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NATIONAL COOPERATIVE
HIGHWAY RESEARCH PROGRAM REPORT **330**

EFFECTIVE UTILIZATION OF STREET WIDTH ON URBAN ARTERIALS

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL

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EFFECTIVE UTILIZATION OF STREET WIDTH ON URBAN ARTERIALS

DOUGLAS W. HARWOOD
Midwest Research Institute
Kansas City, Missouri

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AREAS OF INTEREST

Transportation Safety
Operations and Traffic Control
Traffic Flow, Capacity, and Measurements
(Highway Transportation)

TRANSPORTATION RESEARCH BOARD
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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.

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FOREWORD

By Staff
Transportation Research Board

This report will be useful to traffic engineers and highway designers interested in making the most effective use of the curb-to-curb space on urban arterial streets. The report can be viewed as a companion to NCHRP Report 282, "Multilane Design Alternatives for Improving Suburban Highways," which treated highways having higher speeds than the urban arterial streets covered here. The research reported here evaluated various alternative strategies for reallocating the usage of street width without changing the total curb-to-curb width. A process is recommended for selecting appropriate improvement strategies based on their traffic operational and safety effects. Guidelines for implementation and evaluation of projects are presented and three design examples are used to illustrate the recommended selection process.

New development and changing land use in many urban areas call for increases in street capacity. Frequently, the additional capacity must be provided without an increase in curb-to-curb street width. Lane-width reductions through restriping to provide more lanes, used either alone or in combination with parking prohibitions, median removal, and intersection improvements are among the strategies used to provide additional capacity. Research leading to guidelines was recognized as a high priority need at an NCHRP workshop to develop a program of research in "Traffic Management and Operations," conducted in Baltimore, Maryland, in March 1986. NCHRP Project 3-38(5), "Effective Utilization of Street Width," was initiated in response to this need. The firm of Midwest Research Institute carried out the research with the objective of determining the relationship between capacity and safety for various lane widths and allocations for a given street width.

To accomplish the objective the researchers first conducted a critical review of the literature to determine the effects of traffic operational improvements on the capacity, level of service, and safety of urban arterial streets. Next, a survey of highway agencies was designed and conducted to determine current use of urban arterial improvement strategies. This was followed by a safety evaluation of projects with narrower lane widths wherein accident data, for periods of 1 to 3 years before and after each project were examined. Finally, traffic operations on selected projects were studied through field observations and videotape rcording to determine erratic maneuvers or other traffic conflicts related to the narrow lane widths.

This report contains a wealth of information on the safety and capacity implications of arterial improvement projects and presents a recommended process for selecting appropriate improvement strategies for more effectively using the available width of urban arterial streets. A key element of the process is estimating the anticipated operational and safety effectiveness of the various strategies. The recommended process is meant to provide a flexible approach to the selection of the strategies rather than a rigid methodology. Highway agencies can adapt the process to suit their own needs while retaining its basic principles. Because accident rates and traffic conditions vary widely from state to state and from jurisdiction to jurisdiction, users are encouraged to evaluate their own projects to build up a history of safety effectiveness estimates for use in planning future projects. Guidelines for performing such evaluations are presented in the report.

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The work reported herein was performed under NCHRP Project 3-38(5) by Midwest Research Institute. The work was performed in the Engineering and Statistical Sciences Section, directed by Mr. Robert R. Blackburn, in MRI's Engineering and Environmental Technology Department, directed by Dr. Charles F. Holt.

Mr. Douglas W. Harwood, Principal Traffic Engineer, was the principal investigator for Project 3-85(5) and the author of this report. Mr. Jerry L. Graham of Graham-Migletz Enterprises and Dr. John C. Glennon of John C. Glennon, Chartered, served as consultants to the project team. Other staff members at Midwest Research Institute who contributed to the research include Ms. Rosemary Moran, Ms. Jean E. Pelkey, and Dr. Jairus D. Flora.

The staffs of seven state and local highway agencies located in the States of Illinois, Maryland, Missouri, North Carolina, and Texas made substantial contributions to the safety evaluation of improvement projects involving narrower lanes. These agencies identified candidate sites for the evaluation and provided geometric, traffic volume, and accident data on those sites for analysis by the project team. We are also very grateful to trafic engineers in 141 state and local highway agencies throughout the United States who responded to a questionnaire on the current use of improvement strategies for urban arterial streets.

EFFECTIVE UTILIZATION OF STREET WIDTH ON URBAN ARTERIALS

SUMMARY

The objective of this research was to determine the effectiveness of various alternative strategies for reallocating the use of street width on urban arterials without changing the total curb-to-curb width. The factors that influence the effectiveness of improvement strategies include traffic volume, vehicle mix, capacity and level of service, prevailing speeds, alignment and cross section, and type of development and access to abutting property. The research addressed urban arterial streets with curb-and-gutter cross sections and speeds of 45 mph or less.

The research focused on a range of design alternatives for urban arterial streets from a two-lane undivided cross section to cross sections with as many as eight lanes for through traffic. The research documented the advantages and disadvantages and the traffic operational and safety effectiveness of these alternatives. Specific design features addressed in the study included two-way left-turn lanes, raised medians, curb parking removal, one-way streets, and reversible lanes.

Many urban arterial street improvement projects that are implemented without changing the total curb-to-curb street width incorporate narrower lanes. A safety evaluation was conducted to determine the effect of such projects on accident rate and severity. It was found that projects where narrower lanes are used to provide space for installation of a center two-way left-turn lane generally reduce accidents by 24 to 53 percent. Projects where narrower lanes were installed to provide additional through traffic lanes on an arterial street generally did not affect midblock accident rates, but did increase accident rates at intersections. None of the projects involving narrower lanes had any effect on the accident severity distribution.

The traffic operational effectiveness of these improvement strategies can be determined primarily from the procedures in the *Highway Capacity Manual* and data available in published literature which are summarized in the report.

The research provides a comparison of the advantages and disadvantages of specific design alternatives for urban arterial streets based on their operational and safety performance, including less quantitative aspects such as impacts on abutting businesses, pedestrians, and bicycles. The report presents a recommended process for selecting appropriate improvement strategies as well as recommended guidelines for their implementation and evaluation. Three design examples are presented to illustrate the recommended selection process.

CHAPTER ONE

INTRODUCTION AND RESEARCH APPROACH

New development and changing land use have resulted in increased congestion in many urban areas. Congestion on arterial streets can be alleviated only by increases in street capacity. The most effective methods of increasing street capacity are to add additional lanes for through traffic and to separate through and turning traffic to minimize unnecessary delays. In suburban areas, increased capacity can often be provided by widening the street. Improvement of suburban arterial streets through widening and installation of median treatments is addressed in *NCHRP Report 282* (*1*). The scope of that report includes undivided highways, highways divided by raised medians, and highway with center two-way left-turn lanes. Urban streets are an even greater challenge to designers and traffic engineers because right-of-way, signal spacing, and other physical constraints often make infeasible the otherwise obvious solutions that involve widening the roadway or installing a median treatment. Therefore, urban traffic engineers must focus on methods of reducing congestion without increasing the existing curb-to-curb width.

When a street cannot be widened, its capacity can be increased by changing the street cross section to more effectively utilize the existing street width. Improvement projects of this type require imagination and creativity on the part of urban traffic engineers along with a solid understanding of research results concerning the traffic operational and safety effects of various types of various design features of urban streets.

The most direct method of reallocating street width is to eliminate or narrow an existing feature such as a median, a parking lane, a travel lane, or a turning lane. Improving traffic operations within the existing street width typically involves using narrower lanes in conjunction with *additional through lanes* to increase through traffic capacity; *curb parking removal* to provide space for additional through or turning lanes; *median removal* to provide space for additional through or turning lanes; *separate right- and left-turn lanes* at signalized intersections, unsignalized intersections, and/or major driveways; and *center two-way left-turn lanes* (TWLTLs) between signalized intersections.

The foregoing improvement types emphasize geometric improvements at midblock locations and on signalized intersection approaches. However, signalization improvements (retiming, activation, progression, and computerized control) can also be very effective in conjunction with the types of geometric improvements considered here.

RESEARCH OBJECTIVES AND SCOPE

The objective of this research was to determine the effectiveness of various alternative strategies for reallocating the use of street width on urban arterial streets without changing the total curb-to-curb width. The study addressed both street segments and intersections. The factors that influence the effectiveness of improvement strategies include traffic volume; vehicle mix; capacity and level of service; volume-to-capacity ratio; prevailing speeds; character and quality of horizontal alignment, vertical alignment, and cross section; development environment; frequency and type of access to adjacent property; and functional classification of street.

The preferred lane width for urban arterial streets under most circumstances is 11 ft or 12 ft. However, where traffic operational improvements are needed to relieve congestion or alleviate specific accident patterns, constraints on street widening do not always permit the use of lanes that wide. The research addressed the situations in which narrower lanes can be used effectively as part of urban arterial street improvement strategies.

The project scope focused on urban arterial streets because suburban highways have already been addressed in *NCHRP Report 282* (*1*). Urban streets generally have lower speeds than suburban streets and have curb-and-gutter cross sections rather than shoulders. The specific types of streets studied in the research are addressed further in the next chapter.

RESEARCH APPROACH

The general approach to this research was to make maximum use of both existing data in the literature and unpublished highway agency studies, to identify any gaps in existing data and to fill those gaps through analysis of data collected specifically for this study. This approach is intended to provide highway engineers with both qualitative and quantitative information on the effectiveness of urban arterial street improvement strategies.

A critical review of the literature was conducted to determine the effects of traffic operational improvements on the capacity, level of service, and safety of urban arterial streets. The primary objective of this review was to identify valid research findings on the operational and safety effects of lane width, median treatment, turning lanes, and curb parking on midblock sections and at intersections.

A survey of highway agencies was designed and conducted to determine the current use of urban arterial improvement strategies. The survey was conducted by mail and included both state and selected local highway agencies throughout the United States. The objective of the survey was to identify the types of improvement strategies being used, the reasons for selection of those strategies, and the effectiveness of those strategies.

Over 80 percent of the responding highway agencies reported that they had used narrower lane widths on urban arterial streets to improve traffic operations without increasing the total curb-to-curb street width. However, there was a lack of reliable data in the literature on the effects of narrower lane widths on traffic safety on urban arterials. Therefore, a safety evaluation of projects involving narrower lane widths was undertaken. Candidate projects involving narrower lanes were identified through contacts with participating highway agencies. Accident data were obtained for periods of 1 to 3 years before and after each project and analyzed. Traffic operations on selected projects were studied through field observations and videotape recording. The videotapes were reviewed to identify erratic manuevers (e.g., encroachments on adjacent lanes) and any resulting traffic conflicts related to the narrower lane widths.

The information from the literature and from the data collection and analysis was combined to assess the effects of the improvement strategies on traffic safety. The primary advantages, disadvantages, and limitations of each design alternative and improvement strategy are presented in this report. These results, together with the traffic operational assessment procedures of the 1985 *Highway Capacity Manual* (*2*), provide a rational basis for selection of improvement strategies. The primary emphasis in the research was on the assessment of the safety performance of improvement strategies. Traffic operational performance is addressed primarily through reference to appropriate HCM procedures, while project implementation costs are addressed only indirectly. Implementation costs can be very low for projects that involve only remarking of the roadway, but can be substantially higher for projects involving median removal or other construction activities. Site-specific cost determinations are essential to evaluation of tradeoffs between improvement strategies.

A selection process for urban arterial improvement strategies is presented. This process is intended to illustrate a general approach to the selection of improvement strategies rather than a rigid methodology. Several design examples are used to illustrate the application of the selection process. Guidelines for implementation and evaluation of urban arterial street improvement strategies are also presented.

ORGANIZATION OF THIS REPORT

The remainder of this report, following this introduction, is organized into three chapters and five appendixes. Chapter Two summarizes the findings of the study including the results of the literature review, the safety evaluation, and the field observations of sites with narrower lanes. Chapter Three discusses the interpretation, appraisal, and application of the research findings. That chapter includes the recommended process for selecting improvement strategies for urban arterial streets, guidelines for implementing those strategies, guidelines for use by highway agencies in evaluating future projects, and the results of several design examples. Chapter Four summarizes the conclusions of the study and presents recommendations for future research to assist highway agencies in more effective utilization of street width on urban arterial streets.

The appendixes present the results of the research in greater detail than the main text. Appendix A presents the results of the literature review on the operational and safety performance of geometric improvements for urban arterial streets. The results of a survey of state and local highway agencies on their current use of urban arterial street improvement strategies is presented in Appendix B. Appendix C presents the results of a safety evaluation of urban arterial street improvement projects that involved the use of narrower lanes. The results of field observations of traffic operations on the narrower lane sites are presented in Appendix D. The final Appendix E describes in detail three design examples of the application of the recommended procedures to urban arterial street improvement projects.

CHAPTER TWO

FINDINGS

The research examined a broad range of design alternatives and improvement strategies suitable for use on urban arterial streets. This chapter presents a description of each of these design alternatives and an approach to evaluating improvement strategies involving these alternatives. The chapter summarizes the research findings that influence the selection of one design alternative or another for particular sites. The general advantages and disadvantages of the alternatives are discussed. The information presented in this chapter addresses all of the key considerations in the selection of an appropriate improvement strategy including operational and safety effectiveness and other, less quantitative, selection criteria. The selection process itself is addressed in Chapter Three.

URBAN ARTERIAL STREETS

The research focused on *urban* arterial streets because *suburban* highways have already been addressed in *NCHRP Report 282.* In that study, suburban highways were defined as highways with speeds between 35 and 50 mph, spacing between signalized intersections of at least one-quarter mile, and no curb parking. Each of these three criteria was included primarily to exclude highway sections that were too urban. In this study, however, urban arterials are defined as streets with speeds of 45 mph or less, curb-and-gutter cross section, direct driveway access from abutting properties, and located in a populated area.

Thus, the project scope could include both streets in the central business district and other urban streets where speeds are not too high. All streets considered in this study have curb-and-gutter cross sections rather than shoulders, which are more common in the suburban setting. There were no restrictions on minimum signal spacing or the presence or absence of curb parking.

The definition of an urban arterial was based on the speeds and geometrics of the site and not whether the site was located in a central city or a suburban community.

There is inevitably some overlap between the definition of urban arterial streets used in this report and the definition of suburban highways used in *NCHRP Report 282* (*1*). Both categories could include streets with curb-and-gutter sections and speeds between 35 mph and 45 mph. However, the definition of urban arterials also includes lower speed facilities and the definition of suburban highways used in *NCHRP Report 282* includes both higher speed facilities and roadways with shoulders.

DESIGN ALTERNATIVES

The research presented here was intended to evaluate improvement strategies for use on urban arterial streets. An improvement strategy, as defined here, consists of a plan to convert the street from one geometric design alternative to another without changing the total curb-to-curb street width. In most cases, these improvement strategies involve changing the width of the existing lanes. A design alternative is defined here by the cross section of the roadway between major intersections. Design alternatives are distinguished from one another primarily by the basic number of through lanes and by the presence or absence of a median treatment to control left turns at driveways and minor intersections. Undivided streets, streets with raised medians, and streets with center two-way left-turn lanes (TWLTLs) were within the scope of the research.

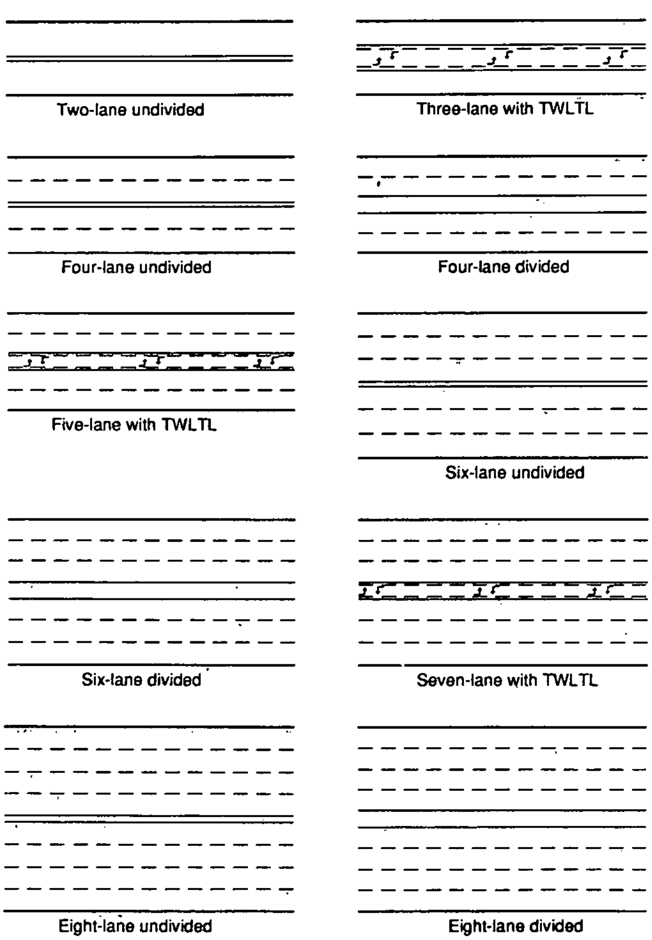

Figure 1. Design alternatives for urban arterial streets.

The research considered ten design alternatives that are widely used on urban arterial streets. These are: (1) two-lane undivided, (2) three-lane divided with center TWLTL, (3) four-lane undivided, (4) four-lane divided with raised median, (5) five-lane divided with center TWLTL, (6) six-lane undivided, (7) six-lane divided with raised median, (8) seven-lane divided with center TWLTL, (9) eight-lane undivided, and (10) eight-lane divided with raised median.

The general geometric design characteristics of these design alternatives are illustrated in Figure 1. In addition to the design alternatives shown in Figure 1, undivided streets with uneven numbers of lanes (3, 5, or 7) are addressed in the report because they can be used as one-way streets.

Many geometric variations of the basic design alternatives considered here are possible. For example, each design alternative can be constructed with a range of lane and median widths. Curb parking lanes may be included on one side, on both sides, or not at all.

Each basic design alternative is briefly discussed below. The advantages and disadvantages of these alternatives are more fully discussed later in this chapter.

Two-Lane Undivided

A two-lane undivided roadway is the basic design alternative for a low-volume urban arterial. This design alternative consists of one lane of travel in each direction separated by a painted centerline. Two-lane undivided roadways can range in width from 20 ft to 54 ft, depending on the lane widths and the presence or absence of curb parking.

Three-Lane with Two-Way Left-Turn Lane

A three-lane design including a center TWLTL is a simple improvement from the two-lane undivided alternative, in which a lane in the center of the roadway is reserved for use as a left-turn lane by vehicles traveling in either direction. The TWLTL in the median provides a deceleration and storage area for vehicles that desire to turn left at a driveway or at an unsignalized intersection so that through vehicles are not delayed by turning vehicles as they wait for a gap in opposing traffic to complete their turn. As shown in Figure 1, the TWLTL is delineated by a broken and a solid yellow centerline adjacent to the through travel lane on each side of the TWLTL.

Five-lane TWLTL designs (see below) have been used effectively for many years, but the use of the three-lane TWLTL alterative has become widespread only recently. It serves as a low-cost alternative to designs with multiple through lanes in each direction and is appropriate for highways with relatively low through traffic volumes, with frequent left-turn demands between intersections and where available funds and/or right-of-way is limited.

Four-Lane Undivided

The most simple design alternative with multiple lanes for through traffic in each direction of travel is the four-lane undivided street. This alternative has two through lanes in each direction of travel separated by a double yellow centerline and requires a total roadway width of 38 ft to 82 ft, depending on lane widths and the presence or absence of curb parking. The four-lane undivided cross section can also be used on one-way streets.

Four-Lane Divided

Another four-lane alternative is the four-lane divided street with a raised median. Four-lane divided streets typically have raised medians from 4 ft to 22 ft in width, with total roadway widths ranging from 42 ft to 88 ft. Wider medians allow space for one-way left-turn lanes at intersections and major driveways. Median openings, either with or without one-way left-turn lanes, are provided at signalized intersections and at selected unsignalized intersections and major driveways to facilitate crossing movements and left-turn movements onto and off of the arterial.

Five-Lane with Two-Way Left-Turn Lane

The five-lane design alternative including a center TWLTL in the median has, in the past 20 years, become a very common multilane design alternative for upgrading urban arterials. This design alternative has two through lanes of travel in each direction and a center TWLTL to provide for left-turn maneuvers at driveways and minor intersections. The total roadway width for a five-lane TWLTL section on an urban arterial ranges from 48 ft to 72 ft depending on the lane widths employed.

Six-Lane Undivided

The six-lane undivided design is analogous to the four-lane undivided design with two additional through lanes. No median treatment is provided to shelter or shadow left-turning vehicles. Typical widths for six-lane undivided streets range from 56 ft to 88 ft, depending on lane widths and the presence or absence of curb parking. The six-lane undivided cross section can also be used on one-way streets.

Six-Lane Divided

Six-lane divided streets with a raised median and one-way left-turn lanes at intersections and major driveways are appropriate for use on higher volume urban streets. This alternative functions in a manner similar to the four-lane divided design alternative except that it provides three through lanes for travel in each direction.

Seven-Lane with Two-Way Left-Turn Lane

The seven-lane TWLTL design alternative operates in a manner similar to five-lane TWLTL alternative, except that three through lanes are provided in each direction of travel.

Eight-Lane Undivided

Eight-lane undivided streets are rare because six-lane divided streets, six-lane undivided streets with parking lanes, or seven-lane streets with a center TWLTL are generally considered to more effectively utilize the available street width. However, the eight-lane undivided design alternative can be used for streets with very high through traffic volumes. An eight-lane undivided street requires a minimum width of 74 ft.

Eight-Lane Divided

Eight-lane divided streets are entirely analogous to four-lane and six-lane divided streets with additional through traffic lanes. One-way left-turn lanes in the median may be provided at intersections and major driveways. Some highway agencies have provided U-turn roadways through the median and other indirect left-turn roadways to avoid the need for direct left-turn movements at signalized intersections and; thus, reserve more time in the signal cycle for through movements.

CLASSIFICATION OF IMPROVEMENT STRATEGIES

A method for classifying design alternatives and, consequently, improvement strategies for urban arterials that do not change the total curb-to-curb street width was developed in the research. Table 1 presents the range of street width allocations that are feasible for particular total curb-to-curb widths. The table covers the range of street widths from 20 ft to 88 ft.

The assumptions used in the development of Table 1 are as follows:

1. Lane widths in the range of 9 ft to 14 ft were considered for through lanes (lanes wider than 12 ft are considered only where excess width is available that is not needed for other purposes).
2. Parking lane widths from 8 ft to 12 ft were considered.
3. Median widths from 4 ft to 22 ft were considered (medians wider than 22 ft are feasible, of course, but it is assumed that highway agencies would not use such wide medians if traffic demand required additional lanes).
4. TWLTL widths in the range from 10 ft to 16 ft were considered. To keep the table as simple as possible, TWLTLs on streets with curb parking were not included in the table. However, it is feasible to include both TWLTLs and parking lanes on urban arterials and the omission of this combination from Table 1 does not imply that this combination should not be considered.
5. A minimum 1-ft allowance for a gutter was provided at each curb line.
6. Uneven numbers of through lanes (3, 5, or 7) were considered because these could be used on one-way streets, for unusual situations with unbalanced numbers of lanes on two-way streets, or for reversible lanes.

Figure 2 shows graphically the range of street widths for which particular lane allocations can be used.

Table 1 and Figure 2 represent a classification scheme that can be used as a first cut in identifying the feasible alternatives for use of the existing street width. The choice among the feasible alternatives will depend on the needs of the site, the physical constraints of the site (including the characteristics of adjoining intersections), and the traffic operational and safety effects of the alternatives.

Table 1. Feasible design alternatives for particular total curb-to-curb widths.

