Eastbound SR 520

Impacts of Freeway Surveillance and Control

WA-RD 99.1

Final Report
February 1987

Washington State Department of Transportation
Planning, Research and Public Transportation Division
in cooperation with the
United States Department of Transportation
Federal Highway Administration

WASHINGTON STATE DEPARTMENT OF TRANSPORTATION

TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO. WA-RD-99.1	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.
4. TITLE AND SUBTITLE IMPACTS OF FREEWAY SURVEILLANCE AND CONTROL ON EASTBOUND SR 520		5. REPORT DATE February 1987
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Nancy L. Nihan, Professor		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS University of Washington Seattle, WA 98195		10. WORK UNIT NO.
		11. CONTRACT OR GRANT NO. Y2811, Task 22
12. SPONSORING AGENCY NAME AND ADDRESS Washington State Department of Transportation Kern Jacobson Planning and Operations Engineer District 1		13. TYPE OF REPORT AN PERIOD COVERED Final
		14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

This study was conducted in cooperation with U.S. Department of Transportation, Federal Highway Administration.

16. ABSTRACT

The project entitled "Impacts of Freeway Surveillance and Control on Eastbound SR520", analyzed and evaluated the impacts of ramp metering and a new ramp HOV lane on eastbound SR520 which connects Seattle and the Eastside suburbs. Data analyzed included origin-destination surveys, manual vehicle occupancy counts, floating car travel-times, queue-length counts, electronic volume and lane-occupancy values, and bus travel-times. The results showed that the numbers of carpools and vanpools were significantly increased on the ramp with the new HOV lane and overall level-of-service was improved for mainline SR520. A significant number of trips were diverted from from the local neighborhood to I-5. Queue-lengths and travel-times to the ramp mergers with the mainline increased significantly for both ramps. This was an expected result and had the desired effect of diverting trips from the neighborhood and increasing HOV ridership.

17. KEY WORDS Freeway Surveillance and Control, Transportation System Management, Ramp Metering, High Occupancy Vehicle Lanes, Before-And-After Studies.	18. DISTRIBUTION STATEMENT

19. SECURITY CLASSIF. (of this report) Unclassified	20. SECURITY CLASSIF. (of this page) Unclassified	21. NO. OF PAGES 84	22. PRICE

DOT FORM 310-022 (11/86) -1216-

IMPACTS OF FREEWAY SURVEILLANCE AND CONTROL ON EASTBOUND SR 520

by

Nancy L. Nihan
Principal Investigator

Washington State Transportation Center
University of Washington
Seattle, Washington

Washington State Department of Transportation
Technical Monitor
Kern Jacobson
Planning and Operations Engineer
District 1

Final Report

Research Project Y-2811
Task 22

Prepared for

Washington State Transportation Commission
Department of Transportation
and in cooperation with
U.S. Department of Transportation
Federal Highway Administration

February 1987

The contents of this report reflect the views of the author who is responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Washington State Department of Transportation or the Federal Highway Administration. This report does not constitute a standard, specification or regulation.

TABLE OF CONTENTS

	Page
List of Illustrations	iv
Abstract	v
Summary	1
Conclusions and Recommendations	6
Review of Previous Work	9
Procedures	10
Discussion (Body)	11
Review of Literature	11
Materials and Methods	13
Results and Discussion	23
Conclusions and Recommendations (Summary)	56
References	58
Appendix A: Literature Review	63
Appendix B: Supplementary Tables and Figures	69

LIST OF ILLUSTRATIONS

		Page
Figure 1.	Study Location	2
Figure 2.	Postcard Questionnaire for Origin-Destination Survey.	14
Figure 3.	Form for Vehicle Occupancy Counts.	15
Figure 4.	Form for Queue-Length Counts.	17
Figure 5.	Location Map for Queue-Length Counts.	18
Figure 6.	Form for Floating Car Travel-Time Records.	19
Figure 7.	Mainline Metering Station Locations.	21
Figure 8.	Zone Map for OD Analyses.	24
Figure 9.	Before and After Speeds (Station 292)	44
Figure 10.	Volume vs. Lane Occupancy, Both Lanes (Station 292).	46
Figure 11.	Volume vs. Lane Occupancy, Both Lanes (Station 117).	48
Figure 12.	Volume vs. Lane Occupancy, Both Lanes (Station 119).	49
Figure 13.	Queue Length Data for Montlake On-Ramp.	50
Figure 14.	Queue Length Data for Lake Washington Blvd. On-Ramp.	51
Figure B1.	Volume vs. Lane Occupancy, Right Lane (Station 292).	74
Figure B2.	Volume vs. Lane Occupancy, Left Lane (Station 292).	75
Figure B3.	Volume vs. Lane Occupancy, Right Lane (Station 117).	76
Figure B4.	Volume vs. Lane Occupancy, Left Lane (Station 117).	77
Figure B5.	Volume vs. Lane Occupancy, Right Lane (Station 119).	78
Figure B6	Volume vs. Lane Occupancy, Left Lane (Station 119).	79

ABSTRACT

The project entitled "Impacts of Freeway Surveillance and Control on Eastbound SR520", analyzed and evaluated the impacts of ramp metering and a new ramp HOV lane on eastbound SR 520 which connects Seattle and the Eastside suburbs. Data analyzed included origin-destination surveys, manual vehicle occupancy counts, floating car travel-times, queue-length counts, electronic volume and lane-occupancy values, and bus travel-times. The results showed that the numbers of carpools and vanpools were significantly increased on the ramp with the new HOV lane and overall level-of-service was improved for mainline SR 520. A significant number of trips were diverted from the local neighborhood to I-5. Queue-lengths and travel-times to the ramp merges with the mainline increased significantly for both ramps. This was an expected result and had the desired effect of diverting trips from the neighborhood and increasing HOV ridership.

SUMMARY

INTRODUCTION

This report covers the activities performed under the Washington State Department of Transportation (WSDOT) Contract for Research Project Y-2811-22, executed by the Department of Civil Engineering at the University of Washington (UW) under the supervision of Dr. Nancy L. Nihan.

The-two phase project focused on the assessment of TSM improvements to two on-ramps to the SR520 eastbound link connecting Seattle and the Eastside. The on-ramps at Montlake and Lake Washington Blvd. are the last eastbound on-ramps before the bridge across Lake Washington. Figure 1 shows the study location including the SR520 link and the two on-ramps. The TSM improvements at the study location consisted of the installment of ramp metering at both ramps and the construction of a high-occupancy vehicle (HOV) bypass lane at the Montlake on-ramp.

The original project which began in August, 1984, involved developing measurements of performance for evaluating the effects of TSM improvements on the Montlake on-ramp and the Lake Washington Blvd. on-ramp on SR520 and conducting a before-data collection to complement the data collection efforts of the Traffic Systems Management Center (TSMC) for District 1 of WSDOT. Collection of the before-data was delayed until February, 1986, due to equipment failures and other problems which delayed the TSMC's data collection effort. This project was further extended to include collection of after-data which was collected in March and April, 1986.

OBJECTIVES

The objectives of this research project included 1) identifying the best performance measures for analyzing the impacts of the introduction of ramp metering on the two on-ramps and an HOV lane at the Montlake on-ramp;

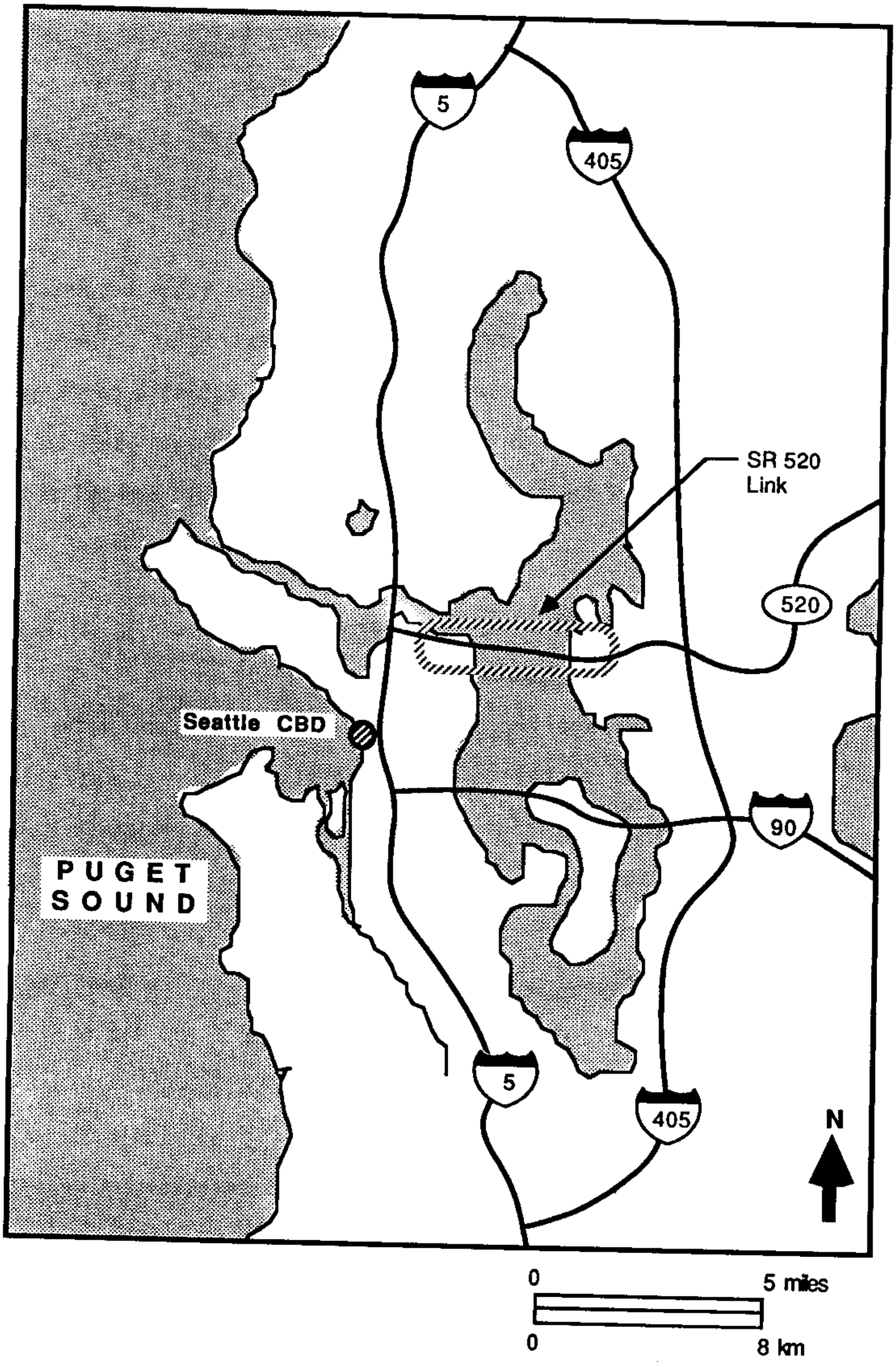

Figure 1. Study Location.

2) coding and analysis of a postcard origin-destination (OD) survey performed by the TSMC in April 1982; 3) collection of before-and-after data for the selected performance measures including additional before-and-after OD surveys; and 4) analysis of the above data to assess the impacts of the introduction of ramp metering and the HOV lane.

DESCRIPTION

The data collected included OD surveys in the form of postcard questionnaires, manual vehicle occupancy counts, electronic volume/lane-occupancy data, manual counts of ramp queue lengths, floating car travel-time runs, manual counts of bus arrival times, and electronic bus travel-time data. The data were analyzed with appropriate statistical tests, time series analysis, and graphics.

CONCLUSIONS AND RECOMMENDATIONS

The major conclusions are summarized below:

1. Level of service was improved on mainline SR520 due to the ramp metering; mainline speeds increased significantly while lane occupancies decreased significantly, and volumes remained stable with slight increases.
2. Travel times from trip origins to the ramp merges with mainline SR520 were increased slightly for both ramps. This resulted in desired route diversions and mode shifts (See items 4 & 5 below).
3. Bus travel times were decreased.
4. Trips from downtown and from southern zones were diverted away from the Lake Washington Blvd. on-ramp (an objective of Montlake residents that was part of the agreement with the city and WSDOT).
5. The number of carpools and vanpools significantly increased on

the Montlake ramp due to the introduction of the HOV bypass lane and increased ramp queue lengths.

6. Although queue lengths increased at both ramps due to the ramp metering, a portion of the resulting time loss was offset somewhat by the time savings on the mainline. The increased queue lengths for SOV's resulted in desired route and mode choice shifts.

The general conclusion is that the ramp metering and HOV lane had the desired results; i.e., these TSM techniques improved mainline travel, increased the attractiveness of carpools, vanpools and buses and diverted unwanted neighborhood traffic coming from other parts of the city. It is recommended that this type of TSM strategy be used in situations such as the SR520 case where mainline volumes are already at or near capacity during the peak hours and even small volume diversions and volume controls have a significant impact upon mainline LOS.

IMPACTS OF FREEWAY SURVEILLANCE AND CONTROL ON EASTBOUND SR520

REPORT Y-2811-22

CONCLUSIONS AND RECOMMENDATIONS

ORIGIN-DESTINATION SURVEYS

Ramp metering appears to have had a diversionary effect upon vehicles entering the Lake Washington Blvd. on-ramp such that a significant percentage of those that had previously come from downtown and southern zones, and passed through the Montlake neighborhood, were diverted to other routes (most likely I-5) which was one of the desired results of the TSM strategy. However, the ramp metering had no such diversionary effect upon vehicles entering the Montlake ramp.

Total perceived trip travel-times increased slightly on both ramps due to the ramp metering. This result was further supported by actual travel times obtained in floating car studies. The before-and-after OD surveys indicated a significant increase in vehicle occupancies for the Montlake ramp but no change for the Lake Washington Blvd ramp. Thus, the OD surveys (which were limited to cars and vans) implied a significant increase in the number of carpools and vanpools caused by the introduction of the HOV lane on the Montlake on-ramp. This was further supported by manual vehicle occupancy counts.

MANUAL VEHICLE OCCUPANCY COUNTS

The data obtained for buses in these counts were not sufficient for analysis. The remaining data indicated a significant decrease in the number of single-person vehicles (SOV's) and significant increases in the number of carpools and vanpools on the Montlake ramp due to the introduction of the HOV lane. The manual counts showed a slight increase in single person auto trips and a corresponding decrease in carpool and vanpool trips on the Lake Washington Blvd. on-ramp indicating a possible shift in carpool and vanpool trips to the Montlake HOV lane. The mainline SR520 lanes did not exhibit significant changes in vehicle occupancy.

VOLUME/LANE OCCUPANCY RESULTS

The time series intervention analyses of volume and lane-occupancy data showed statistically significant improvements in level of service on mainline SR520 after the ramp controls were introduced. Plots of volume/lane occupancy for several days' data supported these time series regression results. Assuming a stable effective vehicle length for the before-and-after traffic streams, the electronic data showed significant improvements in mainline SR520 speeds.

TRAVEL TIMES - FLOATING CAR METHOD

The statistical analysis of several days' travel-time data indicated that a net total increase in travel time was experienced by travelers from the University to the Eastside (an average of 4.7 minutes). The average increase in the time it took to go from the point of origin to the ramp merge with the mainline link was 5.0 minutes. These results and the volume/lane-occupancy results indicated that travelers already on the mainline experienced a slightly improved travel time, while travelers using the ramps were dissuaded from SOV travel and through travel on neighborhood arterials.

RAMP-QUEUE LENGTHS

Plots and statistical tests indicated an increase in queue lengths for the on-ramps after the ramp metering intervention. The increase in queue length was most pronounced for the Lake Washington on-ramp. These queue length increases for single occupant vehicles (SOV's) resulted in desired shifts in route and mode choice. The five-minutes saved by HOV's on the Montlake Ramp resulted in a change in the auto occupancy from 1.3

persons/vehicle to 1.5 persons/vehicle. This change applied to vans and autos only and did not reflect the suspected additional increase in bus occupancy that turned out to be a measurement problem.

BUS ARRIVAL TIMES AND ELECTRONIC TRAVEL TIMES

The manually collected bus arrival-time data did not give conclusive results. Also, the travel-time data sample collected electronically by METRO was too small for adequate analysis. However, the observed mainline speed improvements, the HOV lane time advantage, and the fact that METRO had plans to change their Autumn 1986 schedules to reflect improved travel times led to the conclusion that bus travel times were significantly improved due to the ramp metering and the introduction of the HOV lane.

RECOMMENDATIONS

The above conclusions lead to the overall final determination that the ramp metering and HOV lane had the desired results. That is, these TSM techniques

a) improved mainline travel,

b) increased the attractiveness of carpools, vanpools and buses, and

c) diverted unwanted neighborhood traffic coming from other parts of the city.

It is recommended that this type of TSM strategy be used in situations such as the SR520 case where mainline volumes are already at or near capacity during the peak hours and even small volume diversions and volume controls have a significant impact upon mainline LOS.

REVIEW OF PREVIOUS WORK

Previous related work includes the April 1982 O-D survey conducted by the TSMC that was coded and analyzed by the current project, and a project at the University of Washington to install a telecommunications link between the TSMC and the UW to transfer volume and lane-occupancy data which was used in the LOS analyses for this project. The Telecom Project began in the Summer of 1981 with the initiation of the FLOW ramp metering system by District 1 and was conducted by Dr. Nancy L. Nihan at the University of Washington. The original Telecom Project was performed under a Washington State Department of Transportation contract for Research Project Y-2811-2, and was extended under a second contract with WSDOT for Research Project Y-3399 which is currently being completed.

