NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP Report 369

Use of Shoulders and Narrow Lanes to Increase Freeway Capacity

Transportation Research Board
National Research Council

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Use of Shoulders and Narrow Lanes to Increase Freeway Capacity

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Subject Areas

Highway and Facility Design
Highway Operations, Capacity, and Traffic Control

Research Sponsored by the American Association of State Highway and Transportation Officials in Cooperation with the Federal Highway Administration

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Transportation Research Board of the National Research Council was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state and local governmental agencies, universities, and industry; its relationship to the National Research Council is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway and transportation departments and by committees of AASHTO. Each year, specific areas of research needs to be included in the program are proposed to the National Research Council and the Board by the American Association of State Highway and Transportation Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are the responsibilities of the National Research Council and the Transportation Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

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FOREWORD

By Staff
Transportation Research Board

This report will be of interest and use to the design and operations staffs of state departments of transportation and others responsible for urban freeways. Reducing lane widths and reducing or eliminating shoulders are ways to inexpensively add a freeway lane. The objective of the research was to quantify the safety and operational effects of this type of design.

The American Association of State Highway and Transportation Official's (AASHTO) *Policy on Geometric Design for Highways and Streets*, 1990 Edition (commonly referred to as the AASHTO Green Book), recommends widths for freeway lanes and shoulders. It does not, however, discuss minimum widths for freeway lanes or shoulders or help the designer determine when a narrower width would suffice.

The 1985 Edition of the *Highway Capacity Manual* (*HCM*) (TRB *Special Report 209*) includes factors for analyzing freeway lanes from 9 to 12 ft wide. There are also factors for obstructions less than 6 ft from the edge of the lane. These factors, however, were taken directly from the 1965 Edition because no more recent research had been done.

Tight budgets and right-of-way constraints limit the ability of state departments of transportation to add capacity to urban freeways. Although some states have used lane and shoulder widths narrower than recommended by the AASHTO Green Book to add another freeway lane to reduce congestion, most have refrained because of the lack of information on the safety and operational effects of these designs. Inadequate information and guidance are of particular concern when considering the agency's liability.

This report begins to quantify the effect of narrow lanes and shoulders on the safety and operation of a freeway. It includes an evaluation methodology and design guidelines to help freeway designers evaluate alternatives that minimize or eliminate the need to widen the roadway. It also includes sufficient background information so that designers can have confidence in the methodology and guidelines.

The limited data collected on this project preclude recommending changes to the AASHTO Green Book or the *HCM*. Future research should build on this effort to further quantify the effects of narrow lanes and shoulders.

CONTENTS

ACKNOWLEDGMENTS

The work reported herein was performed under NCHRP Project 3-43 by JHK & Associates. The work was performed in the Transportation Consulting Division, directed by Mr. Morris J. Rothenberg.

Mr. James E. Curren, Senior Associate, was the principal investigator for Project 3-43 and the author of this report. Dr. Robert Dewar of the University of Calgary, Dr. Robert Kuehl of the University of Arizona, and Mr. Sheldon Pivnik of the Dade County Public Works Department served as consultants. Other staff members at JHK & Associates who contributed to the research include Dr. Adolf May, Mr. Eric Metheny, Mr. Stephen Read, Mr. William Reilly, and Mr. David Witheford.

The staffs of California, Georgia, Massachusetts, Minnesota, Virginia, and Washington state highway agencies made substantial contributions by providing operational, physical, and safety data for analysis by the research team. They also assisted in site selection and ensured that the necessary permits for data collection efforts were obtained. The authors are also grateful to traffic engineers in other state and local agencies throughout the United States who responded to questionnaires relating to the research.

USE OF SHOULDERS AND NARROW LANES TO INCREASE FREEWAY CAPACITY

SUMMARY

The objectives of this research were to formulate a methodology to evaluate potential applications of strategies to increase the capacity of urban freeways by using shoulders with or without narrow lanes and to develop recommendations and design guidelines for the implementation of projects involving these strategies. The factors that influence the effectiveness include traffic volume, vehicle mix, capacity, horizontal and vertical alignment, length of application, ability to provide emergency turnouts, and incident response considerations. This research addressed urban freeways with full access control and posted speeds of 55 mph or more.

The research focused on the operational and safety performance of various applications of these strategies in 11 corridors throughout the country. Forty-two altered sites and 10 unaltered sites were evaluated. Analysis of accident data for five corridors and operational data for all corridors was performed. Accident rates for unaltered and altered corridor segments were developed as well as accident rates for specific sites. Operational data were used to assess impacts on the speed-flow relationships and capacity resulting from the use of these strategies.

These strategies have been used to incorporate high-occupancy vehicle lanes and smooth traffic flow by addressing specific problems or bottleneck locations as well as construction zones. Sites studied in this research include applications involving either the left or right shoulder and in some cases both, with and without narrow lanes, under a wide range of geometric and operational conditions.

Traffic volumes in excess of 2000 passenger cars per hour per lane (pcphpl) were observed at both altered and unaltered sites. All sites exhibit "flat" speed-flow relationships, typically in the 55- to 65-mph range across the entire range of observed volumes with the exception being level of service (LOS) F conditions. Altered sites exhibited slightly lower speeds for a given volume range and a slightly greater tendency to fall into LOS F conditions. Accident rates for altered sites tend to be somewhat higher than unaltered sites. However, if strategies are carefully applied in concert with lane balance and lane continuity concepts, rates for altered sections may be lower than for unaltered. Truck accident rates are almost always higher on altered sections, compared with unaltered.

This research confirmed that shoulders and narrow lanes can be used effectively to

increase capacity in congested urban corridors. However, findings indicate that in many instances there may be measurable negative impacts to the overall safety performance of the corridor. These strategies should be considered for areas of limited length and having turbulent flow conditions as one alternative for achieving smoother flow. Such use should be typically limited to sections of 1 mi or less. The report includes a recommended process for evaluating proposed projects and guidelines for implementation of projects.

CHAPTER 1

INTRODUCTION AND RESEARCH APPROACH

PROBLEM STATEMENT

Congestion on urban freeways has reached staggering proportions in many metropolitan areas throughout the United States. The Federal Highway Administration (FHWA) estimates that in 1991, 70 percent of urban interstate freeway vehicle miles of travel (VMT) driven during the peak hour were under congested conditions (Figure 1). For several metropolitan areas, Table 1 lists the percent of peak-period VMT on all roadways driven under congested conditions as estimated by a recent published study (*1*). In 1990 an estimated one billion vehicle hours of delay resulted from recurring congestion on urban freeways. The cost of this congestion is enormous. The total estimated cost of congestion in the urban areas studied by TTI (*2*) was $43.2 billion in 1990. The assumptions used for the TTI analysis were average vehicle occupancy of 1.25 persons per vehicle, 250 working days per year, average cost of time $10.00 per hour, and a vehicle mix of 95 percent passenger and 5 percent commercial vehicles.

At the same time, it has become increasingly difficult to expand facilities to meet the demand. Funding is limited with most public agencies facing deficits. Acquiring right-of-way for facilities in urban areas is increasingly difficult and physical constraints often increase the cost of construction substantially. One means of gaining additional capacity on urban freeways is by the use of shoulders, or a portion of shoulders, to increase the number of travel lanes. Projects implemented to date involve a wide variety of strategies. In some cases only one shoulder has been used, in other cases both shoulders have been used, in still others the lane width has been reduced as well. Some applications have been applied selectively for short distances to address a particular problem with lane balance or to meet a particularly high demand. In other cases a facility, in essence, has been widened with a lane being added for several miles. In some cases the use of the shoulder has been permitted during peak periods only.

The use of shoulders as a travel lane with or without narrower lanes to increase capacity has occurred since the late 1960s. While extensive use has been limited to four states (California, Texas, Virginia, and Washington), more than two dozen states have implemented projects involving the use of shoulders and/or narrow lanes. In addition to projects constructed specifically to increase capacity, there are numerous locations on the freeway system such as viaducts and bridges where shoulders have never been provided. Extensive use of shoulders, often combined with narrow lanes, is occurring in several metropolitan areas in order to provide HOV facilities. The FHWA (*3*) estimates that 3,830

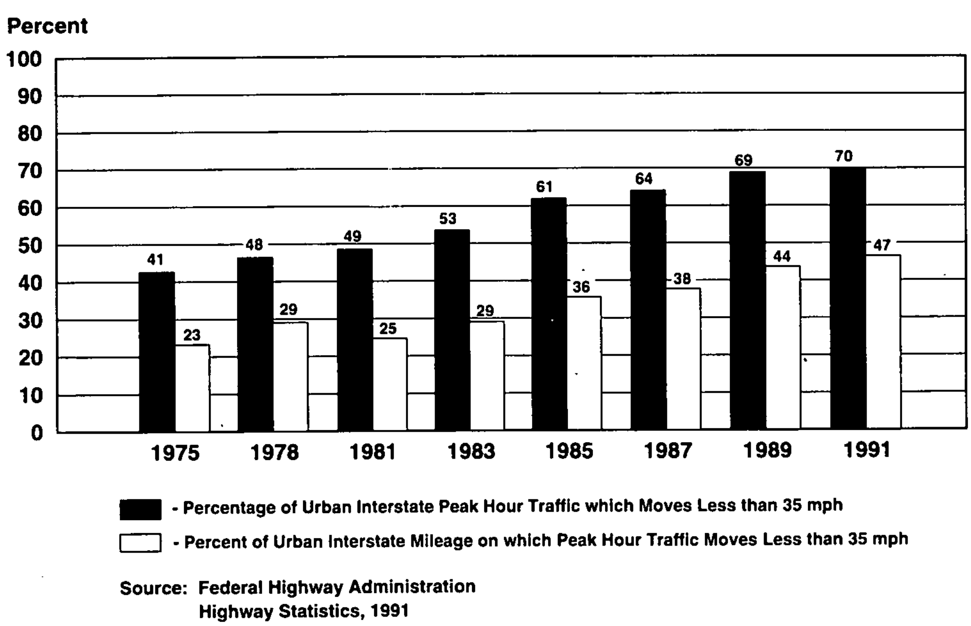


Figure 1. Urban interstate congestion.

TABLE 1. Percent of peak-period VMT driven under congested conditions

Metropolitan Area	%
San Francisco	80
Los Angeles	75
Seattle	70
Houston	70
Washington, D.C.	65
Miami	60
Chicago	55
New York	55
Austin and Dallas	55

mi of urban freeway have cross sections that would permit projects of this type.

In spite of increasing usage, the tradeoffs among facility design, traffic performance, safety, enforcement, and maintenance impacts are not generally well understood. Most studies have found that there are significant increases in throughput and in most cases a decrease in the accident rate. However, many concerns remain, particularly in terms of safety. Most studies completed have focused on specific applications on relatively short segments of freeway. These studies have often concluded, on the basis of an analysis of before and after conditions at the site, that increased throughput combined with a decreased accident rate had been achieved, and the project had been successful. Concerns with site-specific before and after studies have been that they were biased by the fact that the project in most cases addressed a problem area. In doing so, the project may have simply resulted in transferring the problem area downstream a short distance and to a location not observed in the study. Reservations were also expressed that while the immediate result may be an improvement in safety, the longer term effect as growth in traffic created a return to congestion, would be negative, particularly if implemented on a continuous or frequent basis within a corridor.

RESEARCH OBJECTIVES AND SCOPE

The primary objectives of this research project have been to

- Formulate a methodology to evaluate potential applications of strategies to increase freeway capacity by using shoulders as travel lanes with or without narrow lanes and
- Develop recommendations and design guidelines for the implementation of projects involving such strategies.

NCHRP Project 3-43 was undertaken in two phases: Phase I comprised a literature search, a survey of experience, and the development of a research plan for Phase II.

The research plan was implemented in Phase II. It involved the collection and analysis of extensive operational data and the analysis of accident data obtained from the state agencies. The research focused on the differences in the operating and safety performance of altered freeway segments versus unaltered freeway segments. "Unaltered segment" refers to a freeway segment built to standard. "Altered segment" refers to any segment that has an added lane through the use of shoulders or narrower lanes. Considerable emphasis was placed on the collection of field data, because much of the data used to develop current guidelines date from the 1960s or earlier.

RESEARCH APPROACH

The approach to this research included seven elements: 1) examination of current practice to identify concerns, existing guidelines, and evaluation methodologies; 2) performance of a pilot data collection effort; 3) development of a research framework for field and accident studies; 4) selection of sites and data collection to develop initial hypotheses with respect to operational and safety performance; 5) testing and expansion of initial hypotheses; 6) development of an evaluation methodology; and 7) preparation of design guidelines. To accomplish these goals, a set of detailed tasks was defined and followed. Figure 2 presents a flowchart of the tasks completed as part of this research. Each task is described briefly as follows.

To gain a thorough understanding of the current use and application of these strategies, pertinent literature and ongoing research were reviewed, and the experience of state and federal agencies surveyed. Detailed follow-up surveys and interviews with selected states and agencies were conducted as part of this task. In a parallel effort, a pilot study was conducted to test the field procedures for the collection of operational data. The data and information gained in this task were used to develop a research framework for field and accident studies. The research framework identified the critical variables for study in this research effort.

Site selection was conducted in a two-step process. First, a

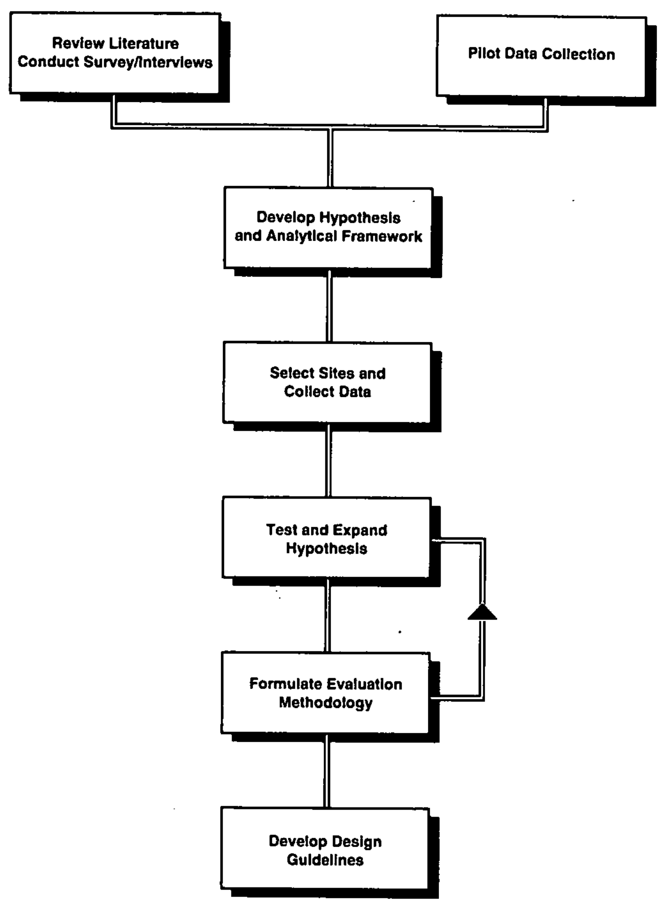


Figure 2. Approach to analysis.

list of potential corridors and sites was developed on the basis of criteria that included geographical location, application type, commuter type, cross section, alignment features, and the ability to collect data. Final selection focused on covering a representative range of each of the values of critical site variables identified in the research framework. Eleven corridors in five states were selected for analysis. Data were collected at 52 sites throughout the 11 corridors. Computerized accident databases in a format that would permit analysis were available for five of the corridors. These databases were reviewed and screened to determine the extent of analysis that could be undertaken. The operational data collected in the field and the accident databases obtained from the states were used to test and expand hypotheses regarding operational and safety performance. Finally, the data and analysis results were used in conjunction with information from the literature review, surveys, and interviews to develop guidelines for evaluation and implementation of proposed projects.

ORGANIZATION OF THE REPORT

The remainder of this report is organized in four chapters. Chapter 2 presents a description of the corridors and sites studied as part of this research. Chapter 3 summarizes the findings of the study including the results of the literature review, surveys, and research plan. Chapter 4 discusses the interpretation, appraisal, and application of the research findings. Chapter 4 also includes the recommended process for evaluating proposed projects and guidelines for implementation of projects. Chapter 5 summarizes the conclusions of the study and presents recommendations for future research to assist highway agencies in programming such research.

CHAPTER 2

STUDY CORRIDORS AND SITES

The corridors chosen for study in NCHRP Project 3-43 were selected from a list of corridors and sites developed during Phase I of the research. The final corridors selected for field data collection and operational analyses are listed in Table 2, which summarizes key characteristics of each.

Within each corridor the freeway was divided into altered and unaltered segments to conduct accident and operational analysis. Within each segment the corridor was further subdivided into sections on the basis of operational characteristics and defined study sites for collection of operational data. Several study sites with reduced shoulder and lane width were chosen in each corridor. A "benchmark" site was chosen in all but one corridor. Benchmark sites had full shoulders and 12-ft lanes. A full description of the approach to data collection and analysis is presented in more detail in Chapter 3. This chapter presents a description of the corridors and sites evaluated as part of this research.

ROUTE 128—BOSTON, MA

The Route 128 corridor serves as a freeway bypass of the downtown Boston area and is part of the I-95 corridor. The northern portion of the corridor has been widened to four lanes in each direction with full shoulders. In the southwest section of the corridor, three full-time travel lanes are supplemented by the use of the right-hand shoulder as a fourth travel lane during the hours of 6 to 10 AM and 3 to 7 PM. At all other times of the day, travel in the shoulder lane is prohibited. The segment of the corridor studied and a typical cross section of this treatment are shown in Figure 3. In order to provide some safe areas for disabled vehicles to use during shoulder use periods, small paved turnouts are provided where possible. This treatment operates from the interchange with Route 9, to the interchange with Route 24, for a total length of 13 mi. Figure 4 illustrates typical conditions in the corridor.

For this study, data were collected from five overpass locations: Kendrick Street (in both the northbound and southbound directions), Ponkapoag Road, South Street (benchmark site), and Washington Street. The key characteristics of each site are presented in Table 3. A brief description of each site follows.

Kendrick Street—Northbound

The cross section at this site consists of three 12-ft, full-time travel lanes, a 12-ft right-hand shoulder used as a peak-hour travel lane, and a 3-ft left-hand shoulder. Immediately downstream from the overpass, in the study area, is a paved turnout intended for use for disabled vehicles by motorists who can no longer use the shoulder as a pulloff area. This study site has minimal grade and no horizontal curvature. There is no direct access to and from the freeway at this location. There is an exit ramp to Needham Street approximately 2000 ft downstream of the study area. This exit ramp was not observed to influence traffic operations.

Kendrick Street—Southbound

The cross section at this location consists of three 12-ft, full-time travel lanes, a 12-ft right-hand shoulder used as a peak-hour travel lane, and a 3-ft left-hand shoulder. This study site has minimal grade and no horizontal curvature. There is no direct access to and from the freeway at this location. There is an entrance ramp from Highland Avenue approximately 2000 ft upstream of the study area. As was the case in the northbound direction, the ramp was not observed to influence traffic operations.

Ponkapoag Road—Northbound

The geometry at this site is a cross section consisting of three 12-ft, full-time travel lanes, a 12-ft right-hand shoulder used as a peak-hour travel lane, and a 2-ft left-hand shoulder. This study site has minimal grade and no horizontal curvature. Ponkapoag Road is fully accessible to/from Route 128 by means of a diamond interchange. In the northbound direction there is an exit ramp approximately 1000 ft upstream of the study area, and an entrance ramp that merges into traffic approximately 1400 ft downstream of the study area. Queuing or slowing from the ramps was not observed in the field.

South Street—Northbound

This site has a cross section consisting of four 12-ft, full-time travel lanes, a 10-ft right-hand shoulder, and a 2-ft left-hand shoulder. This site is located to the north of the I-90 interchange and was used as a benchmark site. There is an entrance ramp from Route 30 and I-90 approximately 2500 ft upstream of the study area. When volumes were moderate through the study area, some influence from this entrance ramp on traffic operations was observed with an increased number of lane changes, from right to left, observed.

TABLE 2. Matrix of corridor conditions

Corridor	Number of Sites	Operational Data	Safety Data	Lane Width		Left Shoulder			Right Shoulder			% Trucks			Illumination		Per Lane
				11'	12'	<2'	2-8'	>8'	<2'	2-8'	>8'	<5%	5-10%	>10%	Yes	No	ADT*
Boston, Rt. 128	5	X			X			X	X					X		X	20,000
VA I-95	2	X			X X X	X X	 X		X X	 X				X X X		X X X	20,000 20,000 20,000
VA I-395	5	X	X	X X		X	 X			 X	X	X X			X X		23,000 23,000
Seattle I-5 (Urban) (Suburban)	4 5	X X	X X	X X		X X			X	 X			X X		X X		25,000 25,000
Seattle I-90	4	X	X	X			X			X			X		X		20,000
Atlanta I-85	5	X	X	X				X			X	X			X		18,000
Minneapolis I-94	4	X	X		X	X			X				X		X		20,000
Los Angeles I-10	5	X	X	X		X					X		X		X		25,000
Los Angeles I-405	5	X		X	 X X		X X	 X	 X		X X		X X X		X X X		25,000 25,000 25,000
Los Angeles SR-57	4	X		X			X				X		X		X		22,000
Los Angeles SR-91	4	X		X			X				X		X		X		20,000

* Maximum Per Lane ADT Reported in Study Area

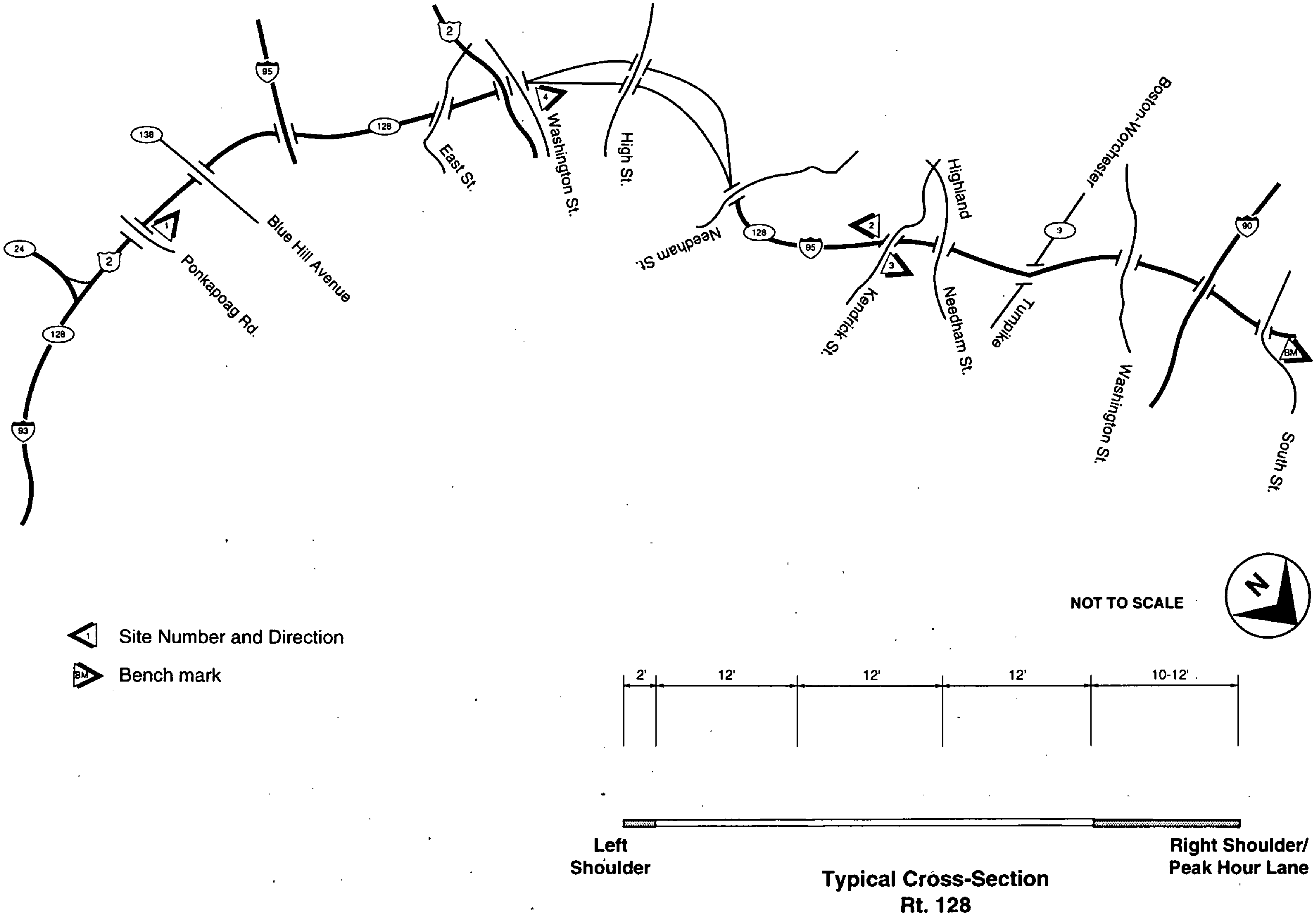


Figure 3. Route 128 corridor, Boston.

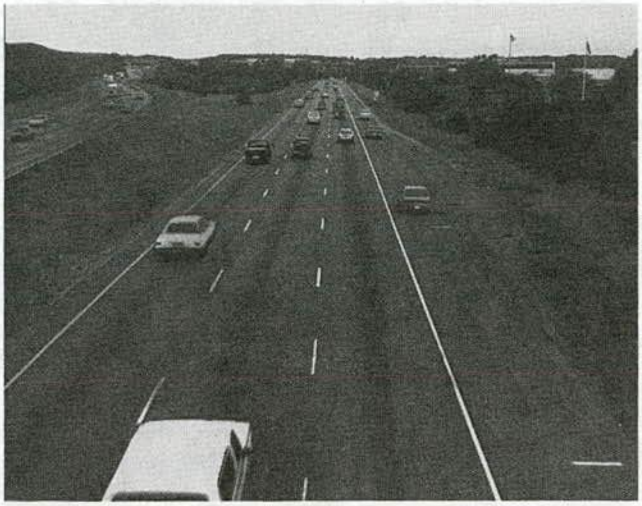


Figure 4. Route 128 at Kendrick Street.

Washington Street—Northbound

This site has a cross section consisting of three 12-ft, full-time travel lanes, a 10- to 12-ft right-hand shoulder used as a peak-hour travel lane, and a 2-ft left-hand shoulder. This study site has a 3 to 4 percent positive gradient and also displays a horizontal curve downstream from the overpass. There is no direct access to the freeway from Washington Street; however, there is full access to and from the freeway just upstream from the site at US Route 1, a full cloverleaf interchange. Because of the proximity of this interchange, several access ramps from US Route 1 are considered as having influence on this study site. There is an entrance ramp from westbound US Route 1 that merges into the freeway directly through the study area. There is also an entrance ramp from eastbound US Route 1 approximately 1000 ft upstream of the study area. The merging on-ramp traffic and the geometry of the site combined to reduce travel speed through this area.

I-95/I-395—ALEXANDRIA, VA

The I-95/I-395 corridor is one of the major freeway corridors serving the metropolitan Washington, D.C. area. The corridor runs in a north-south direction from suburban Virginia into downtown Washington, D.C. This freeway carries a three- to four-lane cross section in each direction.

The I-95 portion of the corridor is part of the principal interstate corridor serving the Eastern seaboard. As a consequence, the percentage of trucks is significantly higher than on I-395. I-95 carries four lanes of traffic in each direction through the study area. The I-95 portion of the corridor was converted from a six-lane to an eight-lane cross section to accommodate the addition of a median HOV lane in each direction. In order to accomplish this, the right shoulder was converted to be a general use traffic lane, leaving the freeway with less than 2-ft of usable shoulder in each direction on both the inside and outside shoulders. Throughout the treated area, paved pullouts were located periodically to provide areas for disabled vehicles. In addition to the revised geometrics, truck restrictions were placed on both the median HOV lane and the converted shoulder lane.

On the I-395 portion there is also a two-lane reversible HOV facility located in the median from the Capital Beltway (I-95/I-495) to the 14th Street Bridge. Interchange spacing varies from approximately a 2-mi spacing to approximately 1 mi inside the Capital Beltway. In an effort to relieve congestion and increase capacity on the I-395 portion, a fourth general use lane was added to the freeway between King Street and Glebe Road in the northbound direction and from Shirlington Road to Duke Street in the southbound direction. This was accomplished by using 11-ft lanes and capturing the shoulder for use as a travel lane by restriping the freeway. Through the treated area, the left shoulder has been reduced to less than 2 ft in width, while the right shoulder varies between 4 and 10 ft.

Sites selected for data collection on I-395 included Edsall Road HOV Flyover (benchmark site), King Street, N. Shirlington Circle, and S. Shirlington Circle (in both directions). On I-95, data were collected in both the northbound and southbound directions. The location of these sites is shown in Figures 5 and 6. Typical conditions are illustrated in Figures 7 and 8. The key characteristics of each site are presented in Table 4. The following paragraphs include a brief description of each site.

Pohick Road—Northbound

The cross section at this site is the same as the southbound section, except a 10-ft pullout with 1-ft shoulder is provided on the right side through the study area. In the AM peak period,

TABLE 3. Site conditions Rt. 128

	Lane Width		Left Shoulder			Right Shoulder			% Trucks			Application Type		Freeway Section		
Site	11′	12′	<2′	2-8′	>8′	<2′	2-8′	>8′	<5%	5-10%	>10%	HOV	Add Lane	Merge/ Div	Weave	BFS
Kendrick Street, NB		X		X		X			P	M			X			X
Kendrick Street, SB		X		X		X			P	AM			X			X
Ponkapoag, NB		X		X		X			P	A			X			X
South Street, NB		X		X				X	AP	M			BM			X
Washington Street, NB		X		X		X			WP	A			X	X		

LEGEND: A—AM Peak P—PM Peak M—Mid-Day X—All Day
W Weekend Period BM—Benchmark

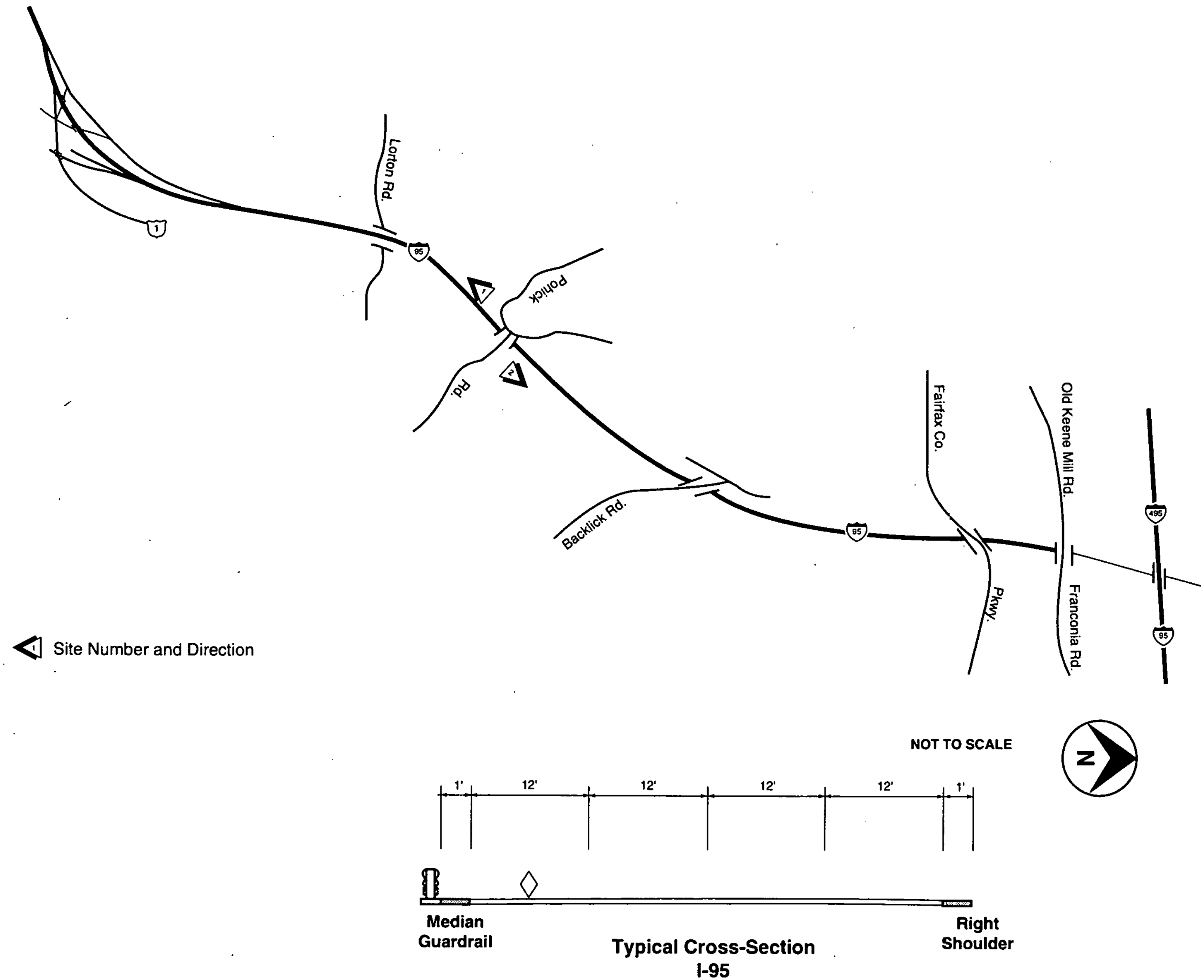


Figure 5. I-95 corridor, Virginia.

