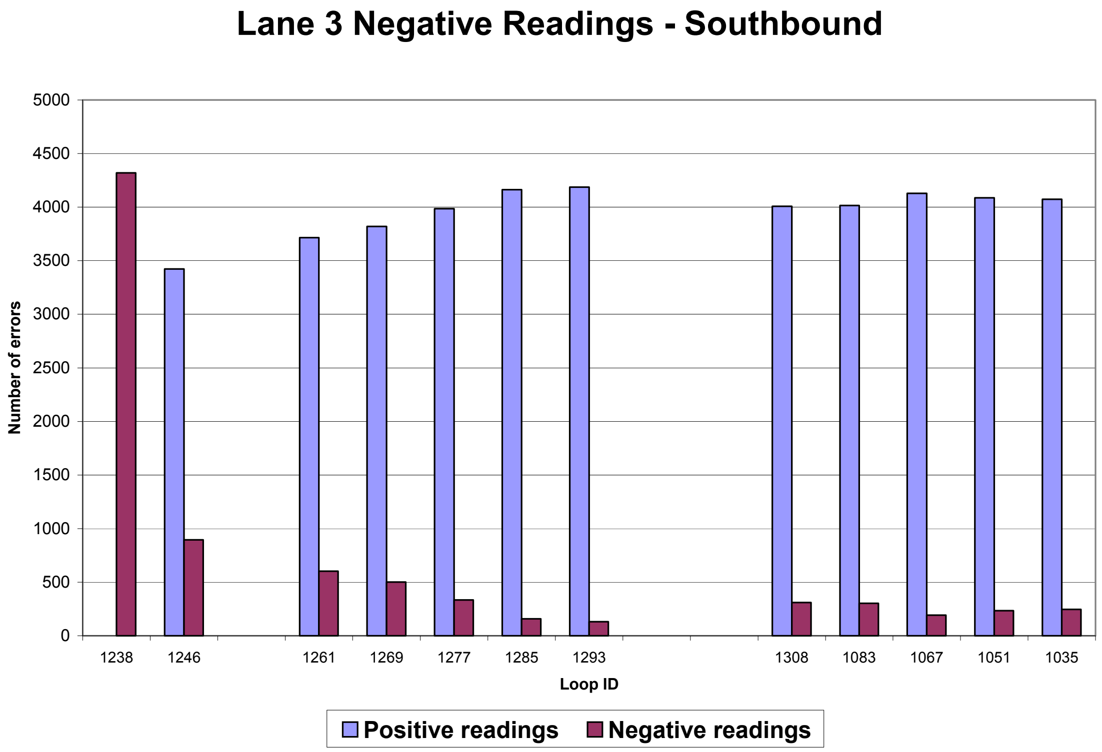


Figure 23 Southbound I-5 Negative Readings – Lane 3

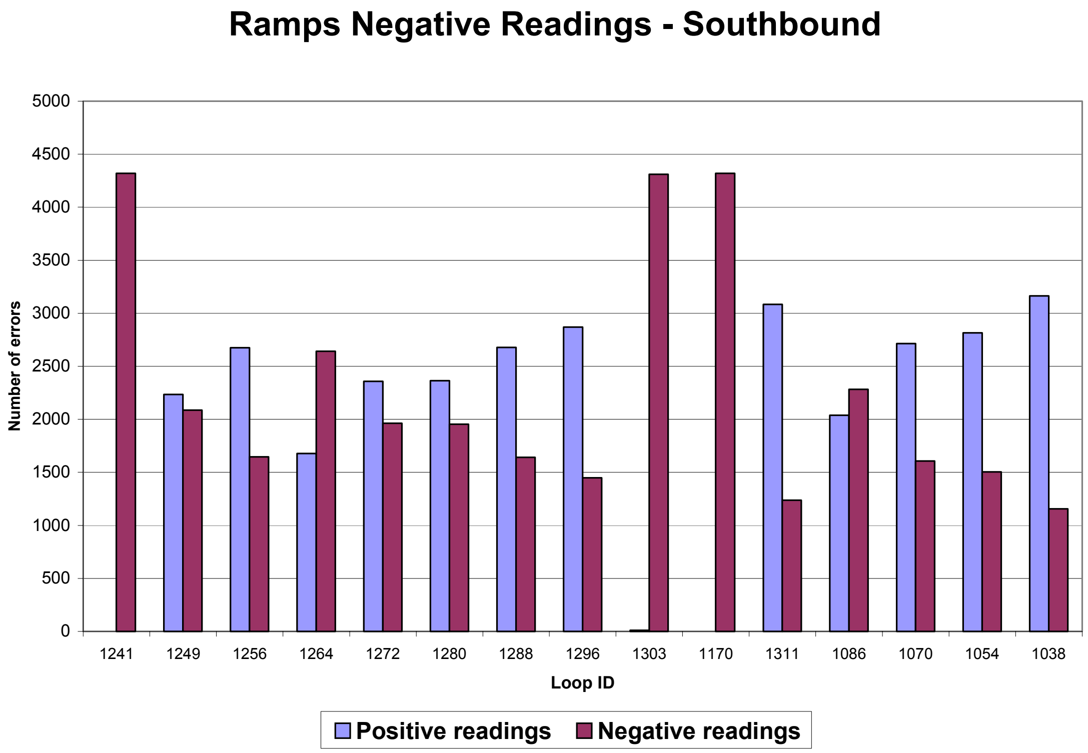


Figure 24 Southbound I-5 Negative Readings – Ramps

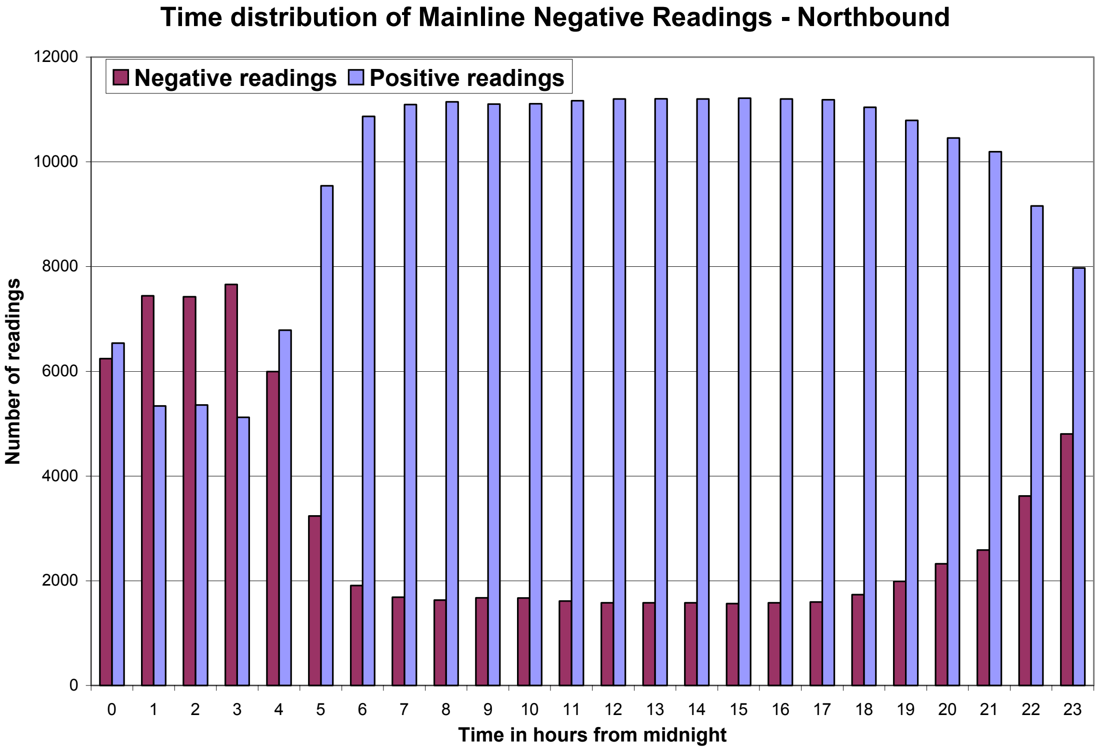


Figure 25 **Loop Detector Data Distribution**

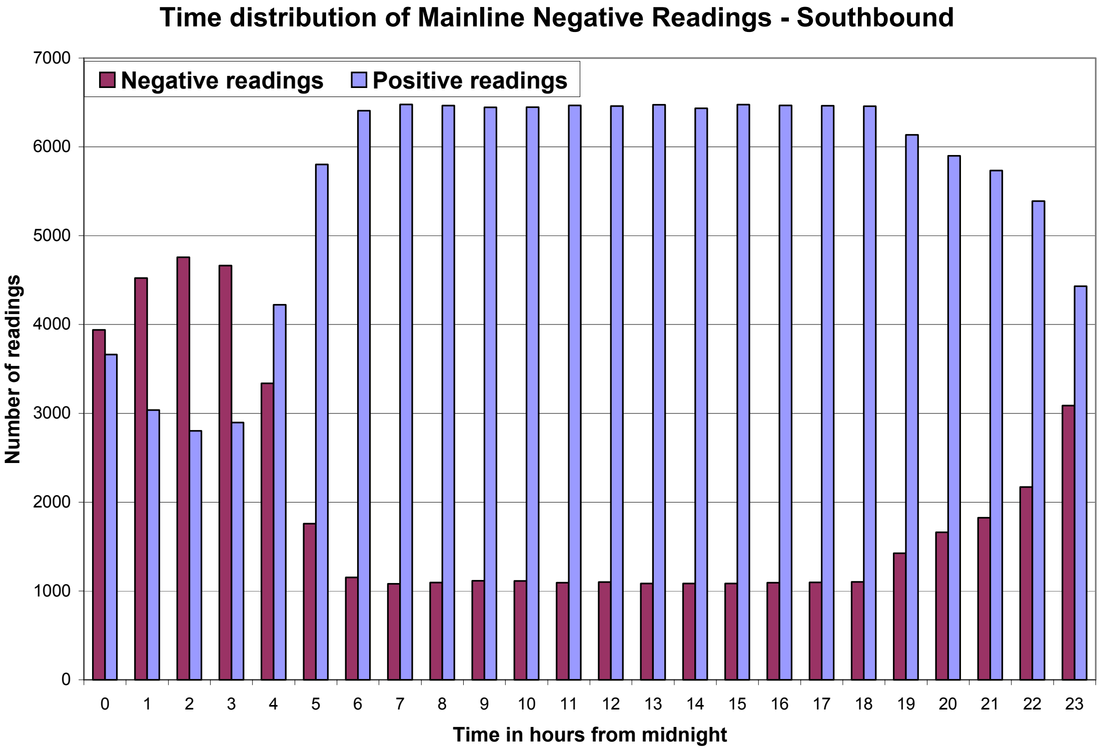


Figure 26 **Loop Detector Data Distribution**

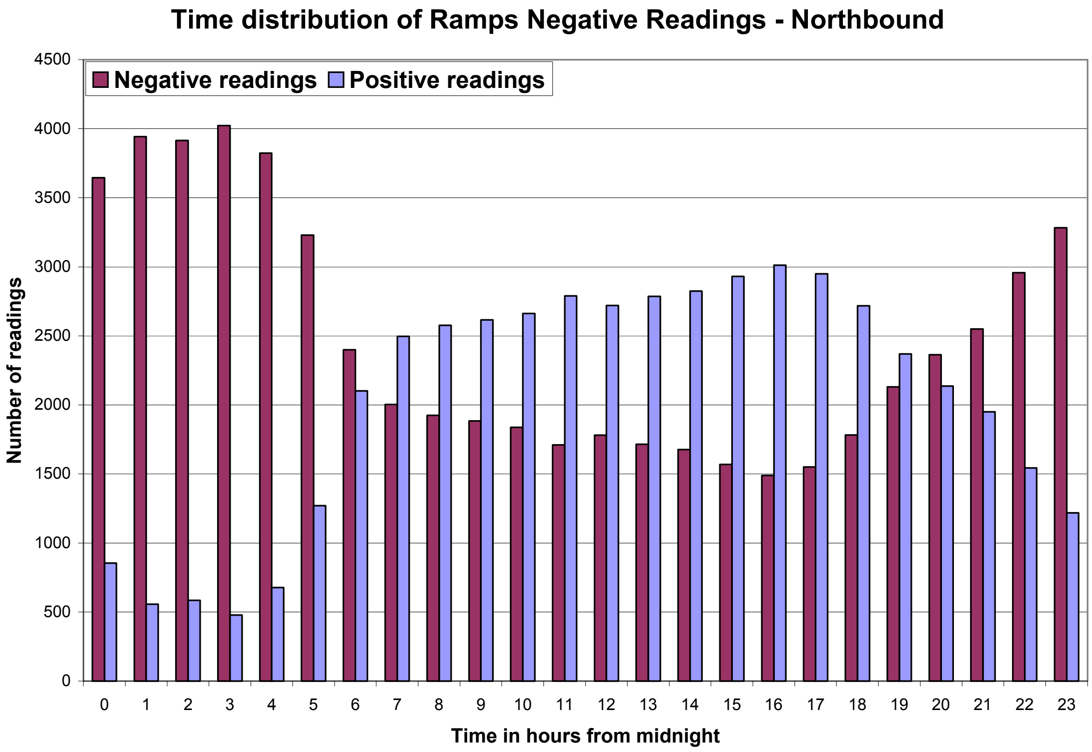


Figure 27 Loop Detector Data Distribution

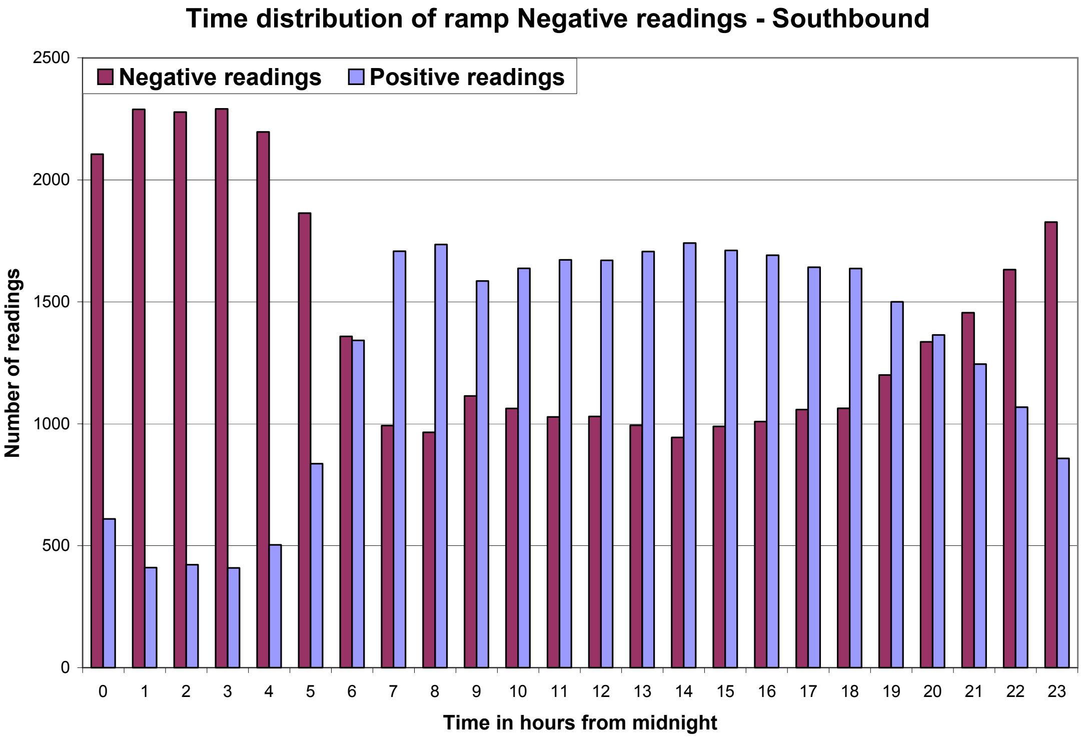


Figure 28 Loop Detector Data Distribution

In order to prioritize the station locations that require detailed review, Tables 8 and 9 indicate the total percentage of negative error codes for each station in the northbound and southbound corridors respectively. Note that the on-ramp detectors are included in the calculations of the percentages of negative error code readings.

Table 8 Loop Detector Summary Northbound

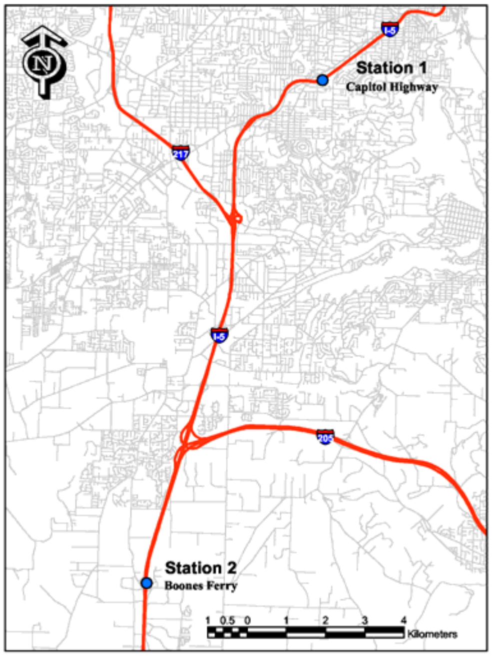
NORTHBOUND I-5			
Station	**MILEPOST**	**LOCATION TEXT**	**Percentage Negative Readings**
Station 1	286.10	Stafford Rd EB to NB	22.57
Station 2	286.30	Stafford Rd WB to NB	32.24
Station 3	289.40	Nyberg EB to NB	22.54
Station 4	289.63	Nyberg WB to NB	19.78
Station 5	290.54	Lower Boones NB	18.70
Station 6	291.38	Upper Boones NB	23.46
Station 7	292.18	ORE 217/Kruseway NB	10.11
Station 8	293.18	Haines St NB	100.00
Station 9	293.74	Pacific Hwy W NB	36.99
Station 10	295.18	Capital Hwy NB	20.42
Station 11	296.26	Spring Garden St NB	26.02
Station 12	296.60	Multnomah Blvd NB	11.44
Station 13	297.33	Terwilliger Blvd NB	23.69
Station 14	297.33	Bertha NB	22.59
Station 15	299.70	Macadam Ave NB	18.73
Station 16	301.09	Morrison BR WB to NB	21.29
Station 17	301.09	Morrison BR EB to NB	26.09
Station 18	302.50	Broadway NB	100.00
Station 19	303.88	Going St NB	24.72
Station 20	304.40	Alberta St NB	100.00
Station 21	305.12	Portland Blvd NB	32.44
Station 22	306.51	Denver Ave NB	24.85
Station 23	306.51	Delta Park NB	26.72
Station 24	307.46	Marine Dr NB	15.98
Station 25	307.90	Jantzen Beach NB	35.23

Table 9 Loop Detector Summary Southbound

SOUTHBOUND I-5			
Station	**MILEPOST**	**LOCATION TEXT**	**Percentage Negative Readings**
Station 1	307.90	Jantzen Beach SB	100.00
Station 2	307.35	Swift Blvd/Marine Dr SB	23.43
Station 3	305.97	Columbia Blvd SB	19.25
Station 4	305.51	Lombard WB to SB	25.01
Station 5	305.40	Lombard EB to SB	20.78
Station 6	304.85	Portland Blvd SB	21.26
Station 7	304.08	Alberta St SB	24.86
Station 8	303.90	Going St SB	23.28
Station 9	303.10	Greeley Ave SB	39.74
Station 10	302.17	Wheeler SB	100.00
Station 11	299.25	Hood Ave SB	15.54
Station 12	291.91	ORE 217 EB to SB	42.93
Station 13	291.25	Upper Boones SB	19.63
Station 14	290.40	Lower Boones SB	18.92
Station 15	289.38	Nyberg SB	17.27

2.6 Site Selection

In order to validate the hypothesis that a negative error code indicates a zero count during the measurement interval, loop detector data were collected and compared with manual and automated video observations at the same locations and during the same time intervals. In order to provide ground truth video data, two ODOT CCTV cameras installed in the I-5 corridor were selected in cooperation with ODOT. The cameras at these locations were directed towards the mainline and the on-ramps during particular study time periods. Figure 29 shows the two selected locations where simultaneous video and loop detector data extraction occurred. As shown, the two locations were the Capitol Highway on-ramp and the Boones Ferry on-ramp.



Projection: NAD 1983 HARN StatePlane Oregon North FIPS 3601

Figure 29 Simultaneous Data Collection Sites on I-5

Figures 30 and 31 show snapshots taken from CCTV cameras at both locations with circles around the studied lanes. The criteria for choosing these locations included having clear visibility during the overnight hours to enable the manual counts to be conducted easily and to avoid errors. Table 10 includes a summary for each location with the detector identification numbers that were used in the study.