PROCEDURES

The data collection procedures involved the following data collection efforts:

1. Origin-Destination surveys by postcard (February 25 and April 29, 1986).
2. Manual vehicle occupancy counts. (February 24, 25 and April 28, 29, 1986).
3. Bus arrival time counts (February 24, 25 and April 28, 29, 1986).
4. Manual ramp-queue length counts (February and April, 1986).
5. Travel-time floating car studies (February through April, 1986).
6. Electronic volume and lane occupancy counts for mainline and ramps. (February through April, 1986).
7. Electronic bus passenger counts and travel-time counts (February through April, 1986).

Statistical analyses including non-parametric tests and time-series intervention analysis as well as graphical analysis were used to assess the TSM strategies of ramp-metering and introduction of a new HOV lane.

DISCUSSION
(Body)

REVIEW OF LITERATURE

The literature review included in Appendix A summarizes the pertinent literature in the areas of freeway surveillance control, performance evaluation, origin destination survey methods, sampling considerations, and general transportation system management topics that were reviewed as background for the SR520 study. The detailed presentation is meant to provide the reader with a cataloging of the references in each area. Of the many references listed, only a few were found to be applicable to the present study. These are summarized in this section.

In designing the data collection approach, the performance evaluation measures were derived from a recommended set of measures-of-effectiveness (MOE's) developed by Abrams, et al. (1981). A subset of the 12 dominant MOE's thought of as most critical for TSM planning was selected for the SR520 project. The Abrams reference, along with basic statistical sources, was also useful in determining sample sizes and other elements of the study design. The TRB (1983, 1986) user's manual for low cost TSM projects was also helpful in the research design.

Although several OD survey methods were reviewed, and are included in Appendix A, the choice of survey method was constrained by the desire to capitalize on a past survey by the TSMC and therefore be consistent with the previous methodology. Thus the same post card technique was used for the followup surveys.

A special technique known as time series intervention analysis was used to analyze the electronic volume/lane-occupancy data for the intervention effects of the ramp control program. This technique is described in Nihan and Davis (1984 -Transportation Research Record) and is demonstrated in other work such as Levin and Tsao (1980) and Ahmed and Cook (1982). At its simplest (models based on non-stationary series), this technique is just linear regression analyses performed on time series data with an intervention variable included as one of the independent variables. The intervention variable has values of 0 for time periods occurring before the intervention of interest and values of 1 for time periods following the intervention. Simple regressions are run for the performance variable of interest (e.g., volume on eastbount SR520), a covariable to pick up trends (e.g., volume on eastbound I-90) and the intervention variable (e.g., variable representing the time that the ramp controls were put into effect). The resulting coefficient of the intervention variable for the above example gives the amount of increase or decrease in SR520 volume due to the ramp controls. If the time series data cannot be modelled with simple linear regression techniques, more complicated time series models known as ARIMA intervention models may be required. Such model forms were not required for the SR520 analysis, but are discussed in Nihan and Davis (1984 - Transportation Research) and Ljung and Soderstrom (1983).

The literature on TSM experiences in other cities such as TRB (1977, 1981), NCHRP (1981), and Rogers (1986) supported the findings of the SR520 study. TSM strategies such as ramp metering and exclusive HOV lanes have been shown to increase mainline speeds and vehicle occupancies in cities such as Minneapolis, Sacremento, Portland, Miami, Houston, Boston, Los Angeles, Washington D. C. and others. These were two prime objectives of the SR520 project as well and two objectives that were satisfactorily realized.

MATERIALS AND METHODS: BEFORE AND AFTER DATA COLLECTIONS

On March 10, 1986, ramp metering on both ramps and HOV lane operation on the Montlake ramp went into effect. The following sections describe the before-and after-data collections taken to assess the effects of this TSM strategy and the subsequent statistical analysis.

Postcard Surveys

On February 25 and April 29, 1986, a postcard origin destination (OD) survey was conducted at both the Montlake and Lake Washington Blvd. on-ramps during the two-hour afternoon peak period. Figure 2 shows an example postcard questionnaire. Approximately 1000 postcards were handed out at each ramp during this period for both the before- and after-data collection. The number of returned cards for the February count and the April count, respectively, were 627 and 531 for the Montlake ramp and 571 and 486 for the Lake Washington Blvd. ramp. The post card questionnaires were duplicates of questionnaires that had been handed out in a previous study in April 1982 by the TSMC. This earlier survey yielded 407 responses for the Montlake ramp and 556 responses for the Lake Washington Blvd. ramp. With the results of this additional survey we had two sets of before-data (April 1982 and February 1986) and one set of after-data (April 1986).

Manual Counts

During the peak hours of February 24 and 25, 1986, and April 28 and 29, 1986, manual vehicle occupancy counts and bus arrival times were recorded. During these periods, vehicle occupancy observations for vehicles entering the two eastbound on-ramps and eastbound vehicles on the mainline ramps were made. Figure 3 shows an example of the form used for the vehicle occupancy counts. In addition, eastbound bus arrival times at the Montlake Freeway Flyer station were also observed. These were later compared to the

EASTBOUND SURVEY

Station No. [ ][ ] Date [ ][ ][ ][ ][ ]
Time [ ][ ][ ] A.M. [ ] P.M. [ ]

DO NOT WRITE ABOVE THIS LINE

1. Origin of Trip (exact address, closest intersection or place where this trip started). ______________________________ 1. [ ][ ][ ][ ][ ]

2. Destination of Trip (exact address, closest intersection or place where this trip will end). ______________________________ 2. [ ][ ][ ][ ][ ]

3. Please indicate the number of people in your vehicle on this trip. (Please include driver) ______________ 3. [ ]

4. Please indicate where you exited the Freeway (check one). 4. [ ][ ]

[ ] 84th Ave NE
[ ] 104th Ave NE Northbound
[ ] I-405 Northbound
[ ] 148th Ave NE
[ ] W. Lake Sammamish Pkwy. NE
[ ] 104th Ave NE Southbound
[ ] I-405 Southbound
[ ] 124th Ave NE (Northup Way)
[ ] NE 51st St.
[ ] Other ______________

5. Exact time of departure from origin ______________ PM 5. [ ][ ][ ][ ][ ]

6. Arrival at destination ______________ PM 6. [ ][ ][ ][ ][ ]

7. Frequency of trips ______________ per day
or ______________ per week using this route. 7a. [ ]
7b. [ ][ ]

8. Please indicate the purpose of trip (check one) 8. [ ]

[ ] WORK [ ] SHOPPING [ ] SCHOOL
[ ] SOCIAL-RECREATION [ ] Other ______________

COMMENTS ______________________________ [ ]

Figure 2. Postcard Questionnaire for Origin-Destination Survey.

VEHICLE OCCUPANCY DATA COLLECTION FORM

Time: ____________________ Location: ____________________

Date: ____________________ Name of Observer: ____________________

1 Person Car & Trucks	2 Per. Car	3 Per. Car	4 Per. Car	5-8 Per. Car	9-11 Per. Car	Reg. Half Bus	Reg. Full Bus	Art. Half Bus	Art. Full Bus	
										2:30-2:35
										2:35-2:40
										2:40-2:45
										2:45-2:50
										2:50-2:55
										2:55-3:00

Figure 3. Form for Vehicle Occupancy Counts.

scheduled bus arrival times.

Queue-length data were also taken manually. Queue lengths were measured every 15 minutes from 2:30 pm to 5:45 pm at both on-ramps. The 10 week-days between 2/17/86 and 2/28/86 provided the before-data. The 10 week-days between 4/14/86 and 4/28/86 provided the after-data. Figures 4 and 5 show the form used for this data collection and the associated location map. Queue lengths were expressed in vehicles and displayed graphically for day and time of day in 3-D plots. The total before-data for each station was also aggregated as was the total after-data and compared using before-and-after histograms and the Mann-Whitney U statistic. We found that the queue lengths were significantly longer at both ramps after the ramp controls were in effect. This had a desired deterrent effect on single-occupant vehicles (SOV's) and non-neighborhood traffic.

Floating Car Studies

Travel-time floating car studies were performed for the months of February and April by the Principal Investigator and TRAC staff. Figure 6 shows the form that was used for this data set. From the collected data, 10 runs from the Montlake parking lot to Evergreen Point made between 4:30 pm and 5:30 pm were available both before and after the ramp controls. This subset of runs was selected for analysis. For each of these runs the time to reach the ramp (t_a), the time on the on-ramp (t_b), mainline time (t_c), time to reach mainline ($t_a + t_b$) and total travel time ($t_a + t_b + t_c$) were computed. Before- versus after-values were compared using the Mann-Whitney U statistic. These results showed an increased time to reach the mainline, an increased total travel-time and a slight decrease in mainline travel time.

Queue Length Data Collection Form

Date:
Observer:

Time	Montlake	Lake Washington Blvd.
2:30		
2:38		
2:45		
2:52		
3:00		
3:08		
3:15		
3:23		
3:30		
3:38		
3:45		
3:52		
4:00		
4:08		
4:15		
4:23		
4:30		
4:38		
4:45		
4:52		
5:00		
5:08		
5:15		
5:23		
5:30		
5:38		
5:45		

Directions: Input the location of the last car in the queue (line of vehicles waiting) for Westbound SR-520. Place the letter of the closest landmark, and the number of vehicles plus or minus from that point. For example, C + 5, means the last vehicle in line was 5 vehicles past point C (the light at HEC Ed).

Figure 4. Form for Queue-Length Counts.

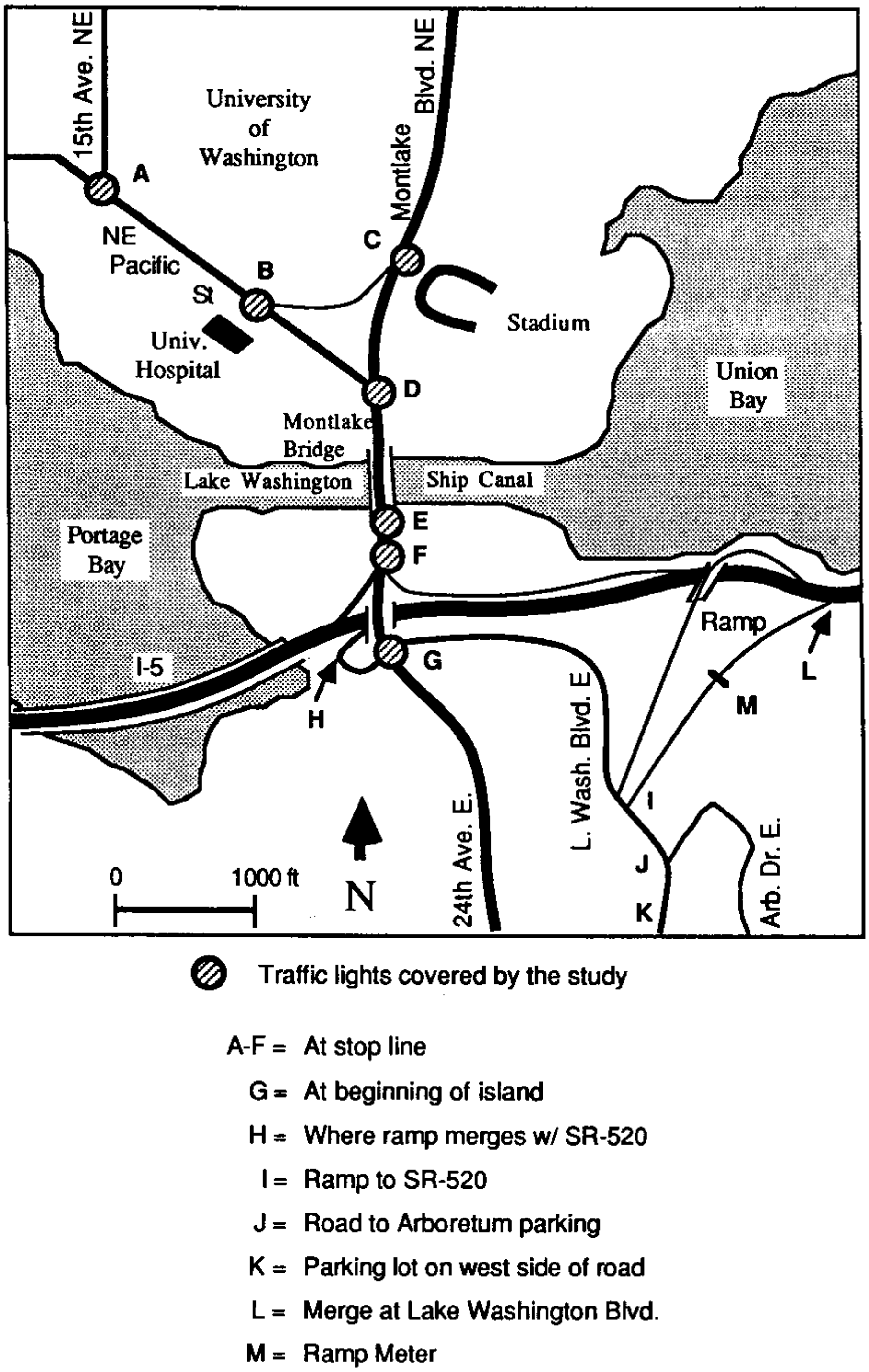

Figure 5. Location Map for Queue-Length Counts.

Travel Time Log
University of Washington

Check Point	Clock Time	Run Time
1. UW HUB or Montlake Parking Lot (Circle which)		
2a. Overpass at Hec Ed (Montlake Only)		
2b. Eastern overpass at the Hospital (Pacific only)		
3. NE Pacific and Montlake Blvd		
4a. Entrance to Montlake Ramp		
5. Merge from Montlake to SR-520		
4b. Entrance to Lake Washington Blvd. Ramp		
6. Merge from Lake Washington Ramp to SR-520		
7. Pedestrian Overpass just east of the Evergreen Point Bus Stop		

Directions: Place time of day in "Clock Time" column, include seconds. Fill in either 2a or 2b depending on your route. Fill in either 4a and 5 or 4b depending on the ramp you use to enter onto SR-520.

"Merge" is defined as that point where you have entered into the main stream of travel, or when a car has completed a merge operation directly in front of your vehicle if you are already in the main freeway lane.

Figure 6. Form for Floating Car Travel Time Records.

Telecom Data

Electronic data for mainline and ramp volumes and lane occupancy was continually being transferred to a University of Washington data-base through a telecommunication link between the TSMC and the UW. These data were in the form of 5-minute volume and lane occupancy values for each lane at particular locations or stations. The 5-minute lane and ramp data could be summarized by time interval and by station.

The telecom data were used to analyze the change in level-of-service (LOS) along the the SR520 section affected by the ramp controls. A methodology called time series intervention analysis, similar to that described in Davis and Nihan (1984), was employed for the statistical tests. Three stations were chosen for these regression analyses (see Figure 7). These included station 292 (between Montlake and Lake Washington Blvd. on-ramps), station 117 (Evergreen Point Bridge toll plaza location) and station 102 (I-90 bridge toll plaza). Stations 292 and 117 were chosen to assess the impact of the ramp controls on SR520 mainline LOS, while station 102 provided covariable information used to control for trend effects. For each half-hour period between 3 pm and 6 pm, for each station, and for each week day between 2/10/86 and 4/30/86, the total volume and average lane occupancy was computed from data contained on tapes and microfiche. The results showed no significant changes in volume or occupancy at station 117, but significant increases in volume and decreases lane occupancy at station 292. This indicates an improved LOS on mainline SR520, probably caused by reduction of merging conflicts.

Plots of 5-minute volumes and lane occupancies for three full days before and after the introduction of ramp controls were also developed for stations 292, and 117, and 119 (beginning point of Eastbound SR-520 coming off I-5 exit ramps; see Figure 7) and for their individual lanes. The data

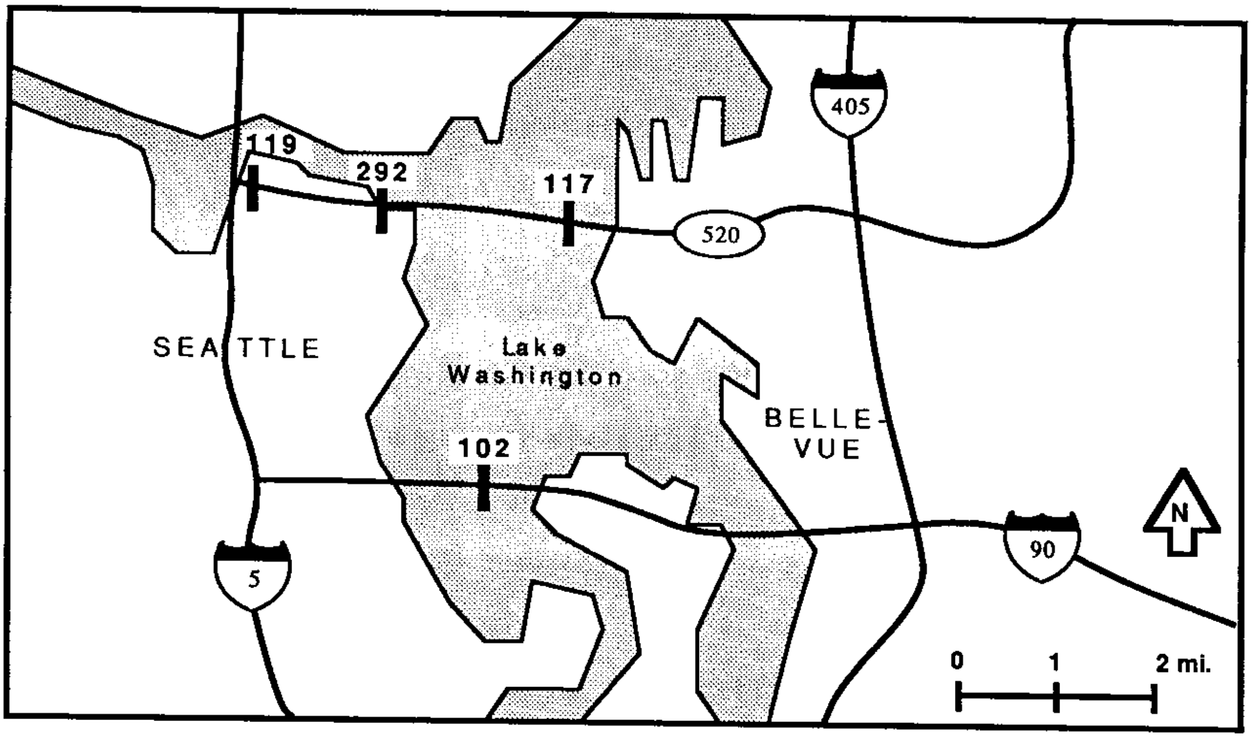

Figure 7. Mainline Metering Station Locations.

included 5-minute values from 6:00 am to 6:00 pm for February 26-28 and March 11-13, (Note: the full-day plots were made to get a complete volume-to-occupancy curve for each location. The affected hours were still peak afternoon hours). These plots further illustrated the LOS improvements observed statistically.