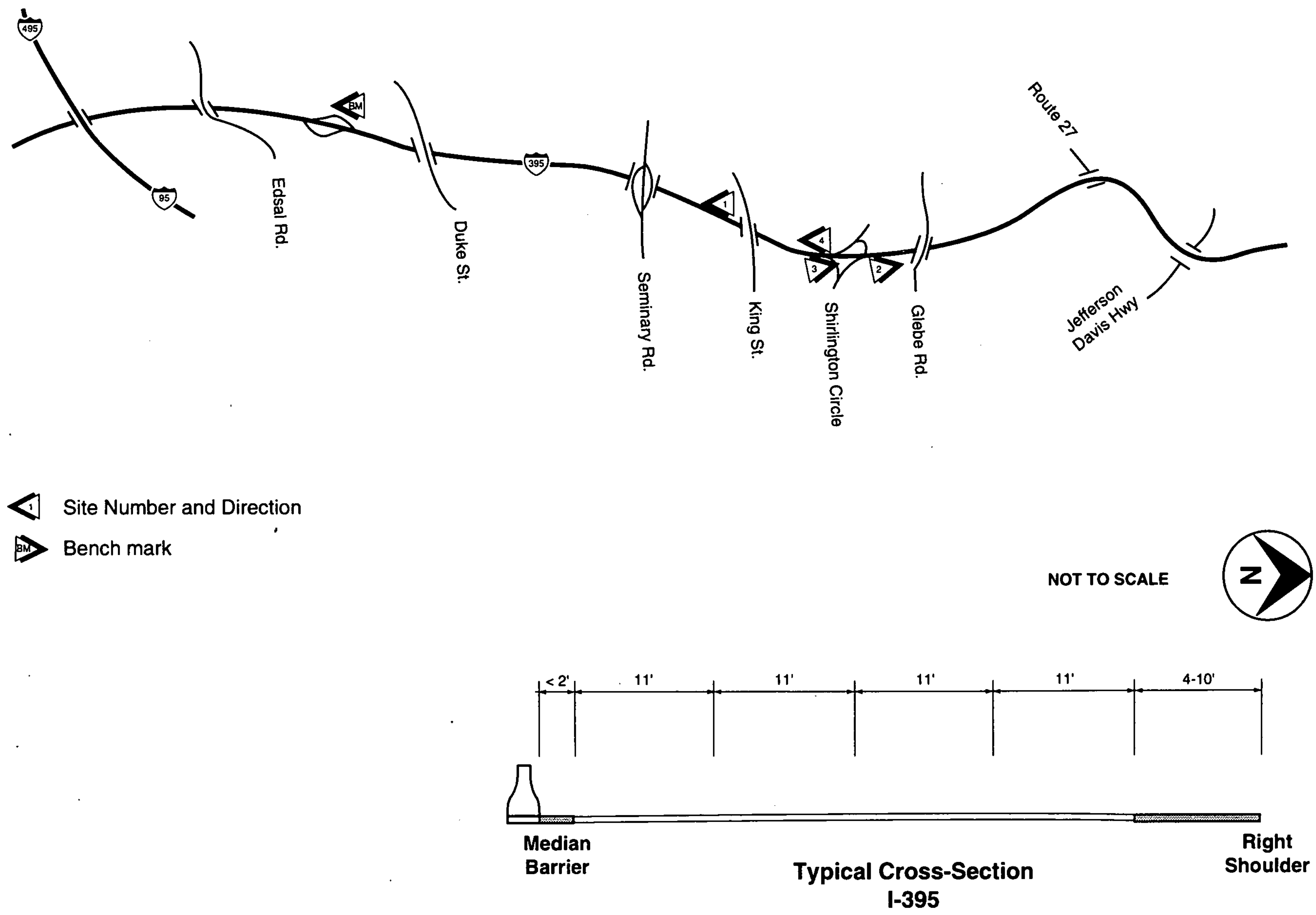


Figure 6. I-395 corridor, Virginia.

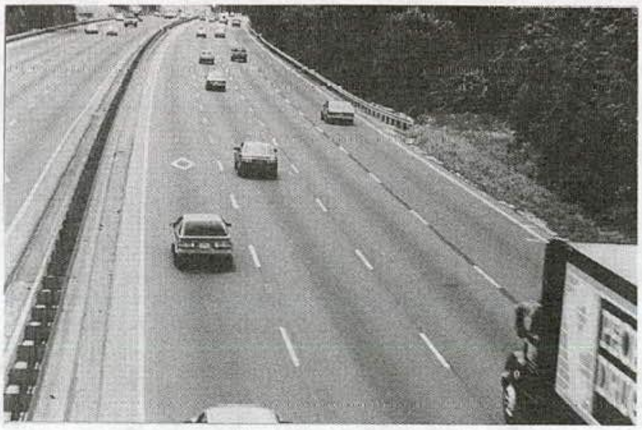


Figure 7. I-95 in Virginia at Pohick Road.

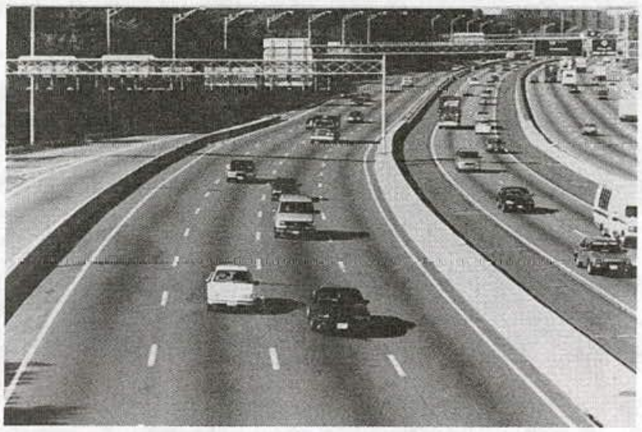


Figure 8. I-395 in Arlington at South Shirlington Circle.

stop-and-go traffic is experienced throughout this portion of the I-95 corridor.

Pohick Road—Southbound

This site consists of a four-lane section of 11-ft lanes with the left lane being an HOV 3+ lane. The left shoulder is 3 ft with an effective width of 1 to 2 ft to a pavement overlay edge. A 1-ft shoulder is provided on the right side. There are no ramps within the analysis area at this location. The HOV 3+ rule applies to the median lane for the peak period (3:30 PM to 6:00 PM). All lanes are open to all automobile traffic the remainder of the day. No trucks are permitted in the right lane.

Edsall Road—Southbound

This site has a three-lane cross section with 12-ft lanes and full-width shoulders. This site, located just north of the Edsall Road interchange, is used as a benchmark site for the corridor. There is an exit ramp approximately 4900 ft downstream of the study area and an entrance ramp that merges into traffic approximately 1480 ft upstream of the area. Neither of these ramps was observed to have an influence on the traffic flow.

King Street—Southbound

This site consists of a four-lane cross section with 11-ft lanes and 2-ft left and standard right shoulders. There is an entrance ramp approximately 1320 ft downstream of the study area and an exit ramp approximately 1160 ft upstream of the area. With ramps located before and after the study area, lane changes were observed, but no slowing or queuing could be attributed to the ramps.

North Shirlington Circle—Northbound

This site consists of a four-lane cross section with 11-ft lanes and 2-ft left and standard right shoulders. There is an exit ramp approximately 1580 ft upstream and an exit ramp approximately 950 ft downstream of the study area. These ramps appear to have a minimal influence on the site.

South Shirlington Circle—Northbound

This site has a four-lane cross section with 11-ft lanes and with 2-ft left and standard right shoulders. There is an exit ramp

TABLE 4. Site conditions I-95/I-395

	Lane Width		Left Shoulder			Right Shoulder			% Trucks			Application Type		Freeway Section		
Site	11'	12'	<2'	2-8'	>8'	<2'	2-8'	>8'	<5%	5-10%	>10%	HOV	Add Lane	Merge/ Div	Weave	BFS
Pohick Road, NB	X		X			X				AP	M	X				X
Pohick Road, SB	X		X			X				PW	AM	X				X
Edsall Road HOV, SB		X			X	X		X	P	AM			BM		X	
King Street, SB	X		X					X					X		X	
N. Shirlington Circle, NB	X		X				X						X	X		
S. Shirlington Circle, NB	X		X				X		M				X	X		
S. Shirlington Circle, SB	X		X					X					X	X		

LEGEND: A—AM Peak P—PM Peak M—Mid-Day X—All Day
W—Weekend Period BM—Benchmark

approximately 840 ft upstream of the study area and an entrance ramp approximately 1690 ft downstream of the area.

South Shirlington Circle—Southbound

This site consists of a four-lane cross section with 11-ft lanes and with 2-ft left and standard right shoulders. There is an entrance ramp approximately 740 ft downstream of the study area. The study area is not in the influence area of any exit ramps. The entrance ramp carries a heavy volume of traffic during peak hours; however, the queuing and congestion in the corridor is not directly influenced by the ramp.

I-5 SUBURBAN—SEATTLE, WA

The I-5 corridor is a major interstate corridor serving the Pacific Coast states in a north-south direction. The section of freeway using treatment strategies analyzed here covers an area from downtown Seattle, extending south into the suburban Seattle area. The treatment strategies are discontinuous and vary in their usage and operating characteristics. Therefore, the I-5 corridor has been divided into two individual analysis sections: Urban and Suburban.

The Suburban section is located in the area of Tukwila and covers approximately 7 mi in both directions. To install a median HOV lane, the existing cross section was restriped from four 12-ft lanes to four 11-ft general use lanes plus one 11-ft HOV lane. The additional width required was taken from the left shoulder, thus leaving a substandard shoulder. Throughout the treated area, a full right shoulder is maintained. Figure 9 illustrates corridor alignment.

The sites selected for this study included 178th Street (in both directions, with the northbound direction being utilized as a benchmark site), 216th Street (in both directions), and Military Road southbound. The key characteristics of each site are presented in Table 5. A brief description of each site follows.

178th Street—Northbound

This site is a benchmark location with four 12-ft travel lanes and full-width shoulders on both sides. The section is at a slight downgrade at this location, with no horizontal curvature.

178th Street—Southbound

With a cross section similar to that at Military Road, there are five 11-ft lanes including the median HOV lane. The site has a 2-ft left shoulder clearance to a guardrail and a full right shoulder. This location is not an access point to the freeway; therefore, there are no ramp influences in the area. There is a slight upgrade through this area. Traffic queues into the site from downstream constraints for brief periods during the afternoon peak period.

216th Street—Northbound

This study site is similar to the southbound direction with a five-lane cross section of 11-ft lanes, including a median HOV lane. The left shoulder is 3 ft wide and the right shoulder is a full-width shoulder. The left shoulder has an additional 3 ft of clearance to a median guardrail.

216th Street—Southbound

This site comprises a five-lane cross section of 11-ft lanes, with the leftmost being an HOV lane. The left shoulder is 3 ft wide and the right shoulder is a full-width shoulder. Both shoulders exhibit additional clearance to a slope. This is a tangent section with no gradient. As with 178th Street, this location is not an access point to the freeway and, as such, does not experience any influence from ramps.

Military Road—Southbound

The site has a five-lane cross section with four general use lanes and one HOV lane as the leftmost lane. All five lanes measure 11 ft in width. There is a 3-ft left shoulder and a full right shoulder. There is a slight upgrade through the section, which combines with a horizontal curve about 500 ft downstream of the area. There is an entrance ramp from Military Road that loops on through the study area, affecting traffic to some degree.

I-5 URBAN—SEATTLE, WA

This urban section of the freeway changes character frequently through downtown Seattle. A portion of the corridor is undergoing construction and has used narrow lanes and shoulders to accommodate traffic; other areas appear to use the strategy on a more permanent basis. Still other sections of the corridor carry an HOV lane, with various strategies used for its operation. As such, a general corridor description would not be appropriate, and each site will be detailed individually. The corridor serves a highly urbanized area, and therefore experiences frequent influence from closely spaced interchanges. Figure 10 shows the alignment of the corridor.

A total of four study locations were observed in this corridor: one benchmark site (Albro Place) and three altered sites (Denny Way, Holgate Street, and Yesler Way). The key characteristics of each site are presented in Table 6. A brief description of each site follows.

Albro Place—Southbound

This site is a benchmark location with four 12-ft general use travel lanes and full-width shoulders on both the right and left sides. The ramps to and from Albro Place use a service road thus removing the turbulence from the study area.

Denny Way—Southbound

This site comprises a cross section of four general use lanes plus a median HOV lane. The lanes are each approximately 11 ft wide, with less than a 2-ft left shoulder and a full right shoul-

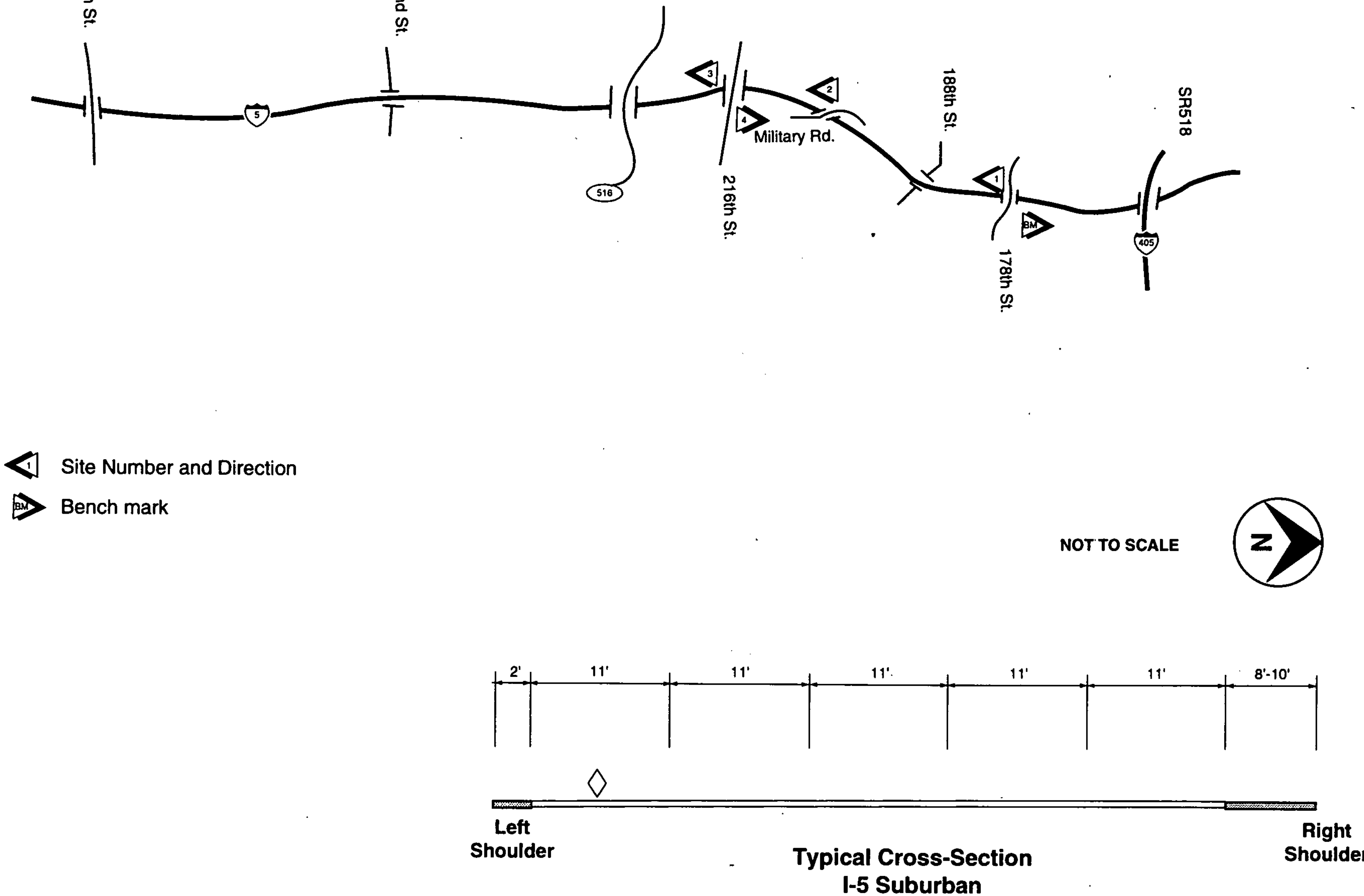


Figure 9. I-5 corridor, suburban Seattle.

TABLE 5. Site conditions I-5 (suburban)

Site	Lane Width		Left Shoulder			Right Shoulder			% Trucks			Application Type		Freeway Section		
	11'	12'	<2'	2-8'	>8'	<2'	2-8'	>8'	<5%	5-10%	>10%	HOV	Add Lane	Merge/ Div	Weave	BFS
178th Street, NB		X			X	X		X		AMP			BM			X
178th Street, SB	X		X					X			A	X				X
216th Street, NB	X			X				X		AM		X				X
216th Street, SB	X			X				X		AM		X				X
Military Road, SB	X			X				X	P	M		X		X		

LEGEND: A—AM Peak P—PM Peak M—Mid-Day X—All Day
W—Weekend Period BM—Benchmark

der. There is a slight downgrade of 1 to 2 percent through the site. Immediately downstream is a series of ramps to the right, entering from and exiting to I-90. This results in some weaving in the right side just past the study area; however, while traffic slows, it continues to move steadily with no stop-and-go conditions experienced.

Holgate Street—Southbound

This site is to the south of the I-90 interchange. The freeway carries a four-lane section through the site, with three lanes coming from I-5 and the fourth being added from I-90. This lane is dropped further downstream creating an area where some weaving will occur. However, this distance is lengthy enough to minimize the impacts through the study area. The travel lanes are 11 ft wide, with a left shoulder less than 2 ft wide and no right shoulder at the study site. There is a downgrade of about 3 percent through the area.

Yesler Way—Northbound

This site comprises a three-lane cross section of 11-ft travel lanes. There is no right shoulder—the right lane runs immediately beside a Jersey barrier. The left shoulder measures 4 ft wide. There is an upgrade of about 3 to 4 percent through the site. There is a left-hand exit ramp leading to the express lanes, which extend through the urban area approximately 700 ft north of the site. The express section is a reversible section and, therefore, the ramp is not open during the AM period. When the ramp is open, volumes in the left lane are heavier due to exiting traffic; however, traffic does not slow enough to back into the study area.

I-90—SEATTLE, WA

The I-90 corridor in the Seattle area runs in an east-west direction. The area with treatment strategies of using shoulders and/or narrow lanes to increase freeway capacity is located through the Mercer Island area, just to the east of Seattle. During data collection for this project, this section of the freeway was at an interim stage of construction to institute a reversible HOV facility located in the freeway median. Each freeway section was physically separated by a median barrier enabling construction on one section to proceed with minimal influence on traffic on another section.

The westbound direction carries a cross section of three 11-ft general travel lanes plus one 11-ft HOV lane to the left. The left shoulder varies but is generally less than 2 ft in width. The right shoulder remains approximately 4 to 6 ft wide through the area.

The eastbound direction on the freeway experienced operational changes during the data collection period and was used as both altered and benchmark data sites. On July 12, 1992, a new phase of construction was begun in the eastbound direction. Prior to that time, the eastbound traffic was traveling in the median freeway section, which is designated for future reversible operation. The median section carried a cross section of three 11-ft lanes with no HOV lane and substandard shoulders. After the changeover, the eastbound traffic was directed onto the newly constructed section of the freeway dedicated to permanent eastbound movement. This section carries a standard travelway section of three 12-ft lanes, and 10-ft shoulders on each side. The use of a common overpass location enabled the data collection crew to observe and gather data on operations before and after the operational changeover. Figure 11 illustrates the alignment of the corridor.

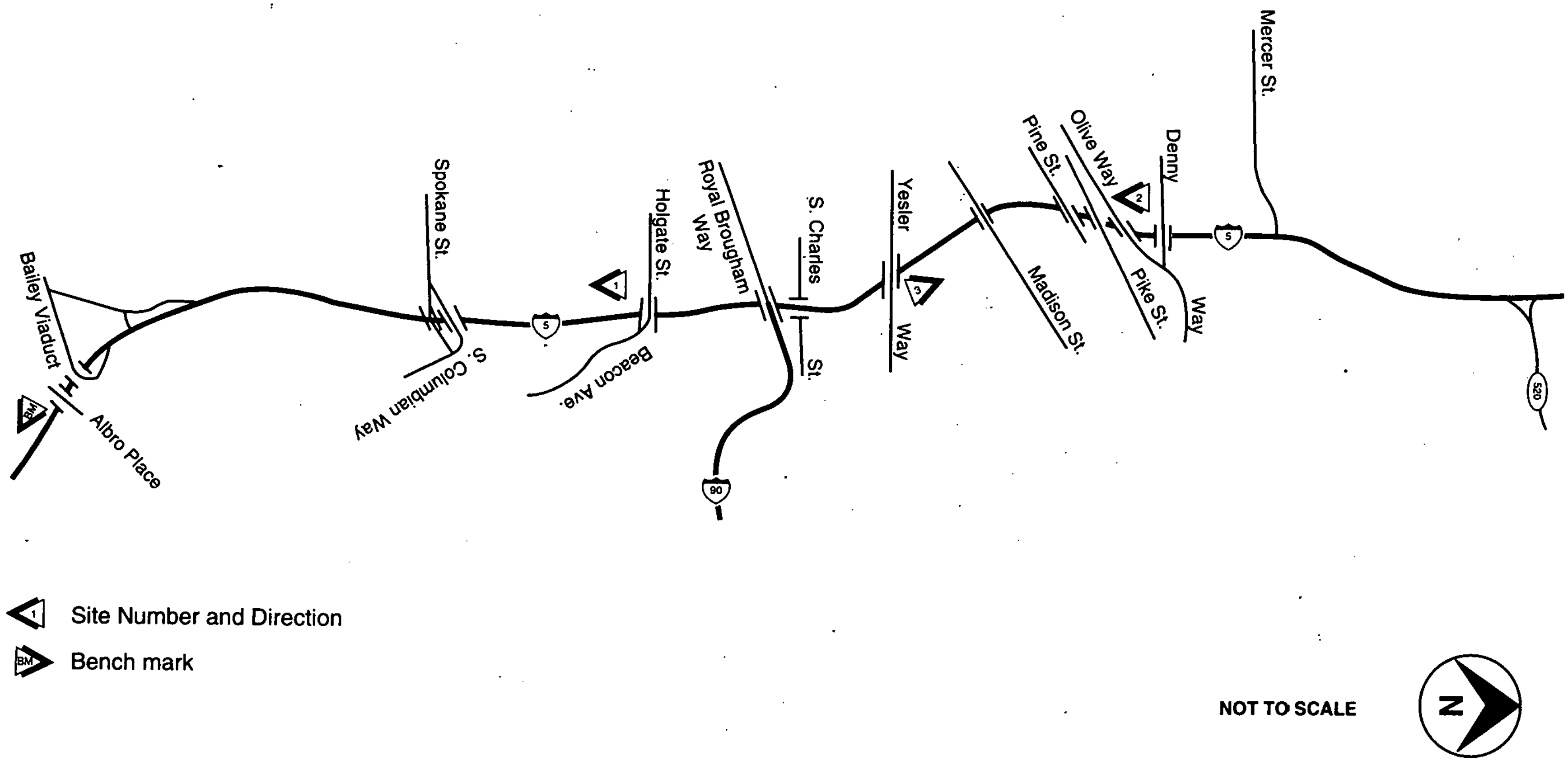
The key characteristics of each site are presented in Table 7. A brief description of each site follows.

Island Crest Way—Westbound

A cross section as described earlier of three 11-ft general travel lanes plus one 11-ft HOV lane existed. The left shoulder is 1 ft wide and the right shoulder is approximately 5 ft wide. There are no ramps in the study area that would influence driver behavior appreciably, nor is there any grade or significant horizontal curvature.

Island Crest Way—Eastbound, Altered

Prior to the conversion, traffic through the area used this section carrying three 11-ft general traffic lanes. The left shoul-



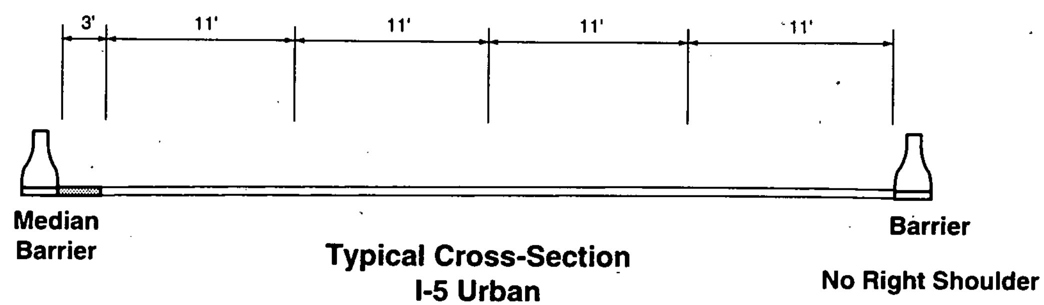


Figure 10. I-5 urban corridor, Seattle.

TABLE 6. Site conditions I-5 (urban)

Site	Lane Width		Left Shoulder			Right Shoulder			% Trucks			Application Type		Freeway Section		
	11′	12′	<2′	2-8′	>8′	<2′	2-8′	>8′	<5%	5-10%	>10%	HOV	Add Lane	Merge/ Div	Weave	BFS
Albro Place, SB		X			X	X		X		AP			BM	X		
Denny Way, SB	X		X					X	P	AM		X			X	
Holgate Street, SB	X		X			X				AM			X	X		
Yesler Way, NB	X			X		X			P	M			X	X		

LEGEND: A—AM Peak P—PM Peak M—Mid-Day X—All Day
W—Weekend Period BM—Benchmark

der was 1 ft wide, and a right shoulder approximately 5 ft wide. No ramps were present that influenced traffic flow through the site.

Island Crest Way—Eastbound, Benchmark

After traffic was transferred from the median section onto the permanent eastbound travel lanes, this location served as a benchmark location for the corridor. It carries a cross section of three 12-ft lanes with 10-ft shoulders on both the right and left sides. There is a right-side entrance ramp downstream of the study area. The volumes on the ramp are moderate at times but merge far enough away so as to not be a source of slowing through the area.

West Mercer Way—Westbound

This site has a section consisting of three 11-ft general travel lanes plus a left-side HOV-only lane. The shoulders are variable through the study area—the right shoulder tapers from 2 to 4 ft through the site, while the left shoulder tapers from about 4 to 2 ft. This shift in pavement markings occurs as vehicles exit a tunnel at the study site and as they are entering a horizontal curve to the right. As with the previous sites, there are no ramps in the immediate area to influence traffic.

I-85—ATLANTA, GA

The I-85 corridor is one of the major freeways serving the Atlanta metropolitan area. The corridor runs in a north-south direction through the city, and then in a northeast-southwest direction when outside the central city area. The northeast corridor serves commuters from Dekalb and Gwinnett Counties, as well as areas further from the metropolitan area, and connects with downtown Atlanta. The freeway carries five to six lanes in each direction on the northeast side. Figure 12 shows the corridor and sites studied as well as a typical cross section of I-85 south of the I-285 interchange in Dekalb County. Figures 13 and 14 illustrate typical operating conditions in the corridor.

For the study, data were collected from five overpass locations: Chamblee-Tucker Road, North Druid Hills Road, Shallowford Road (in both the northbound and southbound directions), and Wood Parkway (benchmark site). The key characteristics of each site are presented in Table 8. The following paragraphs provide a brief description of each site.

Chamblee-Tucker Road—Southbound

The site has a five-lane cross section with four 11-ft lanes and one 12-ft lane, and full-width shoulders on both sides. The study area exhibits a slight negative gradient and no curvature. There is an exit ramp approximately 790 ft upstream of the study area and an entrance ramp that merges into traffic approximately 950 ft downstream of the area. The study area appeared to be clear of the influences of these ramps.

North Druid Hills Road—Southbound

The site has a five-lane cross section with four 11-ft lanes and one 12-ft lane, and full-width shoulders on both sides. The study area exhibits a slight negative gradient and no curvature. There is an exit ramp approximately 680 ft upstream of the study area and an additional exit ramp to Lenox Road approximately 5070 ft downstream of the overpass. There is an entrance ramp that adds a lane to the freeway approximately 840 ft downstream of the area. The influence of these ramps appears to be well beyond the study area.

Shallowford Road—Northbound

The site comprises a five-lane cross section with four 11-ft lanes and one 12-ft lane and full-width shoulders on both sides. The study area exhibits minimal gradient and no curvature. There is an exit ramp approximately 950 ft upstream of the study area and an entrance ramp that merges into traffic approximately 1000 ft downstream of the area. Observation during the data collection indicated that the site was clear of the influences of these ramps.

Shallowford Road—Southbound

The site comprises a five-lane cross section with four 11-ft lanes and one 12-ft lane and full-width shoulders on both sides. The study area exhibits minimal gradient and no curvature. Approximately 9600 ft downstream of the study area, the freeway

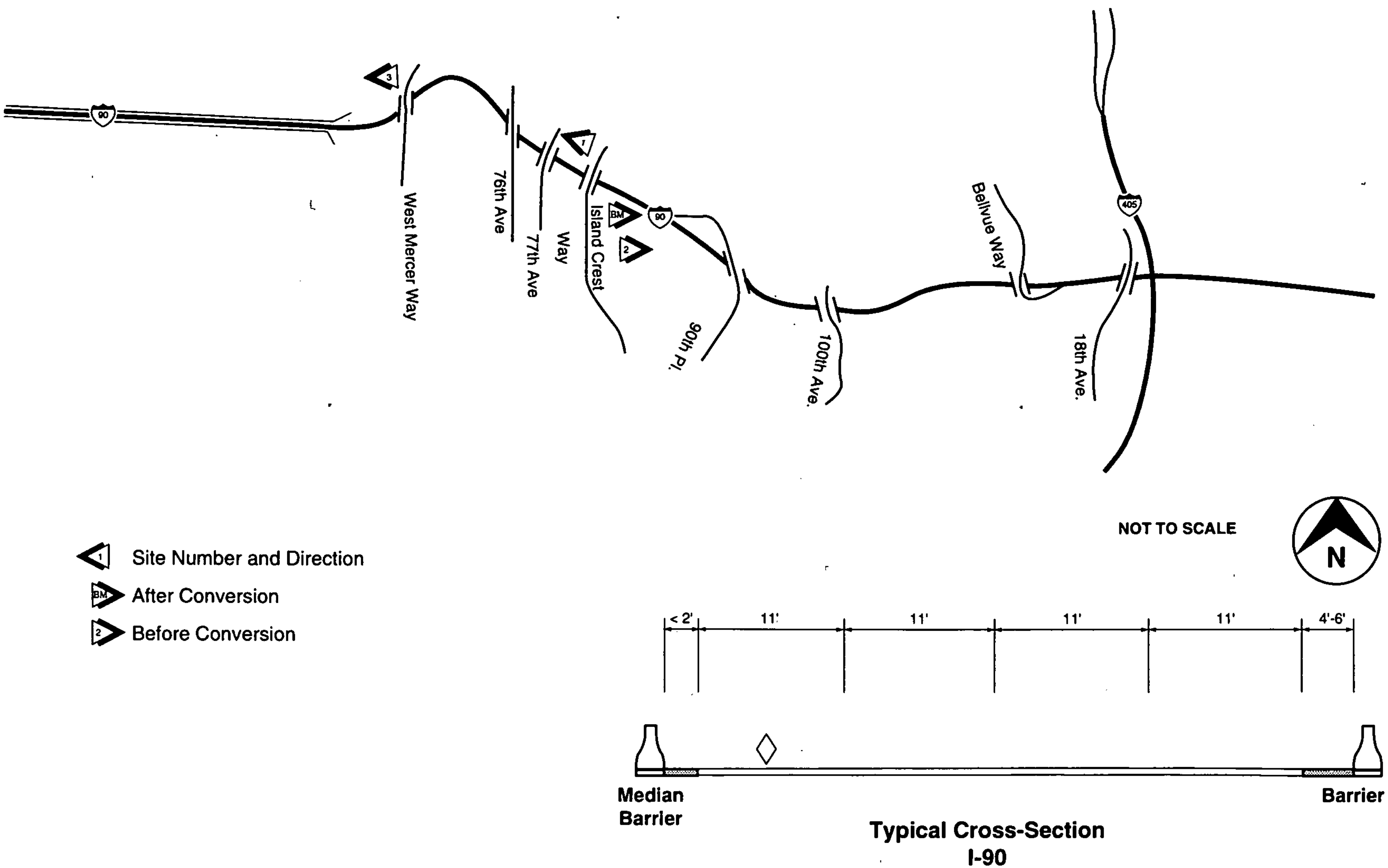


Figure 11. I-90 corridor, Seattle.

TABLE 7. Site conditions I-90

Site	Lane Width		Left Shoulder			Right Shoulder			% Trucks			Application Type		Freeway Section		
	11′	12′	<2′	2-8′	>8′	<2′	2-8′	>8′	<5%	5-10%	>10%	HOV	Add Lane	Merge/Div	Weave	BFS
Island Crest Way, EB	X		X				X		P	A		X		X		
Island Cr. Way, EB-After		X			X			X					BM	X		
Island Crest Way, WB	X		X				X		W	M		X		X		
West Mercer Way, WB	X			X			X					X		X		

LEGEND: A—AM Peak P—PM Peak M—Mid-Day X—All Day
W—Weekend Period BM—Benchmark

has a sharp horizontal curve. There is an exit ramp approximately 1320 ft upstream of the study area and an entrance ramp that merges into traffic approximately 1060 ft downstream of the area. The study area appeared to be clear of the influences of these ramps.

Wood Parkway—Southbound

The geometry at this location is a six-lane cross section with 12-ft lanes and full-width shoulders. This site is located to the north of the I-285 interchange and is used as a benchmark site for the corridor. The study area is not within the influence area of any entrance ramps and is 1050 ft upstream of an exit ramp to Pleasantdale Road. Some influence from the exit to Pleasantdale Road can be observed with traffic slowing under heavy volume conditions in the right-hand lanes.

I-94—MINNEAPOLIS, MN

The I-94 corridor travels in an east-west direction through the Minneapolis-St. Paul area. It serves as the central freeway corridor, which directly connects the two metropolitan areas. Along this corridor there are several sections with shoulder use treatments to alleviate bottlenecks in the corridor. Considerable data have been maintained by the highway department on the characteristics of the corridor with respect to these changes. The section of freeway researched for this effort included the area between the Mississippi River crossing east to Lexington Street. Through this area, shoulders are intermittently used to eliminate bottlenecks caused by lane drops.

Three altered sites were used (East River Road, Snelling Avenue, and University of Minnesota exit ramp)—one less than in other corridors—along with a benchmark site (Pascal Street). Figure 15 shows the alignment of the corridor and a typical cross section. Figure 16 illustrates typical conditions in the corridor. The key characteristics of each site are presented in Table 9. A brief description of each site follows.

East River Road—Westbound

This site overlooks the approach to the bridge over the Mississippi River. It has a cross section consisting of three 12-ft lanes, but it has no right or left shoulders. There is a metered entrance ramp, which merges into traffic upstream of the site. This traffic has completely merged in prior to the site, and its influence is minimal due to the use of ramp metering. There is an exit ramp downstream across the bridge, but it appears to have no operational influence through the study site. Approaching the site, both shoulders are tapered out just prior to a sharp (50 mph) curve. This acts to slow traffic through the site. Speeds do not resume until after the bridge. Therefore, the site is within the constrained or congested segment.

Pascal Street—Westbound

This benchmark site has a cross section of three 12-ft lanes with full-width shoulders on both the right and left sides. As with the Snelling Avenue site, this site is a tangent section with a slight uphill grade. There is an exit ramp 200 ft upstream of the site that carries a relatively light volume and does not appear to impact the study area.

Snelling Avenue—Westbound

The cross section consists of three 12-ft lanes, a 6-ft left shoulder to a barrier, and a full-width right shoulder. The site is a tangent section with a minimal uphill grade of less than 2 percent. There is a metered entrance ramp about 500 ft downstream, which displays no negative influence on the traffic flow. This site is located about 600 ft downstream of the Pascal Street benchmark site and reflects a narrowing of the left shoulder through this area.

University of Minnesota Exit Ramp—Eastbound

This site is within the interchange area for the exit to the University of Minnesota and displays the typical treatment for using the shoulders to maintain lane continuity. The cross section consists of three 12-ft travel lanes with a 1-ft left shoulder to a barrier and a 3-ft right shoulder to a barrier. Traffic is traveling through a slight horizontal curve to the right as well as a slight upgrade of less than 2 percent immediately downstream from the site; however, this does not appear to have a negative influence on the traffic flow. There is an exit ramp that diverges 500 ft upstream of the site. There is also a metered entrance ramp that merges 500 ft downstream from the site. Neither ramp exhibits a negative influence on traffic through the study area.

