NCHRP-225

National Cooperative Highway Research Program

NCHRP Synthesis 225

Left-Turn Treatments at Intersections

A Synthesis of Highway Practice

Transportation Research Board
National Research Council

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Synthesis of Highway Practice 225

Left-Turn Treatments at Intersections

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Topic Panel

Transportation Research Board
National Research Council

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PREFACE

A vast storehouse of information exists on nearly every subject of concern to highway administrators and engineers. Much of this information has resulted from both research and the successful application of solutions to the problems faced by practitioners in their daily work. Because previously there has been no systematic means for compiling such useful information and making it available to the entire community, the American Association of State Highway and Transportation Officials has, through the mechanism of the National Cooperative Highway Research Program, authorized the Transportation Research Board to undertake a continuing project to search out and synthesize useful knowledge from all available sources and to prepare documented reports on current practices in the subject areas of concern.

This synthesis series reports on various practices, making specific recommendations where appropriate but without the detailed directions usually found in handbooks or design manuals. Nonetheless, these documents can serve similar purposes, for each is a compendium of the best knowledge available on those measures found to be the most successful in resolving specific problems. The extent to which these reports are useful will be tempered by the user's knowledge and experience in the particular problem area.

FOREWORD

By Staff
Transportation Research Board

This synthesis will be of interest to traffic engineers in both the public and private sectors, as well as to design engineers, safety and law enforcement officials, traffic signal technicians, and others concerned with the accommodation of nonmotorized transportation (pedestrians and bicycles) on the roadway. The synthesis describes the traffic conditions, signalization, signing, and geometric design issues associated with accommodating left-turning vehicles at intersections.

Administrators, engineers, and researchers are continually faced with highway problems on which much information exists, either in the form of reports or in terms of undocumented experience and practice. Unfortunately, this information often is scattered and unevaluated and, as a consequence, in seeking solutions, full information on what has been learned about a problem frequently is not assembled. Costly research findings may go unused, valuable experience may be overlooked, and full consideration may not be given to available practices for solving or alleviating the problem. In an effort to correct this situation, a continuing NCHRP project, carried out by the Transportation Research Board as the research agency, has the objective of reporting on common highway problems and synthesizing available information. The synthesis reports from this endeavor constitute an NCHRP publication series in which various forms of relevant information are assembled into single, concise documents pertaining to specific highway problems or sets of closely related problems.

This report of the Transportation Research Board discusses the basic concerns related to left-turn movements and the guidelines and requirements for handling these movements in the traffic stream. It also addresses the design criteria for left-turn treatments and the performance measures frequently applied to determine their effectiveness. The synthesis discusses the specific requirements for signing and pavement markings, and the various elements of traffic signal requirements, signal design and installation, phasing, optimization, and lane-use controls. There is also a description of special applications such as U-turn control, pedestrian requirements, bicycles, and transit interface.

It should be noted that, while traffic engineers frequently use standards developed by the American Association of State Highway and Transportation Officials (AASHTO), the Federal Highway Administration, or other agencies in making engineering judgments, they are always well advised to protect themselves by carefully supporting the bases of their decision with factual findings and documenting the reasons for the decisions.

To develop this synthesis in a comprehensive manner and to ensure inclusion of significant knowledge, the Board analyzed available information assembled from numerous sources, including a large number of state highway and transportation departments. A topic panel of experts in the subject area was established to guide the researcher in organizing and evaluating the collected data, and to review the final synthesis report.

This synthesis is an immediately useful document that records practices that were acceptable within the limitations of the knowledge available at the time of its preparation. As the processes of advancement continue, new knowledge can be expected to be added to that now at hand.

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The Principal Investigators responsible for the conduct of this synthesis were Sally D. Liff, Manager, Synthesis Studies, and Stephen F. Maher, Senior Program Officer. This synthesis was edited by Linda S. Mason.

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Information on current practice as provided by many highway and transportation agencies. Their cooperation and assistance are appreciated.

LEFT-TURN TREATMENTS AT INTERSECTIONS

SUMMARY

The left-turn maneuver is one of the more complex driving challenges at high-volume intersections. Drivers turning left must find a gap in opposing traffic and check for pedestrians, bicycles, and other traffic in the intersection all under a dynamic situation of changing traffic patterns. The left-turning vehicles can, at the same time, have a major impact on the intersection traffic operations. Depending on the intersection features provided for turning traffic, the left-turn maneuver can cause major delays to other traffic, be a source of conflict with other maneuvers, and require specific analysis, design consideration, and traffic control to avoid operational and safety problems.

Drivers normally expect to have left-turn lanes provided at major intersections, and many jurisdictions that were surveyed for this Synthesis indicate it is normal practice to construct left-turn lanes with intersection improvements because that is what the public expects. Left-turn treatments range from the prohibition of such movements to specially designed geometric treatments including shared lanes, left-turn lanes in the median area of a divided highway, and lanes separated by a physical barrier. Traffic controls include lane markings and traffic signals. Other considerations are the number and types of vehicles, pedestrian interface, and safety issues such as visibility.

Guidelines for the design and operation of left-turn intersections have been developed by the American Association of State Highway and Transportation Officials (AASHTO) and the Institute of Transportation Engineers (ITE). Other guidance for design and evaluation of left-turn intersections include *NCHRP Report 279* and the *Highway Capacity Manual.* The *Manual on Uniform Traffic Control Devices* (MUTCD) provides guidance on traffic control sign and pavement markings. While these form the basis for implementation of left-turn controls in most jurisdictions, many areas have tailored the guidelines to their own requirements. However, these guidelines must be consistent and universally understood by the road user to be effective. The driver comprehension of some traffic control features indicates a need for additional work in this area. Several applications for which there is less specific guidance, such as reversible turn lanes, are beginning to be used.

The left-turn treatment at intersections must also consider a number of traffic and roadway characteristics, including the intersection traffic volumes, traffic queues, roadway geometrics, accidents, vehicle delays, and intersection sight distances. An adequate turn lane width, properly positioned in the intersection, with sufficient length is required to avoid sight restrictions and traffic blockage. The advent of dual and triple left-turn lanes has resulted in a number of special design considerations for these multiple turn lanes to ensure their full lane utilization.

The signal design for left-turn maneuvers can and does lead to inefficient signalization at many intersections. Left-turn movements are provided separate signal phases when they are not required, given more green time than needed, and frequently interfere with arterial street progression. The left-turn movement should be treated as a minor intersection maneuver and should be provided the minimum traffic control necessary to accommodate traffic without *unnecessarily* long delays and safety problems while adequately providing for the other major intersection through movements. The left-turn signal arrow indications are well understood by drivers. However, the change from arrow indications to other various signal indications for

permitted-exclusive left turns are not well understood by drivers. This problem is a combination of the signal head placement and the distinctive indication of a change in the traffic signal indicators. It is suggested that the signal not only have a change in the indications but also a change in color, head position, and mode of operation for the permitted left-turn signal phase.

Because the intersection traffic volumes, travel patterns, and operational characteristics are always changing, a widely accepted measure of effectiveness for left-turns and intersections is not available. The survey conducted for this Synthesis indicated that only 15 of the 69 responding agencies employ measures of effectiveness for left-turn operations. It is probable, however, that others do have such measures, but do not have a formal process for evaluation, and therefore responded negatively. A variety of situations, such as long queues in the left-turn lanes or increases in left-turn related accidents can trigger public concerns for improvements to left-turning movements. Reliable performance measures are needed to evaluate the intersection operations, tune the intersection traffic control, and maintain the efficiency and effectiveness of the intersection. A number of standard traffic operational measurements are suggested as performance measures. Several computer software packages also provide the means to analyze intersection operations and provide projections of operational characteristics under various traffic volume considerations.

It is generally believed that the left turn is one of the most difficult maneuvers for older drivers. They must slow down in traffic and select a gap in the opposing traffic while avoiding other vehicles, bicycles, and pedestrians. The physical limitations of some older drivers make left-turn maneuvers a stressful situation. It has been recommended that left-turn storage lanes be provided for older drivers to safely wait for adequate gaps at high-volume locations. At high-volume signalized intersections, they may need an exclusive signal phase to provide a protected left-turn movement. These drivers also experience difficulty in watching the left-turn signal, opposing traffic, and pedestrians, requiring them to move their heads and refocus on moving traffic. A far-left traffic signal indication has been suggested for those high-volume intersections frequented by older drivers so that the signal and conflicting traffic is in their field of view at all times.

Some transportation agencies have been very innovative in their designs to provide for left-turn maneuvers. These have included a number of left-turn relocation concepts to provide indirect left turns outside the primary intersections. New York has developed a concept for a continuous flow intersection using only a two-phase traffic signal operation. Heavy bicycle traffic and light rail/transit operations impose additional intersection left-turn requirements that need special consideration. While there is continuing research on left-turn treatments, this Synthesis indicates needs in the areas of traffic control to assist older drivers, increased safety considerations, added performance measures, and standardization of traffic signal phasing.

CHAPTER ONE

INTRODUCTION

PROBLEM

The problem of left turns at intersections has existed since the days of horse-drawn vehicles. It has been normal practice for left-turning vehicles to stop and yield to oncoming traffic and pedestrians. This practice results in delay for following vehicles when there are no additional lanes to accommodate left-turning vehicles or those that follow. As the intersection traffic volumes increase so that traffic signals are required, left-turning vehicles continue to constitute a problem even though turning lanes are provided for the intersection. The left-turn vehicles are frequently unable to find acceptable gaps in opposing traffic to make left turns and accordingly, must be afforded a separate signal phase. The signal green time allocated for left turns can reduce the green time available for heavier-volume through traffic movements. Accommodating left turns at intersections is a progressive improvement process from a situation of no provisions for the left turn, to a special lane to store left-turning vehicles, to special traffic signal phasing for left-turning as well as other intersection traffic. The traffic engineering profession has applied a variety of operational concepts to accommodate left-turning vehicles without unduly delaying the higher-volume intersection through traffic.

It has been said that the greatest challenge of the driving task is to make a left turn at a busy urban intersection (*1*). Drivers turning left must check for opposing traffic, pedestrians, and clearance at the intersection all at the same time. A driver must select acceptable gaps in traffic while relying on the other traffic to remain stationary, continue on a specific course, or take action to avoid a conflict. This is a dynamic situation with a changing traffic pattern requiring drivers to attend to the vehicle operations, make several judgments in a short time frame, and execute a turning maneuver while avoiding a collision with other vehicles and pedestrians. It is not unexpected that older drivers experience some difficulty with this particular turning maneuver. Figure 1 reflects the involvement of left turns as the first harmful event for older drivers in Pennsylvania (*2*). The problem can be alleviated by providing turn lanes and traffic signals to separate the driving decisions and provide time to make the appropriate judgments on safe opportunities for left turns.

Currently, as noted by Hauer (*3*), there is no authoritative guidance on the conditions under which left-turn lanes should be built. Many jurisdictions have adopted guidelines to help in the selection of left-turn treatments for their jurisdictions that attempt to accommodate the local conditions and variations. Mr. Hauer has noted the need to provide a clear procedure for the practitioner to determine quantitative descriptions of the situation, as well as how to make a rational decision on the basis of local conditions. Where available, the rationale for various applications and research data that support left-turn treatments is provided in this synthesis. It should be noted that there is not unanimity on the appropriate methods to handle left turns. An attempt is made to report known methods and procedures so choices can be made on the appropriate methods, procedures, and design details.

GENERAL CONSIDERATIONS

The treatment of left turns at intersections has developed over the years from various practices that have been used successfully to accommodate left-turning vehicles. The need to handle large volumes of vehicles at intersections with the multitude of conflicts between various vehicle maneuvers has resulted in several principles of channelization that are generally considered for intersection design (*4*). The treatment of left turns at intersections is a direct consideration of several of those principles:

- Undesirable movements should be discouraged or prohibited—In some cases, it may be desirable to install islands or barriers that prohibit left turns at intersections or limit the number of turns.
- Desirable vehicular paths should be clearly defined, safe vehicle speeds encouraged, and points of conflict separated—The design of a separate left-turn lane meets these principles.
- High-priority traffic movements and desired traffic control scheme should be facilitated, stopped or slow vehicles removed from high-speed traffic streams—The separate left-turn lane relocates left-turning traffic and provides an opportunity to control left turns.
- Safe refuge provided for pedestrians and other nonmotor vehicle users—The design of a median island and left-turn lane can provide a refuge for nonmotorized users in the middle of a wide intersection.

Items to be reviewed in applying these channelization principles are the number of left-turning vehicles at an intersection, the number of through vehicles delayed by left-turning vehicles, the number of left-turn vehicle conflicts that result in accidents, and the need to separate the left-turn movement into a discrete lane for special traffic control now or in the future.

OVERALL APPROACH AND METHODOLOGY

For this synthesis, a literature search was conducted relative to left-turn treatments at intersections. No attempt was

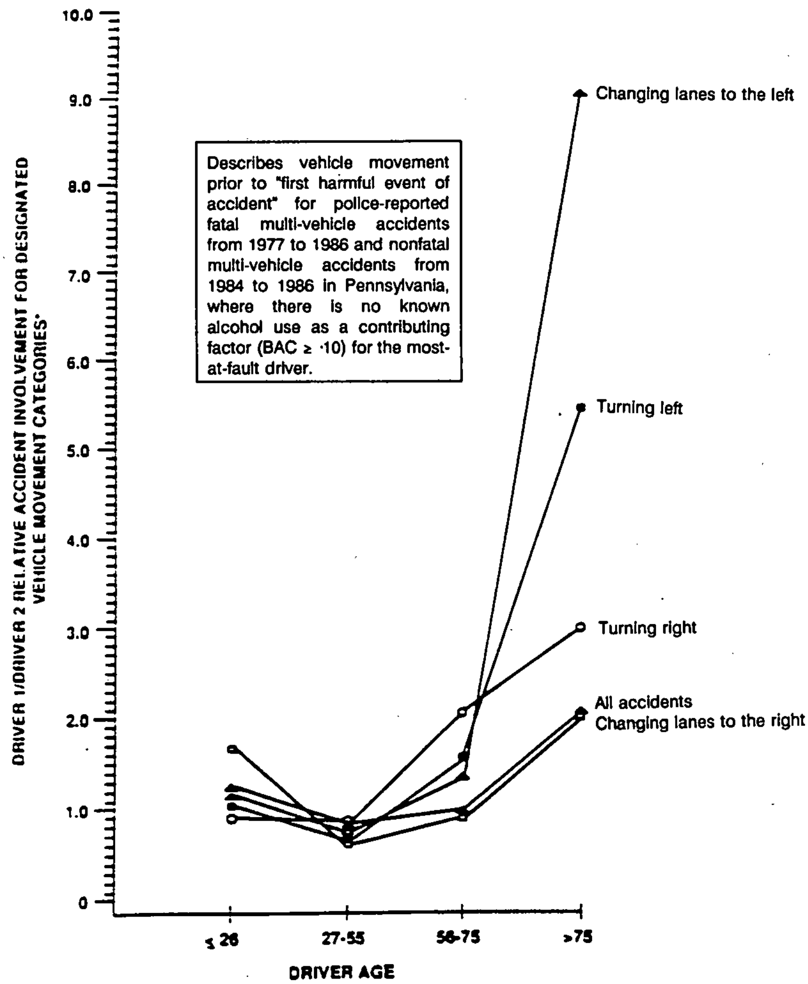


FIGURE 1 Driver accident involvement vs driver age *(2)*.

made to reference all the material that is available on the subject, only the latest and most up-to-date information has been included so that the synthesis reflects the state of the practice on intersection left-turn treatments. Where there are duplicated references in a specific subject area, the references are made first to the authoritative guidelines and second to what appear to be the most useful references on the subject.

A questionnaire, entitled Left-Turn Treatments at Intersections, was mailed to the member states of the American Association of State Highway and Transportation Officials (AASHTO) and to 75 selected cities, counties, and provinces in the United States and Canada. Responses to the questionnaire were received from 33 states, 36 cities and counties, and one province. The questionnaire requested agency response on design, traffic control devices, traffic signals, performance measures, special users and special applications. A copy of the questionnaire is in Appendix A and a summary of the responses is in Appendix B. References are made to the questionnaire responses as appropriate in the text.

AUTHORITATIVE GUIDELINES

The widespread application of left-turn treatments on all road systems and the need for some uniformity to assist the public has resulted in several authoritative publications that address the subject. These publications are also generally recognized by the transportation profession as authoritative sources developed from available research, intersection operational experience, and engineering judgment. It is also understood that these publications generally provide suggested guidelines and are not to be construed as mandatory requirements to be applied unconditionally without consideration of the intersection geometrics and traffic characteristics. The general purpose and application of each of the publications are addressed below.

Manual on Uniform Traffic Control Devices for Streets and Highways (*5*)

This publication, hereinafter referred to as the MUTCD, has been adopted as the national standard for traffic control devices in the United States. Each state has legal provisions for the adoption of the MUTCD or a state manual in substantial conformance with the national MUTCD for application on all the public roadways in that state. In the *Code of Federal Regulations,* Title 23-Highways, Subpart F-Traffic Control Devices on Federal-Aid and other Streets and Highways, Article

655.603-Standards indicates, "The MUTCD, approved by the Federal Highway Administration, is the national standard for all traffic control devices on any street, highway, or bicycle trail open to public travel." Therefore, the MUTCD or the specific state manual should be used as a basic resource for traffic control devices as they relate to left-turn maneuvers. The MUTCD covers the design and application of traffic control signs, pavement markings, traffic signal installations, and traffic islands. The details of these devices are addressed specifically in subsequent chapters of this synthesis.

The MUTCD guidelines for traffic control devices describes the requirements for the devices as either mandatory, "*shall;*" advisory, "*should;*" or permissive, "*may.*" Additionally, it is specified that the decision to install a traffic control device is a matter of engineering judgment and that the MUTCD is not a legal requirement to install any device. However, if the decision is made to install a traffic control device, then the device must comply with the provisions of the MUTCD subject to the mandatory, advisory, or permissive requirements.

The MUTCD is currently being rewritten by the National Committee on Uniform Traffic Control Devices for consideration and adoption by the Federal Highway Administration (FHWA) and individual states as a revised standard. This new edition will involve a complete rewrite of the current MUTCD with a new format. The manual text will be separated into individual paragraphs addressing the **STANDARD-SHALL,** *GUIDANCE-SHOULD,* and OPTION-MAY requirements with supporting information covered separately. This will make the provisions of the manual easier to interpret as to required, recommended, or optional applications. Additionally, the current part on traffic islands is being deleted because it has been determined that a traffic island is not a traffic control device, island provisions are more extensively covered in other publications, and there is no intent to infer that specific traffic island provisions are requirements.