RESULTS AND DISCUSSION

Origin-Destination Surveys

Figure 8 shows the study area and the zones used for the before-and-after OD analyses. Table 1 identifies the zones of interest and their related areas. The zones correspond to those developed by the TSMC for its original 1982 OD survey. This survey and the two 1986 surveys were coded and analyzed as part of the current SR520 project.

Table 2 shows the number of trips recorded from each origin zone for the before-surveys of April 22, 1982 (Survey 1) and February 25, 1986 (Survey 2) and the after-survey of April 29, 1986 (Survey 3). One point of interest to Montlake community residents was the percentage of travelers from downtown and other zones of origin that should reasonably choose the I-5 route to SR520 that were instead using local streets and arterials to enter SR520 at the Montlake and Lake Washington Blvd. ramps. All other things being equal, we assume that most direct routes for zones of origin 41, 46, 48, 49, 50, 54, 55, 56, 59 and 583 would be I5 to SR520. Travelers originating in these zones should not be using local streets and arterials to the Montlake and Lake Washington Blvd. on-ramps. In the April 1982 survey, 11.2% of the vehicles in the Montlake ramp sample and 34.0% of the vehicles in the Lake Washington Blvd. sample were originating from these zones. The percentages from these zones at the Montlake Ramp for the before-survey of February 1986 and the after-survey of April 1986 were 9.7% and 11.7% respectively. The 1986 before-and-after values for the Lake Washington Blvd. ramp were 26.7% and 17.5%, respectively. Thus, an average of 10.3% of trips in the before-surveys on the Montlake ramp came from these zones compared to 11.7% in the after-survey. For the Lake Washington Blvd. ramp, an average of 30.5% of the trips originated in these zones before the ramp controls compared to 17.5% after. These percentages

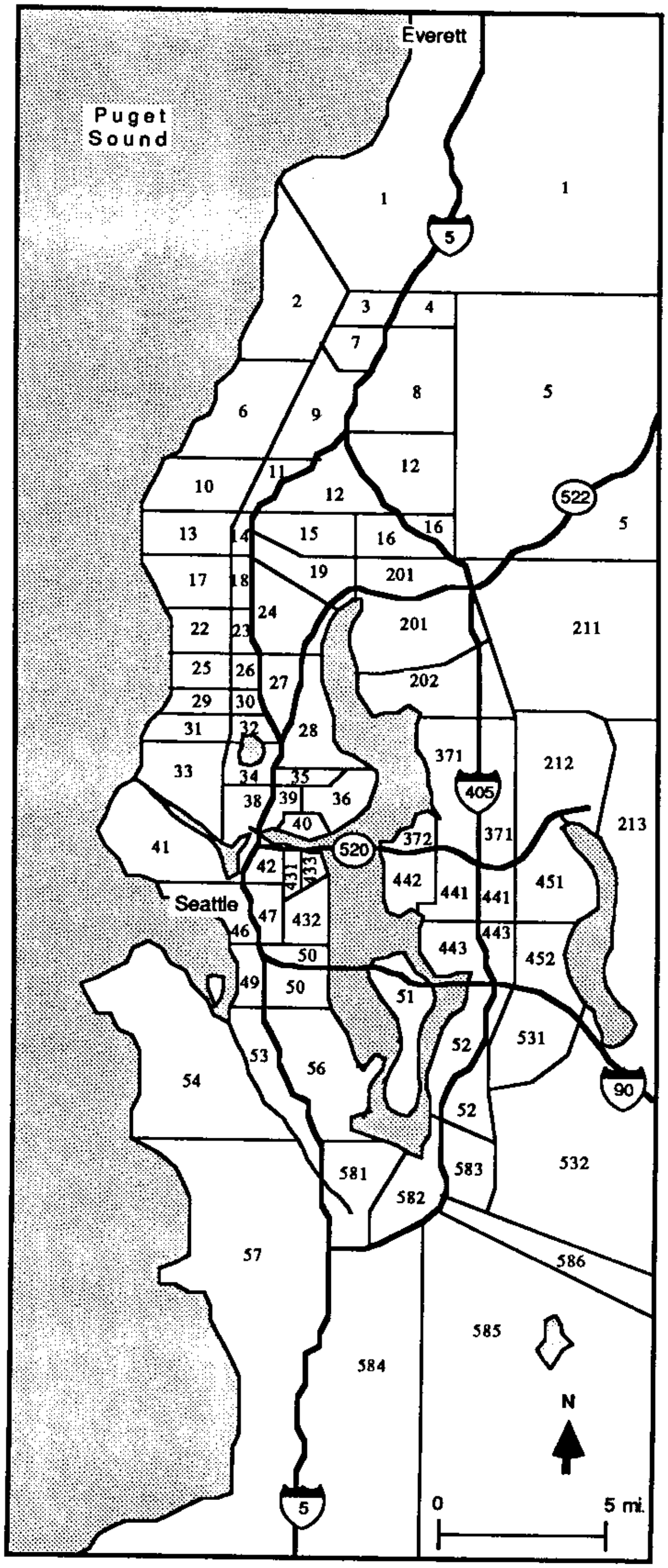

Figure 8. Zone Map for O-D Analyses.

Table 1
List of Zones and Related Areas

Zone:	Area:	Zone:	Area:
1	Outside Area of Map	52	Newport Hills
2	Paine Field	54	West Seattle
5	Monroe	55	Rainier Valley
16	Snohomish County	56	Rainier Beach
17	Innis Arden	57	Boulevard Park
19	Richland Highlands	59	South I-5 (off map)
21	Brier	201	Kenmore
22	Highlands	202	Juanita
24	Sheridan Beach	211	Woodinville
25	Aurora	212	Redmond
27	Eastgate	213	Adelaide
28	Matthews Beach	371	Kirkland
29	Blue Ridge	372	Yarrow Point
30	West Northgate	431	Capitol Hill
31	Crown Hill	432	Madrona
32	Greenwood	433	Madison Park
33	Ballard	441	Bellevue
34	Green Lake	442	Medina/Clyde Hill
36	Laurelhurst	443	Beaux Arts
38	Fremont	451	Overlake
39	University District	452	West Lake Sammamish
40	University of Washington	453	Issaquah
41	Queen Anne Hill	531	Eastgate
42	West Capitol Hill	532	Goal Creek
43	Central Seattle	581	Allentown - Skyway
46	Seattle Center	582	Renton
47	First Hill	583	Kennydale
48	Downtown Seattle	584	Tukwila
49	Harbor Island	585	Fairwood
50	Beacon Hill	586	Maple Valley
51	Mercer Island		

Table 2
Number of Trips by Origin for Ramp O-D Surveys

Origin Zone	Survey 1 (Before)[a] Montlake	Survey 1 (Before)[a] Lake Wash. Blvd.	Survey 2 (Before)[b] Montlake	Survey 2 (Before)[b] Lake Wash. Blvd.	Survey 3 (After)[c] Montlake	Survey 3 (After)[c] Lake Wash. Blvd.
1	1	1		1	1	1
2					1	
5		1				
6	1					
17		1				
22						1
24	1		2		1	
25	1					
27	3	3	3	2	2	
28	12	6	59	5	58	1
29		2				
30		3				
31	4		1			1
32	1			1		1
33	18	8	18	10	11	4
34				1	1	
35	8	1	11		5	2
36	43	14	83	6	61	13
38	14	5	27	10	24	10
39	42	27	82	24	52	26
40	146	62	228	33	188	32
41	36	30	44	44	40	19
42	14	11	19	24	24	23
43		1			1	
46	7	19	2	13	2	8
47	18	161	20	210	26	167
48	16	112	7	65	15	45
49	1	4	1	5	3	3
50		5	1	6		6
51						1
52			1			
54		3	1	4	1	
55	2	8	2	7		2
56		4	1	5		2
59		1	1	3	1	
431	3	5	8	19	11	14
432	2	25		28	1	35
433	10	28	3	45	1	68
443	1					
583			1			
TOTALS	407	556	627	571	531	486

[a]April 22, 1982
[b]February 25, 1986
[c]April 29, 1986

indicate that the ramp metering had no diversionary effect upon the vehicles entering the Montlake ramp. However, ramp metering appears to have had a diversionary effect upon vehicles entering the Lake Washington Blvd. ramp and a significant percentage of those that had previously come from downtown and southern zones were diverted to other routes (most likely I-5).

Table 2 also shows that in April, 1982, 35.9% of the Montlake trips and 11.5% of the Lake Washington Blvd. trips came from the University of Washington (zone 40). In February, 1986, these percentages were 36.3% and 5.7%, respectively, indicating no change for the Montlake ramp and a reduction for the Lake Washington Blvd. ramp. The reduction at the Lake Washington ramp may be the result of a program to encourage bus ridership at the UW, although one would expect similar reductions for the Montlake ramp if this were the case. (In any event, such trips have been discouraged since November, 1977, when a traffic island was installed to prevent drivers coming from the UW from turning directly onto the Lake Washington ramp.) Percentages of 36.4 (Montlake) and 6.5 (Lake Washington Blvd.) indicated no further change in UW originating trips for the after-study of April 1986.

Table 3 gives the average travel times from origin to destination perceived by travelers in the ramp OD survey samples. There is no statistically significant difference between the average travel-times for the two before-surveys for trips entering the Lake Washington Blvd. ramp. However, there is a significant decrease in average travel-time in the before-survey of 1986 compared to the before-survey of 1982 for the Montlake ramp. There is no obvious explanation for this difference in the two Montlake before-surveys. However, the comments on the postcards received for both the before- and after-surveys of 1986 indicated that travel times appeared to be

Table 3
Average Perceived Total Travel Times for Ramp O-D Surveys

		Survey 1 (Before/1982)	Survey 2 (Before/1986)	Survey 3 (After/1986)
Montlake	avg.	41.73	35.94	38.43
	st. dev.	13.53	18.34	16.62
Lake Washington Blvd.	avg.	36.35	35.73	38.87
	st. dev.	12.59	16.35	15.28

Table 4
Average Vehicle Occupancies for Ramp O-D Surveys

		Survey 1 (Before/1982)	Survey 2 (Before/1986)	Survey 3 (After/1986)
Montlake	avg.	1.42	1.30	1.49
	st. dev.	.99	.74	1.39
Lake Washington Blvd.	avg.	1.42	1.32	1.31
	st. dev.	.93	.70	.91

better than usual in general. Thus, a comparison of the 1986 before-and-after OD surveys was considered to be the most reliable test for differences in perceived travel times due to the ramp controls. For the 1986 surveys, there was a statistically significant increase in travel time on both ramps after the introduction of ramp metering. Average total travel time increased from 35.9 min. to 38.4 min. for the Montlake ramp ($p < .05$) and average total travel time increased from 35.7 mph to 38.9 mph for the Lake Washington Blvd. ramp ($p<.01$). It appears, therefore, that total perceived trip travel times increased slightly on both ramps due to the ramp metering. These results are further supported by actual travel time data collected using the floating car method and by the volume/lane occupancy data collected electronically. These results are discussed later in this section.

Table 4 gives the average vehicle occupancies for vehicles sampled in the OD surveys. These include single-auto, carpools, and vanpools but do not include buses. The OD data indicated that vehicle occupancy decreased significantly from 1982 to 1986 on both ramps as shown by the differences for Surveys 1 and 2. Again, explanations for the differences between 1982 and 1986 before-surveys requires additional investigation. The before and after surveys of 1986 indicated no change in vehicle occupancy for the Lake Washington Blvd. ramp resulting from the TSM strategies but a significant increase in vehicle occupancy for the Montlake ramp. Average vehicle occupancy for the Montlake ramp increased from 1.30 persons per vehicle to 1.49 persons per vehicle ($p <.01$) after the introduction of the HOV lane and ramp metering. This implies a significant increase in the number of carpools and vanpools caused by the introduction of the HOV lane on the Montlake on-ramp and by the increased queue lengths caused by the metering on both ramps. This is further supported by manual count data as discussed below.

Manual Vehicle Occupancy Counts

Tables 5 through 8 give the vehicle occupancy counts taken February 24, 25 and April 28, 29, 1986, for the Montlake and Lake Washington Blvd. on-ramps and the two eastbound mainline SR520 lanes. The data available for buses were not sufficient for analysis and will not be discussed here although they are shown in the tables. The tables indicate a significant decrease in the number of percentage of single-person autos and significant increases in carpools and vanpools on the Montlake ramp after introduction of the HOV lane. There was an increase in the percentage of single-person auto trips and a corresponding decrease in carpool and vanpool trips on the Lake Washington Blvd. ramp indicating a possible shift of carpool and vanpool trips to the Montlake HOV lane. (Although the % HOV changes at each ramp were similar, 4% decrease in SOV's at Montlake and 4% increase in SOV's at Lake Washington, volumes on the two ramps indicated a larger absolute increase in HOV's at Montlake than those numbers explained by the shift from the Lake Washington Blvd. ramp.) The mainline SR520 lanes did not exhibit significant changes in vehicle occupancy. With the exception of the possible shift in HOV's between ramps, results support the OD survey data and can be summarized as follows.

1. HOV usage increased at the Montlake ramp. (The OD survey indicated an increase from 1.30 to 1.49 people/vehicle on the Mountlake on-ramp.) The manual counts indicated a change from 1.23 to 1.32.
2. Some carpools and vanpools may have shifted from the Lake Washington Blvd. on-ramp to the Montlake on-ramp. (The manual counts indicated a change from 1.26 to 1.20 persons/vehicles.

Table 5
Montlake Vehicle Occupancy
Number of Vehicles and % Vehicles by Category

Category	Before Number	Before %	After Number	After %
Auto/van				
1person	4123	81.26	2573	77.31
2 person	827	16.30	597	17.94
3 person	74	1.46	98	2.94
4 person	31	.61	39	1.17
5-8 people	16	.32	16	.48
9+ people	3	.06	5	.15
TOTAL	5074	100.00	3328	100.00
Bus				
1/2 full	24	42.11	59	75.64
full	33	57.89	19	24.36
TOTAL	57	100.00	78	100.00
Articulated Bus				
1/2 full	30	44.12	27	44.26
full	38	55.88	34	55.74
TOTAL	68	100.00	61	100.00

Table 6
Lake Washington Boulevard Vehicle Occupancy
Number of Vehicles and % Vehicles by Category

Category	Before		After	
	Number	%	Number	%
Auto/van				
1 person	2784	80.46	2447	83.72
2 person	551	15.92	408	13.96
3 person	92	2.66	49	1.68
4 person	19	.55	13	.44
5-8 people	10	.29	6	.21
9+ people	4	.16	0	0
TOTAL	3460	100.00	2923	100.00
Bus				
1/2 full	0		0	
full	0		0	
TOTAL	0		0	
Articulated Bus				
1/2 full	0		0	
full	0		0	
TOTAL	0		0	

Table 7
Mainline Right Lane Vehicle Occupancy
Number of Vehicles and % Vehicles by Category

Category	Before		After	
	Number	%	Number	%
Auto/van				
1 person	7601	83.67	6197	82.29
2 person	1350	14.86	1111	14.86
3 person	114	1.25	110	1.47
4 person	9	.10	48	.64
5-8 people	1	.01	8	.10
9+ people	0	0	1	.01
TOTAL	9075	100.	7475	100.00
Bus				
1/2 full	0		8	88.89
full	0		1	11.11
TOTAL	0		9	100.00
Articulated Bus				
1/2 full	0		1	100.00
full	0		0	0
TOTAL	0		0	100.00

Table 8
Mainline Left Lane Vehicle Occupancy
Number of Vehicles and % Vehicles by Category

Category	Before		After	
	Number	%	Number	%
Auto/van				
1 person	4167	81.20	6336	82.37
2 person	897	17.48	1091	14.18
3 person	57	1.11	167	2.17
4 person	10	.19	85	1.11
5-8 people	0	.00	13	.17
9+ people	1	.02	0	.00
TOTAL	5132	100.	7642	100.00
Bus				
1/2 full	3	60.00	5	83.23
full	2	40.00	1	16.67
TOTAL	5	100.00	6	100.00
Articulated Bus				
1/2 full	0		3	100.00
full	0		0	0
TOTAL	0		3	100.00

This was disputed by the OD-survey data which indicated no significant change in vehicle occupancy at the Lake Washington Blvd. on-ramp.)