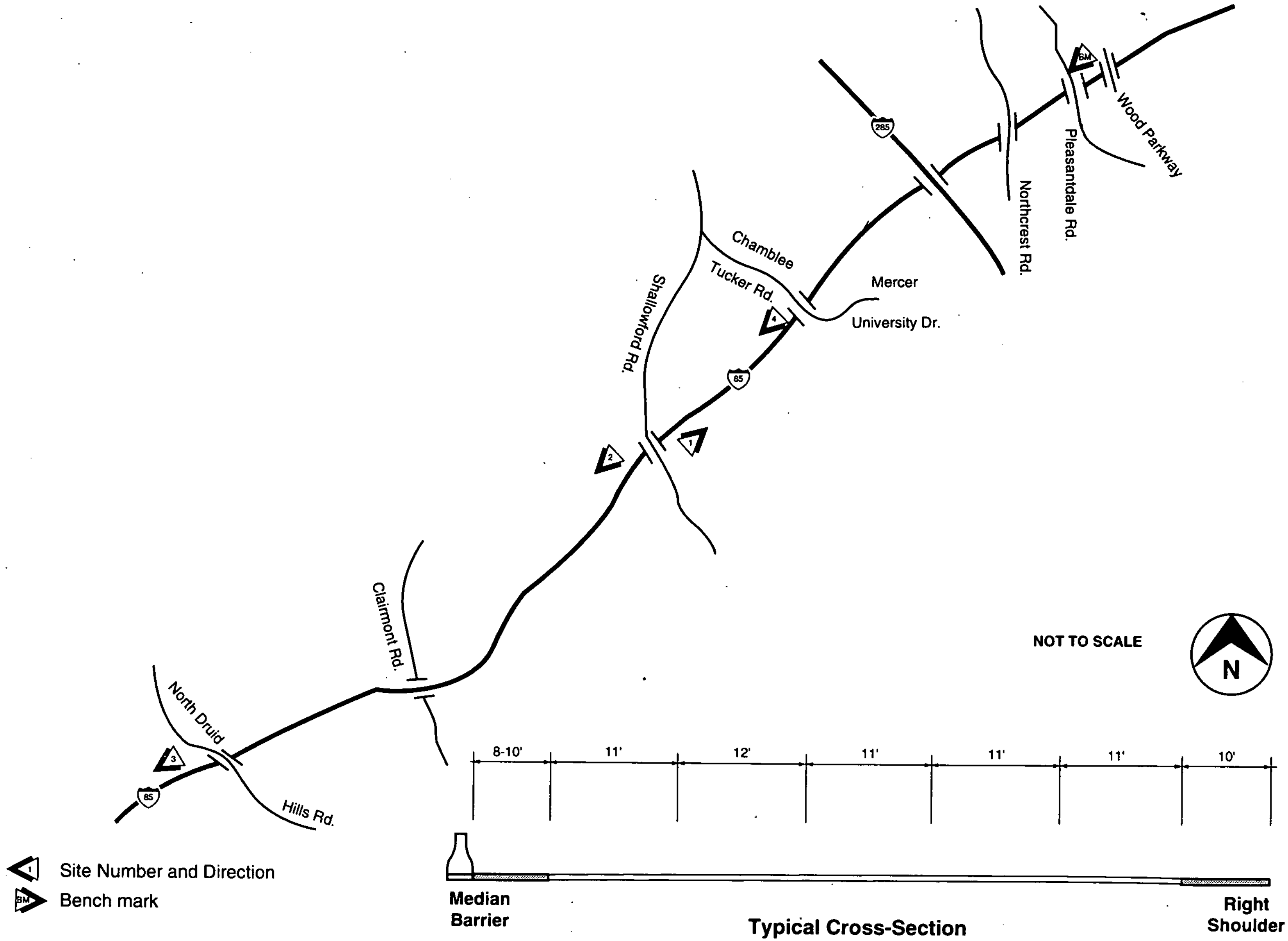


Figure 12. I-85 corridor, Atlanta.

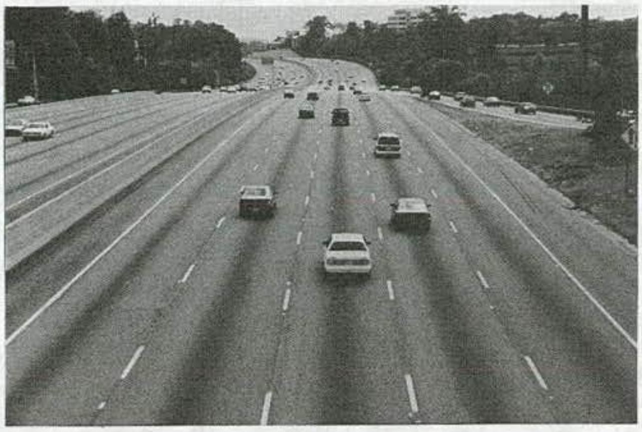


Figure 13. I-85 in Atlanta at North Druid Hills Road.

Figure 14. I-85 in Atlanta at Chamblee-Tucker Road.

I-10 (SANTA MONICA FREEWAY)—LOS ANGELES, CA

The I-10 corridor is a heavily traveled urban corridor serving the downtown Los Angeles area in an east-west direction. It carries eight- to ten-lane cross section, with four continuous lanes in each direction. The heavy volumes of traffic through this corridor combined with heavy entering and exiting traffic volumes at some ramps have resulted in several bottlenecks through the system, resulting in congested traffic flow. To improve traffic flow, the freeway was restriped to better balance demand and capacity by periodically adding a fifth travel lane using the available left shoulder and reducing the lane widths.

This treatment is intermittently in place from the I-405 interchange west of Los Angeles to the I-10 State Route (SR) 110 interchange in the downtown area. For this study, operational data were collected at four altered sites (Crenshaw Boulevard and 6th Avenue in both the eastbound and westbound direction) as well as one benchmark site at West Boulevard. Figure 17 illustrates the corridor location and Figure 18 shows corridor conditions. The key characteristics of each site are presented in Table 10. The following paragraphs provide a brief description of each site.

6th Avenue—Eastbound

The site has a cross section identical to the westbound direction consisting of five 11-ft lanes, a 2-ft left shoulder, and a full right shoulder with a continuous auxiliary lane between an entrance and exit ramp. There is an exit ramp to Arlington Avenue approximately 500 ft downstream, and an entrance ramp from Crenshaw Boulevard approximately 1500 ft upstream from the study site. The influence of these ramps on traffic operations appears to be minimal. This site also mirrors the curvature of the westbound site in that it carries a slight downgrade of about 1 to 2 percent, with a slight horizontal curve upstream of the area.

6th Avenue—Westbound

The cross section at this site consists of five lanes of 11 ft in width, with a full right shoulder of 8 to 10 ft, and a left shoulder of less than 2 ft in width. In addition to the right shoulder there is a continuous auxiliary lane present from an on ramp that is immediately upstream from the site. Due to the presence of this auxiliary lane, the impact of this ramp is minimal. The study area has a slight upgrade of about 1 to 2 percent. Approximately 500 ft downstream of the study site, a horizontal curve to the right is present. Upstream of the area is a tangent section of

TABLE 8. Site conditions I-85

	Lane Width		Left Shoulder			Right Shoulder			% Trucks			Application Type		Freeway Section		
Site	11′	12′	<2′	2-8′	>8′	<2′	2-8′	>8′	<5%	5-10%	>10%	HOV	Add Lane	Merge/ Div	Weave	BFS
Chambee - Tucker, SB	X				X			X	A				X	X		
N. Druid Hills, SB	X				X			X	AP W	M			X	X		
Shallowford Rd, NB	X				X			X	P	M			X	X		
Shallowford Rd, SB	X				X			X	AP				X	X		
Wood Parkway, SB		X			X	X		X					BM	X		

LEGEND: A—AM Peak P—PM Peak M—Mid-Day X—All Day
W—Weekend Period BM—Benchmark

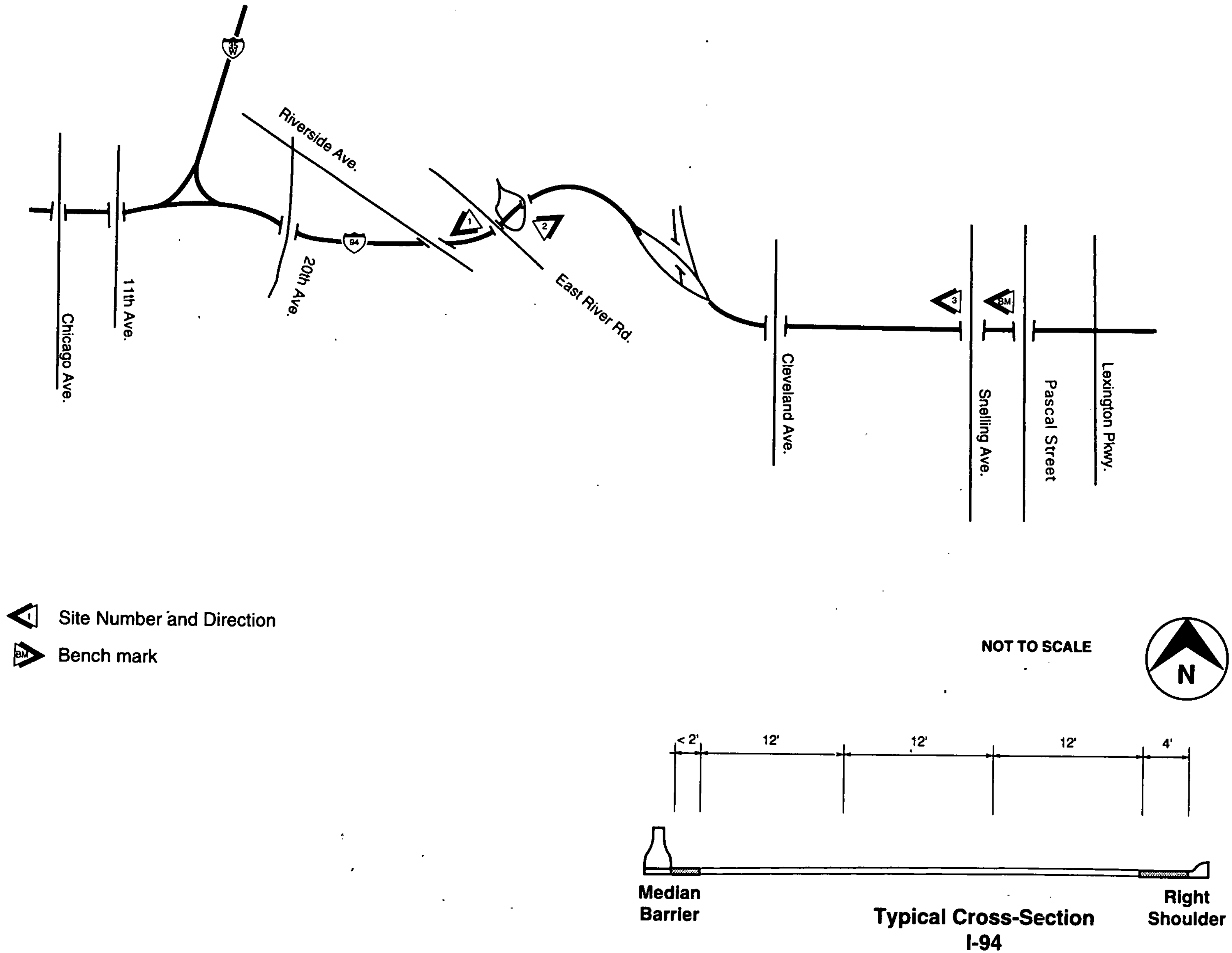


Figure 15. I-94 corridor, Minneapolis, St. Paul.

Figure 16. I-94 corridor in Minneapolis at East River Road.

at least 1500 ft. Stop-and-go traffic backs into the site from downstream congestion for significant periods.

Crenshaw Boulevard—Eastbound

The cross section consists of five lanes of 11 ft in width, with a full right shoulder of 8 to 10 ft, and a left shoulder between 1 and 2 ft wide. This study site is immediately downstream of the benchmark site at West Boulevard. There is an exit ramp 600 to 700 ft upstream and an entrance ramp is located about 700 to 800 ft downstream of the site. The influence from these ramps was observed to be minimal on the study site.

Crenshaw Boulevard—Westbound

This site has a cross section consisting of five lanes of 11 ft in width, with a full right shoulder of 8 to 10 ft, and a left shoulder between 1 and 2 ft wide. There is a slight upgrade of between 1 and 2 percent through the study area. There is an exit ramp approximately 1000 ft upstream and an entrance ramp approximately 500 ft downstream of the study site. Neither of these ramps appears to have an appreciable influence through the study area.

West Boulevard—Eastbound

This site has a cross section consisting of five lanes of 12 ft in width, with full shoulders on both the left and right sides. An entrance ramp from an upstream interchange merges into traffic approximately 1000 ft upstream of the site but does not appear to influence traffic in the study area. Approximately 500 ft downstream of the site an exit ramp leading to Crenshaw Boulevard is present. Influence through the study area on traffic operations is noticeable due to vehicles slowing for the exit. This benchmark site is located within the section of the corridor that displays intermittent treatments for shoulder use and immediately precedes a transition area into a treated section.

I-405—LOS ANGELES, CA

The I-405 corridor travels in a north-south direction to the west of the Los Angeles area. The corridor ties in with I-5 at both the north and south extremes of the metropolitan Los Angeles area. The section of the freeway using treatment strategies is located to the south of the I-605 interchange. The freeway generally carries four or five lanes in each direction. In the treated sections, the implementation of a left-side HOV lane has required the use of a portion of the left shoulder to accommodate the additional travel lane. Although the left shoulder has been used in part to provide for the HOV lane, the right-shoulder width and the travel-lane widths have not been affected. This freeway was analyzed as a full corridor with four altered sites (Bolsa Chica Road, Golden West Street, and Newland Street northbound and southbound) and one benchmark site (Cherry Avenue) being observed. Figures 19 and 20 show the corridor alignment and conditions, respectively. The key characteristics of each site are presented in Table 11. The following paragraphs provide a brief description of each site.

Bolsa Chica Road—Southbound

This site is similar to the Golden West Street site in that it has a cross section of five 12-ft lanes, with the leftmost lane being an HOV lane. There is a 2-ft left shoulder and a full right shoulder of at least 10-ft. There is an entrance ramp that merges into traffic approximately 200 ft downstream from the study site, which will have some influence on right-side traffic, al-

TABLE 9. Site conditions I-94

	Lane Width		Left Shoulder			Right Shoulder			% Trucks			Application Type		Freeway Section		
Site	11′	12′	<2′	2-8′	>8′	<2′	2-8′	>8′	<5%	5-10%	>10%	HOV	Add Lane	Merge/ Div	Weave	BFS
East River Road, WB		X	X			X			P	AM			X	X		
Pascal Street, WB		X			X			X	P	A			BM	X		
Snelling Avenue, WB		X		X				X		M			X			X
U of M Exit, EB		X	X				X		P	AM			X	X		

LEGEND: A—AM Peak P—PM Peak M—Mid-Day X—All Day
W—Weekend Period BM—Benchmark

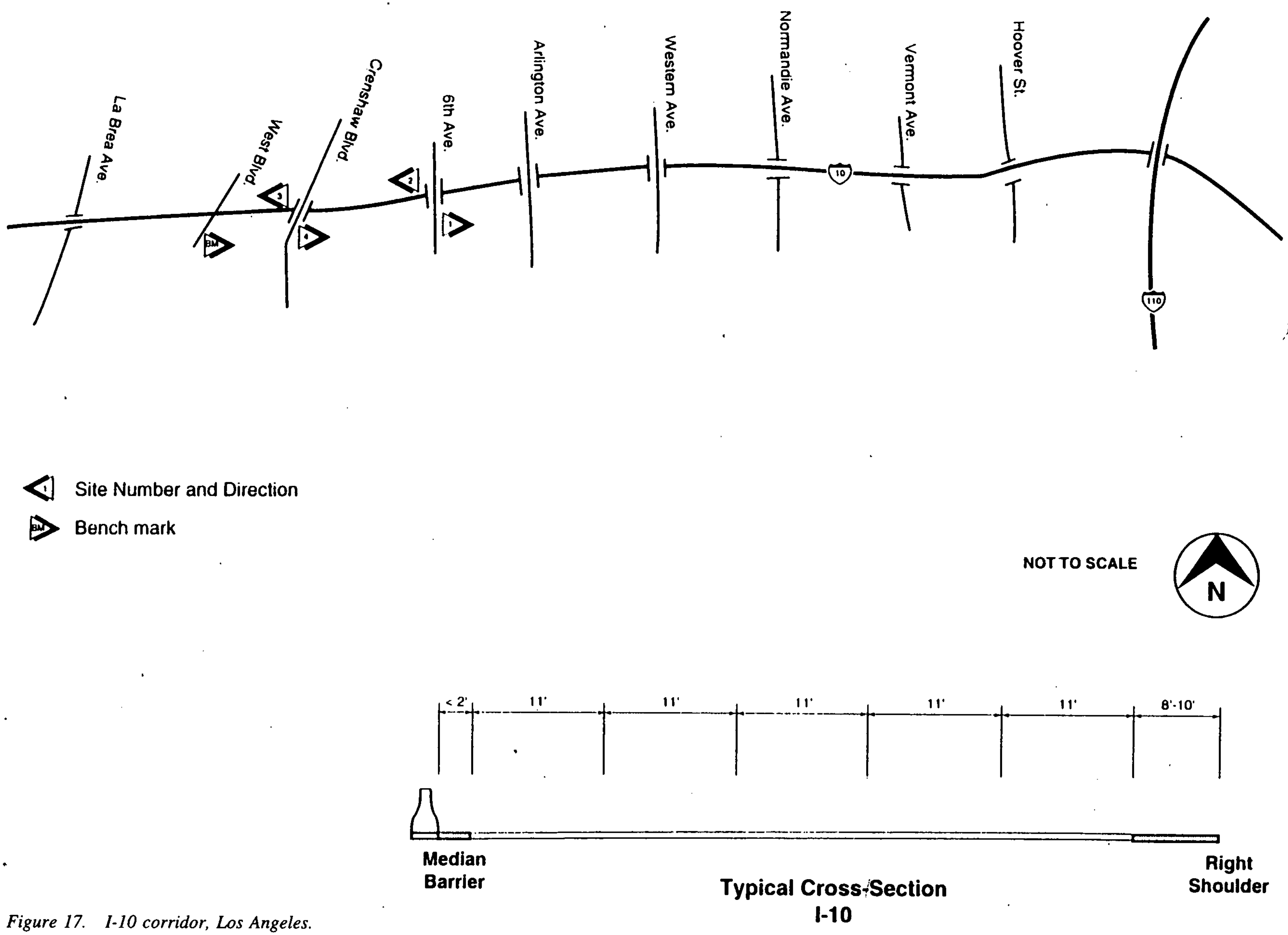


Figure 17. I-10 corridor, Los Angeles.

Figure 18. I-10 in Los Angeles at 6th Avenue.

though the ramp volume was never heavy enough to cause significant slowing or stopping. There is no appreciable grade or horizontal curvature through the study area.

Cherry Avenue—Northbound

This benchmark location has a four-lane cross section of 12-ft general use lanes with a full right shoulder and a full left shoulder. It lies on an upgrade of about 2 to 3 percent with a horizontal curve to the left beginning 1000 ft downstream of the area. There are two exit ramps in the immediate vicinity of the site. The first is located 1000 ft upstream and exits onto Cherry Avenue. The second exit occurs in the study area and exits onto Orange Avenue. There is an entrance ramp from Cherry Avenue located approximately 1500 ft downstream, which has negligible influence on the area.

Golden West Street—Southbound

This site has a five-lane section with the leftmost lane being an HOV lane. All lanes are a full 12 ft in width. There is a 1 to 2-ft left shoulder from the edge of the HOV lane to a median barrier. The right shoulder is a full-width shoulder. There is a 2-ft separation from the HOV lane to the leftmost general travel lane. This interchange area is serviced by a collector-distributor road that parallels the freeway and effectively removes any influence that ramps have on the study site.

Newland Street—Northbound

This is a mirror image of the southbound direction at the same overpass. It has a five-lane cross section of 12-ft lanes with the leftmost lane being used as an HOV lane. There is a 2-ft left shoulder and a full right shoulder. There is also a 3-ft separation between the leftmost general travel lane and the HOV lane. This separation is set off by the use of the double yellow pavement markers. Approximately 900 ft downstream is an exit ramp to Beach Boulevard. Upstream of the site about 1500 ft is an entrance ramp from Wagner Street. Neither ramp appears to influence traffic in the study area. There is no grade or horizontal curvature through this area.

Newland Street—Southbound

The site has a five-lane cross section of 12-ft lanes with the leftmost lane being used as an HOV lane. There is a 2-ft left shoulder and a full right shoulder. There is also a 3-ft separation between the leftmost general travel lane and the HOV lane. This separation is set off by the use of a pair of double yellow pavement markings. This is a tangent section with no appreciable grade. There is an entrance ramp approximately 1000 ft downstream, which appears to have minimal influence through the study area.

SR 57—LOS ANGELES, CA

The SR 57 corridor travels in a north-south direction from the interchange of I-10 to the interchange of I-5 to the east of Los Angeles. The freeway generally carries four to five lanes in each direction and has two distinct sections across its length: one portion with standard-width lanes and shoulders, and another section that was converted to an HOV corridor with the leftmost lane being used for an HOV lane. This was accomplished by narrowing the general travel lanes and by capturing the left shoulder. Data were collected at four altered sites: Imperial Highway in both the southbound and northbound directions, and

TABLE 10. Site conditions I-10

Site	Lane Width		Left Shoulder			Right Shoulder			% Trucks			Application Type		Freeway Section		
	11′	12′	<2′	2-8′	>8′	<2′	2-8′	>8′	<5%	5-10%	>10%	HOV	Add Lane	Merge/ Div	Weave	BFS
6th Avenue, EB	X		X					X	W	MP			X		X	
6th Avenue, WB	X		X					X	P	AM			X		X	
Crenshaw Blvd., EB	X		X					X	AP				X	X		
Crenshaw Blvd., WB	X		X					X	M				X	X		
West Boulevard, EB		X			X	X		X	A	MP			BM		X	

LEGEND: A—AM Peak P—PM Peak M—Mid-Day X—All Day
W—Weekend Period BM—Benchmark

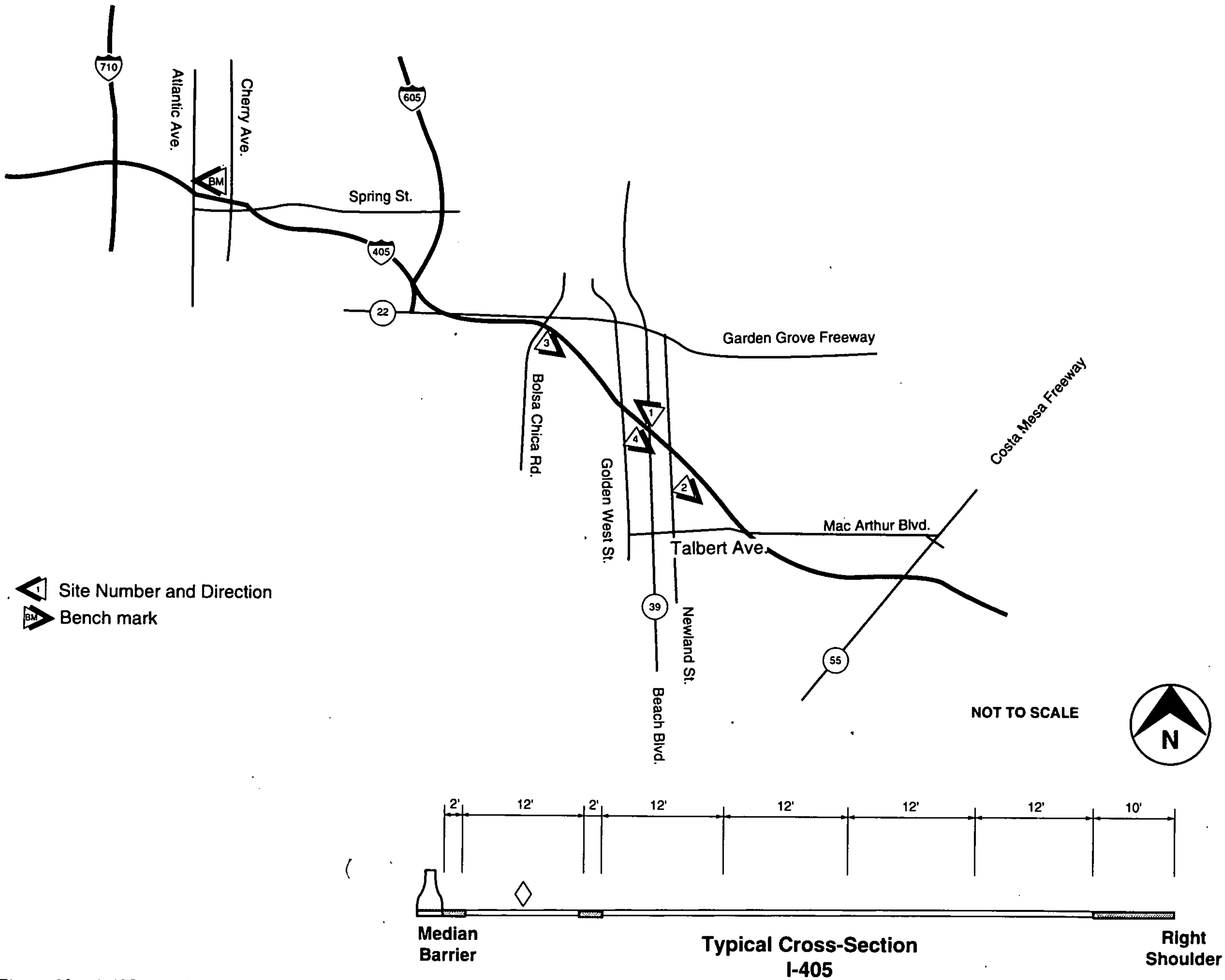


Figure 19. I-405 corridor, Orange County.

Figure 20. I-405 in Los Angeles at Golden West Boulevard.

Miraloma Avenue and Yorba Linda Boulevard in the southbound direction. Unfortunately, there were no locations that would permit data collection that could be used as a benchmark for the corridor available within a distance that could be considered comparable. Figure 21 shows the segment of the corridor studied and a typical cross section. Figure 22 illustrates corridor conditions. The key characteristics of each site are presented in Table 12. The following paragraphs provide a brief description of each site.

Imperial Highway—Northbound

This site comprises a cross section with four 11-ft lanes plus one HOV lane to the median side of the freeway. There is no left shoulder and a full-width right shoulder. The right shoulder through the interchange area carries a loop ramp that tapers in through the study area. There are exit ramps 800 ft downstream and 1500 ft upstream of the study area, which have minor impacts on traffic through the site. This site experiences a brief period of congestion during the AM peak hour (approximately 15 min). There is a downgrade of about 2 percent with a horizontal curve to the right continuous through the section.

Imperial Highway—Southbound

This site has a cross section identical to the northbound direction with four 11-ft lanes plus one HOV lane to the median side of the freeway. There is no left shoulder and a full-width right shoulder. The right shoulder through the interchange area carries a loop ramp that tapers in through the study area, causing minor influence throughout the area, with some minor slowing of traffic.

Miraloma Avenue—Southbound

The Miraloma site has a five-lane cross section with four 11-ft general travel lanes and an HOV lane in the leftmost lane. The left shoulder is less than 2 ft and the right shoulder is a full-width shoulder. There is an upgrade of approximately 3 percent through the section. The study site is immediately downstream of the exit ramp to westbound SR 91 but before the exit to eastbound SR 91. No visible influence on traffic operations occurs as a result of these ramps.

Yorba Linda Boulevard—Southbound

The site has a cross section consisting of four general use travel lanes (each 11 ft wide) and a fifth lane, for HOV-only, located to the left, or median, side of the freeway. The left shoulder, to the left of the HOV lane, is less than 2 ft wide. The right shoulder is a standard-width shoulder. There is an entrance loop ramp that merges in directly through the study area. There is also a direct entrance ramp approximately 1500 ft downstream from the study area. The loop ramp has an obvious impact on traffic in the rightmost lane, while the influence of the direct ramp is minimal.

SR 91—LOS ANGELES, CA

The SR 91 corridor in southern California travels in an east-west direction from the interchange with I-110 south of Los Angeles to the interchange with I-10 to the west of the city. The section of the freeway studied for this research is located in Orange County between the interchanges with I-5 and SR 55. Through this area, the freeway generally carries three lanes of traffic in each direction with interchanges often spaced every mile or less. There is frequent use of auxiliary lanes throughout the area to lessen the impacts of the closely spaced interchanges. To accommodate three travel lanes, this corridor uses a strategy of narrow lanes combined with shoulder use in many areas.

TABLE 11. Site conditions I-405

	Lane Width		Left Shoulder			Right Shoulder			% Trucks			Application Type		Freeway Section		
Site	11′	12′	<2′	2-8′	>8′	<2′	2-8′	>8′	<5%	5-10%	>10%	HOV	Add Lane	Merge/ Div	Weave	BFS
Bolsa Chica Road, SB		X	X			X		X				X		X		
Cherry Street, NB		X			X	X		X	A				BM	X		
Golden West Street, SB		X	X			X		X	W	M		X		X		
Newland Street, NB		X	X			X		X	AP			X			X	
Newland Street, SB		X	X			X		X		M		X		X		

LEGEND: A—AM Peak P—PM Peak M—Mid-Day X—All Day
W—Weekend Period BM—Benchmark

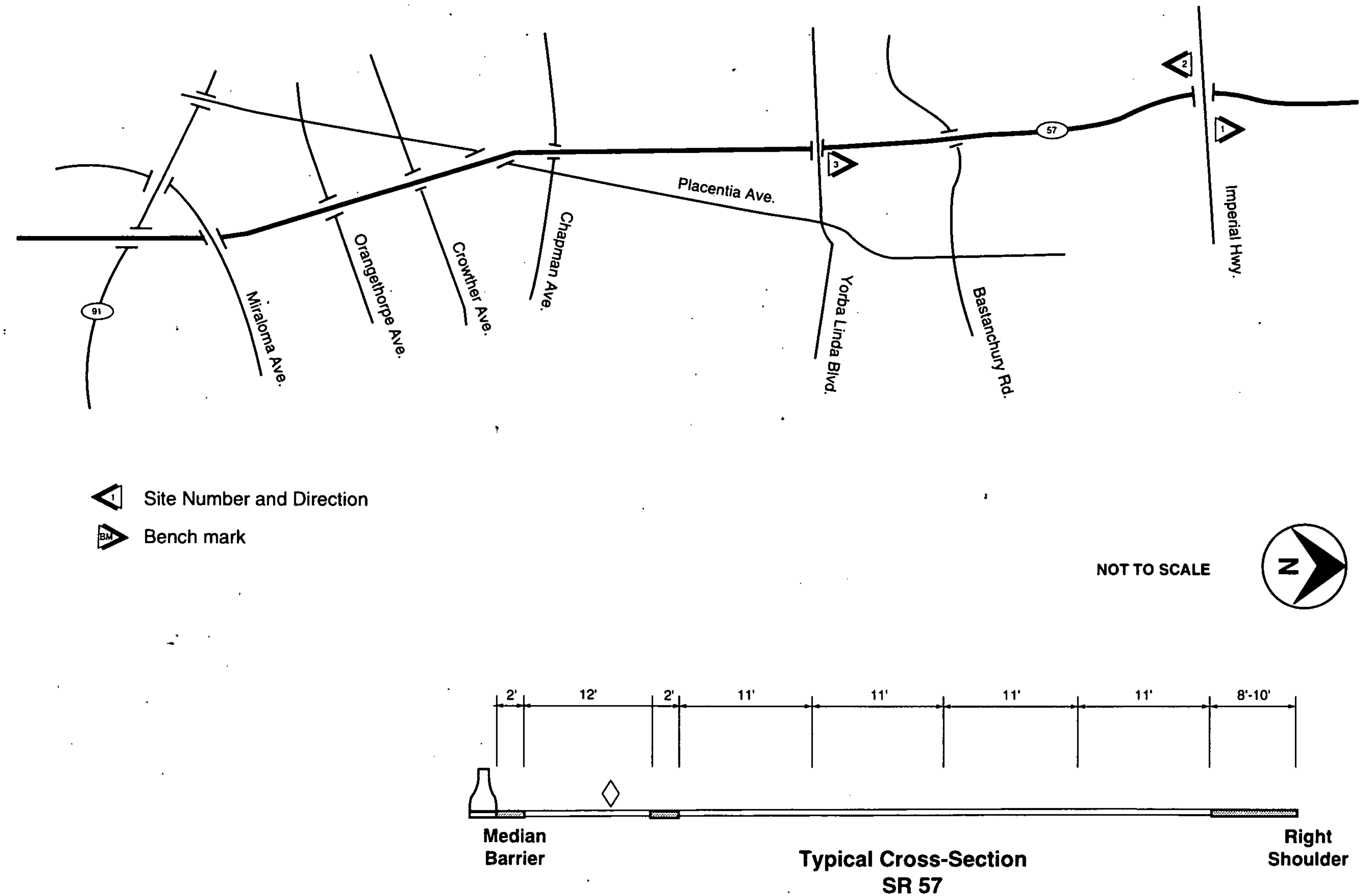


Figure 21. SR 57 corridor, California.

Figure 22. SR 57 in Los Angeles at Yorba Linda Boulevard.

Often where both shoulders were captured for travel lanes, clearance is present on the right side to enable disabled vehicles to pull onto turf areas. Because of the lack of acceptable data collection sites, only three altered sites were included in the effort (Harbor Boulevard, Lemon Street, and Placentia Avenue) in addition to the benchmark site at Kraemer Boulevard. Figure 23 illustrates typical conditions. Figure 24 shows the section of the corridor studied and a typical cross section. The key characteristics of each site are presented in Table 13. The following paragraphs provide a brief description of each site.

Harbor Boulevard—Westbound

This site has a cross section consisting of four 11-ft lanes, with a 1-ft left shoulder to a median barrier, and no right shoulder present. Although there is no right shoulder, a mountable curb exists, which would allow a vehicle to pull off to the side of the road to a turf area. The section exhibits an upgrade of approximately 4 percent, which meets with a horizontal curve to the right approximately 300 ft downstream. At a distance of 600 to 700 ft downstream of the section there is an entrance ramp from Harbor Boulevard that appears to have negligible influence on operations in the study area. Entrance ramps are present approximately 1000 ft and 1500 ft upstream of the site from Harbor Boulevard and Lemon Street, respectively. These ramps appear to have minimal influence through the study area.

Figure 23. SR 91 in Los Angeles at Harbor Boulevard.

Kraemer Boulevard—Eastbound

This benchmark site carries three 12-ft travel lanes with full-width shoulders on both the right and left sides. To the right of the outside shoulder is a 20-ft raised separation from a collector-distributor road, which appears to be mountable, thus giving extra clearance for disabled vehicles. This interchange in the eastbound direction is served by a collector-distributor road, therefore, there are no ramp influences through the study area.