2.7 Data Archives

After selecting the locations, ODOT agreed upon the timeframe for ground truth validation on December 20, 2002. From the data visualizations presented above, it was clear that the majority of the negative error code reports occurred during the overnight period between 10 p.m. and 5 a.m. This observation defined the time period during which the traffic data from the CCTV were recorded for the defined locations. A total of 4 hours of CCTV video data were archived for each location. ODOT directed the cameras towards the defined locations between 2:00 a.m. and 6:00 a.m. on the specified date.

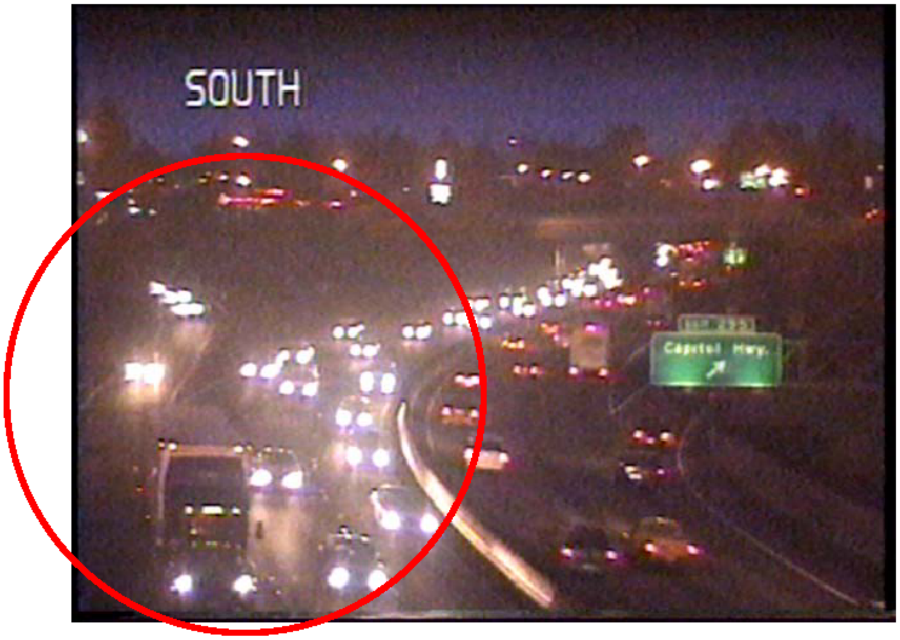


Figure 30 **Camera 27 Facing South at I-5 and Capitol Highway**

Figure 31 **Camera 67 Facing North at I-5 and Lower Boones Ferry**

In parallel with the video archive, ODOT archived the inductive loop detector data for the same time periods. In the interest of recording the archived loop detector data at the most detailed level possible, ODOT agreed to preserve the loop detector data at the 20-second level for the same periods to facilitate detailed analysis.

Table 10 **CCTV Camera Summary**

	Capitol Highway	**Lower Boones**
Location	I-5 & Capitol Highway	I-5 & Lower Boones Ferry Rd
Camera Number	27	67
Direction Validated	I-5 Northbound	I-5 Northbound
Camera Angle	Camera faces south to capture the image of northbound traffic. Focus on both I-5 and on-ramp traffic.	Camera faces north to capture the image of northbound traffic where the on-ramp merges.
Detector ID	1105, 1106, 1107, and 1110.	1041, 1042, 1043, and 1046.

As reported previously, the loop detector data included numerous readings of "-999" and "-1." Approximately 33% of the total readings reported by the loop detectors per day were recorded as negative error codes. A total of 51% of these error code readings occurred between 12 a.m. and 5 a.m. for the freeway lanes and 38% of the ramp detector readings were error codes during the same period. As noted above, these error codes appeared during periods with low traffic volumes when it was plausible that detectors counted zero vehicles during the corresponding 20-second measurement intervals. In order to test this hypothesis several analyses were performed.

2.8 Graphical Analysis

The first step in attempting to validate the loop detector data using the ground truth CCTV data was to synchronize the clocks. The two data sources provide time stamps but are not currently synchronized in time. There was no reference information to indicate whether the clocks had been synchronized previously. The easiest method for determining the time lag between reported times in the loop detector data and the CCTV system was to use curves of cumulative vehicle count versus time, $N(x,t)$. Vehicle arrival times recorded manually from video and loop detector counts were plotted cumulatively on one graph for each station as shown in Figure 32. For this ten-minute time interval at Lower Boones Ferry Rd., the figure indicates that there was no difference between manual and the automated counts except for a time offset. To correct the time offset, the loop data were shifted by 2 minutes as shown in Figure 33.

Now the curves are perfectly superimposed. Even though there are some gaps between the two lines, they can be explained by the nature of the loop detector data that reports the presence of vehicles over 20-second intervals. Similar plots were constructed for all 8 detectors during the five time periods shown in Table 11. After observing the $N(x,t)$, it is clear that most loop detector counts match the counts observed via the CCTV surveillance system. The exception was loop 1106, which will be the subject of further analysis.

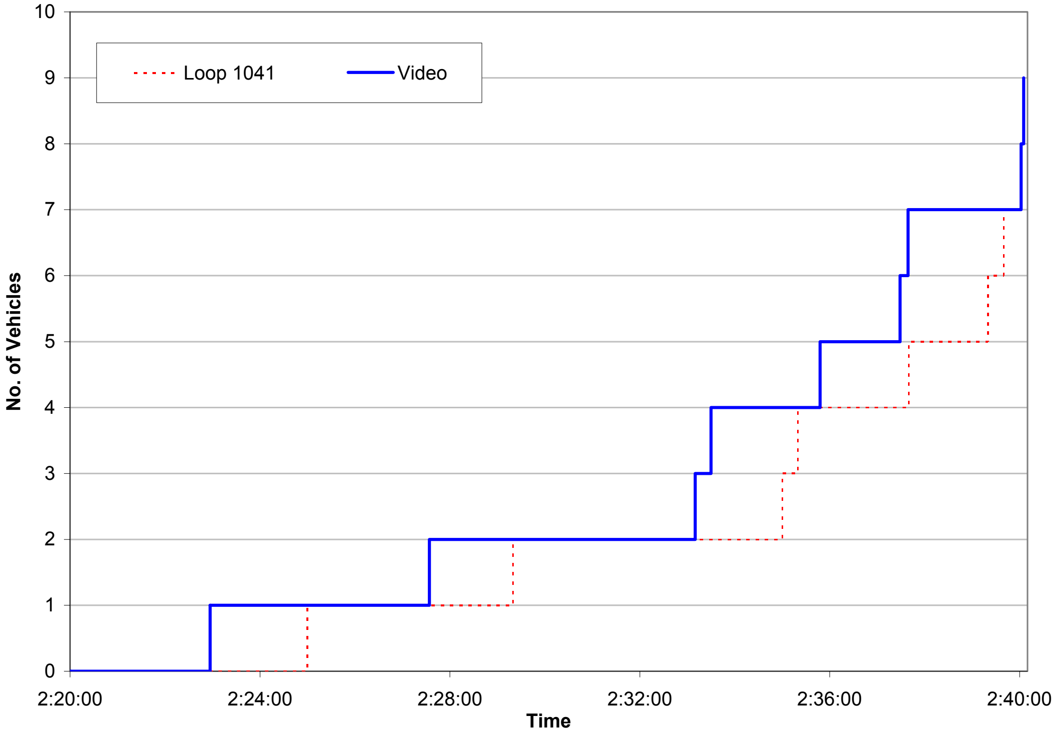


Figure 32 *N(x,t)* **Channel 67 and Loop 1041 [2:20-2:40AM]**

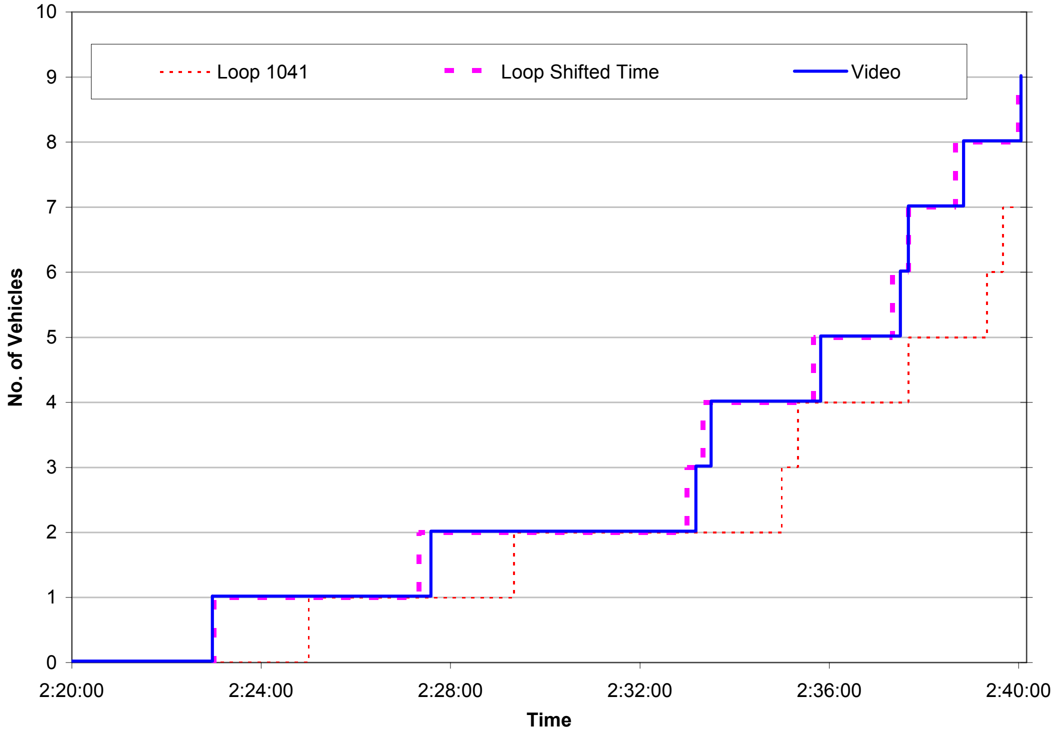


Figure 33 *N(x,t)* **Channel 67 and Loop 1041 [2:20-2:40AM] with Shifted Time**

Table 11 Total Manual and Automated Counts

Time	Loop	Manual [video]	Shifted Time [Loop]	Automated [Loop]	Over Count
Channel 27 Capitol Highway					
2:00 - 2:15AM	1105	6	6	5	0
	1106	32	51	53	19
	1107	46	46	46	0
	1110 [ramp]	5	5	5	0
2:45 - 3:00AM	1105	7	7	6	0
	1106	23	28	32	5
	1107	32	30	38	-2
	1110 [ramp]	6	6	4	0
3:45 - 4:00AM	1105	5	5	6	0
	1106	38	50	48	12
	1107	35	38	38	3
	1110 [ramp]	9	9	8	0
Channel 67 Lower Boones Ferry					
2:20 - 2:40AM	1041	9	9	7	0
	1042	48	48	41	0
	1043	95	98	96	3
	1046 [Ramp]	14	12	12	-2
3:05 - 3:20AM	1041	5	5	5	0
	1042	21	22	21	1
	1043	48	51	51	3
	1046 [Ramp]	11	10	10	-1
	Total	**495**	**536**	**532**	**41**

Figure 34 N-Curve Channel 67 Loop1042 [2:20-2:40AM]

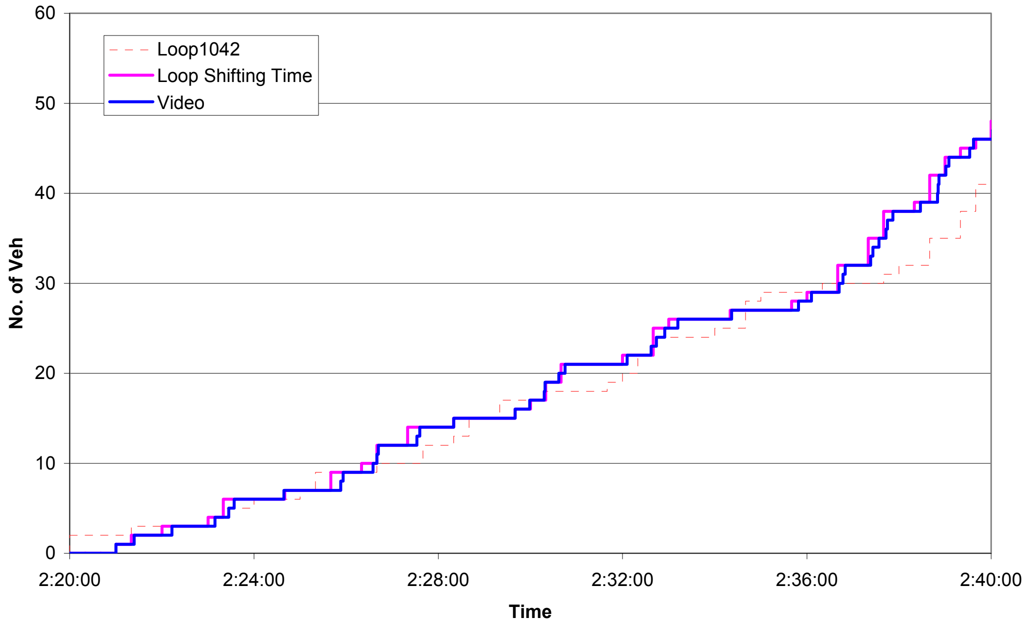


Figure 35 N-Curve Channel 67 Loop1043 [2:20-2:40AM]

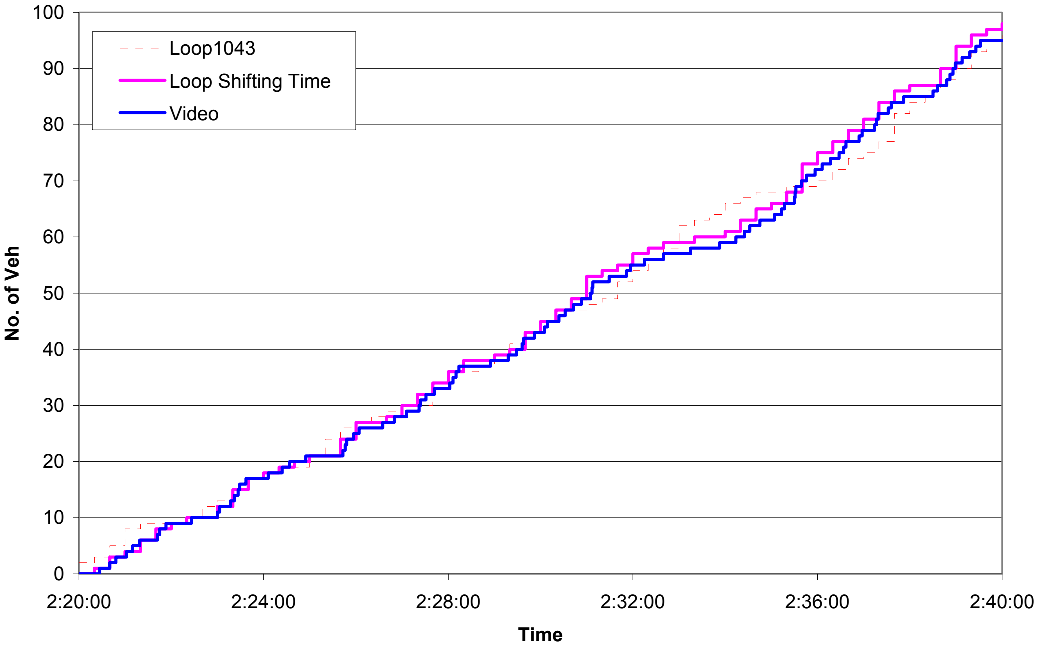


Figure 36 N-Curve Channel 67 Loop1046 On Ramp [2:20-2:40AM]

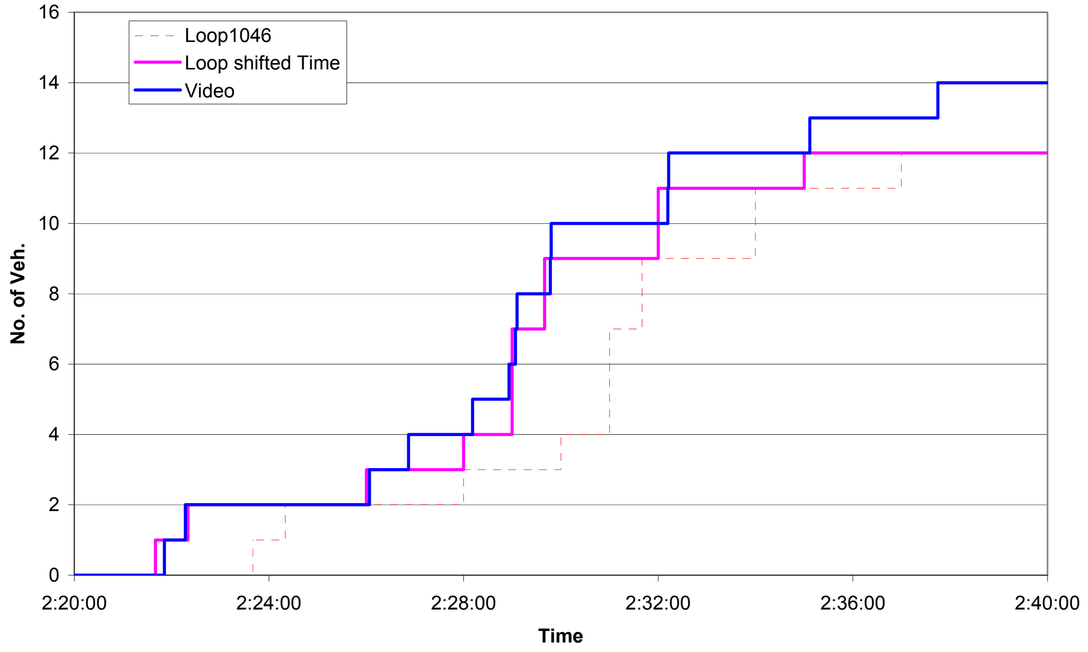


Figure 37 N-Curve Channel 67 Loop1041 [3:05-3:20AM]

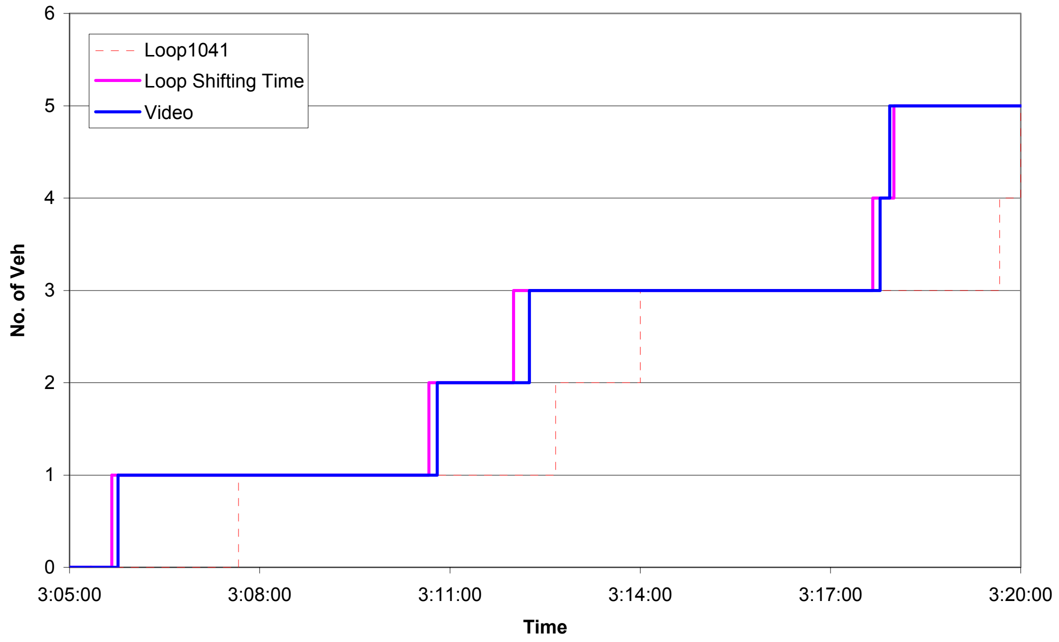


Figure 38 N-Curve Channel 67 Loop1042 [3:05-3:20AM]