Highway Capacity Manual (6)

TRB Special Report 209: The Highway Capacity Manual, Third Edition, 1994, provides the methodology for estimating the maximum number of people or vehicles that can be accommodated by a given facility in reasonable safety within a specified time period. The HCM represents more than 60 years of research and experience in quantifying the capacity of roadways and intersections to handle traffic. Recognizing that intersection left turns block and delay other intersection traffic, the application of the HCM provides a basis to compute the capability of the intersection to handle the traffic and the best alternatives for left-turn treatment. Additionally, computer software has been developed that readily permits the iterative calculation of intersection capacity so that various left-turn treatments can be tested for the best intersection capacity results. The HCM includes applicable research from other countries and is generally recognized as one of the authoritative resources on intersection capacity. The HCM has been updated with a revised analysis of left-turn treatments to provide a realistic procedure for determining intersection capacity.

A Policy on Geometric Design of Highways and Streets (7)

This publication, hereinafter referred to as the AASHTO Green Book, has been updated on a regular basis by AASHTO to reflect established practices and recent research on geometric design. The AASHTO Green Book provides guidelines for geometric design of projects for the improvement of roadways. The fact that new design values are presented does not imply that existing streets and highways are unsafe nor does it mandate a need to initiate an improvement project. The intent of these geometric design policies is to provide guidance to the designer by referencing a recommended range of values for critical dimensions with sufficient flexibility to encourage independent design tailored to particular situations.

The AASHTO Green Book provides guidance for the traffic lanes on various types of roadways with recommendations on turn lane dimensions. Design details for islands, medians, and channelization are provided, as are sight distances and turn lane lengths. As noted in the synthesis questionnaire, 70 percent of the state responses and 62 percent of the city and county replies indicate that they use this publication as their guidelines for turn lane design.

Uniform Vehicle Code (8)

The *Uniform Vehicle Code* (UVC) is a specimen set of motor vehicle laws, designed and advanced as a comprehensive guide for state motor vehicle and traffic laws. It is based on actual experience under various state laws throughout the nation and reflects the need for uniformity in traffic regulation. The UVC is reviewed periodically by the National Committee on Uniform Traffic Laws and Ordinances, an independent, nonprofit, voluntary association and is revised where warranted by new developments in state and federal laws and by practical experience. Certain portions of the UVC set forth rules of the road: the things that people must do as they drive and walk. Universal traffic law wording makes the decisions for drivers, designers, enforcement agencies, judges, and educators easier because everyone is making the same interpretation and application for regulation and operation of the roadway network.

NEED FOR CONSISTENCY

Adjacent Intersections

The driving task depends on the road user receiving and processing information on which to base driving decisions to control the vehicle. The driving task can become very complex and demanding at intersections, especially in urban areas. By providing drivers a pattern of intersection geometrics and traffic control that is familiar, easily recognized, and consistent along the roadway, the driving task can be simplified. A special intersection design requires drivers to use additional time to recognize that the design and operations may not be consistent with other intersections, decreasing the time available for other driving decisions.

Rural and Urban Intersections

The need for consistency exists whether the intersection is rural or urban. The urban intersection is characterized by many vehicles, a variety of turning vehicles, pedestrians, and bicyclists resulting in potential for many vehicle conflicts. The rural intersection may have lower traffic volume, but will have higher vehicle speeds requiring that driving decisions be made in a shorter time frame. Because of the higher rural speeds, the need for intersection approach sight distance becomes more important to provide drivers the opportunity to identify the intersection, diagnose the operational features, and make the appropriate driving decisions.

STANDARDIZATION PHILOSOPHY

It is generally accepted that standards for roadway design, including left-turn treatments, are preferable because consistent use provides a pattern of roadway features that the road user readily recognizes with an immediate and appropriate response. As a result, organizations such as AASHTO and FHWA develop and promote national standards and guidelines for roadway design and traffic control devices. These guidelines represent a consensus of accepted practice used to design the roadway for specific traffic characteristics with consistent regulation, warning, and guidance of traffic. The uniformity of design simplifies the driving task for the motorist and aids in the consistent interpretation of proper driving activities by enforcement officials. However, it should be recognized that the same guidelines cannot always be applied totally to all roadway situations and that they must be adaptable to the geometric features and traffic characteristics at any given site.

ORGANIZATION OF SYNTHESIS

This synthesis is organized along the normal sequence of decisions that must be made relative to left-turn treatments at intersections. The first subject addressed is the basic considerations that must be made relative to left-turn requirements. Chapter 2 provides guidelines on the need for special left-turn lanes and problems that a turn lane may solve. Chapter 3 discusses the traffic studies and design considerations for a left-turn lane. The appropriate signing and pavement markings are covered in Chapter 4. A number of traffic signal phasing, timing, and signal displays have been used for left-turn lanes, these are reviewed in Chapter 5. Chapter 6 provides information and guidelines on performance measures for left-turn lanes. Special applications relative to turn lanes such as prohibition, relocation, and other controls are covered in Chapter 7. The results of a questionnaire to the 50 member AASHTO states and 75 selected cities and counties are contained in Appendix B.

TERMINOLOGY AND DEFINITIONS

This synthesis includes various terminology commonly used throughout the transporation community to describe terms related to left turns at intersections. Most of the terms have developed through usage and application to describe various functions, activities or traffic control features. In several cases, the terms have been modified to provide a clearer descriptive understanding of the terminology. Both the old and new terms are referenced in the synthesis to clarify any misunderstanding of the appropriate usage and application of the term.

The scope of the synthesis encompasses all items relating to left-turn maneuvers, including specific left-turn lanes, traffic control signs, pavement markings, and traffic signals. The term, left-turn treatments, relates not only to the provision for left-turn features, but also to the absence thereof—relocation or prohibition of left turns—which are also considered treatments.

The synthesis addresses criteria for left-turn features as either warrants, standards, practices, policy guidelines, or criteria somewhat interchangeably without religious adherence to the legal definition of these terms. It is not inferred through the use of one of the above specific terms that something is required or recommended by its reference in the synthesis. If there is a question on the feature requirements, then the cited reference should be consulted for specific wording with legal interpretation requested on application requirements.

The terminology and definitions in the synthesis are explained and defined when they are first used in the synthesis.

A number of acronyms are regularly used in transportation publications to abbreviate longer descriptive phrases of organizations, terminology, or traffic related items. The acronyms are cited on their first usage with subsequent reference made only to the acronym. A listing of the acronyms and abbreviations used in the synthesis is included after the references.

CHAPTER TWO

BASIC CONSIDERATIONS

LEFT-TURN REQUIREMENTS

Function and Setting

The quantity of left-turning traffic at an intersection, a minor portion of the total intersection traffic, usually has the largest impact on the intersection operations. A left-turning vehicle must slow down and wait for a gap in the opposing traffic, which impedes the following vehicles. As opposing traffic and pedestrian volumes increase, gaps in opposing traffic become fewer, resulting in a longer delay to make a left turn and greater impedance for the through vehicles waiting behind the left-turning vehicle. A relatively few left-turning vehicles can essentially block an intersection when there are inadequate gaps in traffic for left turns and insufficient traffic lanes. For urban intersections, the need for left-turn lanes is usually based on traffic volumes, turning vehicles, opposing traffic, safety, and unacceptable delays for the intersection through traffic.

Rural roadways usually have lower traffic volumes so left turns have fewer conflicts with other vehicles. An analysis by Hoban (*9*) indicates that there is relatively no delay on rural two-lane highways below 400 vehicles per hour (vph) in both directions but delay increases significantly for volumes above 1,200 vph (Figure 2). However, the rural setting may have higher vehicle operating speeds, which requires a longer traffic gap for left turns and which may create greater accident potential because of speed differentials with a stopped left-turn vehicle. Therefore, the need for a left-turn lane in rural areas should be based more on safety considerations than on traffic volumes.

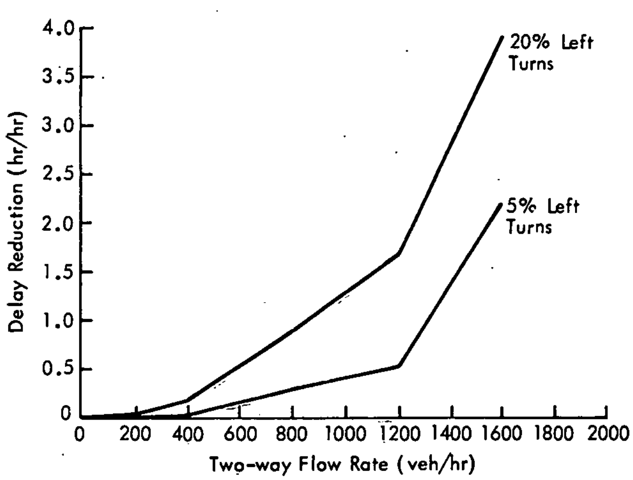


FIGURE 2 Delay savings with turn lanes, two-lane rural highways. (9)

Upgrading an intersection to provide more traffic lanes will temporarily accommodate the left-turning traffic, but may not be the best long-range solution. A traffic lane that is shared by both left-turning traffic and through traffic will not function efficiently because one turning vehicle can unnecessarily delay several through vehicles. Therefore, a need for additional traffic lanes at an intersection should also include strong consideration of left-turn lanes. Additionally, a left-turn lane provides the opportunity to accommodate turning vehicles without unnecessarily penalizing the total intersection traffic.

Traffic Studies

The initial phase for determining appropriate left-turn treatment at intersections is to know and understand the number and impact of left-turning vehicles at the intersection. One of the most important traffic studies is an initial field review of the intersection operation to determine the nature of the left turn problems and potential data collection needs to support intersection geometric and operational improvements. This requires a complete intersection volume count, including turning movements and distribution of traffic in the peak hour and nonpeak periods. It should be recognized that the directional distribution of traffic may cause variable left-turn impacts during the day because of peak hour traffic movements to and from work or other major traffic generators. It is desirable to have some vehicle classification data because larger vehicles, such as semi-trucks and buses, require a larger vehicle turning radius and longer gaps in traffic to complete a left turn. The variation in traffic speeds on the roadway should be known as this differential influences design considerations and the safety impacts of a stopped left-turning vehicle. The projected traffic growth and planned land development in the vicinity of the intersection should be considered so that any left-turn improvements will accommodate future traffic as well as expected changes in the intersection traffic patterns. More extensive traffic studies can include the vehicle queuing characteristics and intersection delays because of inadequate left-turn features. The Institute of Transportation Engineers (ITE) *Manual on Traffic Engineering Studies* (*10*) is a source for detailed study information and guidelines.

Roadway Geometrics

Roadway geometrics influence the impacts of vehicle left turns and dictate the need for left-turn treatments at intersections. A basic two-lane, two-way roadway includes no provisions for left-turning traffic. The left-turning vehicle must stop and wait in the traffic lane until there is an adequate gap in opposing traffic to complete the left turn. As a result, the left-turning vehicle delays all vehicles approaching from behind until the turn maneuver is completed. The safety hazard of a stopped left-turn vehicle in a traffic lane is increased on a higher speed roadway or where there are sight distance restrictions on the intersection approach. A multi-lane approach to the intersection can partially solve some of these problems because there is an additional lane to bypass the turning vehicle on the right. There are other problems, however, because of delay to traffic in that lane, the speed differential between vehicles, and the required lane changing to bypass the turning vehicle. If intersection improvements are feasible, then the provision for a left-turn lane at the intersection will avoid the problems noted above.

Human Factors

The left-turn maneuver is one of the most challenging driving tasks because of the need to direct the vehicle to a different travel path while making multiple decisions relative to speed, available space and time to make the left turn, and avoidance of conflicts with other vehicles and pedestrians within the intersection. This maneuver is particularly difficult for older drivers as illustrated in Figure 1 and as noted by Staplin and Lyles (2) because older drivers may have problems in judging time-to-collision and acceptable gaps, and these limitations may be exacerbated by a slower response and acceleration rate. Providing left-turn lanes and appropriate traffic control at an intersection separates the driving decisions and provides a better opportunity for drivers to cope with other intersection traffic. A left-turn lane provides roadway space for drivers to decelerate and stop, once they have made the decision to make a left turn. In the 1970s, Alexander and Lunenfeld developed the concept of positive guidance to improve the design and placement of driver information to simplify the driving task. They presented the following principles of information and guidance (*11*):

Primacy—The most important information should be presented to the driver when and where it is needed and nonessential information should be relocated.

Spreading—The information required by the driver is spread over space to reduce the driver information load.

Coding—Possible pieces of information are organized based on color, shape, and location to provide additional driver clues on the information content.

Redundancy—The same thing should be said in more than one way to provide several opportunities for the driver to obtain the information.

A left-turn lane facilitates the positive guidance principle of spreading information over time and space, thereby reducing the multiple decisions that a driver must make to negotiate an intersection. The driver can move into the left-turn lane and then wait in relative safety while making a decision on acceptable gaps in opposing traffic and appropriate time to complete the left turn avoiding other vehicles and pedestrians in the intersection. This also satisfies the positive guidance principle of primacy in that the driver does not have to make these decisions until safely stopped at the intersection. The left-turn lane by its design and visual appearance meets the guidance principle of coding in that the driver readily recognizes the left-turn lane and understands the appropriate vehicle maneuver to use the lane. Information redundancy is provided by the combination of pavement markings, signing, and traffic signal indications that duplicate the left-turn messages.

Left-turn lanes on major roadways and at major intersections are expected by drivers, as noted by several responses to the survey (Appendix B). A number of jurisdictions indicated that it was their practice to construct left-turn lanes with intersection improvements because they are expected by the public. One of the components of human factors is driver expectancy, wherein drivers expect certain roadway features based on their driving experience. When these features are not provided or are provided in different variations, the driver's expectancy is violated with resulting hesitation, frustration, and improper driving maneuvers. At a busy intersection, an inappropriate decision by a driver or an improper driving maneuver can result in a safety problem.

TYPES OF LEFT-TURN TREATMENT

Prohibition

The prohibition of the left-turn maneuver is a possible treatment if left-turn volumes are low, if the left-turn vehicle can be diverted to other routes, and if other treatments are not cost-effective. The prohibition can be implemented with regulatory traffic control signs but a traffic island or median channelization is usually a more effective restriction.

Geometric Features

Shared Lane

The basic two-lane, two-way roadway makes no provision for left turns, resulting in left turns being made from the through traffic lane, which must also accommodate all other maneuvers. Hence, this type is usually described as a shared lane, because all intersection maneuvers must share the same lane. A shared lane concept also exists between the left-turn and through traffic lanes for multiple lane roadways where a separate turn lane is not provided for the left-turn maneuver. Shared lane operations are illustrated in Figure 3. The initial through vehicles can proceed unimpeded, the left turn must wait for a gap in opposing traffic, and the following through vehicles are delayed by the left turn. A shared left turn can be operated both with and without intersection signalization. The signal operation and timing must accommodate the shared lane for left turns and other maneuvers. Short signal cycles are preferable for shared lane situations because they reduce the effect of left-turn blockage and allow two or more left-turn vehicles to sneak through on the yellow signal change interval.

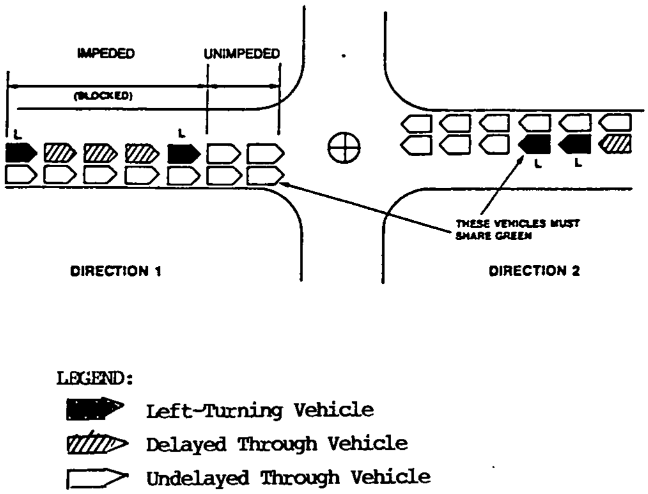


FIGURE 3 Interstate operations—shared traffic lane. *(12)*

Left-Turn Lane

A left-turn lane can be provided at an intersection between the opposing traffic movements to store the left-turn vehicles. This can be accomplished by widening the roadway through the intersection to provide an additional lane for left turns or by including the left-turn lane in the median area of divided roadways. The left-turn lane can be delineated with pavement markings, raised and curbed traffic islands, or depressed median areas. An intersection left-turn lane can also be transitioned with pavement markings from a one-lane, two-way, center left-turn lane into a one-way turn lane for the intersection. Multiple turn lanes are now frequently used; double left-turn lanes are common practice and triple left-turn lanes are used by some jurisdictions. It was noted by Mitchell in a 1993 presentation to the ITE District 6 Annual Meeting *(13)*, that his review of 30 triple left-turn locations in the San Fransico Bay area disclosed no noticeable degree of confusion, surprise, or uncertainty and found that the lanes were used in an orderly and consistent manner with no extraordinary accident patterns.

Traffic Control

Passive Control

The passive control of left turns involves no signalized control of the left-turn maneuver but requires drivers to yield to opposing traffic. The left-turn maneuver is made when the driver determines that there is an adequate gap in the opposing traffic to safely make the left turn at the intersection. This type of control works satisfactorily when the traffic volumes and speeds are low, there is good visibility, and there are adequate gaps in the traffic to accommodate the left turn without undue vehicle delays. A separate left-turn lane does provide left-turning traffic an opportunity to wait for an adequate gap in traffic in relative safety without delaying through traffic.

Time-of-Day Left Turn Prohibition

The partially restrictive control, part-time left turn prohibition, is used at some urban intersections, normally for shared traffic lanes or high-volume locations, to restrict left-turn maneuvers during specific hours of the day, such as peak hours. The restriction is posted as an intersection sign prohibiting left turns at specific times. The National Committee on Uniform Traffic Control Devices considers the most effective signing to be changeable message signs that change legends to display the turn prohibition during restricted periods.

Signalized Control

Traffic signal installations include traffic signal control of the left-turn maneuver as part of the intersection traffic control. The traffic signal controls all of the intersection traffic and may provide a timed period so that left turns can be made when there are not natural gaps in traffic to safely make the left-turn maneuver. Traffic signal applications, including exclusive, permitted, and exclusive/permitted left-turn signal control, are covered in more detail in Chapter 5.

USERS

Vehicles

The characteristics of vehicles making left-turn maneuvers will impact the need for left-turn treatment and the design of the intersection. An automobile normally requires a gap of at least 5.0 seconds *(6)* in the opposing traffic stream to initiate and complete a left turn, whereas a large commercial vehicle will need a longer gap. Accordingly, the left-turning vehicle will require adequate sight distance to make the left turn. If adequate sight distance is not available, then the left turn and opposing traffic must be controlled by signalization or the left turn must be prohibited.