Total Curb-to-Curb Width (ft)	Feasible Design Alternatives	Range of Possible Lane Widths (ft)	Range of Possible Parking Lane Widths (ft)	Range of Possible Median Widths (ft)	Range of Possible TWLTL Widths (ft)
20	Two-lane undivided	9	-	-	-
22	Two-lane undivided	10	-	-	-
24	Two-lane undivided	11	-	-	-
26	Two-lane undivided	12	-	-	-
28	Two-lane undivided	13	-	-	-
	Two-lane undivided with parking on one side	9	8	-	-
30	Two-lane undivided	14	-	-	-
	Two-lane undivided with parking on one side	9 - 10	8 - 10	-	-
	Three-lane divided with TWLTL	9	-	-	10
	Three-lane undivided	9	-	-	-
32	Two-lane undivided with parking on one side	9 - 11	8 - 12	-	-
	Three-lane divided with TWLTL	9 - 10	-	-	10 - 12
	Three-lane undivided	10	-	-	-
34	Two-lane undivided with parking on one side	10 - 12	8 - 12	-	-
	Three-lane divided with TWLTL	9 - 11	-	-	10 - 14
	Three-lane undivided	10	-	-	-
36	Two-lane undivided with parking on one side	11 - 12	10 - 12	-	-
	Two-lane undivided with parking on both sides	9	8	-	-
	Three-lane divided with TWLTL	9 - 12	-	-	10 - 16
	Three-lane undivided	11	-	-	-
38	Two-lane undivided with parking on one side	12	12	-	-
	Two-lane undivided with parking on both sides	9 - 10	8 - 9	-	-
	Three-lane divided with TWLTL	10 - 12	-	-	12 - 16
	Three-lane undivided	12	-	-	-
	Three-lane undivided with parking on one side	9	9	-	-
	Four-lane undivided	9	-	-	-
40	Two-lane undivided with parking on one side	13 - 14	10 - 12	-	-
	Two-lane undivided with parking on both sides	9 - 11	8 - 10	-	-
	Three-lane divided with TWLTL	11 - 12	14 - 16	-	-
	Three-lane undivided	12	-	-	-
	Three-lane undivided with parking on one side	9 - 10	8 - 11	-	-
	Four-lane undivided	9	-	-	-
42	Two-lane undivided with parking on one side	14	12	-	-
	Two-lane undivided with parking on both sides	9 - 12	8 - 11	-	-
	Three-lane divided with TWLTL	12	-	-	16
	Three-lane undivided	13	-	-	-
	Three-lane undivided with parking on one side	10	10	-	-
	Four-lane undivided	10	-	-	-
	Four-lane divided	9	-	4	-
44	Two-lane undivided with parking on both sides	9 - 12	9 - 12	-	-
	Three-lane divided with TWLTL	13 - 14	-	-	14 - 16
	Three-lane undivided	14	-	-	-
	Three-lane undivided with parking on one side	10 - 11	9 - 12	-	-
	Four-lane undivided	10	-	-	-
	Four-lane divided	9	-	6	-
46	Two-lane undivided with parking on both sides	10 - 12	10 - 12	-	-
	Three-lane divided with TWLTL	14	-	-	16
	Three-lane undivided with parking on one side	11 - 12	8 - 11	-	-
	Four-lane undivided	11	-	-	-
	Four-lane divided	9 - 10	-	4 - 8	-
48	Two-lane undivided with parking on both sides	11 - 12	11 - 12	-	-
	Three-lane undivided with parking on one side	12	10	-	-
	Three-lane undivided with parking on both sides	10	8	-	-
	Four-lane undivided	11	-	-	-
	Four-lane undivided with parking on one side	9	10	-	-
	Four-lane divided	9 - 10	-	6 - 10	-
	Five-lane divided with TWLTL	9	-	-	10
	Five-lane undivided	9	-	-	-
50	Two-lane undivided with parking on both sides	12	12	-	-
	Three-lane undivided with parking on one side	12	12	-	-
	Three-lane undivided with parking on both sides	10	9	-	-
	Four-lane undivided	12	-	-	-
	Four-lane undivided with parking on one side	9 - 10	8 - 12	-	-
	Four-lane divided	9 - 11	-	4 - 12	-
	Four-lane divided with parking on one side	9	8	4	-
	Five-lane divided with TWLTL	9	-	-	12
	Five-lane undivided	9	-	-	-
52	Two-lane undivided with parking on both sides	13 - 14	11 - 12	-	-
	Three-lane undivided with parking on one side	13 - 14	8 - 11	-	-
	Three-lane undivided with parking on both sides	10	10	-	-
	Four-lane undivided	12	-	-	-
	Four-lane undivided with parking on one side	10	10	-	-
	Four-lane divided	9 - 11	-	6 - 14	-
	Four-lane divided with parking on one side	9	8 - 10	4 - 6	-
	Five-lane divided with TWLTL	9 - 10	-	-	10 - 14
	Five-lane undivided	10	-	-	-
54	Two-lane undivided with parking on both sides	14	12	-	-
	Three-lane undivided with parking on one side	14	10	-	-
	Three-lane undivided with parking on both sides	10 - 12	8 - 11	-	-
	Four-lane undivided	13	-	-	-
	Four-lane undivided with parking on one side	10 - 11	8 - 12	-	-
	Four-lane undivided with parking on both sides	9	8	-	-
	Four-lane divided	10 - 12	-	4 - 12	-
	Four-lane divided with parking on one side	9	8 - 12	4 - 6	-
	Five-lane divided with TWLTL	9 - 10	-	-	12 - 16
	Five-lane undivided	10	-	-	-
56	Three-lane undivided with parking on one side	14	12	-	-
	Three-lane undivided with parking on both sides	10 - 12	9 - 12	-	-
	Four-lane undivided	13	-	-	-
	Four-lane undivided with parking on one side	11	10	-	-
	Four-lane undivided with parking on both sides	9	9	-	-
	Four-lane divided	9 - 12	-	6 - 14	-
	Four-lane divided with parking on one side	9 - 10	8 - 12	4 - 8	-
	Five-lane divided with TWLTL	10 - 11	-	-	10 - 14
	Five-lane undivided	10	-	-	-
	Five-lane undivided with parking on one side	9	9	-	-
	Six-lane undivided	9	-	-	-

Table 1. Continued

Total Curb-to-Curb Width (ft)	Feasible Design Alternatives	Range of Possible Lane Widths (ft)	Range of Possible Parking Lane Widths (ft)	Range of Possible Median Widths (ft)	Range of Possible TWLTL Widths (ft)
58	Three-lane undivided with parking on both sides	12	10	-	-
	Four-lane undivided	14	-	-	-
	Four-lane undivided with parking on one side	11 - 12	8 - 12	-	-
	Four-lane undivided with parking on both sides	9 - 10	8 - 10	-	-
	Four-lane divided	9 - 12	-	8 - 20	-
	Four-lane divided with parking on one side	9 - 11	8 - 12	4 - 12	-
	Four-lane divided with parking on both sides	9	8	4	-
	Five-lane divided with TWLTL	11	-	-	12
	Five-lane undivided	11	-	-	-
	Five-lane undivided with parking on one side	9	11	-	-
	Six-lane undivided	9	-	-	-
60	Three-lane undivided with parking on both sides	12	11	-	-
	Four-lane undivided with parking on one side	12	10	-	-
	Four-lane undivided with parking on both sides	9 - 10	9 - 11	-	-
	Four-lane divided	9 - 12	-	10 - 22	-
	Four-lane divided with parking on one side	9 - 11	8 - 12	4 - 14	-
	Four-lane divided with parking on both sides	9	8 - 9	4 - 6	-
	Five-lane divided with TWLTL	11 - 12	-	-	10 - 14
	Five-lane undivided	11	-	-	-
	Five-lane undivided with parking on one side	10	8	-	-
	Six-lane undivided	9	-	-	-
	Six-lane divided	9	-	4	-
62	Three-lane undivided with parking on both sides	12	12	-	-
	Four-lane undivided with parking on one side	12	12	-	-
	Four-lane undivided with parking on both sides	9 - 11	8 - 12	-	-
	Four-lane divided	10 - 12	-	12 - 20	-
	Four-lane divided with parking on one side	9 - 12	8 - 12	4 - 16	-
	Four-lane divided with parking on both sides	9 - 10	8 - 10	4 - 8	-
	Five-lane divided with TWLTL	11 - 12	-	-	12 - 16
	Five-lane undivided	12	-	-	-
	Five-lane undivided with parking on one side	10	10	-	-
	Six-lane undivided	10	-	-	-
	Six-lane divided	9	-	6	-
64	Three-lane undivided with parking on both sides	14	10	-	-
	Four-lane undivided with parking on one side	13	10	-	-
	Four-lane undivided with parking on both sides	10 - 11	9 - 11	-	-
	Four-lane divided	10 - 12	-	14 - 22	-
	Four-lane divided with parking on one side	9 - 12	8 - 12	6 - 18	-
	Four-lane divided with parking on both sides	9 - 10	8 - 11	4 - 10	-
	Five-lane divided with TWLTL	12	-	-	14
	Five-lane undivided	12	-	-	-
	Five-lane undivided with parking on one side	10	12	-	-
	Six-lane undivided	10	-	-	-
	Six-lane undivided with parking on one side	9	8	-	-
	Six-lane divided	9	-	-	-

Total Curb-to-Curb Width (ft)	Feasible Design Alternatives	Range of Possible Lane Widths (ft)	Range of Possible Parking Lane Widths (ft)	Range of Possible Median Widths (ft)	Range of Possible TWLTL Widths (ft)
66	Three-lane undivided with parking on both sides	14	11	-	-
	Four-lane undivided with parking on one side	13 - 14	8 - 12	-	-
	Four-lane undivided with parking on both sides	10 - 12	8 - 12	-	-
	Four-lane divided	11 - 12	-	16 - 20	-
	Four-lane divided with parking on one side	9 - 12	8 - 12	4 - 20	-
	Four-lane divided with parking on both sides	9 - 11	8 - 12	4 - 12	-
	Five-lane divided with TWLTL	12	-	-	16
	Five-lane undivided	12	-	-	-
	Five-lane undivided with parking on one side	11	9	-	-
	Six-lane undivided	10	-	-	-
	Six-lane undivided with parking on one side	9	10	-	-
	Six-lane divided	9 - 10	-	4 - 10	-
	Seven-lane undivided	9	-	-	-
68	Three-lane undivided with parking on both sides	14	12	-	-
	Four-lane undivided with parking on one side	14	10	-	-
	Four-lane undivided with parking on both sides	11 - 12	9 - 11	-	-
	Four-lane divided	11 - 12	-	18 - 22	-
	Four-lane divided with parking on one side	9 - 12	8 - 12	6 - 22	-
	Four-lane divided with parking on both sides	9 - 11	8 - 12	6 - 14	-
	Five-lane divided with TWLTL	13 -14	-	-	10 - 14
	Five-lane undivided	13	-	-	-
	Five-lane undivided with parking on one side	11	11	-	-
	Six-lane undivided	11	-	-	-
	Six-lane undivided with parking on one side	9	12	-	-
	Six-lane divided	9 - 10	-	-	6 - 12
	Six-lane divided with parking on one side	9	8	-	-
	Seven-lane divided with TWLTL	9	-	-	12
	Seven-lane undivided	9	-	-	-
70	Four-lane undivided with parking on one side	14	12	-	-
	Four-lane undivided with parking on both sides	11 - 12	10 - 12	-	-
	Four-lane divided	12	-	-	20
	Four-lane divided with parking on one side	9 - 12	8 - 12	8 - 20	-
	Four-lane divided with parking on both sides	9 - 12	8 - 12	4 - 16	-
	Five-lane divided with TWLTL	13 - 14	-	-	12 - 16
	Five-lane undivided	13	-	-	-
	Five-lane undivided with parking on one side	12	8	-	-
	Five-lane undivided with parking on both sides	10	9	-	-
	Six-lane undivided	11	-	-	-
	Six-lane undivided with parking on one side	10	8	-	-
	Six-lane divided	9 - 10	-	8 - 14	-
	Six-lane divided with parking on one side	-	-	-	-
	Seven-lane divided with TWLTL	9	-	-	14
	Seven-lane undivided	9	-	-	-

Table 1. Continued

Total Curb-to-Curb Width (ft)	Feasible Design Alternatives	Range of Possible Lane Widths (ft)	Range of Possible Parking Lane Widths (ft)	Range of Possible Median Widths (ft)	Range of Possible TWLTL Widths (ft)
72	Four-lane undivided with parking on both sides	12	11	-	-
	Four-lane divided	12	-	22	-
	Four-lane divided with parking on one side	9 - 12	8 - 12	10 - 22	-
	Four-lane divided with parking on both sides	9 - 12	8 - 12	4 - 18	-
	Five-lane divided with TWLTL	14	-	-	14
	Five-lane undivided	14	-	-	-
	Five-lane undivided with parking on one side	12	10	-	-
	Five-lane undivided with parking on both sides	10	10	-	-
	Six-lane undivided	11	-	-	-
	Six-lane undivided with parking on one side	10	10	-	-
	Six-lane undivided with parking on both sides	9	8	-	-
	Six-lane divided	9 - 11	-	4 - 16	-
	Six-lane divided with parking on one side	9	8 - 10	4 - 8	-
	Seven-lane divided with TWLTL	9 - 10	-	-	10 - 16
	Seven-lane undivided	10	-	-	-
74	Four-lane undivided with parking on both sides	12	12	-	-
	Four-lane divided	13 - 14	-	16 - 20	-
	Four-lane divided with parking on one side	10 - 12	8 - 12	12 - 22	-
	Four-lane divided with parking on both sides	9 - 12	8 - 12	6 - 20	-
	Five-lane divided with TWLTL	14	16	-	-
	Five-lane undivided with parking on one side	12	12	-	-
	Five-lane undivided with parking on both sides	10	11	-	-
	Six-lane undivided	12	-	-	-
	Six-lane undivided with parking on one side	10	12	-	-
	Six-lane undivided with parking on both sides	9	9	-	-
	Six-lane divided	9 - 11	-	6 - 18	-
	Six-lane divided with parking on one side	9 -10	8 - 12	4 -10	-
	Seven-lane divided with TWLTL	10	-	-	12
	Seven-lane undivided	10	-	-	-
	Seven-lane undivided with parking on one side	9	9	-	-
	Eight-lane undivided	9	-	-	-
76	Four-lane undivided with parking on both sides	13 - 14	9 - 11	-	-
	Four-lane divided	13 - 14	-	18 - 22	-
	Four-lane divided with parking on one side	10 - 12	8 - 12	14 - 22	-
	Four-lane divided with parking on both sides	9 - 12	8 - 12	4 - 20	-
	Five-lane undivided with parking on one side	13	9	-	-
	Five-lane undivided with parking on both sides	10	12	-	-
	Six-lane undivided	12	-	-	-
	Six-lane undivided with parking on one side	11	8	-	-
	Six-lane undivided with parking on both sides	9	10	-	-
	Six-lane divided	9 - 11	-	8 - 20	-
	Six-lane divided with parking on one side	9 - 10	8 - 12	4 - 12	-
	Seven-lane divided with TWLTL	10	-	-	14
	Seven-lane undivided	10	-	-	-
	Seven-lane undivided with parking on one side	9	11	-	-
	Eight-lane undivided	9	-	-	-

Total Curb-to-Curb Width (ft)	Feasible Design Alternatives	Range of Possible Lane Widths (ft)	Range of Possible Parking Lane Widths (ft)	Range of Possible Median Widths (ft)	Range of Possible TWLTL Widths (ft)
78	Four-lane undivided with parking on both sides	13 - 14	10 - 12	-	-
	Four-lane divided	14	-	20	-
	Four-lane divided with parking on one side	11 - 12	8 - 12	16 - 22	-
	Four-lane divided with parking on both sides	9 - 12	8 - 12	4 - 22	-
	Five-lane undivided with parking on one side	13	11	-	-
	Five-lane undivided with parking on both sides	12	8	-	-
	Six-lane undivided	13	-	-	-
	Six-lane undivided with parking on one side	11	10	-	-
	Six-lane undivided with parking on both sides	9 - 10	8 - 11	-	-
	Six-lane divided	9 - 12	-	4 - 22	-
	Six-lane divided with parking on one side	9 - 10	8 - 12	4 - 14	-
	Six-lane divided with parking on both sides	9	8 - 9	4 - 6	-
	Seven-lane divided with TWLTL	10 - 11	-	-	10 - 16
	Seven-lane undivided	10	-	-	-
	Seven-lane undivided with parking on one side	9	12	-	-
	Eight-lane undivided	9	-	-	-
	Eight-lane divided	9	-	-	4
80	Four-lane undivided with parking on both sides	14	11	-	-
	Four-lane divided	14	-	22	-
	Four-lane divided with parking on one side	12	8 - 10	20 - 22	-
	Four-lane divided with parking on both sides	9 - 12	8 - 12	8 - 22	-
	Five-lane undivided with parking on one side	14	8	-	-
	Five-lane undivided with parking on both sides	12	9	-	-
	Six-lane undivided	13	-	-	-
	Six-lane undivided with parking on one side	11	12	-	-
	Six-lane undivided with parking on both sides	9 - 10	9 - 12	-	-
	Six-lane divided	10 - 11	-	6 - 18	-
	Six-lane divided with parking on one side	9 - 11	8 - 12	4 - 16	-
	Six-lane divided with parking on both sides	9	8 - 10	4 - 8	-
	Seven-lane divided with TWLTL	11	-	-	12
	Seven-lane undivided	11	-	-	-
	Seven-lane undivided with parking on one side	10	8	-	-
	Eight-lane undivided	9	-	-	-
	Eight-lane divided	9	-	6	-
82	Four-lane undivided with parking on both sides	14	12	-	-
	Four-lane divided with parking on one side	12	10 - 12	20 - 22	-
	Four-lane divided with parking on both sides	10 - 12	8 - 12	8 - 22	-
	Five-lane undivided with parking on one side	14	10	-	-
	Five-lane undivided with parking on both sides	12	10	-	-
	Six-lane undivided	13	-	-	-
	Six-lane undivided with parking on one side	12	8	-	-
	Six-lane undivided with parking on both sides	10	10	-	-
	Six-lane divided	10 - 12	-	8 - 20	-
	Six-lane divided with parking on one side	9 - 11	8 - 12	4 - 18	-
	Six-lane divided with parking on both sides	9 - 10	8 - 11	4 - 10	-
	Seven-lane divided with TWLTL	11	-	-	14
	Seven-lane undivided	11	-	-	-
	Seven-lane undivided with parking on one side	10	10	-	-
	Eight-lane undivided	10	-	-	-
	Eight-lane undivided with parking on one side	9	8	-	-
	Eight-lane divided	9	-	8	-

Table 1. Continued

Total Curb-to-Curb Width (ft)	Feasible Design Alternatives	Range of Possible Lane Widths (ft)	Range of Possible Parking Lane Widths (ft)	Range of Possible Median Widths (ft)	Range of Possible TWLTL Widths (ft)
84	Four-lane divided with parking on one side	12	12	22	-
	Four-lane divided with parking on both sides	9 - 12	8 - 12	10 - 22	-
	Five-lane undivided with parking on one side	14	12	-	-
	Five-lane undivided with parking on both sides	12	11	-	-
	Six-lane undivided	13	-	-	-
	Six-lane undivided with parking on one side	12	10	-	-
	Six-lane undivided with parking on both sides	10 - 11	8 - 11	-	-
	Six-lane divided	10 - 12	-	4 - 22	-
	Six-lane divided with parking on one side	9 - 11	8 - 12	4 - 20	-
	Six-lane divided with parking on both sides	9 - 10	8 - 12	4 - 12	-
	Seven-lane divided with TWLTL	11 - 12	-	-	10 - 16
	Seven-lane undivided	11	-	-	-
	Seven-lane undivided with parking on one side	10	12	-	-
	Eight-lane undivided	10	-	-	-
	Eight-lane undivided with parking on one side	9	10	-	-
	Eight-lane divided	9	-	10	-
86	Four-lane divided with parking on one side	13 - 14	8 - 12	16 - 22	-
	Four-lane divided with parking on both sides	10 - 12	8 - 12	14 - 22	-
	Five-lane undivided with parking on both sides	12	12	-	-
	Six-lane undivided	14	-	-	-
	Six-lane undivided with parking on one side	12	12	-	-
	Six-lane undivided with parking on both sides	10 - 11	9 - 12	-	-
	Six-lane divided	11 - 12	-	12 - 18	-
	Six-lane divided with parking on one side	9 - 12	8 - 12	4 - 22	-
	Six-lane divided with parking on both sides	9 - 10	8 - 12	4 - 14	-
	Seven-lane divided with TWLTL	12	-	-	12
	Seven-lane undivided	12	-	-	-
	Seven-lane undivided with parking on one side	10	12	-	-
	Eight-lane undivided	10	-	-	-
	Eight-lane undivided with parking on one side	9	12	-	-
	Eight-lane divided	9 - 10	-	4 - 12	-
	Eight-lane divided with parking on one side	9	8	4	-
88	Four-lane divided with parking on one side	13 - 14	8 - 12	18 - 22	-
	Four-lane divided with parking on both sides	10 - 12	8 - 12	14 - 22	-
	Five-lane undivided with parking on both sides	14	8	-	-
	Six-lane undivided with parking on one side	13	8	-	-
	Six-lane undivided with parking on both sides	11	10	-	-
	Six-lane divided	11 - 12	-	14 - 20	-
	Six-lane divided with parking on one side	9 - 12	8 - 12	4 - 22	-
	Six-lane divided with parking on both sides	9 - 11	8 - 12	4 - 16	-
	Seven-lane divided with TWLTL	12	-	-	14
	Seven-lane undivided	12	-	-	-
	Seven-lane undivided with parking on one side	11	9	-	-
	Seven-lane undivided with parking on both side	10	8	-	-
	Eight-lane undivided	10	-	-	-
	Eight-lane undivided with parking on one side	9	12	-	-
	Eight-lane divided	9 - 10	-	6 - 14	-
	Eight-lane divided with parking on one side	9	8 - 10	4 - 6	-

Table 1 and Figure 2 are intended to show every street width allocation that is physically feasible and, thus, identify candidates for consideration at particular sites. The selection of the most suitable improvement strategy from among the feasible candidates is addressed in Chapter Three.

CURRENT USE OF IMPROVEMENT STRATEGIES

A survey of highway agencies was conducted to determine the current use of traffic operational improvement strategies for urban arterials that do not change the total curb-to-curb street width. This survey was conducted with a mail questionnaire, with appropriate follow-up interviews with selected respondents. The questionnaire was intended to determine types of improvement strategies used; rationale for narrower lanes, as opposed to other possible improvement strategies; types of highways where improvement strategies incorporating narrower lanes have been used; operational experience with recent projects; safety experience with recent projects; availability of appropriate recent projects for before-after evaluation later in the research; and person to contact for further information.

The questionnaire used for this survey is presented in Appendix B. In designing the questionnaire, the research team had to balance the amount of information sought with the likely negative effect on the response rate if the questionnaire was too complex. For example, it was not feasible to inquire into specific choices between the improvement strategies shown in Table 1, because the questionnaire would have become too complex. Thus, the questionnaire was kept general while clearly identifying sources of more specific information that could be obtained through follow-up contacts.

The questionnaire was mailed to all 50 state highway agencies and to 150 selected local agencies. The state highway agency addresses were identified from the 1988 American Association of State Highway and Transportation Officials (AASHTO) directory. In all cases, the questionnaire was sent to the state traffic engineer. The local agencies include both cities and counties. These agencies were selected primarily from the Institute of Transportation Engineers (ITE) directory. In local agencies, the

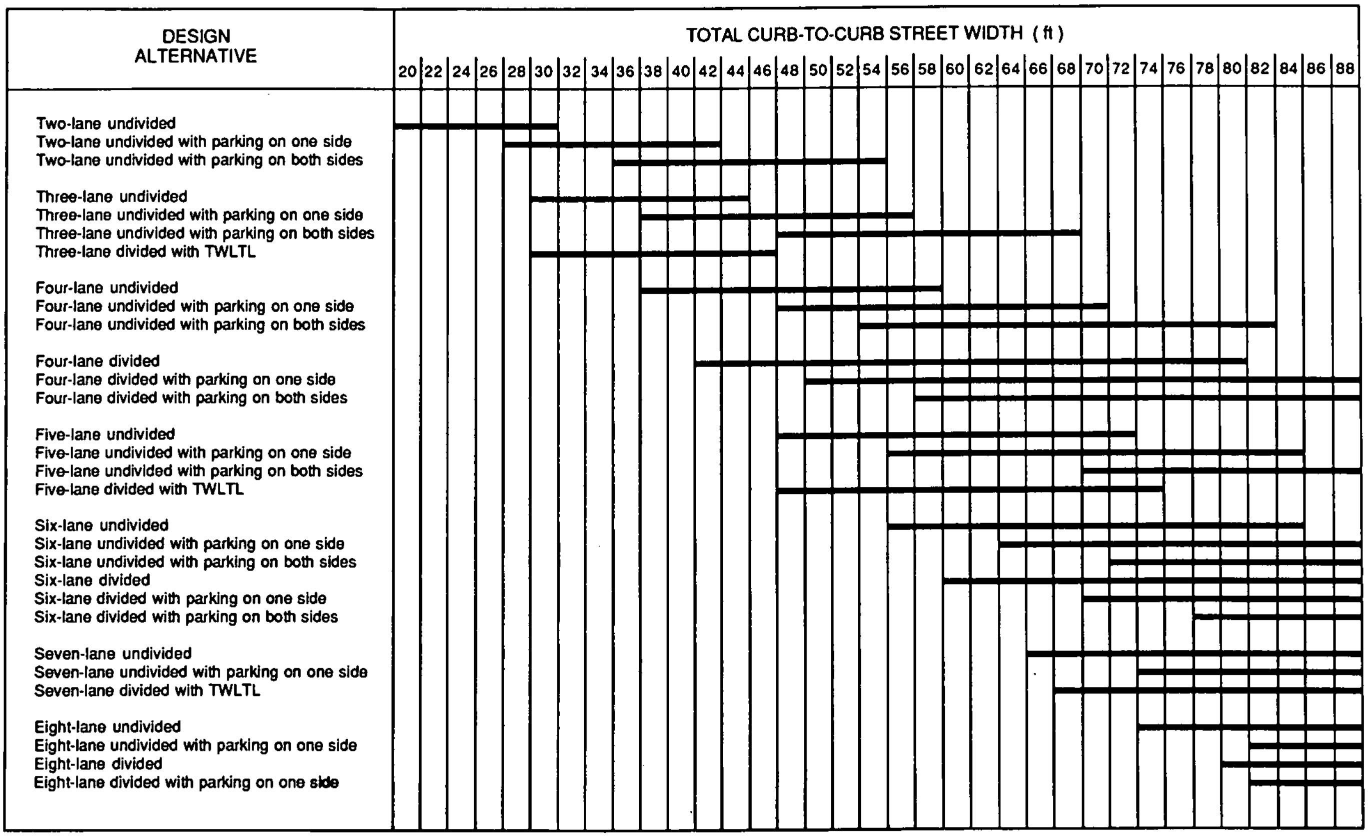

Figure 2. Feasible design alternatives for particular curb-to-curb street widths.

questionnaire was sent to the most senior traffic engineer listed in the directory. The number of agencies selected in each state was chosen in rough proportion to the population of the state. A minimum of one agency in each state was selected.