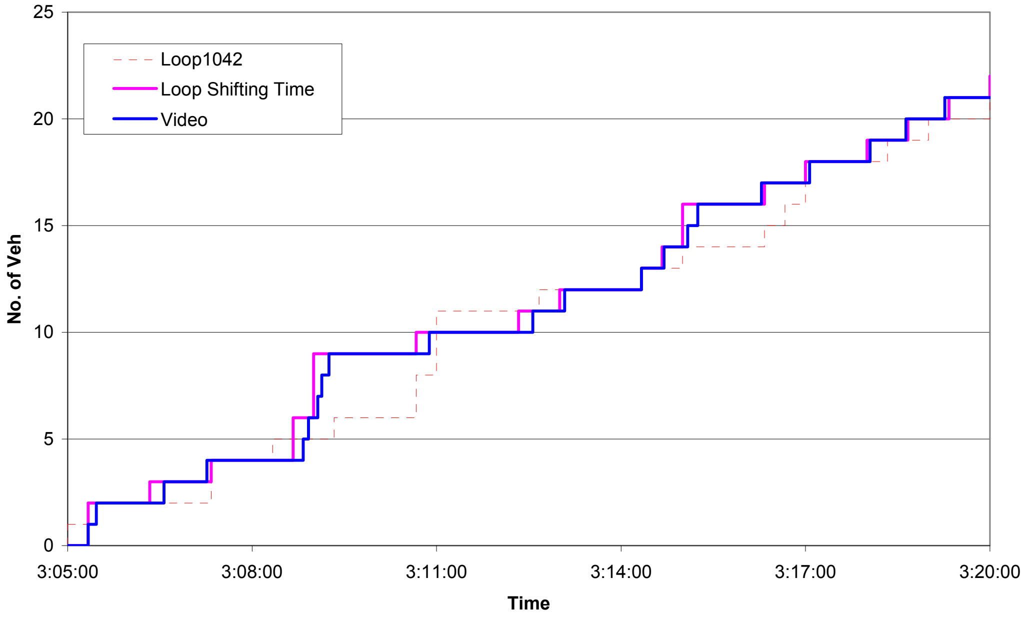


Figure 39 N-Curve Channel 67 Loop1043 [3:05-3:20AM]

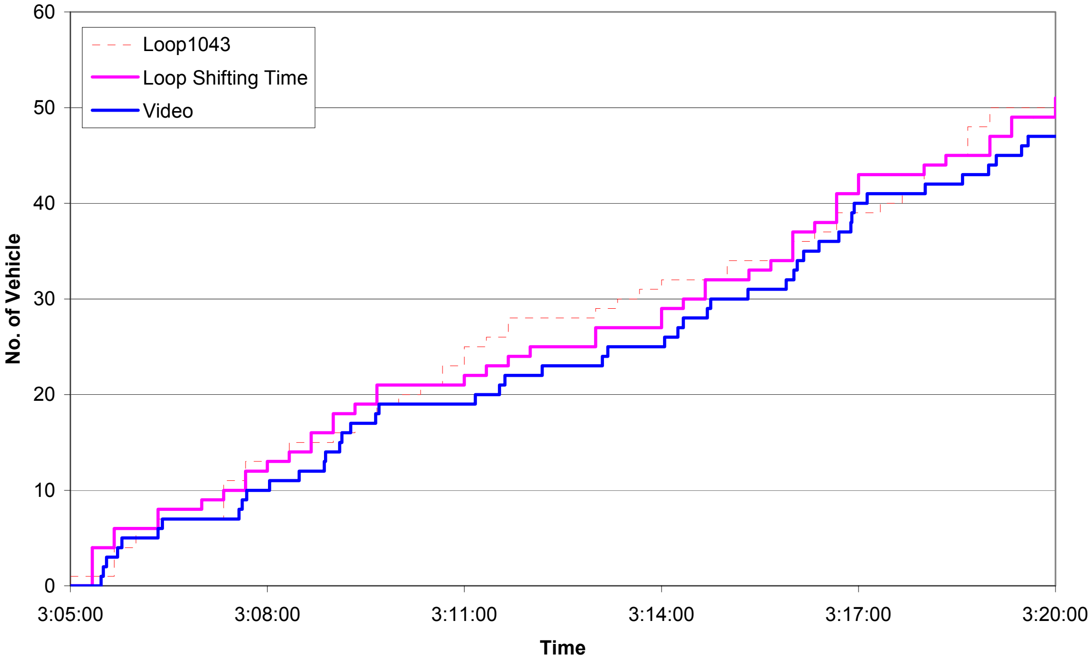


Figure 40 N-Curve Channel 67 loop1046 On-Ramp [3:05-3:20AM]

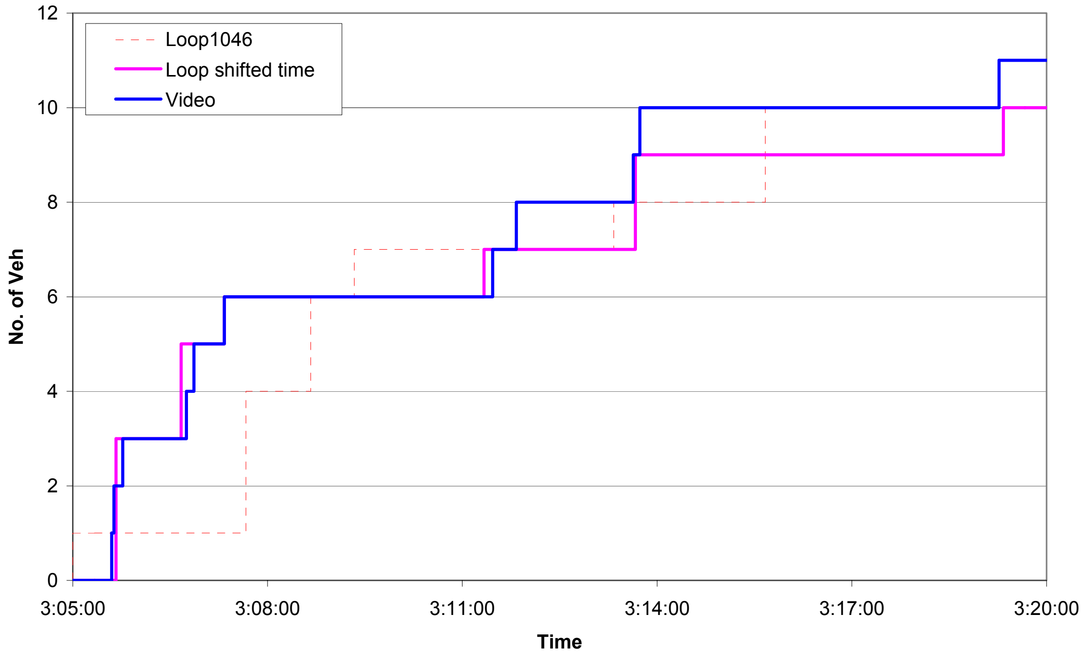


Figure 41 N-Curve Channel 27 Loop 1105 [2:00-2:15AM]

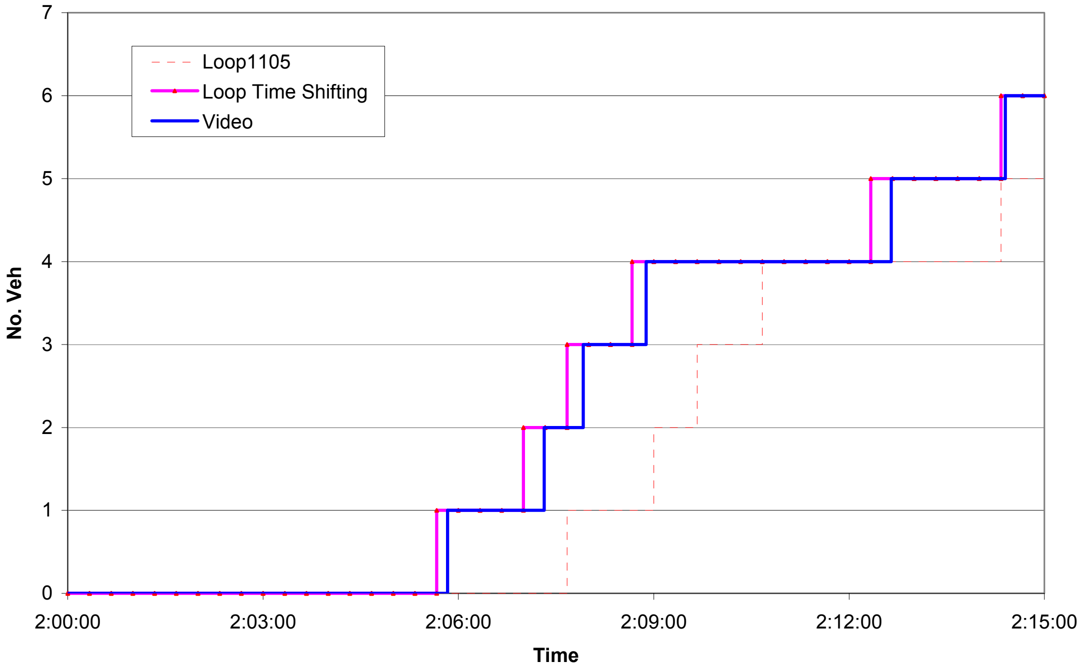


Figure 42 N-Curve Channel 27 Loop 1106 [2:00-2:15AM]

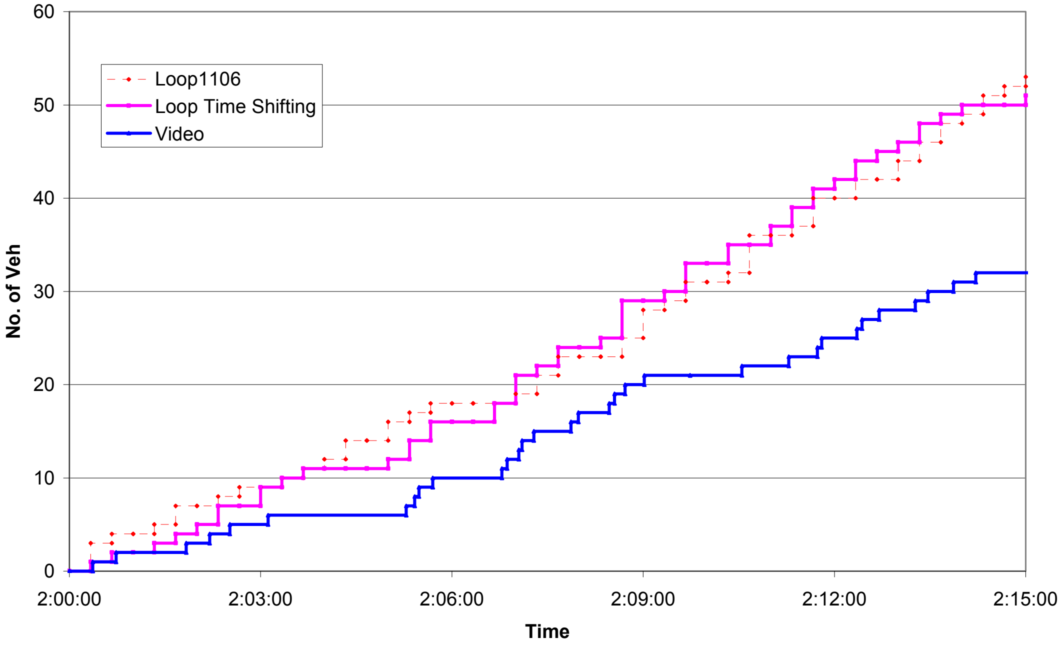


Figure 43 N-Curve Channel 27 Loop 1107 [2:00-2:15AM]

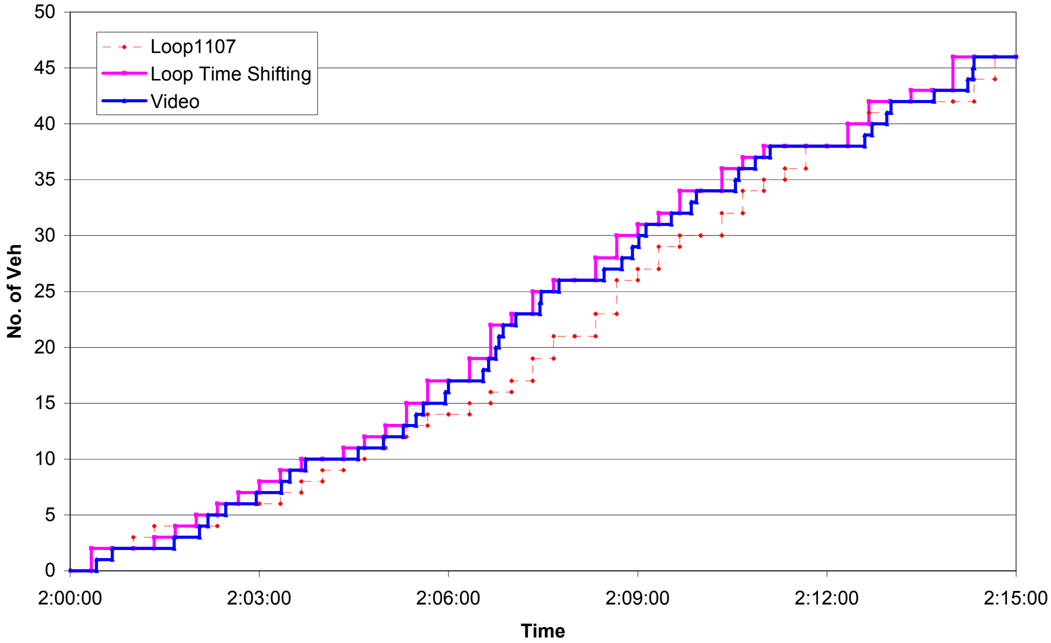


Figure 44 N-Curve Channel 27 Loop 1110 On-Ramp [2:00-2:15AM]

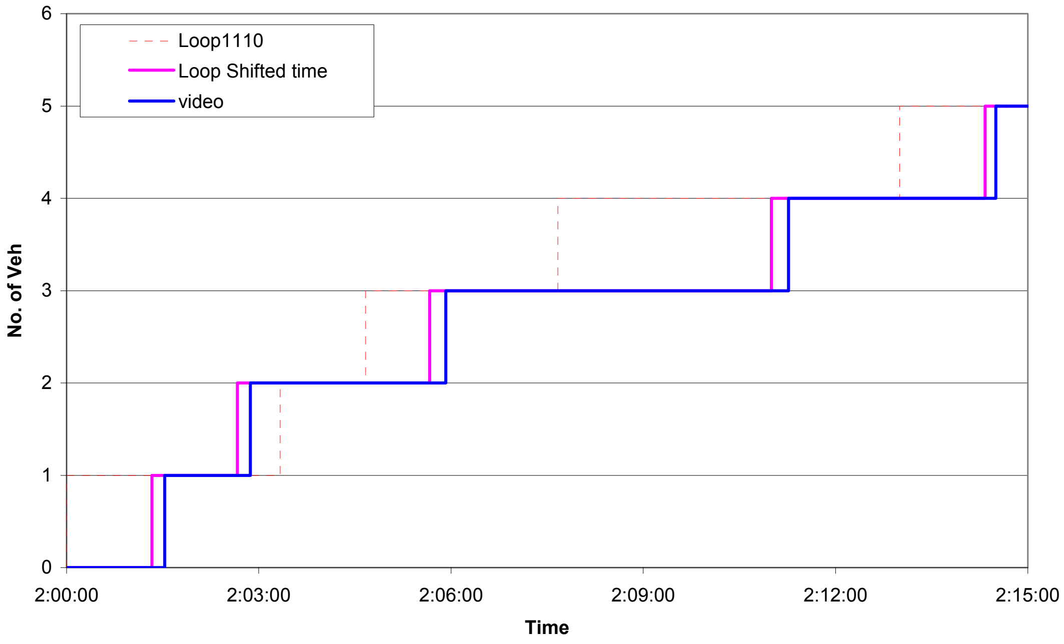


Figure 45 N-Curve Channel 27 Loop1105 [2:45-3:00AM]

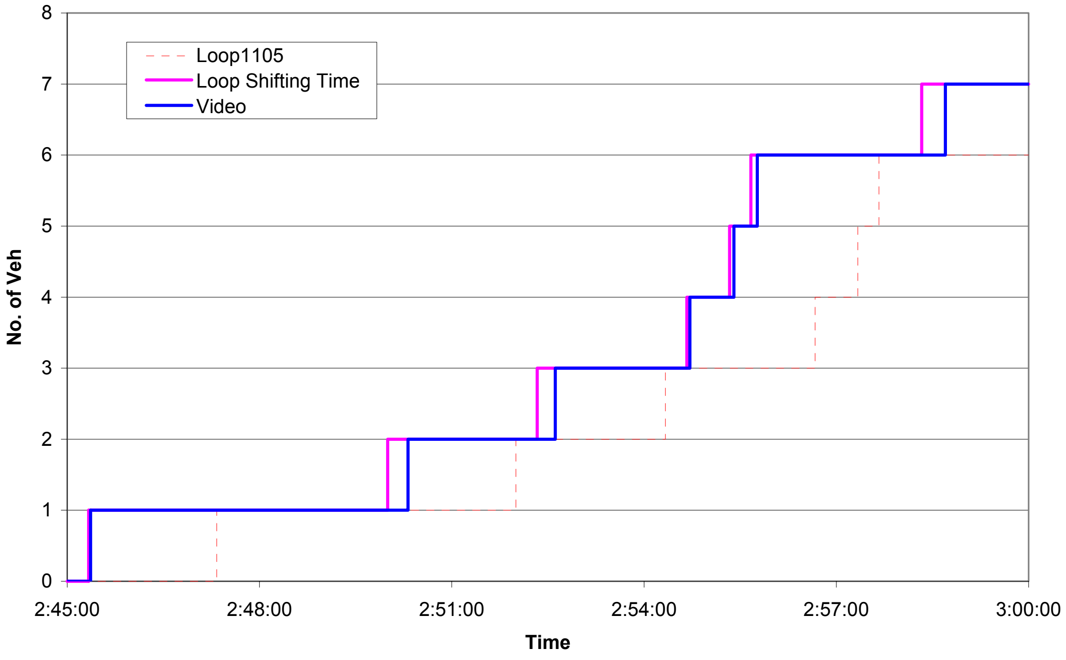


Figure 46 N-Curve Channel 27 Loop1106 [2:45-3:00AM]

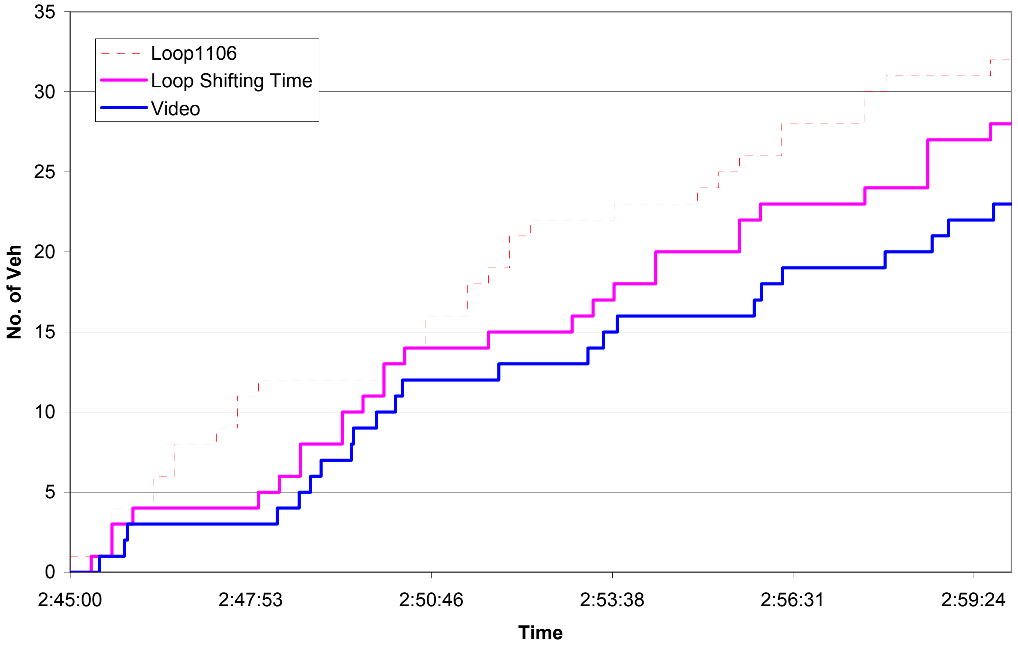


Figure 47 N-Curve Channel 27 Loop1107 [2:45-3:00AM]