The size of vehicle and its turning radius must also be considered in the left turn and intersection design. These considerations are addressed in Chapter 3.

Pedestrians

Provisions for pedestrian movement across major streets should be an initial consideration in intersection delay. The number of pedestrians using the intersection impedes the left-turn movement since the left-turning vehicle must yield to pedestrians using the crosswalks. For wider streets, traffic islands or wide median areas can be provided for pedestrian refuge, which reduces the vehicle-pedestrian conflict.

CAPACITY

The capacity of an intersection is determined by the number of approach traffic lanes including whether separate left-turn lanes are provided. Where a left-turn maneuver shares a lane with the through traffic, the left-turning traffic can be blocked by opposing traffic and the left turns can delay through traffic behind the left turn. The 1994 HCM (*6*) provides an analysis procedure to determine left-turn lane capacity for shared or separate turn lanes and uncontrolled stop or signalized intersections. The HCM also provides improved analysis procedures for left-turn treatments, recognizing permitted and protected-permitted left turns, correcting some of the past concerns for left turn analysis. The HCM should be consulted for the methodology and procedures to accommodate left-turn treatments and determine intersection capacity. This new HCM, however, does not provide realistic results when analyzing intersections with heavily oversaturated conditions. The traffic signal timing optimization models reviewed in Chapter 5 provide better capacity analysis results for oversaturation conditions.

SAFETY

The occurrence of accidents is frequently a basis for providing a left-turn treatment at an intersection. An evaluation by the Ohio Department of Transportation (*14*) in 1973, Figure 4, found that left-turn lanes reduced the accidents at both signalized and unsignalized intersections. A more recent study in Nebraska (*15*) researched the accident patterns for left-turn lanes on four-lane urban roadways. Left-turn lanes were effective in reducing rear-end, sideswipe same direction, and left-turn accidents on urban four-lane highways with design hour volumes (DHV) between 600 and 1,800 vph with cross traffic average daily traffic (ADT) above 1,000 vpd. However, they also found that the left-turn lanes on the uncontrolled approaches of urban four-lane highways resulted in an increase in right-angle accidents, representing a tradeoff with the left-turn accident reduction.

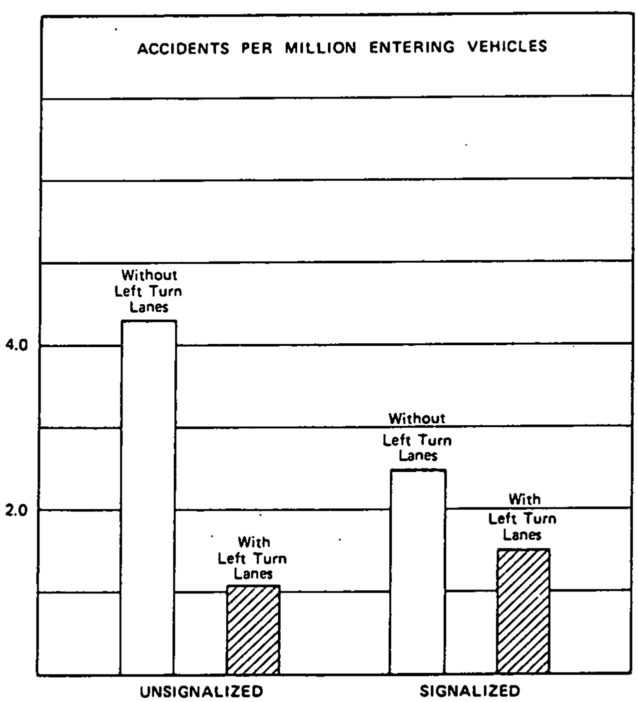


FIGURE 4 Effect of left-turn lanes on accident rates at intersections. (*14*)

A recent study of pedestrian accidents (*16*) found that 65-year old or older pedestrians are overly represented in fatal crashes in which a left-turning vehicle struck a pedestrian. This type of collision occurred in 5.4 percent of the fatal collisions in the United States involving pedestrians over 65 but in only 0.7 percent of the cases involving pedestrians under 45 years of age. It is important to consider pedestrian signals, signal phasing, and adequate pedestrian clearance times to mitigate this problem because of slower walking speeds.

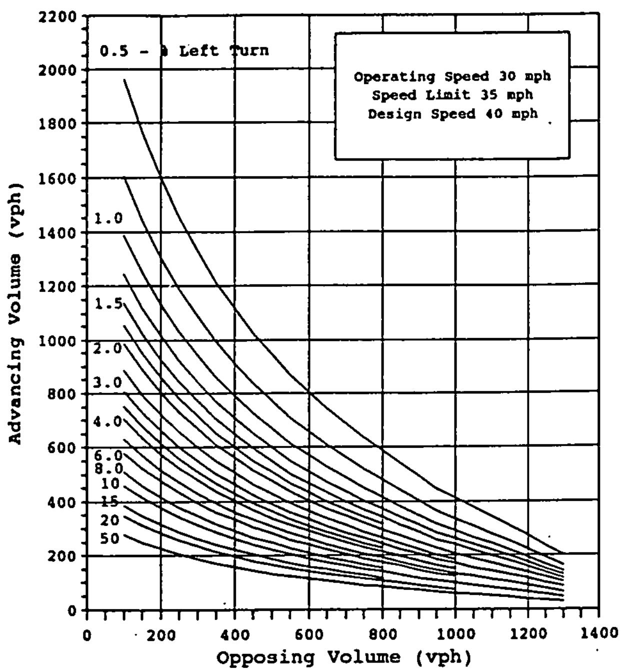
LEFT-TURN TREATMENT GUIDELINES

The majority of states (72 percent) and local jurisdictions (62 percent) that responded to the survey indicated that they use the AASHTO Green Book (*7*) for determining left-turn lane requirements. The AASHTO Green Book, Table 1, indicates that left-turn lanes should be established on roadways where traffic volumes are high enough or safety considerations are sufficient to justify left-turn treatment.

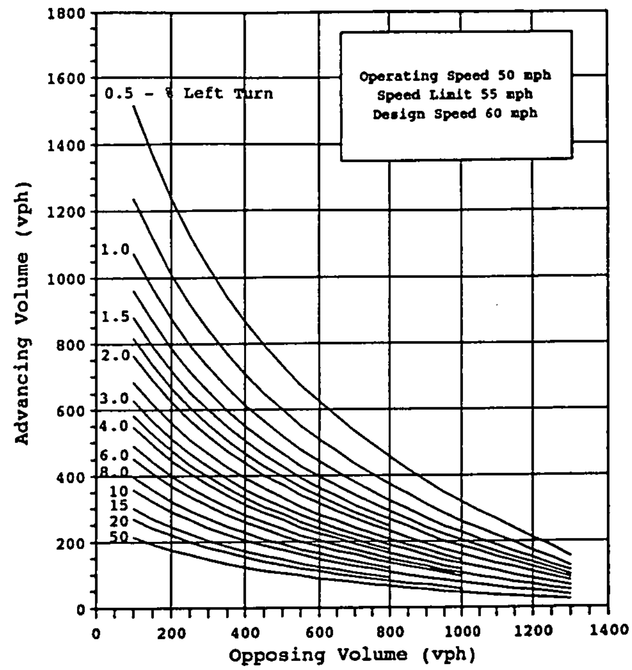
TABLE 1

AASHTO GUIDE FOR LEFT-TURN LANES ON TWO-LANE HIGHWAYS

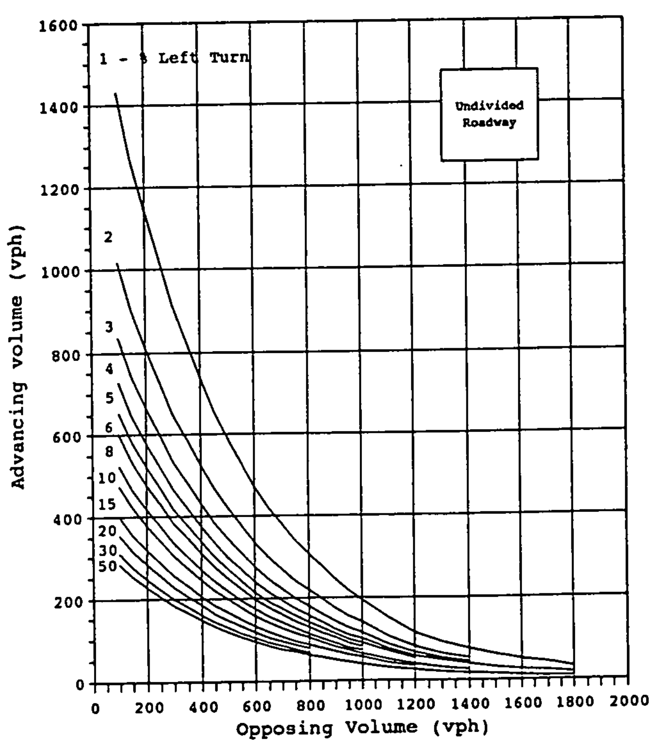
Opposing Volume	Advancing Volume 5% Left Turns	10% Left Turns	20% Left Turns	30% Left Turns
	40-mph Operating Speed			
800	330	240	180	160
600	410	305	225	200
400	510	330	275	245
200	640	470	350	305
100	720	515	390	340
	50-mph Operating Speed			
800	280	210	165	135
600	350	260	195	170
400	430	320	240	210
200	550	400	300	270
100	615	445	335	295
	60-mph Operating Speed			
800	230	170	125	115
600	290	210	160	140
400	365	270	200	175
200	450	330	250	215
100	505	370	275	240



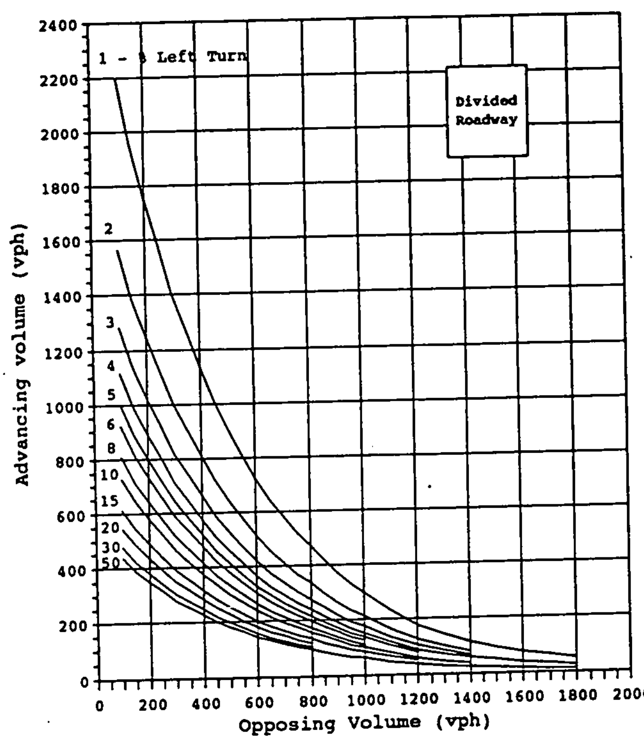
Guidelines for Left-turn Lane at Unsignalized Intersection - Two-lane Roadway



Guidelines for Left-turn Lane at Unsignalized Intersection - Two-lane Roadway



Guidelines for Left-turn Lane at Unsignalized Intersection - Four-lane, Undivided Roadway



Guidelines for Left-turn Lane at Unsignalized Intersection - Four-lane, Divided Roadway

FIGURE 5 ITE guidelines for left-turn lanes. *(18)*

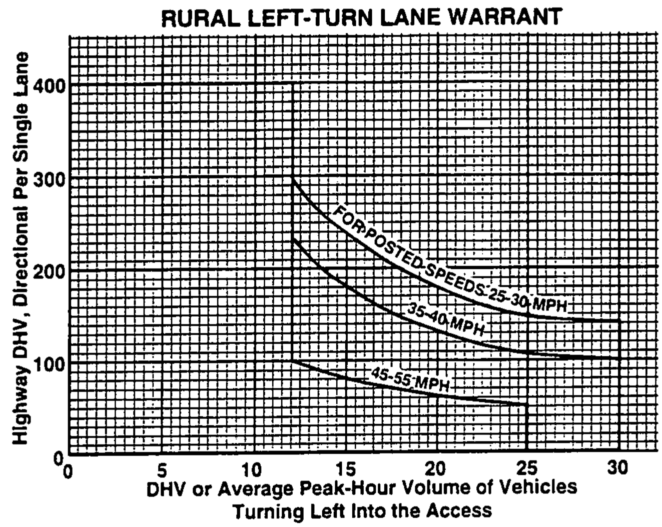


FIGURE 6 Idaho rural left-turn warrant. *(19)*

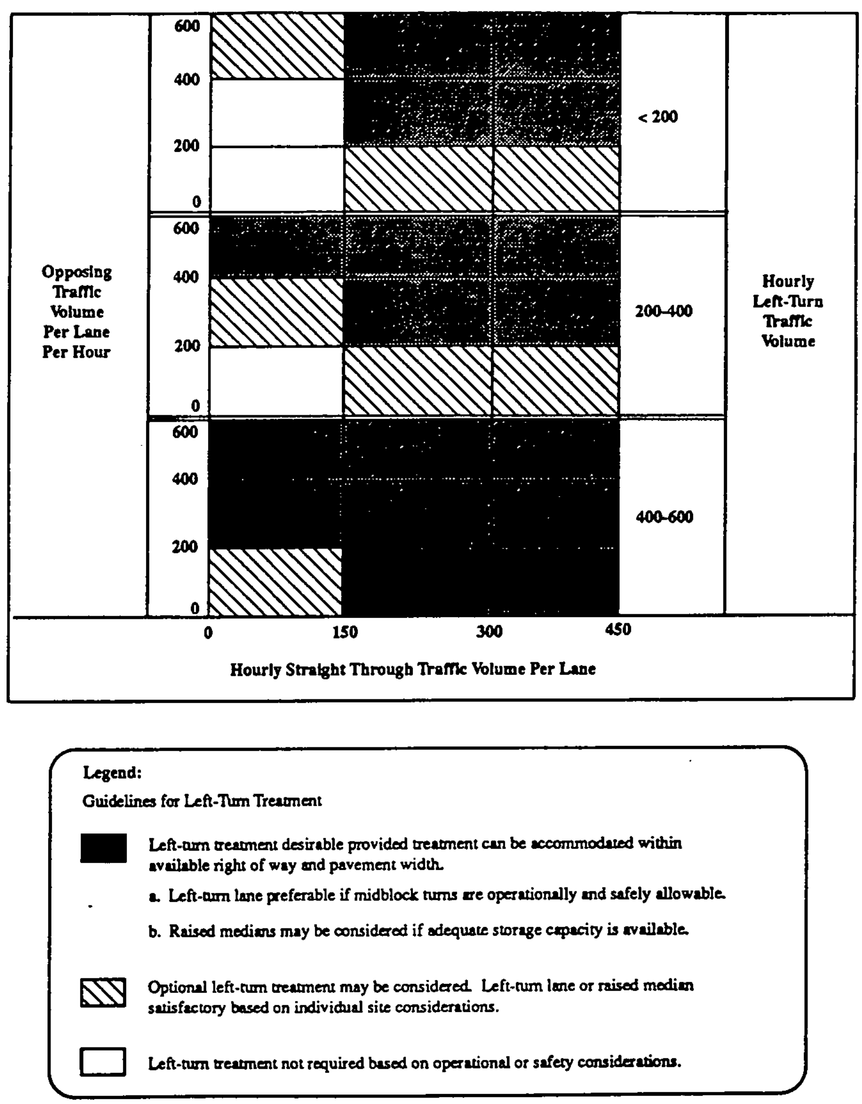


FIGURE 7 Guidelines for left-turn treatment, single isolated intersection. *(20)*

Using this table of AASHTO guidelines, a left-turn lane should be considered when, at 40 mph operating speed, with an opposing hourly volume of 800 vehicles, the advancing vehicle volume, composed of 5 percent left turns and 95 percent through vehicles, exceeds 330 vehicles per hour. The tables are the consolidation of Harmelink's graphs (*17*) developed in 1967 based on a queuing model with arrival and service times assumed to follow a negative exponential distribution. The Harmelink method was expanded in 1990 by ITE Committee 4A-22 (*18*) to provide guidelines for 30 mph operating speeds, two-lane roadway, four-lane undivided roadway, and four-lane divided roadway. Those graphic guidelines covering lower speeds and divided roadways are shown in Figure 5. The Idaho Transportation Department has developed the graphic in Figure 6 as a basic consideration for left-turn lanes with an engineering study required to analyze operating speeds, traffic volumes, sight distance, passing opportunities, number of anticipated turning movements, and accident history. The University of Texas at Austin (*20*) developed criteria for selection of a left-turn median design resulting in the graphic shown in Figure 7. Accidents are the major special consideration other than traffic volumes to justify a left-turn lane. Generally, three or four left-turn accidents per year per direction (not per intersection) is the critical number to justify a separate left-turn lane. Lalani (*21*) found in 1983 that the critical frequency of left-turn accidents was five in 1 year, seven in 2 years and nine accidents in a 3-year period. Several jurisdictions use the various computer analysis models to determine intersection delay as part of their analysis for left-turn treatment. In some jurisdictions, it is standard practice to provide left-turn lanes at all signalized intersections and at major intersections on arterials or intersections on rural expressways.

Multiple left-turn lanes are recommended by the HCM (*6*) when the left-turning volumes exceed 300 vph. The city of Las Vegas (*22*) recommends the consideration of triple left-turn lanes when the left-turning traffic exceeds 600 vph.

CHAPTER THREE

DESIGN

TRAFFIC STUDIES

Introduction

The design of a new intersection or redesign of an existing intersection to provide left-turn facilities requires data relative to the intersection and a full understanding of the intersection operations. It is desirable that any design considerations for the intersection be preceded by a field review. The field review, if made during a peak and an off-peak period, can identify some of the intersection operational problems and be a key to collecting the necessary intersection data. It is important to identify if there is a left-turn problem, the reason for the problem, and possible corrective measures that will be acceptable. The field observations will provide a visual understanding of left-turn delays, queue lengths, gaps in opposing traffic, traffic conflicts, number of large vehicles, bicycle usage, specific vehicle access requirements, and erratic driving behavior.

The AASHTO Green Book (7) suggests that intersection design closely fit the natural transitional paths and operating characteristics of the users with the four basic elements of Table 2 considered in the intersection design. These same elements also apply to intersection left-turn treatments. As noted, some of the data will only be collected through field observation of the road user characteristics while other data can be quantified for more specific analysis. It is necessary to have a condition diagram of the intersection and its approaches to show physical elements, dimensions, alignment, profile, and other features of the roadways and abutting properties. The number of vehicles by type, lane usage, and time period need to be recorded for capacity and intersection design requirements. The human factor elements are generally subjective but do provide some insight toward possible design features to acccommodate the road user or discourage undesirable movements.

