Congestion on SR 520: A Study of Comprehensive Ramp Metering Alternatives

Draft Report 93.4

Washington State Transportation Commission
Innovations Unit

Jua-Ben Chang
Post-Doctoral Research Associate

Edward McCormack
Research Assistant

G. Scott Rutherford
Director

John M. Ishimaru
Senior Staff Member

University of Washington, JD-10
University District Building
1107 NE 45th Street, Suite 535
Seattle, Washington 98105-4631

Prepared for

Policy Development Subcommittee
Washington State Transportation Commission
Olympia, Washington

October 1993

Editor	Stephanie MacLachlan
Production Coordinator	Ron Porter
Technical Graphics	Duane Wright
Graphic Design	Mary Marrah
Report Design	Amy O'Brien
Printing	Washington State Transportation Center (TRAC) University of Washington, Seattle

Printed on Recycled Paper

Production Run 1 (100)

Table of Contents

Section **Page**

Table of Contents (continued)

List of Figures

List of Tables

Abstract

This report summarizes the findings of a study by the Innovations Unit of the Washington State Transportation Commission. It is entitled *Congestion on SR 520: A Study of Comprehensive Ramp Metering Alternatives*. Authorized by the Commission in September 1992, this report describes a research project that used computer simulations to explore potential solutions to the growing congestion problems on one of the Puget Sound region's major commute routes.

SR 520 is one of the region's most congested freeways; slowdowns on this corridor adversely affect traffic on connecting freeways such as I 405 and I 5. Although congestion slows down all vehicles, high-occupancy vehicles (HOVs) are the chief concern in this project. This concern is consistent with a regional effort to improve HOV systems. Improving HOV travel conditions by adding lanes to SR 520 would be difficult. Suitable land is scarce and expensive, and lane construction could engender significant political opposition. Therefore, this study used a computer model to explore selected ramp metering alternatives for improving HOV travel on the SR 520 corridor between I 5 and Redmond.

This report explored two linked, no-build options: 1) ramp metering only, on the on-ramps of SR 520; and 2) ramp metering plus HOV bypass lanes. Computer simulation revealed that metering ramps onto SR 520 would improve the mainline traffic flow. However, the simulation also predicted that it would create long queues at the metered ramps, for both SOVs and HOVs. Given the HOV orientation of this project, an effort was made to give HOVs delay-free access to the improved mainline flow. For this purpose, HOV bypass lanes on the metered ramps were simulated. Model output indicated that bypass lanes would, in fact, give HOVs a clear time advantage over SOVs without degrading mainline flows or significantly worsening ramp delays for SOVs.

At present, the model simulates only the SR 520 mainline and the connecting ramps. It does not explicitly model connecting freeways and arterials; nor does it model the effects of incidents or trip diversion. Expansion of FREQ's model network to account for traffic on I 5 and I 405 is recommended. Further research to model incident effects and diversion would also be useful, as would model runs on planned, but not yet constructed, roadway configurations and traffic volume forecasts.

Related Reports

This white paper is a condensed summary and a stand-alone report. The FREQ10 model user manual, Demand Estimation, Benefit Assessment, and Evaluation of On-Freeway High Occupancy Vehicle Lanes (Scapinakis et al. 1990), is recommended for technical support in running the FREQ10 model.

Acknowledgments

The authors gratefully acknowledge the support of the Washington State Transportation Commission, and of the Transit, Research, and Intermodal Planning Office of the Washington State Department of Transportation. The traffic volume counts and traffic condition information provided by the engineers and TSMC staff of District 1, and the technical assistance of Adolf May and Lannon Leiman of the Institute of Transportation Studies, University of California, Berkeley, are also greatly appreciated. Valuable contribu–tions to the final preparation of this report were made by the production staff of the Washington State Transportation Center (TRAC) at the University of Washington.

I. Introduction

The Seattle metropolitan area ranks as the seventh most congested area in the U.S. (Schrank et. al. 1990). Traffic volumes on the region's freeways are expected to increase by approximately 3 percent every year (Blain 1993). State Route 520 (SR 520), an 11.2-mile, east-west commute route that crosses Lake Washington on the Albert D. Rosellini (Evergreen Point) Floating Bridge, is one of the region's most congested freeways.

Because the floating bridge is almost two miles long and only four lanes wide, congestion is a frequent problem—over 100,000 vehicles use the bridge each day. Congestion on the bridge affects traffic on other sections of the SR 520 corridor, as well as traffic on connecting regional freeways and local arterials. It also affects the level of service of HOVs using the corridor because there is no separate HOV lane on the bridge. Figure 1 shows the regional location of SR 520. Figure 2 shows SR 520's connection to surrounding freeways and arterials.

Increasing the people-moving capacity of SR 520 has been a goal of the Washington State Department of Transportation (WSDOT) and the Washington State Transportation Commission for many years. Expansion of the lane capacity on both the bridge and land portions of the roadway may be difficult, both financially and politically. Therefore, the Commission funded this study to explore selected *ramp metering* options for reducing congestion, with the primary goal of improving travel for HOVs. This emphasis is consistent with a regional effort to improve HOV systems.

Study Background

To study ramp metering options for improving SR 520's effective capacity and HOV travel times along the corridor and across the floating bridge, several computer models were evaluated, and one was selected to simulate vehicle HOV flows under different design options. The area studied is a 12-mile freeway corridor that includes the bridge. The vehicle flow simulation was divided into two steps. The first step sought to improve overall *mainline* travel conditions by exploring various ramp metering configurations. The second step sought to provide *HOVs* with delay-free access to the improved mainline conditions by simulating ramp bypass lanes.

The research was carried out in three phases. In the first phase, the primary goal was to evaluate various computer models, determining which of them might reasonably represent traffic conditions on the corridor. The models were evaluated in terms of their ability to simulate no-build traffic control options. A second goal in the first phase was to evaluate the data requirements for the no-build simulations. Data were assembled and used to develop input files for use with the selected model. An outline of the analytic approach was then written.

During the second phase of the project, a draft report of the model evaluation was

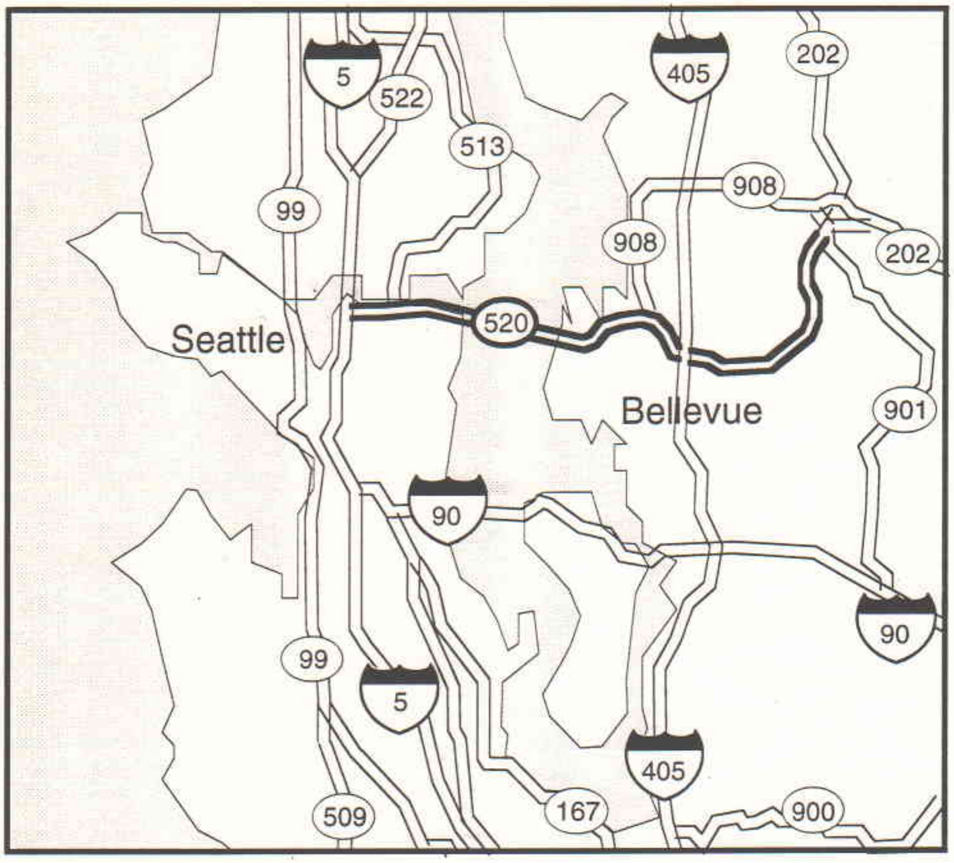


Figure 1. The SR 520 corridor

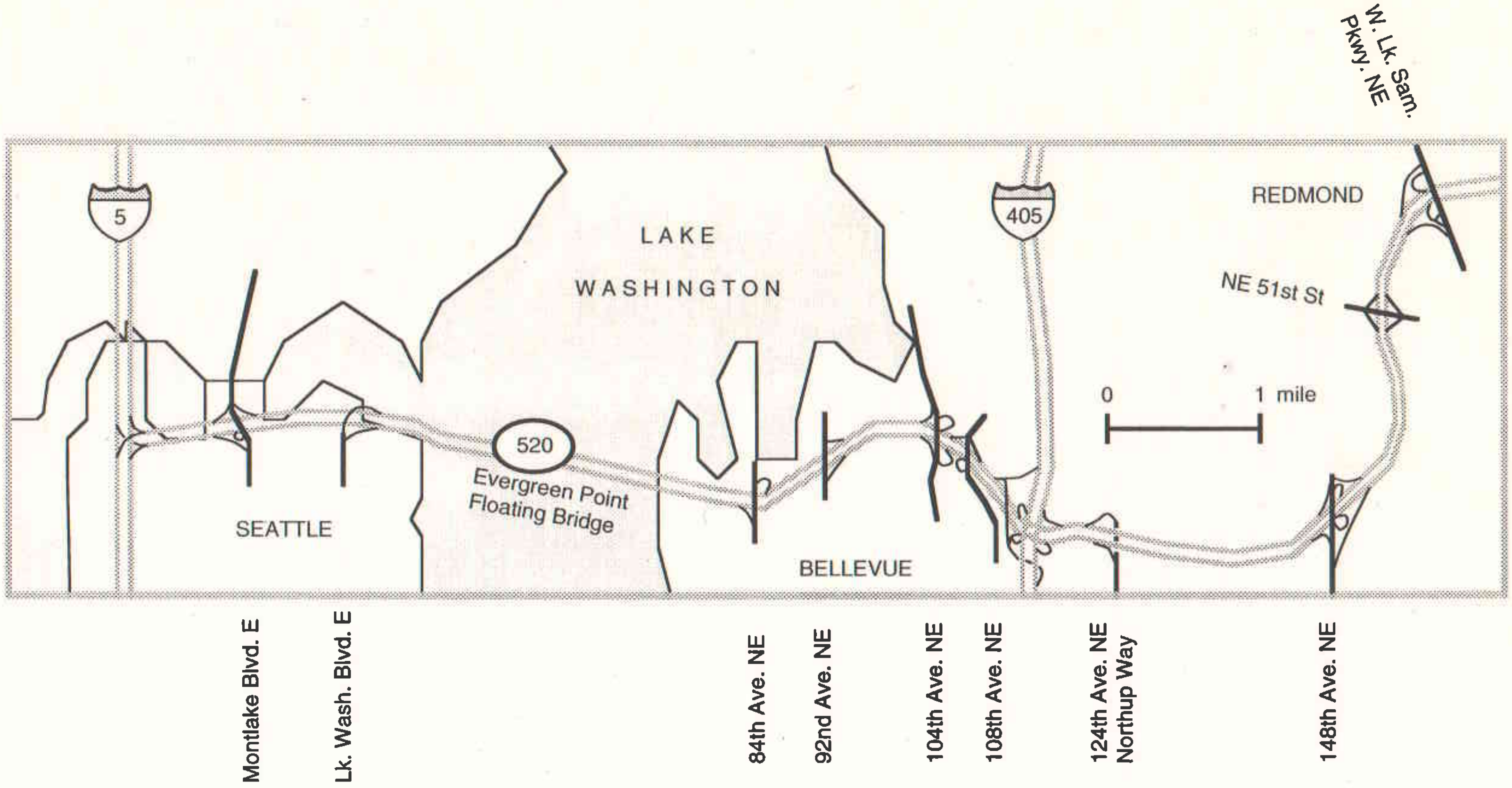


Figure 2. Interchanges on SR 520

prepared. On the basis of the initial findings in this phase, selected traffic control strategies oriented toward improving HOV travel were explored. Completion of the final report summarizing this analysis made up the project's third and final phase.

Organization

This report is divided into six chapters. Following this introductory chapter, Chapter II summarizes the review of seven freeway simulation models in light of the project goals. This review includes information evaluating each model's application strengths, the scope of the model's freeway simulation, and the required computer operating environment. Following the review process, two models, FREQ and CORFLO, are selected as candidates for the SR 520 simulation.

Chapter III discusses the no-build options that the selected model needed to simulate, and compares the relative abilities of the two candidate models selected in Chapter II to carry out this task. Based on this evaluation, the FREQ model is selected for the project.

Chapter IV discusses the model calibration and includes information on the basic assumptions underlying the calibration process. It also describes the data collection procedure necessary for calibration. A description of the model network and current traffic conditions on the network is presented. The results of the model calibration are also discussed.

Chapter V reports the results of the ram metering alternatives analysis. It also covers the predicted advantages and disadvantages of each alternative.

Chapter VI summarizes the project results and suggests directions for further study.

II. Model Review

This chapter reviews simulation models from the following families:

- TRAF,
- CORQ-CORCON,
- FREQ,
- FRESIM,
- INTRAS,
- MACK, and
- SCOT.

Each model was evaluated in terms of its ability to simulate freeway traffic and to model no-build alternatives, including ramp meters, HOV treatments, and toll systems. Four factors—history, efficiency, expense, and model usability—were considered as general measures of each model's utility.

History is an indicator of the level of software maintenance by the developer and software application by various end-users. If a model has not been used or updated for a long time, this may mean that it has significant drawbacks, or that access to user support is limited.

Efficiency is an indicator of the software's maximum processing speed. This factor focuses on the processing time difference between mainframe computers and microcomputers. Current technology makes microcomputers competitive with mainframes; this fact increases the possibility of selecting microcomputer-based simulation software.

Expense includes both capital and operating costs for software and hardware.

Finally, **model usability** indicates the relative ease of operating the software. Most microcomputer models provide a strong, user-friendly interface—mainframe models do not usually support such an environment. Therefore, a model that can be used on a microcomputer is preferable to one that can only be used on a mainframe.

All of the models were reviewed for the following operational characteristics:

Macroscopic or microscopic. Macroscopic traffic simulation models first aggregate vehicles into platoons and then perform the analysis. This process simplifies data input, but reduces the detail of the output. On the other hand, microscopic simulation models treat each vehicle as a separate unit. This type of model requires more complicated input data, but increases the detail of the output.

Deterministic or stochastic. Deterministic models use a consistent procedure to model traffic flow. The same output is always reproduced if the input data are unchanged. Stochastic models use probabilistic algorithms, and output may change from one run to the next (usually only slightly) even if the input data remain the same.

Simulation or optimization. Simulation models are designed to represent the behavior and actions of traffic mathematically. Models of this type do not have an optimization capability. Optimization models, like simulation models, use mathematics to represent traffic behavior. However, optimization models also analyze the traffic flow and use an objective function or performance measure to determine the system configuration (e.g., ramp meter locations and timing) that produces an "optimal" overall traffic condition.

Time-scan or events-scan. Time-scan models simulate traffic flow at constant time intervals. Events-scan models simulate the traffic flow during specified events.

A discussion of families of freeway simulation models follows. Overlap among computer families is common. For instance, FREFLO is a member of the CORFLO, TRAF, and MACK families. Figure 3 depicts the relationships among model families and subfamilies.

The TRAF Family

In 1975, the Federal Highway Administration (FHWA) investigated the feasibility of creating an integrated traffic simulation system to represent traffic flows on existing highway facilities. On the basis of this investigation, a modeling system called TRAF was proposed, and guidelines for its development were established (FHWA 1988).