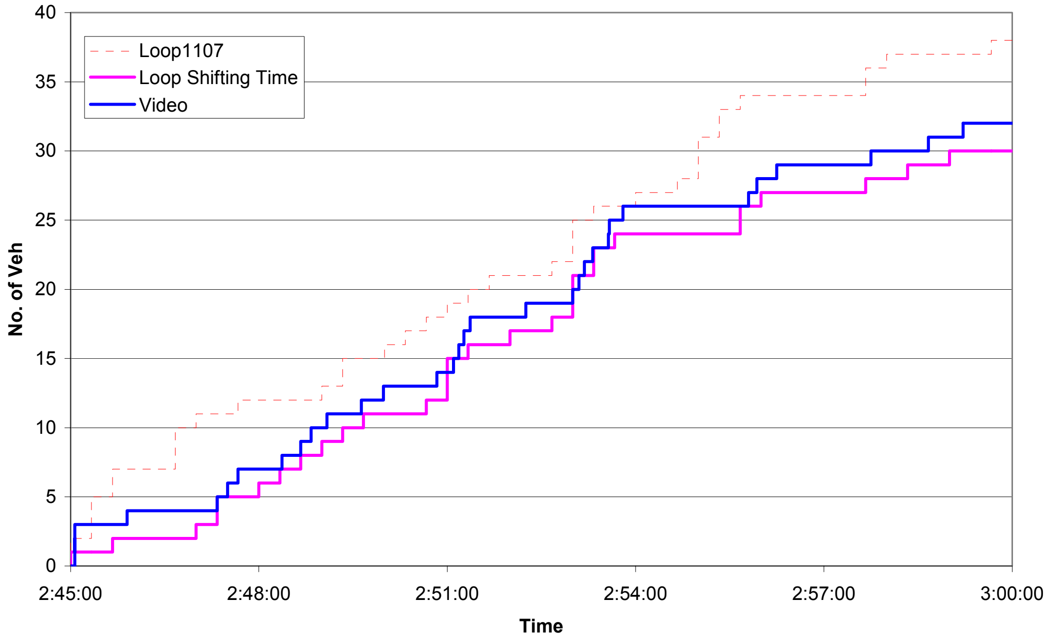


Figure 48 N-Curve Channel 27 Loop 1110 On-Ramp [2:45-3:00M]

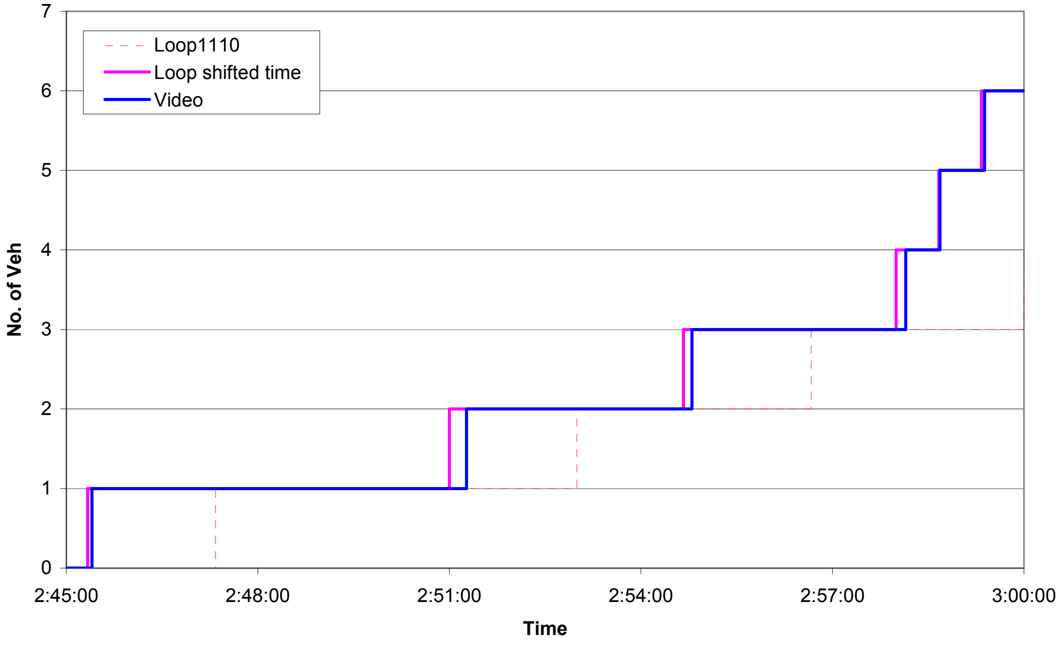


Figure 49 N-Curve Channel 27Loop1105 [3:45-4:00AM]

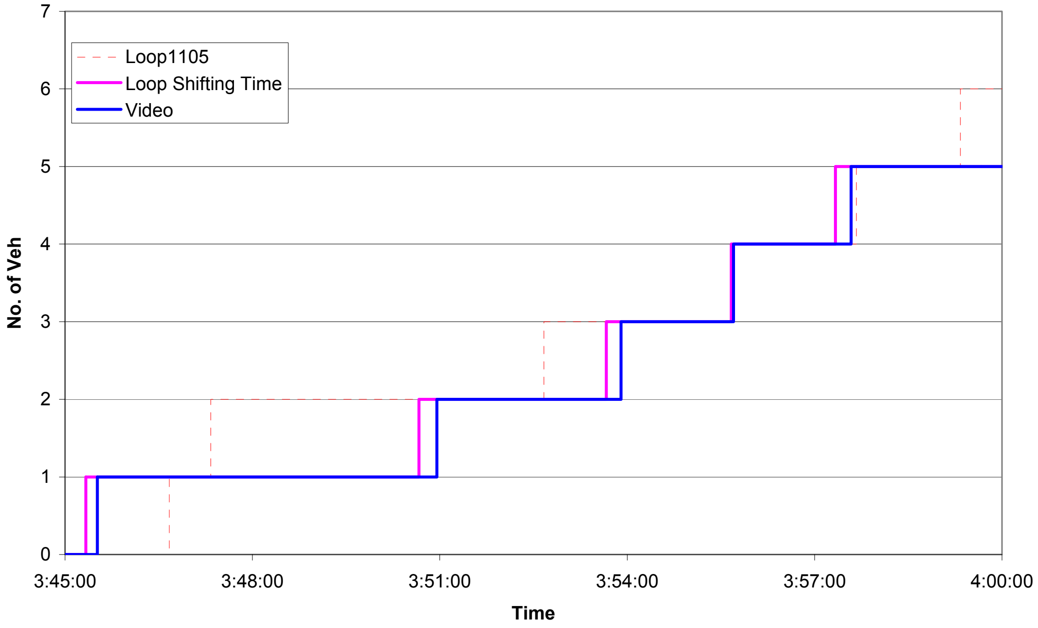


Figure 50 N-Curve Channel 27 Loop1106 [3:45-4:00AM]

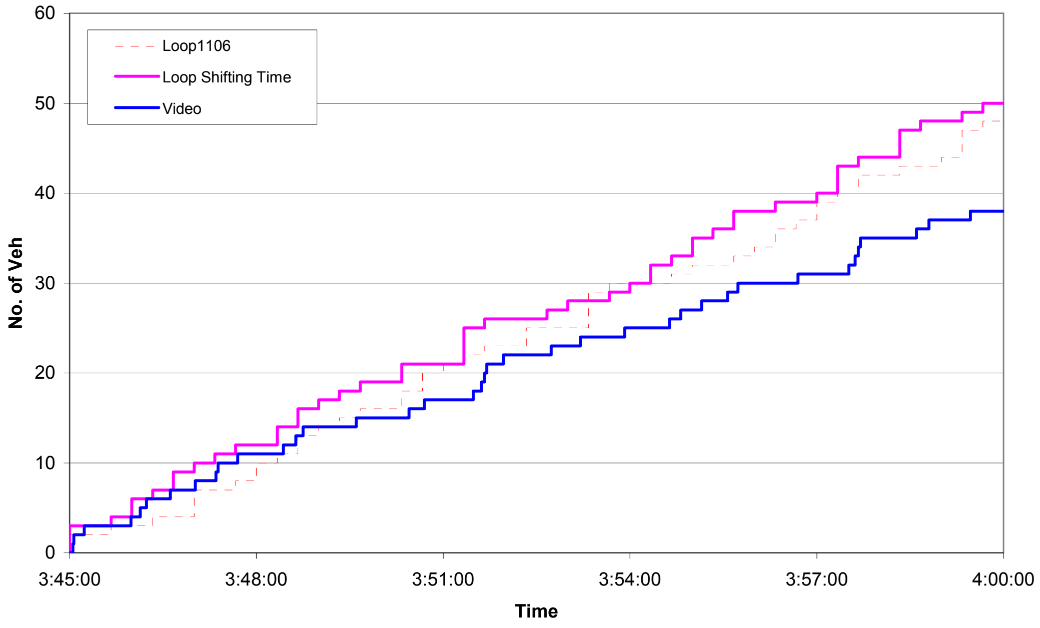


Figure 51 N-Curve Channel 27 Loop1107 [3:45-4:00AM]

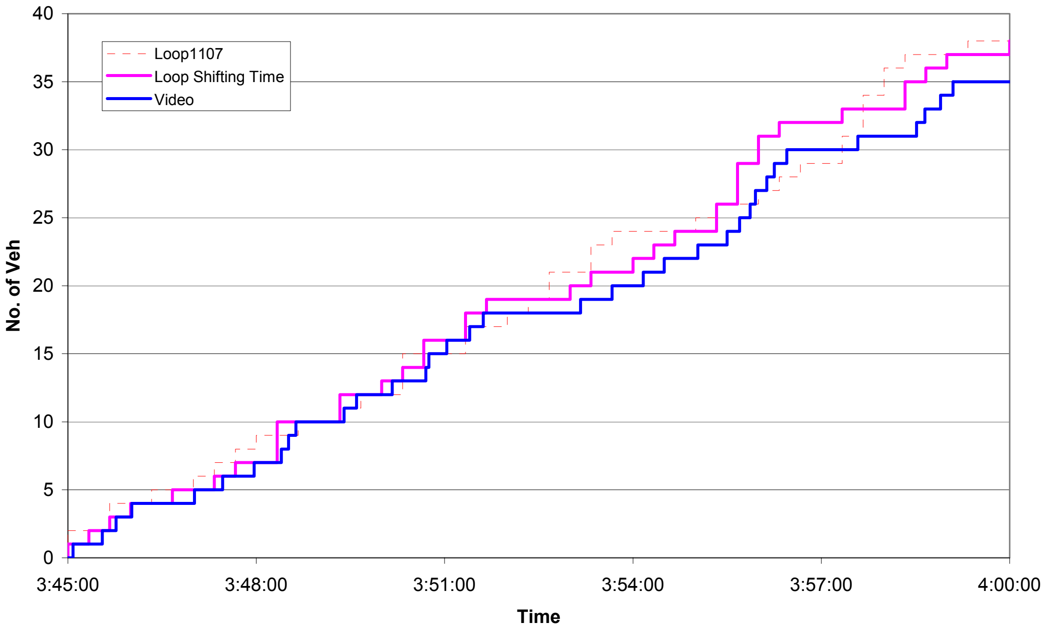
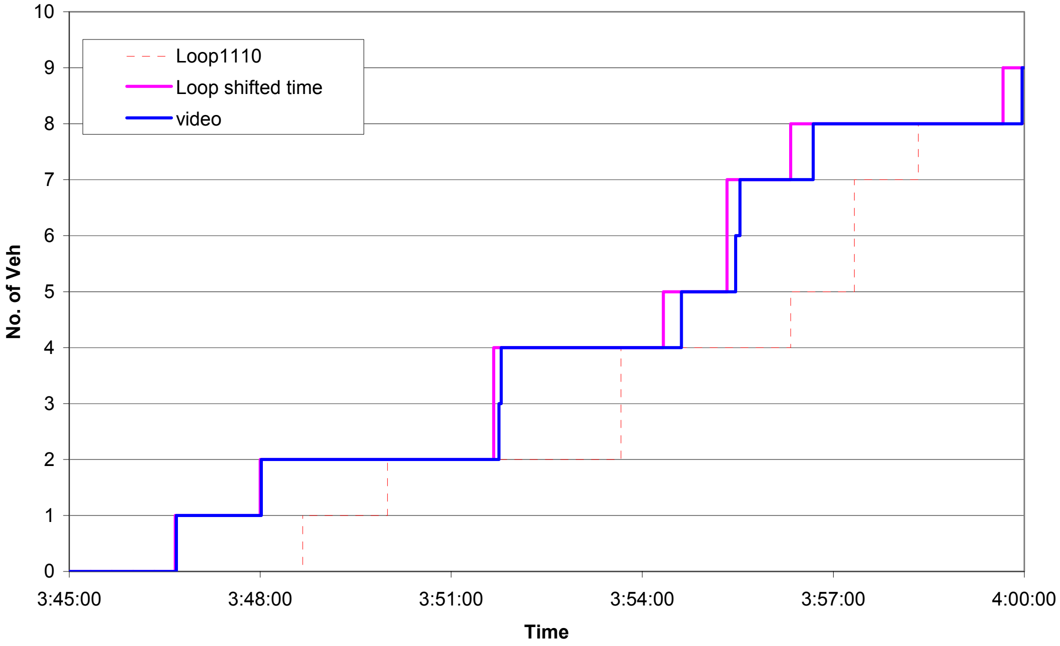


Figure 52 N-Curve Channel 27 Loop 1110 On-Ramp [3:45-4:00AM]



2.9 Statistical Analysis

The next step was to calculate the total count for each loop during each period using the manual counts extracted from the video and the total shifted counts reported by the loop detectors. The total counts for each selected time interval are shown in Table 11. The total counts recorded by the loop detectors were compared to the total CCTV count in each period using reverse regression to test for the relative effects of measurement error. A model was developed with the total count measured by the loop detectors as the dependent variable and the total count recorded by the cameras as the independent variable (see Equation 1). In the second model, the total count recorded by the cameras was established as the dependent variable and the total count recorded by the loop detector was the independent variable (see Equation 2). The inverse beta coefficient from the first regression was used with the beta coefficient from the second regression in *t*-tests (see Equation 3):

$$Y_{\mathrm{Loop}} = \alpha + \beta_{\mathrm{Cam}} X_{\mathrm{Cam}} + \varepsilon \tag{1}$$

$$Y_{\mathrm{Cam}} = \alpha + \beta_{\mathrm{loop}} X_{\mathrm{loop}} + \varepsilon \tag{2}$$

$$\mathrm{Test}_{\alpha=0.05} = \beta_{\mathrm{loop}} - (1/\beta_{\mathrm{Cam}}) = 0 \tag{3}$$

In this study, according to the hypothesis and to the figures shown in the previous section the value of alpha should be zero. Assigning no constant coefficient to the equation and leaving only the beta coefficient will force the regression to zero and will enable us to quantify the bias associated with the loop detectors. The *t*-tests were used to determine whether the measurement error associated with the loop detector counts was significantly different than zero at a 95% level of confidence. The following equation was used to measure the bias attributed to the loop detector readings (Equation 4):

$$\mathrm{BIAS} = ((1/\beta_{\mathrm{Cam}}) - \beta_{\mathrm{loop}}) / (1/\beta_{\mathrm{Cam}}) \tag{4}$$

The results of the reverse regression are presented in Table 12. The *t*-test shows that the measurement error attributable to the loop detector is statistically significant for the shifted readings. The magnitude of the bias for the shifted time counts is 1.7%.

Table 12 Test for Measurement Bias

Dependent Variable	Independent Variable	β_{loop}	$1/\beta_{Cam}$	Bias	Significant	N
Manual	Automated	0.915	0.931	1.7%	Yes	20

The second phase of the statistical study is to prove the hypothesis that the detectors were reporting negative values when recording a count of zero during a measurement interval. A reverse regression can also be used to quantify any measurement error in the loop detectors.

$$Y_{Loop} = 1.07\ X_{Cam} + \varepsilon \tag{5}$$

$$Y_{Cam} = 0.92\ X_{loop} + \varepsilon \tag{6}$$

To measure any errors associated with the loop detectors, according to the above ordinary least square regressions, we need to obtain the inverse of the coefficient X_{loop}. The inverse of the coefficient X_{loop} is 1.092. Thus the loop detectors were over counting by an average value between 1.09 and 1.07 which is approximately equal to 1.08. This means that on average the loop detectors over count by 8.3 % during the time periods analyzed.

A more detailed count was conducted investigating the number of trucks passing over each loop detector during the time period studied. A total of 105 were observed with three to five axles. A total of 33 trucks with five axles were observed, comprising 8.1% of the total number of vehicles observed (406 vehicles). This number is comparable to the total number of vehicles that the statistical model generated, indicating that the over count may be due to a detection problem for large trucks. This will be the subject of continued research.

2.10 Data Validation Summary

This study has pursued the validation of inductive loop detector data for the Portland metropolitan area. This has been an important step toward developing a system for automatically generating mobility measures for the transportation network.

It was determined graphically and statistically that the loop detectors report a negative error code when there was a zero count. This is an important consideration when developing automated methods for processing loop detector data, since any algorithm will need to handle all sources of error. It is still not possible to differentiate between a “-999” error code and a “-1” error code, and thus requires additional research.

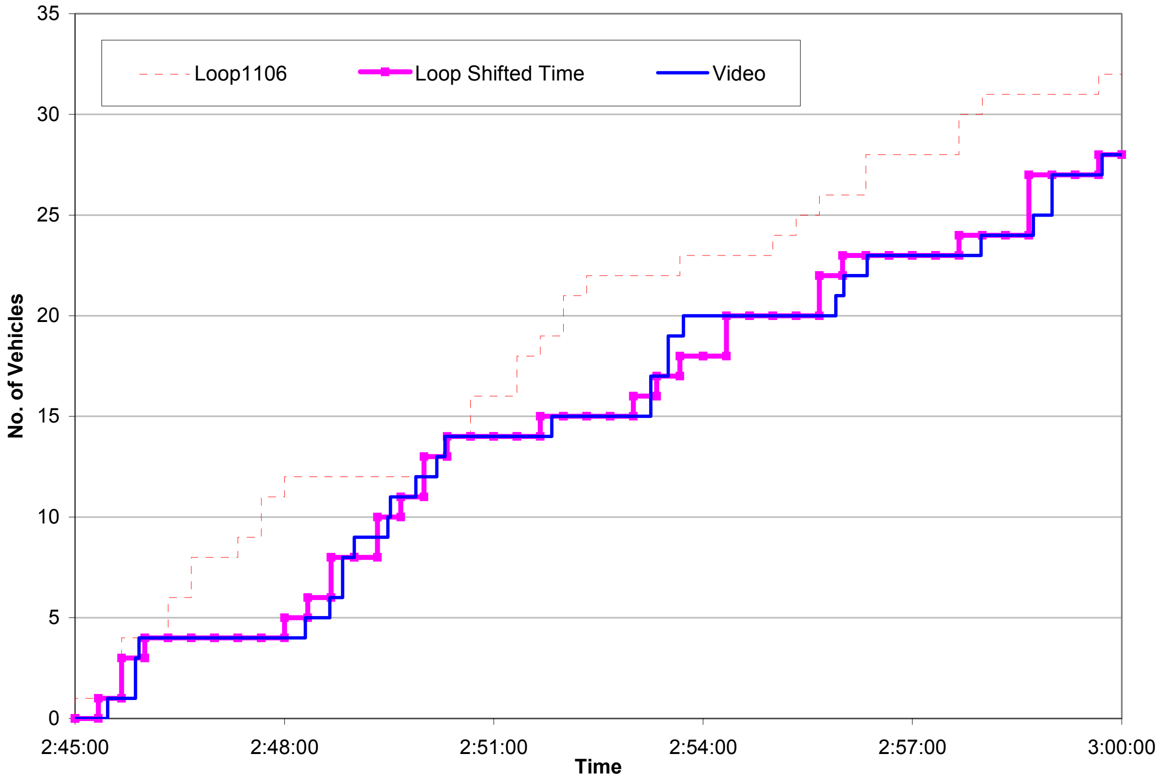


Figure 53 ***N(x,t)*** **Channel 27 and Loop1106 [2:45-3:00AM]**

The inductive loop detector data analyzed here also appeared to over count by an average of 8.3%. According to the video processing, 8.1% of the total vehicles observed were trucks with five axles. The assumption we make in here is that the detector may count the vehicles with three axles as one vehicle while they may count the vehicles with five axles as two vehicles. This is further borne out by Figure 53, which is an adjusted cumulative count curve for loop 1106. For this figure, when a truck was observed on the video, a single vehicle was subtracted from the loop detector curve. As shown, the cumulative count curves appear to be superimposed after the truck over count was manually corrected. Finally, for future TMC applications it is recommended that all data collection systems use a synchronized clock, preferably the atomic clock at http://www.time.gov.

3.0 RAMP METERING ANALYSIS

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 54 is a map of the study corridor, showing detector stations 1 (Haines St.) through 6 (Terwilliger/Bertha Blvd.) on northbound I-5. This freeway section contains between 3-5 mainline lanes and several reverse curves. We will use this corridor as a case study to demonstrate the techniques used for evaluating the ramp metering system.