3. Vehicle occupancy on the mainline SR520 remained stable.

Although both the OD survey and the manual counts indicated a significant increase in vehicle occupancies at the Montlake on-ramp; the actual numbers were lower for the manual counts than for the surveys. This may be due to a sample bias in the OD returns favoring non-SOV drivers or a simple difference in the manual counts due to the 3 extra day's (Monday, in each case) count. Since Tuesday is a more representative day, we may favor the OD survey data here. In any case, both support an increase in HOV travel at the Montlake on-ramp.

Volume/Lane-Occupancy Results

Tables B1, B2 and B3 in Appendix B show summary statistics for volume and lane occupancy data for two stations on the SR520 lane (292 and 117) and a third station used as a control (102) on the parallel I-90 crossing. The data gave volume and lane occupancy averages for each half-hour period between 3 pm and 6 pm for days before and after the origination of ramp metering on SR520. Figure 7 on page 21 shows the three station locations. Station 292 is located on the mainline SR520 between the Montlake ramp and the Lake Washington Blvd. ramp merges. Station 117 is located in the vicinity of the former Evergreen Point bridge toll plaza. The third station (102) located at the I-90 bridge toll plaza was used to provide covariable information to control for trend effects.

Separate time series analyses on the lane occupancy data and on the volume data were performed to assess the true increases or decreases due to ramp metering at Stations 292 and 117. Tables 9 and 10 show the results

Table 9
Regression Analysis for Station 292
Lane Occupancy Data

Period	Variable	Coefficient	T-Ratio	Significance
3:00 - 3:30	Constant	17.12	6.01	$p < .01$
	Covariable	1.08	4.16	$p < .01$
	Intervention Variable	-4.48	-0.10	$p < .05$
3:30 - 4:00	Constant	14.49	5.82	$p < .01$
	Covariable	1.21	6.44	$p < .01$
	Intervention Variable	-3.32	-1.82	$p < .05$
4:00 - 4:30	Constant	20.19	7.15	$p < .01$
	Covariable	0.87	3.56	$p < .01$
	Intervention Variable	-6.06	-3.35	$p < .01$
4:30 - 5:00	Constant	18.53	6.30	$p < .01$
	Covariable	0.69	2.73	$p < .01$
	Intervention Variable	-3.55	-1.83	$p < .05$
5:00 - 5:30	Constant	17.27	5.74	$p < .01$
	Covariable	0.76	3.08	$p < .01$
	Intervention Variable	-1.71	-0.88	insig.
5:30 - 6:00	Constant	23.31	9.61	$p < .01$
	Covariable	0.26	1.44	$p < .10$
	Intervention Variable	-2.52	-1.60	$p < .10$

Table 10
Regression Analysis for Station 117
Lane Occupancy Data

Period	Variable	Coefficient	T-Ratio	Significance
3:00 - 3:30	Constant	6.05	3.59	$p < .01$
	Covariable	0.69	4.93	$p < .01$
	Intervention Variable	1.13	1.00	insig.
3:30 - 4:00	Constant	5.66	2.30	$p < .01$
	Covariable	1.02	6.08	$p < .01$
	Intervention Variable	1.50	0.94	insig.
4:00 - 4:30	Constant	6.72	2.30	$p < .05$
	Covariable	1.14	4.53	$p < .01$
	Intervention Variable	1.13	0.60	insig.
4:30 - 5:00	Constant	6.29	2.01	$p < .05$
	Covariable	1.02	4.06	$p < .01$
	Intervention Variable	1.68	0.84	insig.
5:00 - 5:30	Constant	4.24	1.74	$p < .05$
	Covariable	1.13	6.08	$p < .01$
	Intervention Variable	2.51	1.56	$p < .10$
5:30 - 6:00	Constant	8.76	3.87	$p < .01$
	Covariable	0.68	4.30	$p < .01$
	Intervention Variable	-0.61	-0.41	insig.

of these time series intervention analyses on lane occupancies for the two stations. The data included average lane occupancy values for each half hour period between 3:00 pm and 6:00 pm, for each station and for each weekday between 2/10/86 and 4/30/86.

An intervention variable consisting of values of 0 for days before the ramp control intervention and 1's for days following the intervention was also included in the regressions for each half-hour period. Thus, the intervention variable had values of 0 for days preceding March 10, 1986, when the ramp metering was turned on and the HOV lane opened, and values of 1 for subsequent days. The coefficient of this intervention variable, if significant, gives the value of the change due solely to the intervention. For example, Table 9 shows a significant decrease in lane occupancy at station 292 of 4.48% for the 3:00 pm - 3:30 pm period that is due to the TSM intervention. This corresponds to a total average change from 27.1% to 20.0% due to the ramp controls and other factors (see Table B1). For all periods, the lane occupancy regressions indicate significant decreases in average occupancy for station 292 due to the controls for all half-hour time periods with the exception of the 5:00 pm - 5:30 pm period. The regressions for station 117 indicate no significant changes in average occupancy due to the intervention except for a marginally significant increase during the 5:00 pm -5:30 pm period.

Tables 11 and 12 give parallel intervention analysis results for volume data for station 292 and 117 for the same days and periods. For station 292 there are significant but small increases in average volumes for all periods due to the controls except for the 5:00 - 5:30 period. For station 117 there are no significant changes in volume due to the controls during any half-hour period.

Table 11
Regression Analysis for Station 292
Volume Data

Period	Variable	Coefficient	T-Ratio	Significance
3:00 - 3:30	Constant	1725.91	21.64	p < .01
	Covariable	- 0.08	- 1.29	p < .10
	Intervention Variable	65.5	1.65	p < .05
3:30 - 4:00	Constant	1569.7	18.23	p < .01
	Covariable	0.05	0.89	insig.
	Intervention Variable	80.9	2.04	p < .05
4:00 - 4:30	Constant	1530.5	23.57	p < .01
	Covariable	0.11	2.24	p < .05
	Intervention Variable	37.1	1.40	p < .10
4:30 - 5:00	Constant	1581.1	21.35	p < .01
	Covariable	0.04	0.73	insig.
	Intervention Variable	49.42	1.83	p < .05
5:00 - 5:30	Constant	1514.8	14.22	p < .01
	Covariable	0.11	1.39	insig.
	Intervention Variable	33.9	0.88	insig.
5:30 - 6:00	Constant	1476.5	15.06	p < .01
	Covariable	0.09	1.32	p < .10
	Intervention Variable	70.43	1.79	p < .05

Table 12
Regression Analysis for Station 117
Volume Data

Period	Variable	Coefficient	T-Ratio	Significance
3:00 - 3:30	Constant	1659.9	6.74	p < .01
	Covariable	0.22	1.89	
	Intervention Variable	19.70	0.17	insig.
3:30 - 4:00	Constant	1715.9	5.93	p < .01
	Covariable	0.21	1.09	insig.
	Intervention Variable	51.7	0.39	insig.
4:00 - 4:30	Constant	1565.9	5.22	p < .01
	Covariable	0.40	1.79	p < .05
	Intervention Variable	-50.5	-0.41	insig.
4:30 - 5:00	Constant	1077.0	3.36	p < .01
	Covariable	0.72	3.07	p < .01
	Intervention Variable	30.4	0.26	insig.
5:00 - 5:30	Constant	1028.60	2.98	p < .01
	Covariable	0.71	3.02	p < .01
	Intervention Variable	59.70	0.47	insig.
5:30 - 6:00	Constant	916.50	3.23	p < .01
	Covariable	0.74	3.95	p < .01
	Intervention Variable	54.50	0.46	insig.

The regression results indicate that there is an improved LOS at station 292 which is probably caused by reduction of merging conflicts. The LOS at the Evergreen Point toll plaza location remains essentially the same, indicating that the increase in LOS at Station 292 may be damped by the time it reaches the end of the bridge. The larger average volumes at Station 117 (Table B2) indicate that traffic is already flowing at or near capacity at this station throughout the 3:00 pm - 6:00 pm period making significant flow improvements impossible. However, there was also a problem found with the volume counts at this station,* so the results for Station 292 were taken as the best LOS measures for the mainline.

The changes at Station 292 indicate that flow across the bridge is faster and smoother. There is, therefore, a definite improvement in the LOS on the mainline SR520 due to the ramp controls. To illustrate the impact of this change the 4:00 pm - 4:30 pm period change at station 292 will be used as an example. Table 11 indicates an average <u>increase</u> in volume of 37 vehicles per-lane per-hour due to the ramp metering (two lanes with an increase of 37.1 vehicles for the 30 minute period). This corresponds to a <u>decrease</u> in average lane occupancy of 6% (Table 9) for the same time period. The average volume in vehicles per-lane per-hour for this period for Station 292 before the ramp controls went into effect, was 1668 vlplph (Table B1). The average occupancy for this same period was 29%. From plots of the volume/lane-occupancy data over several days, it is clear that this point represents level of service F. The change due to the ramp controls represents a new point on the volume/occupancy curve of

---

* Later investigation indicated that the loop detectors at station 117 were consistently overestimating volumes. Therefore the results for this station were largely ignored, although <u>relative</u> results were still noted.

1705 vph* and 23% which results in a significant increase in LOS experienced by vehicles on the SR520 mainline link. In other words, there is a significant improvement in speed and flow for mainline travel after the ramp controls are introduced.

Continuing with the volume/lane-occupancy data let's assume the effective vehicle length suggested by the TSMC (18 ft)** and that this effective length remained stable during the entire study period. Then, using the formulas:

$$u = q/k$$

$$k = \frac{5280\ O_c}{100\ L_e}$$

where

u = speed, mph

q = flow, vph

k = density, vpm

O_c = lane occupancy, %

L_e = effective length, ft.

These formulas were used to calculate speeds for Stations 292, 117 and 102 for all days and time periods. The average before-and-after speeds for Station 292 are shown in Figure 9. Tables B4 and B5 in Appendix B show the intervention analyses for Stations 292 and 117. As expected, speeds were not significantly affected at Station 117. However, speeds at Station 292

---

* The actual after- volume is lower due to offsetting trend effects picked up by the covariable.

** A longer effective length would give similar relative results, but slightly lower before and after speeds.

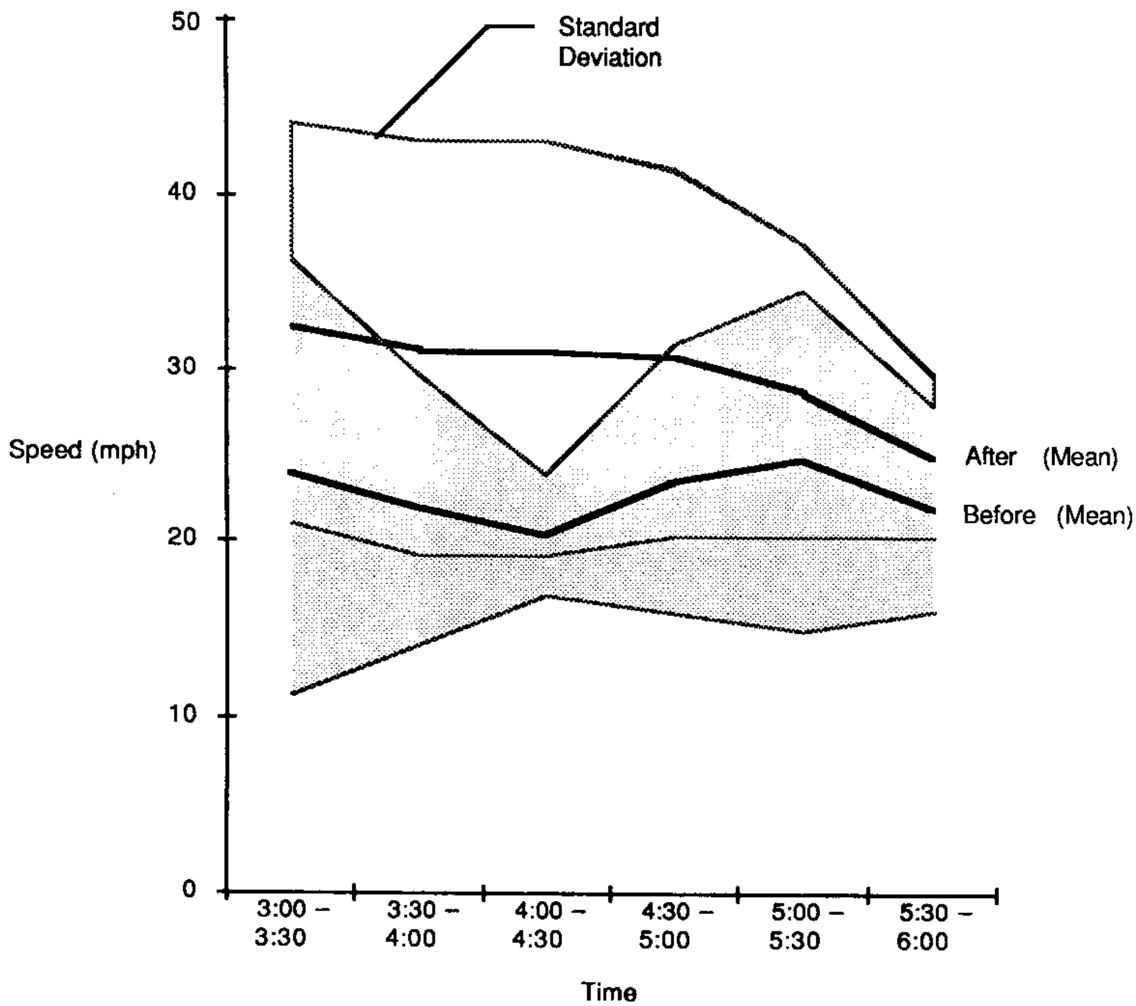

Figure 9. Before and After Speeds (Station 292).

were significantly increased. For the 4:00 pm - 4:30 pm time period, for example, an intervention effect of +9mph was recorded at a significance of $p<.01$. The average speed at this location and time period before the TSM intervention was 20.3mph. The +9mph increase due to the intervention represents a significant improvement in LOS.

In addition to the regression analyses, several days' worth of volume and lane-occupancy data were plotted to produce graphical measures of the impacts of ramp metering on the SR520 mainline. Three sets of volume/lane-occupancy plots were made for stations 292, 117, and 119 and for their individual lanes. The plots involved 5-minute volume and lane-occupancy values for the time periods from 6 am to 6 pm for three days before the ramp control intervention (February 26-28, 1986) and three days after ramp controls were in effect (March 11-13, 1986). Although the ramp controls were in effect only during the afternoon peak period, full-day data sets were used to observe the complete volume/occupancy curves and, therefore, assess the general capacity limitations and LOS ranges. As before, station 292 represented the location between the Montlake ramp merge and the Lake Washington Blvd. merge and station 117 represented the former location of the Evergreen Point toll plaza. Station 119, located at the beginning of the eastbound SR520 lanes just after the junction of I-5 and SR520, represented flow upstream from the ramp merges.