The overall response rate to the questionnaire was 71 percent. Responses were received from 45 of the 50 states (90 percent) and 96 of the 150 local agencies (64 percent) to whom the questionnaire was sent.

The complete results of the questionnaire survey are presented in Appendix B. The key findings of the survey were:

1. *Use of improvement strategies*—Traffic operational improvement strategies that do not involve changing the total curb-to-curb street width have been used on urban arterials by more than 96 percent of the highway agencies responding to the survey.

2. *Narrower lanes*—Approximately 82 percent of the highway agencies responding to the survey have used improvement strategies involving narrower lanes. The most common reasons for use of narrower lanes are provision of additional through lanes (cited by 70 percent of highway agencies) and addition of a TWLTL (68 percent). Less frequently, highway agencies used narrower lanes in order to add a raised median, provide turn lanes at intersections, provide bicycle lanes, provide curb parking or loading zones, provide bus or transit lanes, and provide a wider curb lane.

The narrowest lane widths used by highway agencies on urban arterials ranged from 8 ft to 12 ft, with an average of 9.6 ft. Four percent of highway agencies have used 8 ft lanes on urban arterials, while 42 percent of agencies have used lanes of 9 ft or narrower, and 88 percent of agencies have used lanes of 10 ft or narrower.

Approximately 70 percent of highway agencies consider the narrowest lanes that they actually use to be effective and, therefore, would presumably not change their current policy if given the opportunity. Approximately 8 percent of agencies would consider narrower lanes than they now use, while 22 percent would prefer wider lanes.

More than 67 percent of highway agencies that have implemented narrower lanes reported no adverse traffic operational or safety problems. Other agencies reported some specific problems including: increases in sideswipe accidents; straddling of lane lines, particularly by trucks and buses; and turning problems at intersections, particularly for trucks and buses. Only four agencies stated definitely that total accidents had increased as a result of projects involving narrower lanes and only three agencies reported that they had found it necessary to remark particular streets for wider lanes to eliminate these problems.

3. *Median removal*—Improvement strategies involving median removal (not just narrowing) have been used by 60 percent of the highway agencies responding to the survey. The most common reasons cited for median removal were TWLTL installation (74 percent), provision of additional through lanes (34 percent), and provision of additional left turns at intersections (22 percent).

Only 7 percent of the agencies that have removed medians report any adverse traffic operational or safety problems. Some types of accidents, such as left-turn accidents, increased for some median removal projects, but no agency indicated that there was an increase in total accidents.

4. *Two-way left-turn lanes*—TWLTLs have been used on urban arterials with curb-and-gutter sections (as opposed to suburban highways with shoulders) by 86 percent of the highway agencies responding to the survey.

Highway agencies reported that the narrowest widths they have used for TWLTLs on urban arterial streets range from 8 ft to 16 ft with a mean of 10.5 ft. In response to another question, highway agencies reported that the widest widths they have used for TWLTLs ranged from 10 ft to 20 ft, with a mean of 13.9 ft.

Adverse traffic operational and safety problems with TWLTLs were reported by only 15 percent of the highway agencies that have used them on urban arterial streets. The most common problems cited by highway agencies included: confusion on the part of drivers unfamiliar with TWLTLs; conflicts between opposing left-turn maneuvers; use of a TWLTL as a passing lane; poor operation of TWLTLs that are too wide; and encroachment on through lanes by vehicles waiting to turn in narrow TWLTLs.

5. *Other midblock improvements*—Approximately 90 percent of highway agencies reported projects involving curb parking removal and 55 percent reported restriction of curb parking in the peak hour.

Projects involving conversion of streets from two-way to one-way operation were reported by 54 percent of highway agencies. Four highway agencies reported converting streets from one-way back to two-way operation.

Projects involving provision of reversible lanes (operating in different directions at different times of the day) were reported by 26 percent of highway agencies.

6. *Related intersection improvements*—Over 80 percent of highway agencies have used urban arterial improvement strategies that did not change the total curb-to-curb street width and incorporated right-turn lanes at intersections; left-turn lanes at intersections; signal timing; signal phasing; signal progression; and removal of curb parking on intersection approaches. These results are discussed in more detail in Appendix B.

EFFECTIVENESS OF IMPROVEMENT STRATEGIES

This section of the report summarizes information about the effectiveness of urban arterial street improvement strategies. The section begins with a review of relevant research findings concerning the traffic operational and safety effectiveness of specific design features for urban arterial streets. These design features are the building blocks of the design alternatives and improvement strategies addressed in this report. This review is based on published literature and is as quantitative as possible, given the current state of the art.

New findings concerning the traffic safety effects of improvement strategies involving narrower lanes are presented. These findings are based on traffic accident analyses and field observations of traffic operations conducted in the present study.

The general advantages and disadvantages of each design alternative are then reviewed, incorporating material from both the literature review and the safety analyses. This discussion provides guidance on the use of these design alternatives as part of improvement strategies for urban arterial streets.

The findings presented in this section, based on both the literature and new data, form the basis for the selection of an appropriate improvement strategy. Guidelines for the selection of improvement strategies are addressed in the Chapter Three.

Effectiveness of Specific Design Features

The following discussion reviews the effectiveness of specific design features for urban arterials including capacity and level-of-service procedures, narrower lanes, two-way left-turn lanes, raised medians, curb parking removal, one-way streets, reversible lanes, and bicycle considerations. Each of these topics is summarized briefly, as follows, and is reviewed in more detail in Appendix A.

Capacity and Level-of-Service Procedures

The basic procedures for determining the capacity and level of service on urban arterials are those presented in the following chapters of the 1985 *Highway Capacity Manual* (HCM) (*2*): Chapter 9—Signalized Intersections; Chapter 10—Unsignalized Intersections; Chapter 11—Urban and Suburban Arterials; Chapter 12—Transit Capacity; Chapter 13—Pedestrians; and Chapter 14—Bicycles.

A brief overview of these chapters is presented here. More detailed discussions of specific aspects of these chapters, including the treatment of lane width, median treatments, bicycles, etc., are addressed in subsequent sections dealing with those topics.

Analysis of traffic operations on urban arterials requires consideration of both signalized intersections and street sections between intersections. The signalized intersection analysis procedure in HCM Chapter 9 is one of the most valuable resources available to the urban arterial street analyst. The greatest strength of this procedure, in comparison to previous procedures in the 1965 HCM (*3*) and in *Transportation Research Circular 212* (*4*), is its ability to explicitly determine the effect on delay of a wide variety of lane widths, lane allocations, and signal phasing arrangements. Delay was chosen as the primary measure of effectiveness for the HCM Chapter 9 procedure, which can be used to estimate delay for a signalized intersection as a whole or for specific approaches or lane groups. By contrast, the 1965 HCM used load factor as its measure of effectiveness and Circular 212 used critical lane volumes, neither of which could be directly related to delay.

The unsignalized intersection procedure presented in HCM Chapter 10 is, unfortunately, more limited in scope and not as precise as the signalized intersection procedure. The procedure is applicable to two-way STOP- and YIELD-controlled intersections and the primary purpose of the procedure is to estimate the delay likely to be experienced by vehicles on the minor street. However, the procedure does not estimate the delay experienced by vehicles on the major street due to turns to and from the major street, which is the primary concern to the urban arterial street analyst.

HCM Chapter 11 on urban and suburban arterials attempts to evaluate the combined traffic operational effects of signalized intersections and midblock sections. The signalized intersection procedures of HCM Chapter 11 are very simplified in comparison to HCM Chapter 9 and, thus, do not have the same sensitivity to a wide variety of factors as HCM Chapter 9. The HCM Chapter 11 procedure for midblock sections essentially assumes that traffic between signalized intersections travels at a specified average running speed, supplied by the user external to the procedure. There are no explicit procedures for considering the effects of turning movements at driveways or unsignalized intersections on speed or delay or for considering the reductions in the speed of traffic (if any) as flow rate increases. The free flow speed is assumed to represent the running speed of traffic at all levels of service on the arterial. The chapter states that, while it would be logical to assume that arterial running speeds depend on traffic volumes, the dependence of intersection delay on traffic volume is much stronger and is assumed to dominate in the computation of arterial travel speed. Support for that assumption is found in recent research on multilane rural and suburban highways (*5*), which found no reduction in speed with increasing traffic volume for traffic volumes up to 1,400 passenger cars per hour per lane (pcphpl).

HCM Chapter 12 deals with transit capacity and includes a procedure for evaluation of the traffic operational effect of buses on arterials and the capacity of exclusive or nearly exclusive bus lanes. Factors for the effect of heavy vehicles (including buses) in the traffic stream and stops by local buses at signalized intersections are included in the HCM Chapter 9 procedure.

HCM Chapter 13 deals with the design of pedestrian facilities, including street corners and crosswalks. The HCM Chapter 9 procedure for signalized intersections considers the effect on intersection delay of pedestrian flows that conflict with vehicle movements and the effect on delay of pedestrian signal phases.

HCM Chapter 14 addresses the effects of bicycles on traffic operations for urban arterials including the passenger car equivalencies for bicycles at signalized intersections. Only limited data are available on the operational impact of bicycles on midblock flows.

Effectiveness of Narrower Lanes

Published literature addresses both the traffic operational and safety effects of lane width on urban arterial streets. However, the traffic operational effects of lane width are much better documented than the traffic safety effects.

Traffic Operations. The basic adjustment factor for lane width in the signalized intersection analysis procedure of HCM Chapter 9 is given in Table 2. This factor is one of several multipliers applied to the ideal saturation flow rate for a lane or lane group to determine the actual saturation flow rate. The table shows an adjustment factor of 1.00 for 12-ft lanes, indicating that lanes widths of 12 ft involve no reduction in the ideal saturation flow rate. Narrower lanes of 8, 9, 10, and 11 ft involve reductions to 87, 90, 93, and 97 percent, respectively, in the ideal saturation flow rate which is generally estimated as 1,800 vehicles per hour (vph).

The HCM Chapter 9 procedure makes it easy to estimate the operational effect of various lane widths and lane allocations on delay at signalized intersections. For example, Table 2 implies that three 8-ft lanes will have a saturation flow rate 2.6 times that of two 12-ft lanes (i.e., $3 \times 0.87 = 2.6$) while occupying the same 24 ft of street width. The computational procedure in HCM Chapter 9 can translate this difference in saturation flow rate into a difference in vehicle delay for any specified traffic volume level.

The HCM Chapter 11 procedures for intersection delay address the number of lanes within each lane group, but not the width of those lanes. Thus, this procedure cannot be used directly to examine the effects of proposed improvement strategies that will change the lane widths on intersection approaches. For midblock locations, the effect of changes in lane widths on traffic operations can only be assessed indirectly through the user's judgment about the effects of change on free flow speeds. However, some effects of lane width on speed were suggested in the research conducted to develop HCM Chapter 11 (*6*).

Other operational studies that have addressed the relationships between lane widths and traffic speeds on urban and suburban arterials include a British study by Farouki and Nixon (*7*) and a North Carolina State University study (*8*) that are reviewed in Appendix A.

Traffic Safety

The relationship between lane width and traffic accidents is difficult to determine statistically and has never been adequately quantified for urban arterials. Only three studies in the literature have addressed the safety effects of narrower lanes on urban or suburban arterial streets. Both a 1959 study by the Oregon State Highway Department (*9*) and the 1983 North Carolina State University study (*8*), mentioned above, found inconsistent relationships between lane width and accident rate on arterial streets. *NCHRP Report 282* (*1*) found no statistically significant relationship between lane width and accident rate on suburban arterials. Despite these inconsistent and negative findings, narrower lanes are presumed by many engineers to have an adverse effect on safety on arterial streets. The lack of quantitative data for this relationship is one of the most significant gaps found in the previous published literature concerning traffic operations and safety on urban arterials.

Effectiveness of Two-Way Left-Turn Lanes

The traffic operational and traffic safety effects of two-way left-turn lanes (TWLTLs) are addressed below.

Traffic Operations. The traffic operational effects of TWLTLs have not been clearly established. The installation of a TWLTL will not increase the capacity of an urban arterial street above that provided by the through lanes. However, a TWLTL can

Table 2. Adjustment factor for lane width used in determination of signalized intersection capacity and level of service (*2*).

Lane width (ft)	Lane width factor (fw)
8	0.87
9	0.90
10	0.93
11	0.97
12	1.00
13	1.03
14	1.07
15	1.10
≥ 16	Use 2 lanes

prevent the through-lane capacity from being degraded by delays associated with left-turning vehicles stopped in a through lane waiting for an opportunity to turn.

A field study of three-lane TWLTL sections on highways in urban fringe areas was conducted by Harwood and St. John (*10*). This study found that delay for the three-lane TWLTL design, in relation to the two-lane undivided design, was correlated with the left-turn volume, the through traffic volume, the opposing traffic volume, and the percent of platooned traffic in the opposing direction. However, these independent variables were so strongly correlated with one another that a regression relationship using any of these variables was as good as a relationship using several of them. The opposing traffic volume was found to have the strongest relationship and a regression equation was developed to predict delay reduction (see Eq. A-13 in Appendix A).

McCoy, Ballard, and Wijaya (*11*) and Ballard and McCoy (*12*) at the University of Nebraska have performed simulation studies of three-lane and five-lane TWLTL sections, respectively, in comparison to two-lane and four-lane undivided streets. These studies used a simulation model known as TWLTL-SIM, which incorporates a simplified model of an urban or suburban arterial street. An updated version of the TWLTL-SIM model was used in *NCHRP Report 282* (*1*) to investigate the operational effectiveness of TWLTLs. Table A-6 in Appendix A presents the delay reduction estimates that resulted from this analysis.

Traffic Safety. Numerous traffic safety evaluations of TWLTLs have been reported in the literature, primarily for TWLTL installations on existing four-lane streets (*13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24*). These studies have found that TWLTLs reduce accident rates on arterial streets by 25 to 35 percent. *NCHRP Report 282* (*1*) found a slightly lower effectiveness for TWLTLs (11 to 25 percent, depending on the number of through lanes and the type of development). However, this study compared existing TWLTL sites with existing undivided sites. It is likely that TWLTLs are more effective when installed at sites with a high proportion of rear-end and angle accidents (as they usually are).

The published literature on the safety effectiveness of TWLTLs universally discounts the possibility of substantial increases in head-on accidents between vehicles traveling in opposite directions trying to use the TWLTL to turn left at the same time (*1*). Although the potential for such accidents exists, most drivers appear to understand the operation of a TWLTL and avoid such situations. Those before-after studies of TWLTL installation that have looked at TWLTL effectiveness by accident type have found that head-on accidents usually decrease with TWLTL installation, although not by as much as other accident types, such as rear-end accidents.

There are no data in the literature that specifically address the effect on safety of differences in TWLTL width or through lane width on TWLTL sections.

Effectiveness of Raised Medians

The traffic operational and safety effects of raised medians on arterial streets are reviewed below.

Traffic Operations. Raised medians promote good traffic operations by separating traffic in opposite directions of travel and eliminating left turns except at locations where median openings are provided. Many median designs incorporate left-turn lanes at median openings to reduce delays to through traffic due to turning traffic at those locations. These operational improvements produce safety benefits as well, which are discussed below. There is, however, a traffic operational cost to raised medians that is not as widely recognized. Drivers who desire to make left turns at locations where a median opening is not provided must either (1) travel beyond their destination or (2) use an alternative route so that they approach their destination in the appropriate direction of travel. Either scenario involves an increase in travel time for left-turning vehicles. *NCHRP Report 282* (*1*) has quantified the additional travel time for a typical situation on a divided arterials street for a range of traffic volumes and driveway densities (see Table A-8 in Appendix A). These results indicate that installation of a raised median on a four-lane highway generally increases delay up to a flow rate of approximately 1,000 vph in each direction of travel.

The increases in travel time for left-turning vehicles that result from raised medians may be appropriate on some arterial streets because traffic operations are improved for through vehicles and, on arterial streets, the land access function should not be permitted to dominate the traffic service function. However, raised medians seem to have fallen out of fashion among traffic engineers recently because of the obvious operational benefits of replacing them with TWLTLs or additional through lanes.

Traffic Safety. The literature does not provide very good safety measures of effectiveness for raised medians on urban arterials, although many highway agencies have installed successful projects. *NCHRP Report 282* (*1*) found the accident rates for four-lane undivided and four-lane divided streets to be nearly the same, when adjusted for differences in type of development, driveways per mile, intersections per mile, and truck percentage. However, on suburban highways with commercial development, the percentage of accidents involving fatalities or injuries was slightly lower for four-lane divided highways than for four-lane undivided highways (38.4 percent vs. 33.7 percent); the opposite appears to be true for suburban highways with residential development. In addition, where existing streets with four-lane undivided cross sections have high accident rates and the percentage of accidents susceptible to correction by a median treatment is large enough, installation of a raised median may reduce a substantial number of accidents.

Effectiveness of Curb Parking Removal

The traffic operational and safety effects of curb parking removal are discussed below.

Traffic Operations. The effect of curb parking maneuvers on signalized intersection operations is incorporated in the HCM Chapter 9 procedure using the parking factor shown in Table A-1 in Appendix A. A 1973 study by Yu and Van Dyke (*25*) found that the average parallel parking maneuver requires 32 sec, during which time following vehicles may be delayed. Unparking maneuvers can also delay through traffic, but generally require less time than parking maneuvers. Yu and Van Dyke constructed a model to predict delay from parking maneuvers. However, the model is only applicable to two-lane streets where following drivers are unable to change lanes to pass the parking vehicle.

A 1967 study by Seburn (*26*) reported that the capacity of an arterial could be increased by 40 to 65 percent by removal of curb parking. Table 3 presents a traffic operational warrant for prohibition of curb parking from the Highway Research Board

Table 3. Parking prohibition criteria (*27*).

Type of prohibition	Maximum vehicles per hour per lane when parking allowed (one direction of flow)	
	1 lane	2 or more lanes
Midblock prohibition for entire street	400	600
Intersection prohibition up to 150 ft on approach and departure	300	500

report, *Parking Principles* (*27*). The table includes warrants for prohibiting parking on an entire block or immediately upstream and downstream of signalized intersections.

Traffic Safety. The 1967 study by Seburn (*26*) analyzed the relationships between accidents and curb parking. The study concluded that the percentage of accidents on arterial streets that directly or indirectly involved parked vehicles ranged from 13 to 33 percent. This study found no statistically significant difference in accident experience between sites where parking was prohibited and sites where parking was restricted to 2 hr or less.

An extensive study of parking accidents reported in 1978 by the University of Tennessee (*28*) concluded that substantial reductions in accidents could be achieved by prohibition of curb parking. The study reported that the prohibition of curb parking could reduce accidents by 19 percent for streets with parking utilization of 0.5 million space-hr per mi and by 73 percent with parking utilization of 1 million space-hr per mi. The Tennessee study concluded that there was a definite relationship between accidents and parking turnover rate and that parking accident rates were highest on streets with land uses that generate high turnover rates and high pedestrian activity.

The conventional wisdom in traffic engineering has always been that angle parking results in high accident rates. *Parking Principles* (*27*), published in 1971, states that angle parking is an "obsolete" concept that should be eliminated by any progressive community. A recent Nebraska study (*29*) also found lower parking accident rates for parallel parking than for angle parking, except for painted stalls on multilane streets. However, this conclusion was challenged by the 1978 University of Tennessee study (*28*) which found no statistically significant relationship between parking configuration and accidents. Streets with heavily used parallel parking had accident rates comparable to streets with angle parking with twice the parking utilization rate. Angle parking resulted in lower operational speeds, but allowed more parking spaces per mile of curb. The real operational cost of angle parking is in the street width it consumes (up to 9 ft more than parallel parking), which might be put to better use.

Effectiveness of One-Way Streets

One-way streets have been used extensively for many years to increase both the operational efficiency and safety of urban arterials. Both of these aspects are reviewed, as follows.

Traffic Operations. Conversion of streets from two-way to one-way operation provides operational benefits by separating conflicting traffic movements in time and space. Typically, one-way streets are used in pairs or in alternating blocks of a grid street system. This arrangement reduces the number of turning movements at each intersection of a one-way and a two-way street from eight to four and at each intersection of two one-way streets from eight to two, providing more green time in the signal cycle for through movements. The one-way operation also makes the maintenance of good signal progression easier along the one-way arterial. The *Transportation and Traffic Engineering Handbook* (*30*) reports that the conversion to one-way operation generally increases capacity by about 10 to 20 percent.

It was previously thought that one-way approaches to signalized intersections were more efficient (i.e., had higher saturation flow rates) than two-way approaches because of the elimination of "friction" between the traffic flows in opposite directions. A factor reflecting this effect was included in the signalized intersection capacity procedure in the 1965 HCM (*3*). However, research in the development of the 1985 HCM found exactly the opposite (*31*). Because engineers regarded this finding as counterintuitive, the 1985 HCM does not include a one-way vs. two-way street effect; i.e., both one-way and two-way streets are considered to have the same saturation flow rates if all other conditions are equal.

The operational disadvantages of one-way streets are being increasingly recognized. Traffic volumes and vehicle-miles of travel are increased in a one-way street system, much as they are on streets with raised medians, because drivers cannot follow direct routes to their destinations. This not only increases the total volumes to be served at signalized intersections, but can also increase air pollution levels in already congested portions of a city. Some agencies are known to have converted existing one-way street systems back to two-way operation, although this has sometimes been done without a complete engineering study.

Traffic Safety. There have been 16 published evaluations of the effects on two-way to one-way street conversions, all published between 1938 and 1972. Individual results from these studies are summarized in Table A-10 in Appendix A. The safety effect of the conversion to one-way operation on total accidents reported in the literature ranged from a 30 percent reduction to a 27 percent increase. However, only 2 studies reported accident increases with one-way conversions, and 7 of the 16 studies reported reductions in total accidents between 20 and 30 percent.

The generally reported effects of one-way conversions include: (1) in most cases, rear-end, opposing-direction sideswipe, turning, and parking accidents can be expected to decrease; (2) accidents that involve turns from the center lane may increase; (3) accident severity generally decreases; (4) midblock accidents are generally reduced more than intersection accidents; (5) there is almost always a reduction in total accidents after the first full year of operation; and (6) there may be short-term increases in total accidents during the first year in operation. There are no data in the literature on the effects of conversions from one-way operation back to two-way operation.

Effectiveness of Reversible Lanes

Many urban arterials have strong directional flows during the morning and evening peak periods. One design feature that can be used to increase the operational efficiency of such arterials is the use of reversible lanes that carry traffic in different directions at different times of day. The first reversible lanes carried traffic in one direction of traffic during the morning peak hour and in the opposite direction of traffic during the evening peak hour. More recently, some highway agencies have begun to use reversible lanes as TWLTLs during the off-peak period.

Nine evaluations of reversible lanes are reported in the literature (*18, 32, 33*). Most of these evaluations found a reduction in travel time for through traffic with implementation of reversible lanes. However, the safety effects were mixed with some projects showing accident reductions and others showing accident increases.