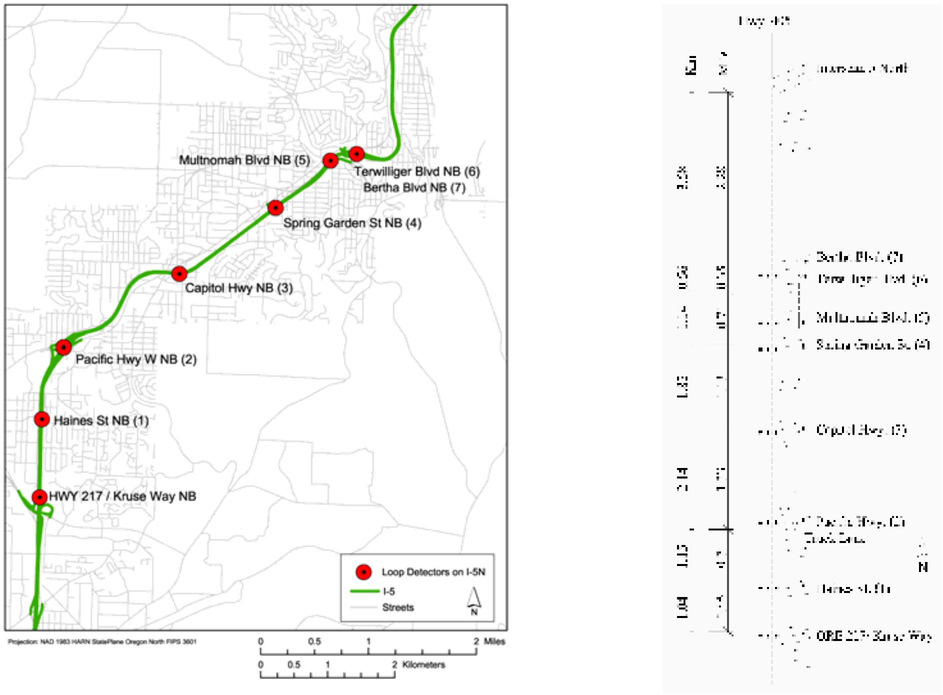


Figure 54 Interstate 5 with Loop Detector Locations and Schematic Diagram

In addition to the use of the 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. AVL may use a variety of techniques to determine the location of the vehicle. The most common system is the use of global positioning systems (GPS), a satellite-based positioning system. The location of the vehicle is identified using a triangulation system based on 24 satellites maintained by the U.S.

government. The principle behind GPS is the measurement of distance (or "range") between the receiver and at least three satellites. The GPS system creates a log file with time, latitude and longitude where the data are collected.

3.1 Analysis Techniques

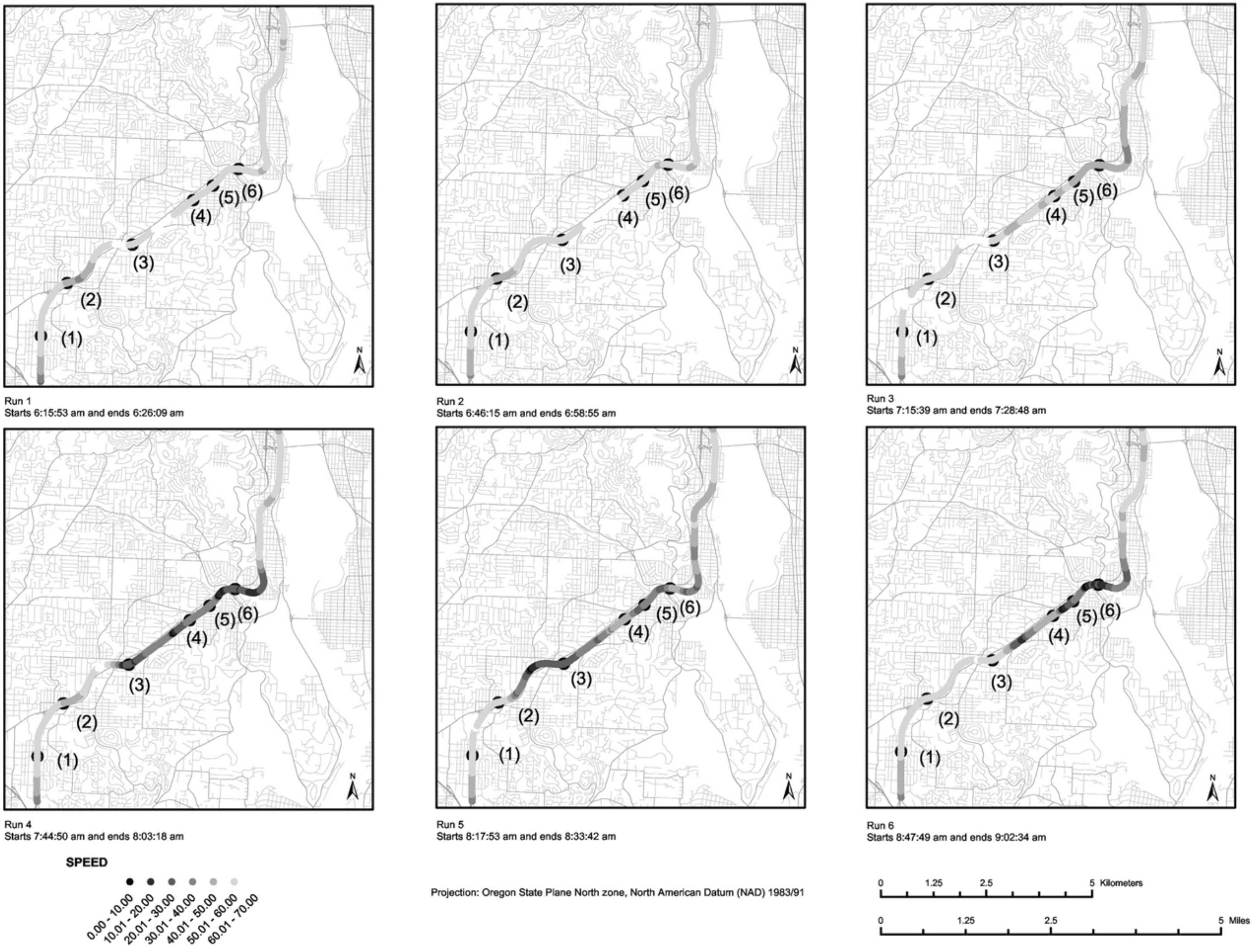
In this section we will discuss the process used to quantify the existing conditions of the freeway corridor using several sources of ITS data. Next, we will demonstrate how to assess the performance of the Portland ramp metering system based on an understanding of traffic conditions and how the freeway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

3.2 Understanding Freeway Operations

A first step in the process of measuring the performance of the ramp metering 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 (*23*). 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 ramp metering system in the corridor began operating at 6:45 a.m. 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 ramp metering 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 55, 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.



Run 1
Starts 6:15:53 am and ends 6:26:09 am

Run 2
Starts 6:46:15 am and ends 6:58:55 am

Run 3
Starts 7:15:39 am and ends 7:28:48 am

Run 4
Starts 7:44:50 am and ends 8:03:18 am

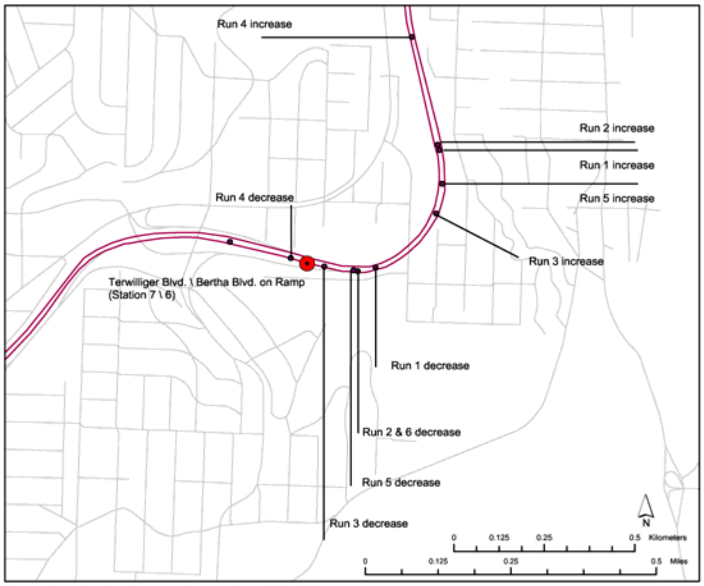
Run 5
Starts 8:17:53 am and ends 8:33:42 am

Run 6
Starts 8:47:49 am and ends 9:02:34 am

Projection: Oregon State Plane North zone, North American Datum (NAD) 1983/91

Figure 55 Runs Represented Geographically with the Speed Displayed in Grayscale

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 56 shows the locations where the probe vehicle speed dropped during each run and where the probe vehicle began to accelerate. As shown in the figure, the locations differ from run to run, indicating that the bottleneck was located in the range between milepost 297.25 to milepost 297.80. The bottleneck may have moved slightly in the 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.



Projection: Oregon State Plane North zone, North American Datum (NAD) 1983/91

Figure 56 Bottleneck Characteristics

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. Measured vehicle count occupancies and speeds are available from the archived loop detector data. 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 as an improved method of plotting loop detector data-better than time series scatter plots. 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 (*24, 25 26, 27*). An oblique plot of cumulative vehicle speed simply displays the vertical difference between the actual cumulative function and a radial line with with slope *Vo*. Similarly, an objective plot of cumulative vehicle occupancy displays the vertical difference between the function describing measured occupancy and a radial line of slope *To*.

Figure 57 shows oblique *V(x,t)* for stations 3, 4, 5, and 6. As shown in Figure 55, the queue did not propagate to stations 1 and 2 during the morning peak period. The speed began to decrease 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 to the point when the impacts diminished at station 6 at approximately 9:11:20 am. The oblique *V(x,t)* clearly highlight time during which the bottleneck was active in the study corridor.

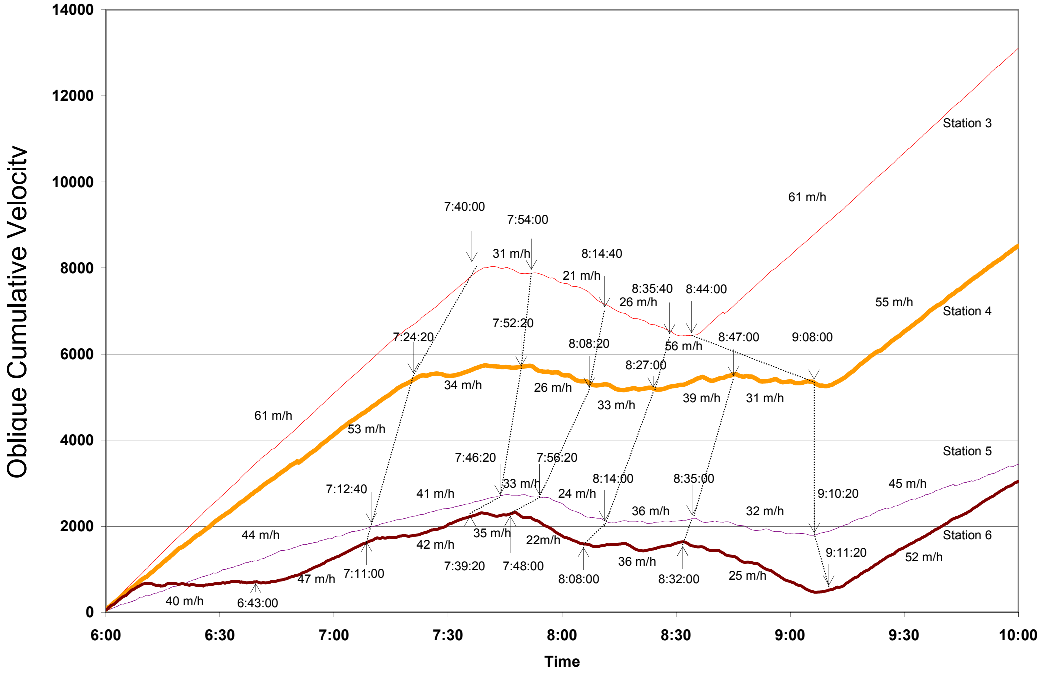


Figure 57 Oblique V(x,t) Upstream of the Bottleneck

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 58 shows the oblique *N(x,t)* and *T(x,t)* for station 6. Figure 58 records the times at which notable changes in flow, occupancy and speed were visible at station 6. As shown, the speed dropped from 42 mph (71 km/h) at 7:20 a.m. with a flow of 5,925 veh/hr to 20 mph (34 km/h) at 7:48 a.m. with a flow of 4556 veh/hr. After comparing Figure 57 with Figure 58 it is clear that the origin of the congestion was observed at station 6 during the period between 7:07 a.m. and 7:20 am. The volume during this period was 5100 vph and the speed was 40.5 mph (67 km/h). Figure 58 shows that the highest speed and flow levels for this location occurred during the period between 9:11 a.m. 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.

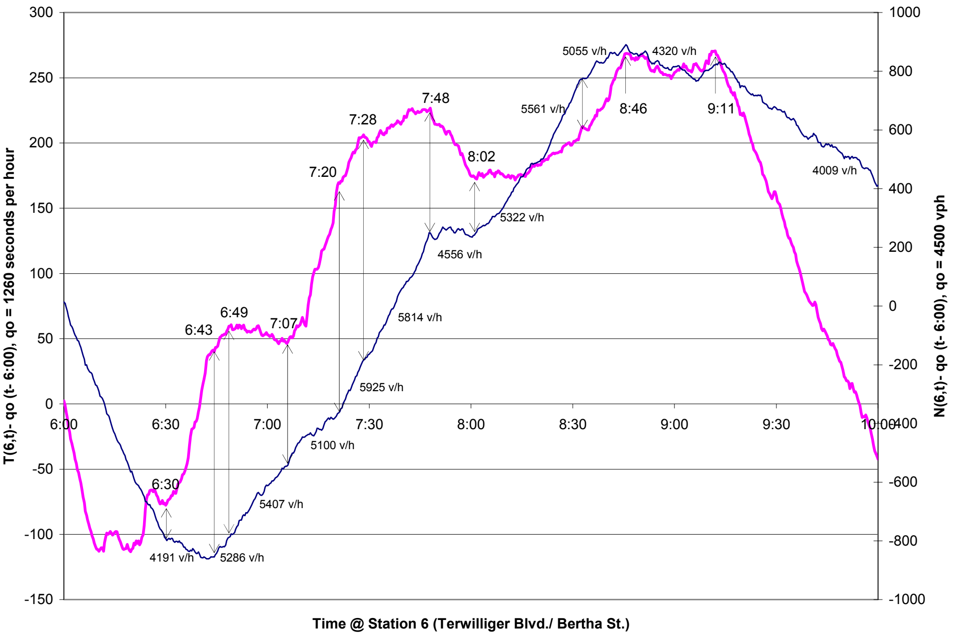


Figure 58 Oblique N(x,t) and T(x,t) at Station 6

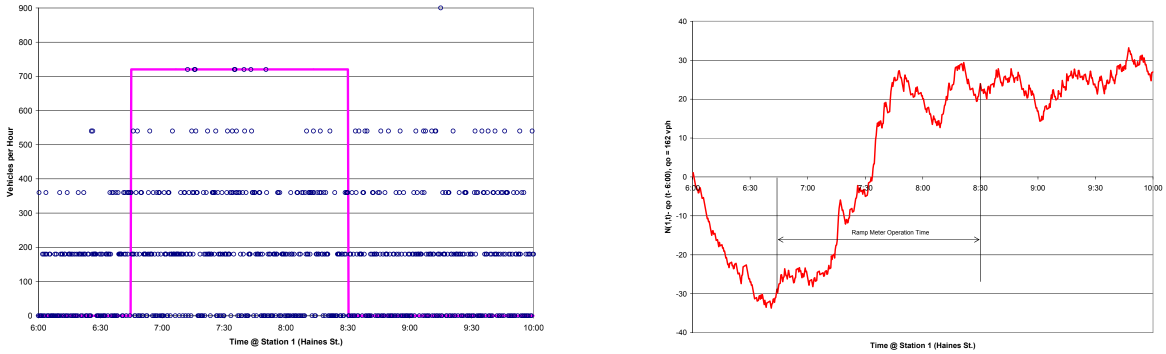
To achieve this level of service, more delay will be imparted to the vehicles entering the freeway via the on-ramps. Accordingly, the best choice for avoiding congestion might have been the level of flow that was present during the period between 6:43 a.m. and 6:49 am, which was 5896 vph with an accompanying 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 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 morning peak period.

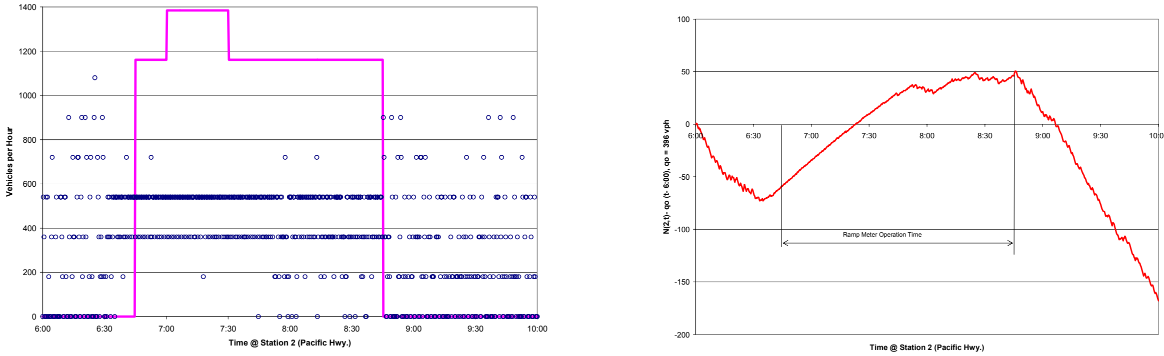
3.3 Pre-timed and Actual Metering Rates

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 ramp metering system to the actual traffic flows recorded on the ramps. Figure 59 shows a comparison between the ODOT ramp metering timing plans and the actual flows recorded on the on-ramps during the same time periods. The ramp metering were activated at 6:45 am; some of the meters were deactivated at 8:30 a.m. 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. This on-ramp shares the same mainline detectors with station 6.