Figures 10, B1 and B2 show the volume/occupancy plots for station 292 and it's right and left lanes, respectively. The black dots represent points of volume and lane occupancy for days before the ramp controls were in effect and thewhite dots represent the points on the volume/lane-occupancy curve for days after the ramp control improvement. The graphs all illustrate a shift in points away from the LOS F range due to the ramp control intervention. (Note the scatter of black dots to the right of each

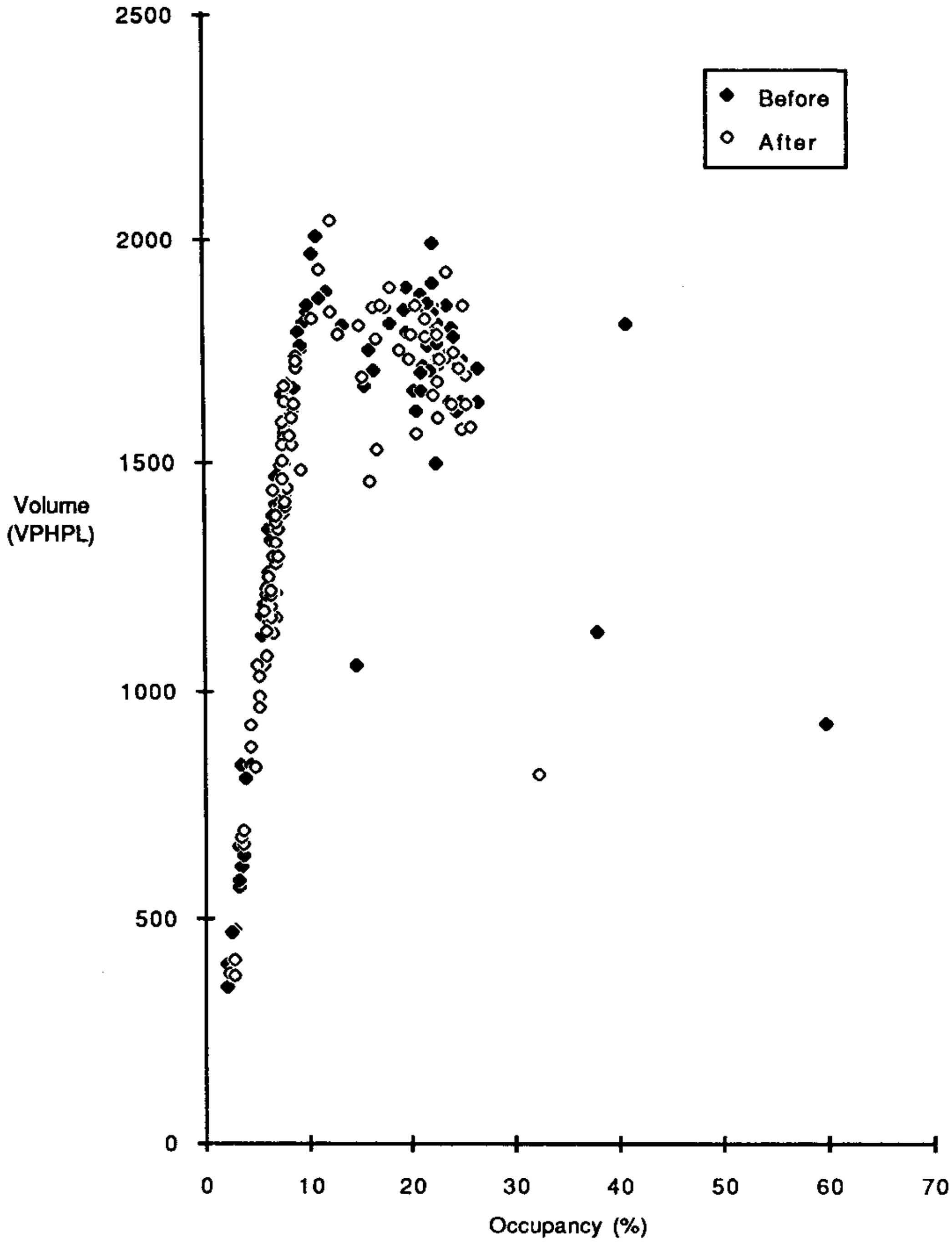

Figure 10. Volume vs. Lane Occupancy (Station 292).

plot indicating level of service F. The white dots corresponding to the same time periods are less scattered and move to the left and vertically up showing an improvement in LOS for these periods.) The right hand lane which is most affected by the Montlake ramp merge shows a pronounced improvement in the right half of the graph and a significant increase in the mode of the graph indicating a possible increase in the actual capacity of the lane due to the ramp improvement. Figures 11, B3 and B4 show similar plots for station 117 and its right and left lanes, respectively. Again, the plots indicate an improvement in LOS although this is less pronounced that the improvement at station 292 which is directly affected by both merges. Again, it should be noted that the consistent overestimation error in the loop detectors at Station 117, make the absolute results for this set of plots unreliable. The relative changes still reflect an improvement, however. Figures 12, B5 and B6 give similar plots for station 119 and it's right and left lanes, respectively. Again, the plots indicate an improvement in LOS for this station which represents traffic upstream from the two ramp merges.

Ramp-Queue Length Results

Figures 13 and 14 show the queue-length data for the Montlake and Lake Washington Blvd. on-ramps for eight days prior to the ramp metering and 10 days following the ramp metering. The before-days included 1/18/86 - 2/21/86 and 2/24/86 - 2/28/86 and the after-days included 4/21/86 - 4/25/86, 4/28/86 - 4/30/86, and 5/1/86 - 5/2/86. The plots show queue length in vehicles by date and time-of-day between 2:30 pm to 5:45 pm. Both plots indicate an increase in queue length for the on-ramps after the ramp metering intervention. This increase in queue length is most pronounced for the Lake Washington Blvd. on-ramp.

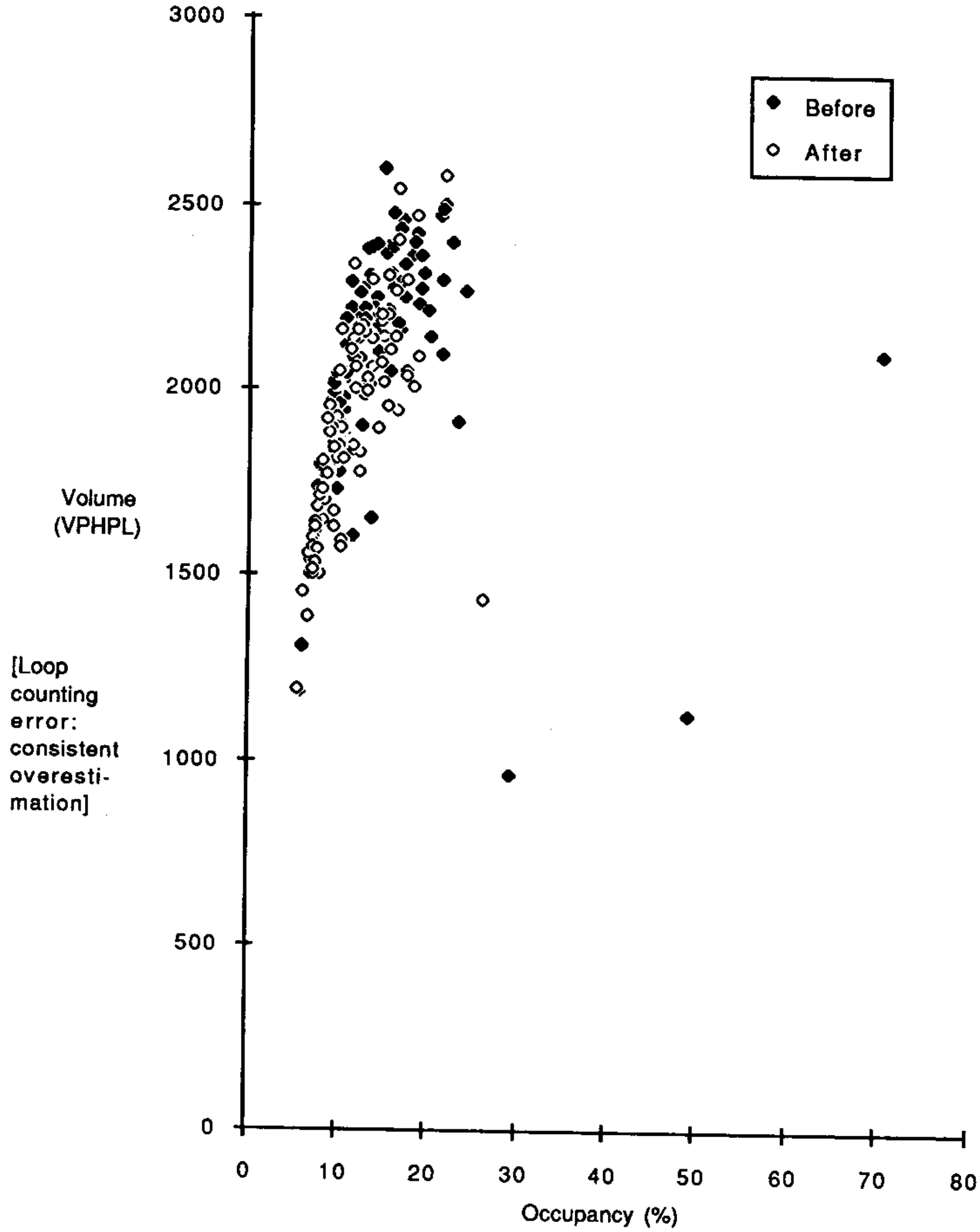

Figure 11. Volume vs. Lane Occupancy (Station 117).

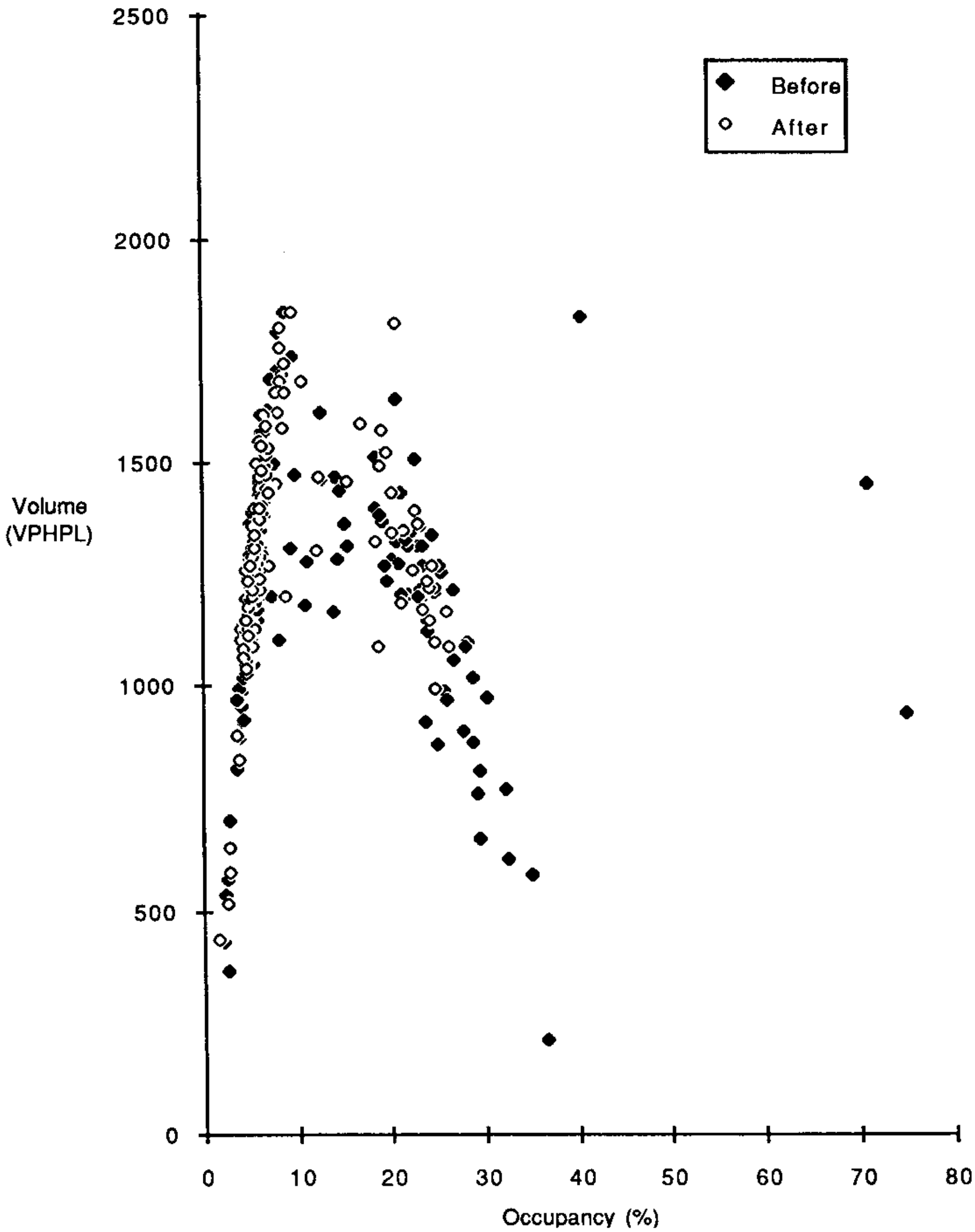

Figure 12. Volume vs. Lane Occupancy (Station 119).

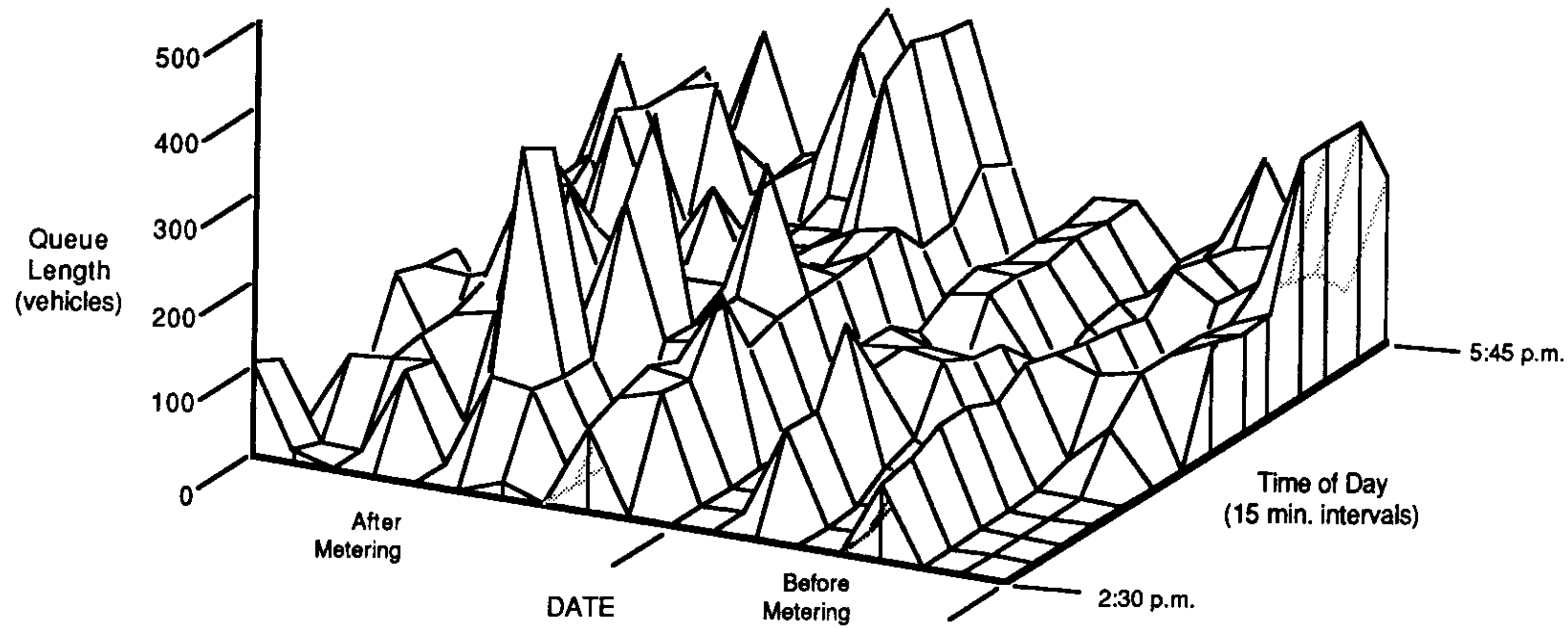

Figure 13. Queue Length Data for Montlake On-Ramp.

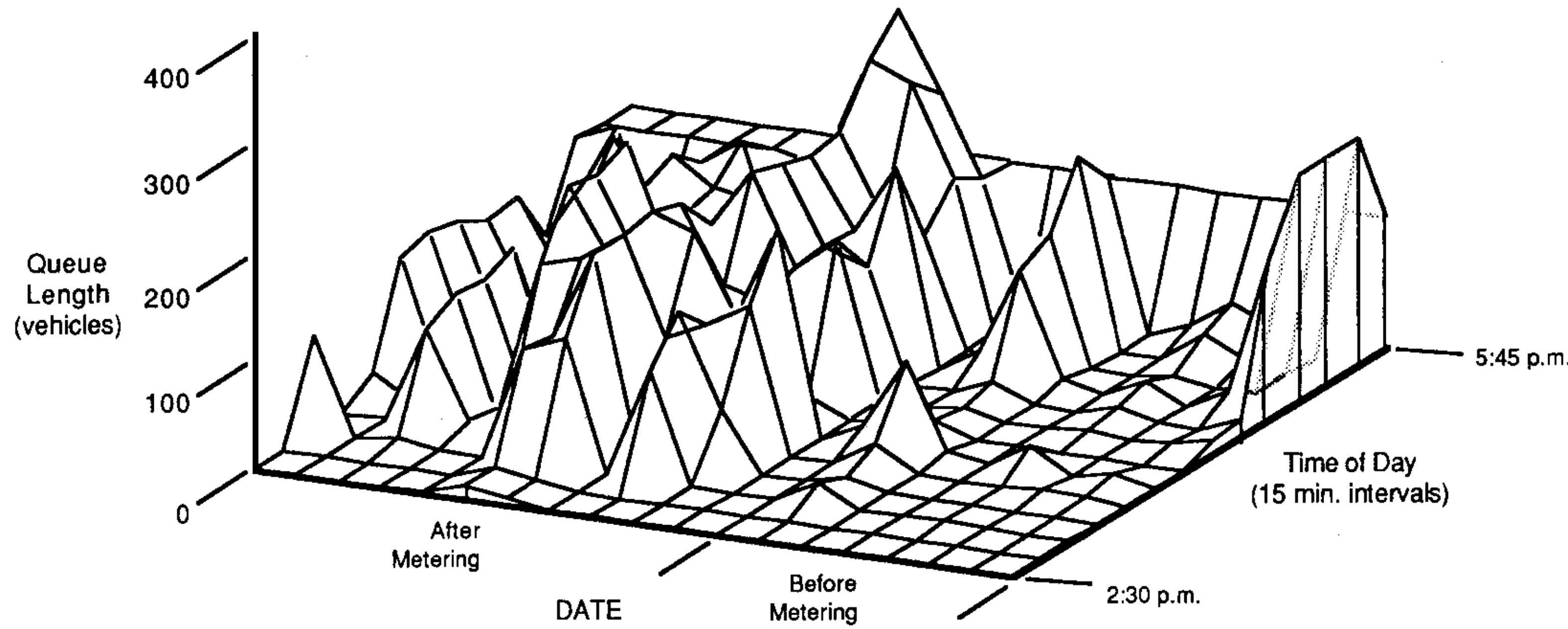

Figure 14. Queue Length Data for Lake Washington Blvd. On-Ramp.