Three different traffic control techniques have been tried for reversible lanes. These are: signs only, lane control signals and signs, and cones and supplementary signs. An evaluation of these traffic control techniques at sites in Tucson, Arizona, found no statistically significant differences in accident rate between the three techniques (*32*). The majority of the accidents occurring in the reversible lanes were left-turn-related, even though left turns were restricted in the reversible lanes.

An FHWA evaluation of reversible lanes used as TWLTLs during the off-peak period evaluated data for 19 sites (*18, 33*). Accident studies at these sites found that the installation of the reversible flow TWLTL usually increased or decreased accidents by only a small amount; head-on accidents were only a small proportion of the total accidents and were not related to the reversible flow operations; and increases in left-turn and sideswipe accidents occurred in the evening peak hour resulting from left turns into and out of the reversible lane.

The reversible lanes at 4 of these 19 sites were eventually eliminated because of operational or accident problems, particularly the left-turn and sideswipe accidents discussed above.

The AASHTO Green Book (*34*) states that reversible lanes are justified when 65 percent or more of the traffic volume moves in one direction of travel during the peak period. Of the 19 sites examined in the FHWA study, only three did not meet this criterion. Travel times at the study sites showed a 10 to 25 percent reduction with installation of the reversible lanes for vehicles in the major flow direction. Vehicles in the minor flow direction experience travel time increases of 11 to 50 percent. At one site in Phoenix, the decrease in travel time for the major flow was completely offset by the increase in travel time for the minor flow.

Bicycle Considerations

Bicycle considerations have a two-fold role in consideration of urban arterial street improvements. First, bicycles can have a substantial impact on traffic flow on urban arterials where they are present in significant numbers. Bicycles constitute only a small proportion of vehicles at most locations in North America. However, in many urban areas and near university campuses, bicycles are present in sufficient numbers to affect traffic flow. Second, highway agencies need to be careful that in implementing urban arterial improvements, especially those that involve narrow lanes, they do not inadvertently make conditions less safe for bicyclists.

There are three primary methods of providing for bicycles in urban corridors with substantial bicycle volumes. These are: separate bicycle paths; marked bicycle lanes in the street along the curb line; and unmarked streets (i.e., shared use of the street by bicycles and other vehicles). Separate bicycle paths are expensive to build and maintain and often have been built in out-of-the-way areas, such as creek beds, that did not serve the needs of the experienced or commuter cyclist. The Maryland State Highway Administration (*35*) has reported a shift from requests for separate bicycle facilities to requests for increased safe access to the existing highway system.

Table 4. Passenger-car equivalents for bicycles and signalized intersections (*2*).

Bicycle movement	Lane width (ft) < 11	11-14	< 14
Opposed	1.2	0.5	0.0
Unopposed	1.0	0.2	0.0

A 1975 report by Mann (*36*) describes the basic paradox of marked bicycle lanes. If a street is wide enough to include a marked bicycle lane that does not interfere with vehicle traffic, then the marking of the bicycle lane is probably unnecessary. In general, both the cyclist and the motorist have more flexibility if no bicycle lane is marked.

A Maryland study (*35*) found that 12-ft curb lanes did not provide sufficient width for shared bicycle and vehicle operations. A New Jersey study (*37*) found that 12-ft curb lanes were acceptable for shared operations only for traffic volumes below 1,200 vehicles per day (vpd). Both the Maryland and New Jersey studies generally recommend the use of 15-ft curb lanes (including the gutter area) for shared mode operations. Both studies also found that the lane width requirements for shared operation increased as the percentage of trucks in the traffic stream increased.

There are no quantitative data on the safety effects on bicyclists when curb lanes narrower than 12 ft are used.

HCM Chapter 14 includes passenger car equivalents for bicycles at intersections (see Table 4). The table shows that for lane widths over 14 ft, bicycles have little or no effect on traffic flow. Bicycles have a modest effect on traffic flow for lane widths between 11 and 14 ft, and have a substantial effect for lane widths under 11 ft. For midblock sections, HCM Chapter 14 states that bicycles have little effect when lane widths exceed 14 ft. The HCM also states that midblock bicycle effects are minimal whenever bicycle volumes are less than 50 bicycles per hour, except where lane widths are less than 11 ft wide. These guidelines are very consistent with the results of the Maryland and New Jersey studies that also encourage curb lane widths wider than 14 ft.

Safety Evaluation of Projects Involving Narrower Lanes

A major gap found in the literature on the effectiveness of design features for urban arterials is the lack of quantitative information on the safety effectiveness of improvement projects involving narrower lanes. Therefore, new data were collected and analyzed to determine whether the use of narrower lanes as part of traffic operational improvement projects on urban arterials leads to any adverse safety problems. The results of this analysis are summarized below and are presented in detail in Appendix C of this report.

Development of Safety Data Base

The safety analyses performed in this study required the assembly of a data base of accident experience before and after improvement projects on urban arterial streets. All of the improvement projects studies were required to meet the same criteria as the overall scope of the study (see discussion of Research Objectives and Scope in Chapter One). In particular, all of the projects studied involved reallocation of the existing street width to different uses without changing the total curb-to-curb street width.

Projects meeting these criteria were identified through contacts with the highway agencies that responded to the survey discussed in Appendix B of this report. Seven highway agencies (including two state agencies, one county agency, and four city agencies) agreed to cooperate in the study. These agencies were located in the states of Illinois, Maryland, Missouri, North Carolina, and Texas.

The seven participating agencies identified a total of 35 projects involving narrower lanes for evaluation in the study. These projects included a total of 26.97 mi of urban arterial streets and ranged from 40 ft to 76 ft in total curb-to-curb width. Six distinct improvement types are represented in the data. These are conversion from: (1) two-lane undivided to four-lane undivided; (2) four-lane undivided to five-lane with two-way left-turn lane (TWLTL); (3) four-lane divided with narrow median to five-lane with TWLTL; (4) five-lane with TWLTL to seven-lane with TWLTL; (5) six-lane undivided to seven-lane with TWLTL; and (6) six-lane undivided to eight-lane undivided.

Many of the projects were implemented by the participating highway agencies over the course of a few days by remarking the existing roadway pavement. However, those projects that involved median removal required construction activity over a longer period.

All of the study sites had minimum lane widths of at least 11 ft before project implementation and some had lanes that were substantially wider. After project implementation, all projects incorporated some lanes with widths of 10 ft or less. The narrowest through lane used in any of the projects was 9 ft wide and the narrowest center TWLTL width was 8 ft.

Data were obtained from the participating highway agencies for study periods both before and after implementation of each project. The data obtained for these periods included geometrics, traffic volumes, and traffic accident experience. The general objective was to use before and after periods that were each at least 2 years in duration but, because of data availability constraints, study periods as short as one year had to be used in a number of cases for the before period, the after period, or both.

The average daily traffic (ADT) volumes on the 35 study sites ranged from 8,900 vpd to 62,800 vpd. Traffic volumes were obtained for each individual year of both the before and after study periods, so that time trends in traffic volume between the before and after periods could be considered in the analysis.

Accident data were obtained from the participating highway agencies for the before and after periods at each site. These data were obtained in various forms including hard copy police accident reports, collision diagrams, and computer listings of individual accidents. Basic accident descriptors, including the accident severity, the accident type and manner of collision, and the relationship of the accident to intersections, were extracted from the data and coded in a common format for computer analyses.

The project data base includes over 7,000 accidents and over 972 million veh-mi of travel in the before and after periods combined.

Analysis Approach

A comparison of the traffic accident experience before and after implementation of projects involving narrower lanes was conducted to determine their effect on accident rate and on the distribution of accident severities and accident types.

The objective of this analysis was to evaluate the overall effects of projects that involved narrower lanes, among other features. It was not our intention to attempt to separate the safety effects of the narrower lanes from other features of the projects such as TWLTL installation or median removal. In fact, previous research has been unsuccessful in developing widely accepted relationships between traffic accidents and the incremental effects of geometric features such as lane widths. The objective was more modest—to determine whether the net effect of projects involving narrower lanes was to increase accident rate (or severity), to reduce accident rate, or to leave accident rate unchanged.

It is likely that very narrow lanes by themselves may lead to accidents that would not otherwise occur. Such accidents would be most likely to involve sideswipe collisions between vehicles traveling in the same direction, although other types of collisions could also be related to narrower lanes. There are no reliable data on the relative severity of collisions related to narrower lanes. However, it would be desirable to know if the accident reduction benefits of improvements such as installation of a center TWLTL made in conjunction with narrower lanes are greater than any increase in accidents associated with lane width, so that the *net* effect of the project on safety is positive. In this situation, if the traffic operational benefits of a center TWLTL can only be obtained through the use of narrower lanes and if the overall effect of the project on safety is positive (or zero), the project is fully justified. If a traffic operational improvement involving narrower lanes would increase accident rate or severity, the tradeoff between improved traffic operations and increased accidents must be considered.

Control sections which were not modified during the study were used to provide a method to account or control for any general time trends in accident experience that affect both the improved sites and control sites. Control sites were selected to provide as good a match as possible with the geometrics and traffic characteristics of the improvement sites before they were modified. Seven control sites were identified that provide a good match to 11 of the 35 improved sites. No statistically significant changes in accident rate between the before and after periods were found for the control sites either individually or as a group. Therefore, it was concluded that there are no general time trends in accident rate to be accounted for.

Several statistical methods were used to evaluate the differences in accident experience between the before and after periods, including a Chi-squared test for differences in accident frequencies and an analysis of variance for differences in accident rate. A difference of proportions test was used to evaluate shifts in the accident severity distribution (differences in the proportion of fatal and injury accidents) between the before and after periods. Each of these statistical approaches is a standard statistical technique that is recommended in the FHWA *Accident Analysis Manual* (*38*). The statistical software used for these analyses included a mainframe computer package, the Statistical Analysis System (SAS) (*39*), and a microcomputer package, SYSTAT (*40*).

Analysis Results

The analysis results for each project type are summarized in Tables 5 and 6. Table 5 presents the effects of each project type

Table 5. Summary of project effects on accident rate and severity.

Project type	Percent change in accident rate (per million veh-mi): Total accidents	Percent change in accident rate (per million veh-mi): Midblock accidents	Change in percentage of fatal and injury accidents
Conversion from two-lane undivided to four-lane undivided	+109.6	0.0[a]	None
Conversion from four-lane undivided to five-lane with TWLTL	-44.1[b]	-45.0	None
Conversion from four-lane divided with narrow median to five-lane with TWLTL	-52.6[b]	-56.6[b]	None
Conversion from five-lane with TWLTL to seven-lane with TWLTL	+23.7[b]	+31.3	None
Conversion from six-lane divided with narrow median to seven-lane with TWLTL	-24.0	-32.1[b]	None
Conversion from six-lane divided to eight-lane divided	+23.0	0.0[a]	None

[a] Change in accident rate was not statistically significant.
[b] May vary substantially from site to site.

Table 6. Summary of project effects (percent change) on specific collision types.

Project type	Midblock accidents			Intersection accidents		
	Angle	Sideswipe[a]	Rear-end	Angle	Sideswipe[a]	Rear-end
Conversion of two-lane undivided to four-lane undivided	+185	-35	-100	-5	+281	+350
Conversion from four-lane undivided to five-lane with TWLTL	-33	-38	-60	0	-53	-68
Conversion from four-lane divided with narrow median to five-lane with TWLTL	+20	+120	-40	-23	-52	-80
Conversion from five-lane with TWLTL to seven-lane with TWLTL	+15	+180	+11	+65	+77	-65
Conversion from six-lane divided with narrow median to seven-lane with TWLTL	+37	-28	-51	-5	-17	-37
Conversion from six-lane divided to eight-lane divided	+46	+104	-37	+41	+88	+70

[a] Same-direction sideswipe collisions only.

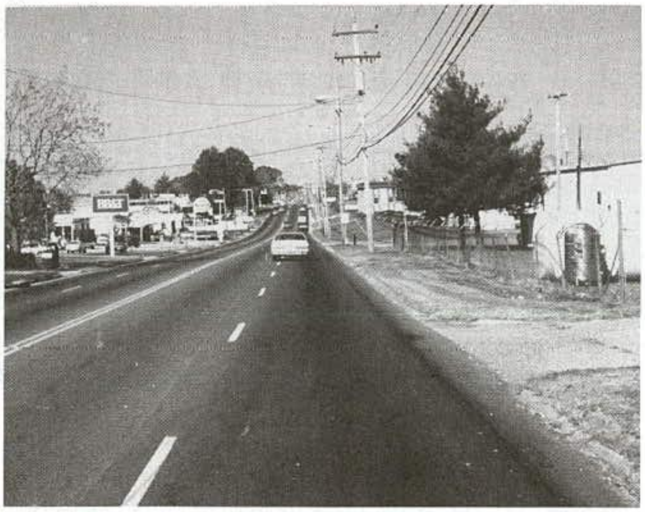

Figure 3. Four-lane undivided street converted from two-lane undivided street.

on total and midblock accident rate and on accident severity. Table 6 summarizes the effects of each project type on the most common accident types: angle, same-direction sideswipe, and rear-end collisions at intersections and at midblock locations.

For three of the six project types a net reduction in total accident rate was found, while a net increase in total accident rate was found for the remaining three project types. A net reduction in midblock accident rate was found for three of the six project types, while a net increase in midblock accident rate was found for one project type, and no net change in midblock accident rate was found for the remaining two project types. The specific effects of each project type are discussed below.

As with most traffic accident countermeasures, the accident reduction effectiveness of these project types can vary substantially from site to site. Confidence intervals for the accident reduction effectiveness of several of these project types are provided in the discussion of the individual project types.

None of the project types were found to affect the accident severity distribution. Each of the six project types slightly reduced the proportion of fatal and injury accidents, but none of those reductions were statistically significant.

As stated previously, the analysis was not intended to isolate the effect of narrower lanes on accidents, but only to determine the overall effect on accidents of projects involving narrower lanes, among other changes. The results in Table 5 indicate that *all three project types that involve the installation of a center TWLTL at a site that is currently without a TWLTL will typically reduce accidents even if the project incorporates narrower lanes.* Projects intended to add an additional through lane by use of narrower lanes increased midblock accidents in one case, but did not increase midblock accidents in two other cases. However, the total accident rate increased for each of the three types of projects that involved additional through lanes but not an additional TWLTL. It is apparent that these increases in total accident rate generally result from increases in intersection accidents.

Special emphasis was placed on the analysis of midblock accidents in the study because both the benefits of center TWLTLs and any safety problems associated with narrower lanes should be most evident at midblock locations. Intersection accidents (especially at signalized intersections) are influenced by many factors in addition to the effects of the improvement strategies being evaluated. Thus, it is particularly significant that midblock accident rates were reduced or remained the same for five of the six project types. Midblock same-direction sideswipe and rear-end accident rates, which may be the best indicator of any safety problems caused by narrower lanes, were reduced for three of the project types and increased for three project types.

Each project type is discussed individually as follows.

Conversion from Two-Lane Undivided to Four-Lane Undivided. The first project type evaluated involved three undivided sites with two wide lanes that were each converted to a four-lane undivided cross-section with narrower lanes. These sites have total curb-to-curb widths of 40 ft to 44 ft. The sites were relatively unusual in that the original two-lane undivided configuration had lanes of 20 ft to 22 ft wide. The sites have ADTs in the range of 7,600 vpd to 11,800 vpd. The highway agency responsible for these sites was concerned about the potential for vehicles to wander within the wide lanes and the potential for unsafe passing maneuvers, so these sites were converted to a four-lane undivided cross section with lanes as narrow as 10 ft. Figure 3 shows a photograph of one of these sites after restriping to the four-lane undivided cross section.

The total accident rate for this project type increased by 109.6 percent from the before and to the after period. There was no statistically significant change in the midblock accident rate and no statistically significant change in the accident severity distribution.

There were substantial percentage increases in driveway-related midblock angle accidents and same-direction sideswipe and rear end accidents at intersections. By contrast, midblock sideswipe and rear-end accidents, which are most directly related to the effects of narrow lanes, decreased substantially. However, it should be recognized that the analysis of this project type is based on a total of only 44 accidents in the before and after period combined, so the results must be interpreted cautiously.

The results of the evaluation for this project type suggest that conversion to a three-lane divided cross section with a center TWLTL might have been a preferable alternative. The relatively low traffic volumes on these sites could be adequately served by two through lanes, while rear-end and angle collisions would have been minimized by the TWLTL. Thus, the three-lane TWLTL alterative could possibly have prevented the increase in accidents that occurred.

Conversion from Four-Lane Undivided to Five-Lane with TWLTL. The most common type of project involving narrow lanes was conversion from four-lane undivided (generally with 12 ft or wider lanes) to five-lane with a center TWLTL (with lanes as narrow as 8 to 10 ft). There are 17 projects of this type in the project data base, representing about half of the evaluated sites. This type of improvement is obviously being made very frequently by highway agencies. Traffic volumes on these sites ranged from 8,900 vpd to 56,900 vpd. Figure 4 is a photograph of a typical five-lane TWLTL site with narrow lanes after improvement.

On the average, this project type reduced total accident rate by 44.1 percent and reduced midblock accident rate by 45.0 percent. Both of these results are statistically significant. The accident reduction effectiveness of this project type can vary substantially from site to site. The 90 percent confidence interval

Figure 4. Five-lane street with center TWLTL converted from four-lane undivided street.

Figure 5. Five-lane street with center TWLTL converted from four-lane divided street with narrow median.

for reduction in total accident rate ranges from 12 to 75 percent, which implies that the reduction in total accident rate for 90 percent of sites should fall within this range. There was no statistically significant change in the accident severity distribution. All major accident types were reduced except angle collisions at intersections, which were unchanged.

These results indicate clearly that the installation of a center TWLTL on a four-lane undivided street is highly desirable from a safety standpoint, even if narrower lanes must be used to provide space for the TWLTL.

Conversion from Four-Lane Divided with Narrow Median to Five-Lane with TWLTL. The third type of project evaluated in the accident study was removal of a narrow median on a four-lane street and use of narrower lanes to provide space for a center TWLTL. The five sites evaluated each initially had a raised or mountable 4-ft median dividing a four-lane, 50-ft to 52-ft street. This cross section had been in common use a number of years ago by one of the participating state highway agencies but is being gradually eliminated, typically replaced by a cross section with a TWLTL. Thus, this project type is equivalent to the previous project type except that the original configuration had a 4-ft median and the improved configuration, consequently, has slightly wider lanes. Traffic volumes on these sites ranged from 13,000 vpd to 24,000 vpd. The improved configuration for a typical site is illustrated by Figure 5.

Removal of a narrow median and installation of a TWLTL was found, on the average, to reduce total accident rate by 52.6 percent and midblock accident rate by 56.6 percent. Both of these results were found to be statistically significant. As in the case of the previous project type, the accident reduction effectiveness of this project type can vary substantially from site to site. The accident reduction effectiveness for 90 percent of sites should fall in the range from 24 to 82 percent, with an expected average reduction in total accident rate of 53 percent. There was no statistically significant change in the accident severity distribution. The implementation of this project type was accompanied by increases in midblock angle and same-direction sideswipe accidents, but a decrease in midblock rear-end accidents and in all major types of intersection accidents.

The accident reduction effectiveness of this project type was slightly higher than the accident reduction effectiveness of TWLTL installation on a four-lane undivided street, possibly because the total curb-to-curb width was generally slightly higher, so the lanes on the improved roadway were slightly wider. It should be noted that, although raised medians are generally considered to be advantageous for safety, in this case, removal of a narrow median resulted in a substantial reduction in accident rate because it was replaced with a more effective median treatment. As with the previous project type, the safety effectiveness of installing a center TWLTL on an arterial street has a greater influence on accident rates than any other factor.

Conversion from Five-Lane with TWLTL to Seven-Lane with TWLTL. The fourth project type evaluated was conversion of an existing five-lane street with 11-ft and 12-ft lanes to a seven-lane street with 9-ft and 10-ft lanes. Both the five-lane and seven-lane configurations included TWLTLs. This project type was evaluated at two adjacent sites that were improved at the same time, but differ in traffic volume and the character and density of development. Both sites had the same speed limit (45 mph), but speeds were noticeably higher on the site with lower traffic volumes and less dense development. Traffic volumes on these sites ranged from 30,400 vpd to 48,500 vpd. Figure 6 shows the final seven-lane configuration at one of these sites.

Conversion from a five-lane to a seven-lane configuration was found to increase total accident rate by 23.7 percent and to increase midblock accident rate by 31.3 percent. Both of these findings were statistically significant. However, it is interesting to note that at the site with higher traffic volumes, higher density of development, and lower speeds, total accident rate increased by only 6.0 percent, and that increase was not statistically significant. However, at the other site with lower traffic volumes, less dense development, and higher speeds, total accident rate increased by 56.7 percent. Thus, the seven-lane TWLTL cross section may lead to safety problems primarily at locations with higher speeds.

There was no statistically significant change in the accident severity distribution for this project type. All major accident types increased except for rear-end collisions at intersections which were reduced by 65 percent.

The evaluation of this project type suggests that where nar-

Figure 6. Seven-lane street with center TWLTL converted from five-lane street with center TWLTL.

Figure 7. Seven-lane street with center TWLTL converted from six-lane divided street with narrow median.

rower lanes are used to incorporate an additional through lane, rather than a TWLTL, into an arterial street cross section, accident rates may increase. The available data suggest that safety problems with this type of project may occur primarily on sites with higher speeds.

Conversion from Six-lane Divided with Narrow Median to Seven-Lane with TWLTL. Another project type evaluated in the accident study was conversion from a six-lane divided cross section with a narrow median to a seven-lane cross section with a TWLTL. This project type is entirely analogous to the four-lane divided to five-lane TWLTL conversion discussed above, except that it was implemented on 74-ft to 76-ft streets, rather than 50-ft to 52-ft streets. As in that project type, the street originally had a narrow 4-ft median that was removed to provide part of the width for the TWLTL. Traffic volumes on these sites ranged from 24,400 vpd to 29,200 vpd. Figure 7 shows a typical site after improvement.

This project type, on the average, reduced total accident rate by 24.0 percent and midblock accident rate by 32.1 percent. Both of these findings were statistically significant. This project type showed much less variation in accident reduction effectiveness than other project types, possibly because all of the four sites evaluated were located in the same metropolitan area and were under the jurisdiction of the same highway agency. The accident reduction effectiveness for this project type for 90 percent of sites should fall in the range from 11 to 38 percent, with an expected value of 24 percent for reduction in total accident rate. There was no statistically significant change in the accident severity distribution. All major accident types were reduced by this project type, except for driveway-related midblock angle collisions which increased by 37 percent.

This evaluation shows that conversion to a seven-lane TWLTL cross section can be effective in reducing accident rate when the project includes installation of a TWLTL in an existing street that does not have one. Even the accident types primarily related to narrower lanes were reduced.

Conversion from Six-Lane Divided to Eight-Lane Divided. The final project type evaluated was conversion from a six-lane divided to an eight-lane divided cross section. The four sites for this project type were four adjacent 1.0-mi to 1.7-mi sections of a major urban arterial (48,800–57,900 vpd) that was converted from six-lane divided to eight-lane divided by remarking the existing roadways. This resulted in eight 9-ft lanes on the same roadways where six 12-ft lanes were previously marked. The existing variable-width median was not changed. This configuration was considered by the highway agency to be a interim measure to improve traffic operations. It remained in use for approximately 5 years until the highway agency was able to obtain funding to widen the roadways so that 12-ft lanes could again be used.

Total accident rate increased by 23.0 percent from before to after restriping at these sites, and this finding was statistically significant. However, there was no statistically significant change in midblock accident rate. Thus, most of the increase in accident rate appears to have occurred at intersections. All major types of intersection accidents increased from before to after the restriping project. Midblock angle and same-direction sideswipe collisions increased, while midblock rear-end accidents decreased.

There was no statistically significant change in the proportion of fatal and injury accidents.

Remarking of these sites led to a decrease in congestion and travel time along the project. The travel time in the peak direction of travel during the peak period was reduced by 10 min over a 6-mi section. Peak period traffic volumes increased by 11 to 34 percent almost immediately after project implementation as traffic was attracted from parallel streets by the decrease in traffic congestion on this project.

As in an earlier case, it appears that the use of narrower lanes to provide additional through lanes on an existing arterial can lead to an increase in accident rate at intersections. However, it is difficult to judge the extent to which these increases in intersection accidents are the result of the installation of narrower lanes because with changing traffic patterns, cross-street volumes and turning volumes may have increased. In addition, because traffic volumes on parallel facilities have decreased, accident rates on those facilities may have decreased as well.

Summary of Accident Analysis Results. As shown in Table 5, total accident rate was found to decrease for conversion from four-lane undivided to five-lane with TWLTL, conversion from four-lane divided with narrow median to five-lane with TWLTL, and conversion from six-lane with narrow median to seven-lane TWLTL. Midblock accident rates also decreased for these same three project types.