TABLE 2

AASHTO BASIC ELEMENTS OF INTERSECTION DESIGN *(7)*

A. Human Factors
1. Driving habits
2. Ability to make decisions
3. Driver expectancy
4. Decision and reaction time
5. Conformance to natural paths of movement
6. Pedestrian use and habits

B. Traffic Considerations
1. Design and actual capacities
2. Design-hour turning movements
3. Size and operating characteristics of vehicles
4. Variety of movements (diverging, merging, weaving and crossing)
5. Vehicle speeds
6. Transit involvement
7. Accident experience

C. Physical Elements
1. Character and use of abutting property
2. Vertical alinements at the intersection
3. Sight distance
4. Angle of the intersection
5. Conflict area
6. Speed-change lanes
7. Geometric features
8. Traffic control devices
9. Lighting equipment
10. Safety features
11. Bicycle traffic

D. Economic Factors
1. Cost of improvements
2. Effects of controlling or limiting rights-of-way to abutting properties where channelization restricts or prohibits vehicular movements
3. Energy consumption

Capacity

The capacity analysis of an intersection can be performed for both signalized and unsignalized intersections recognizing various lane arrangements, left-turn treatments, and traffic control to determine levels of service for the intersection. The HCM may be consulted for the data requirements, analysis methodology, and procedures for intersection capacity determinations.

The capacity of two-way and all-way stop-controlled intersections measures level of service as a function of average total delay and also estimates queue lengths for minor approaches. It is assumed that left-turning vehicles yield to other traffic flows in the intersection and are required to select gaps in the opposing traffic. The capacity of a left-turn maneuver is based on distribution of gaps in the major traffic stream, driver judgment in selecting a gap through which to execute the turn, and follow-up time required by each driver in a queue. At all-way stop intersections, each intersection approach is analyzed relative to departure headways from the stop condition and saturation headways while waiting in a queue. The number of left-turning vehicles at an all-way stop intersection increases the saturation headways since a concurrent maneuver cannot always be made with the left-turning vehicle.

The capacity of signalized intersections can be determined through two methodologies, the operational and the planning analysis. The planning analysis provides an abbreviated method for level of service (delay) estimation based on known or projected traffic volumes, signalization, and geometric design. It relies on approximate input based on assumed default values that represent reasonable operating parameters. The required data provide options for exclusive or shared left-turn lanes and permitted or protected left-turn signal phasing but do not provide the detailed analysis of the operational method. The technique generates an intersection phasing and timing plan representing a reasonable approximation of the conditions that might be expected to occur with the given traffic volumes and intersection configuration, assuming that a reasonable and effective signal timing design is employed.

The primary methodology for capacity determination is the operational analysis. This methodology considers the full details of four components: demand or service flow rates, signalization, geometric design, and delay. There has been past concern that the capacity analysis methods are very complex for shared lane and permitted left-turn movements and do not provide a reasonable estimation of the intersection operational characteristics. The HCM has incorporated new methodologies and procedures that consitute a major change in the analysis of left-turn treatments with clarified instructions to remove ambiguities. The major changes noted by Strong (*23*) in the HCM, Chapter 9, Signalized Intersections, are as follows:

Progression Factor—Provides a new signal progression factor that reflects both field studies and theoretical modeling that can be applied to lane groups, including left turns.

Permitted Left Turn Factor—Provides a new permitted left-turn methodology that is expected to yield realistic results.

Defacto Left Turn Check—Uses a new procedure to determine the proportion of shared permitted left turners in the traffic lane and makes adjustments to the methodology accordingly.

Protected-Permitted Left Turn—Establishes a new methodology using actual signal timing to provide clear and precise procedures for calculating capacity, v/c ratios and delays for protected-permitted and permitted-protected left turn treatments.

Lane Utilization Factors (LUF)—The application of lane utilization factors to dual left-turn lanes is recommended with a field methodology provided to determine LUFs for analysis.

Critical Movement Definition—The definition clarifies how and where movement lost times should be applied in the analysis particularly for protected-permitted and lead or lag left-turn phasing.

The HCM provides the necessary worksheets and procedures for all the necessary intersection calculations but computerized versions of the computations are in universal practice. The computer software permits convenient evaluation of various intersection geometrics, signal timing, and signal phasing alternatives. Additionally, there is a variety of intersection and arterial street computer models available to analyze and evaluate intersection operations; these are addressed in Chapter 5.

Queue Analysis

The number of vehicles queued to make a left turn and the queue of vehicles waiting behind them are indications of the need for a separate left-turn lane. If a separate left-turn lane is provided, it does not necessarily mean that all the left-turning vehicles will be able to turn left without excessive delays. As the opposing traffic volumes increase, there are fewer gaps in the traffic stream for the left-turn maneuver. Also, as the delay to left-turn vehicles increases and the pressure of other queued left turns increases, drivers will attempt the left turn with shorter and shorter gaps, resulting in undesirable vehicle conflicts and potential accidents. At two- and four-way stop intersections, a left-turning vehicle will require added time to make the left turn because the turn cannot be made concurrently with the through movement. Therefore, the queue at a stop-controlled approach should consider the number of left turns as well as approach volumes. The same requirement exists at signalized intersections when a separate signal phase is not provided for the left-turn movement. It is necessary to review and analyze the left-turn queue at an intersection, whether signalized or not, to determine the reason for the vehicle delay and to determine what left-turn treatment is needed to accommodate the demand. The length of the left-turn queue also provides information on the length of the left-turn lane required to store the left-turning vehicles so they do not interfere with and delay through traffic.

Accident Analysis

A thorough analysis of the intersection accidents should be made at least for the past 12 months and preferably for 3 years of accident history. Rear-end and sideswipe accidents may occur if there is not a separate left-turn lane when left-turn vehicles decelerate rapidly to make the left turn, and the left-turn movement is unexpected by the through driver. A relatively few left-turn vehicles on a high-volume street can cause significant traffic disruption if there is not a separate turn lane because of the lane blockage and lane switching in advance of the blockage. The occurrence of vehicle collisions involving left-turning vehicles and opposing traffic may indicate a lack of adequate traffic gaps in the opposing traffic, too many left-turning vehicles for the available gaps, visibility restrictions, or speed problems. The appropriate corrective measure may be to provide a separate left-turn lane or a signal phase for the left-turn maneuver.

The installation of left-turn lanes usually will reduce intersection accidents. The California Department of Transportation obtained the safety effectiveness indicated in Table 3 by adding separate left-turn lanes at intersections (*4*). The accident benefits of installing either two-way, left-turn lanes or raised medians with left-turn lanes were reported in an earlier FHWA study in Tables 4 and 5 (*14*). Note that the data relate to accidents per mile of roadway because they were developed relative to roadway access control considerations and depict the benefits where access to adjoining businesses is restricted

TABLE 3

EFFECTIVENESS OF ADDING LEFT-TURN CHANNELIZATION, CALTRANS *(4)*

Addition of Channelization	Average Accident Reduction
At nonsignalized intersections	35% of all accidents
At signalized intersections	
With no left-turn phase	15% of all accidents
With left-turn phase	35% of all accidents
Two-way left-turn lanes (TWLTL)	25% of all accidents

TABLE 4

FHWA ESTIMATED ANNUAL ACCIDENT REDUCTION (PER MILE) BY INSTALLING RAISED MEDIAN DIVIDERS WITH LEFT-TURN DECELERATION LANES *(4)*

		Highway ADT (vehicles per day)		
Level of Development	Driveways per mile	Low <5,000	Medium 5–15,000	High >15,000
Low	<30	2.2	4.1	6.3
Medium	30–60	5.8	11.2	17.2
High	>60	10.7	20.7	31.2

SOURCE: FEDERAL HIGHWAY ADMINISTRATION, "Evaluation of Techniques for Control of Direct Access to Arterial Highways," Report FHWA-RD-76-86; Volume II, "Detailed Description of Access Control Techniques," Report No. FHWA-RD-76-87 (Washington, DC: U.S. Department of Transportation, Federal Highway Administration, August 1975).

TABLE 5

FHWA ESTIMATED ANNUAL ACCIDENT REDUCTION (PER MILE) BY INSTALLING TWO-WAY LEFT-TURN LANES FOR EACH DIRECTION OF TRAFFIC *(4)*

		Highway ADT (vehicles per day)		
Level of Development	Driveways per mile	Low <5,000	Medium 5–15,000	High >15,000
Low	<30	4.4	8.8	13.3
Medium	30–60	7.1	13.9	20.9
High	>60	9.7	19.0	28.6

SOURCE: FEDERAL HIGHWAY ADMINISTRATION, "Evaluation of Techniques for Control of Direct Access to Arterial Highways," Report FHWA-RD-76-86; Volume II, "Detailed Description of Access Control Techniques," Report No. FHWA-RD-76-87 (Washington, DC: U.S. Department of Transportation, Federal Highway Administration, August 1975).

by the raised median. A number of agencies have developed guidelines using the number of left-turn accidents per direction per year as a baseline for considering left-turn lane requirements. The recommendations of ITE Committee 4A-22 are that a left-turn lane should be considered under the following situations (*18*):

1. Unsignalized Intersections—four accidents per year
2. Signalized Intersection—five accidents per year.

These recommendations are based on a Kentucky study (*24*) that found a 99.5 percent probability of reducing accidents with left-turn lane provisions on the intersection approach at or above these numbers considering accidents involving the left-turning vehicle, rear-end, and sideswipe passing accidents with a left-turning vehicle.

General Guidelines

The following general guidelines are provided by *NCHRP Report 279: Intersection Channelization Guide,* (*4*) relative to left-turn lanes:

New Construction-Signalized Intersection

- Consider left-turn lanes at all new signalized intersections with analysis of capacity and phasing to accommodate left turns.
- Left-turn lanes are required if the left-turn volume exceeds 20 percent of the total approach volume or 100 vehicles during the peak hour.

New Construction-Unsignalized Intersection

- Consider left-turn lanes at all median crossovers on high-speed divided highways.
- Consider left-turn lanes on approaches where sight distance is limited.
- Left-turn lanes should be provided at all nonstopping approaches of rural arterials and collectors.
- Left-turn lanes should be provided on all other approaches where required based on capacity and operational analysis.

DESIGN CRITERIA

Width

The width of the median for an auxiliary (left-turn) lane should be a minimum of 10 ft, up to a desirable width of 20 ft, as recommended in the *ITE Guidelines for Urban Major Streets* (*25*). The 20-ft width provides a 12-ft travelway and an 8-ft median separating the left-turn traffic from opposing traffic. The minimum left-turn lane width can be 9 ft where there are restricted roadway widths and only minor truck usage of the lane is expected. However, this width should not apply to a two-way, left-turn lane. Truck and bus widths range from an AASHTO design vehicle width of 96 in. (8 ft) to a maximum of 102 in. (8.5 ft) and accordingly, intersections where trucks or buses are a significant proportion of the left-turn traffic require wider left-turn lanes. A 10-ft lane width should be considered as the minimum width if trucks or buses are regular users of the left-turn lane and may not be adequate for two-way, left-turn lanes.

Length

The length of the left-turn lane has three components: (1) deceleration length, (2) storage length, and (3) entering (bay) taper. Based on AASHTO criteria (*7*), the deceleration length ranges from 235 ft for 30 miles per hour to 435 ft for 50 miles per hour. Adding the deceleration distance to the storage length can result in a longer left-turn lane that may entice drivers into the lane not realizing it is a left-turn lane. Optimally, the total length of the auxiliary lane is the sum of the lengths for deceleration, storage, and entering taper. Common practice, however, is to accept a moderate amount of deceleration within the through lanes and to consider the taper as a part of the deceleration length. Where intersections occur as frequently as four per mile, it is customary to forego most of the deceleration length and to provide only the storage length plus taper. It is more important to provide adequate storage length to avoid blocking the through traffic lanes. The AASHTO guidelines (*7*) for storage length are as follows:

1. Minimum Storage length—2 passenger cars but with 10 percent truck/bus traffic the minimum length should be one car and one truck/bus.
2. Unsignalized intersection—number of left-turning vehicles likely to arrive in an average 2-minute period of the peak hour.

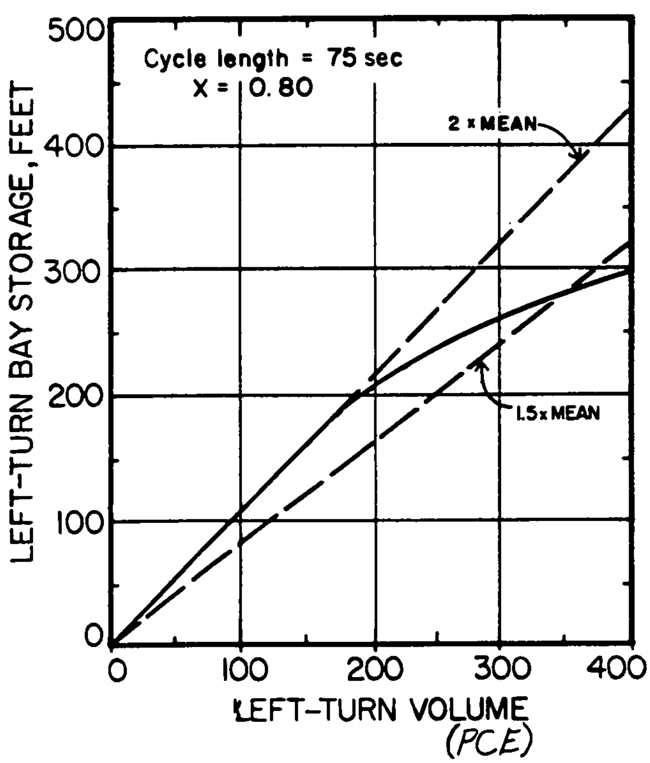


FIGURE 8 HCM left-turn bay length vs turning volume (*6*).

3. Signalized intersection—one and one-half to two times the number of left turns expected to arrive during a signal cycle.

Some agencies use a minimum length for left-turn lanes of 100 ft, which will store about four automobiles. The AASHTO design vehicle dimensions (*7*) for vehicle length are 40 ft to 60 ft for buses, 50 ft to a maximum of 118 ft for combination truck units and 30 ft to 53 ft for recreation vehicles. The left-turn lane storage length should recognize the type, number, and frequency of lane usage by larger vehicles. On high-speed roadways, it is desirable to ensure that a large truck or other vehicles are not forced to stop in the through traffic lane because of minimum storage lengths.

The HCM (*6*) provides a method for determining left-turn bay length using Figure 8 with the values adjusted using Table 6. The length of storage lane is based on random arrival with a five percent probability of left-turn lane overflow. Figure 8 is based on a signal cycle length of 75 seconds and a left-turn volume-to-capacity (v/c) ratio of 0.80. The length from Figure 8 is adjusted by the factors in Table 6 for other cycle lengths and v/c ratios. The AASHTO and HCM guidelines provide comparable left-turn lane lengths.

TABLE 6

HCM LEFT-TURN BAY LENGTH ADJUSTMENT FACTORS (*6*)

v/c RATIO, *X*	CYCLE LENGTH, *C* (SEC)				
	60	70	80	90	100
0.50	0.70	0.76	0.84	0.89	0.94
0.55	0.71	0.77	0.85	0.90	0.95
0.60	0.73	0.79	0.87	0.92	0.97
0.65	0.75	0.81	0.89	0.94	1.00
0.70	0.77	0.84	0.92	0.98	1.03
0.75	0.82	0.88	0.98	1.03	1.09
0.80	0.88	0.95	1.05	1.11	1.17
0.85	0.99	1.06	1.18	1.24	1.31
0.90	1.17	1.26	1.40	1.48	1.56
0.95	1.61	1.74	1.92	2.03	2.14

SOURCE: C.J. Messer, "Guidelines for Signalized Left-Turn Treatments," *Implementation Package, FHWA-IP-81-4,* Federal Highway Administration, Washington, D.C., 1981, Table 1.

A recent study by the University of Delaware (*26*) found that the AASHTO and HCM models do not account for blockage of the left-turn lane entrance when there are lower left-turn volumes and left lane blockage occurs by the queuing of through vehicles, as illustrated in Figure 9b. However, the length required to prevent overflow, Figure 9a, is comparable to these other models. The study recommends that the length should be

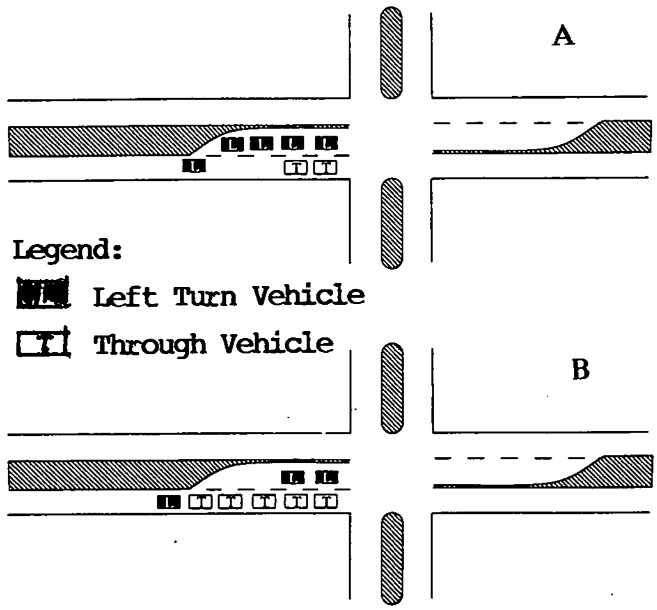


FIGURE 9 Lane overflow and blockage of lane entrance at a signalized intersection. *(26)*

determined for left-turn storage and then checked to determine if the through traffic would block the left lane entrance using whichever left-turn lane length is the longest. Table 7 is the recommended length in number of vehicles to prevent blockage by the through vehicles, as illustrated in Figure 9b.

The survey indicated that 27 states and 26 local agencies generally use the AASHTO design criteria for left-turn lanes. Only 7 states and 8 local agencies reported having their own left-turn lane design criteria. One survey respondent commented that the AASHTO design criteria were deficient in addressing urban arterials, existing streets, lower speeds, and the taper design for an added lane at the intersection.

Taper

The left-turn lane involves a "Bay Taper" leading vehicles into the left-turn lane and an "Approach Taper" if there is not an existing median, as illustrated in Figure 10.