The resulting TRAF family of programs constitutes an integrated system of several traffic simulation submodels. The family includes submodels designed for application to various traffic environments (e.g., freeways, arterials, and rural roads) at two levels of detail (macroscopic and microscopic).

The prefix "NET" indicates that the submodel was designed for rural networks; the prefix "FRE" applies to freeways; and the prefix "ROAD" applies to two-lane rural roads. Submodels with a "SIM" suffix are microscopic, while submodels with a "FLO" suffix are macroscopic.

The TRAF family contains the following submodels: ROADSIM; NETSIM; FREFLO; NETFLO levels 1, 2, and 3; TRAFFIC, an equilibrium traffic assignment; and FRESIM. The TRAF family may be used in mainframe environments only. The rural (ROADSIM), arterial (NETSIM, NETFLO), and traffic assignment (TRAFFIC) submodels were not reviewed because they do not model freeways.

FREFLO; NETFLO levels 1 and 2; and TRAFFIC submodels are also contained in a package known as CORFLO. CORFLO is an integrated set of macroscopic models that simulates traffic flow on networks containing freeways and arterials. CORFLO is part of the large family of TRAF models. It was developed by a consultant (KLD and Associates) and the FHWA as a separate unit for adaptation into the FHWA's Integrated Traffic Data System. The CORFLO subfamily is currently available for microcomputers.

FREFLO is a macroscopic, deterministic, simulation, time-scan model. It is capable of testing and evaluating traffic management strategies such as ramp metering and HOV priority treatment on freeway networks.

FRESIM, an acronym for FREeway SIMulation, is derived from the INTRAS family; it was modified by JFT Associates in 1990. The package is a microscopic, deterministic, optimization, time-scan freeway model. Designed to handle ramp control strategies, FRESIM cannot treat HOV operations directly (Jacobson et al. 1992).

Evaluation. Many TRAF submodels were unsuitable for the proposed project because with the exception of FRESIM, they do not simulate the traffic flow on freeways. While FRESIM models freeways, it is incapable of dealing with HOV vehicles and lanes. The FREFLO submodel *does* deal with both freeways and HOVs; therefore it was considered as a candidate for the project.

The CORQ-CORCON Family

CORQ was developed between 1968 and 1975 to simulate time-varying traffic demands in freeway corridors. CORCON (freeway CORridor assignment and CONtrol model) was developed in 1978 based on earlier CORQ model (May 1987).

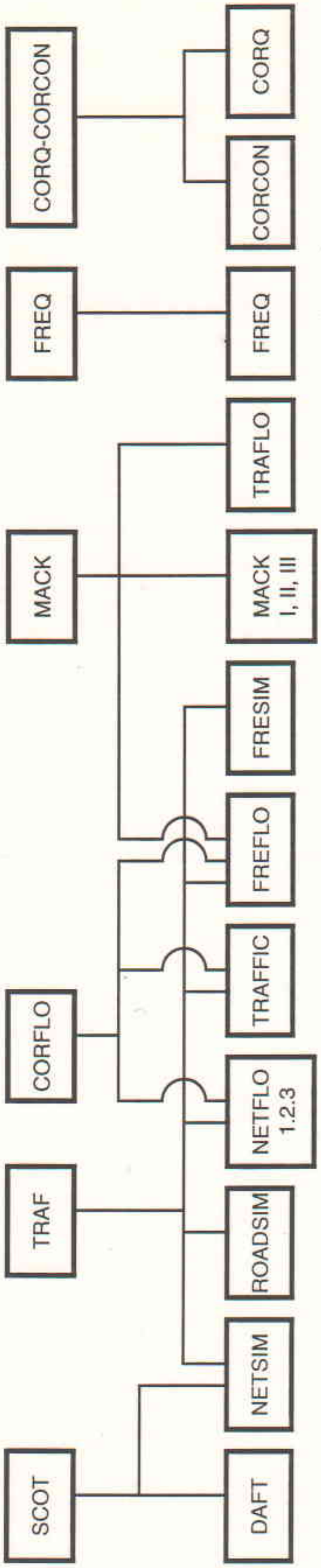


Figure 3. Model family relationships

CORQ and CORCON were developed to simulate traffic on both freeways and on arterials. The programs are simulation, time-scan models. They are macroscopic when applied to freeways, and microscopic when applied to freeways and streets. Both CORQ and CORCON are available only on mainframes.

Evaluation. CORQ and CORCON were not selected for the project because neither is capable of handling HOV treatments directly. Moreover, CORQ reportedly has not been used extensively since about 1980 (May 1987).

FREQ Family

The FREQ family of freeway models was developed at the Institute of Transportation Studies at the University of California, Berkeley. Since its inception, FREQ has been revised ten times. Major changes include the division of the model after version six into separate programs for the evaluation of HOV lane and priority entry, and reprogramming to allow FREQ to run on a microcomputer with an interactive interface.

The FREQ family consists of macroscopic, deterministic, optimization, time-scan freeway simulation models. Primarily, FREQ allows the user to study both priority lane (HOV) treatment and priority entry (ramp control) strategies. FREQ is also able to perform traffic incident analysis and to calculate fuel consumption and general emissions indexing. Additionally, FREQ is capable of modeling alternative (parallel) arterial routes.

Evaluation. FREQ was considered as a candidate for the project primarily because it simulates freeways and models HOVs directly.

FRESIM

FRESIM, discussed in the section on the TRAF family, has been available since 1991 as a stand-alone microcomputer package without a family association.

Evaluation. FRESIM was considered primarily because it provides very detailed output. However, FRESIM's simulations of HOV lane treatments are inadequate, making this model unsuitable for the project.

INTRAS

INTRAS (INtegrated TRAffic Simulation) was developed by Lieberman and Associates with support from the FHWA. INTRAS was later reprogrammed to make it more user-friendly and applicable to a wider range of situations. The revised version is known as FRESIM.

Based on the NETSIM UTCS-1 simulation procedure, INTRAS is a microscopic, stochastic, simulation, time-scan model. It uses car-following and lane-changing algorithms to simulate the movement of individual vehicles. INTRAS was specially designed to study freeway incidents. It is also capable of examining traffic control strategies and different roadway geometric alternatives. INTRAS is available on both mainframes and microcomputers.

Evaluation. As discussed earlier, FRESIM is unable to model HOVs; therefore, both FRESIM and it predecessor, INTRAS, were not selected.

The MACK Family

The MACK family includes the following submodels: MACK I, MACK II, MACK III, FREFLO, and TRAFLO. These submodels, developed by Payne and Associates in the late 1960s, are macroscopic, deterministic, simulation, and time-scan. The MACK models simulate freeway traffic conditions including ramps, incidents, surveillance systems, entry control strategies, and emissions calculations. MACK programs run only on mainframes.

Evaluation. MACK was not selected for this project primarily because the FREFLO submodel is integrated into TRAF and was thus available in a more powerful model family. In addition, there have been no known applications directly of MACK I, II, or III since the early 1980s (Garrison et al. 1990).

The SCOT Family

In the late 1960s, Lieberman and Associates developed a model to simulate the traffic flow within an integrated freeway corridor. SCOT (Simulation of COrridor Traffic) is the result. SCOT is a combination of two simulation models: DAFT (Dynamic Analysis of Freeway Traffic) and NETSIM (NETwork SIMulator). SCOT-Q is the faster version. SCOT analyzes the freeway macroscopically and analyzes freeway ramps, major arterials, and city streets microscopically. A simulation and deterministic model, SCOT is available only on mainframes.

Evaluation. SCOT is able to simulate freeways and can take the bus system into consideration. However, the program is not capable of handling HOV lanes and vehicles directly. Consequently, SCOT was not considered as a candidate for this project. Moreover, there have been no known direct applications of this family since the early 1980s (May 1987).

Summary

The model selected for this project had to be capable of simulating freeway traffic and no-build alternatives to improve the effective capacity on the SR 520 bridge. Many of the models considered were not suitable. For example, CORQ-CORCON, FRESIM, INTRAS, and SCOT are not capable of handling HOV treatments directly. Additionally, some of their methodologies are dated. Most of the submodels in the TRAF and MACK families are also inappropriate for freeway traffic simulation. None of the submodels were developed to study tolls or toll gates directly.

On the basis of the model review, FREQ and CORFLO were selected for more detailed evaluation. These two models were chosen because both can simulate freeway traffic flow under different vehicle-type options, and because both can simulate ramp metering control and HOV bypass lanes on ramps. Although neither model was designed to emulate toll systems, such features could be simulated with alternative techniques.

III. Model Selection

Most of the freeway simulation models were eliminated because they are obviously unsuitable for exploring no-build alternatives. Several models were eliminated because they cannot simulate freeways. Several were ruled out because they do not model HOVs. The two model families that seemed to offer the best prospects were CORFLO and FREQ. Both simulate freeway conditions and allow exploration of no-build alternatives.

The capabilities of CORFLO and FREQ were reviewed, with an emphasis on four no-build options for SR 520, listed below:

- HOV lanes,
- ramp metering,
- HOV bypass lanes on metered ramps, and
- toll gates (with an HOV bypass).

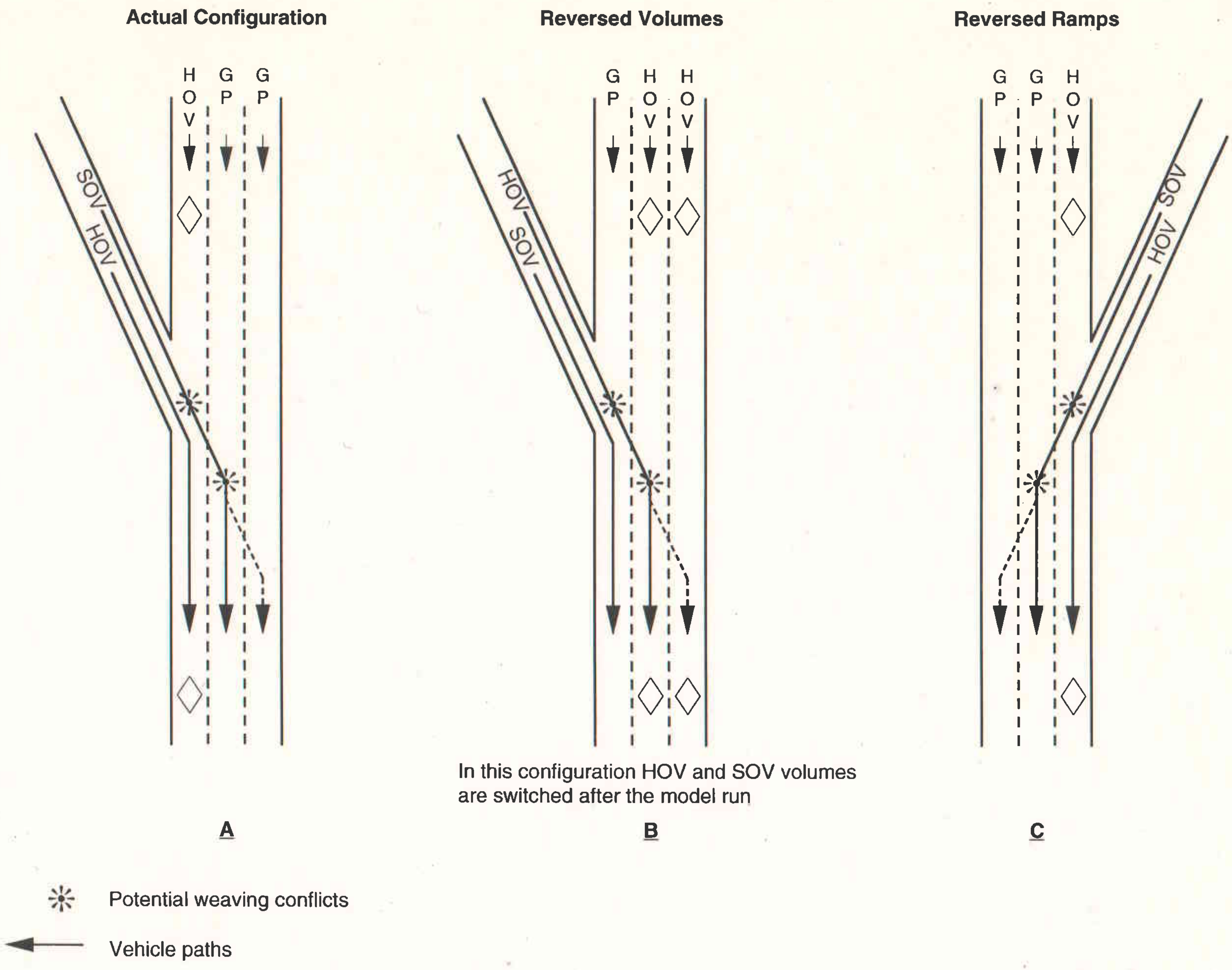
Information on the two packages was obtained from previous users, software manuals, and contact with the model developer (in the case of FREQ) or from the model's product support outlet (in the case of CORFLO). Each package had strengths and weaknesses in terms of its ability to simulate the no-build alternatives. These capabilities and limitations are discussed below.

HOV Lanes

FREQ is capable of modeling HOV lanes. The program assigns general purpose and HOV traffic to appropriate lanes. The model also calculates the traffic flow effects of areas with weaving conflicts such as on-ramps. At such points, entering HOVs may need to cross the mainline to access an inside HOV lane.

On SR 520, the HOV lane is on the outside (to the right) of the mainline. However, FREQ is programmed to model the more typical case, in which the HOV lane is on the inside. Two techniques may be used in FREQ to account for the outside HOV lane and the resulting weaving conflicts. The most direct and preferred method is to artificially model the freeway with the entrance and exit ramps connected to the "opposite," or inside lane (see figure 4). This locates the ramps opposite their actual positions; functionally, however, this correctly models the SR 520 configuration, because FREQ places the HOV lane on the inside as well, opposite its actual position. Because the ramps and the HOV lane are on the same side of the roadway, the level and number of weaving conflicts between HOVs and non-HOVs that result from this adjustment should match those of SR 520's actual lane configuration.

Alternatively, Adolf May, FREQ's developer, indicated that outside HOV lanes could also be accounted for by switching the HOV lane with the mainline lanes (see figure 4). This would mean that the model would have two HOV lanes (with mainline volumes) and one general purpose lane (with HOV volumes). The resulting mainline output would then have to be switched (manually) with the HOV volumes. The package's measures of effectiveness would also have to be recalculated to convert the information back to the actual freeway situation. To the best of the developer's knowledge, this has never been attempted (May 1992). While there is no guarantee that the model would operate correctly



In this configuration HOV and SOV volumes are switched after the model run

Figure 4. Possible HOV lane configurations on SR 520

with this type of manipulation, it would be an option if the HOV lane adjustment technique described earlier did not work.

CORFLO is also designed to simulate HOV lanes. In CORFLO, the HOV lane location does not matter because the package does not account for vehicle weaving between the HOV and general purpose lanes. While this makes CORFLO more directly usable for modeling right-hand HOV lanes, it also means that information about lane-changing conflicts is not evaluated.

RAMP Metering

FREQ can model a metered signal on a freeway ramp directly. Adolf May indicated that the program is fairly flexible because several of its freeway speed and vehicle flow parameters can be adjusted iteratively to emulate ramp metering.

CORFLO contains specific provisions for the inclusion of ramp metering. In fact, a ramp meter can be simulated by using an actuated signal at the ramps. The signal's phasing can be set at a rate that mimics the operation of a ramp meter. Such a manipulation would partially simulate the WSDOT's ramp meters.

Metered Ramp Bypass For HOVs

Neither CORFLO nor FREQ allows users to simulate an HOV bypass lane on a freeway ramp directly. However, in both packages, it is relatively easy to construct parallel ramps with one ramp reserved for HOVs and the others reserved for general purpose traffic.

Toll Gates

Neither FREQ nor CORFLO has specific provisions for toll gates. In CORFLO, a toll gate can be modeled through the use of a programming option that allows simulation of a vehicle-actuated traffic signal. The signal's cycle length can be adjusted to reflect vehicle delays at the toll gate. Whether the package can simulate a situation in which HOVs do not have to stop and pay tolls is unclear. This raises the possibility that the use of CORFLO for the simulation of a toll plaza may require some potentially difficult manipulation of the model network.