Lemon Street—Eastbound

This study site has a cross section consisting of four 11-ft lanes, with a 0- to 2-ft left shoulder to a median barrier and a 0- to 2-ft right shoulder. There is a short auxiliary lane weaving section between an entrance and exit ramp for Lemon Street. These ramps are not heavy volume ramps, thus their impact is minor. To the right of the auxiliary lane is a mountable curb leading to an area capable of receiving disabled vehicles. There is a 3 percent upgrade through the site, with slight curvature to the right approximately 300 ft downstream.

Placentia Avenue—Westbound

This site has a cross section consisting of three 11-ft lanes, with a left shoulder to a median barrier tapering through the study area from 6 ft at the overpass structure to about 2 ft approximately 100 ft downstream, and finally tapering to no shoulder at approximately 200 ft downstream. The right shoulder is approximately 4 ft wide, however, there is a continuous auxiliary lane at this location between an entrance ramp upstream from SR 57 to an exit ramp to State College Boulevard in Anaheim. This appears to eliminate, or at least minimize, the influence of these ramps on traffic operations. There is an upgrade of approximately 3 percent through the area, and at a distance of 200 ft upstream a horizontal curve to the left begins that carries through the study area.

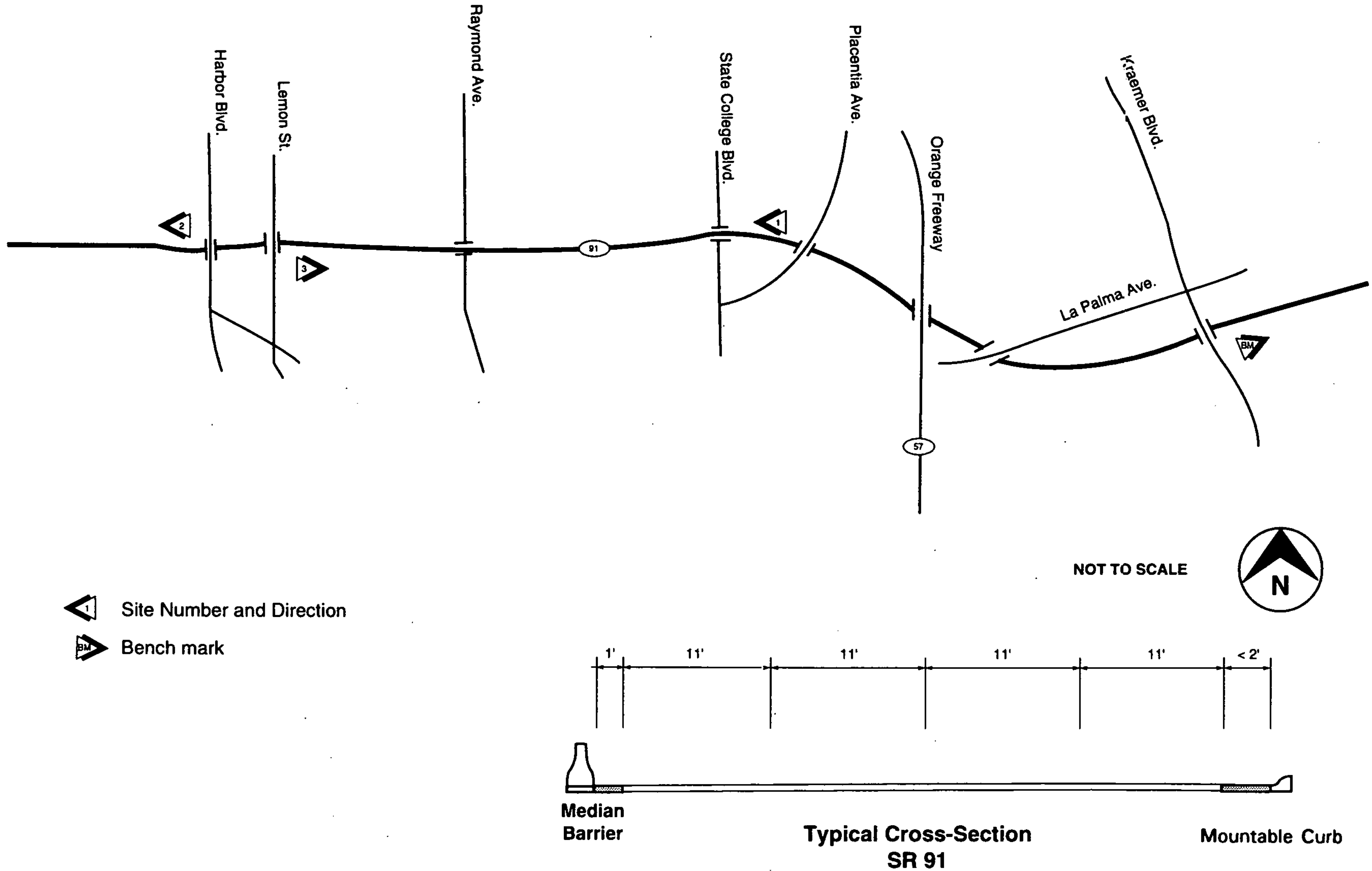


Figure 24. SR 91 corridor, California.

TABLE 12. Site conditions SR 57

Site	Lane Width		Left Shoulder			Right Shoulder			% Trucks			Application Type		Freeway Section		
	11′	12′	<2′	2-8′	>8′	<2′	2-8′	>8′	<5%	5-10%	>10%	HOV	Add Lane	Merge/ Div	Weave	BFS
Imperial Highway, NB	X		X					X		A	M	X		X		
Imperial Highway, SB	X		X					X	W		M	X		X		
Miraloma Avenue, SB		X			X			X			M	X	X		X	
Yorba Linda Blvd., NB	X		X					X			AMP	X		X		

LEGEND: A—AM Peak P—PM Peak M—Mid-Day X—All Day
W—Weekend Period BM—Benchmark

TABLE 13. Site conditions SR 91

Site	Lane Width		Left Shoulder			Right Shoulder			% Trucks			Application Type		Freeway Section		
	11′	12′	<2′	2-8′	>8′	<2′	2-8′	>8′	<5%	5-10%	>10%	HOV	Add Lane	Merge/ Div	Weave	BFS
Harbor Blvd., WB	X		X			X			W	M	A		X	X		
Kraemer Blvd., EB		X			X			X		AP			BM			X
Lemon Street, EB	X		X			X					M		X		X	
Placentia Avenue, WB	X		X				X			A			X	X		

LEGEND: A—AM Peak P—PM Peak M—Mid-Day X—All Day
W—Weekend Period BM—Benchmark

CHAPTER 3

FINDINGS

The primary focus of this research was concentrated on gaining an understanding of the differences in operational and safety characteristics between full standard or "unaltered" freeways and "altered" freeways where shoulders and narrower lanes have been used to increase capacity by adding lanes. To accomplish this, a variety of application types were included in the sites chosen. This chapter summarizes current use of shoulders and narrow lanes to increase freeway capacity and presents research findings that could influence the decision to implement a project using such strategies. Findings have been presented under four headings. The current use of shoulders and narrow lanes is summarized both in terms of use throughout the country and the various implementation strategies. Following this, the findings regarding safety performance based on accident analysis are presented. The results of the operational field studies are presented under operational performance. Finally, other findings and observations are presented. Some findings are anecdotal and subjective in nature or at least will require further investigation beyond the scope of this research to strengthen the basis for the finding. Care has been taken to distinguish between analytical findings and anecdotal findings or qualitative observations. Recommended guidelines and an evaluation methodology are presented in Chapter 4.

USE OF SHOULDERS AND NARROW LANES

Historical

The use of shoulders and narrow lanes on freeway or expressway type facilities has occurred since construction of the first facilities. The earliest urban freeways, or their equivalent (such as the East River Drive and West Side Highway in New York City, Davidson Expressway in Detroit, Lake Shore Drive in Chicago, and the Pasadena Freeway in Pasadena), generally were constructed with narrow lanes and with little or no shoulder width. True urban freeways came into being after World War II for most states, with the evolution of the Interstate System, which was mapped out in the 1930s and 1940s and begun in the 1950s.

One of the first works that led to standards of lane widths was published by Stonex and Noble in 1940 (*4*). Their study showed vehicle placements within lanes on high-speed horizontal curves. This led to a recommendation for 12-ft lanes.

In *The Effect of Roadway Width on Vehicle Operations* (*5*), Taragin reported on how the lateral clearance between vehicles in opposing flows changed as traffic lane widths varied from 9 to 12 ft. The reported driver reactions were later summarized in *Traffic Engineering* (*6*), as follows: "From the point of view of driver comfort, 11 feet is about the ideal lane for passenger-car traffic, and 12 feet is ideal where there is mixed traffic of trucks and passenger vehicles."

At about the same time, in 1946, a National Safety Council study reported to AASHO by David M. Baldwin (*7*), showed a decline in accident rates associated with increases in lane widths from 8 or 9 ft up to 12 ft, suggesting the desirability of wider lanes. Then the impact on highway capacity of different lane widths was documented in the 1950 *Highway Capacity Manual* (*8*). For multilane highways, a table showed that the theoretical design capacity of an 11-ft lane should be reduced to 97 percent of that for a 12-ft lane, while a 10-ft lane would have only 91 percent of the 12-ft lane capacity.

Thus, by 1950, the *Traffic Engineering Handbook* (*9*) was reporting an AASHO standard of 12-ft lanes where volumes exceeded 200 vehicles per hour.

Meanwhile, the value of shoulders was being made sufficiently clear, and design manuals were including them on urban as well as rural projects. For example, Matson, et al. (*6*) cited a California study of accidents on a highway without shoulders (Report of an Investigation of Accidents on the Arroyo Seco Parkway, 1948), indicating that 15 percent of all accidents involved vehicles parked on the traveled way. In *A Policy on Design Standards* (*10*), AASHO in 1950 prescribed the following Interstate System standards:

> Traffic lanes shall be not less than 12 feet wide.
> Medians in urban areas and mountainous areas shall be at least 16 feet wide . . . [can be less in urban areas] . . . but no median shall be less than four feet wide.
> Shoulders usable by all classes of vehicles in all weather conditions shall be provided on the right of traffic. The usable width of shoulder shall be not less than 10 feet.

A Policy on Arterial Highways in Urban Areas (*11*), AASHO's 1957 "Red Book," shows the same figures and notes that "On expressways and freeways, shoulders should be constructed throughout." The recommended clear shoulder width for the Interstate System was 10 ft, with 12 ft desirable for the urban system. Median shoulders were not specifically discussed, and median widths recommended for urban facilities were too narrow to provide shoulders. A minimum lateral clearance of 4½ ft to median bridge piers, with 6 to 8 ft preferred, was recommended.

Publications in the 1960s do show consideration of median shoulders. *The Freeway in the City* (*12*), from the U.S. DOT, says the following: "All freeways should provide a continuous shoulder on both sides of each roadway for disabled vehicles. No moving vehicles should be separated from a pulloff shoulder by more than one traffic lane. Both the safety of the highway

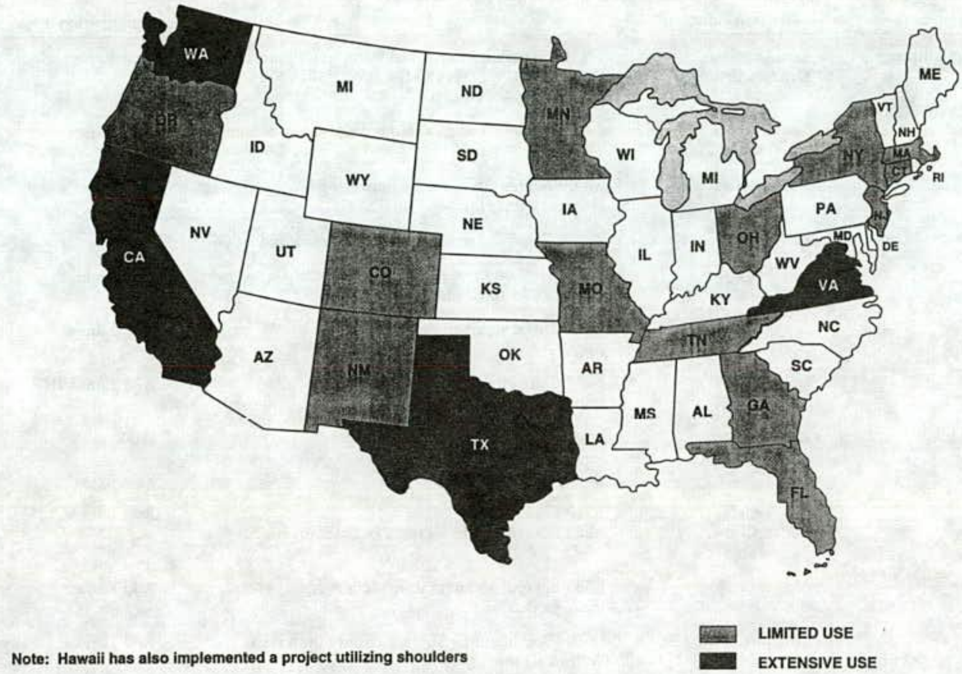


Figure 25. States that have implemented a project using shoulders with or without narrow lanes (past or present) for nonconstruction application.

users and the elimination of tieups are involved. Where a continuous shoulder strip is not feasible, frequent emergency pulloff bays should be provided." A teaching aid of the same period, *Fundamentals of Traffic Engineering—7th Edition* (*13*), illustrates an urban freeway with a median shoulder of 5 to 8 ft in a 22-ft median, and 10-ft right shoulders with a 3-ft transition to back slopes.

In summary, as urban freeway design standards evolved, cross sections became increasingly generous, despite the costs of right of way and impacts of these highway facilities on adjacent communities. However, by the late 1960s congestion had reached significant levels on some freeways and the use of shoulders or narrow lanes to increase capacity on facilities originally constructed with shoulders and 12-ft lanes was employed in the Los Angeles area.

The use of shoulders with or without the use of narrow lanes for purposes other than maintenance of traffic through temporary work zones is restricted to a relatively small number of states. California, Texas, Washington, and Virginia have used these strategies extensively. Usage in other states has been much more limited. Figure 25 summarizes the use across the country. A listing of corridors using these strategies is presented in Table 14. This listing of corridors is based on the literature review, survey, and findings of this research and is not likely to be all inclusive. Additional projects, modifications to projects, and elimination of some applications are at various stages of planning or implementation. Typical applications include the following:

HOV Applications

High occupancy vehicle (HOV) lanes have often been implemented by adding a lane through the use of one or both shoulders. In some cases, lanes for single occupancy vehicles (SOVs) have been narrowed as well. Details of implementation vary; most designate the left (median) lane as the HOV and use the shoulder to maintain the same number of regular lanes as existed prior to project implementation. Figure 26 illustrates a typical HOV application. Specific examples of this type of application include: I-405, SR-57, and SR-91 in Los Angeles; I-66 and I-95 in Virginia; and I-5 in Seattle. In most cases, lanes have been open to traffic all day but in some cases the shoulder lane has been open to traffic only during peak periods.

Auxiliary Lanes

One of the most common uses to date for shoulders or narrower lanes is the construction of an auxiliary lane between closely spaced interchanges in an urban area. This type of application is illustrated in Figure 27. Implementation approach varies; typically the rightmost lane(s) have been narrowed in combination with the use of the right shoulder to gain an extra lane. In some cases, the entire roadway section has been restriped to achieve uniform lane widths. In still other situations, the left shoulder has been used and the roadway restriped for a considerable distance. Using only the right shoulder and rightmost lanes is often the least expensive method; however, trucks tend to travel in these lanes and these lanes experience more vehicle maneuvers. Narrow lane widths are, therefore, more likely to affect traffic operations.

Merge Areas

At heavy merge areas, such as those that occur where two lane ramps from other major facilities join the mainline, the

TABLE 14. Corridors or sites with narrow lanes / shoulder use

State	City/County	Facility	Application Type
California	Los Angeles/ Orange County	I-5 Numerous sections beginning in Orange County at 17th Street to the Simi Valley Freeway in Los Angeles County.	Add Lane
	Los Angeles	I-10 Extensive use of shoulder between I-405 and I-605.	Add Lane
	Los Angeles	SR 60 Numerous sections between I-5 and Hacienda Road.	Add Lane
	Los Angeles	SR 91 Extended sections between I-405 and I-605.	HOV
	Los Angeles	U.S. 101 Numerous short sections from Downtown Los Angeles to Reseda Boulevard.	Add Lane
	Los Angeles	I-110 Three sections approximately one mile in length.	Add Lanes
	Los Angeles	I-210 Four auxiliary lanes with HOV Implemented in 1991.	Add Lanes/HOV
	Los Angeles	I-405 Extensive use of shoulder for implementation of HOV lanes in Los Angeles and Orange Counties.	HOV
	Los Angeles	I-710 Slauson to I-5.	Add Lanes
	Santa Clara/ San Mateo	I-280 Several short sections in both directions.	
	Alameda	I-580 Several sections from Milepost 42 to 46 through Oakland.	Add Lane
	Contra Costra	I-680 (Southbound) Short auxiliary lane near Walnut Creek.	Add Lane
	Marin	Several sections on Route 101 between the Golden Gate Bridge and Milepost 18.	Add Lane
	San Jose	I-280 from Wolfe Road to DeAnza Boulevard.	Add Lane (Part-Time Operation)
	San Mateo	Route 101 (Both Directions) between Milepost 12.0 - 13.3.	Extended Section
California	San Mateo	Route 92 (Eastbound) between Milepost 12.9 - 14.0.	HOV
	San Mateo	Route 92 (Westbound) between Milepost 2.8 - 4.4.	HOV
California	Sacramento	Route 51 (Southbound) from Camino Street to Marconi Road	Add Lane (Part-time Auxiliary Lane)
	Sacramento	Route 51 (Northbound) Over Route 244	Add Lane
Colorado	Denver	I-25 (Northbound) from Steel Street to Emerson Street.	Add Lane

queues that form impede upstream traffic movements on the mainline. By using the shoulder and narrower lanes, an added lane can be achieved—thus providing greater opportunities to merge. The added line is then dropped at a convenient downstream location (see Figure 27).

Deceleration Lanes

Another use has been the extension of deceleration lanes to allow traffic destined to another freeway or arterial to bypass a queue on the mainline or to keep a traffic queue from a ramp from backing onto the mainline. Applications of this type may have a limited useful life due to the growth in congestion. Figure 28 illustrates an application of this type.

Extended Sections

Shoulders with or without narrow lanes have been used to provide additional capacity in areas of recurring congestion. Unlike the applications identified above, the altered cross section is continued for an extended length through several interchanges (Figure 29) and the lane is adopted as another mainline lane. Applications of this type studied previously are more limited but were initially considered to have been successful with most applications occurring within four states: California, Texas, Virginia, and Washington. With the congestion facing many urban areas, this was perhaps the key issue facing this research effort. That is, can narrower lanes and use of the shoulders be considered as a means to provide an increase in basic mainline capacity without compromising safety or other considerations? This is of particular concern given that the implementation of a concurrent HOV lane on an existing facility may be a variation of this application type.

Work Zones

The use of narrow lanes is a common practice during the reconstruction or maintenance of freeways. Figure 28, presented previously, illustrates how narrow lanes and/or reduced shoulder

TABLE 14. Corridors or sites with narrow lanes / shoulder use (continued)

State	City/County	Facility	Application Type
	Denver	I-25 (Southbound) from Emerson Street to University Boulevard.	Add Lane
Connecticut	West Hartford	I-84 EB Trout Brook Connector	Auxiliary Lane
	Wethersfield	I-91 (Southbound) from Route 3 to Elm Street.	Add Lane Eliminate Left merge
Georgia	Dekalb County	I-85 (Northbound and Southbound) from Route 23 to I-285.	Add Lane
	Atlanta	I-20 (Westbound) from I-75 to Hightower Road.	Add Lane (Extended Section)
Massachus etts	Boston	Route 128 from I-95 to I-93.	Add Lane (Part Time)
Minnesota	Minneapolis	I-94 Restriping to eliminate lane drops.	Add Lane
Missouri	St Louis	I-70 from Airport Road to Frost Avenue.	Add Lane
New Jersey		Garden State Parkway has extensive use of Shoulders.	Add Lane
New Mexico	Albuquerque	I-25	Add Lane
New York		Long Island Expressway - Several sections implemented in the summer of 1991.	HOV
Oregon	Portland	I-5/I-405 Marquan Bridge.	Add Lane
	Portland	Banfield Freeway.	HOV
Tennessee	Nashville	I-65/I-265 (Northbound) from I-65/I-265 merge to Trinity Lane Interchange.	Add Lane (Lane Auxiliary)
	Darison County	I-24/I-40 (Eastbound) from I-65 Interchange to Fessler's Lane.	Add Lane
Texas	Houston	I-610 at Route 288 Interchange	Add Lane (Auxiliary Lane)
	Houston	I-610 from I-10 Interchange to Woodway Street.	Add Lane (Elimination of Merge)
	Houston	I-45 North Freeway from I-610 Interchange to Cavalcade Street.	Add Lane (Elimination of Merge)
	Houston	US-59 (Southbound) on Southwest Freeway from Wesleyan.	Add Lane (Extended)
	Houston	US-59 (Northbound) on Southwest Freeway from New Castle to Edlone.	Add Lane (Part-time)
	Houston	I-610 Northbound	Add Lane

widths are implemented at a construction site. Such construction zone applications are primarily concerned with short-term maintenance of as much of the previous capacity as possible. As the primary purpose of this research project was to study applications that were implemented for the purpose of increasing capacity, work zone applications received only limited attention during the research.

Driver behavior through construction zones is influenced by a myriad of other factors. In the majority of construction projects, the detour route through the site changes frequently. Study of these sections would have required a significantly different research approach. The urban I-5 corridor in Seattle could technically be considered a construction zone although traffic patterns were not changing and, therefore, conditions were comparable to many other so-called "interim" applications.

Application Groupings

To conduct this research, it was essential that applications be grouped by similarities. Initially, during the proposal stage, sites were grouped by the categories discussed above. As the project proceeded it became apparent that these were sub-groups of larger groupings distinguished by purpose and operational characteristics. In terms of purpose, the three main groupings used were HOV, Add Lanes, and Work Zones. As the research continued, the most important distinction became whether or not shoulders with or without narrow lanes had been used continuously to add travel lanes or selectively to address specific problems. Figure 30 illustrates the initial groupings assumed at the beginning of Phase II and the final groupings based on the results of the research.

SAFETY PERFORMANCE

Previous research generally conducted safety evaluations based on an analysis of data from specific sites on a before and after basis; however, concerns as to whether this approach was too narrowly focused remained. Projects implemented for short distances that addressed a specific problem often showed a decrease in accident rates; however, as these strategies are being

TABLE 14. Corridors or sites with narrow lanes / shoulder use (continued)

State	City/County	Facility	Application Type
Texas	Houston	I-45 North Freeway from Airline Drive to Little York Road.	HOV Contra Flow Lane
	Houston	I-10 Katy Freeway from Gessner Interchange to North Post Oak Overpass.	HOV
	Houston	I-45 North Freeway from Downtown to North Belt.	Add Lane (Transit in the median)
	Houston	I-45 Gulf Freeway from Downtown to Choate Road.	Add Lane (Transit in the median)
	Alexandria	I-395 (Northbound) from King Street to Glebe Road.	Add Lane (Extended Section)
Virginia	Alexandria	I-395 (Southbound) from Glebe Road to Duke Street.	Add Lane (Extended Section)
	Fairfax County	I-95 from Fairfax County Line to Capital Beltway.	HOV (Part-time Operation)
	Fairfax County	I-66 from Route 50 to Capital Beltway.	HOV (Part-time Operation)
Washington	Seattle	SR-520 (Westbound) from I-5 to Evergreen Point Bridge.	HOV (Part-time Operation)
	Seattle	I-405 from I-5 through Renton.	HOV
	Seattle	I-5 from Spokane Street to Route 527.	HOV
	Seattle	I-90 (Eastbound) Across Mercer Island	Work Zone

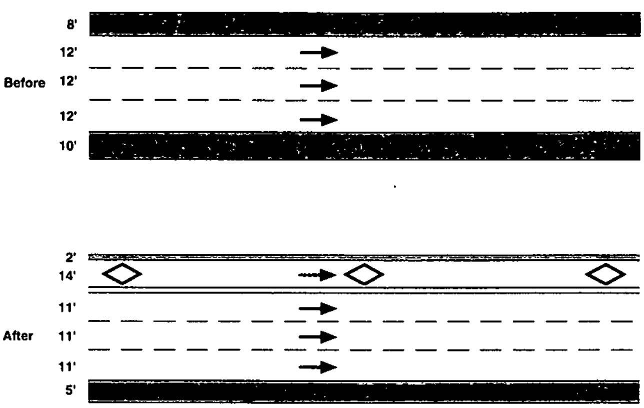


Figure 26. Typical use of shoulders to incorporate an HOV lane.

applied throughout significant portions of urban corridors, either in an intermittent or continuous manner, it was hypothesized that the location of accidents may shift, reducing the accident rate on certain segments and increasing the rate on others. If this was the case it was not clear as to the impact on accident rates for the corridor as a whole. Another concern was that reductions reported in accident rates may be attributable to reduced congestion. If so, when the per lane volumes or congestion reached previous levels the accident rate may actually increase. This research hypothesized that by analyzing a large number of sites contained within several corridors these concerns would be overcome.

The approach used in this study was to examine accident rates on a corridor basis (by comparing the performance of unaltered freeway segments with altered freeway segments) and on a segment basis (by sectioning the freeway according to operational characteristics, e.g., basic freeway, merge, diverge, and weave).

Development of Database

Accident data covering a 3-year period were requested from each agency in computerized format to facilitate analysis. In each case, accident data were requested for the portion of the freeway that included the altered sites and for a similar portion of the corridor that was unaltered. Accident data suitable for analysis were provided by Virginia, Washington, Georgia, and California for the following corridors: I-95, I-395, I-5, I-90, I-85, and I-10. The data were then screened to ensure that meaningful analysis could be conducted. Each database was examined and compared by reviewing its respective accident report and the coding conventions used. This is important because each state has slight variations on how each accident is recorded. For example, in some cases, sideswipe accidents are subdivided into sideswipe and angle accidents. Care was exercised to ensure a consistent data structure for analysis. Multiple vehicle accidents are typically coded as two or more records. These were reduced to single records containing the information required for this research. Only accidents occurring on the mainline, shoulders,

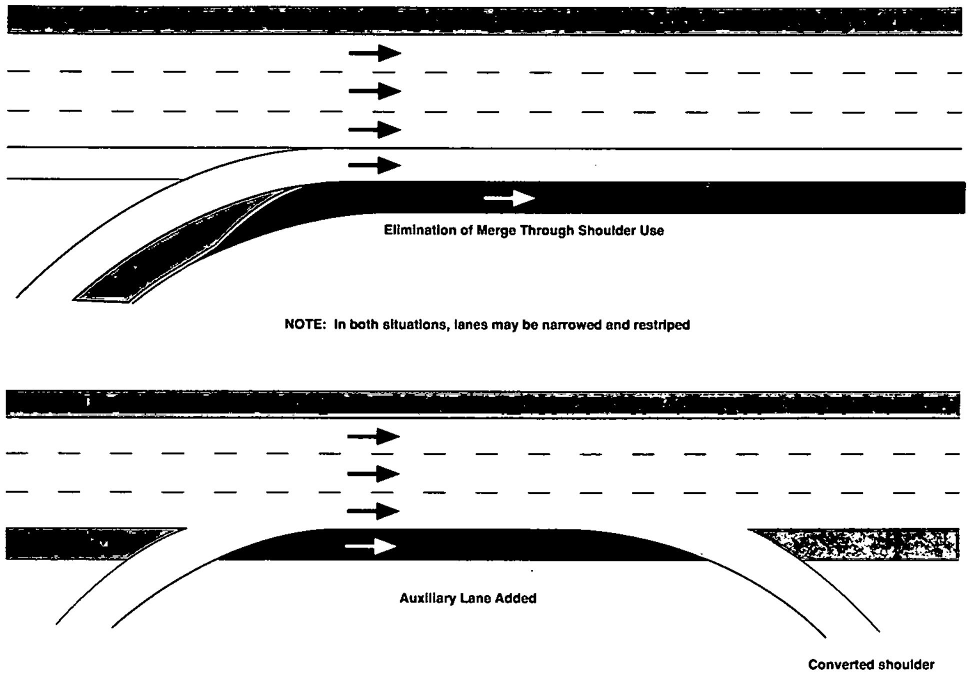


Figure 27. Auxiliary lane/elimination of merge.

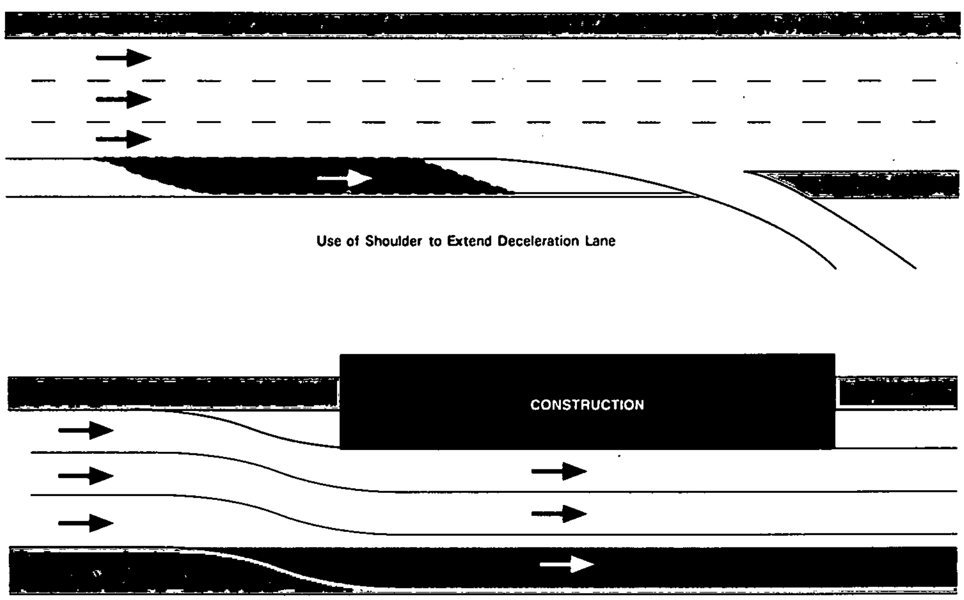


Figure 28. Bypassing mainline queue/construction zones.

and acceleration/deceleration lanes were retained for analysis. Accidents occurring on the ramp were removed as it was assumed they were sufficiently distant from the freeway to be influenced by altered segments. Vehicle types were grouped in two categories: automobile and truck. The automobile category includes passenger vehicles (with and without trailers, and pickups). The truck category includes all other trucks and buses. A summary of the accident data obtained that were usable is presented in Table 15, illustrating the size of the database.

Volume data were obtained from each agency for the same 3-year period as the accident data to allow for development of accident rates. As with the accident data, the volume data format varied from state to state. Some states reported average daily traffic, others reported average weekday traffic. Hourly traffic volumes were obtained to allow development of accident rates for daytime and nighttime conditions. The vehicle miles of travel VMT by segment for each corridor was developed using this information and traffic counts from interchange ramps.

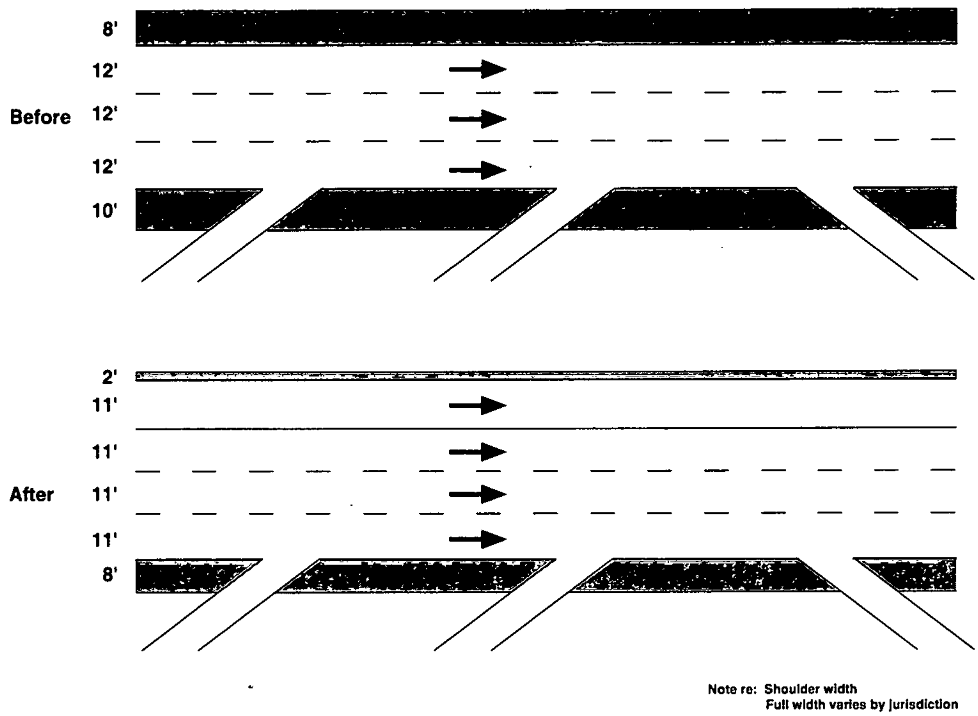


Figure 29. Extended sections.