Total accident rates increased for conversion from two-lane undivided to four-lane undivided, conversion from five-lane with TWLTL to seven-lane with TWLTL, and conversion from six-lane divided to eight-lane divided. Midblock accident rates increased for conversion from five-lane with TWLTL to seven-lane with TWLTL, but remained unchanged for the other two project types.

The analysis results demonstrate clearly that the use of narrower lanes does not have an adverse effect on safety when a TWLTL is installed in conjunction with the project. Other improvement strategies that are known to reduce accidents, such as removal of curb parking, may have a similar effect, although this was not tested in the accident study. By contrast, total accidents may increase in projects involving narrower lanes where the objective of the project is to provide additional through lanes. However, increases in intersection accidents are more likely than increases in midblock accidents on such projects. Particular attention is needed to the design and the available sight distance at intersections on projects where narrower lanes are installed but no left turn treatments are provided.

None of the project types evaluated had any effect on the proportion of fatal and injury accidents. Thus, the accident severity distribution did not change with project implementation.

Field Observations of Projects Involving Narrower Lanes

Field observations were conducted at selected sites from the accident study to determine whether there is any evidence from traffic conflicts or erratic maneuvers that projects involving narrower lanes may lead to safety problems. In addition to on-site observations of traffic operations by the project staff, videotapes of traffic were made in the field and later reviewed in the office to determine the frequency of erratic maneuvers and related conflicts at the narrower lane sites. The videotapes were also used to determine the traffic flow rates, lane distribution, and vehicle mix at the study sites.

Two types of traffic operational videotapes were made. The primary study involved videotaping traffic at selected sites from a roadside camera location. This study addressed both passenger car and truck operations. A supplementary study involved videotaping trucks (and buses) on selected sites from a following vehicle. This study was smaller in size than the primary study and did not include consideration of passenger cars.

The analysis results are summarized in the following and presented in greater detail in Appendix D.

Primary Study (Roadside Videotaping)

Study Approach. Field observations by videotape were conducted at seven sites including four sites with narrower lanes on tangent sections, two sites with narrower lanes on horizontal curves, and one site with 12-ft lanes on a tangent section. These sites were located in three states: Maryland, Missouri, and North Carolina.

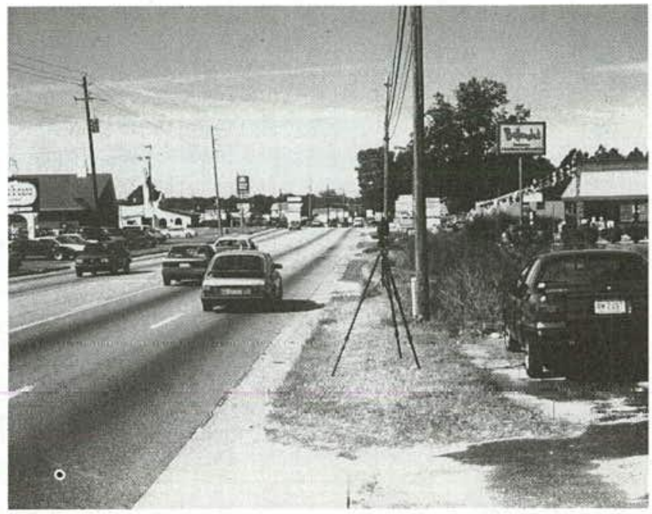

Figure 8. Typical roadside camera location for field observations of traffic operations.

A total of 17.41 hr of traffic operational data were videotaped during which 18,450 vehicles traversed the study sites in the direction of travel being studied. All of the sites had less than 5 percent trucks in the traffic stream, which is indicative of the type of sites where highway agencies have chosen to use narrower lanes. All of the sites evaluated had center TWLTLs.

Narrower lanes make it more difficult for drivers to position their vehicle completely within their travel lane, particularly for trucks and for all vehicle types on horizontal curves. An important objective of the field study was to determine the frequency with which vehicles encroach on adjacent lanes and the frequency with which traffic conflicts result from those encroachments.

The photograph in Figure 8 illustrates a typical data collection set-up. The video camera was mounted on a tripod and placed on the roadside. Whenever possible, the camera was placed behind a sign or a utility pole so it would be as unobtrusive as possible.

Definitions. Vehicle encroachments were instances in which a vehicle moved onto or over the lane line into an adjacent lane. Forced encroachments were those that occurred only because of the actions of another vehicle. For example, if a vehicle pulled too far out of a driveway or intersection and caused a through vehicle to encroach on the adjacent lane, that maneuver was classified as a forced encroachment (except if the vehicle changed lanes). Forced encroachments are not as great a concern as unforced encroachments, because forced encroachments occur frequently where operational side friction is present even on streets with 12-ft lanes.

Unforced encroachments are those that resulted from poor lane positioning not related to the action of another vehicle. Unforced encroachments occur for no apparent reason other than poor vehicle guidance and might be referred to a "wandering over the lane line." Unforced encroachments are relatively rare at sites with 12-ft lanes. Therefore, determination of the frequency of unforced encroachments was of particular concern on sites with narrower lanes to determine whether narrower lanes lead to increased encroachment rates.

Traffic conflicts are interactions between vehicles where one vehicle is forced to brake or swerve because of action of another vehicle. (A forced encroachment, as defined above, is one form of a traffic conflict.) This study focused solely on traffic conflicts that resulted from encroachments whether forced or unforced. Thus, traffic conflicts were noted whenever a vehicle (for whatever reason) encroached on an adjacent lane and forced a vehicle in that lane to brake or swerve. Particular types of traffic conflicts have been shown to be correlated with corresponding accident types and, therefore, traffic conflicts have frequently been used in field studies as a surrogate for accident data. In this study, traffic conflicts were not used as a surrogate (we have accident data for all sites), but rather as a supplement to the accident data. The traffic conflict data assisted in determining the extent to which the observed encroachments on adjacent lanes may lead to accidents.

Results. The analysis of the field observations found that, for all vehicle types, unforced encroachment rates are more frequent for sites with narrower lanes than for sites with 12-ft lanes. Unforced encroachment rates on tangent sites with narrower lanes are four times higher than on tangent sites with 12-ft lanes. In addition to these encroachments on adjacent through lanes, at two sites with narrower lanes, a large percentage of vehicles in the left through lane were observed to encroach on the center TWLTL.

The unforced encroachment rates on horizontal curves with narrower lanes were found to be about 2.5 times higher than for tangent sections with narrower lanes. On one horizontal curve site with narrower lanes, the unforced encroachment rate was found to be three times higher than on a tangent section with the same lane width immediately upstream on the same site. Forced encroachment rates were reasonably comparable for sites with and without narrower lanes.

Despite the higher observed traffic encroachment rates on sites with narrower lanes, these encroachments result in relatively few traffic conflicts. Only 2 of the 200 unforced encroachments that were observed resulted in a traffic conflict. The percentage of vehicles that encountered a traffic conflict when traversing the narrower lane sites was less than 0.05 percent. There was also one traffic conflict that resulted from a forced encroachment by a truck. There is no apparent difference in the traffic conflict rates between tangent sections and horizontal curves with narrower lanes. No traffic conflicts were observed on the site with 12-ft lanes.

Supplementary Study (Truck Following)

Study Approach. The supplementary study involved following trucks (and buses) through selected study sites with a vehicle carrying a video camera. The video camera was mounted between the seats of a passenger minivan with a view of the truck ahead and the traffic situation surrounding the truck.

The study procedure was for the driver of the van to enter the traffic stream behind a truck upstream of one of the study sites with narrower lanes and to follow the truck through the study site with the video camera operating. The resulting videotapes were later reviewed to determine whether the truck encroached on adjacent lanes and whether any traffic conflicts resulted.

The truck-following study was kept to a very limited effort because it involved much more labor per vehicle observed than the primary (roadside) study. However, an advantage of the truck-following study was that each truck was observed over the entire length of a study site, not just in one particular portion of the site.

Truck following studies were conducted at five sites in the states of Maryland and Missouri. A total of 45 trucks were followed and videotaped. Four of the selected sites were adjacent to one another on the same street so that some of the trucks were observed through more than one site.

Results. The truck following study found that 57.6 percent of the single-unit trucks and 41.7 percent of the combination trucks made unforced encroachments on adjacent lanes. These encroachment rates were considerably higher than the average unforced encroachment rate for trucks (13.9 percent) observed in the primary study. It is somewhat surprising that the unforced encroachment rate was higher for single-unit trucks than for combination trucks, because combination trucks are generally wider. However, the sample of trucks on which this finding is based is very small. The forced encroachment rates were very low; only two forced encroachments were observed, both related to vehicles pulling out of driveways that forced the truck being observed to encroach on an adjacent lane. As observed in the primary study, there were also several unforced encroachments on the center TWLTL.

No traffic conflicts were observed related to unforced encroachments. The results of the truck-following study confirm the overall conclusions of the primary study. While encroachments by trucks on adjacent lanes are fairly common on sites with narrow lanes, these encroachments do not appear to cause a large number of traffic conflicts.

Summary

The field observations do not suggest a major safety problem related to narrower lanes. It may be that many of the unforced encroachments on adjacent lanes are made in situations in which the driver is aware that no conflicting vehicles are present in that lane. Thus, in some situations, narrower lanes may increase encroachment rates without necessarily increasing traffic conflict or accident rates.

Advantages and Disadvantages of Design Alternatives

This section summarizes the general advantages and disadvantages of the ten design alternatives identified earlier in this chapter as appropriate for use on urban arterial streets. The advantages and disadvantages identified here are based on the findings of the research performed in this study, the research reported in the literature, the experience and design practices of highway agencies contacted during the study, and judgments and assessments made by the author. The primary intent of this section is to present the nonquantitative advantages and disadvantages of the design alternatives. However, because many of these advantages and disadvantages are closely related to traffic operations and safety issues, the discussion also refers to traffic operational and safety evaluations in the literature.

Table 7 presents an overview of the general advantages and

Table 7. Advantages and disadvantages of design alternatives for urban arterial streets.

DESIGN ALTERNATIVE	ADVANTAGES	DISADVANTAGES
Two-lane undivided	1. Least expensive alternative 2. Minimal street width required	1. Minimal capacity for through traffic movement 2. Delay to through vehicles by left-turning vehicles
Three-lane with TWLTL	1. Reduces frequency of rear-end and angle accidents associated with left-turn maneuvers 2. Provides spatial separation between opposing lanes to reduce head-on accidents 3. Reduces delay to through vehicles by left-turning vehicles 4. Increases operational flexibility	1. No refuge area in median for pedestrians
Four-lane undivided	1. Provides additional lanes to increase capacity for through traffic movement	1. Required street width may not be available 2. Delay to through vehicles by left-turning vehicles 3. May generate safety problems associated with rear-end and lane-changing conflicts
Four-lane divided	1. Provides additional lanes to increase capacity for through traffic movement 2. Reduces rear-end and angle accidents associated with left-turn maneuvers 3. Provides physical separation to reduce head-on accidents 4. Provides a median refuge area for pedestrians	1. Required street width may not be available 2. Increased delay to left-turning vehicles 3. Indirect routing required for large trucks 4. Lack of operational flexibility due to fixed median
Five-lane with TWLTL	1. Provides additional lanes to increase capacity for through traffic movement 2. Reduces delay to through vehicles by left-turning vehicles 3. Reduces frequency of rear-end and angle accidents associated with left-turn maneuvers 4. Provides spatial separation between opposing lanes to reduce head-on accidents 5. Increases operational flexibility	1. Required street width may not be available 2. No refuge area in median for pedestrians 3. May generate safety problems at closely spaced driveways and intersections
Six-lane undivided	1. Same as four-lane undivided alternative	1. Same as four-lane undivided alternative
Six-lane divided	1. Same as four-lane divided alternative 2. Increased turning radius for U-turns	2. Same as four-lane divided alternative
Seven-lane with TWLTL	1. Same as five-lane TWLTL alternative	2. Same as five-lane TWLTL alternative
Eight-lane undivided	1. Same as four-lane undivided alternative	1. Same as four-lane undivided alternative
Eight-lane divided	1. Same as six-lane divided alternative	1. Same as four- and six-lane divided alternatives

disadvantages of the ten basic design alternatives. These advantages and disadvantages are addressed below in individual discussion of each design alternative.

Two-Lane Undivided

A two-lane undivided cross section is the simplest design alternative for an urban arterial street. The major advantages of the two-lane undivided design alternative are relatively low construction cost and minimum right-of-way requirements. The disadvantages of the two-lane undivided alternative are minimal through traffic capacity, because there is only one through lane in each direction of travel, and delays to through vehicles making left turns, because there are no physical restrictions and no deceleration and storage areas for left turns.

Two-lane undivided facilities generally provide acceptable service levels on urban arterial streets with traffic volumes less than 5,000 vpd to 7,000 vpd. Some two-lane undivided facilities without closely spaced signals or commercial development, or both, may provide adequate service on streets with traffic volumes up to 15,000 vpd. However, more typically, two-lane undivided facilities above the 5,000 to 7,000 ADT level experience peak hour congestion and/or increased accidents that suggest the need to upgrade the facility with one of the multilane design alternatives presented in this report. The peak hour traffic volumes, especially on signalized arterials, may require more than one lane to serve the through-traffic volume, while the left-turn traffic generated by commercial development may create unacceptable delays to through motorists. Such congestion can lead to rear end and angle accidents associated with turning maneuvers. However, there are very few strategies for improving traffic operations on two-lane undivided arterials that do not involve widening the street, unless the existing lanes are unusually wide or an existing curb parking lane can be eliminated.

The level of traffic service for two-lane undivided highways under urban conditions cannot be evaluated adequately with the procedure presented in Chapter 8 of the 1985 *Highway Capacity Manual* (HCM) (*2*) on two-lane highways. This chapter is intended for application to two-lane highways with uninterrupted flow, and such conditions do not usually exist on urban arterials. Rather, the procedures of HCM Chapter 11 on arterial streets are most applicable to urban two-lane undivided facilities. These procedures include consideration of the combined effect of traffic conditions on signalized intersection approaches and in midblock sections between signalized intersections.

Three-Lane with Two-Way Left-Turn Lane

The three-lane TWLTL design alternative has several important advantages over the two-lane undivided base condition, which can be gained for only a minimal increase in pavement width. In fact, some two-lane undivided facilities with wide lanes or curb parking can be converted to three-lane with TWLTL simply by remarking.

The primary advantage of a three-lane facility is that the TWLTL provides a storage area in the median for left-turning vehicles. The removal of these vehicles from the through-traffic lanes reduces the risk of rear-end and angle accidents associated with left-turn maneuvers and minimizes the delay to through vehicles caused by left-turning vehicles. The provision of a TWLTL in the median may encourage drivers to wait for an adequate gap in opposing traffic when waiting to turn left; without the TWLTL, left-turning drivers may become anxious or impatient and select an inadequate gap when they are delaying a queue of following vehicles. The TWLTL also introduces a spatial separation between the lanes of traffic moving in opposite directions which may reduce the risk of head-on accidents. On two-lane undivided cross sections substantially wider than 24 ft, the three-lane TWLTL design can reduce potential safety problems from drivers wandering in extremely wide lanes or tempting drivers to make unsafe passing maneuvers. The three-lane TWLTL design alternative does not increase the number of lanes available for through traffic, but does reduce the degradation of the traffic service by turning delays. Finally, the presence of a TWLTL provides operational flexibility on an urban arterial that can increase the freedom of movement for emergency vehicles and simplify the traffic control arrangements when maintenance or construction activity requires a lane to be closed.

NCHRP Report 282 (*1*) identified three primary disadvantages of the use of the three-lane TWLTL design alternative on suburban highways. These were: (1) the installation of a TWLTL provides a wider pavement for pedestrians to cross without providing a refuge area in the median; (2) the increased pavement width needed for a TWLTL may require elimination of a full shoulder which might offset some of the accident reduction gained from the TWLTL; and (3) the installation of a TWLTL may encourage strip commercial development. None of these disadvantages of TWLTL installation on suburban highways are likely to be major disadvantages on urban arterial streets where the TWLTL is installed without increasing the total curb-to-curb street width. The street is no wider for pedestrians to cross with the TWLTL than without; urban arterial streets (according to the definition used in this study) are streets with curb-and-gutter sections rather than full shoulders; and the potential for undesirable strip commercial development is much less in developed urban areas (and older, established suburbs) than on the type of rapidly developing suburban highways that were considered in *NCHRP Report 282.*

A disadvantage of eliminating a curb parking lane to provide space for a TWLTL is that space to store disabled vehicles along the curb may be lost. However, this disadvantage may be offset by the gain in operational flexibility from installation of the TWLTL and potential for reduction of accidents involving parked vehicles and parking maneuvers.

Converting a *wide* two-lane undivided cross section to a three-lane TWLTL cross section may move traffic closer to sidewalks, pedestrians, and fixed objects along the roadside; may increase right-turn delays; and may reduce the ability of the roadway to accommodate bicyclists; however, these potential disadvantages must be weighed against the potential for safety problems due to lack of positive guidance on a wide two-lane undivided cross section and the potential safety benefits of providing a TWLTL.

Three-lane TWLTL sections have not been evaluated as extensively as five-lane TWLTL sections. The following discussion focuses on findings that are specifically applicable to the three-lane TWLTL. A more general discussion of TWLTL effectiveness will be found in the section on the five-lane TWLTL design later in this chapter.

A recent study of median treatments by Walton et al. (*24*) concluded that the use of the three-lane TWLTL design alternative is most appropriate on highways with traffic volumes in the range from 5,000 vpd to 12,000 vpd. Effective applications of the three-lane TWLTL alternative have been noted in the field at even higher traffic volume levels.

It has long been recognized that TWLTLs are effective in reducing congestion on suburban highways with heavy left-turn demands, but efforts to quantify that effectiveness have been made only within the last three years. Harwood and St. John (*10*) performed a field study of the delay reduction effectiveness of three, three-lane TWLTL sites in urban fringe areas. McCoy, Ballard and Wijaya (*11*) performed a simulation study in 1982 to predict the reduction in delay and stops by through vehicles due to installation of a TWLTL on a two-lane undivided street. An updated version of the model used in that study, known as TWLTL-SIM, was used in *NCHRP Report 282* (*1*) to obtain the operational estimates for converting from a two-lane undivided to a three-lane TWLTL design. The results of these studies are presented in Appendix A. These results show that the operational benefits of installing a TWLTL on a two-lane undivided facility are substantial and should be considered on many densely developed facilities.

There are no procedures in the 1985 *Highway Capacity Manual* that directly address the effectiveness of a three-lane TWLTL section. However, on a two-lane undivided arterial without signals or with widely spaced signals, it is suggested that the installation of a TWLTL can restore traffic operations approaching the level of service for uninterrupted flow conditions determined from the procedures of Chapter 8.

The safety effectiveness of the three-lane TWLTL design alternative has been evaluated more extensively than the operational effectiveness. However, no projects in which an existing street was converted to a three-lane TWLTL cross section were found for evaluation in this study. The literature review presented earlier in this section of the report found that accident rates were 11 percent lower for three-lane TWLTL sections than for two-lane undivided sections on suburban arterial highways with commercial development and 25 percent lower for highways with residential development. Thakkar (*23*) reports a reduction in accident rate of 32 percent for all accidents and 31 percent for fatal and injury accidents with installation of a three-lane TWLTL section. One site evaluated by Harwood and St. John (*10*), where a two-lane undivided facility was converted to a three-lane TWLTL design, resulted in a 35 percent reduction in accident rate. Thus, the safety effectiveness of converting from the two-lane undivided to the three-lane TWLTL design alternative is expected to be in the range of 11 to 35 percent accident rate reduction. The lower end of this range may be more likely than the upper end when narrower lanes are used to implement the three-lane TWLTL.

A case study of a two-lane undivided highway remarked as a three-lane TWLTL section was performed by Nemeth (*21*). However, the site evaluated initially had shoulders and is more typical of a suburban highway than an urban arterial. A 0.8-mile section of two-lane highway with an ADT of 13,000–14,000 vpd was remarked to include a 13-ft wide TWLTL. The remarking reduced the width of the through lanes from 15 ft to 11.5 ft and the shoulder width on part of the section was reduced to less than 3 ft. The evaluation of this site found a statistically significant increase in running speed of nearly 3 mph and a 40 to 60 percent reduction in traffic conflicts due to braking and weaving after installation of the TWLTL. It was concluded that the introduction of the TWLTL resulted in a measurable improvement in traffic flow and safety, despite the narrowing of the through lanes and shoulder.

The results of a traffic conflict study by McCormick and Wilson (*41*), presented in Table A-7 in Appendix A, found that three-lane TWLTL streets had lower conflict rates than four-lane divided streets, but higher conflict rates than the five-lane TWLTL streets.

Two studies have examined the conversion of an existing four-lane undivided street to a three-lane TWLTL design, which is a feasible strategy for street widths between 38 ft and 46 ft. Nemeth (*21*) found that the installation of a three-lane TWLTL design on a street with an existing four-lane undivided design and an ADT of 16,000 vpd resulted in an increase in delay because of the reduction in the number of through lanes. He concluded that the access function of the roadway was improved at the price of a measurable delay in the traffic movement function. On the other hand, on a facility with a lower traffic volume, Jomini (*42*) found no significant increase in delay, as well as a substantial reduction in accidents, resulting from a four-lane undivided to three-lane TWLTL conversion.

The three-lane TWLTL design appears to be an effective alternative to a two-lane undivided highway for locations with substantial midblock left-turn demands, especially for sites with street widths over 30 ft and sites with curb parking that can be removed on one or both sides. The three-lane TWLTL design may also be a useful alternative to an existing four-lane divided highway for sites with low volumes of through traffic and high left-turn volumes with street widths from 38 to 46 ft.

Four-Lane Undivided

The four-lane undivided design alternative has the advantage over the two-lane undivided and three-lane TWLTL design alternatives of increased capacity for through traffic because two through lanes are provided for travel in each direction. The major disadvantage of the four-lane undivided design alternative is that there is no special provision for left turns, so that through vehicles are frequently delayed by left-turn vehicles. Traffic turning both left and right at intersections and driveways can create rear-end conflicts and lane changes to avoid delay that are often symptomatic of safety problems.

Guidelines developed by Klatt (*43*) for the city of Omaha, Nebraska, concluded that the four-lane undivided design alternative is best suited for use on streets functionally classified as collectors or minor arterials. Four-lane undivided streets are most suitable for residential and light commercial areas, without high left-turn demands. The use of the four-lane undivided design alternative is not recommended on a street that is, or could become, a major arterial; either the four-lane divided design alternative or the five-lane TWLTL design alternative or both would be more appropriate for a major arterial. Existing four-lane undivided facilities with street widths from 42 ft to 58 ft can be converted to a four-lane divided cross section without widening; streets with widths from 48 ft to 58 ft can be converted to a five-lane TWLTL cross section without widening.

On four-lane undivided streets that are not wide enough to incorporate a median treatment without eliminating a through lane, the use of the variety of access control techniques catalogued by Glennon et al. (*15, 16*) to improve traffic operations and safety at individual driveways is recommended. Table 8 presents a summary of these techniques. While many of the techniques are more applicable to developing areas where new regulations can have more immediate effect, they can be effective

Table 8. Driveway location, design and control techniques to improve driveway operations.

- Regulate minimum spacing of driveways.
- Regulate minimum corner clearance.
- Regulate minimum property line clearance.
- Regulate maximum number of driveways per property frontage.
- Regulate maximum width of driveways.
- Consolidate access for adjacent properties.
- Encourage connections between adjacent properties.
- Deny access for small frontage.
- Require access on collector street (where available) in lieu of additional driveway on highway.
- Channelize driveway to eliminate conflicts between entering and exiting vehicles.
- Use one-way driveways in lieu of two-way driveways.
- Restrict turning maneuvers by signing or channelization.
- Improve corner radii to increase turning speeds.
- Improve vertical geometrics of driveways to increase turning speeds.
- Require driveway paving to increase turning speeds.
- Install right-turn acceleration and deceleration lanes.
- Move sidewalk-driveway crossing further from highway.

Source: Glennon et al. (Refs. 15 and 16).

in established urban areas if applied consistently as part of the process for granting zoning changes and variances. In other words, property owners requesting a change in the use of their property can be required to make appropriate adjustments to their driveways as a condition for granting the request.

The capacity of suburban arterial highways with a four-lane undivided cross section is addressed in Chapter 11 on arterial streets in the 1985 *Highway Capacity Manual* (HCM) (*2*). However, this procedure does not adequately address the effects of adjacent development and associated midblock turning maneuvers on level of service and capacity. The operational analysis of suburban highway sections performed in *NCHRP Report 282* (*1*) found the four-lane undivided design alternative to be less desirable than the five-lane TWLTL design alternative under virtually all operating conditions and less desirable than the four-lane divided design alternative under high-volume conditions (over 1,000 vph in one direction of travel).