The MUTCD (5) recommends that approach taper and roadway tapers should be as follows:

SPEED: 45 mph or greater, Taper Length $L = W \times S$

$$40 \text{ mph or less, Taper Length } L = \frac{WS^2}{60}$$

where

L = Taper length in feet
W = Width of roadway offset for taper in feet
S = Speed in miles per hour

TABLE 7

RECOMMENDED, LEFT-TURN LANE LENGTH THROUGH VEHICLE BLOCKAGE CONSIDERATION, UNIVERSITY OF DELAWARE *(26)*

Left-Turn Volume (vph)	Duration of Through Red = 45 seconds								Duration of Through Red = 60 seconds							
	Through Volume (in vphpl)								Through Volume (in vphpl)							
	500	600	700	800	900	1000	1100	1200	500	600	700	800	900	1000	1100	1200
50	6	7	8	9	10	11	13	14	9	10	12	13	14	16	17	19
75	7	8	9	10	12	13	14	15	9	11	13	14	16	17	19	20
100	8	9	10	11	12	13	14	16	10	11	13	15	16	18	19	*
125	S	9	10	11	13	14	15	16	10	12	13	15	17	18	20	*
150	8	9	10	12	13	14	15	16	10	12	14	15	17	19	20	*
175	8	9	11	12	13	14	16	17	10	12	14	15	17	19	20	*
200	8	9	11	12	13	14	16	17	10	12	14	15	17	19	*	*
225	8	9	11	12	13	15	16	17	10	12	14	15	17	19	*	*
250	8	9	11	12	13	15	16	17	10	12	14	15	17	19	*	*
Left-Turn Volume (vph)	Duration of Through Red = 75 seconds								Duration of Through Red = 90 seconds							
	Through Volume (in vphpl)								Through Volume (in vphpl)							
	500	600	700	800	900	1000	1100	1200	500	600	700	800	900	1000	1100	1200
50	11	13	15	17	18	20	*	*	13	16	18	20	*	*	*	*
75	12	14	16	18	20	*	*	*	14	16	19	*	*	*	*	*
100	12	14	16	18	20	*	*	*	14	17	19	*	*	*	*	*
125	12	14	17	19	20	*	*	*	15	17	20	*	*	*	*	*
150	12	15	17	19	*	*	*	*	15	17	20	*	*	*	*	*
175	12	15	17	19	*	*	*	*	15	17	20	*	*	*	*	*
200	12	15	17	19	*	*	*	*	15	17	20	*	*	*	*	*
225	12	15	17	19	*	*	*	*	15	17	20	*	*	*	*	*
250	12	15	17	19	*	*	*	*	15	17	20	*	*	*	*	*

Note 1: "*" indicates that the required lane length is large. A better way of dealing with the blockage problem may be changing the signal time. In most of these cases the value from this table will not be critical, since required lane length from overflow consideration will be greater.

Note 2: For conversion to length in meters under different vehicle mix, see the section on Recommended Lengths in Actual Distance.

Various types of auxiliary lane entering (bay) tapers are addressed by the AASHTO Green Book (*7*), such as straight line and reverse curves. AASHTO states that a taper rate of 8:1 has been used for design speeds up to 30 mph and 15:1 for design speeds of 50 mph. Drivers are limited in the time that they can comfortably move laterally, such as a lateral movement of 4 ft per second, so a longer taper is needed at higher speeds because in 4 seconds the vehicle travels farther longitudinally. However, long tapers and very short tapers may result in pavement areas that are not used by vehicles, which can result in the accumulation of sand and road debris adjacent to raised medians. Therefore, the trend is to use shorter tapers that delineate the left-turn lane entrance and if a longer taper length is needed for vehicle maneuvering, then the vehicle encroaches on the right edge line for the left-turn lane or the left-turn lane is only partially shadowed, as illustrated in Figure 10.

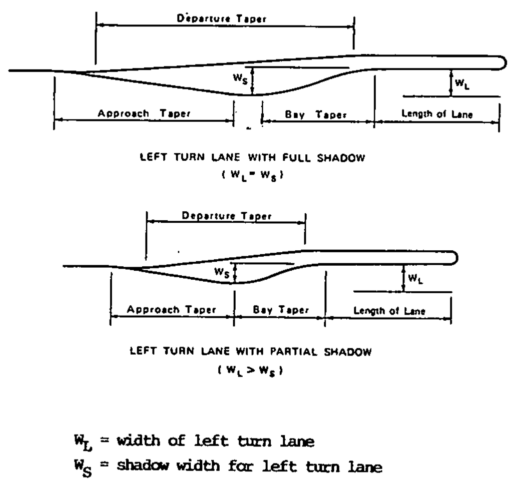


FIGURE 10 Elements of left-turn lane design. (*4*)

Medians

A roadway median is a space in the middle of the roadway separating the opposing vehicle flows. A median can be created with raised islands, flush pavement with pavement markings, or by a depressed area below the roadway shoulder elevations. The existence of a median in the roadway has the advantage of providing space at an intersection to develop a left-turn lane. The type and width of median on a roadway will be determined on the basis of the operational characteristics desired for a length of roadway with secondary consideration of intersection operations. If the only consideration is intersection operations, then the roadway should be widened at the intersection approaches to provide a left-turn lane based on the previous criteria relative to warrants, capacity, and safety.

The recommended width of a median for a left-turn lane by the AASHTO Green Book (*7*) is 18 ft, which provides a 12-ft turn lane and a 6-ft median separation between traffic streams. A minimum median width is 12 ft, providing a 10-ft turn lane and a 2-ft separation. The ITE recommended and desirable widths for various intersection functions are shown in Table 8 (*25*).

TABLE 8

ITE RECOMMENDED MEDIAN WIDTHS (*25*)

Function	Minimum Width (ft)	Desired Width (ft)
Separation of Opposing Traffic	4[1]	10
Pedestrian Refuge and Space for Traffic Control	6[1]	14
Left-turn Speed-change and Storage	14	20
Crossing/Entering Vehicle Protection	20	40
U-turns, Inside-to-Inside Lanes	26	60

Note: 1 foot = 0.3 m.

[1] Cannot accommodate left-turn lanes, hence such turns must be made from the through lanes, unless prohibited by signs.

There is considerable debate on the acceptable treatment of urban arterials. Some argue that flush medians with two-way, left-turn lanes are best because they serve the adjoining properties and have high public acceptance. Others argue that they are not efficient at higher arterial volumes and detract from the operational efficiency of the arterial. The disadvantages of raised medians are cited by Van Winkle (*27*) as follows:

1. Raised medians are obstacles in the roadway and are difficult to delineate.
2. Raised medians inhibit left-turn movements but may create improper turns or transfer turns to other locations, such as intersections, causing a capacity problem. Also, they require some provision for U-turns, either at intersections or midblock.
3. Use of medians to control property access is an inappropriate application. Access must be controlled at the property line with control of the number and type of approaches.
4. Painted medians provide better driver communications, property accessibility, and comparable safety under many conditions.

Gwinnett County, Georgia, (Atlanta area), has recently developed a policy (*28*) requiring the use of more raised medians on its arterials. County officials concluded that adequate gaps do not exist for left turns when the arterial reaches about 28,000 AADT. They indicate that four-lane roads are safer with a raised median than a two-way, left-turn design regardless of the volume, number of signals, or frequency of cross-streets and driveways. Gwinnett County, Georgia, has adopted a policy of providing a raised median on all reconstructed principal

TABLE 9

HCM CRITICAL GAPS FOR UNCONTROLLED LEFT TURNS *(6)*

	Average Approach Speeds- Major Street, 30 mph		
	Number of Lanes on Major Road		
	2 Lanes t_g	4 Lanes t_g	Follow-up Timing t_f
Left Turn, Major Street	5.0 sec	5.5 sec	2.1 sec
Left Turn, Minor Street	6.5 sec	7.0 sec	3.4 sec

t_g = critical gap in opposing traffic.
t_f = follow-up time or the time span between departure of one vehicle from the minor movement and the departure of the next vehicle.

and major thoroughfares, converting existing arterials to raised medians if the traffic growth is expected to exceed 24,000 to 28,000 AADT, and where feasible out-of-direction travel should be minimized by providing interparcel access, joint parking lots, back alleys, frontage roads, or other improved access.

Sight Distance

Vehicles in the left-turn lane require adequate sight distance to see opposing traffic, select an adequate gap in traffic, and make the left turn at nonsignalized intersections. The critical gaps in traffic for automobile left turns from a major road are listed in Table 9. The left-turning driver will also require an appropriate reaction time to initiate the left-turn maneuver with 2.0 seconds used as the design value in the AASHTO Green Book. Therefore, a left-turning vehicle will require from 7.0 to 8.0 seconds to initiate the left-turn maneuver, depending on the number of lanes to be crossed and the speed of the opposing traffic. The vehicle in the left-turn lane must be able to see the opposing traffic for the distance represented by the 7.0 to 8.0 seconds of travel time to safely negotiate the left turn. Sight distance can be restricted by roadway curvature, either horizontal or vertical, roadside features, other vehicles, and median landscaping.

A common sight distance restriction occurs with opposing left-turn lanes where waiting vehicles in the opposing left-turn lane block visibility to oncoming through traffic, as illustrated in Figure 11, because of the wide median. A solution to the problem is to offset the left-turn lanes as shown in Figure 12. A guideline for offsetting opposing left-turn lanes on four-lane divided highways has been developed by Nebraska using AASHTO intersection sight distance criteria on a four-lane divided highway using a critical gap of 8.5 seconds. The guidelines were developed based on the observed positioning of vehicles in the left-turn lane and the 8.5 second critical gap. Table 10 shows the minimum positive offsets as labeled "X_o" in Figure 13. Note that insufficient left-turn lane storage can also restrict sight distance, as shown in Figure 13. The minimum left-turn bay length plus taper to prevent sight blockage for various speeds is shown in Figure 14. The available sight distance for left-turn vehicles at an intersection needs to be reviewed considering other vehicles waiting at the intersection.

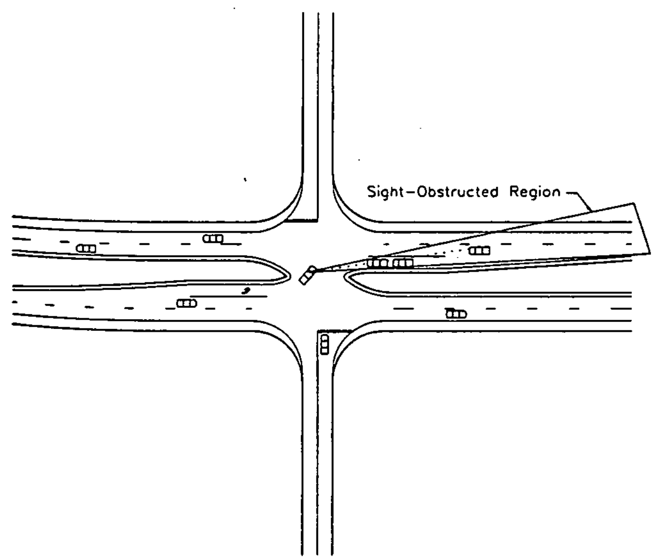


FIGURE 11 Sight obstruction to left-turning vehicles. *(29)*

Intersection Angle

The angle of the intersection can influence the intersection operational and safety characteristics and require special design considerations for the left-turn lane. A skewed intersection may cause the left-turning vehicle to travel a longer distance, increasing the vehicle exposure to conflict. The intersection angle can decrease the driver's sight angle for opposing traffic and convenient observation of pedestrian crossings. It is generally desirable to maintain intersection angles at 65 degrees or more to reduce these problems. Vehicle turning templates showing

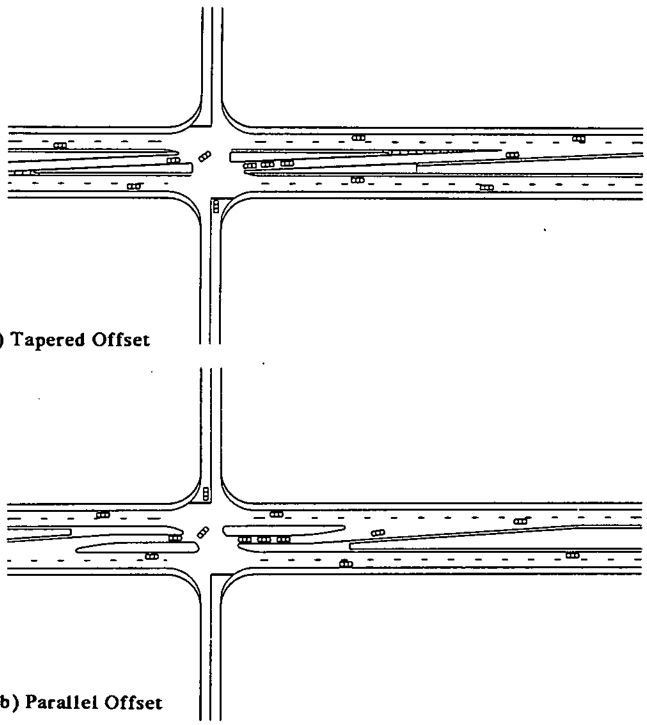


FIGURE 12 Alternative left-turn bay designs. *(29)*

wheel path off-tracking should always be used on skewed and channelized intersections to ensure that adequate openings are provided for the turning vehicle.

Channelization

Channelization is the separation or regulation of traffic movements into definite paths of travel by traffic islands or pavement markings to facilitate the safe and orderly movements of both vehicles and pedestrians. Proper channelization can increase capacity, improve safety, and provide convenience and confidence to the road user. The application of left-turn treatments with the principles of channelization emphasized are as follows (*4*):

Left-turn lanes *define the desirable vehicular paths, separate points of conflict, facilitate high-priority traffic movements* and *remove decelerating, stopped, or slow vehicles from high-speed through traffic streams.* The design of the left-turn lane *encourages desirable or safe vehicle speeds* with a smooth transition into the left-turn lane. Medians and raised traffic islands can *discourage or prohibit undesirable or wrong-way movements* and *provide safe refuge for pedestrians and other nonmotor vehicle users.* The separate left-turn lane with signing and/or traffic signal operation can *facilitate the desired intersection traffic control scheme.*

It is important that intersection channelization be started at a location where the approaching driver has good visibility of the channelization in the roadway. The introduction of channelization in the roadway and any transition preceeding it should be carried over a vertical curve and in advance of a horizontal curve so that the channelization does not present an unexpected surprise to the unfamiliar driver. It is also desirable to offset the approach nose of channelization 2 to 6 ft from the through lanes to minimize accidental vehicle impacts. Pavement markings can be used to transition vehicles laterally to avoid the raised channelization. As noted elsewhere, it is recommended that off-tracking templates of vehicle wheel paths for truck and/or bus design vehicles expected to use the intersection be used to verify that the larger design vehicles can make the intersection turns without encroaching on the channelizing islands or medians.

TABLE 10
LEFT-TURN LANE OFFSET GUIDELINES—NEBRASKA *(30)*

Design Speed (mph)	Minimum Offsets (feet)		Desirable Offsets (feet)	
	Passenger Car[a]	Truck[b]	Passenger Car[a]	Truck[b]
40	1.0	2.5	2.0	3.5
45	1.0	3.0	2.0	3.5
50	1.5	3.0	2.0	3.5
55	1.5	3.0	2.0	3.5
60	1.5	3.0	2.0	3.5
65	1.5	3.0	2.0	3.5
70	1.5	3.0	2.0	3.5

[a] Opposing left-turn vehicle is a passenger car.
[b] Opposing left-turn vehicle is a truck.

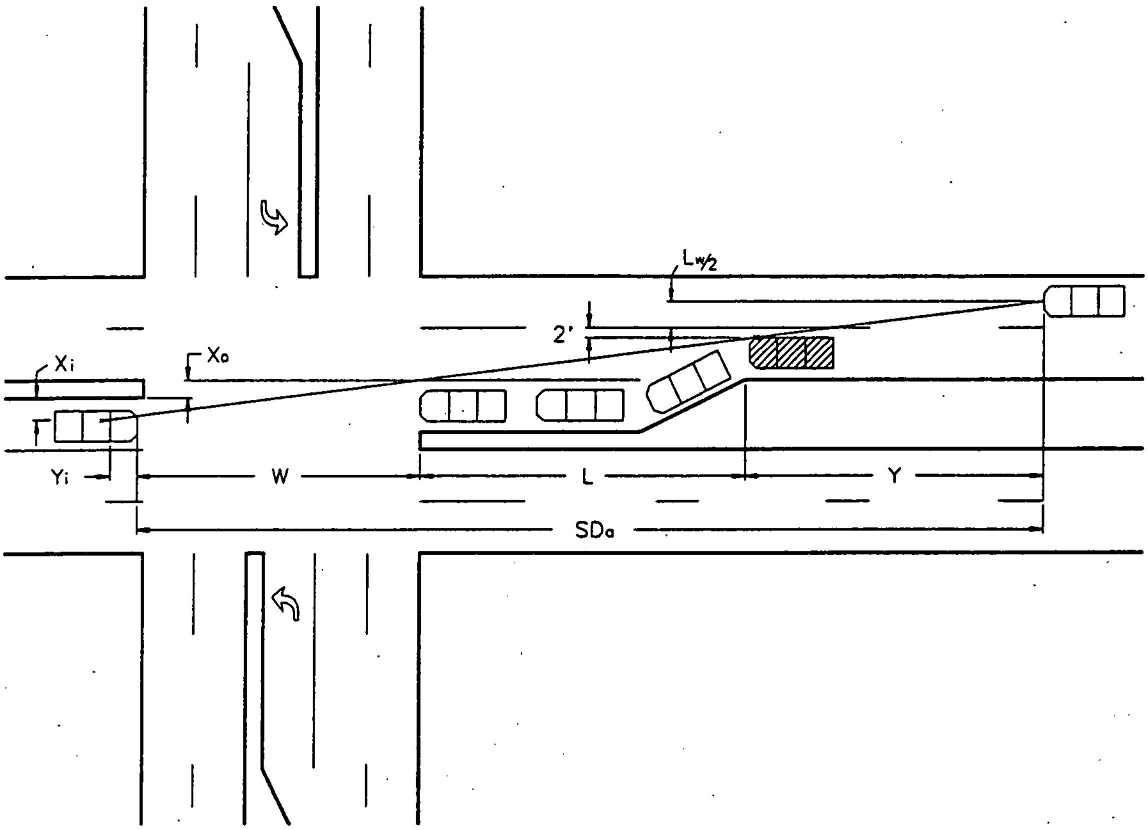


FIGURE 13 Effects of insufficient left-turn lane storage capacity. *(30)*

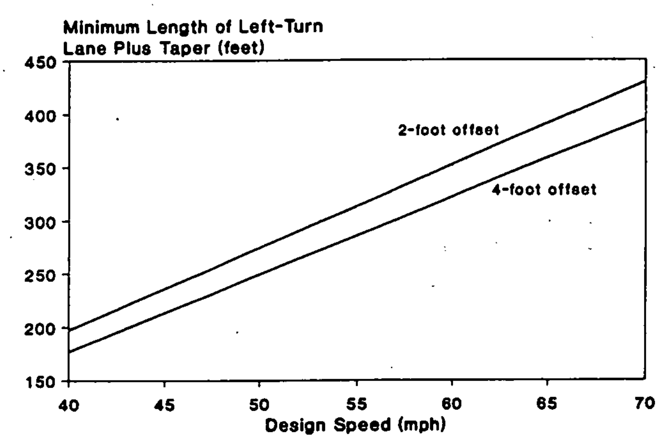


FIGURE 14 Minimum left-turn lane lengths. *(30)*

MULTIPLE LANE CONFIGURATIONS

Multiple left-turn lanes, an economical alternative to interchange construction, are becoming more widely used as traffic volumes increase. Multiple turn lanes should be considered when left-turning volumes exceed:

300 vph for dual left-turn lanes, HCM (*6*)
600 vph for triple left-turn lanes, Las Vegas (*23*).