In FREQ, a toll gate could perhaps be simulated by creating a special section of roadway at the location of the toll plaza. Manipulation of the traffic speed and vehicle flow parameters would allow the user to simulate vehicle slowing at the booths. Because the HOV system is functionally separate from the mainline network, it would be relatively simple to insert an HOV toll booth bypass into the network. This procedure would greatly increase FREQ's utility for the evaluation of toll facilities.

Summary

Unlike CORFLO, FREQ is able to model weaving conflicts between HOVs and non-HOVs. Because weaving conflicts may play an important role in the efficiency of an HOV lane, it is important to model this factor. FREQ has an additional advantage over CORFLO in that FREQ can model ramp meters explicitly. Both packages are able to simulate metered bypasses for HOVs and are equally unable to simulate toll plazas directly. Evaluating toll plazas in either package would require manipulation of the model network and other model elements. Given FREQ's (relatively minor) advantages over CORFLO, FREQ was selected to simulate the no-build options on SR 520.

IV. Model Calibration

Calibration is the process of adjusting a computer model so that it accurately replicates actual conditions. Calibration for this project involved matching FREQ's output to current traffic volumes and patterns. This process was time-consuming and repetitive, but necessary for accuracy. To understand the calibration process, one must examine the assumptions and procedures used, as well as the model components (including the representation of the physical network, traffic volume data, and traffic patterns). This section discusses these components and reviews the calibration process.

Model Network

Because each travel direction on SR 520 operates independently, two model networks were constructed: one for westbound traffic and one for eastbound. The starting point for model construction was an existing 1.6-mile network developed by the WSDOT to study ramp metering in the Montlake area (WSDOT 1992). This network was expanded to model the full 11.2-mile SR 520 corridor. Information used to construct the network included WSDOT's mile post log, aerial photographs, and field surveys. The model network included the general-purpose and HOV lanes of the mainline corridor, connecting on- and off-ramps, and existing ramp meters as they existed in 1992. Traffic volumes produced by connecting arterials and interstates were included in the simulation; however, the characteristics of these roadways beyond their connecting ramps were not explicitly included in the model network.

Data Collection

The model calibration process required current traffic volumes, which were used to replicate existing traffic conditions on SR 520. Traffic volume data for SR 520 were collected by the Washington State Department of Transportation (WSDOT) using buried induction loops and mechanical tube counters. Induction loops were located in the study corridor between I 5 and the floating bridge. Induction loops collected volume data continuously, but for this study, the data were compiled into 15-minute intervals. Mechanical tube counters were temporarily installed through the corridor as part of the data collection process for the WSDOT's annual ramp and roadway report (WSDOT 1992a). These data were likewise compiled into 15-minute intervals.

The volume data used as input for FREQ were collected on weekdays in March 1992. The data included counts for each on- and off-ramp on SR 520. Data from several mainline counters were also obtained for use as controls to determine whether ramp volumes on the corridor were reasonable. The volume data were averaged from three weekdays to obtain average daily weekday counts. This process reduced distortion due to unusual traffic. The data were also filtered to include peak periods only. Morning traffic data covered the period from 6:00 AM to 11:00

AM. Afternoon data covered the period from 2:00 PM to 7:00 PM.

Typical Traffic Patterns

In addition to traffic volumes, typical traffic patterns were used as inputs and were obtained qualitatively in three ways: 1) by driving on SR 520 during peak hours; 2) by meeting with WSDOT Traffic Systems Monitoring Center (TSMC) staff, who are familiar with SR 520's congestion patterns; and 3) by using TSMC's freeway surveillance equipment during peak hours. FREQ's calibration required adjustment of the input parameters so that the model's output could replicate existing peak-hour traffic patterns. Initially, the model network ramp and lane vehicle capacities were based on FREQ's default values. These capacities were then modified as part of the calibration process.

The observations of typical traffic indicate that congestion on SR 520 is caused by incidents and by a combination of roadway geometrics and peak-hour volumes. The relatively predictable daily patterns of peak-period congestion are discussed below. These patterns reflect traffic activity on a typical day without traffic incidents (such as stalled vehicles or accidents). Incidents are an important cause of congestion because they cause traffic flows to deteriorate rapidly, leading to slow or stop-and-go conditions. However, incident-related congestion was not modeled because the location, duration and severity of incidents are difficult to predict.

Eastbound Traffic Conditions

The merge of north- and southbound I 5 traffic onto SR 520 typically causes slow or stop-and-go congestion starting at the Lake Washington Blvd on-ramps. During the evening commute, this slow traffic frequently extends from I 5 to the west-ern high-rise on the floating bridge. During the PM peak, the next area of congestion starts approximately one-quarter mile before the I 405/SR 520 interchange. This location also experiences minor AM congestion. The portion of the corridor from the SR 520/I 405 interchange east to Redmond does not usually experience traffic congestion at any time. Congestion during the AM peak typically starts to build at 7:00 AM and ends by 8:30 AM. During the PM peak, the congestion begins to increase at 3:30 PM and often continues until 7:00 PM.

Westbound Traffic Conditions

Three to four areas of slow or stop-and-go traffic are typically observed during both the AM and PM peak periods. The first area, at the Redmond end of the corri-dor, where two lanes merge into one and pass over SR 901, experiences relatively minor congestion. The second area of congestion occurs around the SR 520/I 405 interchanges. Congestion there results from numerous traffic weaves and merges due to the ramps on 124th Ave NE, I 405, and 108th Ave NE. Congestion also occurs just before the east end of the floating bridge because of the HOV lane merge. The third area of congestion occurs where the Montlake Blvd on-ramps merge onto SR 520. Westbound traffic congestion during the AM peak typically builds starting at 7:00 AM and ends at around 8:30 AM. During the PM peak, congestion starts to increase at 3:30 PM and often continues until 5:30 PM.

Traffic on the SR 520 corridor is fairly balanced in both directions. Daily traffic data reveal that the AM congestion level is higher than the PM congestion level. However, the PM peak period lasts longer than the AM peak.

Calibration Assumptions

Model calibration for this project was a multi-step process that used vehicle travel speed as the primary adjustment variable. The goal was to match the travel speeds predicted by the model to existing freeway conditions. After the travel speed predicted by the model had been adjusted, the model's predicted volume-to-capacity ratio (V/C) and mainline lane densities were examined. The V/C ratio was used in conjunction with speed data from FREQ to fine tune the calibration. The mainline density was used as a final check on the congestion level predicted by the model.

The following example demonstrates the calibration process.

1. Field checks determined that eastbound traffic near the Montlake ramps typically experiences stop-and-go congestion in the middle of the PM peak.

2. FREQ was run and capacities on the mainline and ramps were adjusted. The roadway section was considered calibrated when the FREQ output showed speeds ranging from 10 mph to 20 mph around Montlake during periods of stop-and-go operation.

3. The predicted roadway V/C ratio was examined to ensure that the ratio approached 1.00.

4. Finally, FREQ's lane density output was examined to ensure that the lanes were crowded with vehicles.

The following parameters within FREQ required manipulation: mainline capacities, ramp capacities, and, to a lesser extent, allowable speeds on the freeway sections. During the calibration process, a number of assumptions about the operation of SR 520 were developed. These assumptions, discussed in detail below, pertain to lane capacity, ramp capacity, and speed.

Maximum Lane Capacity

The FREQ default value for mainline lane capacity is 2,000 vehicles per hour. However, the calibrated model for this project contained several freeway sections with lane capacities of 2,100 vehicles per hour. These high capacities were based on freeway lane capacities in the *Highway Capacity Manual* (1985). These capacities assume high levels of driver familiarity with the route and aggressive drivers with minimal headway between vehicles. These volumes on portions of SR 520 were seen as reasonable because the corridor is a commute route, and because a field check confirmed tight headways between vehicles.

Ramp Capacities

Field observation indicated that off-ramps functioned better than on-ramps; this superior performance implies a higher capacity for the off-ramps. In the calibrated model, the off-ramps were given higher vehicle capacities than the on-ramps. Off-ramps that split into double lanes shortly after the gore point were assigned a higher capacity than single-lane ramps.

Existing Ramp Meters

During the evening commute in the eastbound direction, the Montlake Boulevard and Lake Washington Drive on-ramps are metered. The model network used during the calibration process simulated meters at these ramps. This procedure used FREQ's priority entry module and allowed the program to optimize ramp meters at these two locations. The minimum and maximum vehicle flow rates for these meters were based on information obtained from the WSDOT.

SOV/HOV

The number of buses and HOVs as a percentage of total vehicles was based on counts made by the WSDOT on SR 520 as part of a regional HOV monitoring effort. Conducted in 1992, the vehicle breakdown was as follows:

SOV	93.0 %
2 person HOVs	5.3 %
3 + HOVs	0.5 %
Buses	1.2 %

On- and off-ramps that were not used by transit were adjusted accordingly.

I 405 interchanges

Congestion on the reverse weave on eastbound SR 520 at the SR 520/I 405 interchange, which involves the northbound on-ramp and the southbound off-ramp from I 405, was notable. The calibrated model network reflected this congestion with a reduced capacity at this section of the roadway.

Speed

Free-flow traffic speeds used in FREQ were adjusted so that they were five to ten miles above the posted speed limit to compensate for the tendency to speed. In addition, this study determined that the choice of certain categories of FREQ's volume/speed equations was more important than matching the actual speed on the freeway. The volume speed curves for 55 or 65 mph were calculated on the basis of actual data from freeways in the San Francisco Bay area. However, the speed curves for 50, 60, and 70 mph were calculated on the basis of equations from the 1965 *Highway Capacity Manual*. For this study, the 55 and 65 mph curves were used because they matched peak hour corridor conditions more closely.

Calibration

The calibration process involved the iterative adjustment of lane capacity, ramp capacity, and freeway free-flow speeds until FREQ speed matched actual peak-hour conditions. The process entailed over 200 model runs. To assist in the evaluation of each model run, a series of post-processors were developed to manipulate and display the FREQ output in a easy-to-interpret format.

After the model network had been adjusted to account for errors, the calibration procedure was oriented toward the adjustment and location of traffic bottlenecks. A bottleneck marked a location with more incoming than outgoing traffic. As traffic volumes changed, potential bottlenecks determined how well the model simulated the freeway.

FREQ's output and bottleneck locations were sensitive to mainline lane capacity. Thus, much of the calibration involved adjustment of freeway capacity.. Ramp capacity was the other major parameter that was adjusted. These capacity adjustments can be interpreted as modifications to reflect specific driver behavior (e.g., tight headways) and road geometrics. Traffic origin and destination were also adjusted by changing ramp capacity to help control bottlenecks. Freeway speeds were also adjusted, but to a much lesser degree. This process is consistent with the recommendations of FREQ's developers, who suggested adjusting road capacities and speed characteristics to calibrate a FREQ simulation model.

The calibrated model output for westbound traffic in terms of vehicle speeds is presented in figures 5 through 8. As seen in the figures, during the AM peak, traffic slows after crossing the floating bridge, and as it approaches the I 5 interchange. During the PM peak, traffic slows as it approaches the bridge.

The calibrated output for eastbound traffic is presented in figures 9 through 12. During the AM peak, no sections of the corridor have major slowdowns, but traffic does slow slightly before the floating bridge. During the PM peak, traffic slows as it approaches the bridge, and as it approaches the I 405 interchange.

Tables 1 through 4 compare typical observed conditions on the corridor with the model output after calibration. The tables show that the patterns of observed and predicted areas of congestion are the same or similar.

The calibrated models were used as the starting point for exploration of a number of ramp metering alternatives.

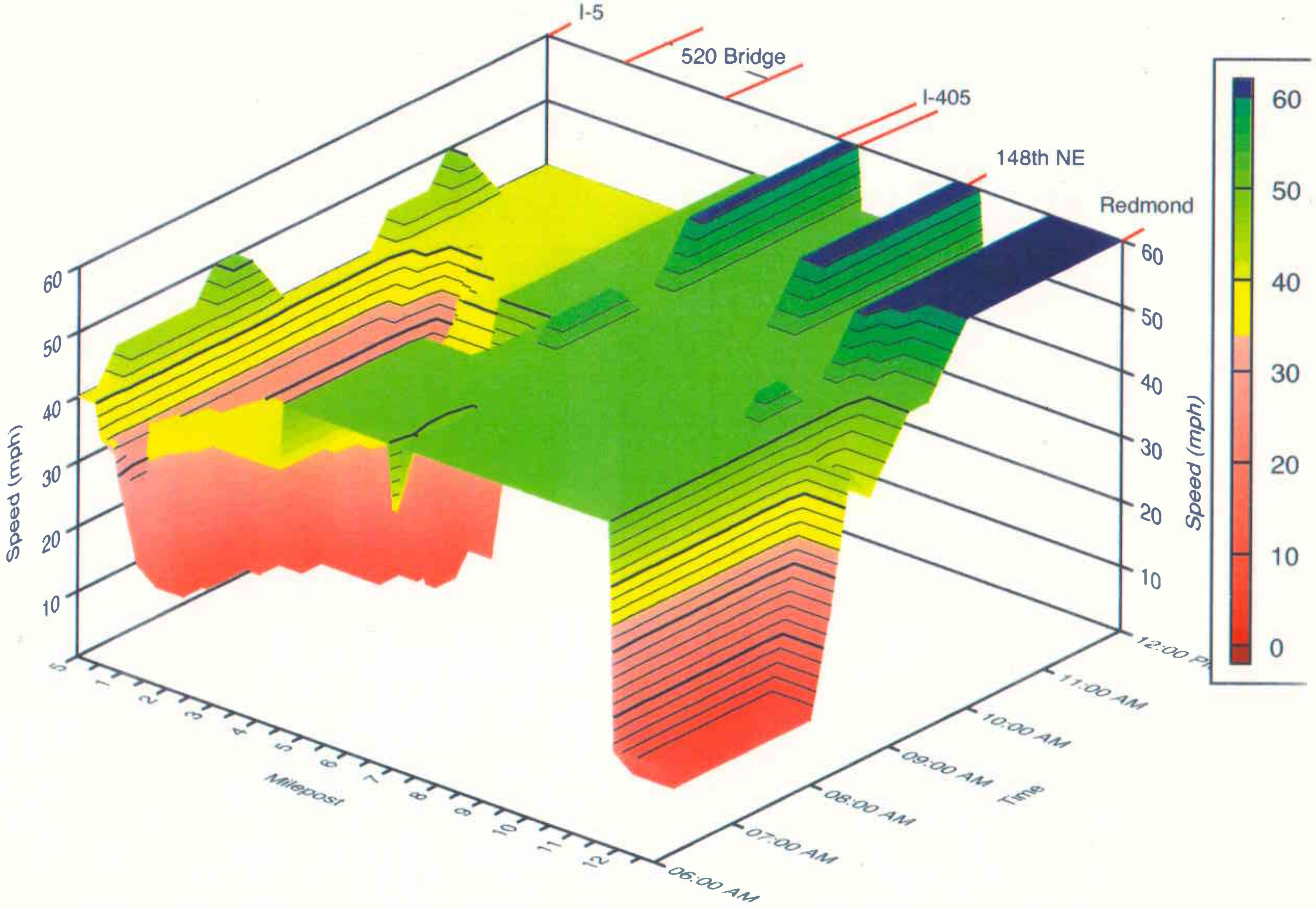
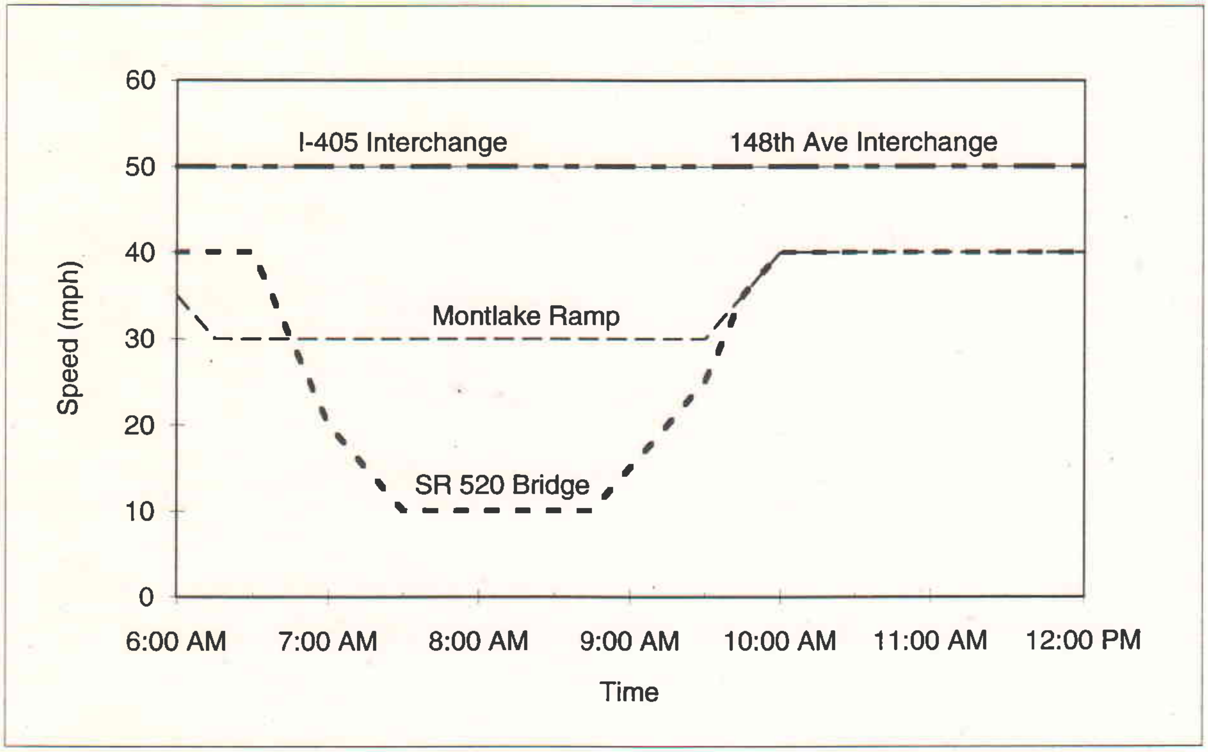