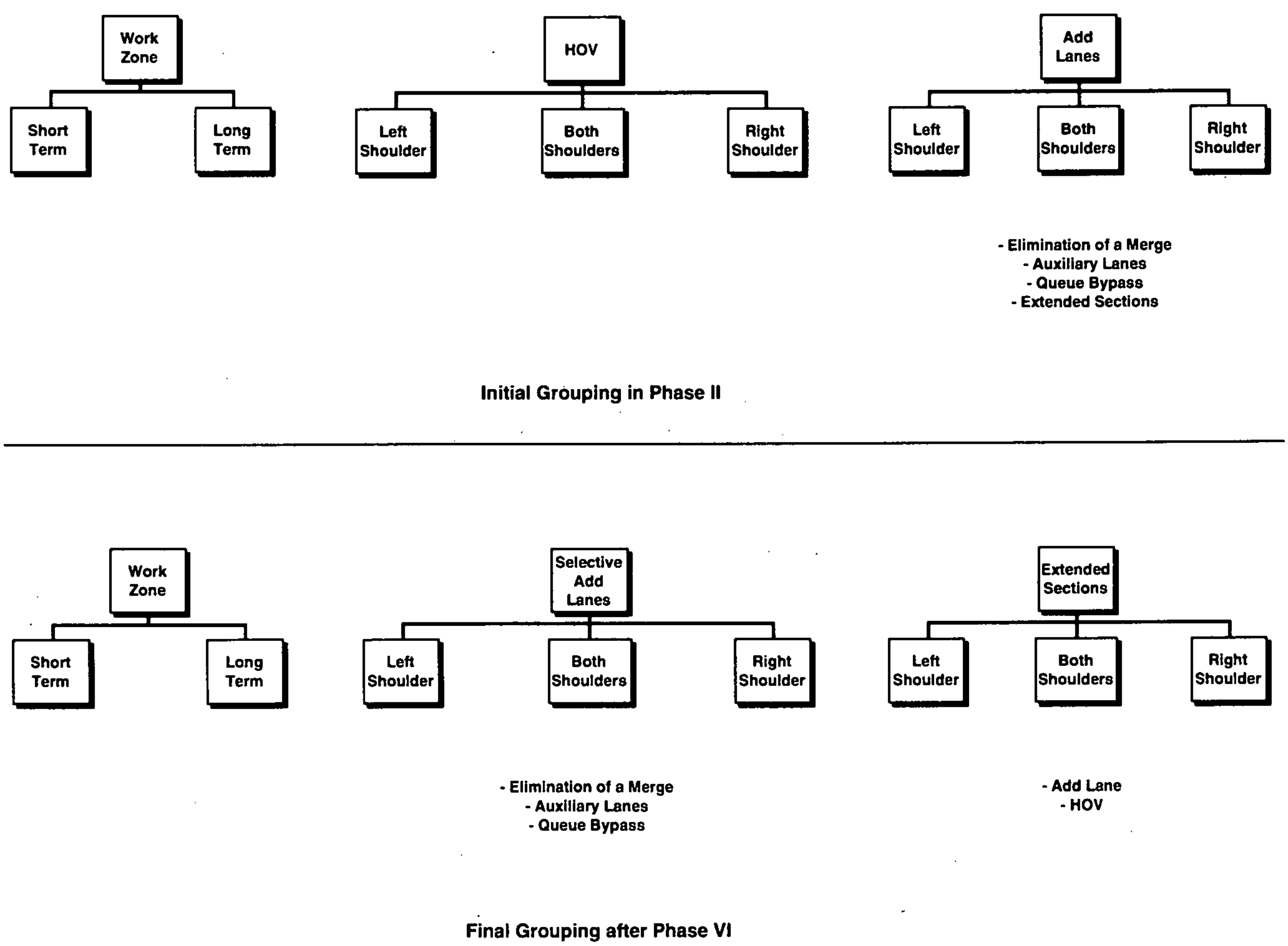


Figure 30. Application groupings.

TABLE 15. Summary of accident data by corridor

Corridor	Years of Data	Total Number of Accidents	Length (Miles)		Total Exposure (Million Vehicle Miles)	
			Unaltered	Altered	Unaltered	Altered
I-395	3.0	1,377	15.10	4.24	1443.3	402.5
I-5 Suburban	3.5	1,598	11.55	8.45	1468.6[1]	292.9
I-5 Urban	3.5	4,656	9.40	8.04	1523.8[1]	485.6
I-85	3.0	2,819	5.73	6.67	1023.1	1158.2
I-10	3.0	2,345	7.71	7.63	1244.1	1258.3
Total:	-	12,795	49.49	35.03	6,693.9	3,597.5

[1]Includes miles traveled both before and after freeway segment was altered.

Analysis Approach

To conduct the analysis, each freeway was segmented—first into altered and unaltered segments, then into sections based on operational characteristics using the guidelines contained in Chapter 3 of the *Highway Capacity Manual.* In addition, the sites (both benchmark and altered) used for operational analysis were identified. The term "benchmark" refers to a specific site within the unaltered segment of the corridor. For the purpose of the accident analysis, sites were defined as the area where operational data were collected and 2500 ft upstream and downstream of the count area, for a total site distance of approximately 6000 ft. Accidents were then tabulated by segment, section, and site. Within each corridor, each site was assigned a number that has been used to reference each site. In two cases, the site numbers assigned for accident analysis varied from those assigned for operational analysis because the definition of the sites for accident analysis resulted in an overlap between sites. Table 16 provides a key to sites by corridor. VMT on an annual basis were developed for each segment, section, and site using the volume data provided by each agency. For the purpose of this study, it was hypothesized that the safety performance of a freeway section may be effectively represented by the accident rate. The effects of shoulder use and reduced lane width on the accident rate may then be estimated by comparing the accident rate for differing field conditions. It was also assumed that the following measures were significant indicators of safety performance:

- Accident severity
- Daytime accident rate versus nighttime accident rate
- Accident rate by type (rear end, side swipe, fixed object)
- Accident rate by vehicle type (automobile, truck)
- Accident rate by freeway characteristic (weaving area, merge or diverge area, basic freeway)

These measures are all influenced by a variety of factors, which will vary from corridor to corridor and site to site. Many of the potential variables are listed in Table 17. Accident rates were developed for a variety of stratifications. A list of the primary stratifications tested is given in Table 18. In this research, the major concern was with isolating the influence of shoulder use and lane width. To determine if any differences found in the accident rate for altered segments versus unaltered segments of freeway were significant, it was assumed that the only significant differences between the altered sites and their respective benchmark sites were the differences in shoulder use and lane width. While not precisely correct, this assumption allowed for paired comparisons of rates on the various stratifications of accidents from the population (exposure to the risk of an accident). Testing was done using the nonparametric Wilcoxon Signed Ranked Test. A nonparametric test was chosen because no assumption concerning the distribution of accidents among the population was made. Results were tested using the following hypotheses:

$$H_O : \text{Unaltered} = \text{Altered versus}$$
$$H_A : \text{Unaltered} \neq \text{Altered}$$

Using a two-sided test, if the probability of the calculated test statistic is greater than the chosen level of significance, then the null hypothesis cannot be rejected. Testing was conducted at a 5 percent level of confidence (i.e., 95 percent confidence level).

Accident rates were expressed as the number of accidents per 100 million vehicle miles. Accident rates were calculated by year and by total period using the equation:

$$\text{Accident Rate } (AR) = \frac{\text{Number of Accidents}}{100 \text{ million vehicle miles}}$$

Analysis Results

The results of the accident analysis are summarized in Tables 19 through 27. A summary of statistical results is given in Table 28 with statistically significant differences noted. Accident rates vary by corridor, from 69 accidents to 288 accidents per 100 million vehicle miles. All corridors, with the exception of the urban I-5 corridor, have accident rates within the range that could be expected on urban freeways based on agency statewide statistics. (The urban I-5 corridor has a higher accident rate because it is constrained and heavily traveled, interchanges are closely spaced with many weaving areas, and many merge-diverge areas to and from ramps are very abrupt.)

Accident rates for altered segments were higher in three out of five corridors (Table 19). If all corridors are considered to

TABLE 16. Key for study site identification

Corridor	Site	Operational Site Number	Accident Study Section Number
RT 128	Kendrick Street, NB	3	
	Kendrick Street, SB	2	
	Ponkapoag NB	1	
	South Street, NB	BM	
	Washington Street, NB	4	
I-95	Pohick Road, NB	2	
	Pohick Road, SB	1	
I-395	Edsall Road, SB	BM	BM
	King Street, SB	1	3
	N. Shirlington Circle, NB	2	1
	S. Shirlington Circle, NB	3	
	S. Shirlington Circle, SB	4	3
I-5 Suburban	178th Street, NB	BM	BM
	178th Street, SB	1	2
	216th Street, NB	4	1
	216th Street, SB	3	4
	Military Road, SB	2	3
I-5 Urban	Albro Place, SB	BM	BM
	Denny Way, SB	2	3
	Holgate Street, SB	1	1
	Yesler Way, NB	3	2
I-90	Island Crest Way, WB	1	
	Island Crest Way, Before, EB	2	
	Island Crest Way, After, EB	BM	
	West Mercer Way, WB	3	
I-85	Chamblee-Tucker Road, SB	4	2
	N. Druid Hills Road, SB	3	3
	Shallowford Road, NB	1	1
	Shallowford Road, SB	2	
	Wood Parkway, SB	BM	BM
I-94	East River Road, WB	1	
	Pascal Street, WB	BM	
	Snelling Avenue, WB	3	
	U of M Exit, EB	2	
I-10	Sixth Avenue, EB	1	1
	Sixth Avenue, WB	2	2
	Crenshaw Boulevard, WB	3	2
	Crenshaw Boulevard, EB	4	1
	West Boulevard, EB	BM	BM
I-405	Bolsa Chica Road, SB	3	
	Cherry NB	BM	
	Golden West Street, SB	4	
	Newland Street, NB	1	
	Newland Street, SB	2	
SR 57	Imperial Highway, NB	1	
	Imperial Highway, SB	2	
	Miraloma Avenue, SB	3	
	Yorba Linda Boulevard, NB	4	
SR 91	Harbor Boulevard, WB	2	
	Kraemer Boulevard, EB	BM	
	Lemon Street, EB	3	
	Placentia WB	1	

be from one population, statistical testing indicates no significant difference between altered and unaltered segments. However, when corridors are stratified or ranked by character, the finding is a significant increase in the accident rate for one population. The accident rate increase for a grouping of the I-395 and I-5 corridors is significant, increasing by up to 36 percent. Interstate 395 and the I-5 corridors are similar in that they use both shoulders and narrow lanes on a continuous basis for an extended length (more than a mile). Shoulder widths varied somewhat but are minimal in all cases (see Table 2). Throughout these corridors, 11-ft lanes have been used.

In Atlanta on I-85, 11-ft lanes have been used but there are generous shoulders. In the Santa Monica corridor, shoulders and narrow lanes have been used extensively for a considerable length; however, the additional lane is not continuous. Shoulders and narrow lanes have been used to relieve specific bottlenecks and improve lane balance and continuity. The result has been a "smoothing" of traffic with a better balance between supply and demand. In both cases, the accident rate has gone down slightly. However, the null hypothesis holds; in the I-10 corridor the change is relatively small, and in the I-85 corridor the rate has varied up and down by year.

TABLE 17. Variables that influence safety performance

- Number of Mainline Traffic Lanes
- Width of Traffic Lanes
- Width of Shoulders
- Proximity of Physical Structures
- Proportion of Trucks in Traffic
- Percent of Commuters
- Horizontal Alignment
- Vertical Alignment
- Level of Nighttime Illumination
- Proximity of Entrance/Exit Ramp
- Interchange Spacing
- Volume of Entering Traffic
- Speed
- Speed Differential (where concurrent-flow HOV lanes exist)
- Level of Service
- Condition of Road Surface
- Weather
- Driver Age
- Alcohol

TABLE 18. Primary stratifications tested

- Accident Rates by Year
- Accident Rates by Vehicle Type
- Accident Rates by Freeway Section
- Accident Rates by Light Conditions
- Accident Rates by Severity
- Accident Rates by Site
- Accident Rates by Collision Type

Because the I-5 corridors were implemented during the period covered by the accident data, a before and after comparison was performed. As shown in Table 20, the accident rate increased for the segments where shoulders and narrow lanes were used. In the unaltered segments where the shoulder and 12-ft lanes have been maintained, the accident rate remained relatively constant. Also notable is that the increase in the accident rate for the altered segments is similar to the difference between unaltered and altered corridors in the I-395 corridor.

Table 21 compares the accident rate by vehicle type. Truck accidents represent all accidents that involved one or more trucks. The accident rate for trucks showed an increase in most cases; however, on a corridor basis, the increases were not found to be statistically significant.

Table 22 shows accident rates for freeway sections as described in the analysis approach. Increases are shown in many cases. However, the research team is reluctant to draw conclusions for the following reasons. In urban corridors the sectioning of the freeway is subject to judgment. Close spacing of interchanges means that many areas of influence overlap. A limited review of accident reports raises concern as to whether the location of accidents is recorded precisely enough for this type of analysis. Accidents are recorded by milepost usually by the officer on the scene (in some cases a milepost is assigned during the data entry process) and is often an estimate of the nearest milepost. Resectioning the freeway with relatively small changes in boundaries results in significant changes in the accident rate. In many cases, the number of accidents within each segment is low. The conclusion of the research team was that this type of detailed analysis would require an extensive effort involving tighter procedures for locating accidents. This concern is similar to the concerns raised with respect to the migration of accidents in response to changed conditions on the freeway. In both cases, conclusions with respect to overall safety performance based on analysis of short sections must be considered carefully.

Table 23 presents the results of analysis based on light conditions. Accident rates for nighttime conditions are higher but are in about the same ratio to daytime accident rates for both unaltered segments and altered segments.

Accident rates by collision type are presented in Table 24. A slight increase in the proportion of sideswipe to rearend accident can be detected. This may indicate drivers are having some difficulty dealing with the narrower lanes; however, on a statistical basis, the proportion throughout the corridor remains unchanged.

The results of an analysis of accident severity are shown in Table 25. Fatal accidents were dropped from further consideration due to the extremely low number of fatalities. No statistically significant change in the ratio of injury accidents to property-damage-only accidents is detectable.

Tables 26 and 27 show the results by site for total accidents and by vehicle type. Similar stratifications to those conducted on a corridor basis were tested but were dropped because the number of accidents in each stratification quickly drops. In 11 of 15 cases, the accident rate was higher for the altered site than for the corridor benchmark (i.e., unaltered) site. This finding reinforces the findings from the corridor analysis.

OPERATIONAL PERFORMANCE

In order to isolate the impacts of shoulder use and narrow lanes from other influencing factors in field studies, two approaches can be taken. A before and after study can be conducted at a site where a project is implemented; however, opportunities for this type of study are limited. Another approach and the one used for this research is to collect data at as many sites as possible where shoulders and narrow lanes have been used and compare them to sites that have remained unaltered and have maintained full shoulders and lane widths. Ideally, comparison or control sites that matched the study sites with the exception of shoulder use or lane width would be chosen. In practice this is virtually impossible. To overcome this constraint, several study sites were chosen in each corridor along with a benchmark site. The benchmark site had full shoulders and 12-ft lanes. Thus two sets of sites were established. The term benchmark was used because it better described the use of the sites (i.e., to establish a point of reference). In total, data were collected at 52 sites: 42 altered sites and 10 benchmark sites.

Development of Database

Operational data were collected at 52 sites in 11 corridors located in 6 states. The corridors studied were listed previously

TABLE 19. Corridor accident rates by year

Corridor	Time Period	Unaltered Accident Rate	Altered Accident Rate	% Difference	Aggregate Accident Rate
I-395	Year 1	64	99	54.7%	72
	Year 2	69	110	59.4%	78
	Year 3	72	81	12.5%	73
	Total	69	97†	40.6%	75
I-5 SUBURB	Total	86	122†	41.9%	100
I-5 URBAN	Total	257	287†	11.7%	275
I-85	Year 1	176	133	-24.4%	154
	Year 2	127	123	-3.2%	125
	Year 3	122	101	-17.2%	111
	Total	142	118	-16.9	129
I-10	Year 1	91	74	-18.7%	85
	Year 2	95	89	-6.3%	92
	Year 3	109	105	-3.7%	107
	Total	98	89	-9.2%	94

Notes: 1. The use of shoulders and narrow lanes in the I-5 corridors was implemented during the three year period for which the accident analysis was conducted. A before and after comparison is presented in Table 28.
2. Shading indicates cases where higher accident rates were observed for altered segments.
3. Accident rates are given by year and for the total period available.
4. Accident rates expressed as accidents per 100 million vehicle miles.
†. Possible difference from unaltered segments inferred by Wilcoxon Test (Table 28)

TABLE 20. I-5 before and after accident rate comparison

Corridor	All Accidents		Auto Accidents		Truck Accidents	
	Before	After	Before	After	Before	After
Suburban						
Segment A	89	75	79	69	224	154
Segment B	86	122	86	131	190	148
Urban						
Segment A	206	183	197	174	324	291
Segment B	257	287	242	271	438	495

Notes: 1. Segment A in both corridors remained unchanged at full standards for the whole time period.
2. Segment B in both corridors was altered to provide an additional lane by utilizing the shoulder(s) and narrow lanes.
3. Accident rates are expressed as accidents per 100 million vehicle miles, 100 million auto miles, and 100 million truck miles.
4. Urban Corridor: 608 Days Before, 791 Days After
5. Suburban Corridor: 781 Days Before, 428 Days After

in Table 2 and described earlier in this chapter. Table 29 provides further information on corridor and site characteristics. These corridors were selected to provide a broad coverage of the application types in use. Criteria used in their selection included: geometric design features, geographic location, vehicle mix, alignment features, availability of comparison or benchmark sites, ability to collect data, and cooperation from the agencies.

Data were collected in a two-step process. First, information was collected from the responsible agency for all potential sites and corridors. This included operational data and physical data necessary to evaluate corridors based on the established criteria. This information was used to make the final selection of sites and corridors. Once the sites and corridors had been collected, contact with the agencies was maintained to verify information and obtain any permits required for data collection.

Operational data were collected in the field during 1992. The primary means of data collection was videotaping. Filming was conducted from freeway overcrossings with traffic filmed from the rear. This procedure ensured that the filming crew was not visible to the traffic being filmed, thus avoiding any influence on the traffic stream. Figure 31 illustrates a typical set-up. At each site, data were collected for a minimum of 6 hours and supplemented as necessary by manual or tube counts. In addition, travel time runs were conducted at each site to allow verification of speed data obtained. When feasible, data were obtained from the videotapes using a system developed by JHK, the Video

TABLE 21. Corridor accident rates by vehicle type

CORRIDOR	Time Period	AUTO			TRUCK		
		Unaltered	Altered	% Diff.	Unaltered	Altered	% Diff.
I-395	Year 1	60	95	58.3	141	189	34.0
	Year 2	62	108	74.2	208	151	-27.4
	Year 3	68	77	13.2	150	166	10.7
	Total	63	93†	47.6	167	168	0.6
I-5 SUBURB	Total	77	131†	70.1	191	148	-22.5
I-5 URBAN	Total	204	271†	32.8	344	495	43.9
I-85	Year 1	136	105	-22.8	594	742	24.9
	Year 2	91	101	10.9	505	580	14.8
	Year 3	95	89	-6.3	410	362	-11.7
	Total	108	98	-9.3	501	552	10.2
I-10	Year 1	85	64	-24.7	218	289	32.6
	Year 2	90	77	-14.4	208	355	70.7
	Year 3	105	98	-6.7	181	257	42.0
	Total	93	80	-14.0	202	300	48.5

Notes: 1. Truck Accident Rates are the number of accidents involving at least one truck per 100 Million Truck Miles. The Total Accident Rate is based on the total three year period.
2. Shading indicates cases where higher accident rates were observed for altered segments.
3. Accident rates are given by year and for the total period available.
4. Accident rates are expressed as accidents per 100 million vehicle miles.
†. Possible difference from unaltered segments inferred by Wilcoxon Test (Table 28)

TABLE 22. Corridor accident rates for freeway sections

Corridor	Time Period	BASIC		RAMP		WEAVE	
		Unaltered	Altered	Unaltered	Altered	Unaltered	Altered
I-395	Year 1	110	109	55	65	64	121
	Year 2	70	94	75	108	60	120
	Year 3	84	58	65	68	78	103
	Total	88	87	61	71†	75	121
I-5 SUBURB	Total	87	153	84	112†	73	64
I-5 URBAN	Total	217	265	236	303†	183	287
I-85	Year 1	190	188	166	114	*	*
	Year 2	127	161	128	109	*	*
	Year 3	113	118	129	95	*	*
	Total	143	154	141	106	*	*
I-10	Year 1	93	163	92	69	74	104
	Year 2	115	230	92	77	65	101
	Year 3	119	273	105	91	115	105
	Total	109	222	96	77	85	103

Notes: 1. * No weave sections in the corridor.
2. Shading indicates cases where higher accident rates were observed for altered segments.
3. Accident rates are given by year and for the total period available.
4. Accident rates are expressed as accidents per 100 million vehicle miles.
†. Possible difference from unaltered segments inferred by Wilcoxon Test (Table 28)

Traffic Data Acquisition System (VTRACS). VTRACS allows the operator to set analysis parameters—marker length, length of count, number of counts, file names, etc.—control the videocassette recorder, extract all the necessary data, and print a concise report of volumes and speed by lane for the time period specified. For some sites having difficult lighting conditions, the videotapes were studied using more traditional manual methods.

Speed, volumes, and percent trucks were obtained for all sites. At sites selected for in-depth analysis, lateral placement, the number of line crossings (line crossings refer to inadvertent line crossings when no lane changes are made), lane changes, brake applications, and lane distribution of traffic were also obtained.

Speed and volume data were reduced by lane for each 5-min period for all videotapes. The 5-min periods were chosen as

TABLE 23. Corridor accident rates for light conditions

CORRIDOR	Time Period	DAY		NIGHT	
		Unaltered	Altered	Unaltered	Altered
I-395	Year 1	61	94	72	114
	Year 2	61	100	91	135
	Year 3	64	71	84	108
	Total	61	88†	83	119†
I-5 SUBURB	Total	71	120†	119	127†
I-5 URBAN	Total	216	295†	207	268†
I-85	Year 1	162	121	225	161
	Year 2	115	120	169	132
	Year 3	115	96	147	117
	Total	131	112	180	140
I-10	Year 1	71	66	151	98
	Year 2	78	80	146	118
	Year 3	99	100	136	121
	Total	83	82	144	113

Notes: 1. Shading indicates cases where higher accident rates were observed for altered segments.
2. Accident rates are given by year and for the total period available.
3. Accident rates are expressed as accidents per 100 million vehicle miles.
†. Possible difference from unaltered segments inferred by Wilcoxon Test (Table 28)

TABLE 24. Corridor accident rates by collision type

Corridor	Time Period	SIDESWIPE		REAREND		FIXED/OBJECT		OTHER	
		Unaltered	Altered	Unaltered	Altered	Unaltered	Altered	Unaltered	Altered
I-395	Year 1	14	15	32	53	15	19	4	12
	Year 2	14	22	34	55	18	21	2	7
	Year 3	10	17	43	57	13	15	4	2
	Total	14	18†	37	54	16	18	3	7
I-5 SUBURB	Total	17	27†	38	74	12	13	18	8
I-5 URBAN	Total	37	56†	132	188	26	26	19	16
I-85	Year 1	43	31	80	66	28	13	25	24
	Year 2	32	21	63	69	11	16	16	18
	Year 3	30	20	67	69	16	16	13	13
	Total	35	23	70	65	18	14	18	17
I-10	Year 1	18	19	55	38	11	11	5	5
	Year 2	21	19	59	54	12	13	3	4
	Year 3	14	17	75	71	13	12	6	5
	Total	18	18	63	55	12	12	5	5

Notes:
1. Shading indicates cases where higher accident rates were observed for altered segments.
2. Accident rates are given by year and for the total period available.
3. Accident rates are expressed as accidents per 100 million vehicle miles.
†. Possible difference from unaltered segments inferred by Wilcoxon Test (Table 28)

opposed to the traditional 15-min period used in the *Highway Capacity Manual* because this research was focused on a specific question, i.e., "Does the lack of shoulders or the use of narrow lanes result in different operating conditions?" The database used can be aggregated into 15-min periods for use in the study of speed-flow relationships in general. Lateral placement, line crossings, and brake applications were obtained for one 5-min period out of each 15 min for a minimum of one site in each corridor.

Traffic volumes presented in this report are presented in passenger cars per hour. Traffic volume data were collected in terms of vehicles per hour and then converted to passenger cars per hour using site- and time-specific truck percentages following the procedures of the *Highway Capacity Manual.*

Analysis Approach

Analysis was conducted on a site-by-site (disaggregate) basis, on a corridor (aggregate) basis, and by stratifications (groupings)

TABLE 25. Corridor accident rates by severity

Corridor	Time Period	PROPERTY DAMAGE ONLY		INJURY	
		Unaltered	Altered	Unaltered	Altered
I-395	Year 1	43	60	21	38
	Year 2	40	74	29	36
	Year 3	48	47	25	34
	Total	43	60	25	36†
I-5 SUBURB	Total	46	67	38	55†
I-5 URBAN	Total	119	165	94	123†
I-85	Year 1	135	100	40	35
	Year 2	95	92	27	30
	Year 3	97	85	29	31
	Total	109	88	32	30
I-10	Year 1	70	58	20	16
	Year 2	79	68	15	18
	Year 3	83	82	24	23
	Total	78	70	20	19

Notes: 1. Shading indicates cases where higher accident rates were observed for altered segments.
2. Accident rates are given by year and for the total period available.
3. Accident rates are expressed as accidents per 100 million vehicle miles.
†. Possible difference from unaltered segments inferred by Wilcoxon Test (Table 28)

TABLE 26. Study site accident rates

Corridor	Year	Benchmark	Site 1	Site 2	Site 3	Site 4
I-395	1	32	120	37	64	
	2	49	126	59	60	
	3	40	80	50	63	
	Total	40	108†	49†	62†	
I-5 SUBURBAN	Total	65	105†	201†	85†	47
I-5 URBAN	Total	58	91†	176†	544†	
I-85	1	248	122	243	144	
	2	147	106	299	58	
	3	173	55	237	128	
	Total	190	92	260	146	
I-10	1	50	63	117		
	2	82	61	133		
	3	94	87	174		
	Total	76	72	141		

Notes: 1. Accident rates per 100 million vehicle miles
2. Shaded blocks indicate a higher accident rate was recorded at the altered site than at the corridor benchmark site. Benchmark sites are specific research sites within unaltered segments of the corridor.
†. Possible difference from unaltered segments inferred by Wilcoxon Test (Table 28)

of sites by physical and operational characteristics. Speed-volume data were plotted by lane and as per lane averages. A variety of plots were used, including a standard speed-flow plot, time-sequenced plots, and two Y-axis plots. Plots were prepared for each site on a corridor basis, and for stratifications of sites. The stratifications examined included: lane width, shoulder width, percentage of trucks, wearing areas, number of lanes, and alignment. Time-sequenced plots were used to identify stable portions of the speed-volume curve and then regression analysis was used to compare "narrow lane" curves with "benchmark" curves. The findings of this research are presented in the following sections primarily through the use of summary plots on a corridor (aggregate) basis because the research team believes that these best show the results.

For the purpose of this research, it was hypothesized that the operational performance of a freeway could be effectively

TABLE 27. Study site accident rates by vehicle type

		Benchmark		Site 1		Site 2		Site 3		Site 4		Average	
CORRIDOR	YEAR	AUTO	TRUCK	AUTO	TRUCK	AUTO	TRUCK	AUTO	TRUCK	AUTO	TRUCK	AUTO	TRUCK
I-395	1	34	0	108	350	39	0	67	0			67	98
	2	49	52	133	0	59	57	57	137			77	68
	3	42	0	84	0	46	114	60	139			61	91
	Total	42	18	108	112	48	79	61	94			68	85
I-5 SUBURBAN	Total	57	169	110	37	193	306	81	134	49	31	104	122
I-5 URBAN	Total	49	172	79	240	176	184	525	797			260	407
I-85	1	201	612	98	674	218	751	121	605			145	677
	2	103	562	92	423	238	1555	142	729			153	894
	3	139	491	53	117	206	865	102	639			115	523
	Total	148	584	79	381	219	1065	121	656			137	697
I-10	1	45	158	52	278	104	387					79	334
	2	73	286	55	413	111	608					84	515
	3	97	38	81	208	162	416					122	312
	Total	72	156	63	267	126	472					95	371

Notes:
1. Auto accident rate per 100 million auto miles
2. Truck accident rate per 100 million truck miles
3. Shaded blocks indicate a higher accident rate than Benchmark.

TABLE 28. Wilcoxon ranked results of paired tests (refer to Tables 19 through 26)

	I-395; I-5 SUBURBAN; I-5 URBAN (5 SAMPLES)			I-85 (3 SAMPLES)			I-10 (3 SAMPLES)		
VARIABLE	WILCOXON PROB.	CONC'N	INFERENCE	WILCOXON PROB.	CONC'N	INFERENCE	WILCOXON PROB.	CONC'N	INFERENCE
VEHICLE TYPE									
AUTO	0.043	Reject	Poss. Diff.	0.59	DNR	No Diff.	0.11	DNR	No Diff.
TRUCK	0.69	DNR	No Diff.	0.29	DNR	No Diff.	0.11	DNR	No Diff.
LIGHT CONDITION									
DAY	0.043	Reject	Poss. Diff.	0.29	DNR	No Diff.	1	DNR	No Diff.
NIGHT	0.043	Reject	Poss. Diff.	0.11	DNR	No Diff.	0.11	DNR	No Diff.
FWY SECTION									
BASIC	0.35	DNR	No Diff.	0.29	DNR	No Diff.	0.11	DNR	No Diff.
RAMP	0.04	Reject	Poss. Diff.	0.11	DNR	No Diff.	0.29	DNR	No Diff.
WEAVE	0.08	DNR	No Diff.	(No Weave Sections in BM)			0.11	DNR	No Diff.
SEVERITY									
PDO	0.08	DNR	No Diff.	0.11	DNR	No Diff.	0.11	DNR	No Diff.
INJURY	0.04	Reject	Poss. Diff.	1	DNR	No Diff.	0.59	DNR	No Diff.
FATAL	0.72	DNR	No Diff.	0.11	DNR	No Diff.	0.11	DNR	No Diff.
COLLISION TYPE									
SIDESWIPE	0.043	Reject	Poss. Diff.	0.11	DNR	No Diff.	0.59	DNR	No Diff.
REAR END	0.08	DNR	No Diff.	1	DNR	No Diff.	0.11	DNR	No Diff.
FIXED OBJ.	0.07	DNR	No Diff.	0.65	DNR	No Diff.	1	DNR	No Diff.
OTHER	0.89	DNR	No Diff.	0.65	DNR	No Diff.	1	DNR	No Diff.
SEGMENT	0.043	Reject	Poss. Diff.	0.29	DNR	No Diff.	0.11	DNR	No Diff.

NOTE: DNR = Do Not Reject

represented by the relationship between speed and volume over a range of LOS from C to E, lateral placement, number of line crossings, number of lane changes, and brake applications. A limited number of site-specific plots are also presented. The primary focus of the analysis was on the speed volume relationship.

The relationship between speed and volume is influenced by a number of factors including the following:

TABLE 29. Site conditions

Freeway	Site	Lane Width		Left Shoulder			Right Shoulder			% Trucks			Application Type		Freeway Section		
		11′	12′	< 2′	2 - 8′	> 8′	< 2′	2 - 8′	> 8′	< 5%	5 - 10%	> 10%	HOV	Add Lane	Merge/Div	Weave	BFS
Rt 128	Kendrick Street, NB		X		X		X			P	M			X			X
	Kendrick Street, SB		X		X		X			P	AM			X			X
	Ponkapoag NB		X		X		X			P	A			X			X
	South Street, NB		X		X				X	AP	M			BM			X
	Washington Street, NB		X		X		X			WP	A			X	X		
I-95	Pohick Road, NB	X		X			X				AP	M	X				X
	Pohick Road, SB	X		X			X				PW	AM	X				X
I-395	Edsall Road HOV, SB		X			X	X		X	P	AM			BM		X	
	King Street, SB	X		X					X					X		X	
	N. Shirlington Circle, NB	X		X				X						X	X		
	S. Shirlington Circle, NB	X		X				X		M				X	X		
	S. Shirlington Circle, SB	X		X					X					X	X		
I-5	178th Street, NB		X			X	X		X		AMP			BM			X
	178th Street, SB	X		X					X			A	X				X
	216th Street, NB	X			X				X		AM		X				X
	216th Street, SB	X			X				X		AM		X				X
	Albro Place, SB		X			X	X		X		AP			BM	X		
	Denny Way, SB	X		X					X	P	AM		X			X	
	Military Road, SB	X			X				X	P	M		X		X		
	Holgate Street, SB	X		X			X				AM			X	X		
	Yesler Way, NB	X			X		X			P	M			X	X		
I-90	Island Crest Way, EB	X		X				X		P	A		X		X		
	Island Cr. Way, EB-After		X			X			X					BM	X		
	Island Crest Way, WB	X		X				X		W	M		X		X		
	West Mercer Way, WB	X			X			X					X		X		
I-85	Chamblee - Tucker, SB	X				X			X	A				X	X		
	N. Druid Hills, SB	X				X			X	APW	M			X	X		
	Shallowford Rd, NB	X				X			X	P	M			X	X		
	Shallowford Rd, SB	X				X			X	AP				X	X		
	Wood Parkway, SB		X			X	X		X					BM	X		
I-94	East River Road, WB		X	X			X			P	AM			X	X		
	Pascal Street, WB		X			X			X	P	A			BM	X		
	Snelling Avenue, WB		X		X				X		M			X			X
	U of M Exit, EB		X	X				X		P	AM			X	X		
I-10	6th Avenue, EB	X		X					X	W	MP			X		X	
	6th Avenue, WB	X		X					X	P	AM			X		X	
	Crenshaw Blvd., EB	X		X					X	AP				X	X		
	Crenshaw Blvd., WB	X		X					X	M				X	X		
	West Boulevard, EB		X			X	X		X	A	MP			BM		X	
I-405	Bolsa Chica Road, SB		X	X			X		X				X		X		
	Cherry NB		X			X	X		X	A				BM	X		
	Golden West Street, SB		X	X			X		X	W	M		X		X		
	Newland Street, NB		X	X			X		X	AP			X			X	
	Newland Street, SB		X	X			X		X		M		X		X		
SR 57	Imperial Highway, NB	X		X					X		A	M	X		X		
	Imperial Highway, SB	X		X					X	W		M	X		X		
	Miraloma Avenue, SB		X			X			X			M	X	X		X	
	Yorba Linda Blvd., NB	X		X					X			AMP	X		X		
SR 91	Harbor Blvd., WB	X		X			X			W	M	A		X	X		
	Kraemer Blvd., EB		X			X			X		AP			BM			X
	Lemon Street, EB	X		X			X					M		X		X	
	Placentia Avenue, WB	X		X				X			A			X	X		

LEGEND: A—AM Peak P—PM Peak M—Mid-Day X—All Day
W—Weekend Period BM—Benchmark

- Number of mainline traffic lanes
- Width of mainline traffic lanes
- Width of right shoulder
- Width of left shoulder
- Proximity of obstruction to the right lane
- Proximity of obstruction to the left lane
- Proportion of trucks in the traffic flow
- Proportion of commuters in the traffic flow
- Horizontal alignment
- Vertical alignment
- Nighttime illumination
- Volume of entering traffic

The relationship between speed and volume can be expressed algebraically as:

Speed (S) = f(volume, other variables)

In addition to the plots, data were developed for three measures of effectiveness (MOE):

1. Average of three highest flow rates in each of the LOS speed ranges. This MOE was chosen to address the question, "Is the maximum flow rate reduced as a result of reductions in lane width or shoulder width?"
2. Average speed within specified volume ranges. This MOE was chosen to address the question, "Does the use of shoulders or a reduction in lane width reduce speeds for a given volume of traffic?"
3. Highest 15-min flow rate. The purpose of this MOE was to determine if the use of shoulders or a reduction in lane width

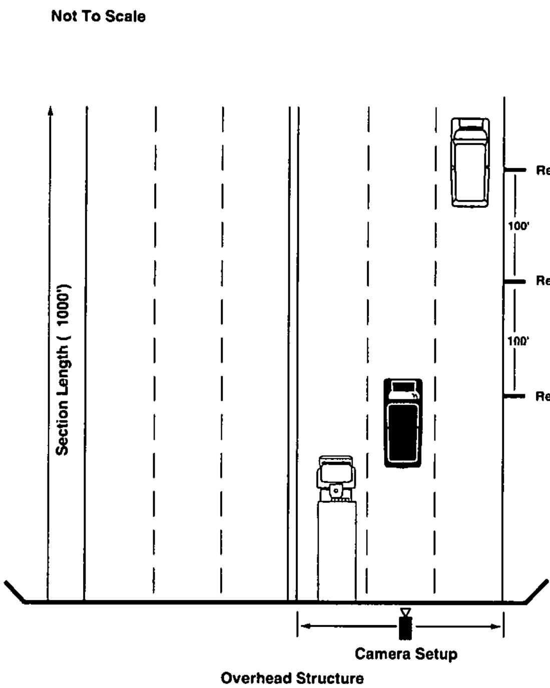


Figure 31. Typical videotaping setup.

decrease the ability to sustain high flow rates over a period of time.