The multiple lanes can be three general types described as (A) exclusive, (B) exclusive with trap lane and (C) exclusive with permitted lane, as illustrated in Figure 15. It is recommended by Ackeret (*23*) that triple left-turn lanes should not be considered under the following circumstances:

- Where there is potential for a high number of pedestrian/vehicle conflicts. [Such conflicts can be prevented by signal control or other measures.]
- When left-turning vehicles are not anticipated to queue evenly within the provided left-turn storage lanes due to downstream conditions.
- Where ice or snow conditions exist that obscure pavement channelization markings within the intersection. [This need not be a major consideration since dual left turns are regularly used with intersection pavement markings in the northern climates without serious operational or safety problems.]
- Right-of-way restrictions prohibit adequate design vehicle turning maneuver space within the intersection.
- The installation is not economically justified when compared with other alternatives to improve intersection capacity.

The same considerations are also applicable for dual left-turn lanes. Geometric design for multiple turn lanes follows the

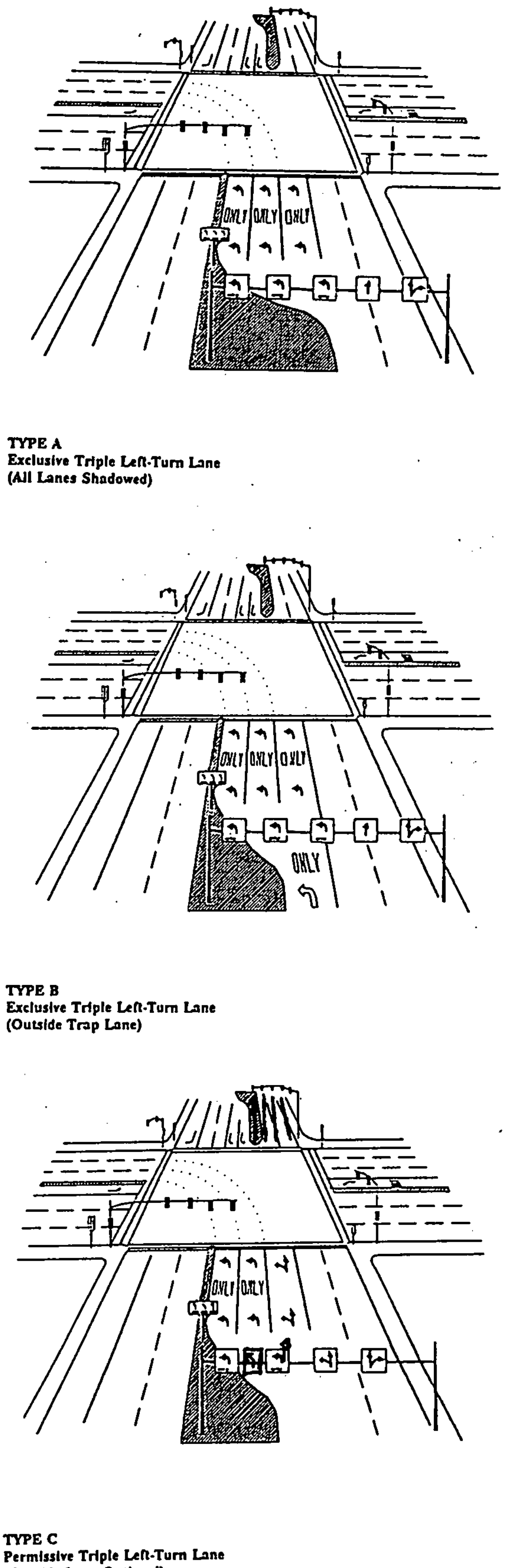


FIGURE 15 Multiple left-turn lane types. *(23)*

recommended design guidelines that should be applied for any good intersection design but are cited below for emphasis.

The design elements recommended by Ackeret *(23)* for triple left-turn lanes are summarized as follows:

- Select design vehicle as a passenger vehicle with a single unit truck/bus or semi-trailer design vehicle.
- Determine design vehicle turning paths with vehicle turning templates. Concurrent opposing left turns should have at least 10 ft vehicle clearance between the opposing left turns.
- Approach and departure lane widths should be adequate to accommodate any vehicle off-tracking.
- Determine storage bay and taper lengths the same as a single turn lane with adjustment for saturation flow rates and lane utilization.
- Engineering judgment needs to be used to provide intersection geometry that will make the multiple turn lane operate safely and efficiently.

Additionally, Ackeret recommends special traffic control features to accommodate triple left turns and provide efficient operation. These traffic control features are summarized as follows:

Advance overhead signs are critical to inform the motorist of lane options, Figure 15. These signs should be supplemented with appropriate downstream lane destination messages if they will reduce downstream weaving maneuvers. The overhead signs also clarify the Type "B" Trap Lane design and Type "C" Optional Lane design.

Lane-use control signs (MUTCD R3-5 and R3-6, Chapter 4) Ground-mounted lane control signs should be installed in the median and on the signal mast arm to supplement the advance overhead signs.

Pavement markings Each turn lane should be marked with a turn arrow and ONLY legend or optional turn arrow as appropriate. Pavement markings through the intersection are required to control the multiple turning paths and safely keep each vehicle within its lane. A white dotted line 2 ft in length with 4-ft or longer gaps (sometimes called cat tracks) is recommended by the MUTCD *(5)* to define the turning path of the lane through the intersection. Figure 16 shows the dotted line intersection markings on a multiple left-turn lane design in Las Vegas, Nevada, with two triple-turn lanes, two dual-turn lanes and pedestrian overpasses on each approach.

Traffic signal design The triple-turn lane design requires that the turn be made only under a fully protected left turn phase with all lanes provided with their individual signal indications. [In some jurisdictions, dual left-turn lanes have been operated successfully with permitted signal phasing.]

A 1993 ITE Committee reported saturation flow rates from 1,400 to 1,600 vehicles per hour of green per lane (vphgpl) for dual left turns with a high value at 1,950 vphgpl *(31)*. The Committee recommended that the higher volumes (1,950

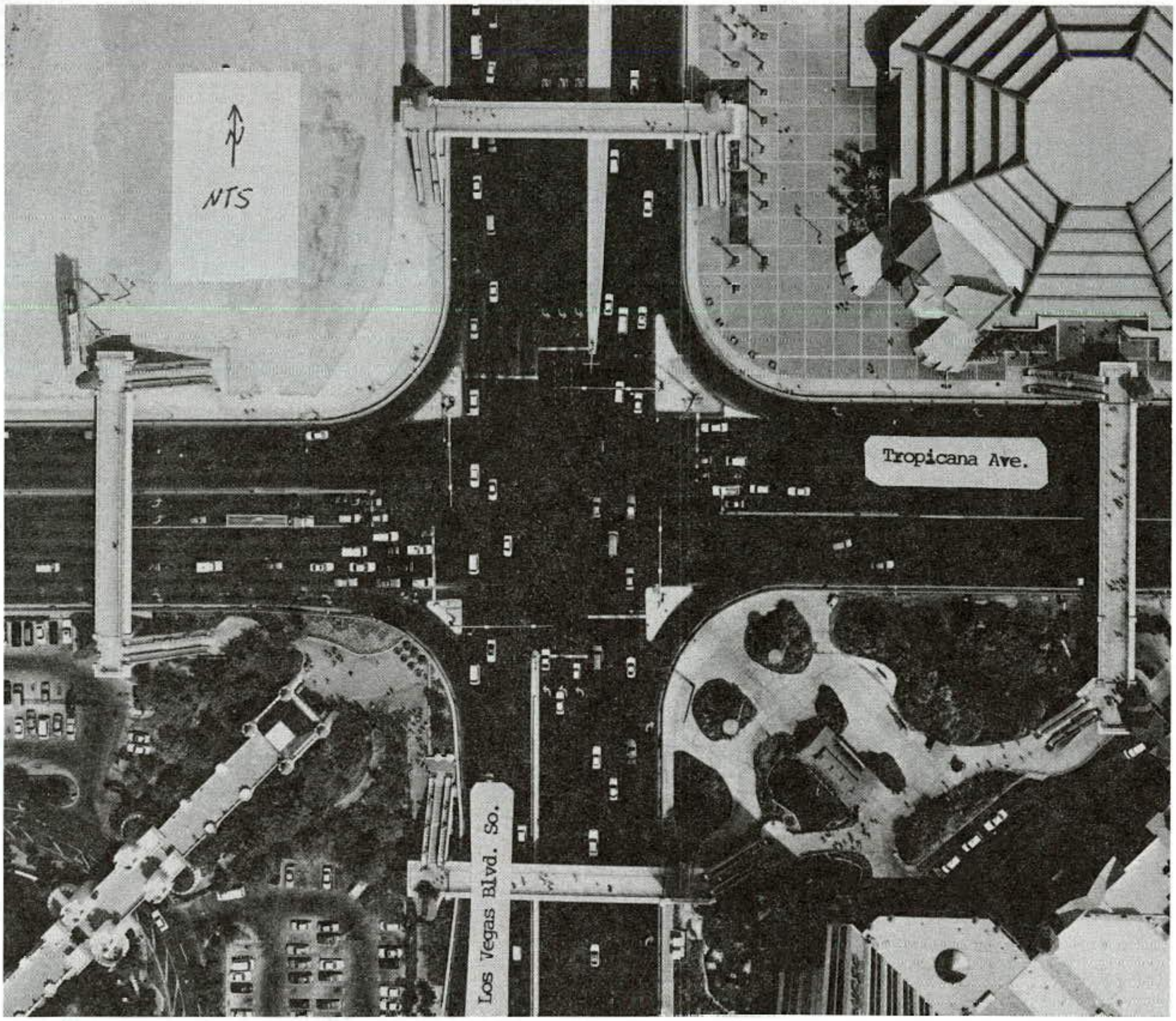


FIGURE 16 Las Vegas triple left-turn lanes. *(23)*

TABLE 11

SUMMARY OF SATURATION FLOW RATE ADJUSTMENT FACTORS FOR TRIPLE LEFT TURNS—CALIFORNIA (32)

Adjustment Factor for Lane Utilization		
Lane Group	Inner and Middle	Outer
Lane Utilization Factor, f_u	1.01	0.98

Adjustment Factor for Time of Day			
Time of Day Period	Morning	Midday	Evening
Adjustment Factor, f_t	1.03	0.96	0.99

Adjustment Factor for Day of Week		
Day of Week Category	Week Day (Monday–Friday)	Week End (Saturday, Sunday)
Adjustment Factor, f_d	1.01	0.94

vphgpl) be used with caution because the value may not represent average saturation flow rates. A recent study of triple left turns in California (*32*) found an average saturation flow rate of 1,930 vphgpl based on the study of five sites. The study found significant differences in saturation flow rates between lanes, time-of-day, and weekday versus weekend. Table 11 provides the adjustment factors to the saturation flow rates for these variations.

CHAPTER FOUR

SIGNS AND PAVEMENT MARKINGS

INTRODUCTION

This chapter, which covers the necessary signs and pavement markings for application on left-turn lanes, addresses the MUTCD as being the national guidelines for traffic control devices at left-turn lanes. It should be understood that the decision to install a specific traffic control device is subject to the engineering judgment of the individual making those decisions. However, once that decision is made and the MUTCD mandates (shall) a specific device or its application for the benefit of the motorist, then there are to be no variations from the MUTCD requirements. The application of traffic control signals is discussed in Chapter 5. Known variations from the MUTCD are addressed with available information on application and experience.

TRAFFIC SIGNS

MUTCD Requirements

Turn Prohibition Signs, Figure 17

At those intersections where it is desirable or necessary to prohibit a left-turn maneuver, it is recommended (should) that left turn prohibition signs, R3-1, be installed where they will be most easily seen by drivers wanting to make a left turn. The signs should be placed over the roadway or at the left-hand corner of the intersection. If it is a signalized intersection, the sign may be installed adjacent to the traffic signal head for the left lane. At intersections where the left turn prohibition applies for only certain periods, i.e. peak hours, and is not restricted at other times, then special signing treatment is required to convey the part-time restriction to the motorist. The MUTCD lists the following order of preference for these signs:

1. Variable message signs or internally illuminated signs that are lighted and made legible only during the restricted hours, particularly at signalized intersections.
2. Permanently mounted signs incorporating a supplementary legend showing the hours during which the prohibition is applicable.
3. Portable prohibition signs that are placed at each corner of the intersection under police supervision and removed at other hours.

Where a NO TURNS sign (R3-3) is used at an intersection to prohibit both right and left turns it is recommended that the NO TURNS sign be placed in the same location of the turn prohibition sign at the left-hand corner of the intersection and optionally adjacent to the traffic signal head.

The U-turn prohibition sign (R3-4) is used at any location where vehicle U-turns are prohibited.

Lane-Use Control Signs, Figure 18

Lane-use control signs shall be used to require drivers in certain lanes to make a turn, such as a mandatory left-turn lane or to permit turns from a lane where such turns would otherwise be illegal, such as dual left turns.

The mandatory left-turn movement is signed with the Left Turn Only sign, (R3-5) designed for overhead mounting over

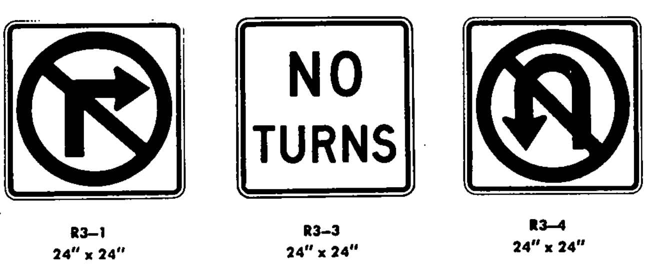


FIGURE 17 MUTCD turn prohibition signs. *(5)*

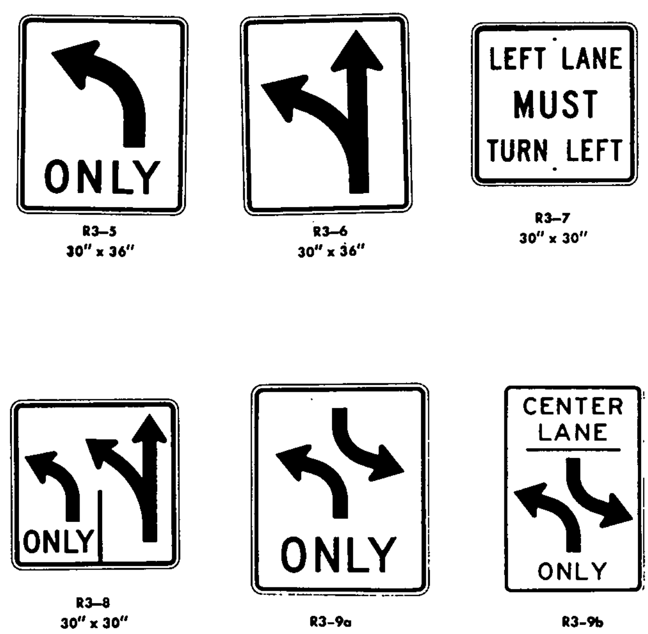


FIGURE 18 MUTCD lane-use control signs. *(5)*

the lane or the projection of that lane at an intersection designating that a motorist in that lane must make a left turn. The legend sign, R3-7, is designed for post mounting in advance of the intersection advising motorists of the mandatory turn ahead from that lane. Lane-use control signs are not required where:

(a) turning bays, designed to not entrap through traffic have been provided by physical construction or pavement markings, and
(b) only the drivers using such turning bays are permitted to turn.

The optional movement sign, R3-6, is used for overhead mounting to permit both through traffic and left turns from that lane. The sign can also be used in conjunction with the Left Turn Only sign (R3-5) to provide a dual lane left turn. In this application, the word OK is an optional addition to the sign legend. The post-mounted double turn sign, R3-8, is the advance lane control sign for the intersection. It may be needed on the left side of one-way streets or the median of divided highways to implement the dual left turn at an intersection. The word OK is an optional addition under the Left-Straight Arrow of sign R3-8. However, if sign R3-8 is modified to depict mandatory left turns from both lanes (no through movement) then the ONLY word legend is required below both arrows. A driver comprehension study of this sign (R3-8 with optional left turn) by the Texas Transportation Institute (33) found that 65 percent of drivers recognized that they must be in the right lane to go straight and 35 percent responded incorrectly.

The Two-Way Left Turn Only signs (R3-9a and R3-9b) should be used with the required pavement markings to designate a lane for exclusive use of left-turning vehicles in either direction but restricted for passing or overtaking other vehicles. The R3-9a is designed for overhead mounting and the post-mounted sign (R3-9b) may be used either for ground mounting or as an alternate for overhead mounting. The Texas Transportation Institute study (*33*) of drivers' comprehension of the R3-9b sign found that only 45 percent of the drivers correctly responded to appropriate maneuvers from the two-way left-turn lane.

The City of Albuquerque, New Mexico, in response to the questionnaire noted the use of a changeable message arrow sign for special lane-use control. The sign legend depicts a Left Turn Only Arrow (R3-5) for the morning peak and a symbolic straight through arrow at all other times. The sign is installed on two overhead sign installations located over the through lane adjacent to the left-turn lane to implement a dual left turn during the morning peak hour. The first mast arm installation is located in advance of the intersection at the left-turn lane entrance and the other mast arm installation is located across the intersection.