Four-lane undivided streets generally have higher accident rates than design alternatives that incorporate a median treatment. The safety evaluation performed in this study found that the installation of center TWLTLs on an existing four-lane undivided street can reduce accident rates by approximately 45 percent, even though narrower lanes had to be used to provide space for the TWLTL.

In summary, although four-lane undivided urban arterial streets are very common, they are most applicable to streets with residential or light commercial development, without heavy left-turn demands, that are not expected to become major arterials. Where these conditions do not apply and where there are existing left-turn delays or accident patterns, both traffic operations and safety can often be improved by addition of a center TWLTL or a raised median. The advantages and disadvantages of these design alternatives are addressed below.

Four-Lane Divided

The primary advantages of the four-lane divided design alternative are adequate capacity for through traffic by the provision of two through lanes in each direction of travel and the protection of that through-traffic capacity by the elimination of left turns except at selected intersections and major driveways. The installation of a median divider also reduces the likelihood of head-on accidents between vehicles traveling in opposite directions and rear-end and angle accidents associated with left-turn maneuvers.

A major disadvantage of the four-lane divided design alternative is the increased travel time for vehicles that desire to turn left at locations where median openings are not provided. These vehicles must either make a U-turn at a location where a median opening is provided or use some other indirect route to reach their destination. While residents or retail customers driving passenger cars may be able to make U-turns at signalized intersections, the geometrics are usually not adequate for large trucks to make U-turns, so delivery vehicles must often use indirect routes. For some kinds of retail businesses, installation of a median may discourage customers who desire to turn left to reach the establishment and, therefore, make midblock locations less desirable (*44*). The installation of a median also reduces the operational flexibility of the roadway to serve special conditions including emergency vehicle movements and work zones with lane closures.

The four-lane divided design alternative is best suited for use on major arterials with high volumes of through traffic and limited access points. The use of the four-lane divided design alternative is recommended only for streets with less than 45 driveways per mile; on highways with more than 45 driveways per mile, the five-lane TWLTL design alternative is probably better suited to serve the existing development. The four-lane divided design alternative is better suited than the five-lane TWLTL design alternative to serve areas with isolated major traffic generators (e.g., shopping centers or office complexes), which have widely spaced, high-volume driveways. However, these conditions are more typical of current development patterns in suburban areas than on more densely developed urban arterials.

The installation of a raised median is the best available technique to preserve the through-traffic movement function on an arterial street, although this is accomplished at the expense of the land access function. Thus, the four-lane divided design alternative is appropriate when a highway agency makes a conscious choice to favor the traffic movement function. Where the four-lane divided design alternative is selected for an urban arterial with existing development, careful consideration needs to be given by the design agency to the adequacy of alternative routes to complete left turns that are prevented by the median. This consideration may include the geometric design, signal timing, and signal phasing at adjacent signalized intersections; the length of separate left-turn lanes at median openings and signalized intersections; the turning radius required to complete U-turns; and the availability and adequacy of alternate routes including parallel streets, alleys and service roads.

The operational evaluation performed in *NCHRP Report 282* (*1*) found that, relative to the four-lane undivided design alternative, the combined delay to through and left-turn vehicles was reduced by the four-lane divided design alternative only for flow rates above 1,000 vph in one direction of travel. The use of the four-lane divided design alternative for highways with peak flow rates less than 1,000 vph is recommended only where other offsetting benefits such as improved safety or preservation of through-traffic capacity are expected.

Raised medians were once used much more extensively on urban arterials than they are today. Traffic engineers have come to recognize both the lack of operational flexibility that comes with installation of a raised median and the many advantages of TWLTLs.

Engineers should be cautious in any decision to install a relatively narrow median (4 ft to 6 ft) on an urban arterial. While narrow medians are effective in separating traffic movements in opposite directions, they do not provide enough space to store a vehicle in the median or provide left-turn lanes at intersections or median openings. The safety evaluation performed in this study found that removal of an existing 4-ft median on a four-lane urban arterial and the installation of a center TWLTL reduced accident rates by over 50 percent even though narrower lanes had to be used to provide space for the TWLTL.

Five-Lane With Two-Way Left-Turn Lane

The five-lane TWLTL design alternative has several important advantages. This alternative reduces delay to through vehicles by providing two lanes for through traffic in each direction of travel and a continuous TWLTL in the highway median to minimize delay to through vehicles by vehicles turning left. TWLTLs are effective in reducing the frequency of rear-end and angle accidents associated with left-turn maneuvers and may also reduce head-on accidents through spatial separation of the lanes of traffic moving in opposite directions. Thus, the five-lane TWLTL alternative reduces the same type of accidents as the four-lane divided alternative without the increased delays often resulting from installation of a raised median. Finally, the installation of a TWLTL enhances the operational flexibility of the facility to meet special situations such as movement of emergency vehicles and lane closures due to traffic accidents or work zones. Another aspect of the operational flexibility of the five-lane TWLTL design alternative is that the center TWLTL lends itself well to reversible flow operation; some agencies have operated the center lane as a travel lane in one direction of travel during the morning peak period, in the opposite direction during the evening peak period, and as a TWLTL during off-peak periods (*18, 33*). Such operation takes advantage of the temporal distribution of traffic, because the peak periods for through movements do not necessarily occur simultaneously with the peak period for left-turn movements. The safety and operational benefits of TWLTLs are substantial and have made the five-lane TWLTL a very widely used design alternative for both urban and suburban arterial streets. Installation of a five-lane TWLTL cross section is feasible on any arterial street at least 48 ft wide.

Despite their many advantages, the five-lane TWLTL design has several disadvantages that should be considered at sites where its use is contemplated. First, unlike the four-lane divided design alternative, the five-lane TWLTL alternative provides no refuge area in the highway median for pedestrians. A pedestrian reaching the median of a five-lane TWLTL facility may be forced to wait in a highly exposed position for an opportunity to cross safely to the far side of the street. However, a five-lane TWLTL facility is no more difficult for a pedestrian to cross than a four-lane undivided facility if the TWLTL is installed without widening the street; pedestrian problems may arise in this case if pedestrians are tempted to cross only the lanes in one direction of travel and to wait in the TWLTL for an opportunity to cross the other direction of travel.

Second, inappropriate use of the TWLTL by drivers and potential conflicts between turning vehicles may occur at driveways located close to a major intersection (e.g., within 100 ft). While this problem arises not directly from the TWLTL, but from lack of adequate access control policies concerning driveway locations, it nevertheless becomes a consideration in selecting and in marking a TWLTL. The usual method of marking a TWLTL section is to provide one-way left-turn lanes at major intersections, while permitting the TWLTL to be carried up to or across minor intersections. Although this policy appears appropriate, the literature provides no formal evidence either for or against this practice. A problem can arise where a one-way left-turn lane is provided at an intersection on a five-lane TWLTL section, if vehicles in the opposing direction may continue to use it as a TWLTL to turn left into driveways near the intersection. Some agencies have reported accident problems related to such movements that could be alleviated by installation of a raised median on the intersection approach.

The five-lane TWLTL design alternative is most appropriate for streets with commercial development, driveway densities greater than 45 driveways per mile, low to moderate volumes of through traffic, high left-turn volumes and for high rates of rear-end and angle accidents associated with left-turn maneuvers. There has been little effort in the past to measure left-turn demand or to establish traffic volume ranges that would warrant installation of a TWLTL. The operational evaluation performed in *NCHRP Report 282* (*1*) indicates that the installation of a TWLTL on existing four-lane undivided facilities provides operational benefits at all volume levels. These benefits are relatively modest (7.8 sec to 10.2 sec of delay reduced per left-turn vehicle) at a flow rate of 650 vph in each direction of travel, but are substantial at a flow rate of 900 vph (as much as one minute of delay reduced per left-turn vehicle) and even greater at higher flow rates.

Many safety evaluations of the five-lane TWLTL design alternative have been conducted. The results of these studies are summarized in Appendix A of this report. These studies generally concluded that TWLTLs reduce accident rate by from 19 to 35 percent. Even higher accident reduction effectiveness was found for TWLTL installation in the safety evaluation conducted in this study. Conversion from a four-lane undivided cross section to a five-lane TWLTL cross section with narrower lanes reduced accident rates, on the average, by 45 percent. Conversion from a four-lane divided cross section with a narrow (4-ft) median to a five-lane TWLTL cross section with narrower lanes reduced accident rates by over 50 percent.

These findings concerning the safety effectiveness of the five-lane TWLTL alternative are reinforced further by the traffic conflict evaluation by McCormick and Wilson (*41*) presented in Table A-7 in Appendix A, which found the five-lane TWLTL alternative to have the lowest traffic conflict rate for all of the design alternatives considered.

The published literature on the safety effectiveness of TWLTLs universally discounts the possibility of substantial increases in head-on accidents between vehicles in opposing directions trying to use the TWLTL to turn left at the same location. While the potential for such accidents exists, drivers appear to understand the operation of a TWLTL clearly and avoid such situations. Those before-after studies that have looked at TWLTL effectiveness by accident type have found that head-on accidents usually decrease with TWLTL installation, although not by as much as other accident types such as rear-end accidents.

Six-Lane Undivided

The advantages and disadvantages of six-lane undivided streets are similar to four-lane undivided streets discussed above. The minimum feasible width for a six-lane undivided street is 56 ft.

Six-Lane Divided

The six-lane divided cross section is feasible on urban arterial streets with widths of at least 56 ft. The advantages and disadvantages of the six-lane divided design alternative are similar to the advantages and disadvantages of the four-lane divided design alternative discussed above. One advantage of the six-lane divided alternative over the four-lane divided alternative is that the additional roadway width provides a more generous turning radius for vehicles to make U-turns at signalized intersections to accomplish midblock left-turn maneuvers that are prevented by the median.

Seven-Lane With Two-Way Left-Turn Lane

The advantages and disadvantages of the seven-lane TWLTL design alternative are similar to the advantages and disadvantages of the five-lane TWLTL alternative. The seven-lane TWLTL cross section is feasible on any urban arterial street with a width of at least 68 ft. *NCHRP Report 282* (*1*) suggested that most highway agencies appear to limit the use of the seven lane TWLTL alternative to residential and light commercial areas with relatively low left-turn volumes. However, several seven-lane TWLTL sites in areas of heavy commercial development (over 80 driveways per mi) were evaluated in this study and these sites were found to operate safely and effectively. Installation of a TWLTL on an existing six-lane divided street with a narrow (4-ft) median was found to reduce accident rate by approximately 25 percent. However, the conversion of an existing five-lane TWLTL site to a seven-lane TWLTL cross section was found to improve traffic operations, but to increase accident rates by approximately 25 percent. The available data suggest that safety problems with this type of project may occur primarily on sites with higher speeds.

Eight-Lane Undivided

Eight-lane undivided streets are relatively rare for urban arterials since the same width may be used more effectively as a six-lane divided street, as a six-lane undivided street, or as a seven-lane street with a center TWLTL. However, the eight-lane undivided design alternative could be used for streets with very high through-traffic volumes. The minimum curb-to-curb width for an eight-lane undivided street is 74 ft. The advantages and disadvantages of eight-lane undivided streets are similar to four- and six-lane undivided streets.

Eight-Lane Divided

The advantages and disadvantages of eight-lane divided streets are similar to four- and six-lane divided streets discussed earlier. The minimum feasible lane width for an eight-lane divided street is 80 ft.

CHAPTER THREE

INTERPRETATION, APPRAISAL, APPLICATION

The findings presented in Chapter Two illustrate the traffic operational and safety performance of urban arterial street improvement strategies. Thus, these findings provide a basis for selecting appropriate improvement strategies for particular sites. This chapter shows how the findings can be used to accomplish this objective. The chapter presents a recommended selection procedure for improvement strategies, and includes guidelines for implementing the strategies and evaluating their results. Three design examples to illustrate the recommended selection procedure are presented in Appendix E and summarized in this chapter.

SELECTION PROCESS

This section outlines the recommended process for selecting an appropriate improvement strategy for an urban arterial street. The purpose of this discussion is to show how the various effectiveness measures and advantages and disadvantages of design alternatives can be used together in the decision-making process. The recommended process is meant to provide a flexible approach to selection of improvement strategies rather than a rigid methodology. Highway agencies should adapt the process to fit their own needs while retaining its basic principles.

Table 9. Critical factors in selection of improvement strategies for urban arterial streets.

Existing Conditions	• Existing geometrics and traffic control • Existing operational demands • Existing operational conditions (level of service, speed, delay) • Existing land use • Other existing conditions
Projected Future Conditions	• Projected future operational demands • Projected safety conditions • Anticipated lane use changes
Constraints	• Physical constraints (existing street width, intersection spacing) • Economic constraints (available funds) • Access control laws and ordinances • Public opinion
Potential Benefits and Disbenefits	• Operational effectiveness • Safety effectiveness • Impact on through traffic vs. land access traffic • Impact on abuting businesses • Impact on future traffic volumes • Impact on pedestrians • Impact on bicycles • Impact on transit

Table 10. Steps in recommended process for selecting improvement strategies.

Step 1	Determine existing conditions
Step 2	Determine projected future conditions
Step 3	Identify constraints
Step 4	Identify feasible design alternatives
Step 5	Eliminate alternatives that do not address existing problems
Step 6	Examine possible geometric variations
Step 7	Determine benefits and disbenefits
Step 8	Select the preferred improvement strategy

The critical factors that influence the selection of an improvement strategy for an urban arterial street are presented in Table 9. These critical factors are classified into five major categories: existing conditions, projected future conditions, constraints, priorities, and potential benefits and disbenefits. The critical factors set the framework for the improvement strategy selection process.

Table 10 presents eight steps in the recommended process for selecting a design alternative. Each step is discussed below.

Step 1—Determine Existing Conditions. The first step in the process of selecting an appropriate improvement strategy is to document the existing conditions at the site. Table 11 presents a list of existing conditions relevant to the selection of an improvement strategy. These include existing geometrics and traffic control; existing operational demands; existing operational conditions such as capacity, level of service and delay (which are the combined results of geometrics, traffic control, and operational demands); existing safety conditions; existing land use; and other relevant site-specific conditions.

The documentation of existing conditions needed to implement an urban arterial street improvement strategy within the existing street width may be more limited than that needed for a widening project. The same traffic operational and safety data are needed as for a widening project, but extensive surveys of site conditions outside the curb line may not be necessary, which should reduce the cost of the design process. Many common elements of widening projects such as right-of-way acquisition, utility relocation, changes in driveway access, and mitigation of impacts on abutting properties are not major considerations when the street is not widened. However, potential impacts on access to adjoining properties does need to be considered whenever a median treatment, such as a raised median or a TWLTL, is installed or removed.

The traffic operational and safety data collected for the existing site should be oriented toward documenting the existing traffic operational and safety problems addressed by an improvement strategy. In particular, analyses should be conducted to determine the existing level of service on the facility; the major reasons for any existing traffic congestion (i.e., left-turn delays vs. lack of sufficient number of through lanes and intersection delays vs. midblock delays); the accident rate and the distribution of accident severities and collision types (in comparison to other similar facilities in the same community).

Step 2—Determine Projected Future Conditions. Projected future conditions at the site over the design life of the proposed improvement should also be determined. Decisions concerning projects that involve construction work, such as median removal, should normally have a relatively long design life (e.g., 20 years). However, projects that involve only remarking the existing roadway can have much shorter design lives (e.g., 2 to 5 years) and still be very cost effective. On streets that cannot be widened, it may not be possible to serve the projected future traffic volumes at the desired level of service. However, the goal of the urban traffic engineer should be to use the available width as effectively as possible. An improvement strategy involving remarking only can also be an excellent short-term solution to a problem which may require more extensive construction for which funds are currently unavailable. Since the improvement strategies under consideration here do not change the total curb-to-curb width, they do not make it more difficult to implement any particular long-term plan for improving the site.

Step 3—Identify Constraints. Constraints that limit the feasibility of any particular improvement strategy or make particular strategies more or less desirable should be identified. Such constraints may include physical constraints, economic constraints set by availability of funds, access control laws, and ordinances, zoning policies, and public opinion. The physical constraints are design controls which, for all practical purposes cannot be changed, such as intersection spacing and surrounding developments. The procedures in this report assume that the existing curb-to-curb width is a physical constraint that cannot be changed. If the street can, in fact, be widened, the procedures in *NCHRP Report 282* (*1*) are more applicable than the procedures in this report.

Some constraints may also be operational in nature. For example, the need to serve current and future bicycle volumes on the facility may also create a constraint on the use of narrower lanes. For each project, a determination of the need to serve bicycles in a shared lane with motor vehicles should be made based on existing and projected bicycle volumes on the facility and the availability of alternative routes that may be more suited to bicycles.

Step 4—Identify Feasible Design Alternatives. The next step in the selection process is to identify all feasible design alternatives that can be implemented within the existing total curb-to-curb

Table 11. Existing conditions relevant to selection of improvement strategies for urban arterial streets.

<u>Existing Geometrics and Traffic Control</u>

Current design alternative
Pavement and lane widths
Presence or absence of curb parking
Presence or absence of median
Type of median
Median width
Speed limit
Spacing between major intersections (and/or major driveways)
Intersection geometrics
Intersection traffic controls

<u>Existing Operational Demand</u>

Average daily traffic (vpd)
Hourly traffic volumes and peaking characteristics
Percent trucks
Directional split
Turning volumes at intersections and driveways (especially left turns)
Bicycle volumes
Pedestrian volumes and desired movements
Type and frequency of transit service

<u>Existing Operational Conditions</u>

Capacity (vph)
Level of service
Volume/capacity ratio
Mean and 85%ile speed (mph)
Travel-time or delay (veh-sec)

<u>Existing Safety Conditions</u>

Accident rate (accidents per million vehicle-miles)
Accident frequency per mile per year
Accident severity distribution (fatal/injury/PDO)
Accident type distribution (by relationship to intersection, number of vehicles involved, and type of collision)
Existing accident problems (specific locations and/or specific accident types)

<u>Existing Land Use</u>

Type of development (commercial/residential)
Continuity of development (strip development/isolated major traffic generators)
Driveway density (driveways per mile)
Intersection density (minor intersections per mi)

<u>Other Existing Conditions</u>

Site-specific conditions relevant to improvement strategies

width. Table 1 and Figure 2 provide a guide to the design alternatives and the range of lane widths for those alternatives that can be considered within the existing street width. The range of possible design alternatives should be as broad as possible at this stage to assure that no reasonable possibility is overlooked.

Step 5—Eliminate Alternatives That Do Not Address Existing Problems. A preliminary review of the feasible design alternatives should be conducted to eliminate any that do not address the existing traffic operational and safety problems at the site or might exacerbate existing problems. Many of the design alternatives noted in Table 1 and Figure 2 may be obviously inappropriate for a particular site. For example, if the major existing problem at a site is lack of a sufficient number of through lanes, alternatives that do not increase the number of through lanes should be eliminated. If the major operational problem is left-turn delays, further analyses should focus on alternatives that incorporate a median treatment, such as a center TWLTL or a raised median with left-turn lanes. If the major reason for the project is to reduce traffic accidents at the site, only design alternatives that address the predominant types of accidents that occur should be retained.

Step 6—Examine Possible Geometric Variations. Possible geometric variations of the feasible design alternatives should be considered, including the widths of through lanes, parking lanes, two-way left-turn lanes, and medians. Table 1 is a guide to the range of possible widths for each of these elements for any given design alternative and street width. For any given design alternative, the combination of lane and median widths that best meets the traffic demands at the site should be selected. Considerations at this stage should include the need for curb lanes to be wider than inside lanes (especially considering the type of curb-and-gutter section, the presence of curb inlets, and the need to serve shared bicycle and motor vehicle operations); the appropriate widths of parking lanes and TWLTLs; and the appropriate median widths (considering the frequency of median openings, the type of left-turn lanes at those median openings, and the need to store vehicles in the median). The design speed of the facility and the actual operating speeds used by drivers should be considered in the design of the detailed geometrics of the facility. Each combination of a design alternative and specific geometrics selected should be regarded as a candidate improvement strategy for further evaluation.

Step 7—Determine Benefits and Disbenefits. Each feasible improvement strategy should be evaluated to determine its quantitative and nonquantitative benefits and disbenefits.

The traffic operational effects of each alternative should be quantified primarily through the procedures of the *Highway Capacity Manual* (*2*), supplemented by results from the literature presented in this report (see Chapter Two and Appendix A). In particular, the HCM contains no quantitative estimates of the delay reduction effectiveness of TWLTLs so the estimates developed in *NCHRP Report 282* (*1*) are recommended for this purpose (see Table A-6 Appendix A). Similarly, *NCHRP Report 282,* contains the only available estimates of the delay reduction effectiveness of raised medians on four-lane arterials (see Table A-8 in Appendix A).

The safety effectiveness of each improvement strategy can be quantified from the safety analyses presented in this report (see Tables 5 and 6 in Chapter Two and Appendix C) and in the literature (see Appendix A). The results presented in this report are most applicable to improvement strategies that incorporate through lane or TWLTL widths of 10 ft or less.

At sites being improved where the existing accident rates are higher than average for the communities in which they are located, there may be a correctable safety problem. In such cases, improvement strategies that directly address the existing safety problems may be more effective than the average values presented in Table 5. For example, accident rates for left-turn-related angle and rear-end accidents should be substantially reduced by improvement strategies that involve installation of TWLTLs or raised medians on streets that do not currently incorporate a median treatment. The magnitude of the accident reduction for sites with a correctable safety problem must be based on engineering judgment considering the magnitude of the existing problem, the impact of the particular improvement strategies on that type of problem, and each agency's experience with similar types of improvements.

Table 12 and Figure 9 summarize the traffic operational and safety impacts of improvement strategies and form the basis for making judgments of the type discussed above. Table 12 lists 9 operational factors and 12 safety factors whose relative merits have been rated for a range of geometric variations for five major design alternatives with two to five lanes. Figure 9 presents the ratings that were developed by the project staff. Each design has been rated for a range of roadway widths that correspond to narrower lane and wider lane alternatives. Ratings for six-, seven-, and eight-lane alternatives are similar to the analogous four- and five-lane configurations. A five-unit ordinal scale was used to rate each operational and safety factor—from least desirable to most desirable (− −, −, 0, +, and + +). Alternatives with curb parking on one or both sides of the street would generally be expected to have lower operational and safety performance than sites without curb parking. The more the operational safety factors are improved by a particular improvement strategy and the greater the improvement in the rating for those factors, the greater the safety effectiveness that would be expected from the improvement.

Other less quantifiable benefits and disbenefits of improvement strategies should also be identified, because no quantifiable or qualitative factors may often have as important an influence as traffic operations and safety on the choice of an improvement strategy. Other benefits and disbenefits that should be considered include the impact of the improvement strategy on through traffic vs. land access traffic, the impact on growth of future traffic volumes (including traffic that might be attracted from parallel facilities), the impact on pedestrians, the impact on bicycles (particularly for streets with curb lanes less than 15 ft wide), and the impact on bus transit operations.

Step 8—Select the Preferred Improvement Strategy. The final step in the process is to consider the tradeoffs among benefits, the disbenefits, and the costs of the feasible improvement strategies and select the most appropriate strategy for the site in question. The improvement strategies are usually considered through engineering judgment, although a formal cost effectiveness procedure, such as the procedure of the AASHTO user benefit analysis manual (*45*), could be used to examine the quantitative aspects of traffic operations, traffic safety, and construction cost. The procedures presented in this AASHTO manual are currently being updated in NCHRP Project 7-12 and are expected to be available to users in a microcomputer program.

IMPLEMENTATION GUIDELINES

This section presents guidelines for implementation of improvement projects on existing urban arterial streets based on the results obtained in this study and the experiences of the highway agencies who participated in this study and responded to the highway agency survey (see Appendix B). These guidelines address many of the nonquantitative issues in successful implementation of improvement strategies for urban arterial streets, especially those involving narrower lanes. These guidelines are intended to supplement, rather than supersede, existing design policies such as those of AASHTO and individual state highway agencies. The guidelines indicate situations in which such policies may be relaxed without compromising safety in improvements to existing facilities. The guidelines developed in this study are:

- Narrower lane widths (less than 11 ft) can be used effectively in urban arterial street improvement projects where the additional space provided can be used to relieve traffic congestion or address specific accident patterns. Narrower lanes may result in increases in some specific accident types, such as same-direction sideswipe collisions, but other design features of a project may offset or more than offset that increase.
- Projects involving narrower lanes nearly always reduce accident rates when the project is made to implement a strategy known to reduce accidents, such as installation of a center TWLTL or removal of curb parking. Highway agencies should not hesitate to implement such projects on urban arterial streets.
- Projects involving narrower lanes whose purpose is to reduce traffic congestion by providing additional through lanes may result in a net increase in accident rate, particularly for intersection accidents. Such projects should be evaluated carefully on a case-by-case basis, considering the agency's previous experience with that type of project. Both the traffic operational and traffic safety effects of the project should be evaluated and the feasibility of incorporating geometric improvements at intersections (such as left-turn lanes) to reduce intersection accidents should be considered.