Table 13 shows the average queue lengths by day for the before-and-after collections. Table 14 shows the summary statistics for these collections. The Mann-Whitney U test applied to the values for all days before and all days after indicates that the queue-length differences are definitely significant in both cases. In other words, the queue lengths subsequent to the ramp controls are significantly longer than the queue lengths prior to the controls for both on-ramps.

Travel Times: Floating Car Method

From the total sample of travel-time runs made from the UW to the Eastside, 10 before-runs and 10 after-runs were chosen for the analysis. These were runs from the Montlake parking lot to Evergreen point between 5 pm and 6 pm. For each of these runs, the time to reach the ramp (t_a), the time on the on-ramp (t_b), the mainline time (t_c), the time to reach the mainline ($t_a + t_b$) and the total travel time ($t_a + t_b + t_c$) were analyzed using the Mann-Whitney U test. When analyzed separately, the results indicated no statistically significant changes in the times to get to the on-ramp and the times on the on-ramp. However, the times were increased marginally in both cases. When combined ($t_a + t_b$), there was a statistically significant increase in the total time to reach the ramp-merging point. This median increase was 243.5 seconds. The results also indicated an insignificant decrease in mainline travel time but a significant increase in the total travel time from point of origin to point of destination. The median increase in total travel time was 238.5 seconds.

The mean differences in total travel time ($t_a+t_b+t_c$) and time to the ramp merge (t_a+t_b) were 281 seconds and 301 seconds, respectively. The travel time results, therefore, indicate that a net total increase in travel time was experienced by travelers from the UW to the Eastside, this increase being completely due to an increase in the time it took to go

Table 13
Ramp Queue Length Averages (# of vehicles)

Ramp	Period	Date	MEAN	STANDARD DEVIATION
MONTLAKE ON-RAMP	BEFORE METERING	2/18	100.0	117.0
		2/19	60.6	50.0
		2/20	37.4	46.1
		2/21	111.5	24.8
		2/25	14.0	28.0
		2/26	40.9	33.8
		2/27	102.3	42.5
		2/28	69.3	48.3
	AFTER METERING	4/21	122.5	42.1
		4/22	181.8	87.5
		4/23	82.6	57.8
		4/24	161.1	94.3
		4/25	124.0	105.0
		4/28	93.6	83.0
		4/29	159.3	91.7
		4/30	65.2	45.0
		5/1	70.1	71.3
		5/2	66.7	45.9
LAKE WASHINGTON BLVD ON-RAMP	BEFORE METERING	2/18	54.1	81.7
		2/19	2.8	5.0
		2/20	2.4	5.8
		2/21	8.8	11.7
		2/25	1.0	3.6
		2/26	0.9	2.3
		2/27	47.8	53.5
		2/28	5.2	8.3
	AFTER METERING	4/21	62.6	47.8
		4/22	74.3	42.3
		4/23	90.7	72.3
		4/24	89.9	37.6
		4/25	64.7	24.3
		4/28	73.5	55.3
		4/29	44.6	50.6
		4/30	37.2	27.1
		5/1	25.4	32.3
		5/2	50.5	29.0

Table 14
Summary Queue Length Statistics

	MONTLAKE	
	All Days Before	All Days After
Mean	59.5	112.7
Standard Deviation	63.4	84.0
Median	45.0	105.9
N	126	140
Mann-Whitney Test	Significant at p << .01	

	LAKE WASHINGTON BLVD.	
Mean	13.7	79.2
Standard Deviation	37.7	59.4
Median	0.0	93.3
N	117	130
Mann-Whitney Test	Significant at p << .01	

from the point of trip origin to the ramp merge. These results and the volume/lane-occupancy results indicate that travelers already on the mainline experience a slightly improved travel-time.

Bus Arrival Times

Bus arrival times for February 24, 25 and April 28, 29, 1986 were collected at the Evergreen Point Freeway Station between the hours of 3:30 pm - 6:00 pm. These data did not show significant differences in late and early times when compared to the actual schedules for these days. This may be due, in part, to the fact that more incidents were recorded by the TSMC for the after-study than for the before-study resulting in possibly increased bus delays. A parallel data collection by METRO involving specially equipped buses, provided only 11 values of travel-times for all before-and-after periods and all bus routes. This sample was inadequate for serious study.

A better indication of the effect of the ramp metering on bus service is the fact that METRO has determined over several months' experience that buses are arriving at the Montlake Evergreen freeway flyer stations earlier as a result of the ramp controls and HOV lane and METRO is, therefore, revising its Fall 1986 schedules to reflect these time savings. This fact coupled with the time savings realized by the HOV lane on the Montlake ramp and the faster speeds on mainline SR520 due to the metering indicated that all bus service benefitted from the TSM improvedment. (There was no bus service using the Lake Washington Blvd. ramp either before or after the improvements.)

CONCLUSIONS AND RECOMMENDATIONS

In compliance with the desired report format outlined by the WSDOT, the conclusions and recommendations developed from the above results are included as a separate chapter at the beginning of this report. These are summarized below.

1. Level of service was improved on mainline SR520 due to the ramp metering; mainline speeds increased significantly, lane occupancies decreased significantly, and volumes remained stable with slight increases.
2. Travel times from trip origins to the ramp merges with mainline SR520 were increased slightly for both ramps. This resulted in desired route diversions and mode shifts (See items 4 & 5 below).
3. Bus travel times were decreased.
4. Trips from downtown and from southern zones were diverted away from the Lake Washington Blvd. on-ramp (an objective of Montlake residents that was part of the agreement with the city and WSDOT).
5. The number of carpools and vanpools significantly increased on the Montlake ramp due to the introduction of the HOV bypass lane and increased ramp queue lengths.
6. Although queue lengths increased at both ramps due to the ramp metering, a portion of the resulting time loss was offset somewhat by the time savings on the mainline. The increased queue lengths for SOV's resulted in desired route and mode choice shifts.

The general conclusion is that the ramp metering and HOV lane had the desired results; i.e., these TSM techniques improved mainline travel, increased the attractiveness of carpools, vanpools and buses and diverted unwanted neighborhood traffic coming from other parts of the city. It is recommended that this type of TSM strategy be used in situations such as the SR520 case where mainline volumes are already at or near capacity during the peak hours and even small volume diversions and volume controls have a significant impact upon mainline LOS.

REFERENCES

1. Abrams, C. M. et al. (1981). "Measures of Effectiveness of TSM Strategies." Final Report to FHWA, U.S. Department of Transportation Report No. FHW/RD-81/177.

2. Ahmed, S. J. (1980). "Patterns and Projections of Technical Developments in Freeway Surveillance and Control in the U.S.A." Transportation Planning and Technology, No. 3, Vol. 6.

3. Ahmed, S. J. and A. R. Cook (1982). "Application of Time-Series Analysis Techniques to Freeway Incident Detection". Transportation Research Record 841, pp. 19-21.

4. Allen, W. G., Jr. et al. (1980). "Development and Application of Performance Measures for a Medium-Sized Transit System." Transportation Research Record 746, pp. 8-12.

5. Barton-Aschman Associates, Inc., (1979). "The Development of Service Standards and Operating Guidelines for the Delaware Authority for Regional Transit." Report to Urban Mass Transportation Administration.

6. Barton-Aschman, Assoc., Inc., (1981). "Traveler Response to Transportation System changes", U.S. DOT.

7. Betts, S. M. et al. (1983). "FLOW: A Two Year Evaluation." Washington State Department of Transportation.

8. Blumentritt, C. W. (1981). "Guidelines for the Selection of Ramp Control Systems." Texas Transportation Institute.

9. Brant, A. E. and D. E. Low (1967). "Cost-Saving Techniques for Collection and Analysis of Origin-Destination Survey Data", Highway Research Record 205, pp. 50-56.

10. Burwick, J. A. (1982). "Evaluation of Two Isolated Responsive Ramp Control Tactics." Illinois Department of Transportation.

11. Carlson, G. C. et al. (1976). "Results of the Bus-On-Metered Freeway Evaluation - I-35W, Minneapolis." Traffic Engineering, March.

12. Cherniack, N. (1960). "Critique of Home-Interview Type O-D Surveys in Urban Area", Highway Research Board Bulletin 253, pp. 156-188.

13. Childs, W. S. (1946). "Origin and Destination Survey Methods as Applied to the Transportation Study-Baltimore Metropolitan Area," Highway Research Board Proceedings, Vol. 26, pp. 422-430.

14. Crabtree, L. D. and G. Krause (1982). "Vehicle Origin Survey", Transportation Research Record 866, pp. 23-27.

15. Courage, K. G. et al. (1976). "Operating Parameters for Mainline Sensors In Freeway Surveillance Systems." Transportation Research

Record 601.

16. Davies, P. and D. R. Salter (1983). "Reliability of Classified Traffic Count Data", Transportation Research Record 905.

17. Duff, J. T. (1968). "O.T.A. Study Week: General Report on Theme 8. Motorway Surveillance and Control." Traffic Engineering and Control, Vol. 10, No. 6, pp. 314-316.

18. Everall, P. F. (1972). "Urban Freeway Surveillance and Control: The State of the Art." FHWA. Washington, D. C.

19. Fielding, G. J., R. E. Clauthier and C. A. Lave (1977). "Applying Performance Indicators in Transit Management." Paper presented at the National Conference on Transit Performance, Norfolk, VA.

20. Foster, R. E. Stover, G. E. and J. D. Benson (1977). "Effects of Small Sample Origin-Destination Data on Transportation Study Results", Transportation Research Record 637, pp. 33-39.

21. Fuller, E. (1978). "Performance Measures for Public Transit Service." Division of Mass Transportation, Sacramento, CA.

22. Geva, I. and E. Hauer (1982). "Estimation of O-D Flows from Traffic Count and License-Plate Survey Information", PTRC, Summer Annual Meeting, pp. 333-342.

23. Gamble, R. W. and H. F. Ilgner (1946). "Purpose, Analysis and Application, Origin-and Destination Survey, Milwaukee Metropolitan Area", Highway Research Board Proceedings, Vol. 26, pp. 404-421.

24. Glennon, J. C. and V. G. Stover (1968). "A System to Facilitate Bus Rapid Transit on Urban Freeways." Prepared by Texas Transportation Institute for UMTA, U.S. Department of Transportation.

25. Goodell, R. G. B. (1974). "Preferential Access for Multioccupant Vehical at Metered On-Ramps." Traffic Engineering, September. (1976) "Experience with Car Pool Bypass Lanes in the Los Angeles Area." In, "Preferential Facilities for Carpools and Buses: Seven Reports." FHWA, U.S. Department of Transportation.

26. Hauer, E. and B. Persaud (1983). "Common Bias in Before- and After-Comparisons and Its Elimination". Transportation Research Record 905.

27. Highway Research Circular No. 108 (1970). "An Inventory of Freeway Surveillance and Operational Control Activities," Highway Research Board.

28. Hudson, B., M. Wachs and J. Schofer (1974). "Local Impact Evaluation in the Design of Large-Scale Urban Systems." Journal of the American Institute of Planners, Vol. 40, No. 4.

29. Levin, N. and Y. Tsao (1980). "On Forecasting Freeway Occupancies and Volumes." Transportation Research Record 773.

30. Levinson, H. S. et al. (1973). "Bus Use of the Highways: State of the Art." NCHRP Report 143, Highway Research Board.

31. Link, D. (1975). "Planning for Bus/Carpool By-Passes at Metered Freeway Ramps." Traffic Engineering, November.

32. Ljung, L. and Soderstrom, T. (1983). Theory and Practice of Recursive Identification, Cambridge, MA: MIT Press.

33. Lockwood, S. C. and F. A. Wagner (1977). "Methodological Framework for the TSM Planning Process." In "Transportation Systems Management," TRB Special Report 172, pp. 100-118.

34. Lovejoy, W. E. (1959). "Continuous Sampling Method of Conducting Origin-Destination Survey", Highway Research Board Bulletin 224, pp. 41-50.

35. Lyles, R. W. and J. H. Wyman (1983). "Traffic Data Collections Systems: Current Problems and Future Problems", Transportation Research Record 905.

36. Lynch, J. T. (1944). "Origin- and Destination-Surveys in Urban Areas", Highway Research Board Proceedings, Vol. 24, pp. 239-254.

37. Lynch, J. T. (1959). "Home-Interview Surveys and Related Research Activities", Highway Research Bulletin 224, pp. 85-88.

38. Mayer, A. J. and R. B. Smock (1960). "The Continuing Traffic Study: Methods of Keeping O-D Data Up-To-Date, Highway Research Board Bulletin 253, pp. 109-113.

39. McCastland, W. R. (1975). "Review of Research on Controlling the Level of Service on Urban Freeways." TRB Special Report 153.

40. McDermott, J. M. (1975). "Incident Surveillance and Control on Chicago Area Freeways." TRB Special Report 153.

41. Metropolitan Council of the Twin Cities (1975). "I-35W Urban Corridor Demonstration Project." Final Report, prepared for UMTA, U.S. Department of Transportation Project No. DOT-FH-11-7953.

42. Meyer, M. D. and E. J. Miller (1984). Urban Transportation Planning: A Decision-Oriented Approach, McGraw-Hill Book Company, New York.

43. Miller, I., P. E. Irick, H. L. Michael and R. N. Brown (1950). "Sampling Methods for Roadside Interviewing", Highway Research Board Bulletin 26, pp. 31-51.

44. Murray, S. J. (1951). "Controlled Postcard Surveys in Ohio", Highway Research Board Bulletin 41, pp. 1-20.

45. National Cooperative Highway Research Program (1981). Experiences in Transportation System Management, Report No. 81, Transportation

Research Board.

46. National Cooperative Highway Research Program (1983). Simplified Procedures for Evaluating Low-Cost TSM Projects: User's Manual Report No. 263, Transportation Research Board.

47. National Cooperative Highway Research Program (1986). Training Aid for Applying NCHRP Report 263 , Report No. 283, Transportation Research Board.

48. Newman, L., A. Dunnet and C. J. Meis (1969). "Freeway Ramp Control - What It Can and Cannot Do." Traffic Engineering, Vol. 19, No. 7, pp. 14-21.

49. Nihan, N. L. (1982). "Procedure for Estimating Freeway Trip Tables," Transportation Research Record 895, pp. 1-5.

50. Nihan, N. L. and G. A. Davis (1984). "Estimating the Impact of Ramp Control Programs," Transportation Research Record 957.

51. Nihan, N. L. and G. A. Davis (1984). "Use of Time-Series Designs to Estimate Changes in Freeway Level of Service Despite Missing Data," Transportation Research, 18A, No. 5/6, pp. 431-438.

52. Nihan, N. L. and G. A. Davis (1986). "Recursive Estimation of OD Matrices Using Inflow/Outflow Counts", Transportation Research,in print.

53. Parvatanem, R., P. R. Stofpher and C. Brown (1982). "Origin-Destination Travel Survey for Southwest Michigan", Transportation Research 886, pp. 1-8.

54. Rogers, C. A. (1985). "Effects of Ramp Metering with HOV By-Pass Lanes on Vehicle Occupancy", Transportation Research Record 1021, pp. 10-15.

55. Rothrock, C. A. (1951). "Origin and Destination Surveys in West Virginia by Postcard Questionnaires", Highway Research Board Bulletin 41, pp. 21-24.

56. Sosslau, A. B. and G. E. Brokke (1960). "Appraisal of Sample Size Based on Phoenix O-D Survey Data", Highway Research Board Bulletin 253, pp. 114-127.

57. Spielberg, S. et al. (1980). "Evaluation of Freeway High Occupancy Vehicle Lanes and Ramp Metering", U.S. DOT, PB82--161258.

58. Stover, V. G. and J. C. Glennon (1969). "Bus Rapid Transit on Urban Freeways Using Traffic Surveillance and Control." Report to UMTA U.S. Department of Transportation.

59. Thomas, E. and J. Schofer (1970). "Strategies for the Evaluation of Alternative Transportation Plans" NCHRP Report 96.

60. Transportation Research Board (1977). Transportation System Manage-

ment, Special Report 172.

61. Transportation Research Board (1977). Transportation System Management in 1980, State of the Art and Future Directions, Special Report 190.

62. Uematsu, T. T. (1982). "Evaluation of Preferential Lanes for High Occupancy Vehicles at Metered Ramps." California Department of Transportation, Traffic Operations Branch.

63. Washington State Department of Transportation (1983). "I-5 HOV Lanes: Three Month Report," WSDOT, District 1.

64. Wattleworth, J. A. (1971). "Accomplishments in Freeway Operation in the United States." Highway Research Record 368.

65. Winfrey, R. and R. J. Hansen (1955). "Sampling Procedures for Roadside Interviews in Origin-Destination Traffic Surveys", Highway Research Board Bulletin 76, pp. 52-65.

66. Willumsen, L. G. (1982). "O-D Matrices from Network Data: A Comparison of Alternative Methods for Their Evaluation", PTRC, pp. 294-304.

APPENDIX A

LITERATURE REVIEW

Freeway Surveillance and Control

Freeway surveillance and control involves the management of freeway traffic flow by the monitor and control of mainline and entering ramp traffic, the objective being to improve the quality of flow and safety of operations for all vehicular traffic. This is achieved through the use of loop detectors in the mainline lanes and on-and-off ramps with associated ramp metering at the on-and-off ramps. Such metering can also act to discourage or restrict vehicular traffic on adjacent streets and, when combined with HOV bypass lanes, give preferential treatment to HOVs. In addition, this strategy may incorporate closed-circuit television surveillance for incident detection and management and to facilitate manual override of ramp metering rates. In general, individual surveillance and control systems vary with respect to both the extent of freeway coverage and the level of sophistication in their monitoring and control functions. While most applications clearly lie within the realm of TSM actions, some area-wide surveillance and control systems in large cities fall beyond the scope of TSM due to time and cost considerations.