Traffic Signal Signs, Figure 19

The LEFT TURN SIGNAL sign (R10-10) shall be used adjacent to a separate left-turn traffic signal face when the signal displays a circular red that is visible to other traffic. A circular red indication can be used without the sign if it is visually shielded from through traffic by signal louvers or a programmable signal head. One of the advantages of using a red arrow indication in the left-turn signal head is that this sign can be eliminated. The nationwide practice is to use the LEFT TURN SIGNAL (R10-10) sign only for a separate left-turn signal face when the signal provides an exclusive left-turn signal phase. The LEFT ON GREEN ARROW SIGN (R10-5) may be used with a separate left-turn signal head that uses all arrow indications and is an optional sign to clarify when the left-turn maneuver can be made. The R10-10 is not required under this application because of the use of all arrow indications. The Standard Highway Signs publication also makes provisions for an older version of the R10-5 sign that reads, LEFT ON ARROW ONLY. The left-turn signal requirements cannot be met by adding a green arrow indication to one of the through signal faces and using the LEFT ON ARROW ONLY (R10-5) sign. The LEFT ON ARROW ONLY sign has been replaced by the LEFT ON GREEN ARROW sign for this reason. The LEFT TURN YIELD ON GREEN (symbolic green ball) R10-12 may be used for an exclusive/permitted left-turn signal operation to clarify the permitted nature of the circular green indication. If this sign is used, the R10-10 is not required and shall not be used as noted above. The Texas Transportation Institute Study (*33*) on sign comprehension found that 74.5 percent of responses correctly indicated that a driver should stop and wait for a gap under a circular green indication. A recent study by Bonneson and McCoy, University of Nebraska, (*34*) confirmed earlier studies by Agent (*35*) and Florida ITE Section (*36*) that use of the LEFT TURN YIELD ON GREEN sign (R10-12) is no more effective than omission of the sign. It was found that the sign helped during the permitted phase but tended to confuse more drivers during the overlap and exclusive or protected phases. Grover (*37*) opined that the R10-12 sign may have some merit but sees very little reason because of liability to use the sign when a single mast arm signal controls both through and left-turn lanes. His opinion on design is to not locate permissive signal displays directly in front of a left-turn driver and to omit the R10-12 sign. A limited study by the Maryland Department of Transportation (*38*) found that the use of the R10-12 sign at permitted or exclusive/permitted left-turn locations did not particularly enhance traffic safety.

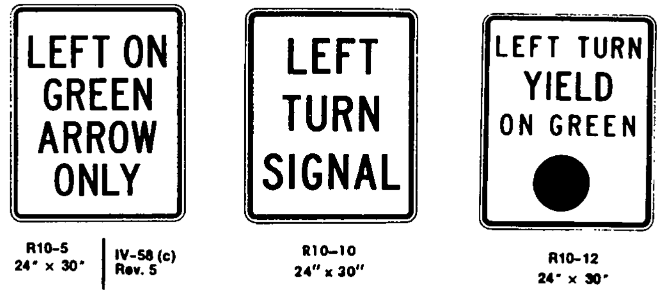


FIGURE 19 MUTCD traffic signal signs. (*5*)

Currently, there are revisions to this portion of the MUTCD that have been approved for inclusion in the next edition.

These revisions address the Variable Left Turn signal indications where the exclusive (protected left turn) indication occurs during one or more periods of the day and the permitted or the combined exclusive/permitted indication occurs during other periods of the day. An informational sign is not required, but if one is used, both the R10-10 and R10-12 signs shall be mounted adjacent to the left-turn signal head. The use of both signs has promoted the application of a combination sign in Texas (Figure 21) which is discussed later.

Signing Variations

The Texas Manual on Uniform Traffic Control Devices at one time provided for two signs, PROTECTED LEFT ON GREEN and PROTECTED LEFT ON GREEN ARROW, as information signs for left-turn signals. The first sign had only a 15.5 percent correct response while the second sign had a 53 percent correct response in the Texas Transportation Institute (*33*) sign comprehension study. This study of Texas drivers concluded that these two signs do not effectively communicate the right-of-way assignments at the left-turn signal. The PROTECTED LEFT ON GREEN has been deleted from the current Texas MUTCD.

The University of Texas at Arlington (*39*) reviewed the driver comprehension of a variety of left-turn auxiliary signs as illustrated in Figure 20 representing the MUTCD, Texas MUTCD, or sign applications in at least one Texas city. Traffic signal scenarios both with and without the signs were tested through a survey of Texas motorists. Sign types 2, 6, and 11 provided the lowest percentage of incorrect responses under various signal indication scenarios. It appears that signs that state the left turn is protected under a green arrow indication are superfluous because drivers appear to have a good understanding of the meaning of a green arrow signal indication. The recommended sign for permitted left-turn operations is sign type 6, the MUTCD sign, which should be used if a sign is necessary and it should always accompany the left-turn signal head indicating a circular green for left-turning traffic. Some initial application of special left-turn signal phasing in Texas used the application of a modified sign combining the R10-10 and R10-12 sign, depicted in Figure 21 (*40*). The University of Texas at Arlington study (*39*) reviewed this sign and recommended that it not be used because it has a longer text and depicts two opposite meanings. The LEFT TURN SIGNAL (R10-10) portion of the sign implies there is a protected left turn *with no need to yield* and the YIELD ON GREEN ball (R10-12) portion of the sign is used for permitted left turns on circular green signal indications *requiring a yield* to opposing traffic.

A study of Indiana drivers by Hummer, Montgomery, and Sinha (*40*) compared the driver understanding of No Signs, R10-10 and R10-12 and two other alternative signs as illustrated in Figure 22. For protected signal operations, there were no significant differences between either of the two signs and no sign usage. The LEFT TURN ON GREEN OR ARROW performed slightly better than no sign or LEFT TURN YIELD ON GREEN Ball for protected/permitted signal operations.

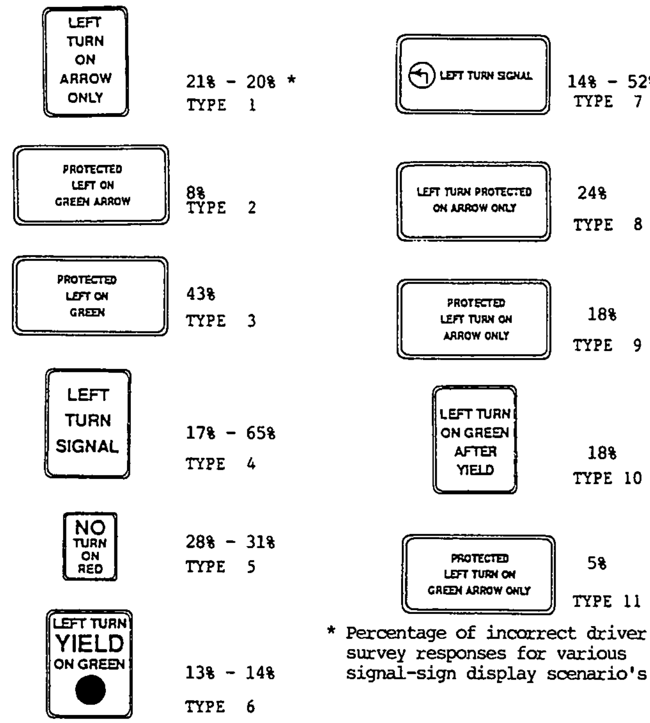


FIGURE 20 Left-turn auxilliary signs—Texas. (*39*)

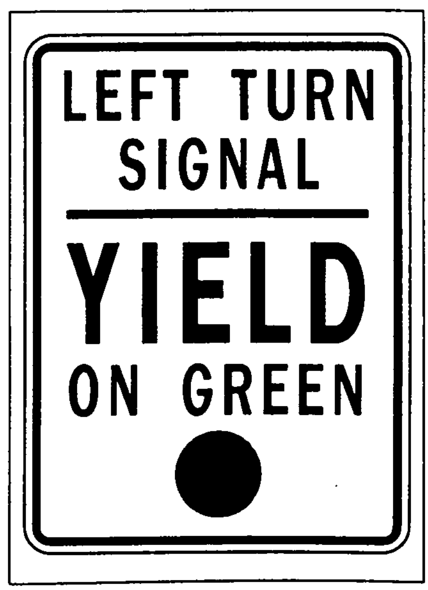


FIGURE 21 Texas combined R10-10 and R10-12 sign. (*40*)

The Illinois Department of Transportation, District 8, (*42*) has experimented with a fiber optic sign LEFT TURN YIELD mounted adjacent to the left-turn signal and illuminated with the green indication for the left-turn permitted phase. The sign was installed to reduce left-turn accidents at several intersections. They do not recommend further use of the sign because:

1. It does not reduce the permitted signal left turn delay which is the root cause of left-turn accidents under congested traffic conditions.

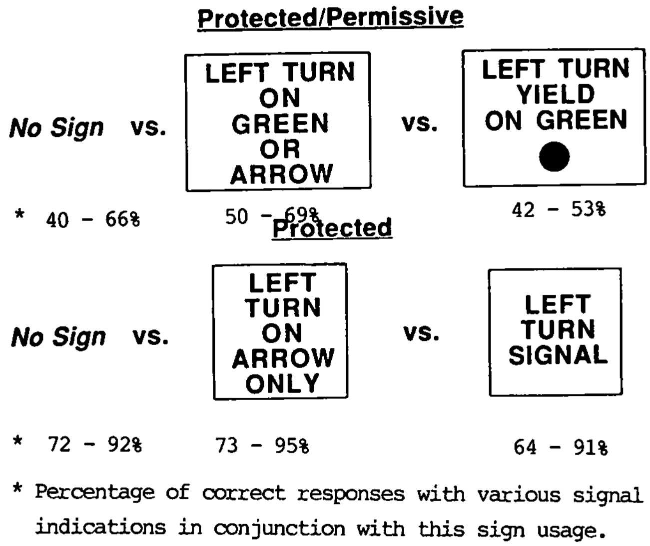


FIGURE 22 Signing study for protected-permitted signal operations, Indiana. *(41)*

2. It creates non-uniformity in traffic control; and
3. Past applications have been inconclusive in reducing accidents.

The State of New York has two optional signs, WAIT FOR GREEN LIGHT and WAIT FOR GREEN ARROW for use at signalized intersections which they submitted in response to the questionnaire (Appendix A). The WAIT FOR GREEN LIGHT is used at intersections where motorists frequently enter the intersection before they receive a green indication, most commonly where the opposite intersection approach has a leading green phase. The WAIT FOR GREEN ARROW is used at left-turn lanes controlled by red, yellow, and green arrow indications with motorists frequently turning when the red arrow is displayed.

PAVEMENT MARKINGS

MUTCD Requirements

The MUTCD (*5*) establishes pattern and color for pavement markings to facilitate driver's understanding of their responsibilities relative to pavement markings. Yellow pavement markings separate opposing traffic flows and are used for left edge lines on divided roadways or one-way streets. White pavement markings separate traffic flowing in the same direction and are used for right pavement edge lines. Broken lines are permissive, solid lines are restrictive, and the width of line indicates the degree of emphasis in the pattern for pavement markings. Double solid lines are used for the maximum restriction in the pavement markings. A double solid yellow line is used to divide a two-way street, prohibit passing in both directions, and delineate the left-turn bay at an intersection. An older version of the Uniform Vehicle Code (1962) paraphrased to omit barriers indicated that when any highway has been divided into two roadways by leaving an intervening space, no vehicle shall be driven across or within such dividing space except through an opening in such dividing section. In 1971, an interpretation was added that this section does not apply to a median indicated only by paint (*43*). The state of California has maintained the wording of the older version revised to specifically prohibit left turns across a painted intervening space of at least 2 feet. It is the current wording and interpretation of the Uniform Vehicle Code (*8*), application of the MUTCD (*5*), and most states that left turns are not prohibited across painted medians. The general understanding is that lines on the pavement will not discourage vehicle turns if that is where the driver desires to go, so prohibition of left turns across painted medians is unenforceable.

The typical markings for left turn bays and lanes are shown in the MUTCD (*5*). The line pattern and color for markings permit or restrict particular vehicle maneuvers. The broken line adjacent to a solid line pattern for the two-way left-turn lane prohibits crossing the line in a longitudinal travel path along the roadway (passing) but does not restrict a left turn across the line. The white right edge line for the left-turn lane separates vehicles moving in the same direction and is partially restrictive to discourage motorists from pulling out of left-turn lanes once they have made that commitment. The Left Turn Arrow markings are optional in the two-way left-turn lane and a left-turn bay. It should be noted that the double left turn pavement arrow for a two-way left-turn lane is optional as approved in a Uniform Manual errata correction, November 2, 1989. A study by the city of Phoenix (*44*) on 380 miles of their streets with two-way left-turn lanes found that the left-turn pavement arrows are unnecessary and represent a pavement marking cost that cannot be justified. The study concluded that once drivers are familiar with the unique two-way left-turn lane markings that the pavement arrows should not be needed. A study by the Texas Transportation Institute (*45*) of Texas drivers found that 85 percent of the respondents correctly identified the solid-dashed line pattern for two-way, left-turn lane and the appropriate usage. The typical MUTCD markings for an intersection are shown in Figure 23. The lane lines approaching the intersection are white broken lines and are recommended in the following locations:

1. At approaches to major intersections.
2. At congested locations where the roadway will accommodate more than one lane so the lane lines can separate and distribute traffic in the lanes at the intersection.
3. On one-way streets and other roadways to obtain the maximum use of the existing roadway pavement.

When there is a mandatory turn lane, as illustrated Figure 23 (a) and (c), then the left-turn arrow is recommended (should) and the ONLY pavement legend is required (shall) when the pavement arrow is used. Appropriate signs and pavement legends are recommended in advance of the mandatory turn lane to prevent vehicle entrapment in the lane and to permit drivers to select their proper lane before reaching a line of waiting vehicles. The normal height of the ONLY and ARROW legends is 8 ft with a spacing of 4 to 10 times the legend height

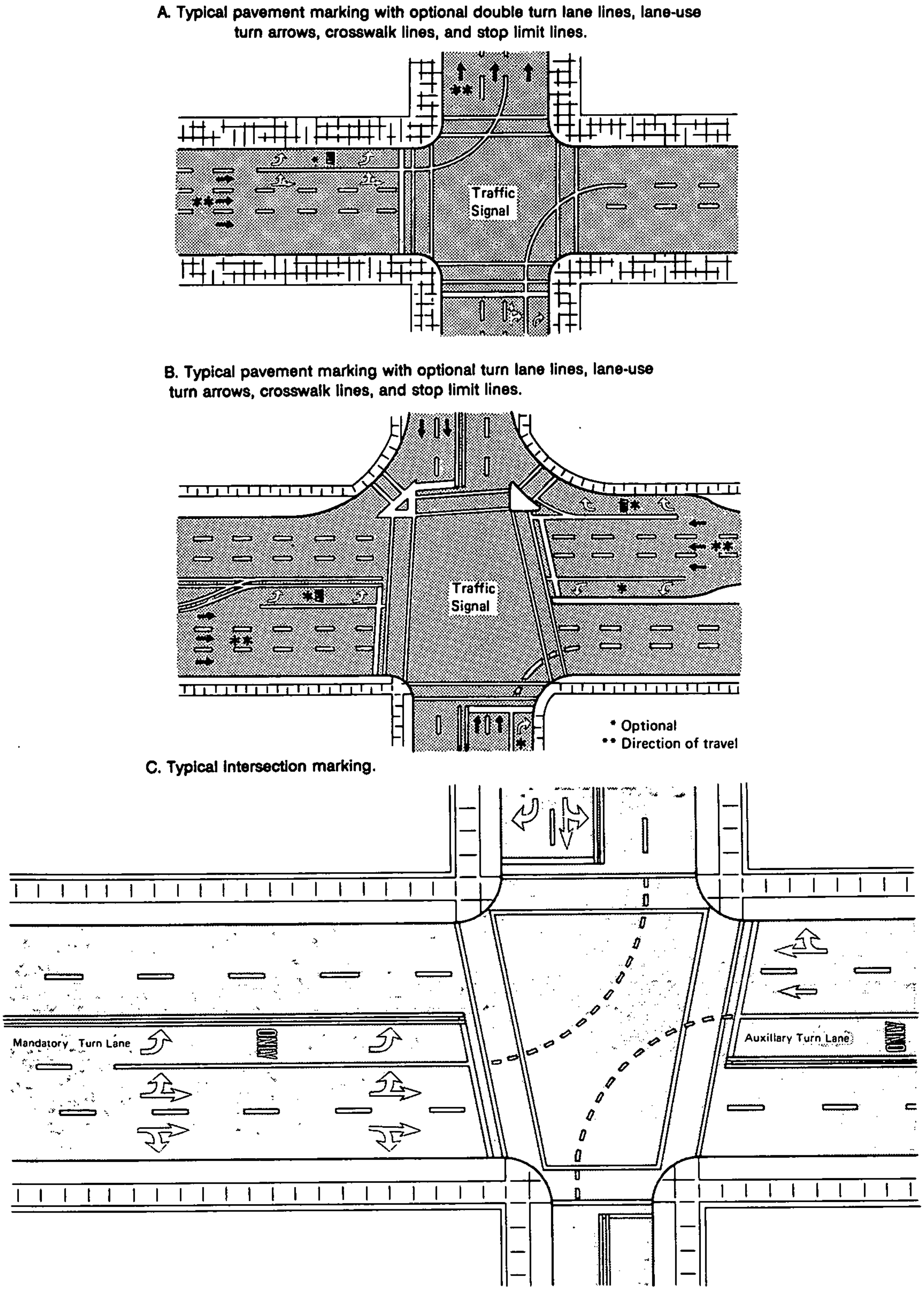


FIGURE 23 MUTCD Typical pavement markings for intersections. *(5)*

between legends. The legend size may be decreased by approximately one-third where traffic speeds are low. Note that a dotted line is shown in Figure 23 (c) to guide left turns through the intersection. Dotted lines are normally 2 ft in length with gaps of 4 ft or longer. The dotted line is recommended for dual and triple left-turn lanes to guide and separate adjacent turning vehicles.

Pavement Marking Variations

The MUTCD provides little specific guidance with respect to the formation of left-turn lanes using pavement markings. The design guidelines in Chapter 3 can be adapted to pavement markings for left-turn lanes and bays.

Montgomery County, Maryland, in response to the questionnaire, provided Figure 24 to depict its four options for left-turn lane markings. The application of the options is as follows:

Option No. 1—This is the most common application where the width of the island is the same as the left-turn lane. A deficiency in this design is that an aggressive driver travels across the neutral island area passing a slower driver or drivers respecting the neutral island area, which limits the storage capacity of the left-turn lane. The use of a left-turn arrow and ONLY legend is not needed except for extremely long left-turn lanes. The median island area should be crosshatched.

Option No. 2—This option is the same as Option No. 1 except the reverse curve is included as part of the median taper length. A dotted line is used to continue the redirection of traffic into the through lanes. The width of the island is less than Option No. 1 and provides an effective increase in the length of the left-turn lane. Crosshatching the island is usually required but the left-turn arrow and ONLY legend are not usually needed.

Option No. 3—This option may be used in special cases to maximize the left-turn lane storage length. A dotted line is used to redirect the traffic to the through lane although it has marginal redirection capabilities because left-turning traffic is encouraged to run over the dotted line. It does reduce the painting needs because a neutral island area is not provided. The left-turn pavement arrow and ONLY legend are required for this option.