Table 12. Operational and safety factors rates for design alternatives on urban arterial streets.

Operational Factors

1. Minimize or eliminate delay to through vehicles by left-turning vehicles
2. Minimize delay to through vehicles by right-turning vehicles
3. Allow provision of turning lanes at intersections and high volume driveways
4. Ease the movement of emergency vehicles
5. Provide for storage of disabled vehicles
6. Facilitate U-turns
7. Shadow vehicles making crossing maneuvers at unsignalized intersections (eliminate blocking of one direction while waiting for gap in the other direction)
8. Facilitate pedestrian crossings
9. Minimize high-volume of left-turn and U-turn movements at intersections

Safety Factors

1. Minimize rear-end conflicts between left-turning and through vehicles and allow left-turn drivers time to evaluate opposing gaps
2. Minimize high concentration of driveways and overlapping conflict patterns
3. Control conflicts between left turns into and out of driveways
4. Minimize or eliminate conflicts between opposing left-turns off of the arterial
5. Minimze or eliminate conflicts between left turns and right turns from/to the same lane
6. Minimize or eliminate conflicts caused by encroachment on opposing lanes of vehicles turning right into and out of driveways
7. Minimize or eliminate conflicts caused by encroachment on adjacent lanes of vehicles turning right into and out of driveways
8. Minimize or eliminate conflicts in opposing lanes of vehicles turning left off of the arterial
9. Minimize time during which left-turn conflicts with opposing traffic can occur
10. Provide protected position in median for crossing vehicles
11. Provide protected position in median for crossing pedestrians
12. Minimize conflicts between bicycles and motor vehicles

• Lane widths as narrow as 10 ft are widely regarded by urban traffic engineers as being acceptable for use in urban arterial street improvement projects. Except for one specific project type that is not common (conversion from a two-lane undivided to a four-lane undivided street), all projects evaluated in this study that consisted exclusively of lanes widths of 10 ft or more resulted in accident rates that were either reduced or unchanged. Where streets cannot be widened, highway agencies should give strong consideration to the use of 10-ft lanes where they are necessary as part of a geometric improvement to improve traffic operations or alleviate specific accident patterns.

• Lane widths less than 10 ft should be used cautiously and only in situations where it can be demonstrated that increases in accident rate are unlikely. For example, numerous project evaluations in this study found that 9- and 9.5-ft through-traffic lanes can be used effectively in projects to install a center TWLTL on existing four-lane undivided streets. Such projects nearly always result in a net reduction in accident rate. On streets that cannot be widened, highway agencies should consider limiting the use of lane widths less than 10 ft (1) to project types where their own experience shows that they have been used effectively in the past or (2) to locations where the agency can establish an evaluation or monitoring program for at least 2 years to identify and correct any safety problems that develop. Guidelines for evaluation of urban arterial improvement projects are presented in the next section.

• In highly congested corridors, agencies should anticipate that traffic operational improvements on one street, such as provision of additional through lanes, may attract traffic to that street from parallel streets. This may lead to increased traffic volumes and increased accidents on the improved street, but may still reduce delays and accidents in the corridor as a whole.

• Projects that change the geometrics of signalized intersection approaches should be accompanied by adjustments in signal

Design Alternative	Street Width (ft)	Lane Width (ft)	Median Width (ft)	OPERATIONAL FACTORS									SAFETY FACTORS											
				1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9	10	11	12
Two-lane	20-22	9-10	None	--	--	--	--	--	--	+	+	+	--	--	--	--	--	--	0	--	+	--	--	--
Undivided	24-30	11-14	None	--	--	--	--	--	--	+	+	+	--	--	--	--	--	-	0	+	+	--	--	-
Three-lane	30-32	9-10	None	+	--	--	+	--	--	--	+	+	+	--	-	-	-	++	--	--	+	--	--	--
with TWLTL	34-46	11-14	None	++	--	--	+	--	-	-	-	+	++	--	-	-	+	++	+	+	+	-	--	-
Four-lane	38-44	9-10	None	-	-	--	-	--	-	--	--	+	--	--	--	--	++	++	--	-	-	--	--	--
Undivided	46-58	11-14	None	-	-	--	-	--	-	--	--	+	--	--	--	--	++	++	+	+	-	--	--	-
Four-lane Divided	42-52	9-10	4-12	+	-	--	-	--	-	--	--	-	+	++	++	++	++	++	--	-	-	--	++	--
	54-68	11-12	4-14	++	-	--	-	-	+	-	-	-	++	++	++	++	++	++	+	++	-	-	++	-
	70-80	11-14	16-22	++	-	--	++	++	++	++	++	-	++	++	++	++	++	++	+	++	-	++	++	-
Five-lane	48-54	9-10	None	+	-	--	+	--	-	--	--	+	+	--	-	-	++	++	--	--	-	--	--	--
with TWLTL	54-74	11-14	None	++	-	--	+	--	+	-	--	+	++	--	-	-	++	++	+	++	-	-	--	-

Scale of Operational and Safety Ratings

++ Most desirable
+
0
-
-- Least desirable

Figure 9. Relative ratings of operational and safety factors for design alternatives.

timing (and, in some cases, changes in signal phasing). Traffic volumes on the project (and, possibly, on parallel streets) should be reviewed 1 month or 2 months after project implementation to determine if there is a need for further adjustments in signal timing.

- Truck volumes are an important consideration in the implementation of projects involving narrower lanes. There appears to be general agreement that narrower lanes do not lead to operational problems when truck volumes are less than 5 percent. Sites with truck volumes between 5 and 10 percent should be evaluated carefully on a case-by-case basis. Use of narrower lanes should be discouraged on streets with more than 10 percent trucks.
- Higher truck volumes may not cause operational problems on streets with narrower lanes if the trucks travel straight through the site without turning.
- Trucks may be a greater concern on streets with horizontal curves than on tangents.
- Tractor-trailer combination trucks may be more critical than single-unit trucks because of their greater width and their greater offtracking.
- Curb lanes should usually be wider than other lanes by 1 ft to 2 ft to provide allowance for a gutter and for greater use of the curb lanes by trucks. Center or left lanes for through traffic and TWLTLs can usually be narrower than the curb lane. One city engineer has pointed out that the left lane for through traffic on an arterial street can be quite narrow if it is adjacent to a center TWLTL which increases the "effective width" of the through lane. The presence of a TWLTL adjacent to a through lane is obviously less restrictive than the presence of a curb or another through lane.
- Narrow lane projects do not work well if the right lane provides a rough riding surface because of poor pavement condition or the presence of grates for drainage inlets. Drivers may avoid the right lane if they feel uncomfortable driving over rough drainage inlets. Thus, projects with narrower lanes may be most satisfactory at sites with curb inlets that do not have grates in the roadway.
- The needs of bicyclists should be considered in implementing projects involving narrower lanes. The literature indicates that curb lane widths of at least 15 ft are desirable to accommodate shared operation of bicycles and motor vehicles (*35, 37*); thus, it may not be possible to fully accommodate bicyclists even on many existing streets with 12-ft curb lanes. Decisions concerning implementation of projects with narrower lanes should consider the volume of bicyclists using the roadway and the availability of other bicycle facilities in the same corridor.
- When lanes are narrow, operational efficiency at some sites may be reduced because of staggering of traffic in adjacent lanes. The capacity per lane may be reduced because drivers are reluctant to travel side-by-side. However, drivers in adjacent lanes still travel at shorter headways than they could in a single lane, so the overall through traffic capacity of the street should increase, but not by as much as would be possible if wider lanes could be used.
- Projects that can be implemented by remarking only can be implemented very quickly, often in a single day. However, projects that involve construction, such as median removal, require more time to complete.
- A common problem in remarking projects is that it is difficult to remove the existing pavement markings completely. Figure 10 illustrates the confusion that can be created by incomplete removal of pavement markings. Current removal methods include grinding, sandblasting, and waterblasting. Because of these problems, some agencies implement almost all remarking projects in conjunction with pavement resurfacing.
- Remarking projects may be confusing to drivers if the new lane lines no longer match the pavement joint lines (or the reflections of the pavement joint lines). This potential problem is another indication that implementation of remarking projects in

Figure 10. Example of incomplete removal of obsolete pavement markings which can create confusion to drivers on urban arterial streets

conjunction with pavement resurfacing is very desirable.

• Access control regulations concerning driveway location and design are important on all urban arterial streets, but especially for streets that are not wide enough to install a median or a center TWLTL. Driveway design and location measures that have been found to be effective are summarized in Table 8.

EVALUATION GUIDELINES

Evaluation of urban arterial street improvement projects is an important activity for highway agencies to document the effectiveness of various project types. Good evaluations can serve as a basis for justifying future funding of those project types and can assist designers in the selection of design features and geometrics.

Both traffic operational and safety evaluations of projects should be performed. Traffic operational evaluations should consist of documenting actual traffic volumes and performing capacity and level-of-service analyses or field studies of travel time and delay after project implementation. The traffic accident analyses in Appendix C of this report provide an example of how the safety evaluations should be performed. Guidelines for performing these evaluations are presented in the following sections.

Traffic Operations

Traffic operational evaluations should consist of capacity and level-of-service analyses of signalized intersections and travel time and delay studies over the length of the project.

The implementation guidelines given previously included the recommendation that traffic volumes on the project should be reviewed 1 month or 2 months after project implementation to determine whether there is a need for further adjustments in the signal timing. The collection of this volume data provides a good opportunity to apply the signalized intersection analysis procedures of HCM Chapter 9 to determine whether the effects of the project on level of service were as expected.

The evaluation of the traffic operational effects over the projects as a whole, not just at the signalized intersections, requires a field evaluation of speeds or travel times to confirm whether the assumptions made in the design process (e.g., in the application of HCM Chapter 11) are correct. The literature contains only very limited data on the effect of median treatments in reducing midblock delay, so this type of evaluation is desirable to document the reduction in midblock delays at locations on projects where a raised median or a center TWLTL is installed. Travel time studies using a test car are the preferred method for this type of evaluation although spot speed studies at a midblock location require less effort and may be suitable for some projects.

Traffic Safety

Traffic safety evaluations should be conducted by comparison of accident rates, accident severity distributions, and accident type distributions before and after project implementation. Safety evaluations are especially important for improvement types being attempted by an agency for the first time or for design features that represent a departure from normal practices (e.g., lanes widths less than 10 ft). The following guidelines are suggested:

• Site conditions, accident experience, and traffic volumes before project implementation should be documented for comparison with the experience after project implementation.

• An evaluation period of at least 2 years both before and after project implementation should be used.

• For improvement types being tried for the first time, monitoring of accident experience at 1-month to 3-month intervals over the first year after project implementation may be appropriate in addition to the 2-year evaluation to assure that correctable accident patterns are identified.

• Traffic volumes should be counted after project implementation to assure that the effect on traffic accident rates of any changes in the traffic volumes are documented. Changes in traffic volumes may occur both because of normal growth and traffic attracted from parallel facilities.

• Accident rates, accident severity distributions, and accident type distributions before and after project implementation should be compared using appropriate statistical tests such as those presented in the FHWA *Accident Research Manual (38)* and in Appendix C of this report.

• Where appropriate, other safety evaluation procedures should also be used, such as preparation of collision diagrams, review of hard copy police accident reports, use of traffic conflicts studies, monitoring of complaints from the general public, and interviews with local residents and motorists.

DESIGN EXAMPLES

Three design examples to illustrate the recommended selection procedures are presented in Appendix E. These examples, reviewed here in brief, are based on actual sites from the safety evaluation performed as part of the research.

Design Example 1

Design Example 1 illustrates a four-lane undivided urban arterial street with peak hour volumes of 800 to 1,250 vehicles per hour per lane (vphpl). The total curb-to-curb street width was 40 ft to 50 ft. Improvement of this site was considered by the responsible highway agency primarily because of left-turn delays and the need to provide better left-turn access to driveways and unsignalized intersections. Motorists had complained about the need to wait in a through-traffic lane to complete left turns. The motorist complaints were perceptive because a majority of accidents on the site were found to involve rear-end collisions. The delays to through traffic caused by left-turning vehicles were not quantified, but were substantial.

The two feasible design alternatives for improving this site were four-lane divided and five-lane TWLTL cross sections. Comparison of these alternatives concluded that the five-lane TWLTL alternative would generally provide greater traffic operational and safety benefits than the four-lane divided alternative and would cost less to implement.

The five-lane TWLTL alternative was installed at four locations along this street over a period of several years. The cross sections actually installed by the highway agency at this site used through lanes as narrow as 9.7 ft and a TWLTL width of 9 ft. The projects were found to reduce accident rate by 40.6 percent. Rear-end collisions were reduced by 59.9 percent. The traffic operational benefits of the TWLTL installation have not been quantified, but are estimated to be substantial.

Design Example 2

Design Example 2 illustrates a four-lane divided street with peak hour volumes of 450 vphpl to 700 vphpl. The street is 52 ft wide and is divided by a narrow (4-ft) median. Improvement of this site was considered primarily because it was identified as a high-accident location in the highway agency's accident surveillance program. The accident pattern consisted primarily of rear-end, turning, and sideswipe accidents.

The two feasible design alternatives for improving this site were four-lane undivided and five-lane TWLTL cross sections. It was concluded that the four-lane undivided cross section was unlikely to reduce accidents at the site, while the five-lane undivided cross section would not only reduce accidents but would improve traffic operations as well. The cost differences between these alternatives were minimal, because it was only a question of how the roadway was marked after the median was removed and the street was resurfaced.

The five-lane TWLTL alternative was installed at three locations along this street section for a total length of 1.48 mi. The cross section selected had two 11-ft curb lanes, two 10-ft inside lanes, and a 10-ft TWLTL. The projects reduced accident rate by 52.0 percent, including reductions in angle, sideswipe, and rear-end collisions. The traffic operational benefits of the TWLTL installation have not been quantified, but are estimated to be substantial.

Design Example 3

Design Example 3 illustrates a six-lane divided street in a high-volume urban corridor with peak hour flow rates from 850 vphpl to 1,100 vphpl. The existing site had two 36-ft roadways each with three 12-ft lanes. The primary problem that prompted improvement of this site was traffic congestion. In the evening peak hour, a 6-mi trip on this street required 28.5 min, equivalent to an average speed of 13 mph. The need for additional through lanes at this site was evident.

The responsible highway agency did not have funds available for the widening project that would be required to widen the roadway to provide an additional 12-ft lane in each direction. Therefore, a decision was reached to remark the roadway with four 9-ft lanes in place of the three 12-ft lanes in each direction of travel. This improvement was considered to be an interim measure to obtain an immediate increase in capacity until funds became available to widen the roadway.

After the project was implemented, the highway agency performed travel time studies which found that the time for a 6-mi trip in the evening peak hour was reduced by 10 min, corresponding to an increase in average speed from 13 to 20 mph. Traffic counts found that the peak hour volumes on the remarked facility increased by 11 to 34 percent, while the peak hour volumes on parallel facilities decreased by 5 to 14 percent. Thus, traffic was attracted to the facility by the improved operational conditions, or the travel time improvement might have been even greater.

The traffic accident rate on the project increased by 23 percent. This increase was primarily at intersections because there was no statistically significant increase in midblock accidents. There were increases in all major types of intersection accidents, including angle, sideswipe, and rear-end collisions. However, it is difficult to judge the extent to which these increases were the result of the installation of narrower lanes because, with changing traffic patterns, cross-street volumes and turning volumes may have increased. In addition, because traffic volumes on parallel facilities have decreased, accident rates on those facilities may have decreased as well.

CHAPTER FOUR

CONCLUSIONS AND RECOMMENDATIONS

The major conclusions of the research concern the effective use of narrower lanes as part of traffic operational improvement strategies for urban arterial streets. The preferred lane width for urban arterial streets under most circumstances is 11 ft or 12 ft. However, constraints on street widening do not always permit the use of lanes that wide. The research found that in many situations traffic operational benefits, traffic safety benefits, or both can be obtained from the use of narrower lanes.

A survey of state and local highway agencies throughout the United States found that 96 percent of the highway agencies that responded have used traffic operational improvement strategies for urban arterial streets that do not change the total curb-to-curb street width and 82 percent of highway agencies that responded have used narrower lanes as part of those strategies.

The most common reasons for use of narrower lanes are to install additional through lanes and to install a TWLTL.

The research documented the advantages and disadvantages and the traffic operational and safety effectiveness of a range of design alternatives for urban arterial streets from a two-lane undivided street to streets with as many as eight through lanes. A safety evaluation conducted as part of the research determined the change in accident rates and severities from before to after urban arterial street improvement projects that include narrower lanes. This evaluation included 35 sites located in five states.

It was found that lane widths narrower than 11 ft can be used effectively in urban arterial street improvement projects where the additional space provided can be used to relieve traffic congestion or address specific accident patterns. Narrower lanes may result in increases in some specific accident types, such as same-direction sideswipe collisions, but other design features of a project may reduce other accident types by as much or more.

Improvement strategies involving narrower lanes nearly always reduce accident rates when the purpose of the project is to make an improvement known to reduce accidents, such as installation of a center TWLTL or removal of curb parking. Highway agencies should not hesitate to implement such projects on urban arterial streets even when narrower lanes must be used.

The following accident rate reductions were found for improvement strategies that involved installation of a TWLTL:

	Accident Rate Reduction	
Project Type	Expected Value (%)	90 Percent Confidence Interval (%)
Conversion from a four-lane undivided street to a five-lane street with a TWLTL	44	13 to 75
Conversion from a four-lane divided street with a narrow median to a five-lane street with TWLTL	53	24 to 82
Conversion from a six-lane divided street with a narrow median to a seven-lane street with TWLTL	24	11 to 38

These estimates indicate that there can be substantial site-to-site variation in the accident reduction effectiveness of these project types. The expected value is the single best estimate of accident reduction effectiveness. The accident reduction effectiveness for 90 percent of sites should fall within the confidence intervals shown. None of these improvements had any effect on the distribution of accident severities (i.e., the proportion of total accidents that involved fatalities and injuries remained the same).

Improvement strategies using narrower lanes whose purpose is to reduce traffic congestion by providing additional through lanes may result in a net increase in accident rate, particularly for intersection accidents. Such projects should be evaluated carefully on a case-by-case basis, considering the agency's previous experience with that type of project. Both the traffic operational and traffic safety effects of the project should be evaluated and the feasibility of incorporating geometric improvements at intersections (such as left-turn lanes) to reduce intersection accidents should be considered. In addition, where an improvement project results in a shift in traffic volumes between parallel facilities, it may be necessary to evaluate the anticipated traffic operational and safety effects on the corridor as a whole.

Lane widths as narrow as 10 ft are widely regarded by urban traffic engineers as being acceptable for use in urban arterial street improvement projects. All projects evaluated in this study that consisted exclusively of lanes widths of 10 ft or more resulted in accident rates that were either reduced or unchanged. (The only exceptions to the previous statement were three sites converted to the four-lane undivided design alternative where a different design alternative should have been used.) Where streets cannot be widened, highway agencies should give strong consideration to the use of 10-ft lanes where they are necessary as part of a geometric improvement to improve traffic operations or to alleviate specific accident patterns.

Lane widths less than 10 ft should be used cautiously and only in situations where it can be demonstrated that increases in accident rate are unlikely. For example, numerous project evaluations in this study found that 9-ft to 9.5 ft through-traffic lanes can be used effectively in projects to install a center TWLTL on existing four-lane divided streets. Such projects nearly always result in a net reduction in accident rate. On streets that cannot be widened, highway agencies should consider limiting the use of lane widths less than 10 ft to project types where their own experience shows that they have been used effectively in the past or to locations where the agency can establish an evaluation and monitoring program for at least 2 years to identify and correct any safety problems that develop.

Field observations of traffic operations on urban arterial streets found that vehicle encroachments on adjacent lanes are more likely on streets with narrower lanes. Vehicle encroachments on narrower lane sites were more likely to involve trucks than passenger cars and more likely to occur on horizontal curves than on tangents. However, very few traffic conflicts associated with these encroachments were observed.

The needs of bicyclists should be considered in implementing projects involving narrow lanes. The literature indicates that curb lane widths of at least 15 ft are desirable to accommodate shared operation of bicycles and motor vehicles. Decisions concerning implementation of projects with narrower lanes should consider the volume of bicycles using the roadway and the availability of other bicycle facilities in the same corridor.

The report presents a recommended process for selecting appropriate improvement strategies for more effectively using the available width of urban arterial streets. A key element of this process is estimating the anticipated operational and safety effectiveness of alternative improvement strategies. The recommended process is meant to provide a flexible approach to the selection of improvement strategies rather than a rigid methodology. Highway agencies should adapt the process to suit their own needs while retaining its basic principles.

The safety effectiveness of various improvement strategies for urban arterial streets is quantified in this report. However, because accident rates and traffic conditions vary widely from state to state and from jurisdiction to jurisdiction, users are encouraged to evaluate their own projects to build up a history of safety effectiveness estimates for use in planning future projects. Guidelines for performing such evaluations are presented in the report.

The operational effectiveness of urban arterial street improvement strategies can be quantified using the procedures of the HCM (*2*). The most useful tool for such evaluations is the signalized intersection analysis procedure in HCM Chapter 9. The analysis procedure for arterial streets in HCM Chapter 11 can be used to evaluate street sections including both signalized intersections and midblock sections between signals. However, application of the HCM Chapter 11 procedure to midblock sections would generally require the highway agency to conduct speed or travel time studies before or after each improvement. Estimates from the literature on the effects of improvement strategies on midblock delay are presented in the report, but further research is needed to develop better quantitative estimates.

Finally, while traffic operations and safety should be the key factors in most decisions concerning urban arterial street improvement strategies, other less quantitative factors and constraints should receive due consideration. Such factors may include available funding levels, impacts on abutting properties and businesses, impacts on pedestrians, access control laws and ordinances, and public opinion.

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APPENDIXES A, B, C, D—UNPUBLISHED MATERIAL

Appendixes A, B, C, and D contained in the report as submitted by the research agency are not published herein. Their titles are listed here for the convenience of those interested in the subject area. A limited number of copies are available on loan or may be purchased at a cost of $8.00 by written request to the NCHRP, Transportation Research Board Business Office, 2101 Constitution Avenue, N.W., Washington, D.C., 20418.

The titles are:
Appendix A—Literature Review
Appendix B—Survey of Highway Agencies
Appendix C—Accident Analysis of Projects Involving Narrower Lanes
Appendix D—Field Observations of Traffic Operations on Projects Involving Narrower Lanes

APPENDIX E—DESIGN EXAMPLES

This appendix presents three design examples that illustrate the application of the recommended procedures for selecting improvement strategies for urban arterial streets. The design examples address the following situations:

- Conversion of a four-lane undivided street to five-lane with a center TWLTL.
- Conversion from a four-lane divided street with a narrow median to five-lane with a center TWLTL.
- Conversion from a six-lane divided street to an eight lane divided street.

These examples are based on actual sites that were analyzed in the safety evaluation presented in Appendix C. All of the data presented in the examples are based on information provided by the participating highway agencies. The hourly traffic volumes presented are estimated from ADTs using estimates of the proportion of traffic in the design hour (K) and the estimated directional factor (D). Although each of these sites has already been improved, these examples focus on the factors that entered into that decision and the alternatives that were or could have been considered.

DESIGN EXAMPLE 1

This design example illustrates the conversion of a four-lane undivided arterial street to five-lane with a center TWLTL. Figure E-1 illustrates the street cross-section before and after improvement of this site.

Existing Conditions

This design example addresses four sections of arterial street located in a large metropolitan area. This street is located in a suburban area, but all of the land along the street is already developed. Nevertheless, the traffic volumes on the street may grow in response to new developments in other parts of the metropolitan region.

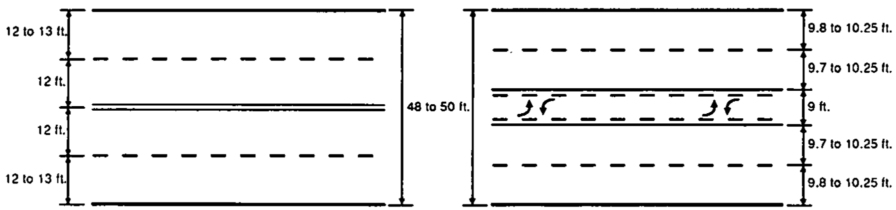

Figure E-1. Design alternatives before and after improvement for design example 1.