Figure 5. Westbound AM – simulation of existing conditions



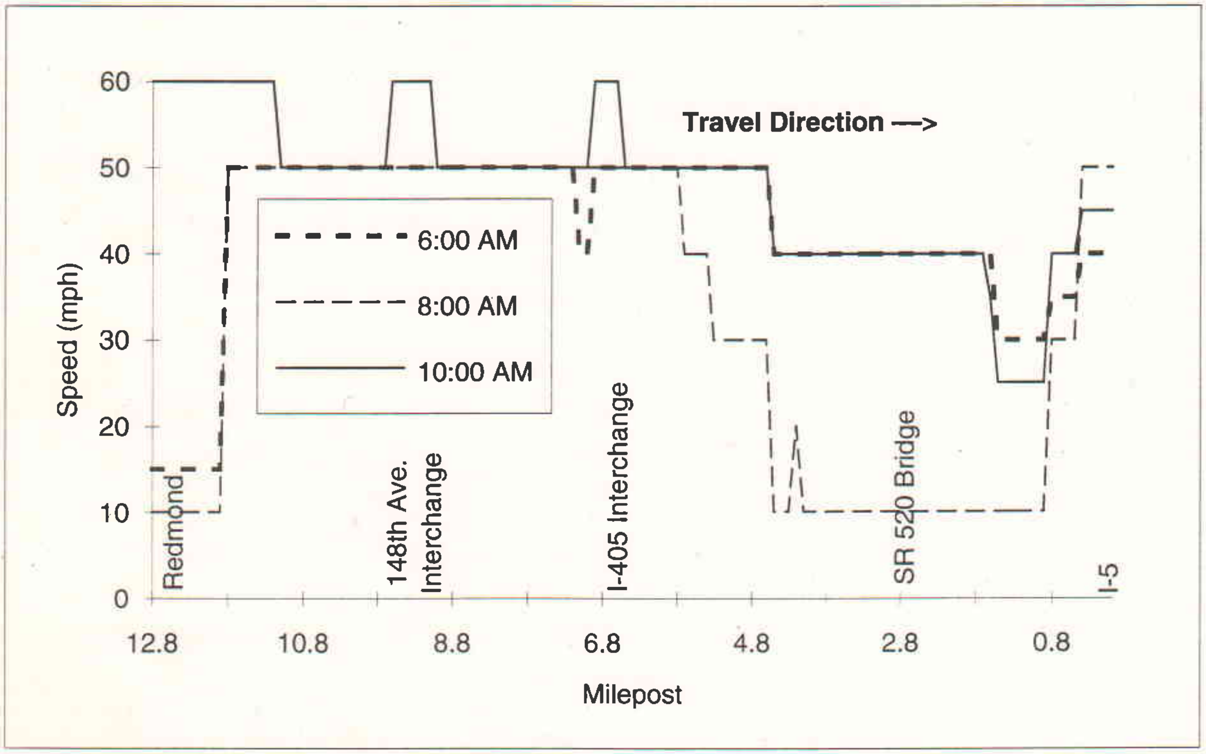


Figure 6. Westbound AM simulation of existing conditions: time and milepost slices

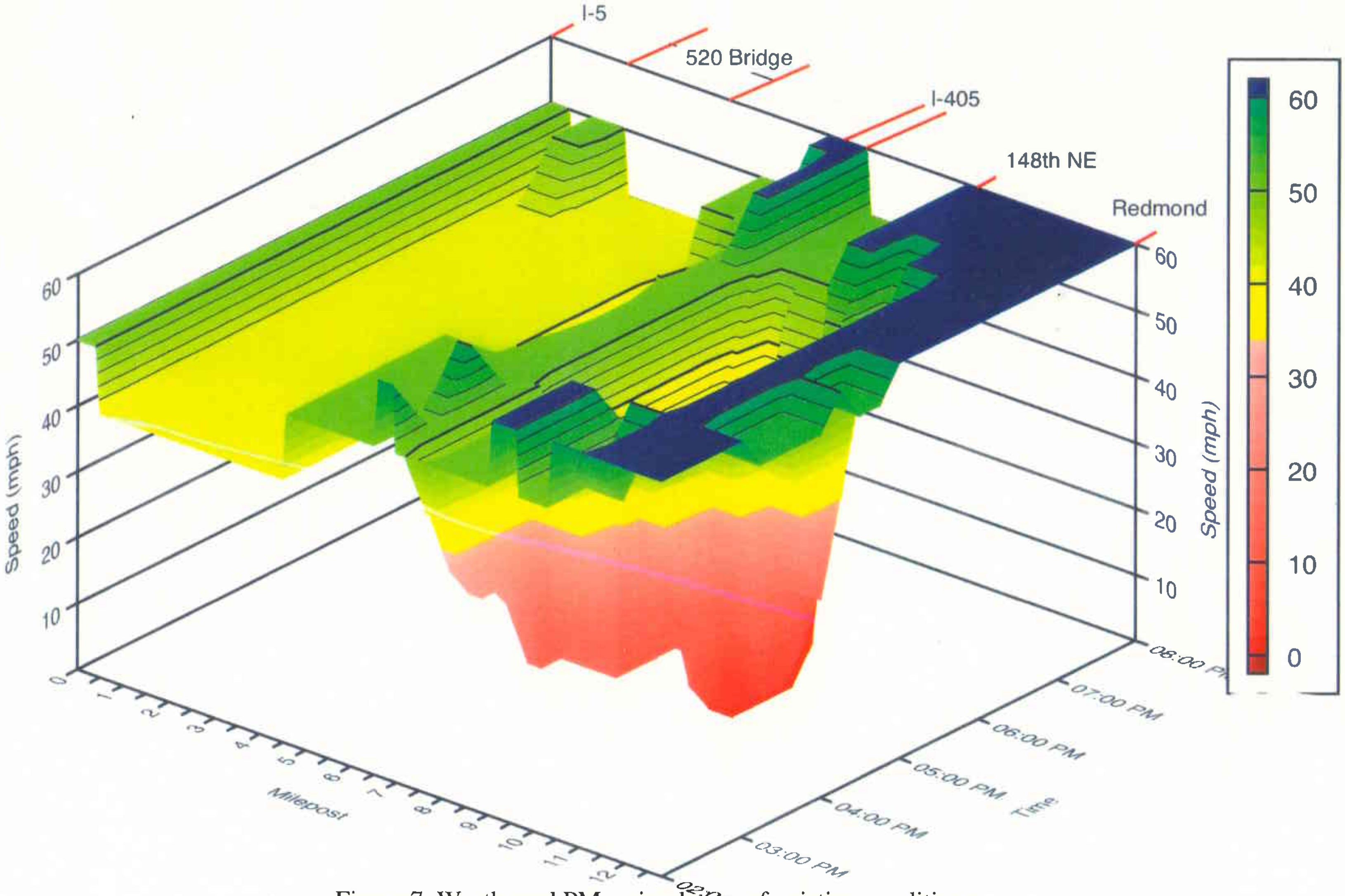


Figure 7. Westbound PM – simulation of existing conditions

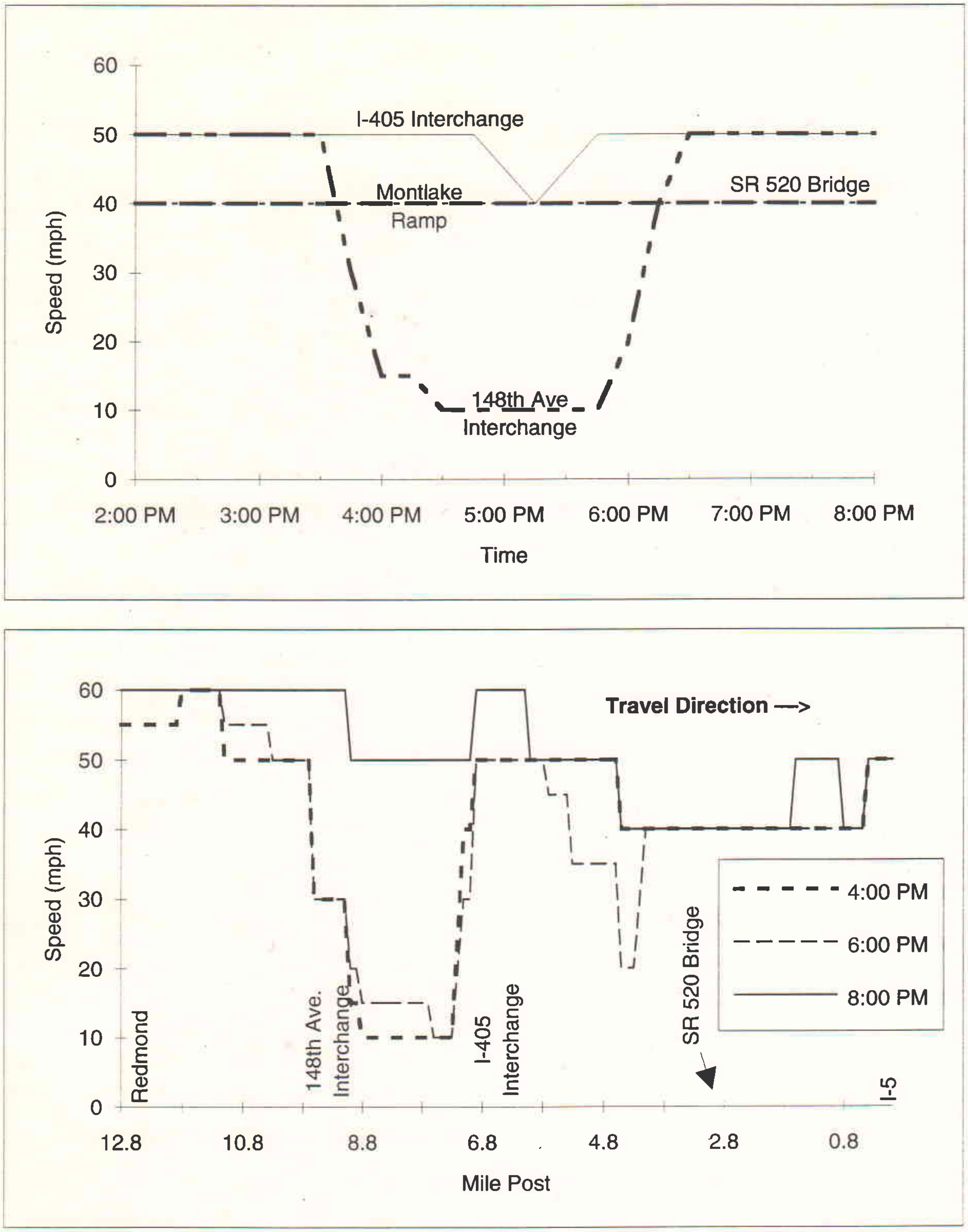


Figure 8. Westbound PM simulation of existing conditions: time and milepost slices