The first generation of freeway surveillance and control systems in the U.S. was initiated with electronic expressway surveillance in Chicago in 1961 (McDermott, 1975). Applications in Los Angeles, New York, and Dallas followed. More recently, surveillance and control systems have been developed in Seattle, Minneapolis, Tampa, Atlanta and Phoenix. By 1980, there were about 15 operational surveillance and control systems covering about one percent of the urban freeway mileage in the U.S. (Ahmed, 1980). The development of and experience gained with these systems is described by Duff (1968), Moskovitz and Jorgensen (1970), Highway Research Circular No.

108 (1970), Wattleworth (1971). Everall (1972), McCastland (1975), McDermott (1975) Courage (1976), Paine and Helsenvein (1976) and Ahmed (1980).

Literature in the area which emphasizes ramp metering includes Glennon and Stover (1968), Newman, et al. (1969), Metropolitan Council of Twin Cities (1975), Blumentritt (1981), Burdwick (1981), and in the case of Seattle, Betts et al. (1983). Also, a number of authors have discussed the use of bypass lanes at metered ramps for buses, carpools or HOV's in general, e.g., Stover, and Glennon (1969), Goodell (1974, 1976), Levinson et al. (1975), Link (1975), Carlson (1976), Spielberg et al. (1980), Uematsu (1982) Washington State Department of Transportation (1983), and Rogers (1985). Finally, in addition to the benefits of improved quality and safety of traffic flow, automatic vehicle detection systems on freeways also enable use of powerful mathematical techniques such as time series analysis to identify the impact of specific ramp control strategies and to forecast future congestion problems, e.g., Levin and Tsao (1980), Nihan and Davis (1984), and Ahmed and Cook (1982).

Performance Evaluation

Traditionally, one of the first steps in the transportation planning process has been the identification of a set of goals and objectives to guide planners in their analysis and evaluation of transportation proposals. The development of such a set of goals, even for short-range, transportation planning and TSM, can be hindered by the difficulty of defining exactly what is meant by values, goals, objectives, measures of effectiveness (or criteria) and standards, and in understanding the interrelationships between each (Meyer and Miller, 1984). For purposes of discussion, these terms can be defined as follows (Wachs and Schofer, 1969; Thomas and Schofer, 1970):

<u>Values</u>: Basic social drives that govern human behavior, e.g., the

desire to survive, the need for order, security, etc.

Goals: Generalized statements which broadly relate the physical environment to values, but for which no test of fulfillment can be readily applied.

Objectives: Specific statements related to the attainment of goals which are measurable.

Measures of Effectiveness: Measures or tests which reflect the degree of attainment of specific objectives.

Standards: Minimum acceptable levels for the values of measures of effectiveness.

Clearly, as one proceeds from values to standards, the degree of specificity increases.

In the case of multi-modal TSM strategies, considerable effort has been devoted in recent years to defining appropriate goals, objectives, and measures of effectiveness (MOE's) e.g., Lockwood and Wagner (1977), Abrams et al. (1981). In the case of transit, operators have become increasingly concerned with route and system evaluation, and many properties have begun to develop their own service standards defined in terms of various performance measures. Pertinent work in this area includes that of Fielding et al. (1977), Fuller (1978), Barton-Aschman Associates (1979, 1981) and Allen et al. (1980). However, one of the most comprehensive multimodal studies in the TSM area is that of Abrams, et al. In this study a recommended set of goals and objectives was derived for evaluating specific TSM strategies and/or packages of strategies within individual urban areas. From five major goals, twenty related objectives were derived. Having developed recommendations for TSM goals and objectives, Abrams, et al, undertook an extensive study to develop specific MOE's for each objective. It was found that of these MOE's, 12 were dominant and could be thought of as the most critical MOE's for TSM planning. These were:

Person hours of travel

Point to point travel time

Vehicle delay

Vehicle hours of travel

Number of vehicles by occupancy

Person miles of travel

Traffic volumes

Vehicle miles of travel

Transit passenger miles of travel

Transit passenger volumes

Energy consumption

Emissions

For the SR520 project, a subset of the above MOE's considered most important to the before and after analysis was chosen for the performance evaluation of the ramp metering/HOV bypass TSM strategy. In addition to the above considerations, an origin destination survey was also considered an important component of the analysis.

Origin Destination Survey Methods

In order to analyze various transportation problems, transportation planners need origin/destination data (OD) data. The OD survey gives information on the origin and the destination of a trip, the mode, purpose, and characteristics of the trip maker, as well as the activities at the origin and destination of the trip. The most often used survey methods include home interview, roadside interview, and license plate surveys. Home interview survey methods are discussed by Lynch (1944, 1959), Childs (1946), Gamble

(1946), Murray (1951), Rothrock (1951), Cherniack (1960), Brant (1967) and Foster et al. (1977). Roadside interview techniques are discussed in Miller et al (1950), Winfrey and Hansen (1955), Lovejoy (1959), Mayer and Smock (1960), and Sosslau and Brokke (1960). License plate OD surveys are discussed in Crabtree and Krause (1982) and Parvatanem et al. (1982). A recent development in OD matrix estimation has been experiments with forecasting such matrices from link traffic volume counts. Examples of this type of approach are Nihan (1982), Geva and Hauer (1982), Willumsen (1982) and Nihan and Davis (1986).

Sampling Considerations

The Abrams' reference details the sampling considerations for the assessment of MOE's with regard to sample size, parameters and errors. Meyer and Miller (1984) elaborate with a capsule description of the essential elements of data collection procedures and sampling considerations. In the absence of other reports on this subject which target HOV lanes and metering, other references have been exampled which discuss the problem of transportation data collection in general. Several references highlight the inaccuracies of both manual and automatic data collection. Davies and Salter (1983) have concluded that manual classified traffic counts are often totally inaccurate and may be the cause of suboptimal design decisions and questionable performance evaluations. Automatic classification was criticized for inaccurate or ambiguous vehicle classification schemes; Lyles and Wyman (1983) also note this shortcoming. A problem with before/after comparisons of accident rates, which may be relevant to the 520 study, is pointed out by Hauer and Persaud (1983). They note the problem of regression to the mean, which in essence refers to the problem of assuming that before-data is an accurate estimate of the data which would have been measured afterward if no changes had been made. The authors point out several empirical verifications of this problem, as well as possible estimation schemes to overcome this difficulty. (The use of a covariable to account for trend effects in the time series analyses that were performed for the current SR520 project is one way to overcome this problem.)

Other Transportation System Management Studies

Several case studies of TSM experiences in other cities support the findings of the SR520 study. These can be found in references such as TRB (1977, 1981), NCHRP (1981) and Rogers (1986). Transportation System Management strategies such as ramp metering and exclusive HOV lanes were tested Minneapolis, Sacremento, Portland, Miami, Houston, Boston, Los Angeles, Washington D. C., and other cities. These TSM strategies were shown to increase vehicle occupancies and mainline speeds. These were two prime objectives of the SR520 project as well and were two objectives that were realized.

APPENDIX B

SUPPLEMENTARY TABLES AND FIGURES

Table B1
Summary Statistics for
Volume & Lane Occupancy Data
Station 292

Period	Volume Before		Volume After		Lane Occ. Before		Lane. Occ. After	
	Mean	Std.Dev.	Mean	Std.Dev.	Mean	Std.Dev.	Mean	Std.Dev.
3:00 - 3:30	1632	177	1706	88	27.1	6.0	20.0	5.8
3:30 - 4:00	1641	182	1711	75	28.1	7.3	20.9	6.4
4:00 - 4:30	1668	92	1688	86	29.0	6.8	20.4	5.8
4:30 - 5:00	1633	93	1678	75	25.5	4.4	20.0	5.3
5:00 - 5:30	1657	115	1671	118	25.5	7.6	21.3	5.2
5:30 - 6:00	1599	126	1651	117	26.4	8.2	23.0	3.2

Table B2
Summary Statistics for
Volume & Lane Occupancy Data
Station 117

Period	Volume Before Mean	Volume Before Std.Dev.	Volume After Mean	Volume After Std.Dev.	Lane Occ. Before Mean	Lane Occ. Before Std.Dev.	Lane. Occ. After Mean	Lane. Occ. After Std.Dev.
3:00 - 3:30	1827	396	1917	341	12.4	3.6	11.8	3.6
3:30 - 4:00	1926	404	2028	383	17.4	6.2	15.1	5.2
4:00 - 4:30	1983	359	1966	378	17.8	5.8	15.9	5.9
4:30 - 5:00	1902	392	1935	375	16.7	6.4	15.3	5.7
5:00 - 5:30	1906	401	1943	399	16.4	5.3	15.1	5.3
5:30 - 6:00	1929	399	1920	412	16.2	5.2	13.8	4.4

Table B3
Summary Statistics for
Volume & Lane Occupancy Data
Station 102

Period	Volume Before Mean	Volume Before Std.Dev.	Volume After Mean	Volume After Std.Dev.	Lane Occ. Before Mean	Lane Occ. Before Std.Dev.	Lane. Occ. After Mean	Lane. Occ. After Std.Dev.
3:00 - 3:30	1079	228	1057	292	7.8	3.5	7.1	3.4
3:30 - 4:00	1266	274	1201	314	9.3	4.2	8.4	4.2
4:00 - 4:30	1145	186	1123	252	8.3	3.4	7.5	3.3
4:30 - 5:00	1215	198	1167	233	8.8	3.6	7.8	3.5
5:00 - 5:30	1297	205	1207	242	9.4	3.8	8.1	3.6
5:30 - 6:00	1328	234	1270	287	10.2	4.4	8.9	4.0

Table B4
Regression Analysis for Station 292
Speed Data

Period	Variable	Coefficient	T-Ratio	Significance
3:00 - 3:30	Constant	4.89	0.69	insig.
	Covariable	0.40	2.95	p < .01
	Intervention Variable	4.62	1.18	insig.
3:30 - 4:00	Constant	0.29	.05	insig.
	Covariable	0.46	3.98	p < .01
	Intervention Variable	5.11	1.54	p < .10
4:00 - 4:30	Constant	11.59	1.78	p < .05
	Covariable	0.19	1.50	p < .10
	Intervention Variable	9.00	2.39	p < .01
4:30 - 5:00	Constant	14.36	2.37	p < .05
	Covariable	0.19	1.69	p < .05
	Intervention Variable	5.30	1.54	p < .10
5:00 - 5:30	Constant	16.53	3.02	p < .01
	Covariable	0.17	1.63	p < .10
	Intervention Variable	2.27	0.73	insig.
5:30 - 6:00	Constant	19.41	6.23	p < .01
	Covariable	0.05	0.87	insig.
	Intervention Variable	2.63	1.42	p < .10

Table B5
Regression Analysis for Station 117
Speed Data

Period	Variable	Coefficient	T-Ratio	Significance
3:00 - 3:30	Constant	32.52	6.89	p < .01
	Covariable	0.41	4.37	p < .01
	Intervention Variable	-0.52	-0.18	insig.
3:30 - 4:00	Constant	15.43	2.22	p < .05
	Covariable	0.59	4.18	p < .01
	Intervention Variable	-1.99	-0.48	insig.
4:00 - 4:30	Constant	22.73	2.91	p < .05
	Covariable	0.38	2.51	p < .01
	Intervention Variable	0.72	0.16	insig.
4:30 - 5:00	Constant	24.33	3.03	p < .01
	Covariable	0.38	2.45	p < .01
	Intervention Variable	-0.16	-0.02	insig.
5:00 - 5:30	Constant	24.68	3.08	p < .01
	Covariable	0.39	2.61	p < .01
	Intervention Variable	-0.16	-0.03	p < .10
5:30 - 6:00	Constant	63.83	8.03	p < .01
	Covariable	-0.37	-2.35	p < .01
	Intervention Variable	-2.40	-0.48	insig.

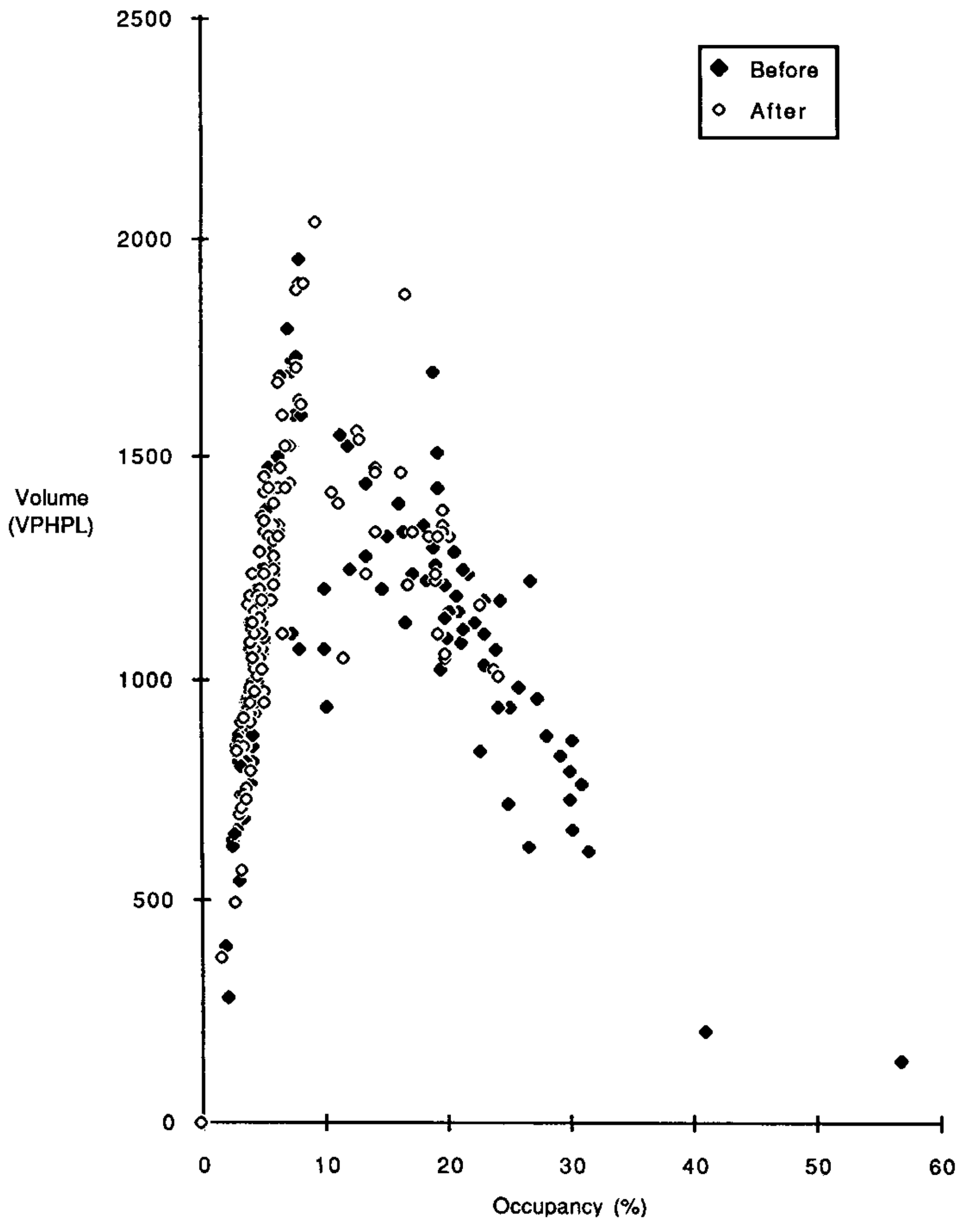

Figure B6. Volume vs. Lane Occupancy – Right Lane (Station 119).