FINDINGS AND OBSERVATIONS

Speed-Flow Relationship

The analysis of data indicates that the lack of shoulders or narrow lanes has little if any impact on speed at lower volume ranges. At higher volume ranges, there is a slight reduction in average speed in some cases. At maximum volume ranges (LOS E and F), no difference in speed is detectable. There is a noticeable increase in the speed variability at higher volume ranges.

Figure 32 is a chart showing a plot for all benchmarks. It is notable for the fact that data from 10 corridors and 6 different cities with varying physical and operational characteristics fit a relatively "tight" band, matching the curves adopted in the revised version of Chapter 3 in the *Highway Capacity Manual.*

Figures 33 through 44 illustrate speed-volume data by corridor. Data have been distinguished by site. For reference, the speed volume curves have been shown for free-flow speeds of 55 and 70 mph used in Chapter 3 of the 1993 revision of the *Highway Capacity Manual* are shown on each chart, as well as the curve developed from data from all of the 10 benchmark sites as in Figure 32.

In summary, at volume ranges below 1600 pcphpl, speeds recorded at altered sites are essentially identical to speeds at the benchmark sites. At flow rates between 1600 pcphpl and 2000 pcphpl (LOS C and D), speeds at the altered sites are slightly lower in most cases. Speed differences are small, typically less than 5 mph. At higher volume ranges, above 2000 pcphpl (LOS E and F), no significant difference in speed can be determined between altered and benchmark sites. Table 30, which compares data from specific sites to benchmark sites for the same time period and direction of flow within a corridor, highlights the fact that any differences are small.

The most notable difference is in the speed variability or range of speeds observed at many sites. The range of speeds observed at the altered sites is almost double that of the benchmark sites, with speeds for the benchmark sites ranging between 50 mph and 70 mph up to flow rates approaching 2000 pcphpl while speeds ranged from 30 mph to 70 mph at altered sites. However, it must be noted that, based on regression analysis, even this finding was not statistically significant. Table 31 presents the results of regression analysis on a corridor basis. Figures 45 and 46 illustrate regression analysis completed in which lines of best fit were developed on a "segmental" basis using volume ranges.

Individual sites were reviewed using time sequenced plots as illustrated in Figures 47 and 48. In addition, "double" Y-axis plots were developed on a site-by-site basis to review speed and volume relationships. Examples of these are shown in Figures 49 and 50. No specific conclusions regarding differences between unaltered (benchmark) and altered sites can be drawn.

Tables 32, 33, 34, and 35 present the MOEs defined in the previous section. Paired comparisons were tested using Student's t-test. For statistical testing only, data from sites that experienced a breakdown in traffic flow during the time period filmed were used to test MOEs 1 and 3. A summary of the statistical tests is presented in Tables 36 and 37.

For certain time periods, the MOE values reflect only a relatively low traffic volume and provide no insight on capacity. The MOE is only applicable to sites that experience a breakdown in traffic flow.

The results of the analysis presented in Tables 36 and 37 support the findings based on the speed-flow curves and regression analysis that any variance in operational characteristics between altered and unaltered sites is speed related.

Lateral Placement, Line Crossings, and Brake Applications

Lateral placement, line crossings (inadvertent lane line crossings not lane changes), and brake applications were obtained from the videotapes for altered sites and benchmark sites.

The percent of traffic within a foot of the leftmost lane line was considerably lower at most altered sites as compared to benchmark sites. Figure 51 illustrates lateral placement at an altered site. Figure 52 illustrates lateral placement at the corresponding benchmark site. This indicates that lateral clearance does have an impact on lateral placement within a lane because drivers clearly shy away from the barrier. The degree to which this occurs varies by the type of median; however, drivers still tend toward the left of the median lane and the right shoulder lane as opposed to centering themselves as in other travel lanes.

Inadvertent line crossings per hour increased significantly with narrow lane sites when compared with benchmark sites. Table 38 summarizes line crossings and lane changes at several sites. Both of these measures indicate a degree of driver discomfort. Line crossings in particular are intuitively consistent with poorer safety performance; however, a direct correlation was not possible and would be extremely difficult to accomplish.

Brake applications at all sites were virtually nonexistent with the exception of when the queue from downstream congestion backed up toward a study site.

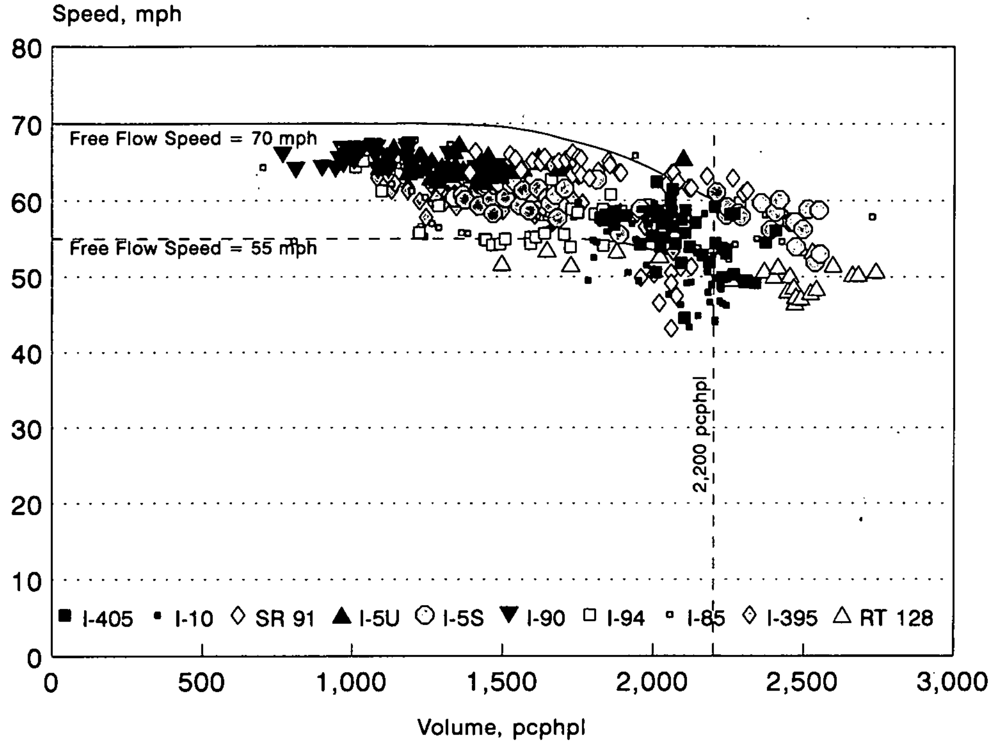


Figure 32. Speed-flow data for benchmark sites (5-min sampling periods).

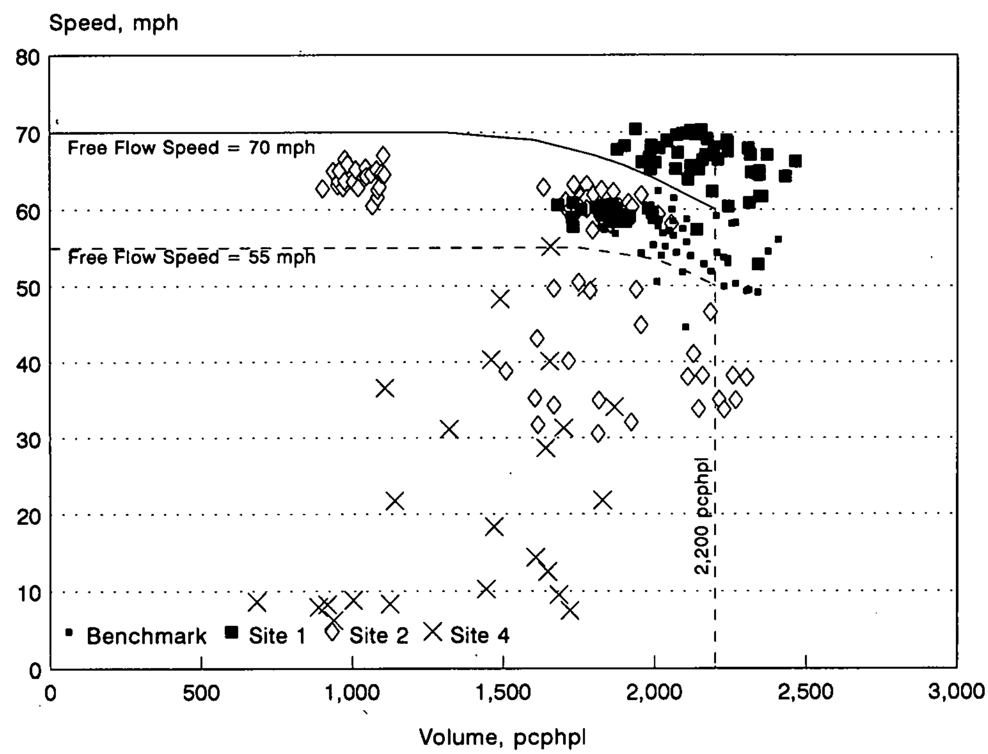


Figure 33. Speed-flow data for I-405 (5-min sampling periods).

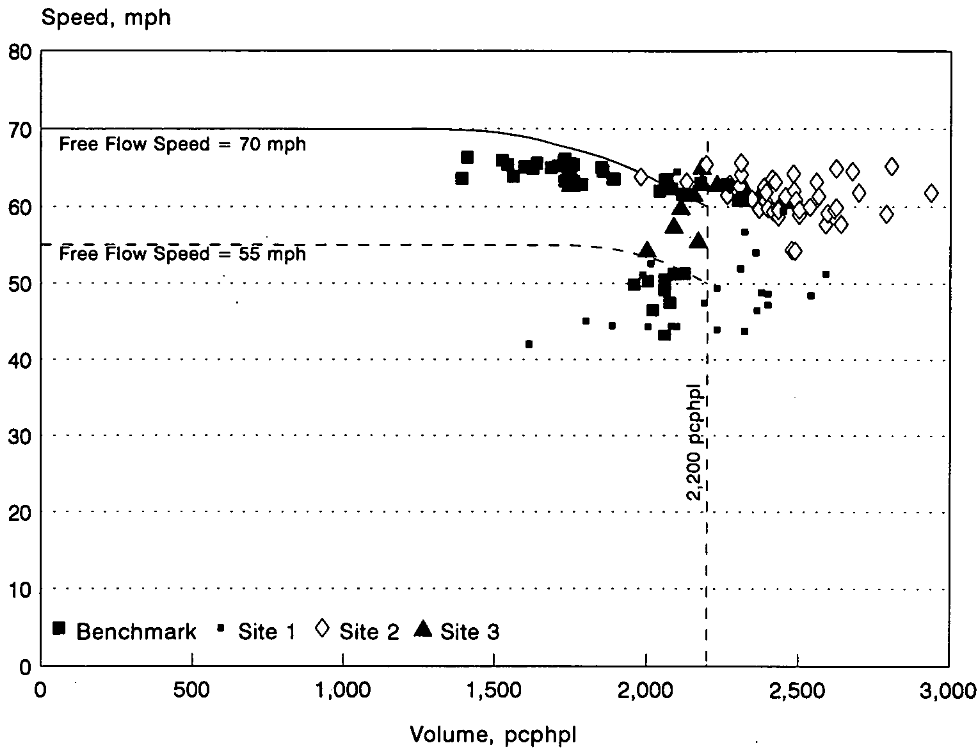


Figure 34. Speed-flow data for SR 91 (5-min sampling periods).

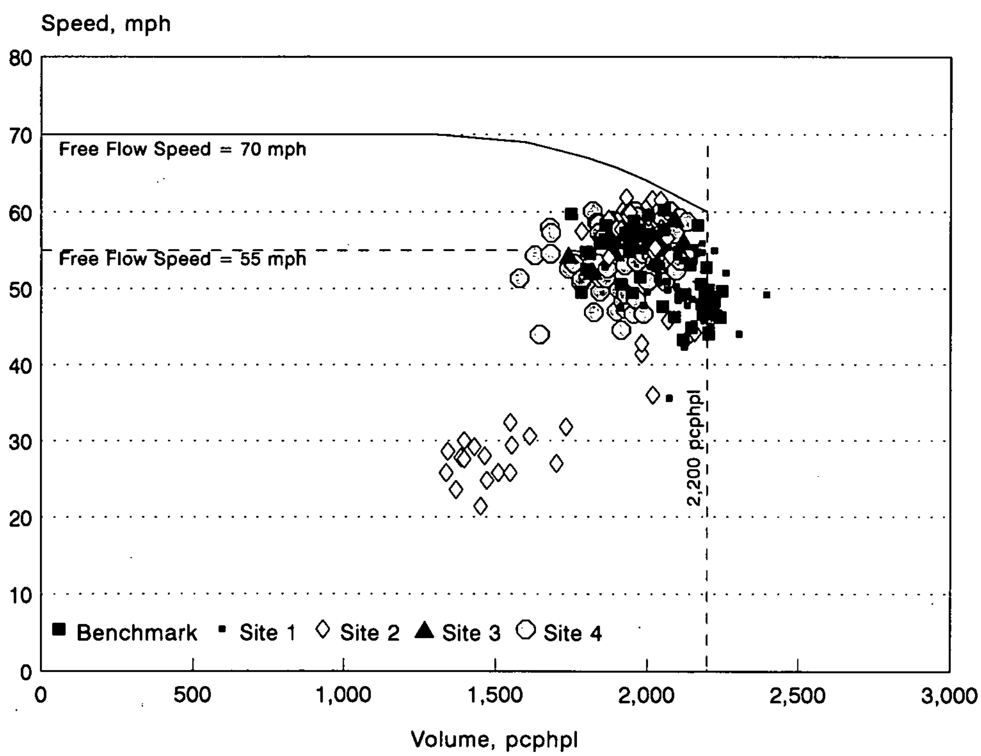


Figure 35. Speed-flow data for I-10 (5-min sampling periods).

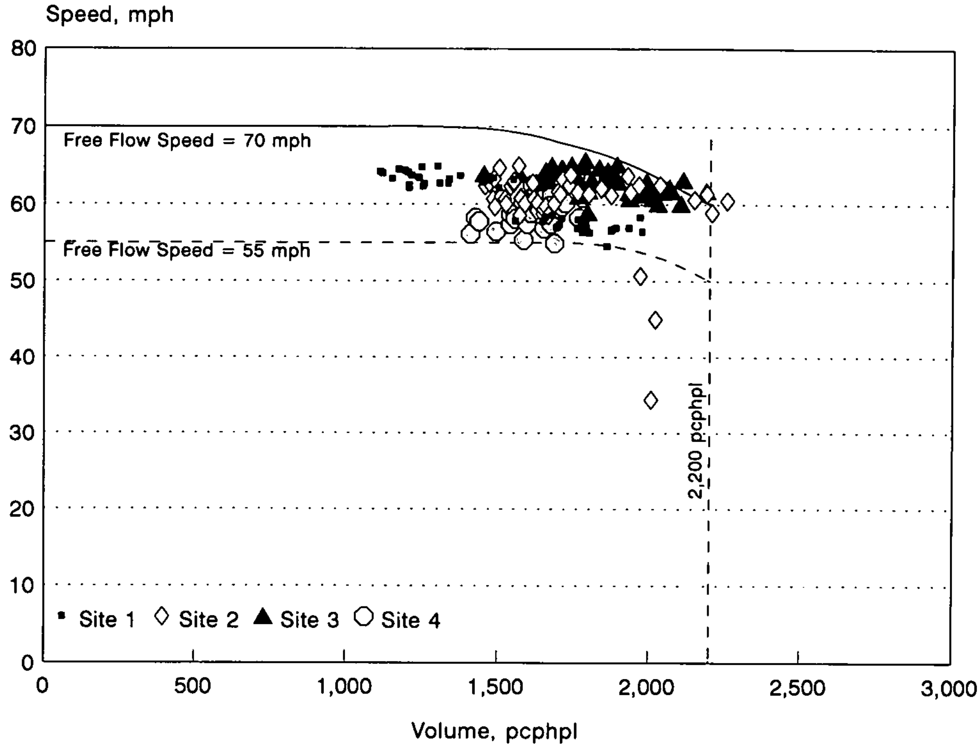


Figure 36. Speed-flow data for SR 57 (5-min sampling periods).

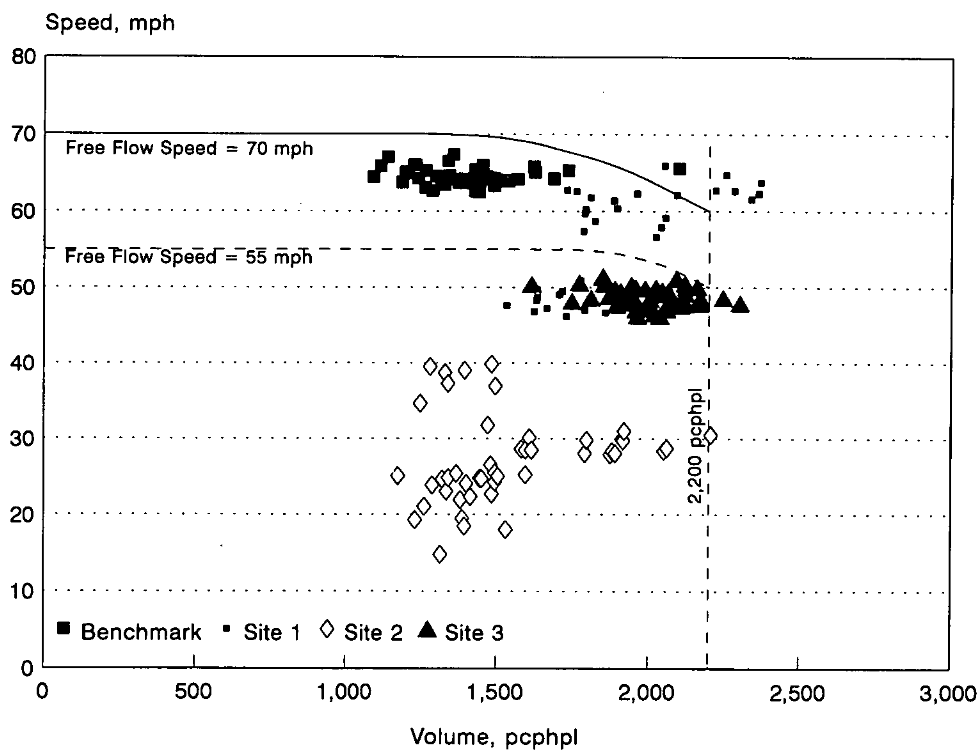


Figure 37. Speed-flow data for I-5 urban (5-min sampling periods).

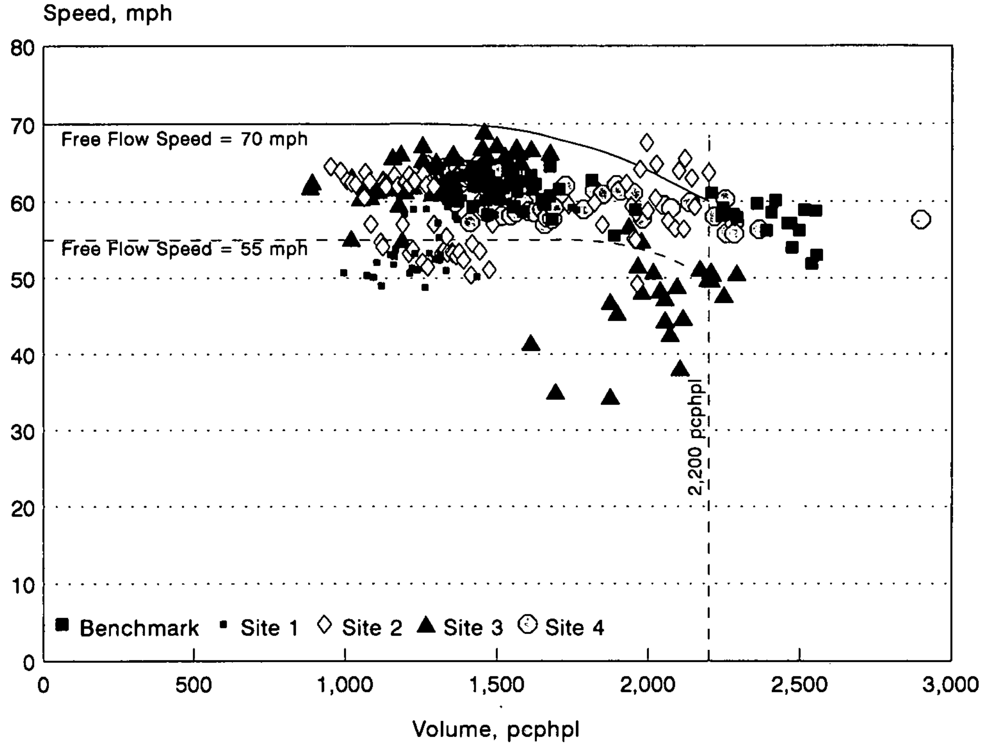


Figure 38. Speed-flow data for I-5 suburban (5-min sampling periods).

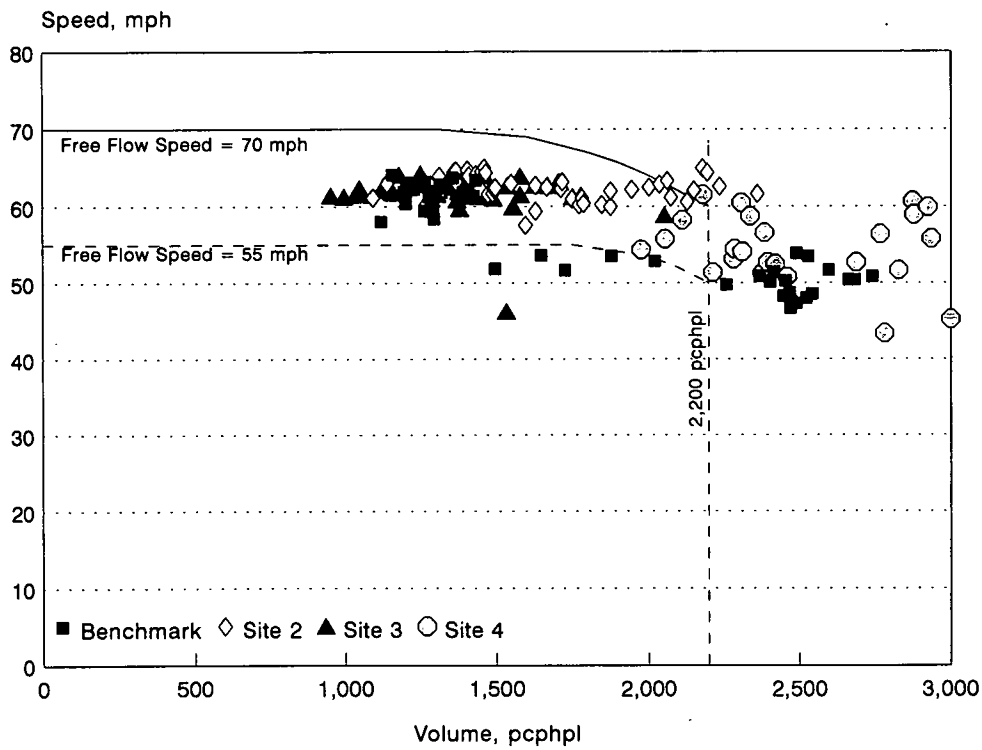


Figure 39. Speed-flow data for Rt 128 (5-min sampling periods).

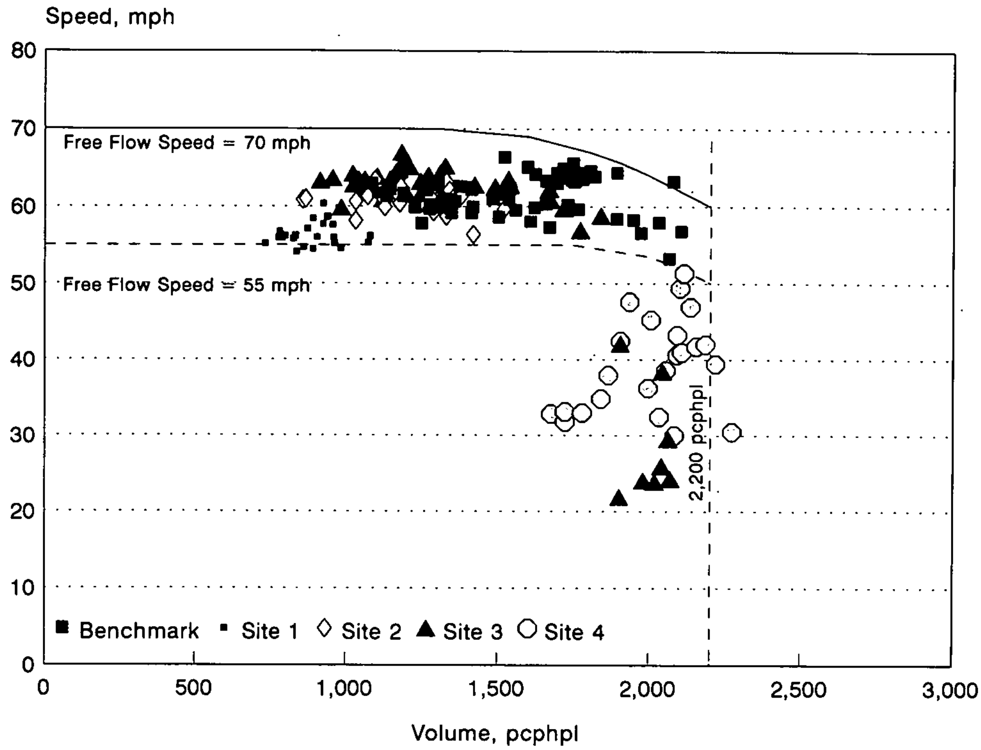


Figure 40. Speed-flow data for I-395 (5-min sampling periods).

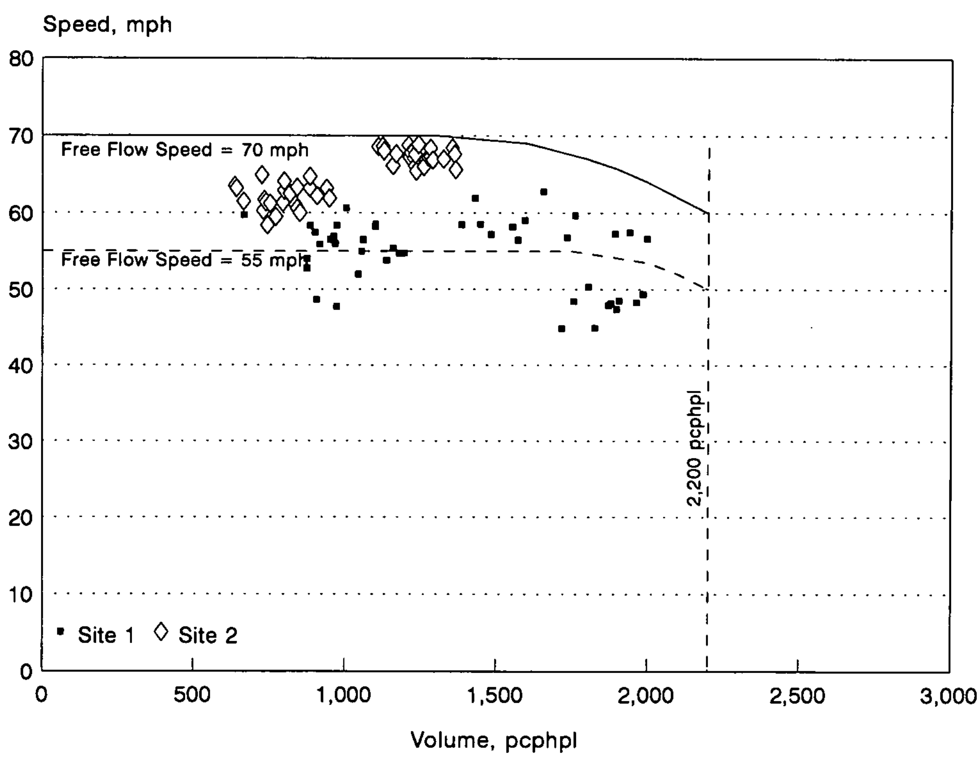


Figure 41. Speed-flow data for I-95 (5-min sampling periods).

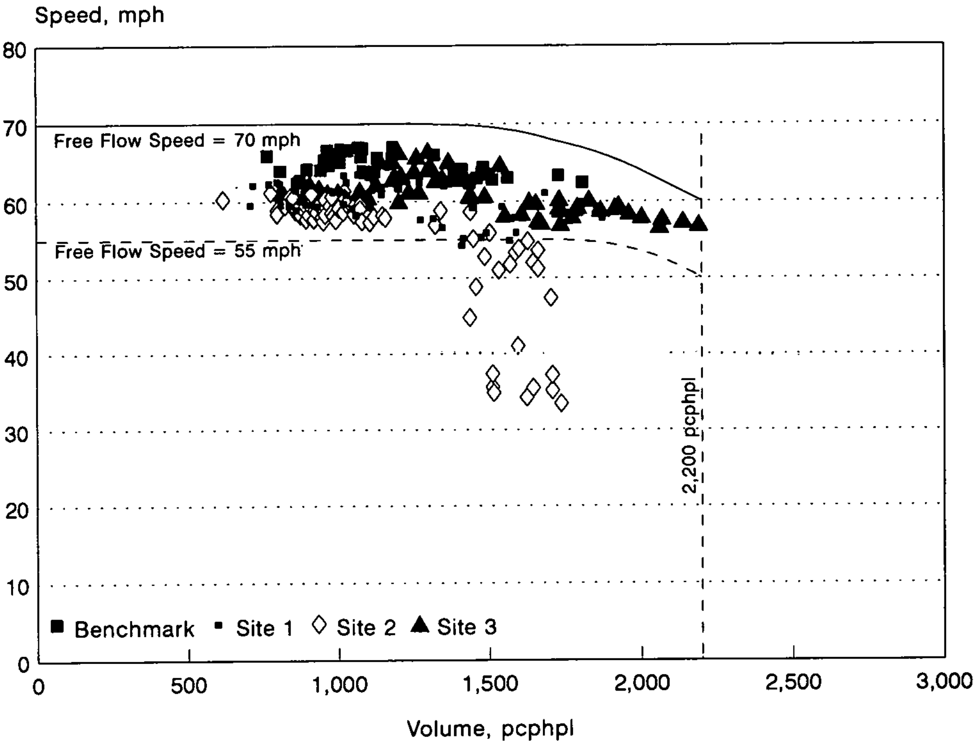


Figure 42. Speed-flow data for I-90 (5-min sampling periods).

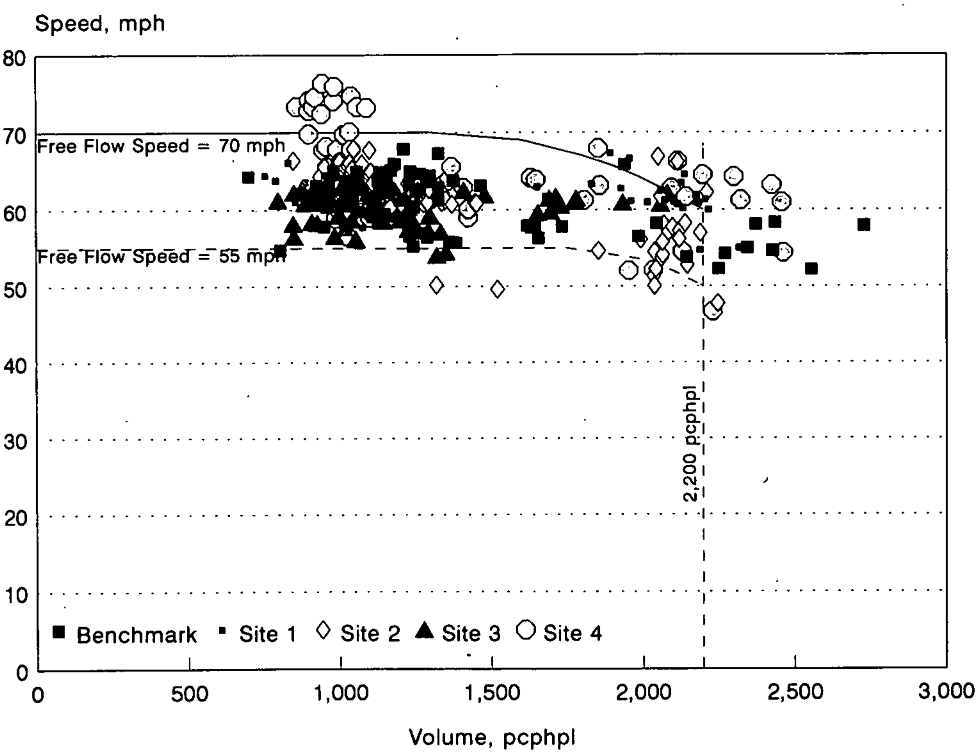


Figure 43. Speed-flow data for I-85 (5-min sampling periods).

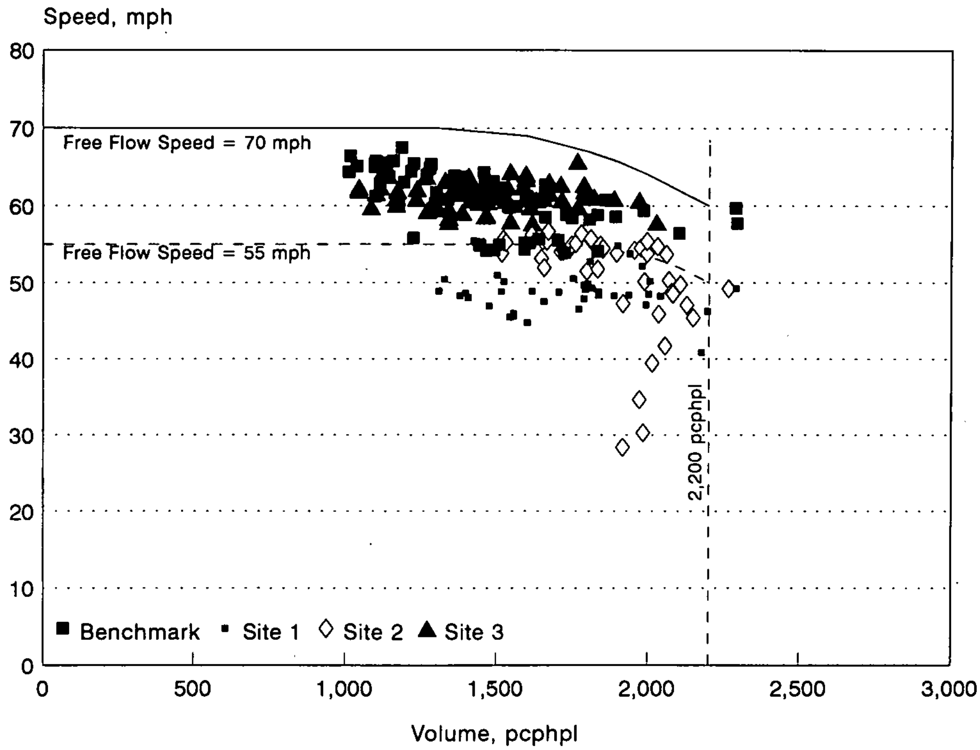


Figure 44. Speed-flow data for I-94 (5-min sampling periods).