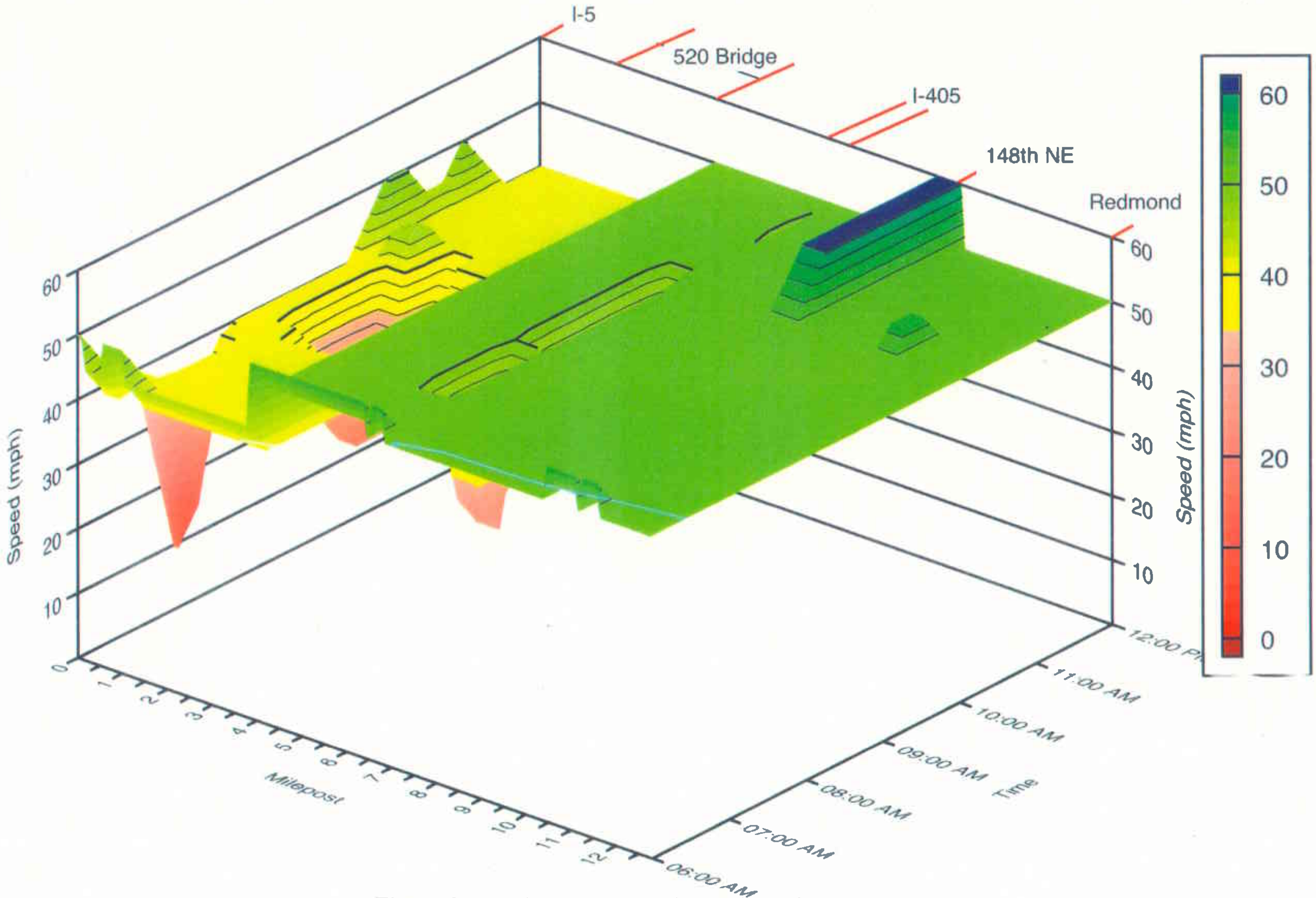


Figure 9. Eastbound AM – simulation of existing conditions

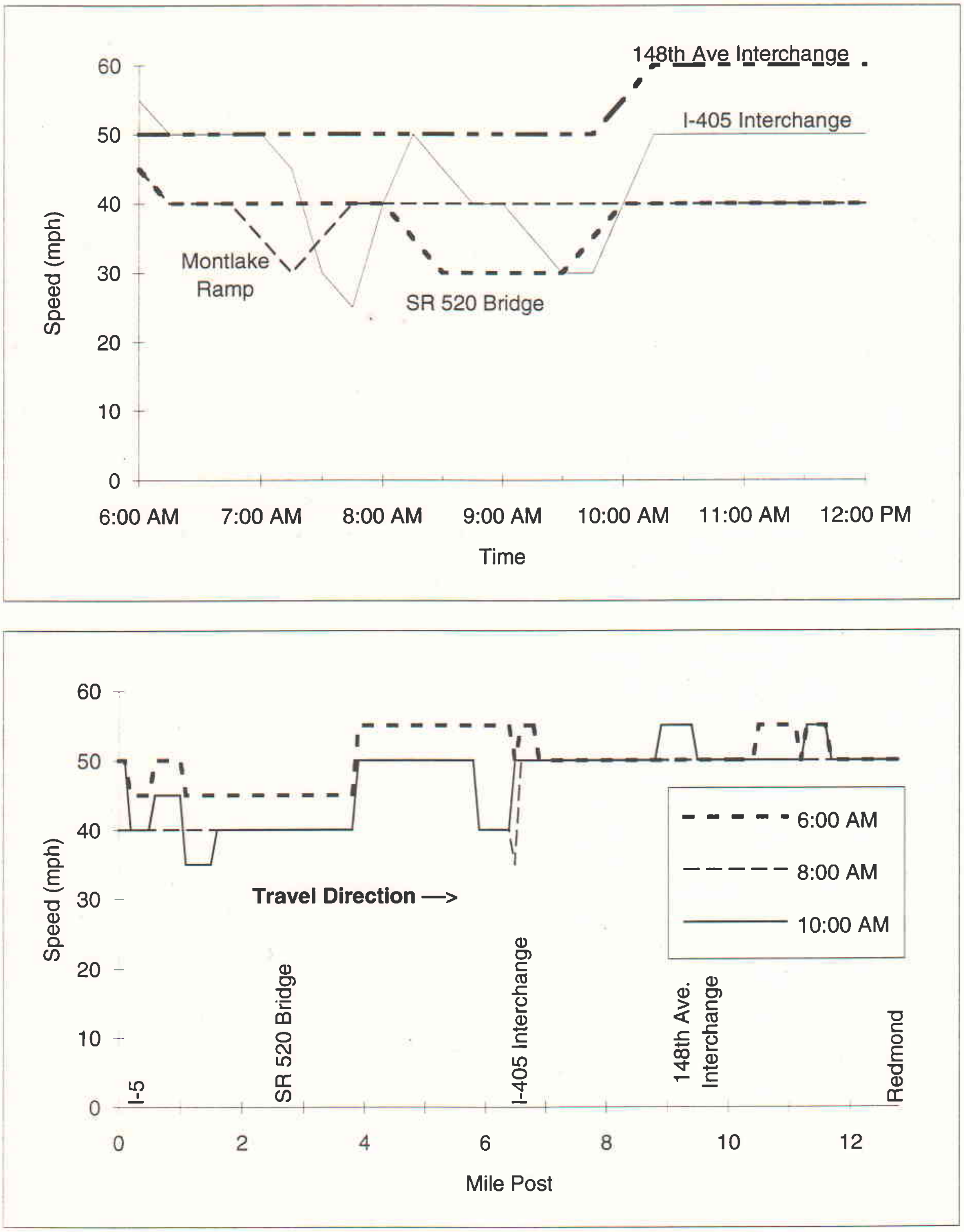


Figure 10. Eastbound AM simulation of existing conditions: time and milepost slices

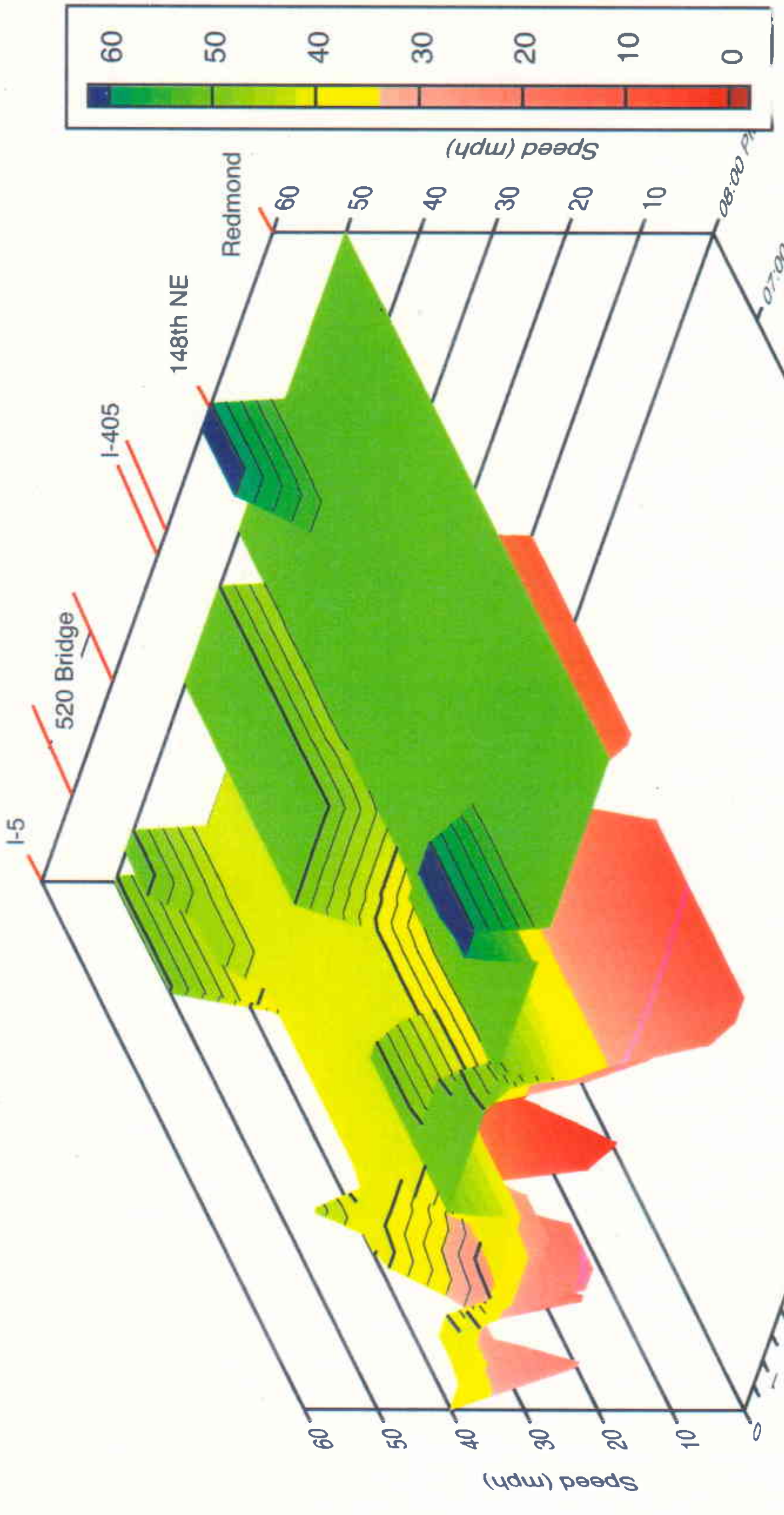


Figure 11. Eastbound PM – simulation of existing conditions

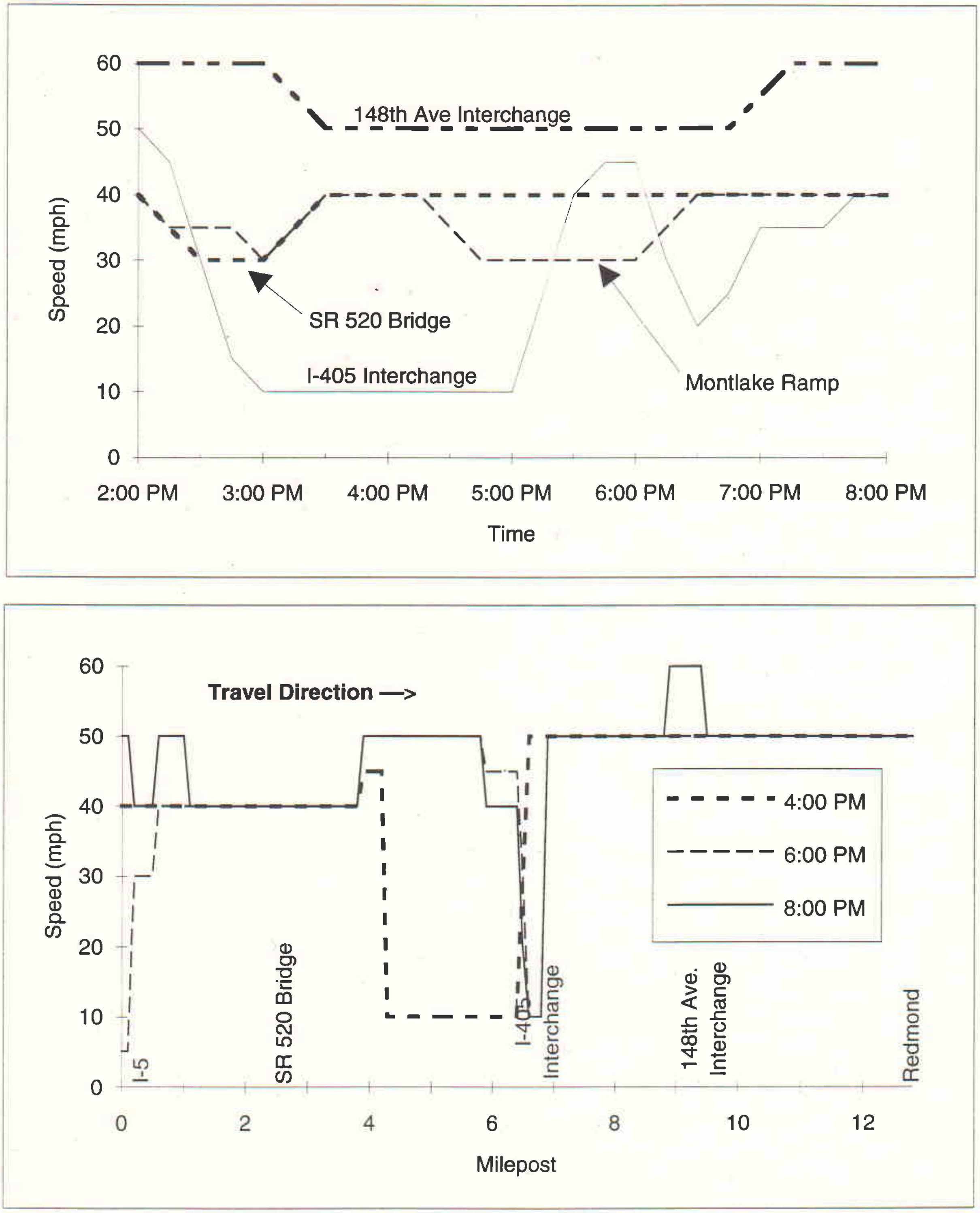


Figure 12. Eastbound PM simulation of existing conditions: time and milepost slices

Table 1. Comparison of Existing Conditions and the Calibrated Model: Eastbound AM

Corridor Section	Existing Conditions (1992)	Calibrated Model
I 5 on-ramps to bridge	Traffic is slow or stop-and-go, especially around 8:00 AM.	Traffic speeds vary between 30 mph and 50 mph, with the slowest speeds between 7:30 AM and 10:00 AM.
Evergreen Point Floating Bridge	Traffic usually travels close to the posted speed limit of 50 mph.	Traffic speeds vary between 30 mph and 50 mph.
Bridge to the I 405 interchange	Traffic is slower before the I 405 interchange, especially between 8:00 AM and 9:00 AM.	Between 8:00 AM and 10:00 AM, traffic approaching the I 405 interchange drops from 50 mph to 30 mph
I 405 interchange to Redmond	Traffic operates at or close to free flow conditions.	Traffic speeds vary between 50 mph and 60 mph.

Table 2. Comparison of Existing Conditions and the Calibrated Model: Eastbound PM

Corridor Section	Existing Conditions (1992)	Calibrated Model
I 5 on-ramps to bridge	Traffic is slow, especially between 4:00 PM and 6:00 PM.	Traffic speeds drop to 30 mph between 2:00 PM and 3:00 PM and between 5:00 PM and 6:00 PM. For the rest of the period, the speed on this section is 40 mph.
Evergreen Point Floating Bridge	Traffic is usually close to the posted speed limit of 50 mph.	Traffic speed is 40 mph.
Bridge to the I 405 interchange	Traffic is congested one-half to one mile before the I 405 interchange, especially between 4:30 PM and 6:00 PM.	Between 2:00 AM and 5:00 AM, traffic speeds vary between 20 mph and 50 mph. Traffic approaching (within one-half mile) of the interchange moves at 10 mph to 20 mph for much of the peak period.
I 405 interchange to Redmond	Traffic operates at or close to free flow conditions.	Traffic speeds vary between 50 mph and 60 mph.

Table 3. Comparison of Existing Conditions and the Calibrated Model: Westbound AM

Corridor Section	Existing Conditions (1992)	Calibrated Model
Redmond to I 405 interchange	Traffic operates at close to free flow conditions, with minor congestion at start of the section.	Traffic speeds vary between 50 mph and 60 mph, except at start of corridor, where speeds drop to 10 mph for most of the AM peak.
I 405 interchange to bridge	Traffic is usually close to the posted speed limit of 50 mph with the exception of just before the bridge, where there is often congestion.	Traffic operates at 50 mph, except before the bridge, where speeds drop between 8:00 AM and 9:30 AM. The speeds during this time are 10 mph to 20 mph.
Evergreen Point Floating Bridge	Traffic is usually close to the posted speed limit of 50 mph.	Traffic operates at 40 mph except between 8:00 AM and 9:00 AM, when traffic speeds drops to 10 mph.
Bridge to I 5	Congestion occurs where the Montlake on-ramps merge.	Traffic travels at 30 mph to 40 mph between 6:30 AM and 9:30 AM. In the later hours of the morning, traffic travels at 40 mph.

Table 4. Comparison of Existing Conditions and the Calibrated Model: Westbound PM

Corridor Section	Existing Conditions (1992)	Calibrated Model
Redmond to I 405 interchange	Traffic operates at close to free flow conditions, with minor congestion at start of the section and some slowdowns as traffic approaches the I 405 interchange.	Traffic speeds vary between 50 mph and 60 mph. Traffic is congested, with speeds dropping to 10 mph approaching the I 405 interchange.
I 405 interchange to Bridge	Traffic is usually close to the posted speed limit of 55 mph, except just before the bridge, where there is often congestion.	Traffic operates at 40 mph to 50 mph, except before the bridge, where speeds drop to 20 mph.
Evergreen Point Floating Bridge	Traffic is usually close to the posted speed limit of 50 mph.	Traffic operates at 40 mph.
Bridge to I 5	Minor congestion occurs where the Montlake on-ramps merge.	Traffic travels at 40 mph to 50 mph.