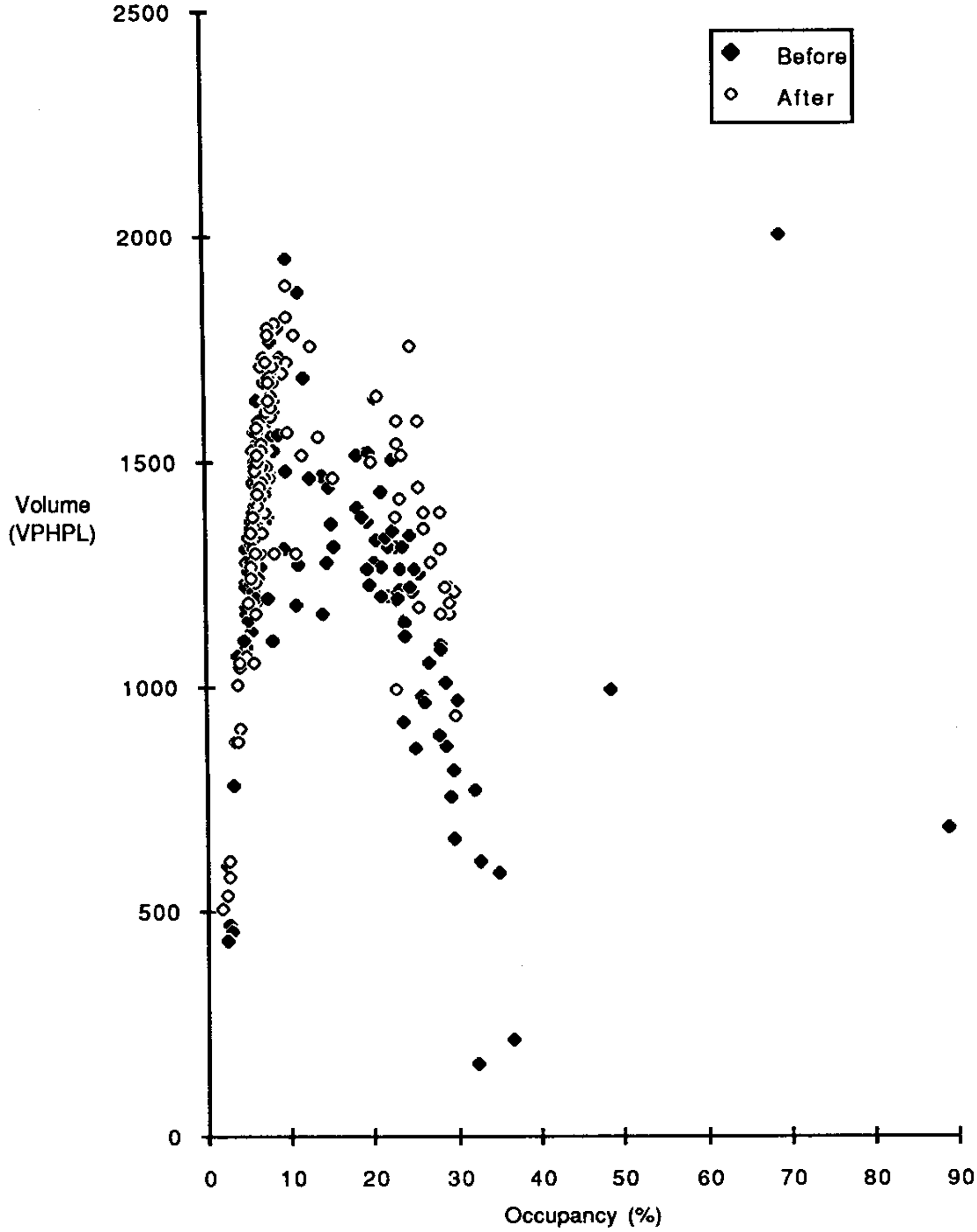

Figure B5. Volume vs. Lane Occupancy – Left Lane (Station 119).

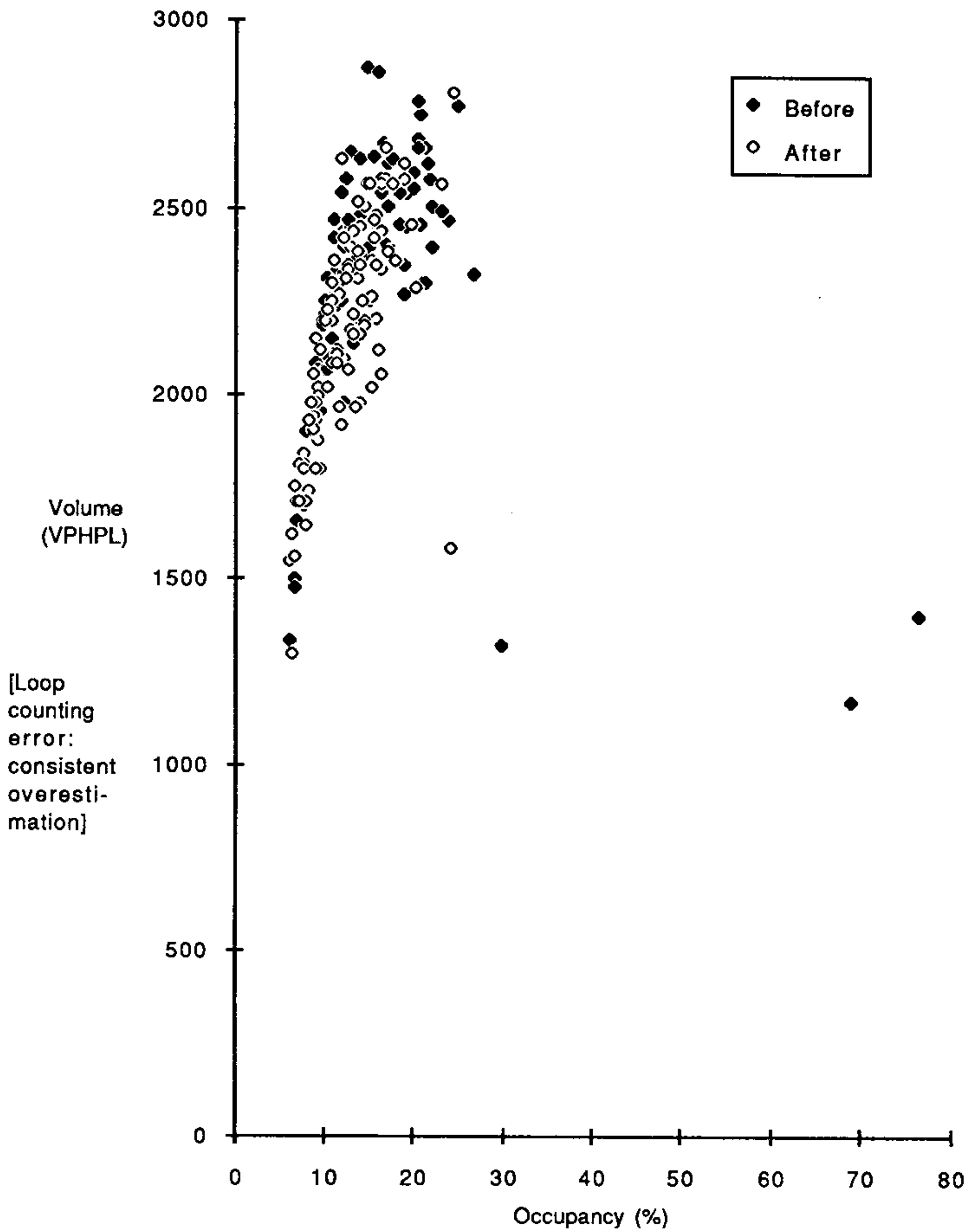

Figure B4. Volume vs. Lane Occupancy – Left Lane (Station 117).

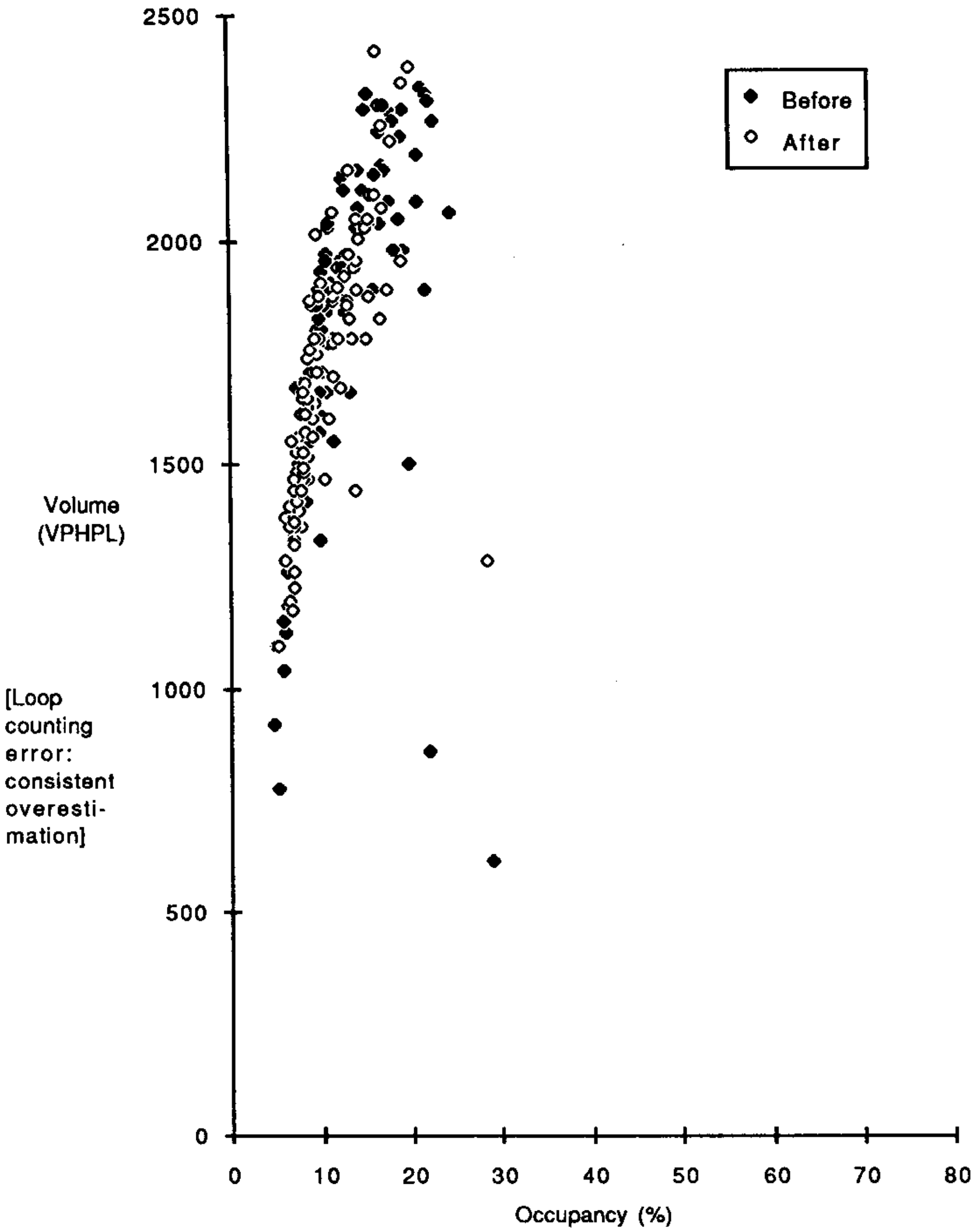

Figure B3. Volume vs. Lane Occupancy – Right Lane (Station 117).

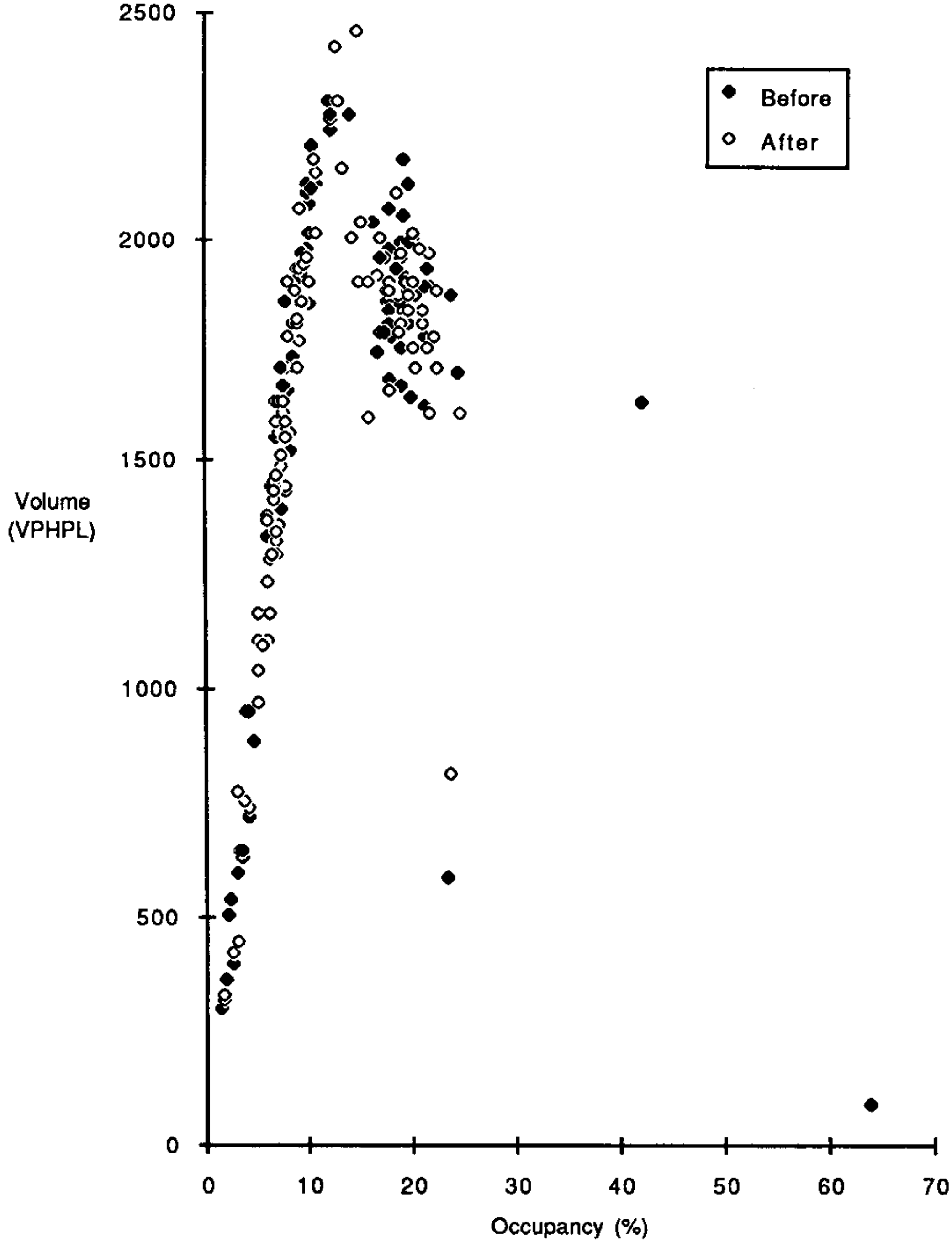

Figure B2. Volume vs. Lane Occupancy – Left Lane (Station 292).

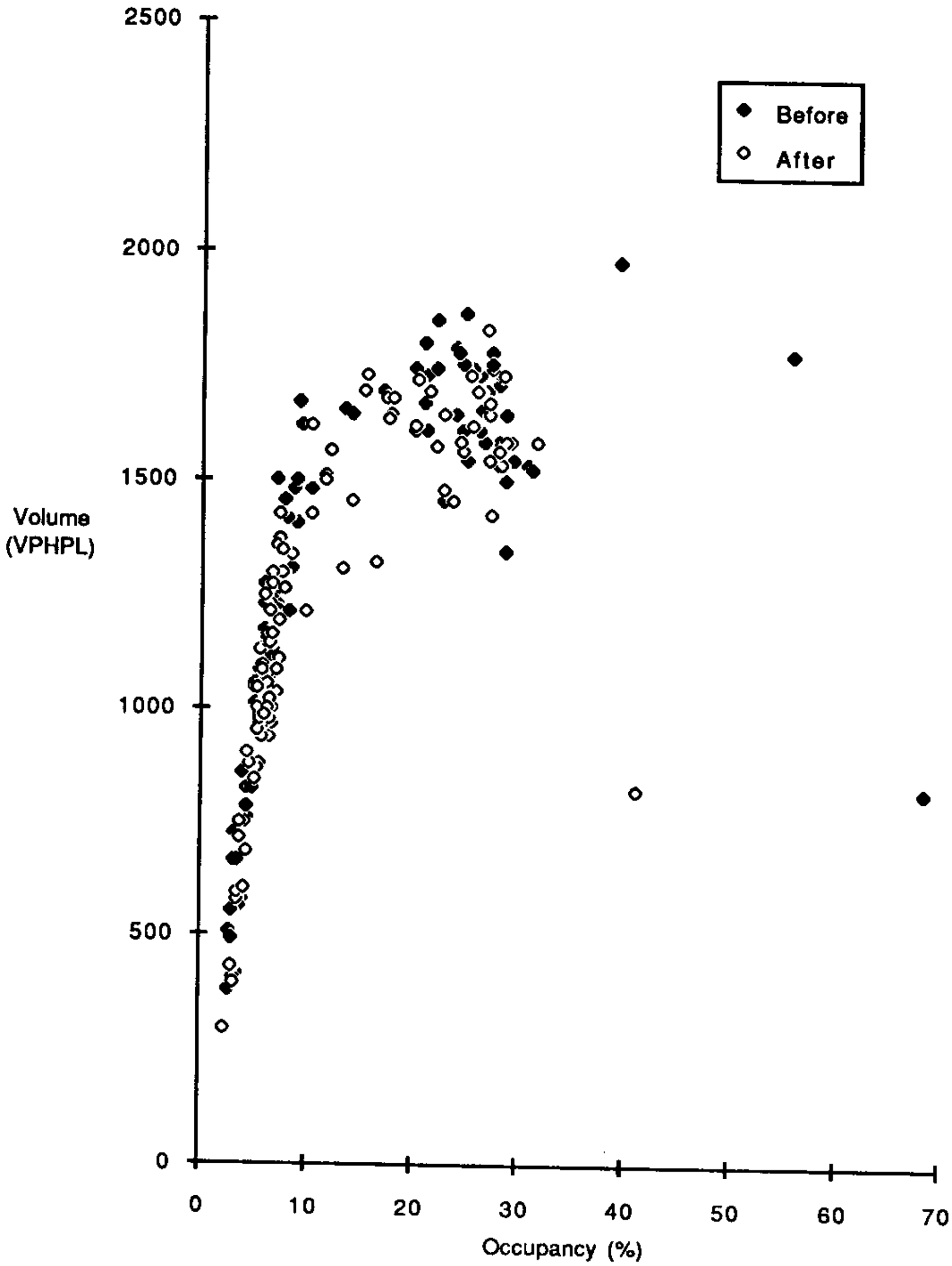

Figure B1. Volume vs. Lane Occupancy – Right Lane (Station 292).