TABLE 30. Comparison of mean speeds between individual sites

Corridor	Compare	# of Data Points	PCPHPL BM	PCPHPL Site	Mean Speed BM	Mean Speed Site	Note
I-405	BM NB/S1	9	2145	2163	54.2	66.5	
I-10	BM EB/S1	7	2172	2154	48.3	48.5	PM ONLY
I-5S	BM NB/S4	6	1901	1897	61.1	57.6	>1600
I-5S	BM NB/S4	9	1471	1460	61.6	62.1	<1600
I-94	BM WB/S3	3	1721	1708	58.9	60.0	>1600
I-94	BM WB/S3	6	1251	1238	63.7	62.1	<1600
I-85	BM SB/S4	3	2161	2172	56.8	60.1	>1600
I-85	BM SB/S4	8	1285	1286	61.5	61.5	<1600
I-90	BM EB/S2	7	1076	1080	64.9	56.9	

Further analysis of these measures was not pursued as the data were not sufficient to establish a practical correlation.

Distribution of Traffic

The distribution of traffic among available traffic lanes was examined at altered sites. With the exception of Route 128 in Massachusetts, no significant difference in distribution was found during heavier traffic flows above 1600 pcphpl. In the case of Route 128, the shoulder has had limited improvements made to accommodate traffic. During periods of lighter traffic, there is a tendency to use the other lanes particularly if the shoulder pavement surface is different from the travel lane surface.

Part-Time Use of Shoulders

On Route 128, the use of the shoulder is permitted only during the peak period. Field observations and traffic count data indicate that if traffic remains slow, many drivers will ignore the restrictions and use the shoulder anyway. This has been the experience on facilities in California and Virginia. To date, the ability to recapture the shoulder as a refuge area has been limited. Virginia

TABLE 31. Summary of regression analysis

	Corridor	#Points	Minimum	Maximum	Average	Median	Std. Dev	Co	R^2
Data points >50 mph	I-95	34	51.97	62.8	57.1	57.1	2.34	0.294	0.086
All Data Points	I-95	69	41.4	62.8	51.5	50.3	5.98	0.318	0.101
Data points >50 mph	I-395	86	54.1	66.9	60.8	61.7	3.08	0.439	0.193
All Data Points	I-395	94	21.9	66.9	58.1	61.55	9.63	0.588	0.346
All Data Points	I-5S	159	34.4	67.6	58.0	60.9	6.46	0.339	0.115
All Data Points	I-5N	111	14.8	65.9	41.8	45.2	13.80	0.578	0.334
Data points >50 mph	I-90	130	51.0	66.6	59.74	59.65	3.26	0.421	0.177
All Data Points	I-90	142	33.5	66.6	57.9	59.3	6.78	0.352	0.124
All Data Points	I-85	180	46.7	67.9	60.3	60.9	3.61	0.243	0.059
Data points >50 mph	I-94	61	50.1	65.8	59.4	61.2	4.30	0.517	0.267
All Data Points	I-94	89	28.4	65.8	54.9	55.5	8.09	0.493	0.243
Data points >50 mph	I-10	84	50.0	64.06	55.6	55.71	3.13	0.023	0.00053
All Data Points	I-10	156	16.6	64.1	47.7	50.9	10.8	0.488	0.238
Data points >50 mph	I-405	70	50.5	70.4	65.1	65.2	3.64	0.234	0.055
All Data Points	I-405	116	6.2	70.4	51.3	62.8	19.3	0.260	0.07
Data points >50 mph	SR 57	136	50.70	65.7	61.5	62.2	2.64	0.302	0.191
All Data Points	SR 57	138	34.4	65.7	61.2	62.2	3.75	0.314	0.098
Data points >50 mph	SR 91	85	51.1	66.8	60.6	61	3.50	0.018	0.000038
All Data Points	SR 91	122	25.6	66.8	54.0	59.4	11.1	0.346	0.119
All Data Points	Benchmark	424	43.1	67.9	59.0	59.9	5.59	0.688	0.473

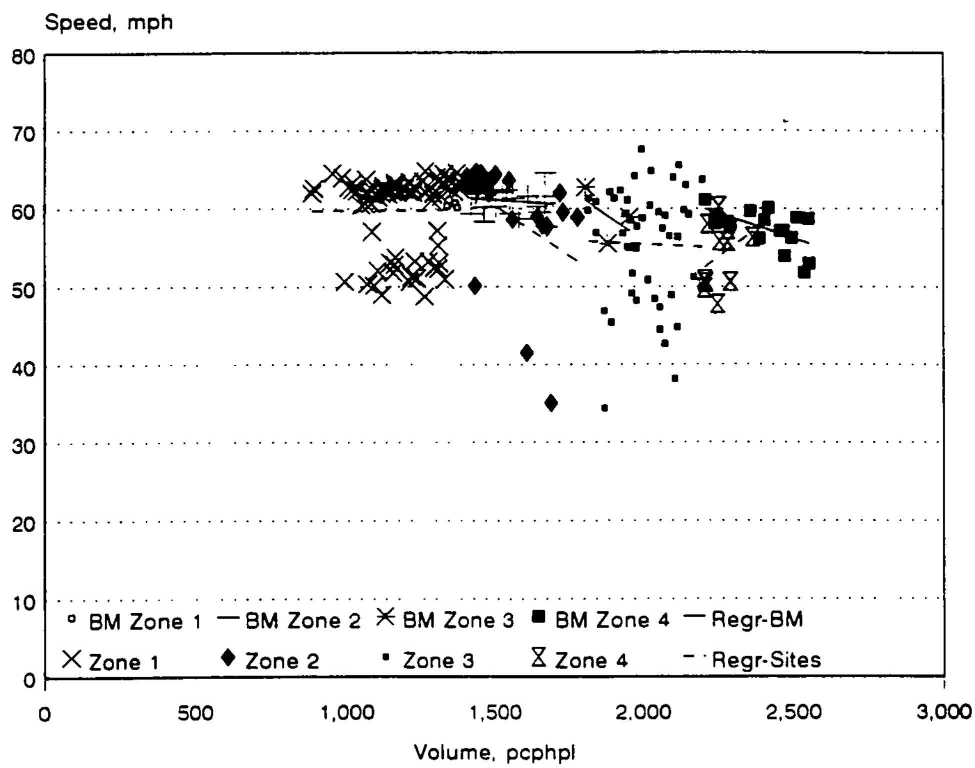


Figure 45. Zoned regression for I-5 suburban.

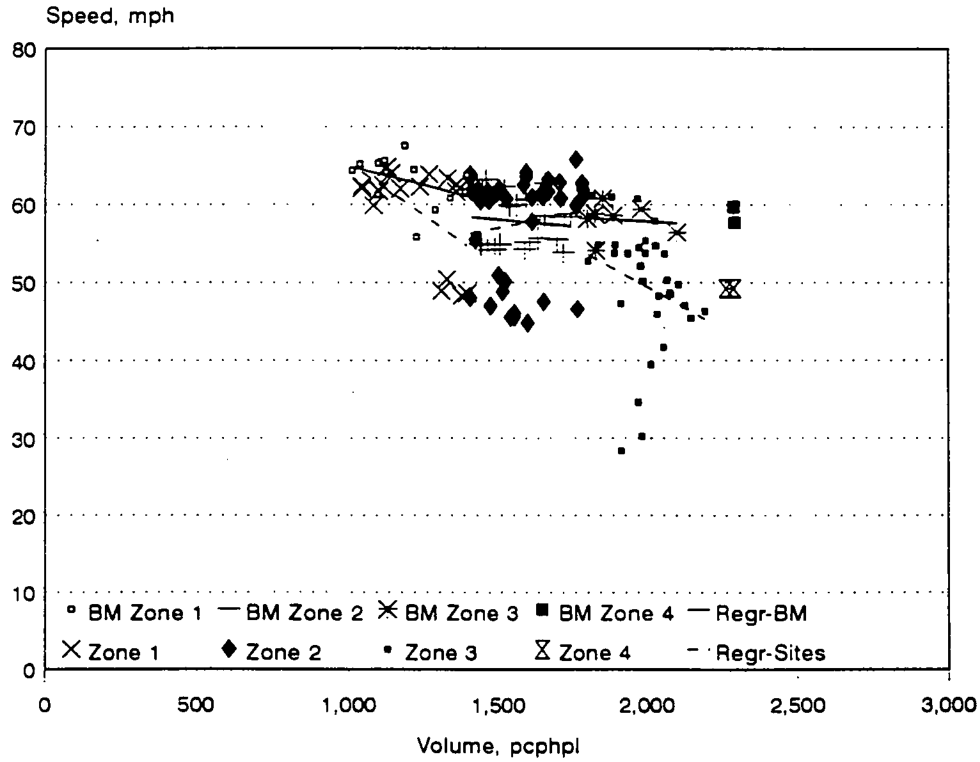


Figure 46. Zoned regression for I-94.

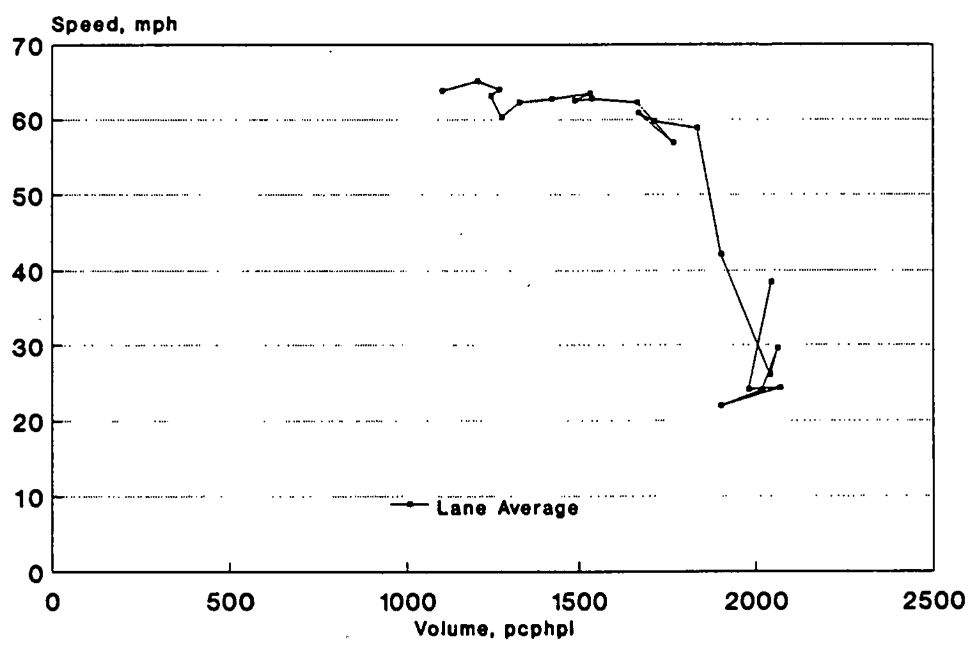


Figure 47. Time sequence flow, I-395 NB at Shirlington Circle.

has recently implemented part-time use of shoulders on I-66 with the use of lane controls signals and extensive signing.

Maintenance Activities

Although it is generally accepted that maintenance activities on freeways with one or both shoulders used as travel lanes becomes more difficult and expensive, little documentation exists in the published literature or is available from the agencies. The following are usually cited as the major factors contributing to the increased costs:

- Many highway appurtenances such as signs, guardrails or barriers, drains, landscaped runoff areas, and luminaries are

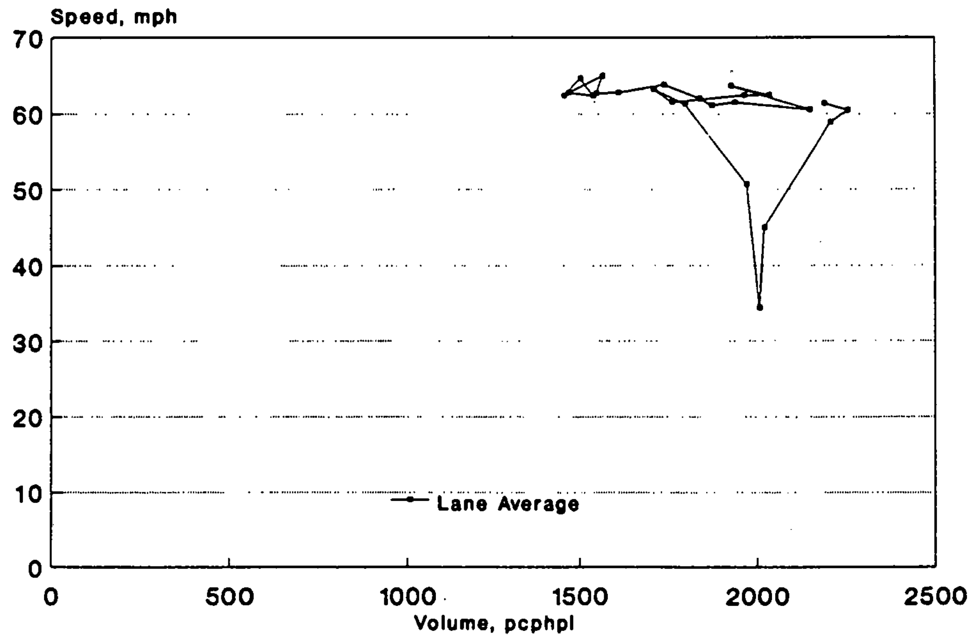


Figure 48. Time sequence flow, SR 57 SB at Imperial Highway.

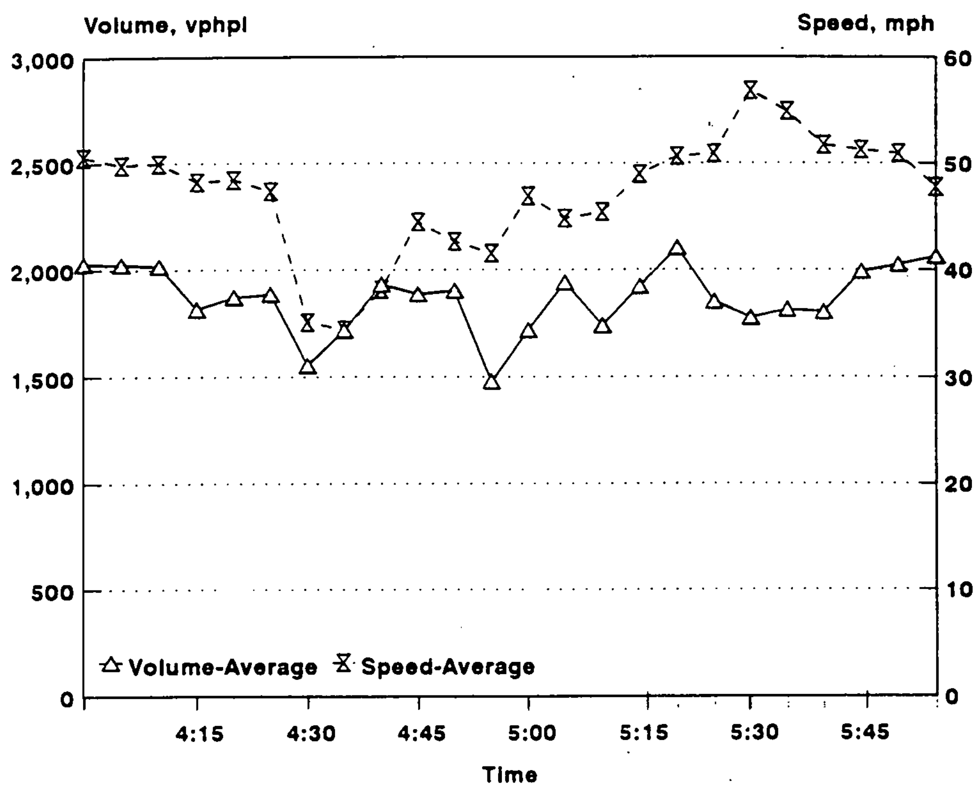


Figure 49. Speed-flow vs. time for I-5 SB at 216th Street.

closer to moving traffic and can be damaged more often and more severely.

• Maintenance activities must be scheduled for the time periods when traffic volumes are reduced. Lane closures are required more often. This results in less daily production.

• Additional personnel and equipment are required to close lanes and provide work area protection.

• Most incidents, from minor to major accidents, require some action by maintenance personnel. Spilled items are often moved out of travel lanes and stored on shoulders until traffic

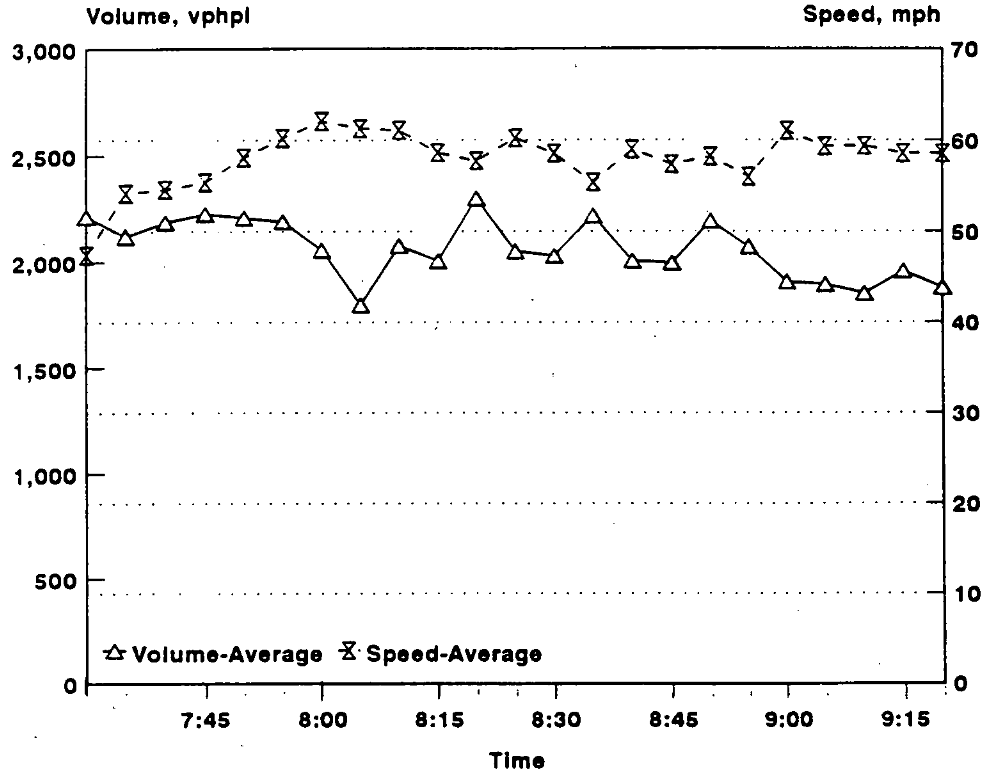


Figure 50. Speed-flow vs. time for I-405 NB at Newland Street.

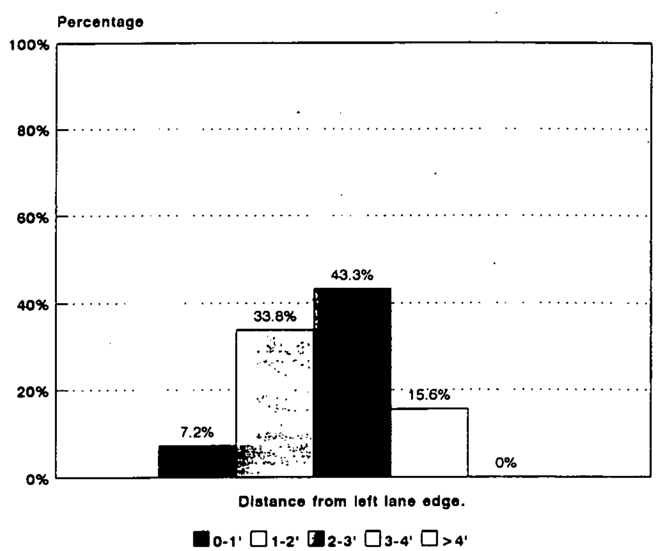


Figure 51. Median lane lateral placement for I-10 EB at Crenshaw Boulevard.

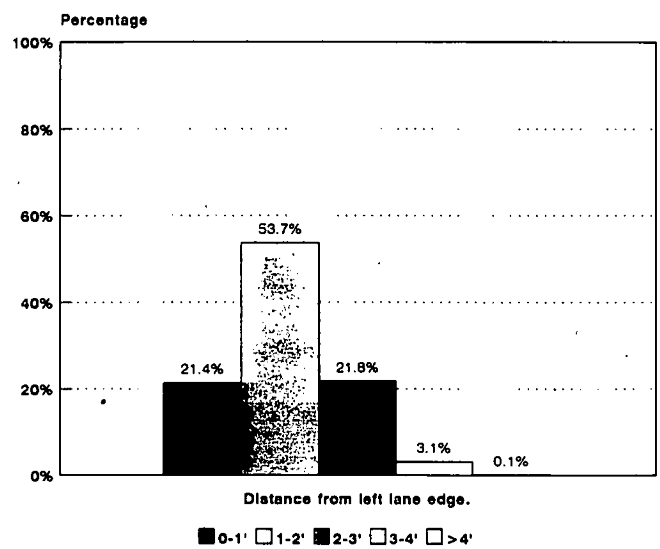


Figure 52. Median lane lateral placement for I-10 EB at West Boulevard.

clears and equipment and personnel arrive to remove items. If there are no shoulders, the lanes involved must stay closed until all items are removed. Estimates by involved personnel indicate that clearance time for many incidents, particularly minor ones, doubles.

Emergency Response and Enforcement

Emergency response is a major factor that must be considered. Most incidents, no matter how minor, result in lengthy queues on congested urban freeways. Often emergency vehicles must use shoulders to reach the scene of the incident. Elimination of

TABLE 32. MOE 3 highest 15-min flow rate

Average AM Peak Hour Volume (pcphpl)					
Corridor	Benchmark	Site 1	Site 2	Site 3	Site 4
Rt 128	2673	2283	2257	--	2866
I-95	--	1206	--	--	--
I-395	1702	1043	2195	2041	--
I-5S	2516	1320	1233	1326	2480
I-5U	1818	2338	2106	2241	--
I-90	1230	1842	1369	2097	--
I-85	2573	1177	2155	1974	2402
I-94	2158	2176	1889	1962	--
I-10	2070	2156	2123	2132	1940
I-405	2353	2336	2184	--	1753
SR 57	--	1463	2217	2122	--
SR 91	1934	2352	2576	2383	--

Average PM Peak Hour Volume (pcphpl)					
Corridor	Benchmark	Site 1	Site 2	Site 3	Site 4
Rt 128	2287	2483	2259	1675	2534
I-95	--	1944	902	--	--
I-395	2035	1892	1303	1328	2203
I-5S	1616	--	2123	2210	1468
I-5U	1486	--	1531	1959	--
I-90	1700	1291	1697	1418	--
I-85	1351	2218	1380	1352	1331
I-94	1715	2094	2181	1724	--
I-10	2230	2165	2062	2038	2052
I-405	2269	2358	2548	--	--
SR 57	--	1933	1717	1882	--
SR 91	2247	2385	2808	2123	--

the shoulder or the use of narrow lanes makes reaching the scene more difficult. This results in delayed response time for emergency vehicles; longer periods of congestion; an increase in the opportunity for a secondary accident; and increased difficulties in clearing incidents, stalls, and spills. Police agencies indicate that a minimum 10-ft shoulder width is required to make a safe enforcement stop, thus placing added importance on the full-time availability of shoulders for "nontravel" use. Pullout areas can be used for enforcement as long as they are not completely blocked for emergency use.

TABLE 33. MOE 1 and 2 level of service C

	Average AM Peak Hour Volume (pcphpl)									
	Benchmark		Site 1		Site 2		Site 3		Site 4	
Corridor	MOE 1	MOE 2	MOE 1	MOE 2	MOE 1	MOE 2	MOE 1	MOE 2	MOE 1	MOE 2
Rt 128	--	--	--	--	--	--	--	--	--	--
I-95	--	--	1179	--	--	--	--	--	--	--
I-395	--	62	1045	--	--	--	--	63	--	--
I-5S	2454	62	1311	54	--	62	--	62	2303	58
I-5U	--	65	2023	61	--	--	--	50	--	--
I-90	--	66	--	57	1325	58	2063	59	--	--
I-85	--	--	--	--	--	--	--	--	2297	64
I-94	--	--	1661	--	--	--	--	61	--	--
I-10	1927	--	2230	--	--	27	2220	--	1655	53
I-405	2219	--	--	--	--	39	--	--	1656	28
SR 57	--	--	--	--	--	63	--	63	--	--
SR 91	--	65	2340	42	--	--	2085	--	--	--

	Average PM Peak Hour Volume (pcphpl)									
	Benchmark		Site 1		Site 2		Site 3		Site 4	
Corridor	MOE 1	MOE 2	MOE 1	MOE 2	MOE 1	MOE 2	MOE 1	MOE 2	MOE 1	MOE 2
Rt 128	--	--	--	--	--	62	--	61	--	--
I-95	--	--	1768	59	--	--	--	--	--	--
I-395	2037	60	--	--	--	62	--	63	--	--
I-5S	--	61	--	--	2055	--	1958	42	--	64
I-5U	--	64	--	--	--	23	1366	46	--	--
I-90	--	63	--	62	1528	47	--	64	--	--
I-85	--	--	--	--	--	62	--	--	--	--
I-94	1725	58	--	--	2001	--	--	62	--	--
I-10	--	--	--	--	2074	--	--	--	2060	--
I-405	2229	--	--	--	--	--	--	--	--	--
SR 57	--	--	1906	58	--	60	--	64	--	--
SR 91	--	--	--	--	2482	64	--	60	--	--

MOE 1 is the average of the three highest flow rates (average lane volume per hour across all lanes) in each LOS speed range. MOE 2 is the average speed within the LOS volume range.

TABLE 34. MOE 1 and 2 level of service D

	Average AM Peak Hour Volume (pcphpl)									
	Benchmark		Site 1		Site 2		Site 3		Site 4	
Corridor	MOE 1	MOE 2	MOE 1	MOE 2	MOE 1	MOE 2	MOE 1	MOE 2	MOE 1	MOE 2
Rt 128	2715	53	--	--	--	--	--	--	--	29
I-95	--	--	1052	--	--	--	--	--	--	--
I-395	--	--	--	--	--	--	--	52	--	--
I-5S	2546	59	1361	--	--	--	--	--	--	61
I-5U	--	66	--	61	--	--	2196	49	--	--
I-90	--	--	--	59	--	--	--	59	--	--
I-85	2317	60	--	--	--	--	--	--	2074	64
I-94	--	59	2176	--	--	--	--	61	--	--
I-10	2081	55	2087	35	--	38	2110	--	1970	50
I-405	2318	--	2342	68	1970	42	--	--	1633	28
SR 57	--	--	--	--	1971	56	--	61	--	--
SR 91	--	64	2509	49	--	60	--	61	--	--

	Average PM Peak Hour Volume (pcphpl)									
	Benchmark		Site 1		Site 2		Site 3		Site 4	
Corridor	MOE 1	MOE 2	MOE 1	MOE 2	MOE 1	MOE 2	MOE 1	MOE 2	MOE 1	MOE 2
Rt 128	--	--	--	--	--	61	--	63	--	--
I-95	--	--	1951	51	902	--	--	--	--	--
I-395	2065	59	--	--	--	--	--	--	2116	34
I-5S	--	--	--	--	1964	58	2251	47	--	--
I-5U	--	--	--	--	--	--	1959	45	--	--
I-90	--	63	--	--	1676	44	--	--	--	--
I-85	--	--	2254	64	--	--	--	--	--	--
I-94	1724	56	--	--	2166	46	--	63	--	--
I-10	2241	49	2207	49	--	58	--	--	2094	56
I-405	2192	57	--	68	--	--	--	--	--	--
SR 57	--	--	--	57	--	62	--	64	--	--
SR 91	2097	49	--	35	--	62	--	61	--	--

MOE 1 is the average of the three highest flow rates (average lane volume per hour across all lanes) in each LOS speed range. MOE 2 is the average speed within the LOS volume range.

TABLE 35. MOE 1 and 2 level of service E

	Average AM Peak Hour Volume (pcphpl)									
	Benchmark		Site 1		Site 2		Site 3		Site 4	
Corridor	MOE 1	MOE 2	MOE 1	MOE 2	MOE 1	MOE 2	MOE 1	MOE 2	MOE 1	MOE 2
Rt 128	--	53	--	--	--	--	--	--	2897	30
I-95	--	--	--	--	--	--	--	--	--	--
I-395	--	--	--	--	--	--	1974	28	--	--
I-5S	--	61	--	--	--	--	--	--	--	60
I-5U	--	--	--	63	--	--	--	--	--	--
I-90	--	--	--	--	--	--	--	58	--	--
I-85	--	56	--	--	--	--	--	--	--	56
I-94	--	56	2287	--	--	--	--	--	--	--
I-10	--	56	2103	40	2125	45	--	56	1780	47
I-405	2103	57	0	66	2277	38	--	--	1740	--
SR 57	--	--	--	--	2015	60	--	62	--	--
SR 91	--	64	2218	47	--	--	--	62	--	--

	Average PM Peak Hour Volume (pcphpl)									
	Benchmark		Site 1		Site 2		Site 3		Site 4	
Corridor	MOE 1	MOE 2	MOE 1	MOE 2	MOE 1	MOE 2	MOE 1	MOE 2	MOE 1	MOE 2
Rt 128	--	--	--	--	--	63	--	--	--	--
I-95	--	--	1772	--	902	--	--	--	--	--
I-395	--	56	--	--	--	--	--	--	--	41
I-5S	--	--	--	--	--	61	2098	46	--	--
I-5U	--	--	--	--	1471	--	--	--	--	--
I-90	--	--	--	--	1718	--	--	--	--	--
I-85	--	--	--	63	--	--	--	--	--	--
I-94	--	--	--	--	2080	47	--	--	--	--
I-10	2186	46	2185	48	--	59	--	--	--	53
I-405	--	54	--	69	--	64	--	--	--	--
SR 57	--	--	--	--	--	--	--	--	--	--
SR 91	2059	56	2373	29	--	62	--	--	--	--

MOE 1 is the average of the three highest flow rates (average lane volume per hour across all lanes) in each LOS speed range. MOE 2 is the average speed within the LOS volume range.

TABLE 36. Summary of paired *t*-tests[1] on operational data measures

	MOE 1[2]			MOE 2[3]		
LOS	Number of Pairs	Prob "t"	Infers	Number of Pairs	Prob "t"	Infers
C	7	0.373	DNR[5]	21	0.007	Reject
D	11	0.226	DNR	21	0.10	Reject
E	4	0.918	DNR	16	0.305	DNR
F	0	-	-	10	0.728	DNR

1 H_o: There is no difference between the benchmark and the altered sites measure (2-Tailed Test)
2 MOE 1 is the average of the three highest flow rates[4] in each LOS speed range
3 MOE 2 is the average speed within the LOS volume range
4 Flow rate is calculated as the average lane volume per hour across all lanes
5 Do not reject H_o

TABLE 37. Summary of paired *t*-tests[1] on measures of effectiveness three highest 15-min volume (MOE3)

Comparison Sample	Number of Pairs[1]	Paired "t"	Conclusion	Inference
1	9	0.72	DNR[2]	No Difference
2	8	0.39	DNR	No Difference
3	4	0.18	DNR	No Difference
4	7	0.75	DNR	No Difference

1 Test between benchmark sample and random samples of altered site sample volumes. For each sample the corridor benchmark was paired with an altered site. The number of pairs varies by sample as data are not available for all sites and the number of sites per corridor varies. The null hypothesis is H_o: = $\mid U_{altered} - U_{benchmark} \mid = 0$

2 Do Not Reject Ho

3 Only data from sites that experience a breakdown in traffic flow can be used for this MOE.

TABLE 38. Line crossings, lane changes

Corridor	Site	Line Crossing/ Hour	Lane Changes/ Hour	# of Lanes	Average Volume/ Lane Hour
Rt 128	South St, NB, AM	0	48	4	2530
Rt 128	South St, NB, PM	9	63	4	1847
I-95	Pohick Rd, SB AM	63	39	4	571
I-95	Pohick Rd, SB, PM	6	30	4	1202
I-395	Edsall HOV, SB, AM	8	33	3	979
I-395	Edsall HOV, SB, PM	17	64	3	1505
I-395	S. Shirl. Cir, NB, PM	75	234	4	1176
I-395	S. Shirl. Cir, NB, Sat	105	177	4	1129
I 5S	178th St, NB, AM	8	42	4	2054
I 5S	178th St, NB, PM	5	46	4	1353
I 5S	178th St, SB, AM	6	57	5	791
I 5U	Albro Pl, SB, AM	0	39	4	1507
I 5U	Albro Pl, SB, PM	0	42	4	1575
I 5U	Holgate St, SB, AM	9	39	4	1726
I-85	Wood Pkwy, SB, AM	12	63	6	1367
I-85	Wood Pkwy, SB, PM	15	39	6	1120
I-94	Pascal Rd, WB, AM	6	48	3	1424
I-94	E. River Rd, WB, AM	18	54	5	1910
I-94	E. River Rd, WB, PM	27	72	5	1687
I-10	Sixth Ave, EB, PM	14	74	5	1801
I-10	Crenshaw Blvd, EB, AM	12	45	5	1915
I-10	Crenshaw Blvd, EB, Mid	9	60	3	1795
I-10	Crenshaw Blvd, EB, PM	9	42	3	1923
I-10	West Blvd, EB, AM	0	33	5	1820
I-10	West Blvd, EB, PM	0	66	5	1986
I-405	Cherry St, NB, AM	5	30	4	2005
SR 91	Harbor Blvd, WB, AM	18	44	4	1328
SR 91	Harbor Blvd, WB, Mid	21	48	4	1535
SR 91	Harbor Blvd, WB, PM	17	54	4	1317
SR 91	Placentia Blvd, WB, AM	2	36	3	2009
SR 91	Placentia Blvd, WB, Mid	15	75	3	1990
SR 91	Placentia Blvd, WB, PM	6	48	3	1960

*Benchmark sites are shaded

CHAPTER 4

INTERPRETATION, APPRAISAL, AND APPLICATION

The findings presented in Chapter 3 illustrate characteristics of the traffic safety and operational performance of freeway corridors that have used shoulders with or without narrow lanes to increase capacity. This chapter relates these findings to existing standards and theories, recommends an evaluation methodology, and presents design guidelines for the application and implementation of projects involving the use of shoulders and narrow lanes.