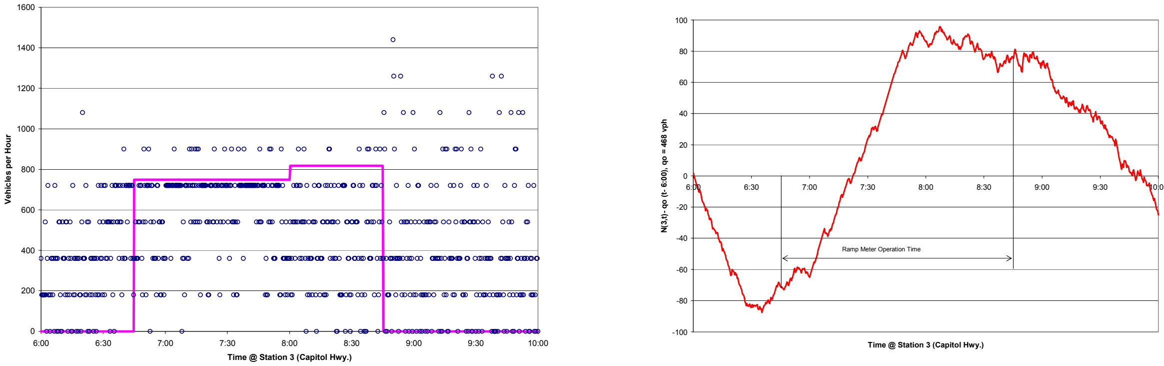
Figure 59 Actual and Planned PRM Timing



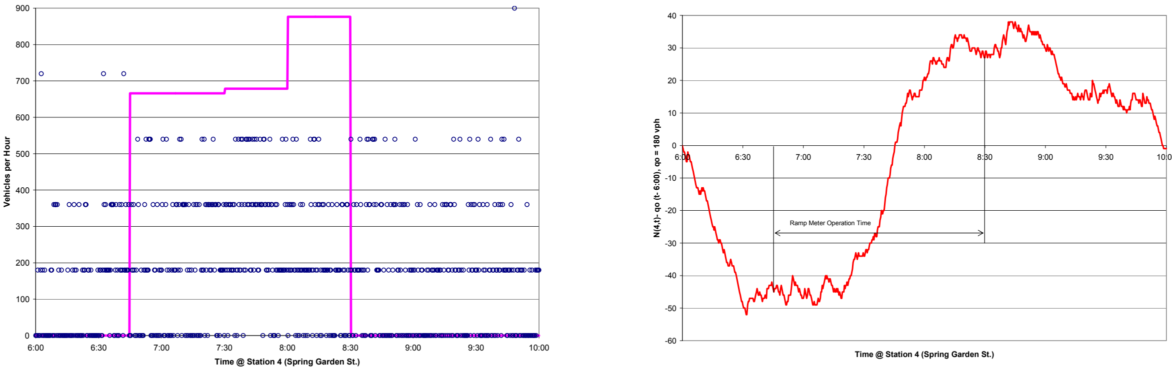
Station 1



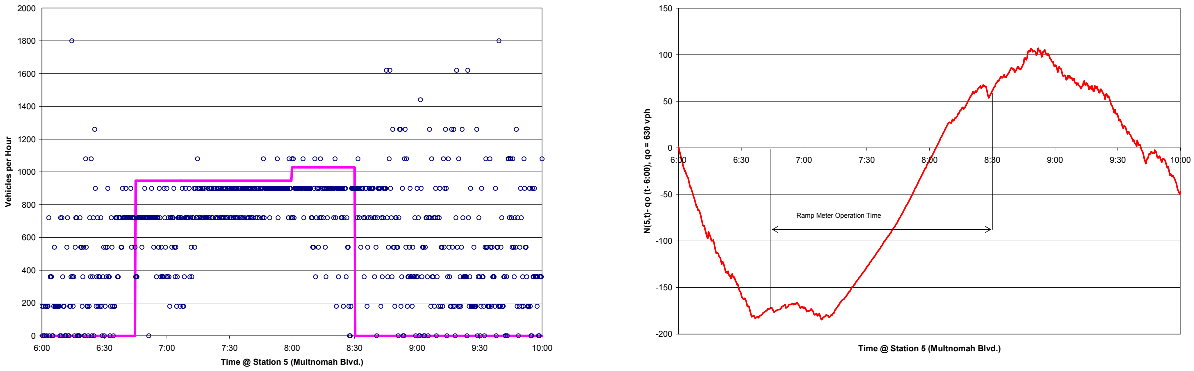
Station 2



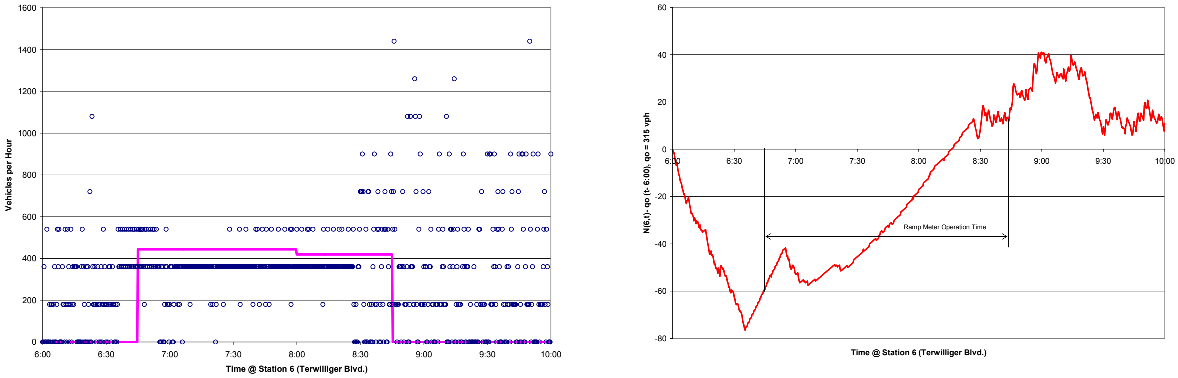
Station 3



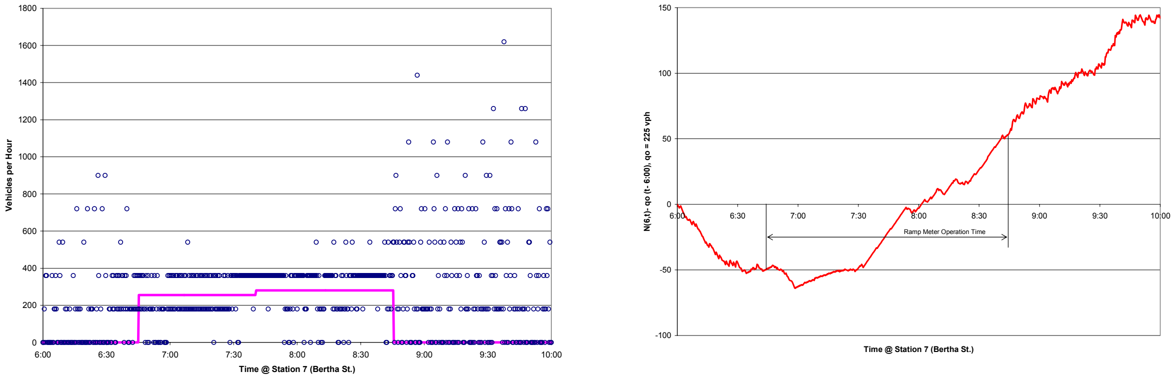
Station 4



Station 5



Station 6



Station 7

The ramp metering 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 ramp metering is turned off automatically to flush the ramp. In these situations, higher flows of platooned vehicles entered the freeway. This clarifies why at station 3, 5, 6, and 7 at some points there were more vehicles passing than was planned.

At stations 1, 2, and 4 the ramp metering 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 ramp metering 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 ramp metering system was 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.

3.4 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 ramp metering. This comparison used the loop detector data to construct oblique cumulative curves. Table 13 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 ramp metering were activated at 6:45 a.m. 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 the ramp metering system.

Table 13 Traffic Parameter Changes at Station 4

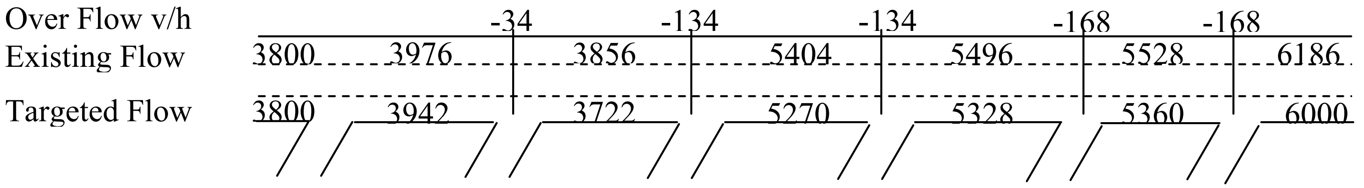
From	To	Speed (mi/hr)	Occupancy (percent)	Mainline Flow (veh/hr)	Ramp Flow (veh/hr)
6:00:00	6:29:00	58.78	3.99	3355	82
6:29:20	6:40:00	56.86	6.58	4947	180
6:40:20	6:49:00	56.49	7.64	5400	207
6:49:20	6:52:00	50.00	6.78	5060	80
6:52:20	6:54:00	58.33	7.06	5340	300
6:54:20	7:19:00	56.40	7.86	5650	173
7:19:20	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

3.5 Manual Traffic Simulation

Manual traffic simulation using the information obtained from the previously presented analytical methods can help in tuning the ramp metering system. Knowing the ideal level of service will help in evaluating the performance of ramp metering. 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 55, 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 a.m. and 7:20 a.m. the volume was 5100 vph 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.

Figure 60 Manual Simulation from 6:45 to 7:00

	Station 1	Station 2	Station 3	Station 4	Station 5	Station 6 and 7



	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 (St 6) 172 v/h (St 7)
Proposed Flow	142 v/h	391 v/h	492 v/h	130 v/h	628 v/h	344 v/h (St 6) 380 v/h (St 7)
Additional Queue	34 v/h	101 v/h		34 v/h		
	8 v/15 min	25 v/15 min		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		

The next step is to attempt to understand the demand for the entry to the freeway. From Figure 59 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 60 shows the results of a manual simulation based on a straight forward demand and supply analysis (*28*). 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 ramp metering system temporal resolution. Knowing that the on-ramp queues exceed 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 ramp metering system by flushing the ramp. The metering rate at station 7 should be increased 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 59 and 60, 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 ramp metering 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 ramp meter timing plans.

3.6 Conclusions

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

This section has demonstrated different techniques for understanding the characteristics of a freeway corridor and how to evaluate the performance of a ramp metering 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.

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 ramp metering 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 for possible alternate routes with the estimated travel time savings.

4.0 CASE STUDY: RAMP METERING IN PORTLAND, OREGON

4.1 History of Ramp Metering in Portland

Ramp meters were first implemented in the Portland metropolitan area by the Oregon Department of Transportation (ODOT) in January 1981, along a 6-mile stretch of Interstate 5 (I-5) from the Broadway Bridge to the Interstate Bridge. I-5 is a major north-south link and a significant commuter route through the metropolitan area, and this section carries some of the highest volumes of any roadway in the state. Prior to the implementation of the ramp metering system, the afternoon peak-hour traffic conditions on northbound I-5 were the worst in the state of Oregon. The initial ramp metering system, the first in the Pacific Northwest, was a part of a freeway improvement program created in conjunction with the Federal Highway Administration, the Oregon State Highway Division, and the City of Portland to improve traffic flow. Ramp metering, a relatively low-cost traffic management technique, was initially identified as one of several projects to improve the flow of traffic on I-5. Other projects included construction of additional traffic lanes in several sections and restriping of several locations to increase capacity. The original system consisted of 16 meters installed in fixed-time operation, with rates varying between 160 to 900 vehicles per hour (vph). Due to the variation in traffic demand from day to day in this corridor, ODOT believed that fixed-time metering provided a smoother, more dependable system than the real-time system. Once Interstate 205 (I-205) was open to traffic, it would provide an alternate route to this corridor, and it was widely believed that I-5 traffic volumes would be reduced, allowing for the use of the real-time system. Nine of the meters controlled the northbound entrances during the afternoon peak, and seven of the meters were used for the southbound direction during the morning peak. Before metering was implemented, it was typical along this portion of I-5 for platoons of vehicles to merge onto the Interstate and worsen the already congested traffic. After the installation of these meters, the average speeds in the northbound lanes rose from 16 to 41 miles per hour (mph), and travel time was reduced from an average of 23 minutes to approximately nine minutes. In the southbound lanes, pre-metered conditions were not as severe. Hence, in these lanes, the average speed rose from 40 to 43 mph with only a minor decrease in travel time. In addition to these improvements, the afternoon peak period was reduced from four hours to three hours. Fuel consumption was estimated to have decreased by 540 gallons per weekday, and the improvements to traffic flow resulted in a 43% reduction in peak period accidents *(35).*

4.2 Current State of Ramp Metering in Portland

The state of Oregon has experienced a significant increase in population and business growth in the past decade. This has produced demands on the freeway infrastructure that has also increased at a rapid pace *(37).* The early success of ODOT's use of ramp meters resulted in the continued growth and use of meters to mitigate congestion caused by this growth in the number of vehicles using Oregon's highways.

The Oregon Statewide ITS Strategic Plan was created by ODOT in 1998 to direct the implementation of ITS in Oregon over the next 20 years. This plan functions as a roadmap to execute appropriate technology, infrastructure, and services to support transportation efficiency, mobility, and congestion reduction *(37).* Figure 61 shows the existing and proposed ramp meter system under the ITS Strategic Plan for Region 1 (the Portland metropolitan area). ODOT's long-term ITS Implementation Plan for Region 1 includes a budget of $5 million in capital costs and $250,000 for annual operations and maintenance costs for the ramp metering system shown in Figure 61.

ODOT currently maintains 118 ramp meters in the Portland metropolitan area (*38*), and all the meters are operated in a fixed-timed operation, turning on and off at the same time every weekday. In order for the entire system to work, all ramps must be metered, even those with relatively low flows. When ramps are left unmetered, drivers will switch to them instead of using metered ramps, resulting in traffic problems on and off the highways. The meters also deter motorists from making short trips on the highways during peak periods when the highway capacity is most needed for commuters making longer trips. One of ODOT's goals of ramp metering is the preservation of mobility in the Portland metropolitan area during peak hours. With so much of Portland's recent growth centered around freeway interchanges, there is naturally a significant demand for immediate freeway access. Without meters, the highway system would break down at lower volumes caused by less stable flow. Although metering might result in queuing on arterial streets in a few areas, it is significantly less than without meters. ODOT's goal is to maximize the capacity of the freeway while minimizing the effects on the arterial street system.

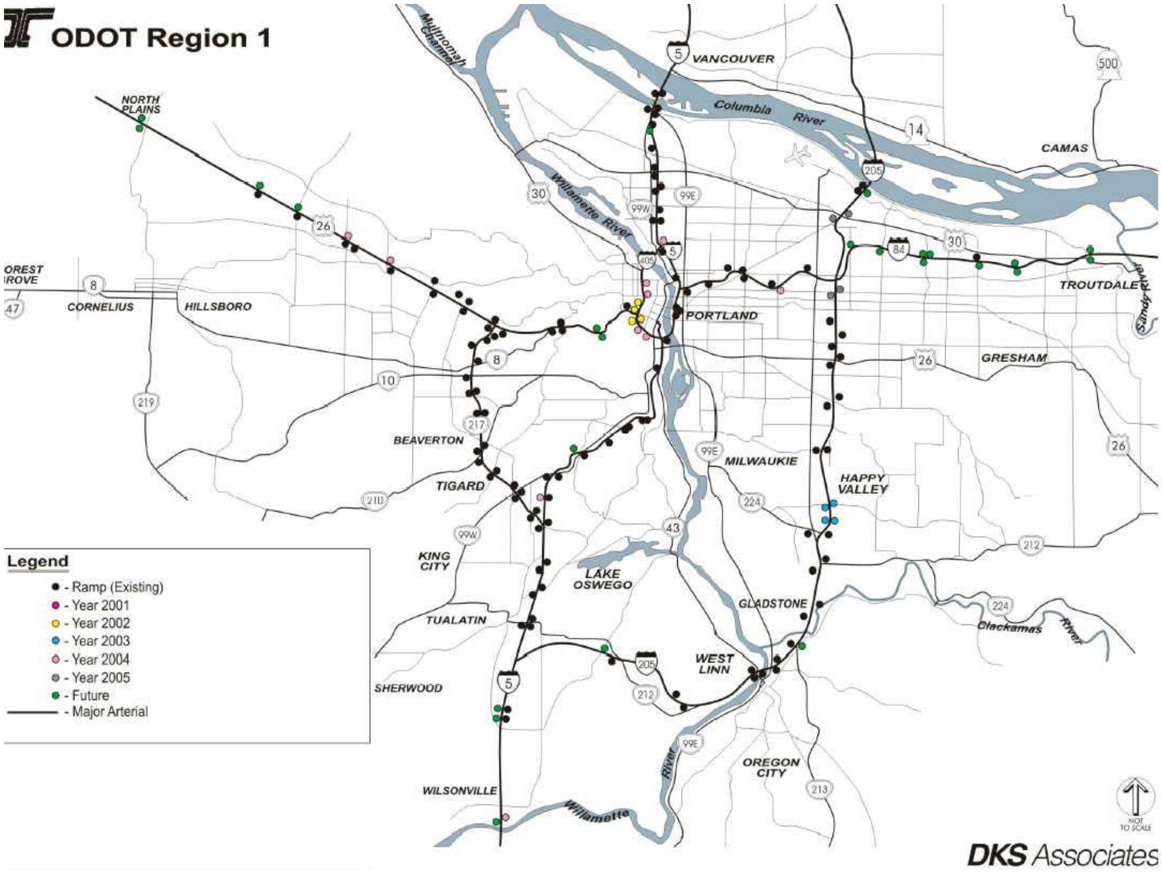


Figure 61 Portland Existing and Proposed Ramp Meter System

ODOT currently estimates that the use of ramp metering in the Portland metropolitan area reduces sideswipe accidents caused by merging by 50% and produces a significant decrease in travel time. Without metering, a typical weekday commute from Hillsboro to downtown Portland during peak hours would take an average of 45 minutes. With metering, the same trip could be made in an average of 33 minutes *(39).*

4.3 Weekend Ramp Meter Shutdown on U.S. Highway 26

4.3.1 Background

U.S. Highway 26, also known as the Sunset Highway, is the major east-west link between the Oregon Coast and Portland. It is also the major commuter route between Portland and the rapidly growing Westside, which includes several residential communities as well as the Silicon Forest, which contains the area's high tech industry *(40)*. In 1993, meters were implemented on this highway to address congestion caused by the morning and afternoon peaks. However, weekend metering had not initially been considered. Over the past few years, ODOT has received an increasing number of complaints related to weekend congestion on this highway. To address this issue, it was later decided to consider the option of ramp metering during the weekends.

4.3.2 Conditions Before the Operation of Weekend Ramp Meters

In 2001, ODOT performed studies, collected data, and compiled traffic flows for a typical Saturday and a typical Sunday for each month of the entire year. The results showed that at one of the critical locations on the highway, between Murray Road and Cornell Road, traffic flow had substantial congestion from May through December, between the hours of 12:00 noon and 6:00 p.m. During the periods of congestion, speeds were reduced to considerably less than 30 mph.

4.3.3 Conditions After the Operation of Weekend Ramp Meters

In response to frequent weekend congestion on the eastbound lanes of Highway 26, ODOT implemented weekend ramp metering along an 11-mile corridor, between Helvetia Road and Skyline Road, as shown in Figure 62. This segment consists of 2 lanes in the eastbound direction from stations 1 through 9 and three lanes at station 10. Weekend ramp metering of these ramps began on Saturday, August 25, 2001, and will be in effect each year from May through December, between the hours of 12:00 noon and 6:00 p.m. Studies performed after activation of the weekend meters revealed that traffic was functioning in free flow conditions through the entire corridor. ODOT continues to monitor weekend traffic conditions along this corridor to guarantee that ramp metering is beneficial to the highway without inflicting unnecessary delay on the entrance ramps.

4.3.4 Recent Weekend Monitoring Experiment

As an example of ODOT's continued monitoring of this corridor, the agency recently deactivated the weekend ramp meters to ensure that the weekend metering operation was beneficial. Ramp meters were turned off during the weekend of October 11 and 12, 2003 along all the eastbound ramps of this 11-mile corridor. The following weekend (October 18 and 19, 2003), the ramp meters were turned back on.

4.4 Data

The surveillance system in this section of the highway includes 10 mainline inductive loop detector stations (with detectors placed in each lane) and corresponding entrance ramp detectors at 10 eastbound entrance ramps *(40)*. The data recorded for this experiment includes vehicle count, occupancy and speed, as measured by each lane's and ramp's detectors, and are aggregated locally every 20 seconds.

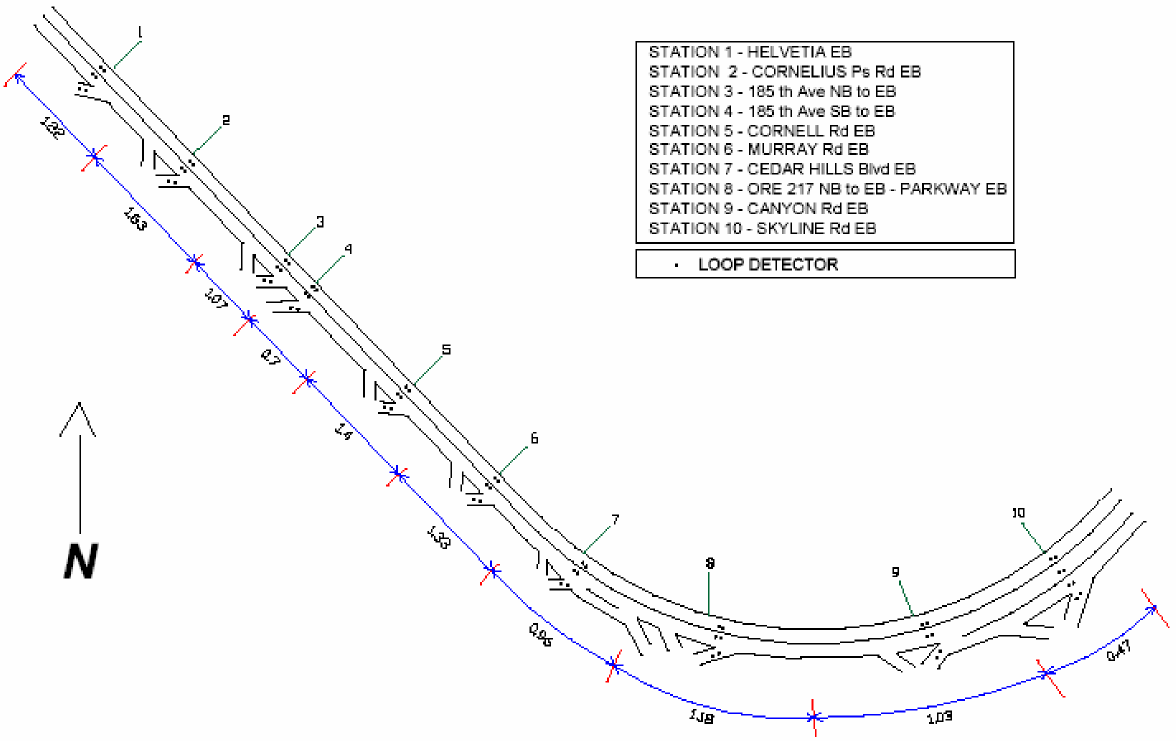


Figure 62 Site Map of 11-Mile Corridor Analyzed *(40)*.