V. Analysis of No-Build Alternatives

The analysis of ramp metering alternatives involved two steps:

Step 1. In an effort to improve overall mainline traffic flow, a range of ramp metering configurations was analyzed: three for eastbound and five for westbound traffic. In each direction, one alternative metered *all* on-ramps in that direction. The other alternatives metered *selected* high-volume ramps that would be expected to have a significant impact on mainline traffic flows.

Step 2. Once it had been determined that ramp metering could improve travel speeds and travel times on the *mainline* (at the cost of long waits at the ramps), efforts were made to reduce the waits for *HOVs* by simulating HOV ramp bypass lanes. Accordingly, bypass lanes for a representative ramp metering alternative were input into FREQ. Essentially, this effort was aimed at determining whether bypass lanes would allow HOVs to benefit from the improved mainline flow while avoiding the ramp queues created by the meters.

FREQ outputs a number of corridor statistics, including travel speeds and delays on the mainline and ramps. This output is a valuable indication of how the SR 520 corridor would operate under the various ramp metering alternatives. However, as with any computer model, FREQ cannot quantify every aspect of human behavior. One notable example of FREQ's limitations appears in the calculation of vehicle queues and delays at on-ramps. Although the model output may indicate long queues at ramps, in reality people would become impatient and divert to alternative routes or ramps. FREQ does not explicitly model such behavior. Therefore, its output must be considered with these model limitations in mind.

Ramp Metering Alternatives

The analysis explored the ability of metering to improve mainline travel flows by addressing problem areas.

For eastbound mainline traffic, there are two primary problem areas:

1. Slow or stop-and-go congestion that starts at the Lake Washington Blvd. on-ramps. During the evening commute, this slow traffic frequently extends from I 5 to the western high-rise on the floating bridge.
2. Congestion that starts about one-quarter mile before the I 405/SR 520 interchange.

Typical periods of congestion eastbound:

AM peak:	7:00 AM to 8:30 AM
PM peak:	3:30 PM to 7:00 PM

For eastbound traffic, the first alternative metered traffic on all ramps. The second alternative metered traffic from I 5 to SR 520, which involved controlling the ramps connecting northbound and southbound I 5 to eastbound SR 520. The meters in this alternative were in addition to the existing ramp meters at the Montlake and Lake Washington Blvd on-ramps. The third and final eastbound alternative metered the I-5 ramps, the existing Montlake and Lake Washington Blvd on-ramps, the I 405 on-ramps, and the on-ramp at 108th Ave NE (just east of the I 405/SR 520 interchange). The three eastbound alternatives are depicted in figure 13.

For westbound mainline traffic, there are three areas of slow or stop-and-go traffic during both the AM and PM peak periods:

1. Congestion that starts at the Redmond end of the corridor (where two lanes merge into one and pass over SR 901).

2. Congestion that occurs around the SR 520/I 405 interchanges, the result of numerous traffic weaves and merges due to the ramps on 124th Ave NE, I-405 and 108th Ave NE. Congestion is also a problem just before the east end of the floating bridge because of the HOV lane merge.

3. Congestion that occurs where the Montlake Blvd on-ramps merge onto SR 520.

Typical periods of congestion westbound:

AM peak:	7:00 AM to 8:30 AM
PM peak:	3:30 PM to 5:30 PM

For westbound traffic, five metering alternatives were examined. The first assigned meters to every on-ramp in the study corridor. The second metered all on-ramps along the corridor from I 405 to I 5. The third assigned meters to every on-ramp in the study corridor with the exception of on-ramps from I 405. The fourth metered all on-ramps between the I 405 interchange and the I 5 interchange, but excluded the on-ramps from I 405. The fifth and final alternative metered every on-ramp with the exception of the two on-ramps from the I 405 and Montlake interchanges. The five westbound alternatives are depicted in figure 14.

Ramp metering rates used in the alternatives analysis ranged from 180 to 1,200 vehicles per hour. The upper values were based on rates used by the WSDOT at existing ramp meters, while the minimum metering rates were suggested by FREQ default values. The use of a lower minimum rate than is currently used by the WSDOT was an attempt to improve mainline traffic flows.

The FREQ output for each alternative is discussed below. Tables 5 through 8 show overall corridor statistics, speeds on the bridge, and statistics for major on-ramps. It is important to bear in mind that these statistics describe computer simulation output; as such, they only represent the probable effect of each alternative. As with any model simulation, the output should be viewed critically.

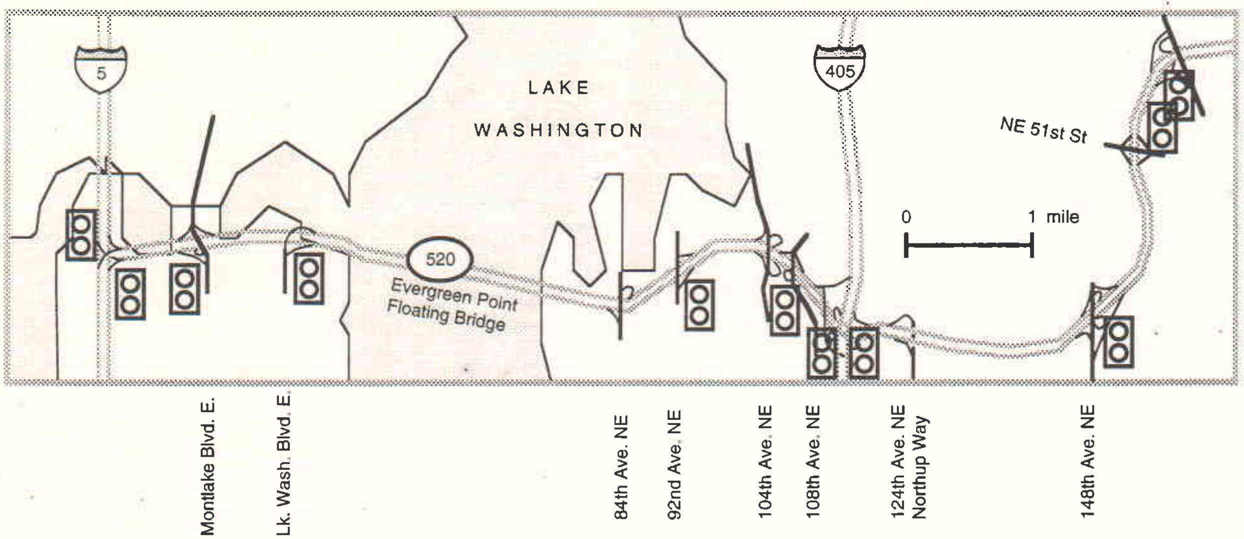
Ramp Metering Alternatives: Eastbound AM

On the basis of the calibrated existing conditions (see table 5), FREQ calculated that morning traffic on eastbound SR 520 typically travels at an average speed of 51 mph, while traffic on the bridge itself travels at 46 mph. The only location with long delays and queues is the on-ramp linking northbound and southbound I 405 to SR 520. Some queuing and delays also occur on the Montlake ramp.

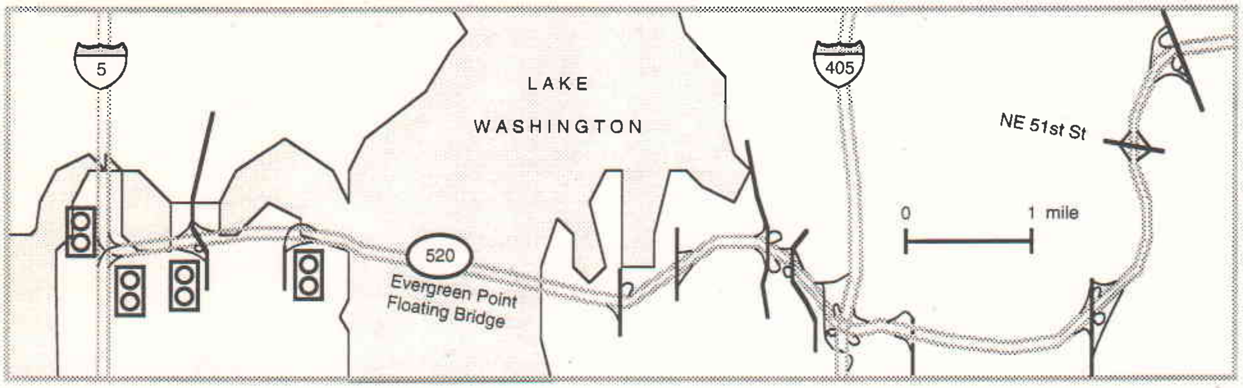
Eastbound Alternative 1: AM case (meter all on-ramps on SR 520). FREQ predicted that travel times for the corridor would improve by 10 percent and that overall speeds would improve by 6 percent over existing conditions (to 54 mph). Traffic speeds across the bridge would show a minor improvement of 3 percent (to 48 mph). However, under Alternative 1, the corridor improvements would be negated by an increase in overall ramp delays of 21 percent. The on-ramps from I 5 would worsen to an average delay of approximately 8 minutes per vehicle. The average delay at the on-ramps from I 405 would remain at 11 minutes.

Eastbound Alternative 2: AM case (meter the on-ramps from I 5 in addition to existing meters at the Montlake and Lake Washington Blvd ramps). FREQ output indicated that metering at I 5 on-ramps would improve overall travel times by 26 percent and corridor traffic speeds by 8 percent. However, overall ramp delays would jump by

Eastbound Alternative 1 – All Ramps Metered



Eastbound Alternative 2 – I-5, Montlake Boulevard, and Lake Washington Boulevard Metered



Eastbound Alternative 3 – I-5, Montlake Blvd., Lk. Wash. Blvd., 108th Ave. NE and I-405 On-ramps Metered

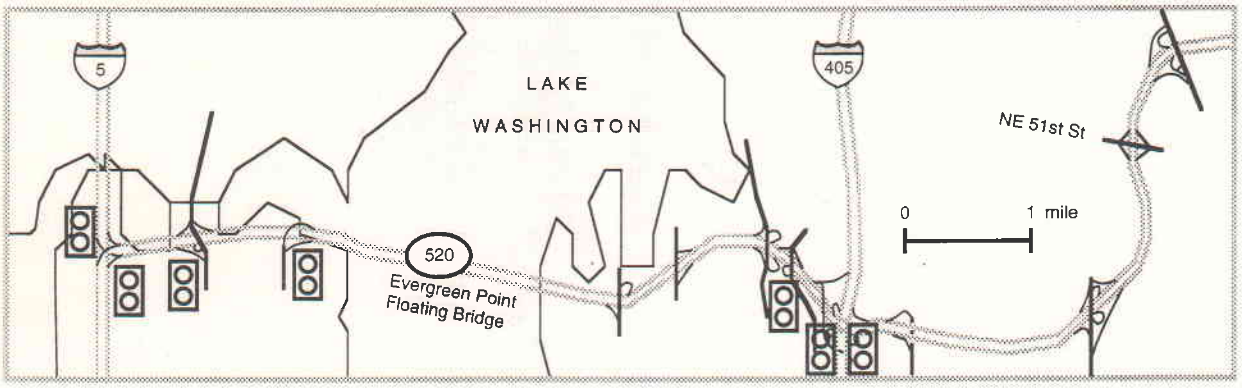
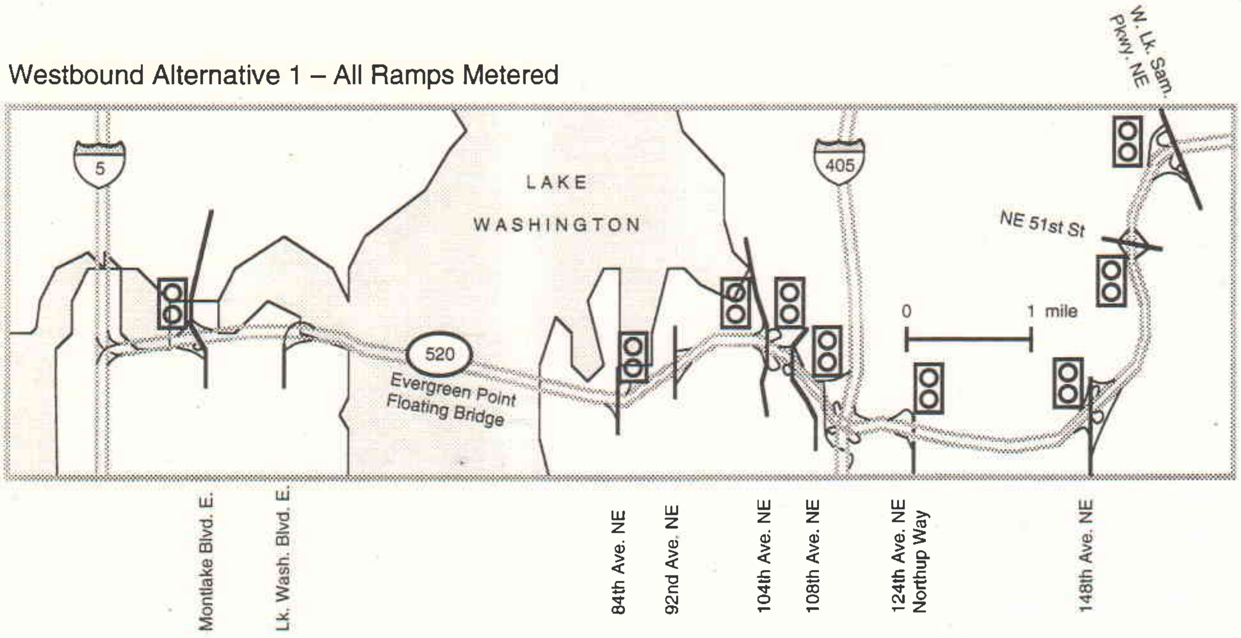
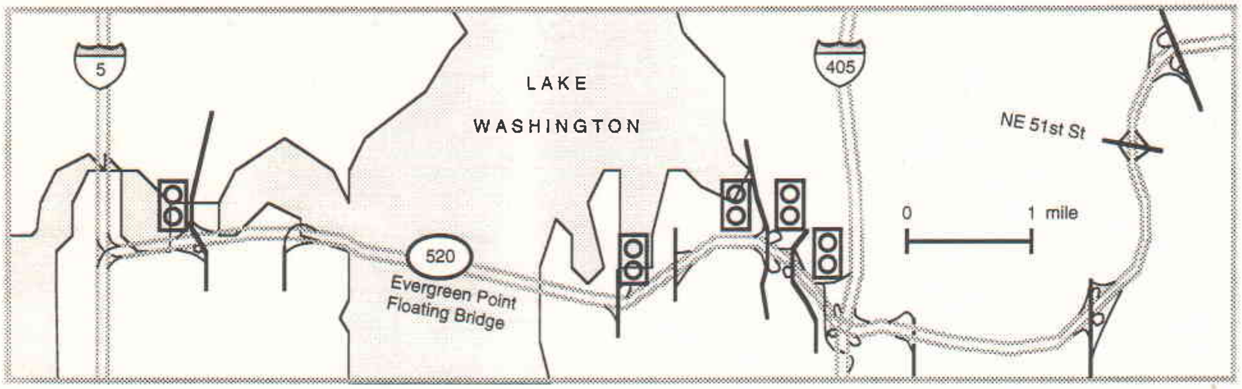