SPEED-FLOW RELATIONSHIP

The relationship between speed and flow on freeways has been the subject of investigation and debate for many years. Traditional interpretations have been based in large part on the work of Greenshields in the 1930s, based on speed-flow relationships on two-lane roads, which assumed a parabolic shape. Recent research has come increasingly to question this interpretation.

This research has been focused on potential differences in the speed-flow relationships between freeway segments with full shoulders and standard 12-ft lanes versus freeway sections without shoulders and narrower lanes; however, in order to make these comparisons, assumptions regarding the speed-flow relationship were made. The relationship presented by Hall et al. appeared to characterize the data that were collected in the field. This relationship is presented in Figure 53. The curve is broken into three segments. Segment 1 commences with low-flow and free-flow speed and remains constant until roughly 75 percent of capacity is reached, at which point speeds start to fall off sharply reaching a level of roughly 80 percent of the free-flow speed at a maximum volume. Segment 2 is a vertical band representing a constant volume across a range of speeds. Segment 3 reflects the behavior of vehicles as they move through the queue itself.

The data plots in Chapter 3 show that this research focused on Segment 1 conditions (LOSs C, D, and E). The plots also show some data in the Segment 2 and Segment 3 realms. An inspection of these plots generally indicates that flow and capacity may not be significantly affected by the use of shoulders and narrow lanes; however, it does appear that speeds (for a given volume level) may be slightly lower for altered segments compared with benchmark sites.

The traditional approach [embodied in the 1985 *Highway Capacity Manual* (HCM)] for analysis of the effects of lane width and lateral clearance on freeway LOS used factors that reduced the capacity threshold. More recent research, which led, in 1992, to a new *HCM* Chapter 7 (Multilane Highways), uses factors that reduce the speed for a given volume to reflect the impacts of reduced lane and shoulder widths.

The findings of this research tend to support this latter theory; that is, speed is marginally reduced and flow is maintained. The recently revised *HCM* Chapter 3 (Basic Freeway Sections) uses the curves presented in Figure 54. This research suggests that free-flow speeds of different facilities may be similar at very low flow rates and then diverge as flow rates increase. In practical terms, this is somewhat of an academic question because in practice there is little concern with freeway operations at these flow levels other than the enforcement of speed limits consistent with design standards. More importantly, this research indicates that a more accurate approach to analyzing projected conditions would be to make adjustments, for restricted lane width and reduced lateral clearance, to speed (as in Chapter 7 of the *HCM*) rather than to flow. Although this research project indicates adjustments to the free-flow speed would better reflect conditions than adjustments applied to capacity, the database does not yield conclusive numerical factors. Further research to develop adjustment factors will be required and is recommended. However, in the interim, it is recommended that consideration be given to applying speed adjustments (as in *HCM* Chapter 7), rather than or in addition to flow adjustments (as in *HCM* Chapter 3) to account for reduced lane or shoulder width on freeways.

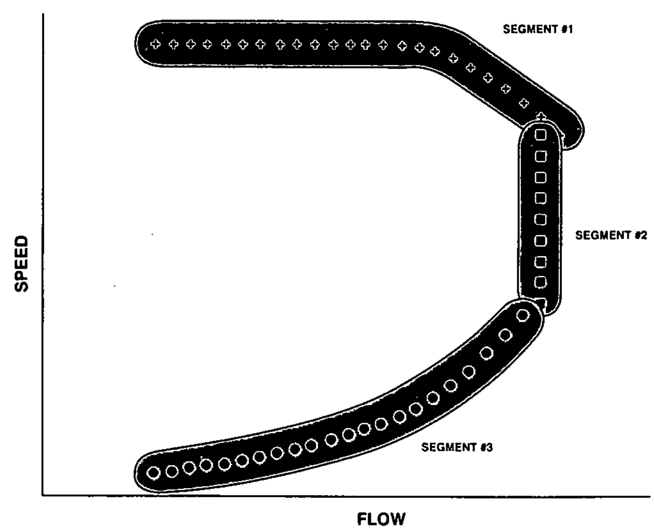


Figure 53. Conceptual speed-flow curve (14).

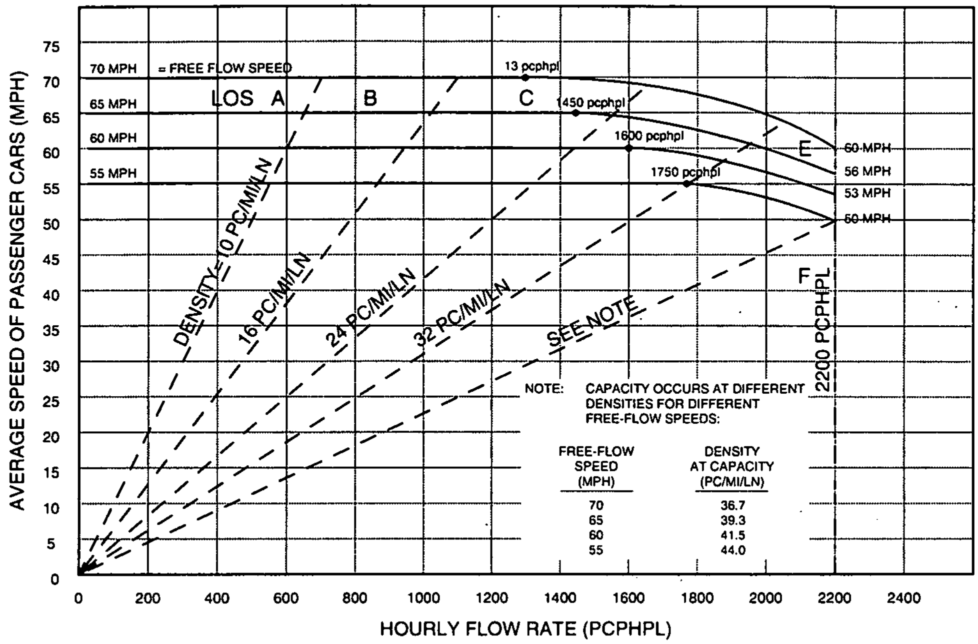


Figure 54. 1994 Highway Capacity Manual speed-flow curve.

APPLICATION TYPE

This research has found that when an additional lane is achieved through simply using the shoulder or narrower lanes over an extended distance, the safety performance of the corridor can be negatively impacted. On the other hand, more selective applications of these strategies throughout a corridor—to address lane balance, lane continuity, and bottlenecks—have been much more successful with no significant change in accident rates. In addition, a difference in lane width (12 to 11 ft) by itself has had no significant impact.

Based on these findings and the experience and observation of the research team, it is hypothesized that the accident rate is related to the quality of the traffic flow. The variability of speeds and the turbulence are indicators of the quality of the traffic flow. Accidents have typically occurred near entry or exit ramps and are more frequent in congested conditions with stop-and-go traffic. Chapter 6 of the HCM has presented analysis procedures that involve segmenting by freeway section and then assigning a LOS to that section as illustrated in Figure 55. This can be viewed as a supply-demand curve and expressed as a ratio of volume to capacity (Figure 56). At higher flow rates and LOS C through E, turbulence may be experienced when there is a change in the volume-to-capacity ratio. This change may be due to a high-volume entrance ramp, a high-volume exit, a weaving area, or a lane drop. A typical application in the I-10 corridor is illustrated in Figure 57 where successive on ramps at Western Avenue had created a bottleneck condition. An additional lane was created by using the left shoulder and narrow lanes. This approach has resulted in better opportunities for entering traffic to merge into the mainline traffic stream.

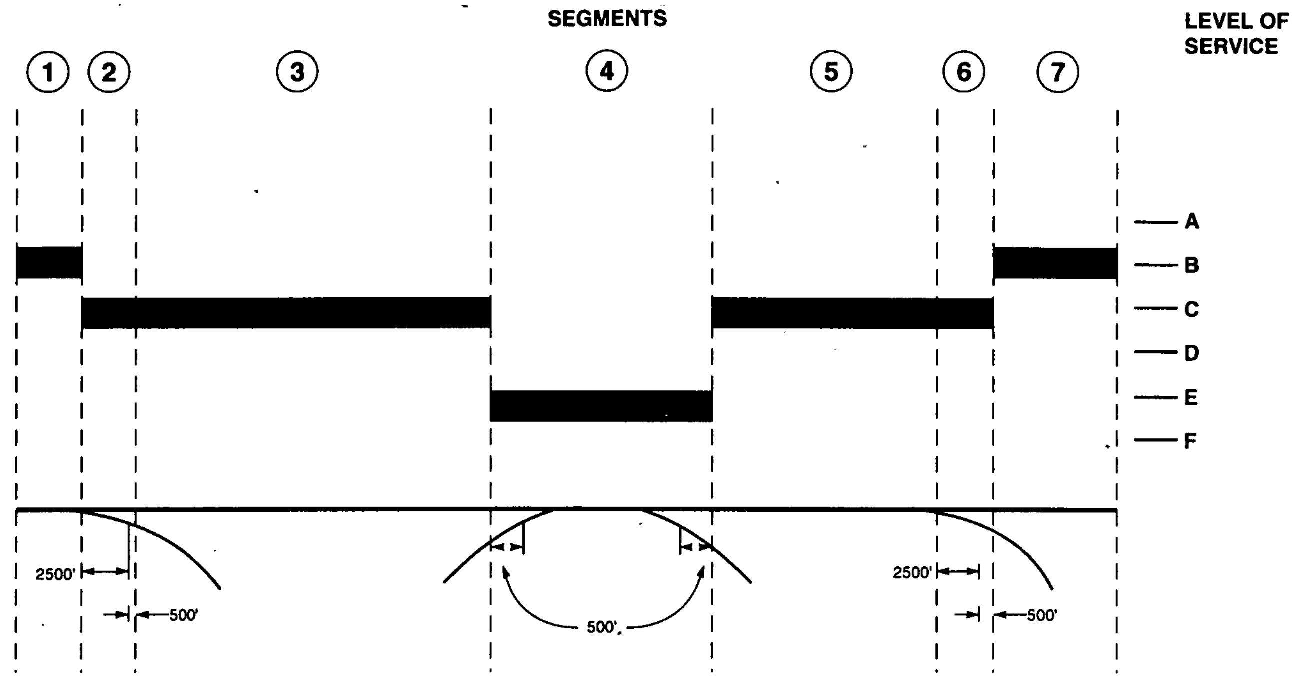
Findings from this research on altered [11-ft lanes, use of shoulder(s) for moving traffic] versus unaltered freeway sections can be summarized as follows:

- Capacity (maximum flow per lane) values (pcphpl) in excess of 2000, and even 2200 were observed at both altered and unaltered sites.
- There is a greater tendency for altered sites to fall into lower-speed LOS F conditions (20 to 40 mph) at high volumes than for unaltered sites to do so.
- Both altered and unaltered sites exhibit "flat" speed-flow relationships typically in the 55 to 65 mph range across the entire range of observed volumes (exceptions being at LOS F conditions).
- For a given per lane flow rate, the range of observed speeds along an unaltered section will be somewhat greater than along a comparable altered section.
- Accident rates for altered sites tend to be somewhat higher than rates for unaltered sites; however, if strategies are carefully applied in concert with lane balance and lane continuity concepts, rates for altered sections may be lower than for unaltered.
- Truck accident rates are almost always higher on altered sections, compared with unaltered.
- Changes in accident rates, unaltered to altered, for daytime conditions are similar to changes for nighttime conditions.

EVALUATION METHODOLOGY

The findings of this research project have confirmed previous findings that, under specific conditions, shoulders and narrow lanes can be used to improve freeway operating performance. However, the findings also provide evidence that there can be negative impacts, particularly in terms of safety. The findings suggest that the resulting performance is dependent on the approach used in implementing such strategies.

These findings underscore the need for careful evaluation of all such projects before proceeding. The steps contained in the



Source: 1985 Highway Capacity Manual

Figure 55. Graphic representation of overall level of service.

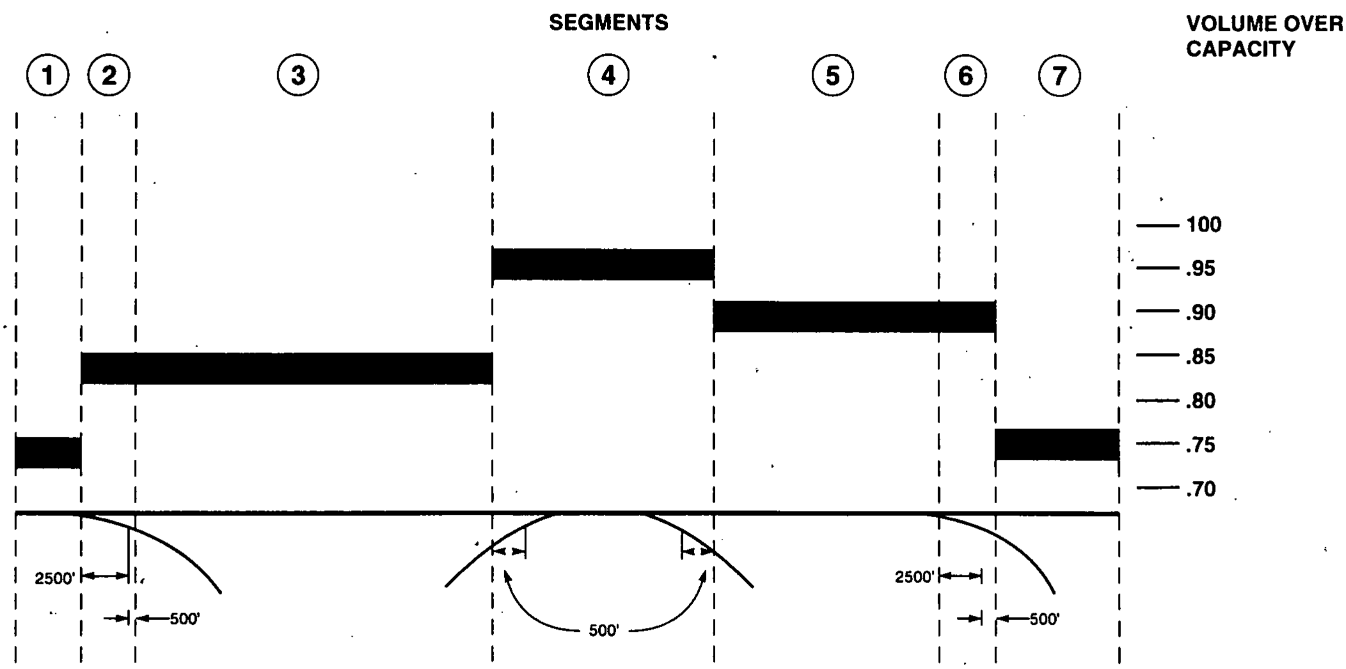


Figure 56. Graphic representation of volume over capacity.

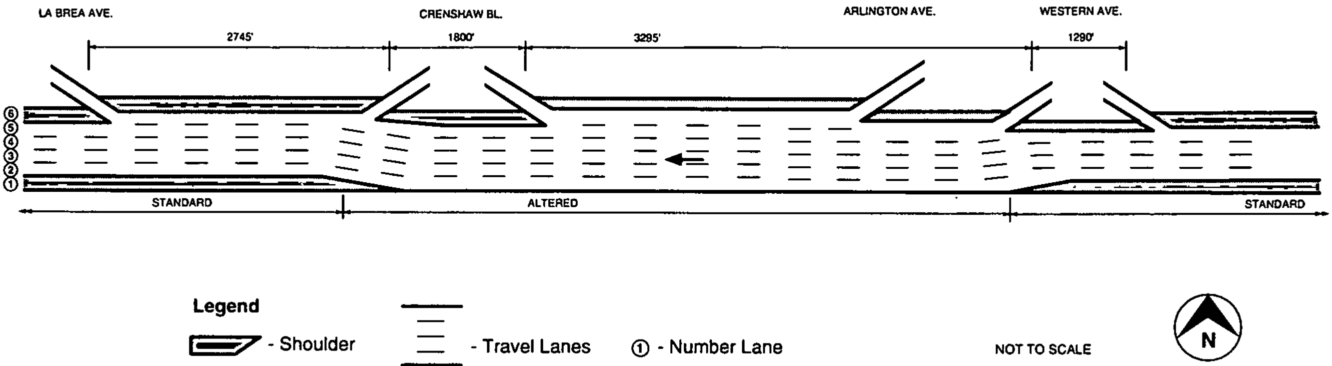


Figure 57. Westbound I-10 lane balance and continuity.

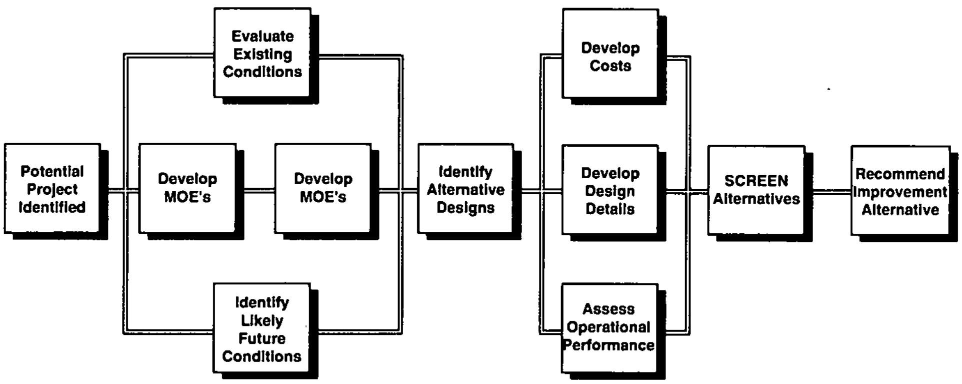


Figure 58. Recommended approach to evaluating proposed project applications.

TABLE 39. Key factors for existing conditions evaluation

Existing Geometrics	Existing Operational Characteristics
Pavement, lane, and shoulder widths	Average daily traffic
Median type	Hourly volumes and peaking characteristics
Horizontal sight distance	Percent trucks/heavy vehicles
Vertical alignment	Level of service
Interchange spacing	Speed profile
Merge/diverge conditions	Location of recurring congestion
Lateral clearances	• mainline
Edge treatment	• ramp and crossroad
Median width	Lane balance / lane continuity
Lateral clearance at structures	Ramp metering
HOV treatment	Speed limit
Volume to capacity ratio	HOV operations
	Nighttime illumination

flow chart presented in Figure 58 are recommended. In many respects the approach simply recommends using sound engineering principles and practices that should be applied to all highway projects.

Evaluate Existing Conditions

A thorough inventory of both physical and operational conditions should be undertaken. Table 39 lists key factors to be considered. The number and width of lanes along with the width of shoulders should be documented for the segment of the corridor under consideration. Potential sites for emergency turnouts should be identified. Horizontal and vertical sight distances should be carefully checked. As illustrated in Figure 59, the recommended sight distance may be difficult to maintain depending on the type of median or shoulder used. With limited refuge area for disabled vehicles, sight distance is critical.

A review of existing traffic operations in most cases should include extensive data collection. In many cases, however, avail-

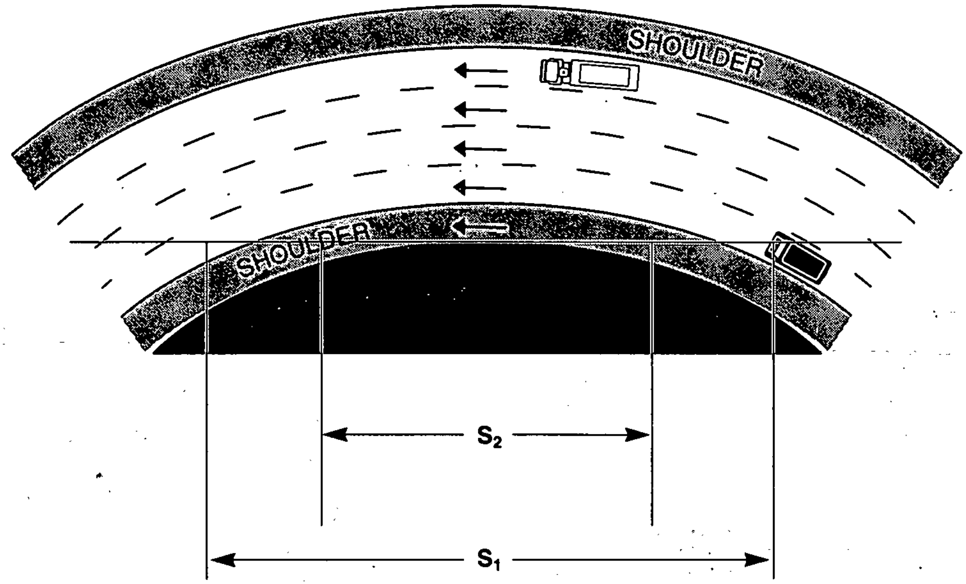


Figure 59. Impact on horizontal site distance.

able information is limited with estimations based on very few recent counts. As successful implementations are placed in locations where traffic operations have been improved, it is key that the location and cause of congestion be understood. Lane balance and lane continuity information along with detailed traffic counts, for the mainline and all ramps in the area under consideration, is critical.

One important consideration is the pavement joint or seam patterns that exist, relative to the existing and future (altered) pattern of striping. The future location of wheel paths in each lane must not create a safety problem.

Evaluate Future Conditions

Most projects of this type will probably be considered "temporary." However, temporary can turn out to be a long time. A project time frame of 10 years is recommended. Future traffic forecasts for the corridor should be reviewed along with approved or proposed improvements to the intersecting arterials. Improvements may result in substantially increased demand on specific ramps. Thus, geometrics and operations for entrance and exit ramps must be assessed and improvements identified as required. It is recommended that a micro simulation model be developed in order to determine LOS, queues, and delay. Manual methods do not adequately address upstream and downstream conditions.

Review Long-Range Plans for the Corridor

The approved long-range plan for the corridor should be reviewed along with other plans for the area. In evaluating proposed alternatives and assessing the benefits and disbenefits, long-range plans should provide an indication of the potential duration of any proposed alternative involving temporary use of narrow lanes or shoulders.

Identify Alternatives

Once the information has been gathered and initially reviewed, feasible alternatives should be identified. This is particularly important as the research findings may indicate that simply adding another lane will likely not be of benefit. Alternatives should be developed in detail showing proposed locations, turnouts required, and any mitigating measures required. It is suggested that, in general, improvements be first implemented downstream of bottlenecks at locations where there is downstream capacity to handle additional traffic demand. Simply moving a problem from one location to another is of little benefit. However, in some cases it may be determined that moving congestion downstream may move queues to a safer location.

Develop Preliminary Cost Estimates

Preliminary cost estimates should be developed for all alternatives. Care should be taken to objectively assess both physical and operating costs. In some cases additional costs have been incurred when mitigating measures have been implemented in response to public reaction or unforeseen circumstances.

Screen Alternatives

At this point it should be possible to eliminate all but two or three alternatives from further consideration. This should be

TABLE 40. Potential measures of effectiveness

Capacity	Construction Cost
Level of Service	Delay
V/C Ratio	Air Quality
Accident Rate	Queuing
User Cost	

done based on the measures of effectiveness identified in Table 40. It is suggested that a matrix covering all alternatives be developed using these criteria and others that may be developed by the implementing agency.

Develop Design Details

At this point all design details should be developed for the remaining alternative(s). Details include lane markings, lane balance and continuity, signing, enforcement strategies, emergency response, improvements to ramps, and other information. Recommended design guidelines are discussed further in the following section.

Identify Advantages and Disadvantages

Using an approach similar to that of the initial screening, all advantages and disadvantages should be assessed for each alternative. In most cases, the assessments will be done through engineering judgment. A more formal cost-benefit analysis may be attempted. However, this may be difficult because of the number of qualitative assessments that must be made. One aspect to consider is the benefit that relates to the "deferral of major capital investment" by achieving an additional freeway lane through relatively low cost techniques.

DESIGN GUIDELINES

This section presents design guidelines for the implementation of projects involving the use of shoulders and narrow lanes. These guidelines are based on the results of this research and the experience of agencies that participated in this study and responded to the survey.

This research did not find any unique design standards that should be applied to these projects. Existing geometric and traffic policies such as those of AASHTO and the Manual on Uniform Traffic Control Devices and the individual state standards are appropriate. The guidelines developed in this research represent more of a guide for *applying* these standards. They are intended to supplement rather than supersede existing standards.

Geometric

Field observations indicate that operational impacts of reduced shoulder or lane widths are most notable in the transition area. Slowdowns are noticeable at the beginning of many restricted areas. It is recommended that the transition area be located on a tangent, preferably in an area where there are no crossing structures, retaining walls, or other roadside appurtenances. Because of the typically observed slowdown and turbulence at the beginning of a transition, it is recommended that at least 2000 ft be maintained between transition and the next upstream ramp.

In cases where the right shoulder is encroached upon, on and off ramps should be analyzed and improved if necessary. The addition of a lane can reduce the length of acceleration and deceleration lanes. Sight distances for entering traffic may be reduced. These features become critical with the lack of a right shoulder (or left shoulder for left exits and entrances).

If possible, edge treatments should be improved to allow room for emergency stops. Guardrail locations should be reviewed. It may be possible to relocate guardrail further from the travel lane. The need for crash attenuators should be considered.

Horizontal sight distances should be reviewed. In cases where there are retaining walls, high concrete medians or glare screens, reduction or elimination of shoulders may drop sight distances below the minimum standards. These situations should be carefully reviewed to ensure the best design. This was illustrated previously in Figure 59.

Vertical alignment and sight distance also needs to be reviewed, particularly for freeways that are "at grade" with humps or dips at each interchange.

Operational

On facilities with high truck percentages, it is recommended that trucks be restricted from using a right shoulder lane, which typically does not have adequate pavement structure to support heavy trucks. The shoulder should be reinforced to allow trucks to use the right lane to enter and exit the freeway. A minimum distance of 1500 ft prior to or following the beginning/ending of the taper for/from exit or entrance ramp locations is recommended. While improving the pavement structure would allow a right shoulder lane to accommodate trucks, the restriction might still be desired to reduce conflicts with merging traffic.

This study did not find a significant difference in nighttime performance of altered freeway segments. However, nighttime accident rates are considerably higher (altered versus unaltered) in general, therefore, improved lighting and/or delineation is recommended. Emergency turnouts should be lit along with interchange areas and lane width transition areas.

As discussed previously, implementation of these strategies should address other preexisting problems such as lane balance and continuity, if such strategies are to be successful.

Emergency turnouts and crossovers should be provided along altered sections. It is recommended that enforcement and emergency response personnel be involved in selecting locations. These turnouts should be large enough to accommodate a tractor trailer unit and at least one piece of emergency equipment. A typical turnout is illustrated in Figure 60. Emergency turnouts are recommended every 1500 ft. The location of crossovers should be considered in conjunction with incident management plans.

While lowered speed limits are used on altered sections of the Garden State Parkway, most jurisdictions have not lowered the speed limit except in construction zones. This study did not find any differences between altered and unaltered free-flow speeds that would support a reduction in the speed limit.

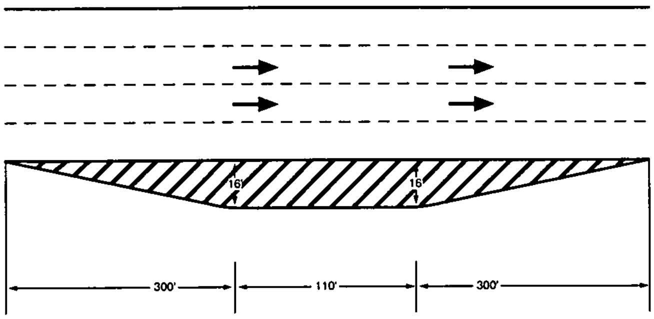


Figure 60. Recommended emergency turnout.

Signing

Signing for segments of freeways with narrowed lanes and/or reduced width shoulders varies considerably from state to state. In many cases there is no (or at least very limited) signing to advise the motorist of changes in the cross section. The project team recommends the following as a minimum. Advance warning of shoulder use should be provided at least ½ mile in advance of the beginning of a section or series of freeways sections where shoulders are reduced below minimum standards. Such notices should be repeated (along with altered section) at approximately 1-mile intervals. Motorists should be advised of turnouts at the beginning of a project and 1000 ft in advance of each individual turnout. Turnouts should be striped to clearly indicate that they are for emergency use only.

Maintenance

Maintenance is more difficult on segments of freeways where shoulders have been removed and lanes narrowed. The following suggestions from agencies and maintenance personnel should be considered:

- Establish staging areas for maintenance crews. In some cases, emergency turnouts will be acceptable. However, it is not desirable to have emergency turnouts occupied for any length of time.
- Eliminate or relocate items that require maintenance if possible. Replace items with low maintenance designs.
- Select low maintenance landscaping, making use of shrubs or trees.
- Improve coordination of various maintenance activities. It should be possible to have several crews work during the same evening thus reducing the number of lane closures required. In some cases, it may be necessary to close a segment of a freeway completely.
- Provide access to landscape areas or equipment such as freeway surveillance cameras from surface streets and other areas outside of the freeway.
- Replace cable or metal median barriers with concrete barriers if it is anticipated that the application will be in place for an extended time period. Glare screens should be replaced with low maintenance designs.

Enforcement

Enforcement becomes increasingly difficult as the cross section is narrowed; however, the following actions can be taken:

- Involve the enforcement agencies in the design process. They have extensive firsthand knowledge of the corridor and will enable the designer to address key areas.
- Increase highway patrol staffing in order to maintain a visible presence.
- Use public information and signing to educate and alert the public to acknowledge the officer and then proceed to the next turnout or exit for enforcement stops.
- Consider the use of ticketing by mail. This has been used in Virginia for HOV occupancy violations. Safe areas can be provided for motorcycle patrols to observe traffic.

Incident Response

Incident response is more difficult when lanes and shoulders are narrower; however, the following actions can be taken.

- Provide more frequent crossovers. This should be done in conjunction with the agencies. Strategically located crossovers will allow emergency response teams to approach from the opposing direction to bypass queues. Emergency access from surface streets should also be considered.
- Develop pre-established response routes when implementing a project. In most urban areas, some form of freeway management team has been established. The freeway management team should be consulted to ensure response time is minimized. In some situations with major incidents, it may be appropriate to block all traffic so emergency equipment can approach from downstream. Locations where this is appropriate should be identified in advance as this emergency decision must be made rapidly.
- Consider implementing freeway surveillance if not already in place. The surveillance system should include full camera coverage using closed circuit television (CCTV). In addition to decreasing incident detection time, camera coverage allows the precise location of the incident to be identified.
- Increase motorist aid and safety patrols on such facilities to ensure the quick removal of minor incidents. Provide call boxes in emergency turnouts.
- Provide frequent milepost markings that are visible to the motorist. To reduce response time, quick and accurate identification of the location is key.
- Follow standard procedures when approaching incidents through a queue. In cases where there is a shoulder, response is usually along the shoulder. If no shoulders are present, equipment must work its way through a queue. This is usually done in the left lane by most agencies. Public information efforts may help to educate the driving public so that they may respond safely in such situations.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

This research project has confirmed that shoulders and narrow lanes can be used effectively to increase capacity in congested urban corridors. However, unlike previous research that concentrated on specific sites, this study attempted to look at the broader implications of frequent or extended use of such strategies. Findings indicate that, in many instances, there may be measurable negative impacts to the overall safety performance of the corridor. Operational impacts seem to be less apparent but the finding of greater variability in operating speeds for altered sections is intuitively consistent with findings that indicated higher accident rates in a majority of cases.

While the safety analysis clearly indicates higher accident rates in three of the corridors, two show a decrease. Even though higher accidents rates in one altered segment versus an unaltered (baseline) segment can be established, it is extremely difficult to tie the differences to specific causes. As discussed earlier, accidents are related to many factors involving the driver, the roadway, and environmental conditions. However, the findings combined with the experience and judgment of the research team suggest that where smooth traffic flow is maintained, accident rates are lower. In the case of the I-10 corridor, the use of shoulders has been selective, addressing lane balance, continuity, and the volume-to-capacity ratio. This suggests that if the use of shoulders can improve traffic flow, negative impacts related to narrower lanes and lack of shoulder can be offset.

Based on these findings, it is recommended that these strategies be reserved for use as techniques to improve traffic flow in congested corridors. Widening of a corridor for an extended length through the use of these strategies is not recommended. Applications of these strategies should be viewed as a technique for congestion relief, not as a means to widen facilities for extended lengths.

Reduction in the travel-lane width to 11 ft should be the first modification considered. Reduction of the left shoulder should be considered before reducing the right shoulder. Research and observations by enforcement personnel indicate that the right shoulder is the preferred refuge area. Also, emergency response is easier to provide if the right shoulder is maintained. If the right shoulder is used and the left shoulder maintained, emergency equipment entering a congested area must work its way across the queue to the left shoulder as opposed to proceeding on the right shoulder. In some cases, the right shoulder or both shoulders have been used. Table 41 summarizes the primary advantages and disadvantages of each approach.

This report has presented an approach for evaluating and screening proposed projects. A complete evaluation of each project on a case-by-case basis is essential. The evaluation must comprise a full assessment of existing conditions, including a full operational analysis. A realistic assessment of the time period that a project may stay in place should be made. The use of narrow lanes and shoulders involves a series of tradeoffs and the impact of such use can only be quantified to a limited extent. Each jurisdiction must consider qualitative factors, which include funding levels, other projects, and public perception, in addition to capacity and safety impacts.

Design guidelines have been presented in this report. These guidelines include geometric considerations, operational factors, signing, maintenance and enforcement, and incident management considerations.

TABLE 41. Primary advantages and disadvantages of design alternatives

Design Alternative	Advantages	Disadvantages
Use of Left Shoulder	Left shoulder not used as much for emergency stop/or emergency enforcement	Usually requires restriping
	Least expensive if width is available	Slight distance problem with some median treatments
	Trucks often restricted from left lane	
Use of Right Shoulder	Often the easiest to implement	Right shoulder is preferred area for emergency stops and enforcement
		Sight distance changes at merge and diverge areas of ramps
Use of Both Shoulders	Not recommended	Requires restriping
		Safety concerns (no refuge)
	Use ONLY in extreme cases	Enforcement is difficult
		Incident response longer
		Maintenance more difficult and expensive

The findings of this research have lead to the following recommendations:

- Use of shoulders and narrow lanes to achieve an additional travel lane should *not* normally be considered as an option to a traditional widening project for adding capacity to a freeway corridor.
- For areas of limited length and having turbulent flow conditions, use of shoulder(s) and narrow lanes should be considered as one alternative for achieving smoother flow. Such use should typically be limited to sections of 1 mi or less.
- Where large truck traffic is a significant proportion of peak period (i.e., 5 to 10 percent), use of shoulders and narrow lanes is not recommended.
- For projects involving possible application of shoulders and narrow lanes, a step-by-step approach (site specific) must be used to ensure an adequate evaluation.
- Additional research efforts on traffic flow and safety impacts of the use of shoulders and narrow lanes should be made part of other freeway-oriented research projects. It is also recommended that additional accident data (1992–1993) be assembled for the corridors used for this research to determine if the findings remain as reported here.

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APPENDIX A

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