4.5 Data Analysis

4.5.1 Mainline Flows and Speeds

The first parameters to be examined are the mainline freeway flows and speeds. Vehicle-hours-traveled (VHT) and vehicle-miles-traveled (VMT) were calculated in one-hour increments between 12:00 noon and 6:00 pm. The VMT data capture the amount of travel while the VMT captures the travel time component of the travel that occurred. As shown in Table 14 the Saturday VHT increased overall by 5.8% with ramp metering, and the Saturday VMT increased slightly with metering. During several one-hour periods it is clear that trends varied. For example, early in the afternoon the Saturday VHT was noticeably higher and during the late afternoon the VMT was noticeably higher. This reflects a freeway mainline speed improvement late in the afternoon with metering.

Table 14 Mainline Flows by VMT and VHT

Saturday

	OFF	**ON**		**OFF**	**ON**	
Date	**11-Oct**	**18-Oct**		**11-Oct**	**18-Oct**	
Time	**Total VHT**	**Total VHT**	**%**	**Total VMT**	**Total VMT**	**%**
12pm-1pm	690	770	10.4	32100	31800	-0.9
1pm-2pm	630	830	24.1	33500	31400	-6.7
2pm-3pm	700	860	18.6	31200	32100	2.8
3pm-4pm	740	800	7.5	31700	30200	-5.0
4pm-5pm	790	750	-5.3	30000	31400	4.5
5pm-6pm	980	800	**-22.5**	29800	32700	8.9
Total	4530	4810	5.8	188,300	189,600	0.7

Sunday

	OFF	**ON**		**OFF**	**ON**	
Date	**12-Oct**	**19-Oct**		**12-Oct**	**19-Oct**	
Time	**Total VHT**	**Total VHT**	**%**	**Total VMT**	**Total VMT**	**%**
12pm-1pm	740	760	2.7	33500	35400	5.4
1pm-2pm	880	810	-8.6	35300	34600	-2.0
2pm-3pm	860	820	-4.9	34400	35300	2.5
3pm-4pm	780	670	**-16.4**	33500	33700	0.6
4pm-5pm	620	770	19.5	33500	33400	-0.3
5pm-6pm	580	710	18.3	32200	32000	-0.6
Total	4460	4540	1.8	202,400	204,400	1.0

Examining the Sunday data in Table 14 reveals that the Sunday VHT increased slightly overall as did the Sunday VMT. Notably, between 3:00 and 4:00 pm, the VHT decreased substantially, while during the following two hour period the VHT increased with metering. The VMT increased slightly with the metering in place.

Table 14 shows that on both Saturday and Sunday, the total VMT increased slightly over the period during which the metering was on. There are many other dimensions left to examine. For example, it is possible to determine the percent of time (between the hours of 12:00 noon and 6:00 p.m. on all four days) that traffic conditions fell into a particular freeway level of service (LOS) category. As shown in Table 15, VMT is tabulated by LOS for the entire metering period for each day. The Saturday data indicate that the proportion of time spent by drivers in LOS D, E and F dropped from 42% to 39% and the Sunday data indicate that the percentage dropped from 37% to 32%. Taking into account variations in total volumes, this indicates that the ramp metering led to more travel at better quality of service through the corridor.

Table 15 VMT by Level of Service

Analysis Time Period = 12 P.M. to 6 P.M.

		11-Oct		18-Oct			12-Oct		19-Oct		
LOS	Occupancy	VMT	% Total	VMT	% Total	% Diff	VMT	% Total	VMT	% Total	% Diff
		(i)		(ii)		(ii) - (i)	(iii)		(iv)		(iv) - (iii)
A	0 < 5	34,866	19%	33,405	18%	-4.4	31,656	16%	34,353	17%	7.9
B	5 < 8	33,736	18%	33,851	18%	0.3	44,893	22%	50,993	25%	12.0
C	8 < 12	40,144	21%	47,552	25%	15.6	52,302	26%	52,973	26%	1.3
D	12 < 17	49,296	26%	45,275	24%	-8.9	47,632	24%	42,620	21%	-11.8
E	17 < 28	24,879	13%	26,818	14%	7.2	23,300	12%	20,536	10%	-13.5
F	28 and above	5,378	3%	2,699	1%	-99.3	2,616	1%	2,926	1%	10.6
	Total VMT	188,300	100%	189,600	100%		202,400	100%	204,400	100%	

4.5.2 Ramp Flows

Often it is argued that ramp metering favors mainline flow at the expense of ramp delays. While it was not possible to quantify ramp delay per se, it is possible to examine total ramp flows. This ramp meter shutdown experiment was not publicized; therefore it can be reasonably assumed that drivers did not make major routing decisions based on the presence or absence of weekend metering on these days. Table 17 summarizes the total ramp flows on the four days by hour. In the table, the shaded cells indicate situations with higher flow on non-metered days and the bold text shows cases where the difference in flows was greater than 10% in favor of non-metered days.

Table 16 Ramp Flow by Ramp by Hour

Location Helvetia EB

Ramp Flow (vph)

Day	Saturday			Sunday		
Date	11-Oct	18-Oct		12-Oct	19-Oct	
Time			%			%
12 pm - 1 pm	439	412	-6.6	381	439	13.2
1 pm - 2 pm	376	428	12.1	373	376	0.8
2 pm - 3 pm	337	465	27.5	373	337	**-10.7**
3 pm - 4 pm	360	409	12.0	328	360	8.9
4 pm - 5pm	375	415	9.6	376	375	-0.3
5 pm - 6 pm	353	448	21.2	357	353	-1.1
Total	2240	2577	13.1	2188	2240	2.3

Location Cornelius Pass Rd. EB

Ramp Flow (vph)

Day	Saturday			Sunday		
Date	11-Oct	18-Oct		12-Oct	19-Oct	
Time			%			%
12 pm - 1 pm	587	646	9.1	553	596	7.2
1 pm - 2 pm	588	595	1.2	486	502	3.2
2 pm - 3 pm	511	556	8.1	552	490	**-12.7**
3 pm - 4 pm	528	509	-3.7	481	470	-2.3
4 pm - 5pm	459	514	10.7	395	423	6.6
5 pm - 6 pm	451	543	16.9	396	422	6.2
Total	3124	3363	7.1	2863	2903	1.4

Location 185th Ave. NB to EB

Ramp Flow (vph)

Day	Saturday			Sunday		
Date	11-Oct	18-Oct		12-Oct	19-Oct	
Time			%			%
12 pm - 1 pm	702	780	10.0	671	735	8.7
1 pm - 2 pm	799	899	11.1	732	736	0.5
2 pm - 3 pm	799	882	9.4	740	795	6.9
3 pm - 4 pm	809	823	1.7	727	726	-0.1
4 pm - 5pm	793	843	5.9	679	718	5.4
5 pm - 6 pm	759	781	2.8	689	679	-1.5
Total	4661	5008	6.9	4238	4389	3.4

Location 185th Ave. SB to EB

Ramp Flow (vph)

Day	Saturday			Sunday		
Date	11-Oct	18-Oct		12-Oct	19-Oct	
Time			%			%
12 pm - 1 pm	360	325	**-10.8**	259	298	13.1
1 pm - 2 pm	327	322	-1.6	228	243	6.2
2 pm - 3 pm	271	247	-9.7	263	215	**-22.3**
3 pm - 4 pm	250	287	12.9	190	204	6.9
4 pm - 5pm	224	227	1.3	225	222	-1.4
5 pm - 6 pm	227	240	5.4	211	202	-4.5
Total	1659	1648	-0.7	1376	1384	0.6

Location Cornell Rd. EB

Ramp Flow (vph)

Day	**Saturday**			**Sunday**		
Date	**11-Oct**	**18-Oct**		**12-Oct**	**19-Oct**	
Time			**%**			**%**
12 pm - 1 pm	789	800	1.4	807	785	-2.8
1 pm - 2 pm	759	818	7.2	759	757	-0.3
2 pm - 3 pm	746	687	-8.6	694	676	-2.7
3 pm - 4 pm	731	748	2.3	627	716	12.4
4 pm - 5pm	713	795	10.3	714	580	**-23.1**
5 pm - 6 pm	583	668	12.7	746	615	**-21.3**
Total	4321	4516	4.3	4347	4129	-5.3

Location Murray Rd. EB

Ramp Flow (vph)

Day	**Saturday**			**Sunday**		
Date	**11-Oct**	**18-Oct**		**12-Oct**	**19-Oct**	
Time			**%**			**%**
12 pm - 1 pm	611	554	**-10.3**	554	585	5.3
1 pm - 2 pm	637	477	**-33.5**	568	588	3.4
2 pm - 3 pm	572	466	**-22.7**	496	529	6.2
3 pm - 4 pm	523	449	**-16.5**	440	502	12.4
4 pm - 5pm	480	469	-2.3	453	470	3.6
5 pm - 6 pm	468	567	17.5	449	425	-5.6
Total	3291	2982	**-10.4**	2960	3099	4.5

Location Cedar Hills Blvd. EB

Ramp Flow (vph)

Day	**Saturday**			**Sunday**		
Date	**11-Oct**	**18-Oct**		**12-Oct**	**19-Oct**	
Time			**%**			**%**
12 pm - 1 pm	598	624	4.2	584	627	6.9
1 pm - 2 pm	599	588	-1.9	673	657	-2.4
2 pm - 3 pm	624	576	-8.3	562	562	0.0
3 pm - 4 pm	579	530	-9.2	458	542	15.5
4 pm - 5pm	504	528	4.5	476	489	2.7
5 pm - 6 pm	574	543	-5.7	480	462	-3.9
Total	3478	3389	-2.6	3233	3339	3.2

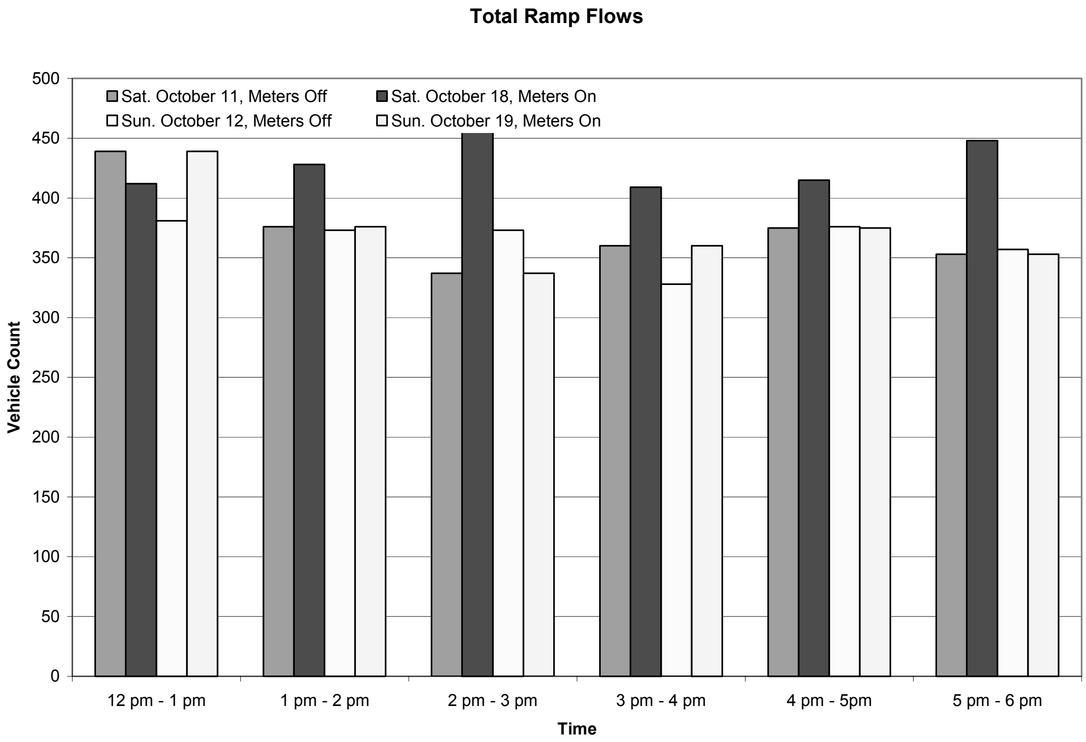
Location Canyon Rd. EB

Ramp Flow (vph)

Day	**Saturday**			**Sunday**		
Date	**11-Oct**	**18-Oct**		**12-Oct**	**19-Oct**	
Time			**%**			**%**
12 pm - 1 pm	675	692	2.5	516	608	15.1
1 pm - 2 pm	642	651	1.4	607	663	8.4
2 pm - 3 pm	650	677	4.0	564	668	15.6
3 pm - 4 pm	669	649	-3.1	521	608	14.3
4 pm - 5pm	717	631	**-13.6**	513	607	15.5
5 pm - 6 pm	702	625	**-12.3**	491	512	4.1
Total	4055	3925	-3.3	3212	3666	12.4

To enhance the results, Figure 63 shows the total on-ramp counts for all four days by hour. As shown, in nearly all cases, the total on-ramp flows were higher (or nearly the same) on the days when the ramp meters were operational. The exceptions are on Saturday between 12:00 noon and 1:00 p.m. and on Sunday between 2:00 p.m. and 3:00 p.m.

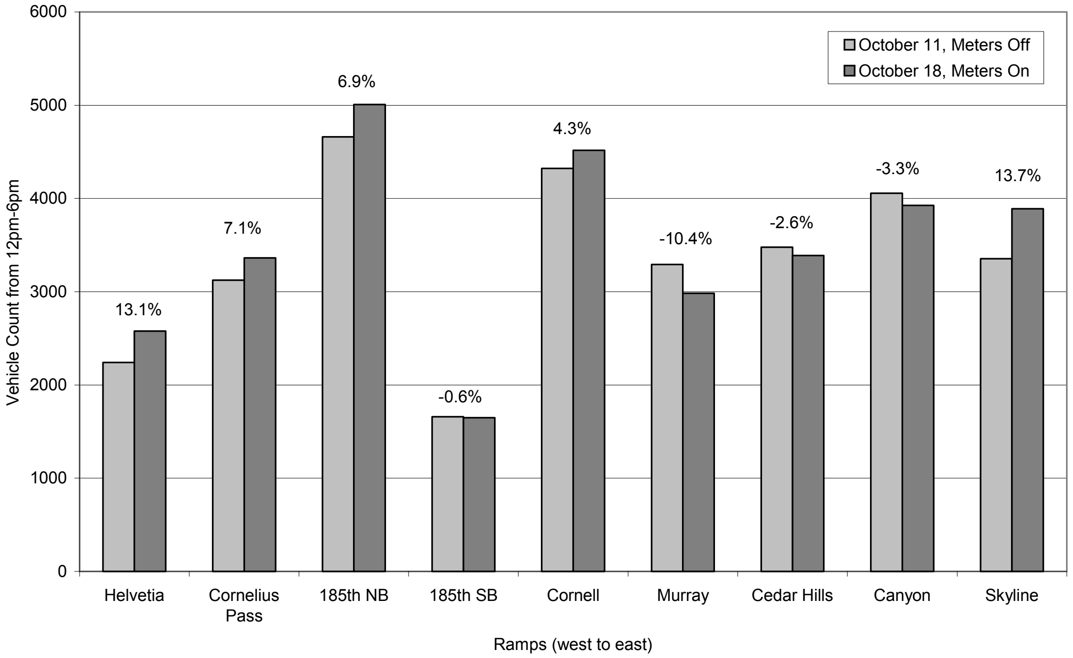
Figure 63 Total Ramp Flows



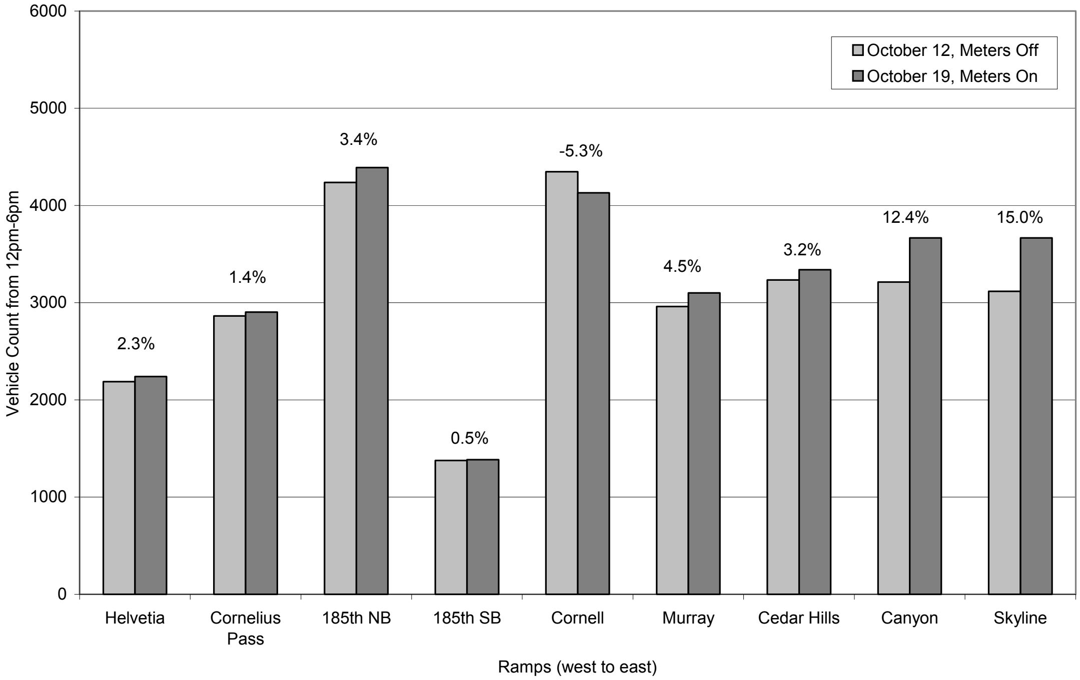
While Figure 63 provides an overall picture of ramp characteristics, it is important to understand the spatial impacts of ramp metering, since it is often said that metering penalizes the drivers who are closer to the bottleneck (in this case the downstream-most ramps). As shown in Figure 64, there does not appear to be a systematic bias in favor of the western-most ramps (e.g., Helvetia and Cornelius Pass). The Saturday data indicate that higher flows prevailed at the outer ramps (Helvetia to Cornell) while the next three ramps (Murray, Cedar Hills and Canyon) experienced somewhat lower flows. It is difficult to attribute all of the variation solely to the metering since there may have been other factors influencing demand from day to day.

Figure 64 Vehicle Count at Ramp Meters

Saturday Ramp Flow



Sunday Ramp Flow



The Sunday data indicate that all ramps exhibited higher flows except for Cornell. While on Saturday some bias toward the upstream ramp may be evident, it is clear that it was not the case on Sunday.

4.5.3 Speed and Travel Time Data

Average speed is a primary parameter that describes the condition of a given stream of traffic. Reduced vehicle speed indicates the lower mobility motorists are subjected to when congestion exists. The duration of congestion can be established by examining the time periods during which lower velocities are encountered *(41)*. For this experiment, the 20-second speed data were used along with freeway section length to estimate corridor travel time, which was plotted versus time in greyscale in Figures 65, 66, 67 and 68.

For example, Figure 65 shows the corridor travel time as it evolves over the entire day of October 11, 2003. The mean travel time was 13.7 minutes with a standard deviation of 2.7 minutes without ramp meters. Using the right hand *y*-axis, the travel time was also plotted cumulatively (solid line) along with the free-flow travel time (estimated to be 12.7 minutes). By viewing the slopes of these lines, the deviation of actual travel time from freeflow travel time is clearly visible when the curves deviate from one another. The beginning of non-freeflow conditions began on this unmetered Saturday at 11:30 a.m. and continued until 6:22 pm, when the slopes of the two travel time curves again became parallel. The mean travel time during this period was 15.8 minutes.