Figure 13. Eastbound SR 520 ramp metering alternatives

Westbound Alternative 1 – All Ramps Metered



Westbound Alternative 2 – Ramps from I-405 to I-5 Metered



Westbound Alternative 3 – All Ramps, Except from I-405 Metered

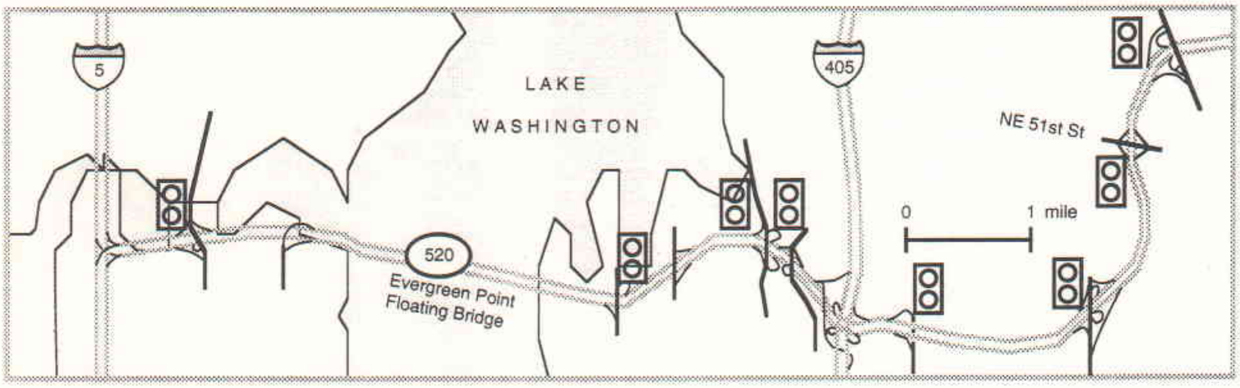
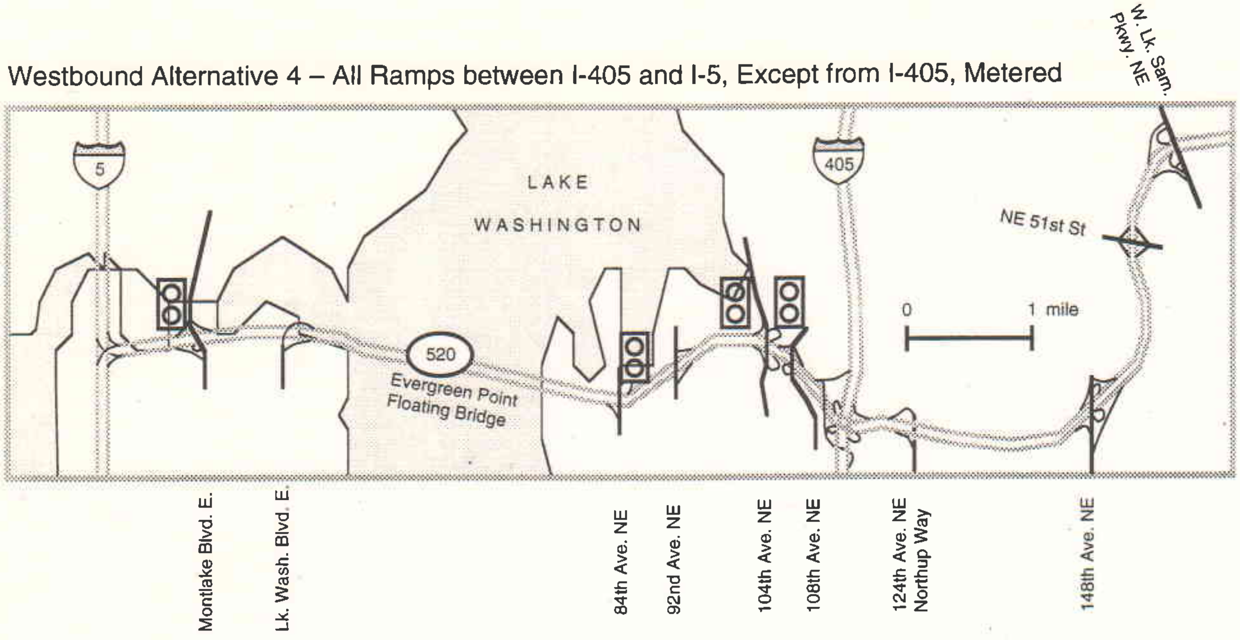


Figure 14. Westbound SR 520 ramp metering alternatives

Westbound Alternative 4 – All Ramps between I-405 and I-5, Except from I-405, Metered



Westbound Alternative 5 – All Ramps, Except I-405 and Montlake Boulevard, Metered

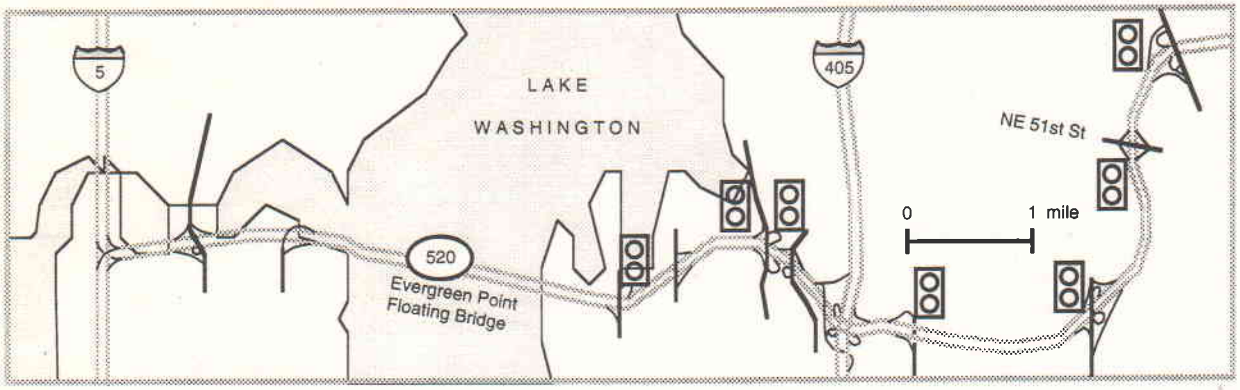


Figure 14. Westbound SR 520 ramp metering alternatives (continued)

Table 5. Comparison of Alternatives: SR 520 Eastbound AM

	Simulation of Existing Conditions	Alternative 1: AM case All Ramps Metered		Alternative 2: AM case I 5 Metered		Alternative 3: AM case I 5 & I 405 Metered	
		Simulated result	% change from existing conditions	Simulated result	% change from existing conditions	Simulated result	% change from existing conditions
Travel Time (Vehicle-Hours)							
Entire Mainline	3,611	3,247	-10.10%	2,661	-26.30%	3,247	-10.10%
Ramp Delay	20,477	24,850	21.40%	35,493	73.30%	24,850	21.40%
Total	24,088	28,097	16.60%	38,154	58.40%	28,097	16.60%
Average Mainline Speed (mph)							
Bridge	46.3	47.8	3.20%	49.3	6.50%	47.8	3.20%
Entire Mainline	51.3	54.2	5.70%	55.6	8.40%	54.2	5.70%
Average Metering Delay (Minutes per Vehicle)							
I 5 NB	0 (not metered)	8.1	*	9.4	*	8.1	*
I 5 SB	0 (not metered)	8.2	*	11.6	*	8	*
Montlake	4.4 (metered)	0	-100%	3.4	-22.7%	0	-100%
I 405	10.8 (not metered)	11.4	*	10.5	*	11.4	*

*Percentage change is not calculated, because there is no existing meter at this location.

Table 6. Comparison of Alternatives: SR 520 Eastbound PM

	Simulation of Existing Conditions	Alternative 1: PM case All Ramps Metered		Alternative 2: PM case I 5 Metered		Alternative 3: PM case I 5 & I 405 Metered	
		Simulated result	% change from existing conditions	Simulated result	% change from existing conditions	Simulated result	% change from existing conditions
Travel Time (Vehicle-Hours)							
Entire Mainline	4,588	3,234	-29.50%	2,431	-47.00%	3,234	-29.50%
Ramp Delay	33,622	42,699	27.00%	57,701	71.60%	42,699	27.00%
Total	38,210	45,933	20.20%	60,132	57.40%	45,933	20.20%
Average Mainline Speed (mph)							
Bridge	46.0	47.9	4.10%	50.6	10.00%	48	4.30%
Entire Mainline	42.4	54.5	28.50%	56.2	32.50%	54.2	27.80%
Average Metering Delay (Minutes per Vehicle)							
I 5 NB	0 (not metered)	5.9	*	13.4	*	5.9	*
I 5 SB	0 (not metered)	5.9	*	12.7	*	5.9	*
Montlake	8.5 (metered)	0	-100%	8	-5.9%	0	-100%
I 405	11.9 (not metered)	12.8	*	11.6	*	12.8	*

*Percentage change is not calculated, because there is no existing meter at this location.

Table 7. Comparison of Alternatives: SR 520 Westbound AM

	Simulation of Existing Conditions	Alternative 1: AM case All Ramps Metered		Alternative 2: Am case All Ramps Metered From I 405 to I 5		Alternative 3: AM case All Ramps Metered Except I 405		Alternative 4: AM case All Ramps Metered West of I 405 to I 5		Alternative 5: AM case All Ramps Metered Except I 405, Montlake	
		Simulated result	% change from existing conditions	Simulated result	% change from existing conditions	Simulated result	% change from existing conditions	Simulated result	% change from existing conditions	Simulated result	% change from existing conditions
Travel Time (Vehicle-Hours)											
Entire Mainline	4,878	3,415	-30.00%	3,440	-29.50%	3,761	-22.90%	3,793	-22.20%	4,489	-8.00%
Ramp Delay	2,119	9,905	367.40%	8,762	313.50%	1,733	-18.20%	625	-70.50%	3,404	60.60%
Total	6,997	13,320	90.40%	12,202	74.40%	5,494	-21.50%	4,418	-36.90%	7,893	12.80%
Average Mainline Speed (mph)											
Bridge	35.4	48.2	36.40%	48.2	36.30%	47.2	33.40%	47.1	33.20%	39.6	12.10%
Entire Mainline	41.2	51.2	24.20%	50.4	22.40%	50.5	22.50%	50.2	21.90%	43.5	5.60%
Average Metering Delay (Minutes per Vehicle)											
124th	0 (not metered)	0.7	*	0	*	0.7	*	0	*	0.7	*
I 405	0 (not metered)	11.3	*	11	*	0	*	0	*	0	*
84th	0 (not metered)	0	*	0	*	0	*	0	*	4.2	*
Montlake	0 (not metered)	0.8	*	0.9	*	2	*	2.5	*	1.8	*

*Percentage change is not calculated, because there is no existing meter at this location.

Table 8. Comparison of Alternatives: SR 520 Westbound PM

	Simulation of Existing Conditions	Alternative 1: PM case All Ramps Metered		Alternative 2: PM case All Ramps Metered From I 405 to I 5		Alternative 3: PM case All Ramps Metered Except I 405		Alternative 4: PM case All Ramps Metered West of I 405 to I 5		Alternative 5: PM case All Ramps Metered Except I 405, Montlake	
		Simulated result	% change from existing conditions	Simulated result	% change from existing conditions	Simulated result	% change from existing conditions	Simulated result	% change from existing conditions	Simulated result	% change from existing conditions
Travel Time (Vehicle-Hour)											
Entire Mainline	4,606	2,996	-35.00%	4,013	-12.90%	3,396	-26.30%	4,415	-4.10%	3,394	-26.30%
Ramp Delay	1,587	16,548	942.70%	12,781	705.40%	5,302	234.10%	1,702	7.20%	5,339	236.40%
Total	6,193	19,544	215.60%	16,794	171.20%	8,698	40.40%	6,117	-1.20%	8,733	41.00%
Average Speed (mph)											
Bridge	46.6	47.9	2.90%	47.9	2.90%	46.7	0.20%	46.6	0.10%	46.7	0.20%
Entire Mainline	41.8	53.2	27.30%	43.5	4.00%	52.0	24.30%	43.2	3.30%	52.0	24.30%
Average Metering Delay (Minutes per Vehicle)											
124th	0 (not metered)	10.1	*	0.0	*	10.1	*	0.0	*	10.1	*
I 405	0 (not metered)	12.2	*	12.2	*	0.0	*	0.0	*	0.0	*
84th	0 (not metered)	0.0	*	0.0	*	1.6	*	2.1	*	2.4	*
Montlake	0 (not metered)	0.0	*	0.0	*	0.5	*	1.0	*	0.4	*

*Percentage change is not calculated, because there is no existing meter at this location.

73 percent. The on-ramps from I 5 would worsen to an average delay of over 11 minutes per vehicle. The average delay at the on-ramps from I 405 would remain at 11 minutes.

Eastbound Alternative 3: AM case (meter the on-ramps from I 5, I 405, and 108th Ave NE in addition to the existing meters at the Montlake and Lake Washington Blvd ramps). Under this alternative (which is similar to Alternative 1 in terms of improvements on mainline traffic flow), the overall freeway travel time would improve over existing conditions by 10 percent and overall corridor speed would increase by 6 percent; however, the total ramp delay would worsen by 21 percent. The average delay per vehicle for the on-ramps from I 5 would be eight minutes, while the delay for the on-ramps from I 405 would remain at around 11 minutes.

Ramp Metering Alternatives: Eastbound PM

Based on calibrated existing traffic conditions (table 6), FREQ calculated that PM traffic on eastbound SR 520 operates at an average speed of 46 mph while traffic on the bridge flows at 42 mph. Several of the ramps had significant delays; the Montlake on-ramp had an average delay of eight minutes per vehicle and the I 405 ramps had a delay of almost 12 minutes per vehicle.

Eastbound Alternative 1: PM case (meter all on-ramps on SR 520). FREQ forecasted that travel times for the overall corridor would improve by 30 percent over existing conditions and that overall traffic speeds would improve by 29 percent (to 54 mph). Traffic speed on the bridge would improve by 4 percent, to 48 mph. However, under this alternative, overall ramp delays would increase by 27 percent, and the on-ramps from northbound I 5 would change from having no delay to an average delay of 12 minutes per vehicle. The delay at the on-ramp from I 405 would remain at around 12 minutes. The Montlake on-ramp delay would disappear.

Eastbound Alternative 2: PM case (meter the on-ramps from I 5 in addition to the existing meters at the Montlake and Lake Washington Blvd ramps). In this alternative, overall travel times would improve by 47 percent, and corridor speed would improve by 32 percent (to 56 mph). However, overall ramp delays would increase by 71 percent. The on-ramps from I 5 that have no delays under existing conditions would suffer average delays of more than 12 minutes under Alternative 2.

Eastbound Alternative 3: PM case (meter the on-ramps from I 5, I 405, and 108th Ave NE in addition to the existing meters at the Montlake and Lake Washington Blvd ramps). This alternative metered the on-ramps from I 5, I 405, and 108th Ave NE. Under this alternative (which is close to Alternative 1 in terms of improvements on mainline traffic flows), overall freeway travel time would improve over existing conditions by 30 percent; speeds would improve by 28 percent. However, total ramp delay would increase by 27 percent. The average delay per vehicle for the on-ramps would be similar to Alternative 1 — I 5 northbound on-ramps would show a delay of 12 minutes, and I 405 northbound ramps would experience a delay of 13 minutes.

Ramp Metering Alternatives: Westbound AM

On the basis of calibrated existing traffic conditions (table 7), FREQ calculated that AM traffic on westbound SR 520 operates at an average speed of 41 mph, while the traffic on the bridge moves at an average speed of 35 mph. None of the ramps would experience significant delays.

Westbound Alternative 1: AM case (meter all on-ramps on SR 520). FREQ calculated a 34 percent speed improvement (to 41 mph) over existing conditions. Travel speed on the bridge would improve 36 percent (to 35 mph). However, ramp delays would increase by 350 percent, and delays at the on-ramps from I 405 would change from no delay to a delay of 11 minutes. Delays at other on-ramps would also increase.

Westbound Alternative 2: AM case (meter on-ramps from the I 405 interchange to I 5). This alternative showed speed improvements similar to those of Westbound Alternative 1. However, this alternative would result in large delays on the on-ramps from I 405 (again, similar to Westbound Alternative 1) and increased queuing on the Montlake metered ramps.

Westbound Alternative 3: AM case (meter every on-ramp except those at the I 405 interchange). This alternative would produce speed and travel time improvements similar to those provided by Westbound AM alternative 1. The long queuing delay seen on I 405 in Alternative 2 would not occur. However, FREQ forecasted slightly longer ramp delays at other ramps; this included an average 0.7 minute delay on the 124th Ave NE on-ramp and an average two-minute delay on the Montlake on-ramp.