Table E-1. EXISTING CONDITIONS -- DESIGN EXAMPLE 1

	Site 5	Site 6	Site 12	Site 13
Section length (mi)	0.25	0.41	0.24	0.32
Existing design alternative	<----------------Four-lane undivided-------------->			
Existing street width (ft)	48	48	50	50
Existing lane width (ft)	4 @ 12	4 @ 12	13-12-12-13	13-12-12-13
Average daily traffic volume (vpd)	56,900	36,400	38,000	46,800
Estimated peak hour flow rate (vphpl)	1,250	800	850	1,050
Estimated percent trucks	2.0	2.0	2.0	2.0
Type of development	Commercial	Residential	Residential	Commercial
Access points per mi	56	71	19	31
Speed limit (mph)	35	35	35	35
Pedestrian activity	Medium	Medium	Medium	Medium

The existing street was 48 to 50 ft wide with a curb-and-gutter section. The four street sections of interest here have a total length of 1.22 mi and are located along the same street within a total length of approximately 2 mi. The remaining 0.78 mi within this 2-mi arterial street section consists primarily of six signalized intersections and their approaches. These signalized intersections were not modified by any of the improvements made at this site and, therefore, have been excluded from this example. Table E-1 documents the existing conditions on the four sites, which were referred to as Sites 5, 6, 12, and 13 in the safety evaluation in Appendix C. These sites were also included in the field observations of truck operations in Appendix D.

The primary condition at these sites that indicated a need for an improvement was the delay associated with midblock left turning movements and complaints from motorists who felt uncomfortable when stopped in the left through traffic lane waiting to make a left turn. In particular, complaints from motorists over a period of several years about the difficulty of turning left into a particular church driveway first prompted interest in this improvement within the highway agency. The four sites had ADTs ranging from 36,400 to 56,900 vpd with estimated peak hour volumes from 800 to 1,250 vphpl. These high volumes on a signalized arterial indicate the presence of peak hour congestion.

Table E-2 summarizes the existing accident experience at the four sites. The existing accident rates on the site (1.25 to 2.20 accidents per million veh-mi) were relatively low for an urban arterial. However, a majority of the accidents involved rear-end collisions, which often indicate the existence of a correctable safety problem. In fact, these accidents could be symptomatic of the problem indicated by the motorist complaints discussed above.

Projected Future Conditions

Traffic volumes on these sites had been growing steadily and were expected to grow at 3.5 to 5.0 percent per year. Thus, the congestion, motorist delays due to turning vehicles, and rear-end accidents were likely to continue unless an improvement project was implemented.

Constraints

Because of surrounding development, major portions of the existing street cannot be widened. In addition, funds to implement a widening project were not available, while a remarking project could be implemented at minimal cost.

Table E-2. EXISTING ACCIDENT EXPERIENCE -- DESIGN EXAMPLE 1

	Site 5	Site 6	Site 12	Site 13
Duration of study period (months)	24	36	24	24
Exposure (million veh-mi)	10.38	16.36	6.67	10.94
Total number of accidents	13	36	13	15
Accident rate (per million veh-mi)	1.25	2.20	1.95	1.37
Distribution by accident severity:				
Fatal and injury	8	24	7	9
Property damage only	5	12	6	6
Distribution by relationship to intersections:				
Midblock	13	19	5	15
Unsignalized intersection	0	17	8	0
Signalized intersection	0	0	0	0
Distribution by accident type:				
Single-vehicle	1	5	2	1
Head-on collision	1	2	1	5
Angle collision	2	6	1	3
Sideswipe collision (same dir.)	3	2	0	1
Sideswipe collision (opp. dir.)	0	2	0	0
Rear-end collision	7	13	9	5

Feasible Design Alternatives

The following design alternatives are feasible for 48- and 50-ft streets based on Table 1 and Figure 2:

- Two-lane undivided with parking on both sides
- Three-lane undivided with parking on one side
- Three-lane undivided with parking on both sides
- Four-lane undivided
- Four-lane undivided with parking on one side
- Four-lane divided
- Five-lane with TWLTL
- Five-lane undivided

However, most of these design alternatives are not appropriate for the location in question. The alternatives with curb parking lanes are not appropriate because they do not address the existing problems at the site. There is no established need for curb parking on these sites. Addition of a parking lane would reduce capacity due both to interference of parking maneuvers with through traffic and to the reduction in the number and/or width of the through lanes. The three-lane undivided and five-lane undivided alternatives are appropriate primarily for one-way streets rather than two-way streets. Thus, the only two feasible alternatives that require further evaluation are four-lane divided and five-lane with TWLTL.

Geometric Variations

On a 48-ft street, there are two general geometric variations for a four-lane divided cross-section:

- Two 11-ft curb lanes; two 10-ft inside lanes; and a 6-ft median.
- Two 10-ft curb lanes; two 9-ft inside lanes; and a 10-ft median.

And, of course, many combinations of lane widths between those shown are also feasible. For the five-lane TWLTL alternative, a typical cross-section would be:

- Two 10-ft curb lanes; two 9-ft inside lanes; and a 10-ft TWLTL.

On a 50-ft street, there are three general geometric variations for a four-lane divided cross-section:

- Two 12-ft curb lanes; two 11-ft inside lanes; and a 4-ft median.
- Two 11-ft curb lanes; two 10-ft inside lanes; and an 8- ft median.
- Two 10-ft curb lanes; two 9-ft inside lanes; and a 12-ft median.

As in the previous case, many combinations of lane widths between those shown are also feasible. For the five-lane TWLTL alternative, typical cross-sections would be:

- Four 10-ft lanes and a 10-ft TWLTL.
- Two 11-ft curb lanes; two 9-ft inside lanes; and a 10-ft TWLTL.
- Two 10-ft curb lanes; two 9-ft inside lanes; and a 12-ft TWLTL.

Benefits and Disbenefits

Both the four-lane divided and five-lane TWLTL design alternatives would be expected to improve traffic operations for through traffic and to reduce rear-end accidents associated with congestion and left-turn maneuvers. The peak hour traffic volumes above the level of 1,000 vph in one direction of travel at which raised medians on four-lane streets have been found to involve less delay than undivided highways (see Table A-6 in Appendix A). However, the installation of a raised median would substantially increase delay to left-turning vehicles by forcing them to use indirect routes to reach their destinations. NCHRP Report 282 (1) found that the operational effectiveness of TWLTLs is generally greater than for raised medians at all levels of flow rate, left-turn demand, and driveway density. Furthermore, the installation of a raised median at this site would involve a substantial construction cost, while installation of a TWLTL would involve only remarking which could be performed in conjunction with scheduled resurfacing projects. Therefore, conversion to a five-lane cross-section with a center TWLTL is the preferred improvement strategy for these sites.

Implementation and Evaluation

The highway agency responsible for these sites chose to convert each of them to five-lane with a center TWLTL. The specific geometrics chosen for the 48-ft street were:

- Two 9.8-ft curb lanes; two 9.7-ft inside lanes; and a 9-ft TWLTL.

The cross-section used for the 50-ft street was:

- Four 10.25-ft lanes and a 9-ft TWLTL.

These cross-sections with relatively narrow TWLTLs, which differ slightly from the typical cross-sections discussed above, were chosen by the highway agency to keep the through traffic lanes as wide as possible.

TWLTLs were installed at the four sites in stages over the period from 1982 through 1987. Through this staged approach projects were implemented in later years after the highway agency had found that the earlier projects had been successful.

There have been no field studies to document the traffic operational effectiveness of this improvement, although the removal of left-turning vehicles from the through traffic lanes has obviously helped to reduce delay. The complaints related to left turns into the church driveway that originally prompted the project disappeared immediately after the TWLTL was installed at the first site. One resident that the research team met stated that, while the lanes on the street were narrow, she would not like to have to turn left into her driveway without the TWLTL.

A safety evaluation found that the projects at these four sites collectively reduced total accident rate by 40.6 percent. In particular, rear-end accidents, which the project was intended to ameliorate, were reduced by 59.9 percent. Thus, the project was not only effective in reducing midblock delay, but resulted in a substantial reduction in traffic accidents as well. The latter finding is important, since this reduction in accident rate could not have been obtained without the use of narrower lanes. These finding are consistent with the general safety evaluation of this project type presented in Appendix C.

DESIGN EXAMPLE 2

The second design example illustrates the conversion of a four-lane divided street with a narrow median to a five-lane cross-section with a center TWLTL. Figure E-2 illustrates the street cross-section before and after improvement of this site.

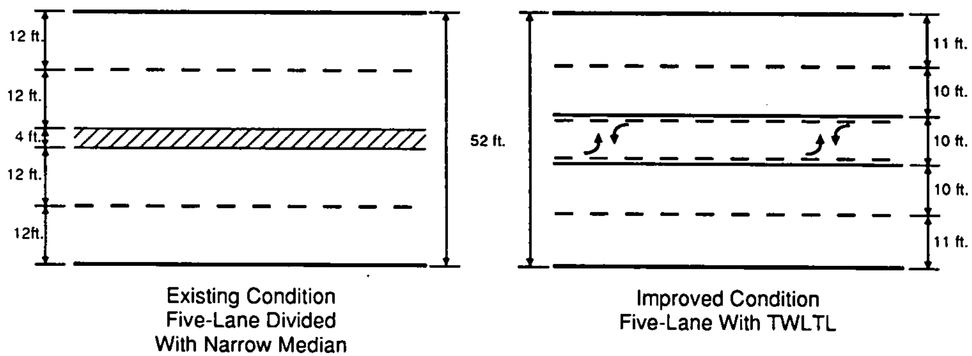

Figure E-2.. Design alternatives before and after improvement for design example 2.

Existing Conditions

This design example addresses three sections of arterial street which serves as a radial arterial from the central business district in a small city (population 35,000) that is part of a medium-sized metropolitan area.

The existing street is 52 ft wide with 4-ft raised and mountable medians. The three street sections of interest have a total length of 1.48 mi and are located along the same street within a total length of approximately 2 mi. Table E-3 documents the existing conditions at these three sites, which are referred to as Sites 22, 23, and 24 in the safety evaluation in Appendix C.

These sites were proposed for improvement primarily because of their high accident rates and the existing pattern of rear-end, turning, and side-swipe accidents. The existing accident patterns at these sites are illustrated in Table E-4. The responsible highway agency decided that the existing narrow median design was obsolete, since it restricted left turns.

The highway agency's priority plan for this project was consistent with the accident rates shown in Table E-4. The highest priority was assigned to the improvement of Sites 22 and 23, with improvement of Site 24 to be accomplished as funds became available.

Projected Future Conditions

Traffic volumes on these sites were expected to grow very little. An economic slowdown was underway at the time implementation of these projects was considered in 1981 and 1982. There was substantial unemployment in the surrounding area and a shopping mall near one end of the project was experiencing a high vacancy rate. While it was recognized that traffic operational benefits could be obtained from improvement at these sites, even if traffic volumes did not increase much, the primary rationale for the projects was to reduce accidents.

Table E-3. EXISTING CONDITIONS -- DESIGN EXAMPLE 2

	Site 22	Site 23	Site 24
Section length (mi)	0.58	0.35	0.55
Existing design alternative	Four-lane divided with narrow median		
Existing street width (ft)	52	52	52
Existing lane width (ft)	4 @ 12 plus 4-ft median		
Average daily traffic volume (vpd)	13,100	13,000	22,000
Estimated peak hour flow rate (vphpl)	450	450	700
Estimated percent trucks	4.5	5.4	4.0
Type of development	Mixed	Residential	Commercial
Access points per mi	67	20	86
Speed limit (mph)	35	35	35
Pedestrian activity	Medium	Medium	Medium

Table E-4. EXISTING ACCIDENT EXPERIENCE -- DESIGN EXAMPLE 2

	Site 22	Site 23	Site 24
Duration of study period (months)	18	24	24
Exposure (million veh-mi)	4.14	3.32	8.83
Total number of accidents	64	68	46
Distribution by accident severity:			
Fatal and injury	20	25	19
Property damage only	44	43	27
Distribution by relationship to intersections:			
Midblock	6	4	8
Unsignalized intersection	53	64	38
Signalized intersection	5	0	0
Distribution by accident type:			
Single-vehicle	12	6	5
Head-on collision	0	1	0
Angle collision	25	17	12
Sideswipe collision (same dir.)	4	8	6
Sideswipe collision (opp. dir.)	0	1	1
Rear-end collision	23	35	22

Constraints

Widening of a major portion of these sites was considered infeasible because of the impact on adjoining property. Two horizontal curves located adjacent to Site 23 were widened to improve their geometrics and reduce accidents. This widening required right-of-way acquisition and, since it increased the total curb-to-curb street width, fell outside the scope of this study. Therefore, these horizontal curves were excluded from the safety evaluation of Site 23.

Feasible Design Alternatives

The following design alternatives are feasible for a 52-ft street based on Table 1 and Figure 2:

- Two-lane undivided with parking on both sides
- Three-lane undivided with parking on one side
- Three-lane undivided with parking on both sides
- Four-lane undivided
- Four-lane undivided with parking on one side
- Four-lane divided
- Four-lane divided with parking on one side
- Five-lane with TWLTL
- Five-lane undivided

However, most of these design alternatives are not appropriate for the sites in question. The alternatives with curb parking lanes are not appropriate because they do not address the existing problems at the site. There is no established need for curb parking on these sites. Addition of a parking lane would result in poorer traffic operations due both to interference of parking maneuvers with through traffic and to the reduction in the number and/or width of the through lanes. The three-lane undivided and five-lane undivided alternatives are appropriate primarily for one-way streets rather than two-way streets. Thus, the only two feasible alternatives that require further evaluation are four-lane undivided and five-lane with TWLTL.

Geometric Variations

On a 52-ft street, the most common cross-section for a four-lane undivided facility is:

- Two 14-ft curb lanes and two 12-ft inside lanes.

For the five-lane TWLTL alternative, the possible cross-sections would include:

- Two 11-ft curb lanes; two 10-ft inside lanes; and a 10-ft TWLTL.

- Four 10-ft lanes and a 12-ft TWLTL.

- Two 10-ft curb lanes; two 9-ft inside lanes and a 14-ft TWLTL.

Of course, many combinations of lane widths between those shown are also feasible.

Benefits and Disbenefits

The four-lane undivided alternative would be expected to reduce delay in the portions of these sites where existing raised medians restricted left turns, except during the peak hour on Site 24 where volumes are so high that the presence of a raised median could reduce delay. However, implementation of the four-lane undivided alternative would not be expected to reduce accidents, which is the primary rationale for the project. Indeed, removal of the median without its replacement by another median treatment might increase accidents.

By contrast, the five-lane TWLTL design alternative has the potential both to reduce accidents and to improve traffic operations. Table E-4 shows that accidents on these sites are primarily concentrated at unsignalized intersections, where no left turn lanes are provided under the existing configuration. The installation of a TWLTL would provide a left-turn lane at these unsignalized intersections, as well as at all midblock driveway locations. Removing turning vehicles from the through lanes would be expected to reduce traffic conflicts and delay at both intersections and driveways.

Implementation and Evaluation

The highway agency responsible for these sites chose to convert each of them to a five-lane design with a center TWLTL. The specific cross-section chosen for the 52-ft street was the first option considered above:

- Two 11-ft curb lanes; two 10-ft inside lanes; and a 10-ft TWLTL.

This choice was intended to make the through traffic lanes as wide as possible. (Note that this agency preferred a slightly wider TWLTL width than the agency in Design Example 1.)

A safety evaluation found that the projects at these three sites collectively reduced accident rate by 52.0 percent. In particular, the accident types that were intended to be addressed by the improvements -- angle, sideswipe, and rear-end accidents, were reduced by 21.4, 36.2, and 79.2 percent, respectively. It is important to realize that these accident reductions were accomplished despite removal of a median, which is generally regarded as a safety feature in arterial street design, and despite use of narrower lanes. These results are consistent with the overall results for improvements of this type presented in Appendix C.

There have been no studies of the traffic operational effectiveness of this improvement, although the removal of left-turning vehicles from the through traffic lanes has obviously helped to reduce delay.

DESIGN EXAMPLE 3

This design example illustrates the conversion of a six-lane divided street to an eight-lane divided street. Figure E-3 illustrates the street cross-section before and after improvement of this site.

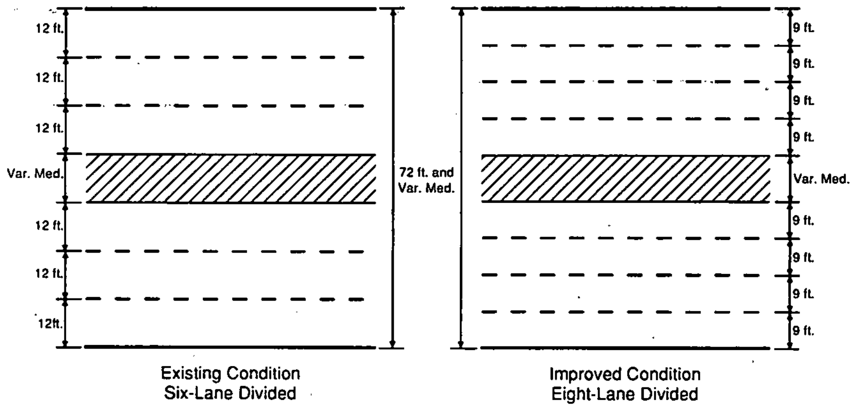

Figure E-3. Design alternatives before and after improvement for design example 3.

Existing Conditions

This design example addresses adjoining four sections of arterial street in a large metropolitan area. The existing street consists of two 36-ft roadways divided by a variable width median. These four street sections have a total length of 4.84 mi and are directly contiguous to one another. These sites have 15 signals over their 4.84-mi length. (In fact, improvements on this street were actually made over a 6-mi length. One portion of this length contained a number of auxiliary lanes that changed its cross section and it was, for that reason, excluded from the safety evaluation performed in this study. These sites were evaluated as four separate projects, because the traffic volumes and density of development vary over the length of the improvement.)

Table E-5 documents the existing conditions on these sites, which were referred to as Sites 32, 33, 34, and 35 in the safety evaluation in Appendix C. This arterial street is located in a high-volume congested corridor. It carries more traffic than any other nonfreeway facility in the metropolitan area. The ADTs range from 48,800 to 57,900 vpd and the peak hour volumes range from 850 to 1,100 vphpl.

The primary condition at these sites that led to the need for an improvement project was traffic congestion resulting from insufficient capacity to serve the high through traffic volumes and the high turning and cross-traffic volumes at the signalized intersections. The average peak-direction travel time for a 6-mi trip in the morning peak hour was 17.5 min, equivalent to an average speed of 21 mph. The corresponding 6-mi trip in the opposite direction in the evening peak hour required 28.5 min, for an average speed of 13 mph.

Table E-6 summarizes the existing traffic accident patterns at the sites. The traffic accident rates are particularly high, especially on Sites 32 and 34. The predominant accident types are angle and rear-end collisions at midblock locations and at signalized intersections.

TABLE E-5. EXISTING CONDITIONS -- DESIGN EXAMPLE 3

	Site 32	Site 33	Site 34	Site 35
Section length (mi)	1.72	0.97	1.06	1.09
Existing design alternative	<--------------Six-lane divided---------------->			
Existing street width (ft)	72 + med	72 + med	72 + med	72 + med
Existing lane width (ft)	<----------6 @ 12 plus variable median--------->			
Average daily traffic (vpd)	57,900	56,400	51,400	48,800
Estimated peak hour flow rate (vphpl)	1,100	1,100	900	850
Estimated percent trucks	1.0	1.0	1.0	1.0
Type of development	Commercial	Commercial	Commercial	Commercial
Access points per mi	65	65	52	57
Speed limit (mph)	40	40	40	40
Pedestrian activity	Low	Low	Low	Low

Table E-6. EXISTING ACCIDENT EXPERIENCE -- DESIGN EXAMPLE 3

	Site 32	Site 33	Site 34	Site 35
Duration of study period (months)	12	12	12	12
Exposure (million veh-mi)	36.45	20.02	19.94	19.47
Total number of accidents	519	172	202	107
Accident rate (per million veh-mi)	14.24	8.59	10.13	5.50
Distribution by accident severity:				
Fat and injury	122	39	47	32
Property damage only	397	133	155	75
Distribution by relationship to intersections:				
Midblock	284	111	139	78
Unsignalized intersection	47	10	17	23
Signalized intersection	188	51	46	6
Distribution by accident type:				
Single-vehicle	19	8	9	5
Head-on collision	3	1	1	0
Angle collision	215	58	87	46
Sideswipe collision (same dir.)	36	20	19	11
Sideswipe collision (opp. dir.)	0	0	0	0
Rear-end collision	242	82	84	44
Unknown	4	3	2	1

Projected Future Conditions

Traffic volumes at these sites and on parallel streets have been growing rapidly. Traffic volumes in this corridor had doubled over a 10-year period and were expected to continue to increase rapidly, especially since some of the adjacent land was still undergoing development. Thus, congestion in this already-congested corridor was expected to increase.

Constraints

The major constraint on improvements in this corridor was available funding. Sufficient right-of-way to widen the roadway could be acquired, but funds for the required construction were not available because of multiple demands elsewhere in this rapidly growing metropolitan area.

Feasible Design Alternatives

A broad range of feasible design alternatives are available if the roadway could be widened. Four improvement alternatives, in addition to the existing condition or "do-nothing" alternative, were investigated by the responsible highway agency. These were:

- Remark the existing roadways with narrower lanes to provide additional through lanes.
- Install reversible lanes on the existing roadways or a parallel street.
- Convert from two-way to one-way operations on this street or a parallel street.
- Narrow or remove the existing median to provide additional through lanes.

The installation of reversible lanes or conversion to one-way operation were found to be infeasible without major reconstruction of the existing divided roadway.

Providing additional through lanes by removing the median was found to be feasible at a cost of over $2,400,000. The major drawback of this approach was that, to obtain the full benefits of the additional through lanes, the existing left-turn lanes at signalized intersections would need to be removed and left turns restricted. No reasonable alternate routes to provide for these left turn movements were available. Thus, it would be better to widen the roadways on the outside but this would require right-of-way acquisition and, consequently, cost substantially more.

Therefore, the only feasible alternative that remained was to remark the existing roadways with narrower lanes to provide an additional through lane in each direction. This approach had the advantage of being inexpensive and able to provide an immediate improvement in capacity. Therefore, a decision was made to remark the existing roadways with narrower lanes as an interim measure and to make a more extensive geometric improvement at a later date when funds were available.

Geometric Variations

Only one geometric configuration was reasonable for remarking the two existing 36-ft roadways. Each existing roadway has three 12-ft lanes and was remarked with four 9-ft lanes.

Benefits and Disbenefits

The benefits of the proposed project were expected to include a substantial increase in capacity and a reduction in travel time. Obviously, the peak hour volumes of 1,100 vphpl could be immediately reduced to approximately 800 vphpl. The safety effects of the project were not known, but 9-ft lanes were in use at other locations in the metropolitan area. The highway agency was concerned that drivers might feel uncomfortable with 9-ft lanes, and it was anticipated that some traffic might be diverted to parallel facilities. In the interest of safety, the speed limit was lowered from 40 to 35 mph.

Implementation and Evaluation

The 6-mi arterial street section was remarked with narrower lanes in a 10-hr period on a Sunday at a cost of $4,200, including materials and labor. Thus, the project was very simple and inexpensive to implement.

Travel time studies by the highway agency found that the most substantial reduction in travel time occurred in the evening peak hour. The travel time for a 6-mi trip was reduced by 10 min, corresponding to an increase in average speed from 13 to 20 mph.

Traffic counts found that peak hour volumes on the remarked facility increased by 11 to 34 percent with installation of the additional lane while the peak hour volumes on parallel facilities decreased by 5 to 14 percent. Thus, far from diverting traffic away from the facility with 9-ft lanes, as the highway agency staff had feared, the improved operational conditions attracted traffic from parallel streets. The improved operational conditions were very apparent to the motoring public. Highway agency staff report that this project was one occasion when public response to a project was immediate and very positive.

Traffic accidents on the four sites collectively increased by 24 percent. This increase was primarily at intersections because there was no statistically significant increase in midblock accidents. There were increases in all major types of intersection accidents, including angle, sideswipe, and rear-end collisions. However, it is difficult to judge the extent to which these increases in intersection accidents are the result of the installation of narrower lanes because, with changing traffic patterns, cross-street volumes and turning volumes may have increased. Accident rates on parallel streets may have decreased due to the decrease in traffic volume. Midblock angle and sideswipe accidents increased by 46 and 104 percent, respectively, but this was offset by a 37 percent reduction in midblock rear-end collisions. The reduction in rear-end collisions is probably the result of reduced congestion (shorter signal queues and less stop-and-go driving) on the facility.

The 9-ft lanes at this site remained in place for approximately 5 years and were eventually eliminated when funds were available to widen the facility. The widened facility is operating today with 12 ft lanes.

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TRANSPORTATION RESEARCH BOARD
National Research Council
2101 Constitution Avenue, N.W.
Washington, D.C. 20418

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