Turning to Figure 66, the situation on the following metered Saturday is similar. The free flow travel time for the entire day on October 18, 2003 was 13.5 minutes with a standard deviation of 2.0 minutes. The peak period was approximately the same length—it began at 11:15 and ended at 6:34 (the meters were on between 12:00 noon and 6:00 pm). As shown, during the actual peak period, the average travel time was 15.7 minutes, slightly faster than on the previous unmetered Saturday (less than a 1% corridor improvement).

Figure 67 shows a similar plot for October 12, the unmetered Sunday. The day's mean travel time was 13.1 minutes with a standard deviation of 1.7 minutes. The peak period occurred only while the meters would have been operating—it began at 12:19 and ended at 4:08 pm. The mean travel time along the corridor was 15.9 minutes. On the following Sunday, October 19, with the metering in operation, the daylong mean travel time was 13.2 minutes and the standard deviation of the travel time was also 1.7 minutes. On this day the corridor was congested between 12:15 and 5:51, completely inside the timeframe of metering. As shown in the figure, the mean travel time was 15.0 minutes, reflecting a 6% improvement in corridor travel time during the peak.

One of the secondary goals of ramp metering is more uniform traffic speeds. The variance of the travel times did drop slightly from 7.5 min^2 to 4.2 min^2 on Saturday with metering and from 2.9 min^2 to 2.8 min^2 on the Sunday with metering. Despite the results of these two particular weekends, traffic typically functions in free flow conditions through the entire corridor when ramp meters are activated on the weekends, while speeds are generally below 30 mph without ramp metering. ODOT will continue to meter and monitor the eastbound ramps in this corridor on weekends as long as the benefits exceed the costs.

4.6 Conclusion

Several agencies across the globe have experienced success with their ramp metering programs. Some have even seen freeway capacity above 2,000 vph per lane. Unfortunately, ramp meters are not a cure-all. While they can generate significant improvements in some areas, they cannot eliminate all congestion or every accident. The true measure of their effectiveness, however, is the continued increase of ramp metering implementations such as those demonstrated in cities such as Portland, Oregon.

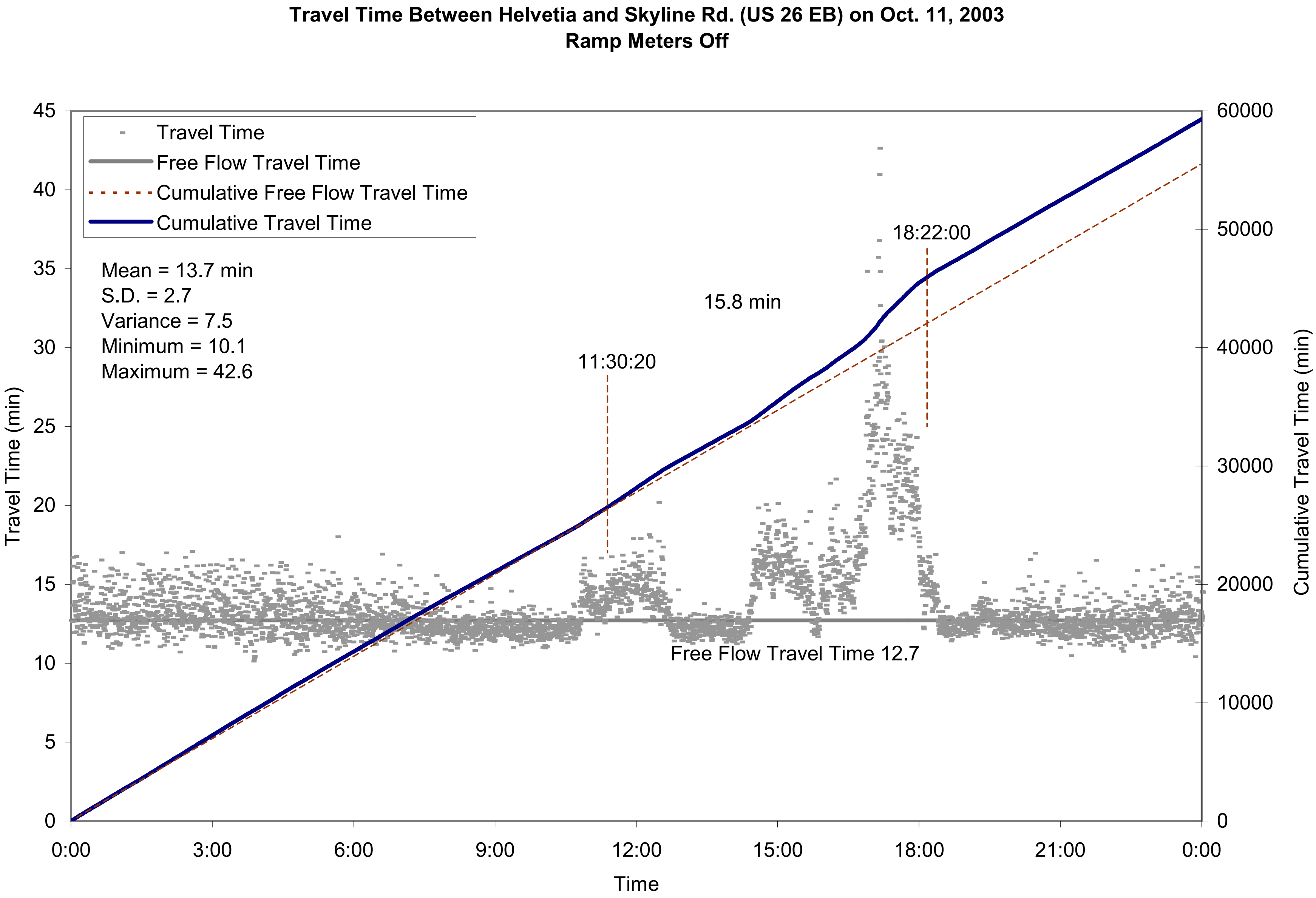


Figure 65 Travel Time on Saturday October 11 (Meters Off)

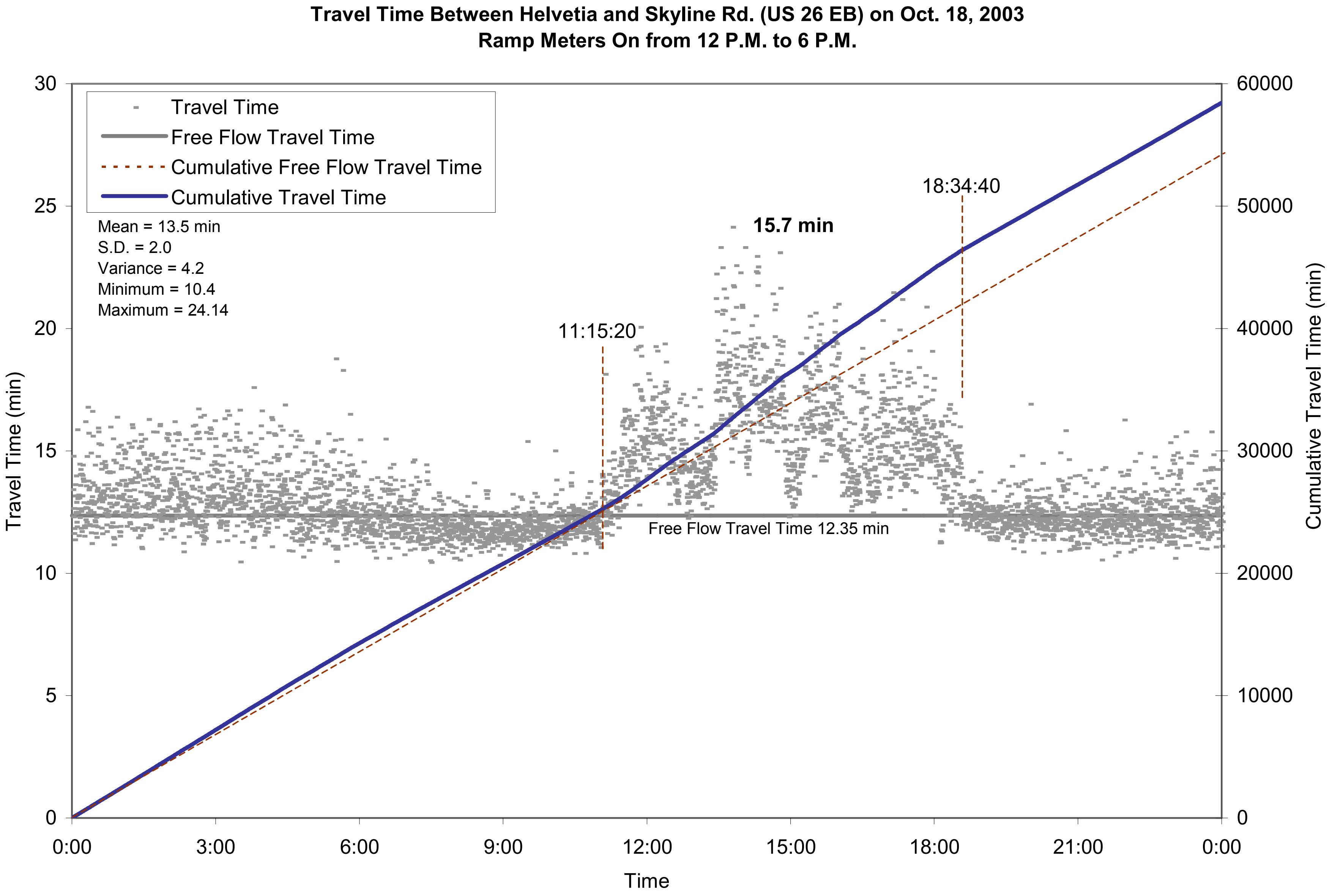


Figure 66 **Travel Time on Saturday October 18 (Meters On)**

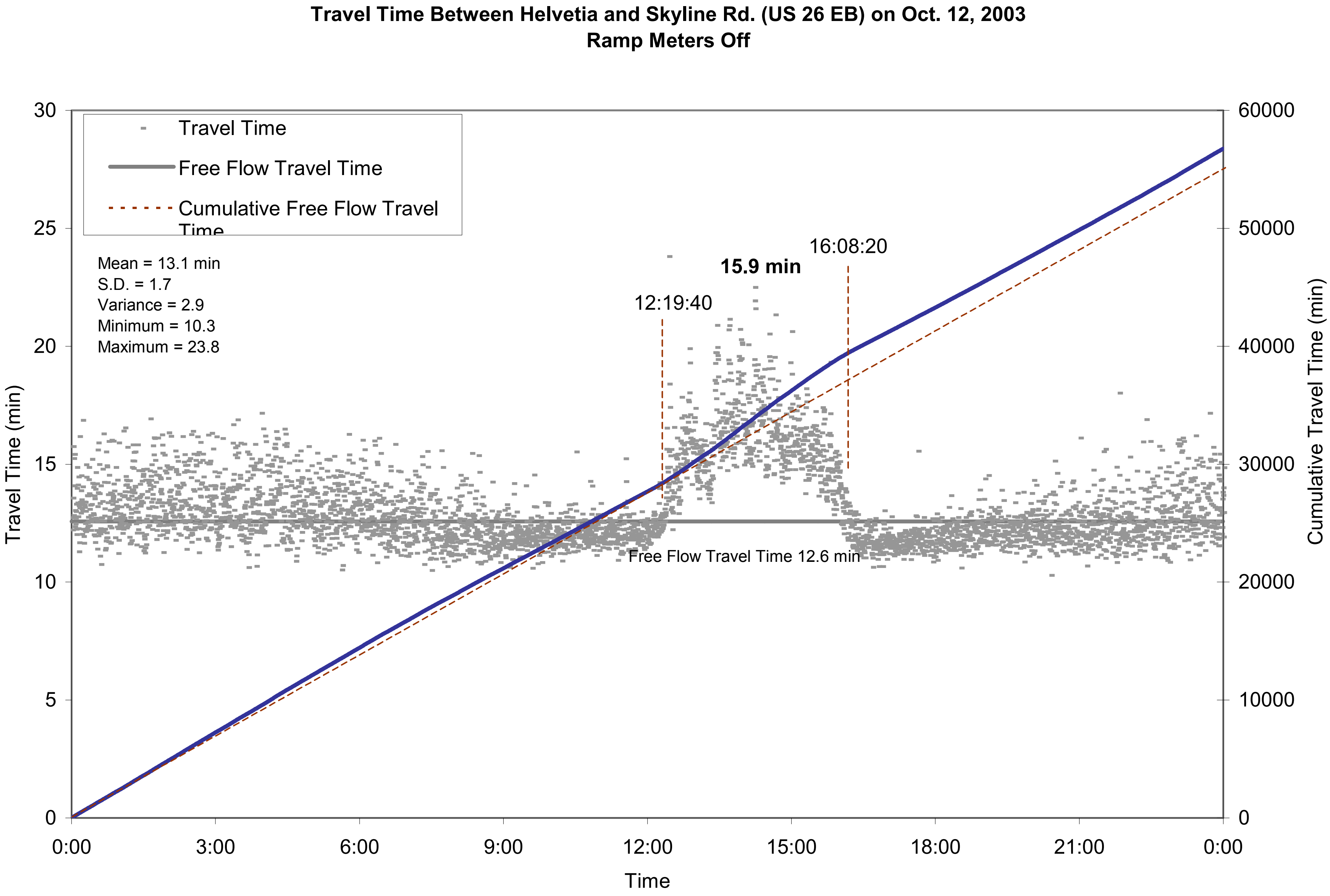


Figure 67 **Travel Time on Sunday October 12 (Meters Off)**

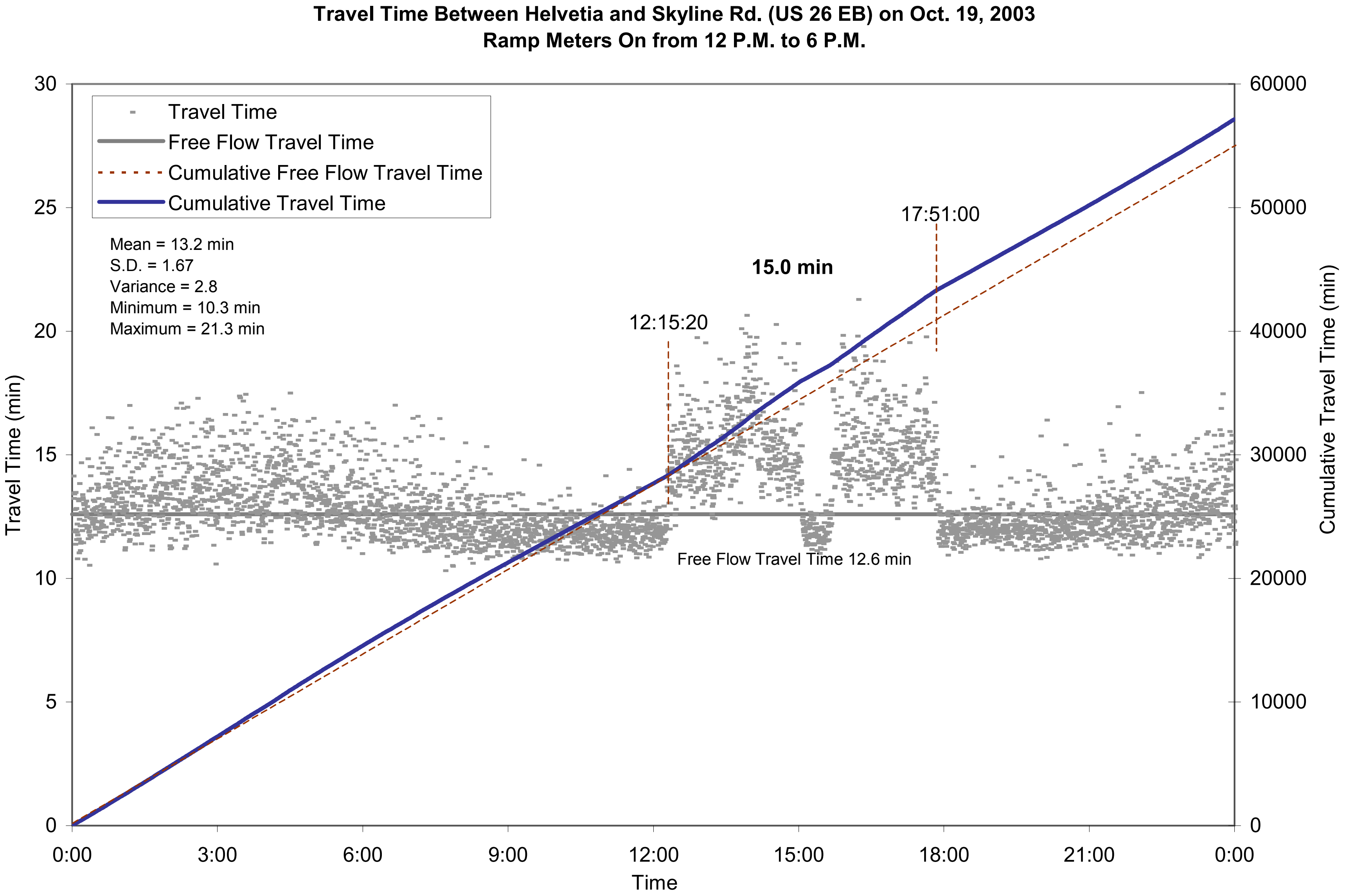


Figure 68 **Travel Time on Sunday October 19 (Meters On)**

5.0 DISCUSSION

This project accomplished much of what it set out to achieve. This research project represented the first use of ODOT's 20-second loop detector data, and presented some initial challenges with its interpretation and validation. Initially the data were reporting erroneous speed and occupancy values (off by a factor of 256), and subsequently we examined the -999 and -1 reports, now attributed to communications failures and zero count readings coupled with a divide by zero error. This study has been valuable in that it revealed these issues and has led to improvements in ODOT's data collection and archiving algorithms.

The second main benefit of this study is that it has established that the ramp metering system that is currently in place is performing reasonably well given its own limitations. It was shown that many times the preprogrammed metering rates do not match the actual ramp flows measured in the field. The reasons for this are not completely clear, but can be attributed to meter violations and uncounted vehicles on the on-ramps. We recommend that better ramp detection be installed in future implementations of ramp metering (e.g., several loops tied together across wide ramps so that vehicles are not missed). In addition, we recommend that off-ramp detection be included in future implementations to facilitate preservation of vehicle conservation when analyzing mainline count data between merges and diverges.

A third benefit is that we have established a baseline for a "before" and "after" evaluation of the new SWARM system that is being readied for deployment. This coupled with the new data archive being established at Portland State University will facilitate a more comprehensive analysis of the performance of the new metering system. Based on the valuable results of the Minnesota ramp meter shut down study, ODOT should consider a transition period prior to the start-up of the new SWARM system where the current meters along selected segments are shut down during particular periods in order to collect better traffic demand data.

Finally, a small study was conducted both with and without ramp metering in one corridor, resulting in a unique level of analysis for the eastbound Route 26 corridor on two weekends. The results confirm that the metering is most definitely not leading to deteriorated conditions and appears to improve traffic operations in the corridor.

In conclusion, the literature review included the examination of many ramp metering studies, some based on simulation and some based on analysis of empirical data. The Minnesota study included several key points for successful ramp metering deployments that will be reiterated here:

- Meter the Proper Location – In order to realize significant benefits, it is necessary to implement ramp metering in freeway sections that actually need it. Locations typically have the following characteristics: peak-period speeds less than 30 mph; flow of 1,200 to 1,500 vphpl; high accident rate; and significant merging problems.
- Secure Funding – Before embarking on a ramp metering program, make sure that the local politicians and city officials are committed to funding the program.
- Good Public Support – All implementing cities believe that public education and support are critical to the success of their ramp metering programs.
- Ample Storage Capacity – Most cities would like to have longer and wider ramps to prevent queues from extending beyond the ramps onto the arterials. If long queues with backups onto the arterials occur on a consistent basis, implementation of queue detection systems and adoption of a more conservative strategy may be necessary.
- Synergy – Use other forms of Intelligent Transportation Systems (ITS) to eliminate disadvantages found in ramp metering alone (e.g., couple ramp metering with ramp queue wait time signs or a Traveler Information System that can inform motorists of travel conditions and options for different travel modes, times, or routes).
- Avoid Conflicting Solutions – Mainline freeway HOV lanes and ramp meters may not work well together. Without HOV-bypass lanes or direct HOV connectors, metering may impose unnecessary delay to buses and carpools.
- Eliminate Technical Problems – Make sure the system is free from technical breakdowns to sustain high public trust and compliance rates.
- Consistent Enforcement – Consistent police enforcement, though costly, is the most effective enforcement strategy.
- Continuous Improvement – Upgrade the system to central or fuzzy logic controllers. Central control offers monitoring of an entire system, while fuzzy logic eliminates the possibility of processing and applying imprecise or erroneous traffic data.

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