Westbound Alternative 4: AM case (meter on-ramps from the I 405 interchange to I 5 except at the on-ramp from I 405). This alternative would remove the queue delays on the I 405 on-ramps and would improve corridor and bridge speeds. However, the absence of ramp metering control would cause more than three times the system-wide ramp delay of the other alternatives.

Westbound Alternative 5: AM case (meter all ramps except for the on-ramps from I 405 and Montlake). This alternative was developed to reduce the queuing at the on-ramps from I 405 and Montlake Boulevard. FREQ output indicated shorter queue and ramp delays; however, corridor and bridge speeds would be nearly unchanged over existing conditions.

Ramp Metering Alternatives: Westbound PM

Under the calibrated existing conditions (table 8), FREQ calculated that evening traffic on westbound SR 520 typically operates at an average speed of 41 mph, while traffic on the bridge operates at 46 mph. None of the ramps would experience significant delays.

The same alternatives used for westbound AM traffic were applied to westbound PM traffic.

Westbound Alternative 1: PM case (meter all on-ramps on SR 520). This alternative provided a travel speed improvement of more than 27 percent over existing conditions and a 3 percent speed improvement for the bridge. FREQ calculated that freeway travel time would also improve by 35 percent over current conditions. However, these improvements would be offset by a worsening of overall ramp delays by a factor of nine. In addition, delays at the on-ramps from I 405 and 124th Ave NE would change from no delay to an average delay of more than ten minutes.

Westbound Alternative 2: PM case (meter on-ramps from the I 405 interchange to I 5). This alternative showed lower corridor speeds and improved bridge speeds. This alternative would cause 12-minute delays at the on-ramps from I 405.

Westbound Alternative 3: PM case (meter every on-ramp except those at the I 405 interchange). This alternative performed similarly to Westbound PM Alternative 1 in terms of speeds and freeway travel time improvements. Under this alternative, the long queuing delay on I 405 that would occur in Alternatives 1 and 2 would not take place. However, this alternative would cause a slightly longer delay at the other ramps.

Westbound Alternative 4: PM case (meter on-ramps from the I 405 interchange to I 5 except at the on-ramp from I 405). This alternative was similar to Westbound PM alternative 2. FREQ output indicated that this alternative would remove delays on the on-ramps from I 405, but that it would not significantly improve travel speed for the corridor.

Westbound Alternative 5: PM case (meter all ramps except for the on-ramps from I 405 and Montlake). The last alternative was developed to reduce the queuing at the on-ramps from I 405 and Montlake Blvd. FREQ showed that while this alternative would improve the queues and ramp delays on I 405, it would cause longer delays in other areas. In addition, the average traffic speed over the bridge would be nearly unchanged over existing conditions.

Ramp Metering Summary

Tables 9 and 10 summarize each ramp metering alternative in terms of its effect on the number of minutes a driver would need to 1) travel the entire study corridor; and 2) cross the bridge itself. Travel times for both the bridge and the corridor are provided because the bridge is much shorter than the entire corridor, and a modest travel time improvement on the bridge may be more significant than a larger improvement for the corridor.

For eastbound traffic (table 9), none of the three ramp metering alternatives explored would notably improve travel times across the bridge. However, each alternative would improve travel time for the entire corridor, especially during the PM peak. Based on the travel times, the most effective alternative would involve metering ramps from I 5 to I 405.

In the westbound direction (table 10) during the AM peak, Alternatives 1 through 4 would improve travel times for both the corridor as a whole and for the bridge. Alternative 5 would result in a more modest travel time improvement for the corridor and for the bridge. During the PM peak, each ramp metering alternative would improve travel times on the corridor as a whole, but not on the bridge. The travel time improvement for the corridor as whole would be greatest with Alternatives 1, 3, and 5.

In both directions of travel on SR 520, FREQ predicts that ramp metering would create long delays at most metered ramps. The worst delays would be at the ramps with the highest volumes. This prediction has serious repercussions because the ramps with the highest volumes are the feeders from I 5 and I 405. FREQ predicts that average delays at these on-ramps could reach 12 minutes per vehicle. Thus, any travel time benefit gained on the mainline would be lost if vehicles were forced to wait at the ramps.

Because the goal of this study is to improve travel conditions for HOVs, the second step of the analysis examined HOV bypass lanes on the metered ramps. It was anticipated that HOV bypass lanes would allow HOVs to benefit from the improved corridor and bridge travel times while avoiding the queues created by the ramp meters.

HOV Bypass Lanes

It was hypothesized that the addition of HOV bypass lanes would improve travel times for HOVs, without changing conditions for SOVs and mainline traffic. To test this hypothesis, HOV bypass lanes were added to one of the FREQ alternatives developed in the initial ramp metering exploration. The alternative selected for analysis was Eastbound Alternative 1: PM case (with all ramps metered).

This alternative was selected for the HOV bypass addition because it represents travel in the peak direction, and because it experiences more congestion than other alternatives. Given these factors, it seemed likely that an HOV bypass lane in conjunction with this alternative would have the greatest effect. An additional factor in selecting an eastbound alternative was that this direction does not currently have any mainline HOV lanes to confound the analysis (unlike westbound SR 520, which has a 1.6-mile HOV lane).

Bypass lanes and meters were simulated on all on-ramps on the corridor, with the exception of the on-ramp from southbound I 5. The on-ramp from southbound I 5 combines an elevated and tunnel structure; adding a bypass lane was considered a build option, and as such, beyond the scope of this study.

With the expanded network as a starting point, FREQ was rerun in order to test the following hypotheses:

- that the addition of HOV bypass lanes would make ramp delays for HOVs negligible;
- that shifting HOVs to a separate lane would not significantly reduce the wait time for SOVs; and
- that allowing HOVs direct access to the mainline would not affect overall mainline travel conditions.

Table 9. Eastbound Modeled Mainline Travel Times (in minutes)

AM

Scenario	**Overall Corridor**	**Bridge Only**
Existing conditions	14.6	2.9
Alternative 1: AM case	13.9	2.9
Alternative 2: AM case	13.5	2.8
Alternative 3: AM case	13.9	2.9

PM

Scenario	**Overall Corridor**	**Bridge Only**
Existing conditions	17.6	2.9
Alternative 1: PM case	14.0	2.9
Alternative 2: PM case	13.7	2.8
Alternative 3: PM case	14.8	2.9

Table 10. Westbound Modeled Mainline Travel Times (in minutes)

AM

Scenario	**Overall Corridor**	**Bridge Only**
Existing conditions	18.5	5.1
Alternative 1: AM case	14.4	3.1
Alternative 2: AM case	14.5	3.1
Alternative 3: AM case	14.5	3.2
Alternative 4: AM case	14.6	3.2
Alternative 5: AM case	17.1	4.3

PM

Scenario	**Overall Corridor**	**Bridge Only**
Existing conditions	18.6	3.2
Alternative 1: PM case	13.4	3.1
Alternative 2: PM case	17.8	3.1
Alternative 3: PM case	13.6	3.2
Alternative 4: PM case	18.0	3.2
Alternative 5: PM case	13.6	3.2

HOV Bypass Summary

Table 11 shows the FREQ output for the expanded alternative. As expected, a bypass lane would give HOVs a clear time advantage over SOVs at the ramps. FREQ output indicated that the bypass ramps would free HOVs from delays and queues. The table also shows that adding HOV bypass lanes would not change average ramp delays for SOVs, or alter *mainline* travel times (for all vehicles).

To illustrate the HOV travel time advantage created by the addition of an HOV bypass ramp, consider the following example. *Without* an HOV bypass lane, but with meters on all ramps, an HOV trip from I 5 to I 405 along 520 would take an average of 13.6 minutes (the same amount of time it would take an SOV). With meters on all ramps, but *with* an HOV bypass lane, the same trip would take an HOV only 7.8 minutes, while the SOV trip would still take 13.6 minutes.

Table 11. Eastbound PM

	Simulation of Existing Conditions	**All Ramps Metered**		**All Ramps Metered with HOV bypass**	
	SOV/HOV	SOV	HOV	SOV	HOV
Travel Time (minutes)					
Bridge	2	2	2	2	2
Entire Mainline	18	14	14	14	14
Average Mainline Speed (mph)					
Bridge	46	48	48	48	48
Entire Mainline	42	55	55	54	54
Ramp Delay (minutes)					
I-5 NB	not metered	6	6	6	0
I-5 SB	not metered	6	6	6	6*
Montlake	9 (metered)	0	0	0	0
108th	4	6	6	5	0
I-405	12	13	13	13	0

* This ramp does not have an HOV bypass lane

VI. Conclusions

Congestion on the SR 520 mainline is caused by 1) incidents; and 2) a combination of roadway geometrics and peak-hour volumes. In the absence of incidents, peak-period traffic on most sections of SR 520 typically flows at speeds close to posted limits. Traffic is usually free flowing on the eastern half of the study corridor (between Redmond and I 405). On the floating bridge, during both the morning and afternoon, traffic is usually not stop-and-go in either direction as long as there are no incidents; under those conditions, the bridge operates at speeds close to posted limits. In this study, incident-related congestion on SR 520 was not modeled because the location, duration, and severity of incidents are unpredictable. The model was calibrated with non-incident traffic patterns; therefore, the simulated results reflect only incident-free conditions.

The mainline areas characterized by predictable daily congestion that have the most potential for improvement using the ramp metering techniques studied in this project include the following:

- eastbound traffic, during both AM and PM peaks, from I 5 to the Montlake Blvd or Lake Washington Blvd on-ramps,
- westbound AM traffic on the approach to the Evergreen Point Floating Bridge (roughly 84th Ave NE to the eastern high-rise), and
- westbound PM traffic from the bridge to I 5.

Metering vehicles onto SR 520 could eliminate or reduce non-incident-related congestion on the corridor and could improve travel across the floating bridge. However, these improvements would come at the cost of longer delays at the on-ramps that feed SR 520. Such on-ramp delays would degrade travel times for both HOVs and SOVs.

For *eastbound traffic*, ramp metering would improve the traffic flow across the bridge and on the corridor as a whole. Because of the high traffic volumes moving from I 5 to SR 520, any effective traffic flow improvement on SR 520 would require metering the I 5 on-ramps. This would cause long queues on the I 5 ramps. Overall, eastbound traffic is worse during the PM peak than during the AM peak. Thus, ramp metering would be more effective in the afternoon than in the morning.

For *westbound traffic*, ramp metering would improve traffic flows on much of the SR 520 corridor and on the bridge. Several of the alternatives metered traffic from I 405, but this would greatly increase vehicle queues on the I 405 ramps. The alternatives that did not meter the I 405 ramps resulted in long queues on other on-ramps. In the westbound direction, traffic volumes are about the same during both peaks. However, because morning traffic patterns fluctuate significantly throughout the peak period, metering would be more effective for AM traffic, because it would have a greater potential to even out the peaks and valleys of flow, and to produce an overall speed improvement.

Ramp metering at the areas of SR 520 with predictable daily congestion would improve mainline travel times for both HOVs and SOVs. However, this improvement would come at a cost: lengthy delays at the metered on-ramps for all vehicles. HOVs could escape such delays with bypass lanes; but again, at a cost; in this case extremely long, perhaps unacceptable delays for SOVs at major on-ramps. Because the major on-ramps to SR 520 are the feeders from the region's major north-south freeways, I5 and I 405, the negative spillover effects would be quite serious.

Further Research

Findings from this project suggest additional research in several areas.

Incident Simulation. Given that incidents have a notable influence on SR 520 traffic, it may be useful to model their effects. Incident simulation may indicate whether a ramp metering system or other alternative would mitigate incident-related congestion.

FREQ expansion to include regional freeways. Another area for further research is expansion of the current FREQ model to account for the freeways that are linked to SR 520. At this point, the model does not explicitly model I 5 or I 405; nor does it consider trip diversion to alternative routes to avoid lengthy queues. It would make sense to account for I 405 and I 5, perhaps including the weaving traffic coming from the Mercer Street on-ramp. It would also be useful to expand FREQ to account for trip diversion to alternative east-west routes. FREQ data could be combined with regional model traffic volumes to address these issues.

Further model adjustment. Refining the existing SR 520 FREQ network may provide additional insight into improving the corridor's traffic flows. For example, further adjustment of metering rates at various on-ramps (in order to spread ramp delays and queuing more equitably throughout the system) may improve flows.

Puget Sound-based field parameters. Many of FREQ's input parameters were developed in California. It may be possible to create a more accurate model by calculating model input parameters based on field data specific to driver and traffic characteristics of the Puget Sound area.

Toll facilities. Tolls plazas are another no-build option not explored in this phase of the project. Using FREQ to model toll gates with HOV bypasses might indicate whether a toll system would be an effective SR 520 alternative.

Future simulations. Model runs based on planned, but not yet constructed, roadway configurations and traffic volume forecasts could be completed. Such runs might take into account, for example, the HOV lanes planned from Redmond to I 405 on SR 520 or the new SR 520/I 405 interchange.

References

Blain, Larry, Puget Sound Regional Council, telephone conversation with author (22 September 1993).

Garrison, Dan H., Fred Mannering, and Brad Sebranke, "Generation and Assessment of Incident Management Strategies, Volume III: Seattle—Area Incident Impact Analysis: Microcomputer Traffic Simulation Results," Washington State Transportation Commission, January, 1990.

Federal Highway Administration (FHWA), *TRAF User Guide*, Washington D.C., March 1988.

Jacobson, Eldon, Mark E. Hallenbeck, Toby Rickman, Jau-ben Chang, G. Scott Rutherford, and others, *Evaluation of the TRAF Family of Models: Testing of the CORFLO and FRESIM Models*, Washington State Transportation Center, August 1992.

May, Adolf, Institute of Transportation Studies, University of California at Berkeley, Telephone conversation with author (November 1992).

May, Adolf, Leonard Newman, Vincent Wong, *An Educational Program for Freeway Operations Analysis*, Institute of Transportation Studies, University of California, Berkeley, January, 1990.

May, Adolf, *Freeway Simulation Models Revisited*, Transportation Research Record 1132, National Research Council, Washington D.C. 1987.

Scapinakis, Dimitris A., Lannon Leiman, Mourad Bouaouina, and Adolf May, *Demand Estimation, Benefit Assessment, and Evaluation of On-Freeway High Occupancy*, Institute of Transportation Studies, University of California Berkeley, August 1990.

Schrank, David L., Shawn M. Turner, and Timothy Lomax, *Estimates of Urban Roadway Congestion-1990*, .Research Report 1131-5, Texas Transportation Institute.

Washington State Department of Transportation, *Ramp and Roadway Traffic Volumes*, Summary Report 1992a, Traffic Operations, District #1.

Washington State Department of Transportation, *Evaluation of the Feasibility of Metering Eastbound SR 520 during the Morning Commute*, District #1, Bellevue, Washington, 3, April 1992b.

Transportation Research Board, *Highway Capacity Manual, Special Report 209* National Research Council, Washington D.C. 1985.

About the Innovations Unit

The Innovations Unit is an advisory group to the Washington State Transportation Commission that conducts technology and policy research on emerging transportation developments and opportunities in Washington State. The goals of the Innovations Unit are to

- provide long-range program development support to the Transportation Commission,
- generate unfiltered visions of a wide range of future short-term and long-term transportation technology and policy options, and
- establish a research methodology that fosters development of innovative transportation concepts.

The Innovations Unit has three objectives representing successively more detailed and focused studies:

Objective 1. ***Monitor emerging technologies and strategies.*** Compile and synthesize up-to-date information about emerging and innovative transportation technologies, strategies, and policies.

Objective 2. ***Research selected topics of Commission interest.*** Conduct detailed background research of specific technology and policy issues, under the direction of the Commission's Policy Development Subcommittee. Produce a series of white papers outlining technology and policy implications germane to the Washington State transportation system.

Objective 3. ***Support in-depth technology and policy research.*** Conduct and/or coordinate detailed research of key enabling technologies, strategies, and policies.

The research activities of the Innovations Unit emphasize early, preparatory studies of emerging potential transportation solutions, and include interaction with elected officials, public agencies, university researchers, the private sector, and members of the public. Its activities are intended to complement and support in-depth applied research and implementation by the Washington State Department of Transportation (WSDOT), and reinforce ongoing State Transportation Policy Plan activities.