Option No. 4—This option provides the maximum storage space while retaining the redirection capabilities of a double yellow line and a neutral island area. The 5-ft island width is small enough to discourage use by an aggressive driver and avoids the appearance of a trap lane. Crosshatching the island area is not required, although the width exceeds 4 ft for a short distance. The use of a left-turn arrow and ONLY legend may be required but is not mandatory.

The Idaho Transportation Department in response to the questionnaire provided Traffic Manual and Standard Drawings of typical pavement marking and signing diagrams for left-turn lanes as illustrated in Figure 25 and Figure 26.

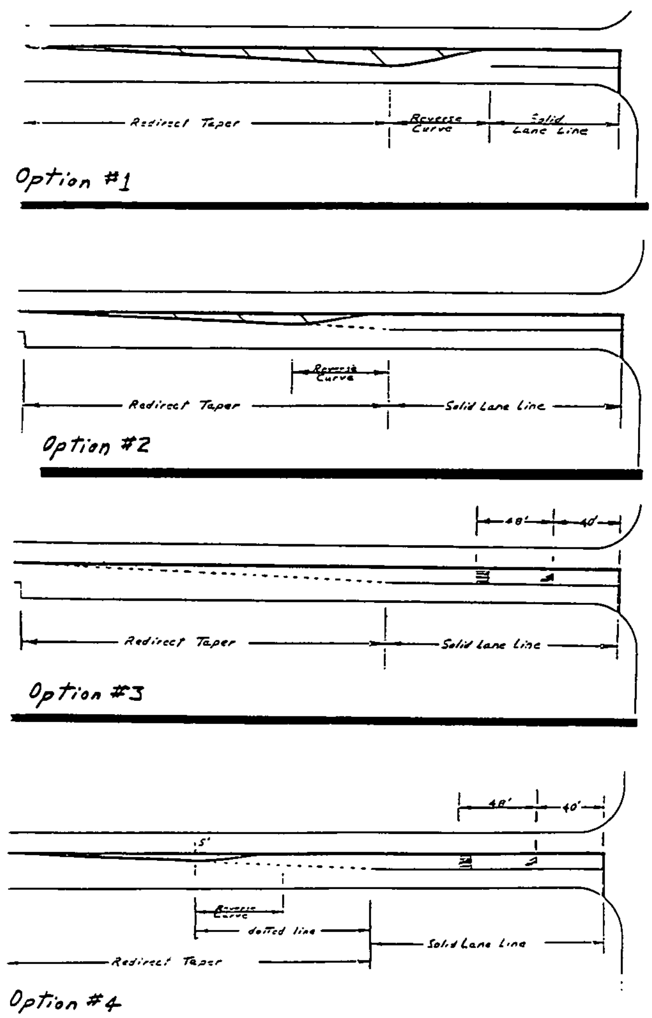


FIGURE 24 Left-turn lane marking options, Montgomery County, Maryland.

SPECIAL APPLICATIONS

Multiple Left-Turn Lanes

The use of dual left-turn lanes is becoming very common at major intersections and triple left turns are not uncommon. Multiple lanes can be one of three design types: completely shadowed, outside left-turn lane as a mandatory turn or a trap lane, and the outside lane as an optional turn or through lane, as illustrated in Figure 15. The MUTCD recommends that lane-use control signs, R3-5 and R3-6, be used over the lanes for each left-turn lane. Overhead advance lane-use control signs are also desirable for triple left-turn lanes, as addressed in Chapter 3.

The left-turn pavement arrow would be required for the trap and optional left-turn lanes with an ONLY legend with the trap lane arrow. It is desirable that left-turn arrows be used in each multiple turn lane to emphasize that more than one lane of traffic will be making the left turn. A dotted line through the intersection is useful to guide left-turning vehicles through their turning maneuver and to separate the two or more lanes of traffic (Figure 23c).

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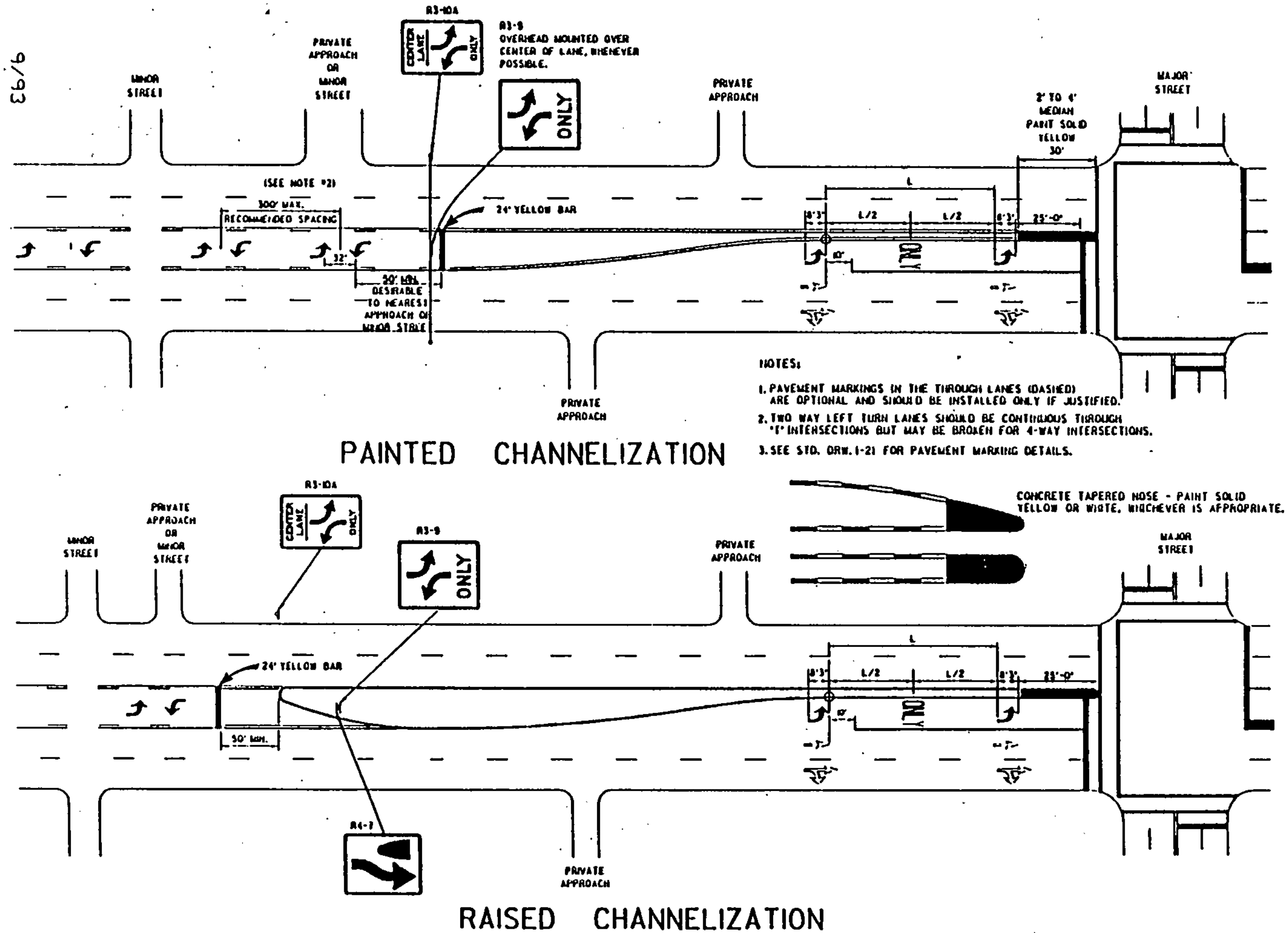


FIGURE 25 Guidelines for painted and raised channelization, Idaho.

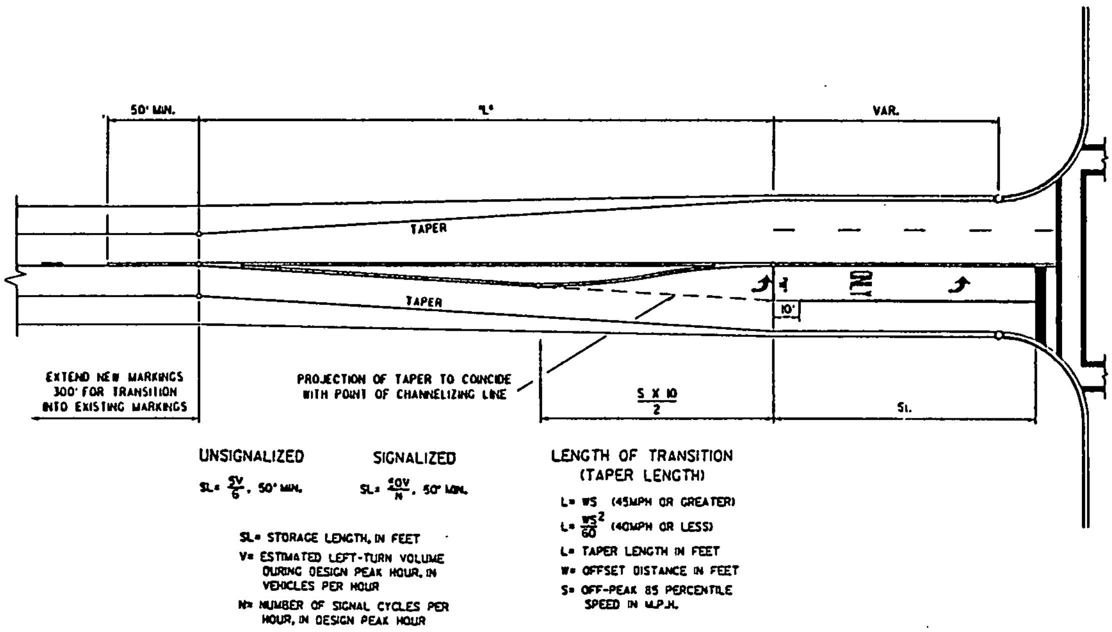


FIGURE 26 Guidelines for left-turn bay and tapered roadway section, Idaho.

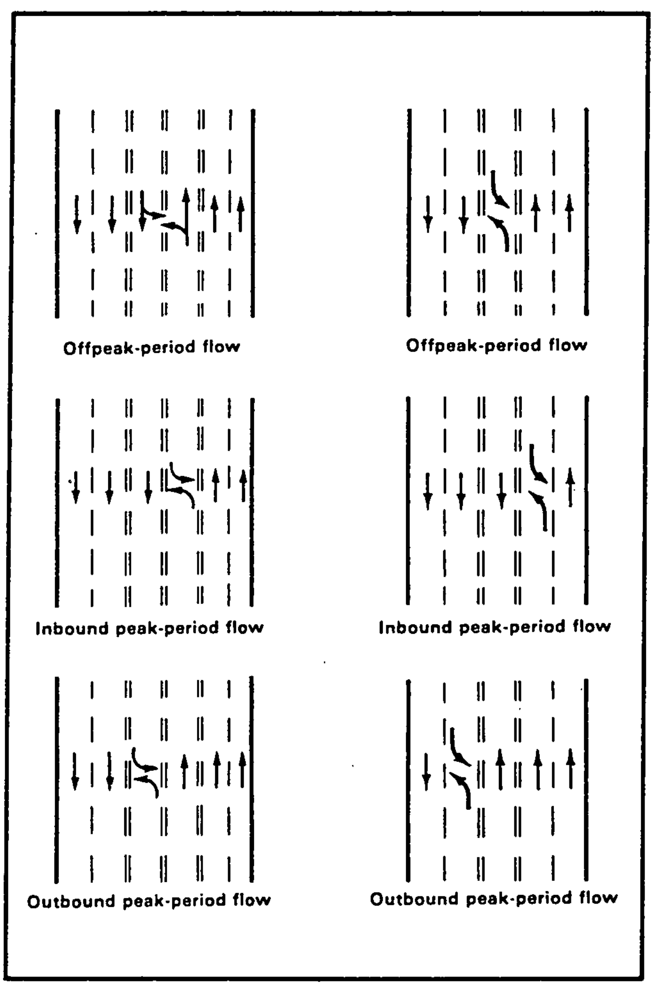


FIGURE 27 Examples of reversible lanes and left-turn patterns. *(46)*

Reversible Lanes

Reversible traffic lane operations are being used more frequently on urban arterials to provide a low-cost improvement for relief of traffic congestion. However, reversible lane operations require the careful consideration of left-turn treatments at intersections and for property access. If left turns are not totally prohibited throughout the length of the reversible lane, then they must be accommodated in the reversible lane design and operations. Examples of special reversible lane use with left turns accommodated are illustrated in Figure 27 (*46*). The cities of Phoenix and Tucson are using reversible lane operations during peak hours on a typical five-lane roadway with the center lane directional in the peak periods and a two-way, left-turn lane during off-peak periods implemented by static signs only.

The MUTCD has not been specific on traffic controls for reversible lanes and does not mandate particular signs or signals. However, new revisions and changes to the MUTCD have been recommended and are expected to be incorporated in the next edition. The new requirements indicate that a traffic engineering study should be conducted to determine whether a reversible lane operation can be controlled satisfactorily by static signs or whether lane use control signals are necessary.

The static reversible lane control signs are an option to lane-use control signals based on an engineering study. The signs comprise words and symbols as shown in Figure 28 indicating the type of lane use and time of day that use is applicable. The maximum spacing of the overhead lane control signs shall be one-quarter mile.

The city of Tucson, Arizona, has reviewed reversible lane operations on two-way, left-turn lanes throughout the country

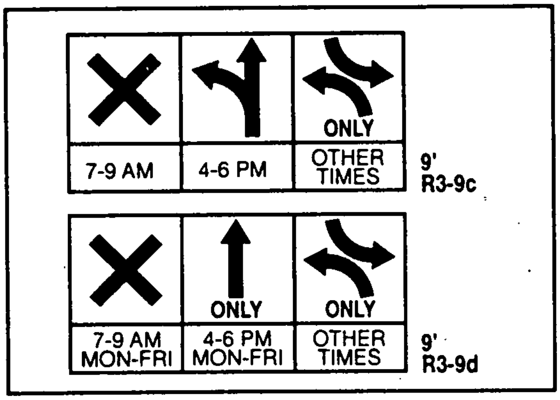


FIGURE 28 MUTCD static reversible lane-use control signs. *(5)*

relative to its application in Tucson *(47)*. Nineteen reversible lane operations were identified in the United States, 15 of which are still in operation. A review of the accidents at those locations found that operations using signs/signals had 2.15 accidents/mvm (million vehicle miles), operations with signs/cones had 2.01 accidents/mvm and static sign-only operations had 1.76 accidents/mvm. The static sign-only operations had more accidents than single reversible lane operations involving left turns across the reversible lanes and sideswipe collisions out of the reversible lane. Other accidents, such as rear-end, head-on, and other left-turn maneuvers were fewer on the signs-only reversible lane operations. The installation costs ranged from the least expensive, overhead static sign system, at $40,000 per mile, to the more expensive lane control signal system at $400,000 per mile.

CHAPTER FIVE

TRAFFIC SIGNALS

MUTCD REQUIREMENTS

The operation of a left-turn movement at a signalized intersection involves a number of choices, depending on the left-turn option. These choices impact the number and location of traffic signal indications, phasing of the traffic signal, and signing to be installed with the left-turn signals. Left-turn phasing is a complex subject requiring consistent, nationally uniform, and understandable left-turn displays to reduce any driver confusion. The following material is a clarification of the MUTCD requirements provided by the Traffic Signals Technical Committee to establish a clear understanding of the MUTCD left-turn signal provisions (*48*). To determine the proper left-turn signal displays, the mode of left-turn operation must be determined. The modes of left-turn operation are defined as follows in the proposed MUTCD revisions:

Permitted Mode—a mode of traffic control signal operation in which left or right turns may be made when a CIRCULAR GREEN indication is displayed after yielding to oncoming traffic and/or pedestrians.

Exclusive Mode (formerly "protected mode")—a mode of traffic control signal operation in which left or right turns may be made only when a left or right GREEN ARROW indication is displayed and there is no conflict with other traffic or pedestrians.

Permitted and Exclusive Mode—a mode of traffic signal operation in which the left-turn movement may be protected by the exclusive mode during part of the signal cycle and be unprotected in the permitted mode during another part of the cycle.

General Requirements for All Modes

Several requirements apply to all of the modes of left-turn signal operation. The MUTCD (*5*) requires minimum and maximum distances of the traffic signal faces from the intersection stop bar, lateral location of the traffic signal displays within the motorist's cone of vision, and size of the traffic signal display. There is a requirement that primary traffic signal faces, i.e. those for straight-through traffic movements, shall have a minimum of an 8-ft separation, but this requirement does not apply to the distance between a primary traffic signal face and a separate left-turn signal face. The position of the separate left-turn signal face should make it readily visible to left-turning drivers and overhead supported signal faces should be located in line of the drivers' normal view. A pedestrian WALK and flashing DON'T WALK signal shall not be displayed for a pedestrian movement and concurrently with a green arrow for a conflicting left-turn movement during the exclusive left-turn mode. The various MUTCD combinations of signal lens displays are illustrated in Figure 29. The Signals Technical Committee of the National Committee on Uniform Traffic Control Devices (NCUTCD) has developed a series of figures with application notes summarized below to clarify the signalization of left-turn movements (*48*).

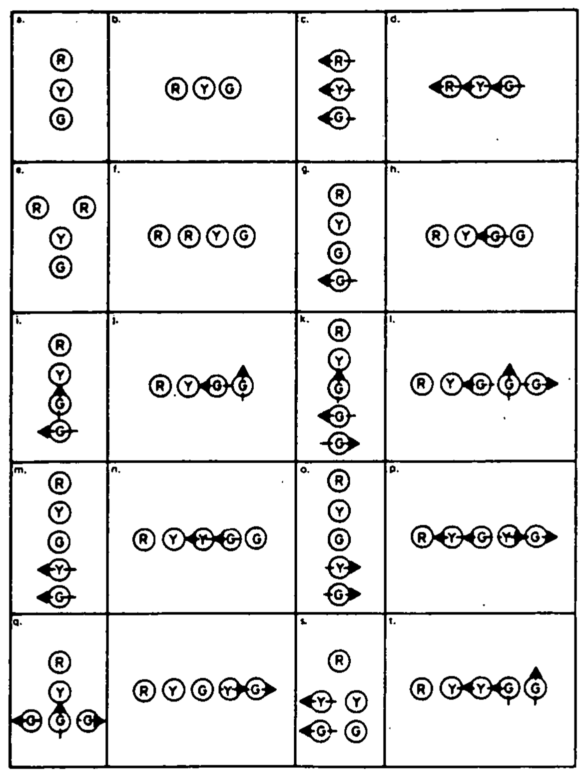
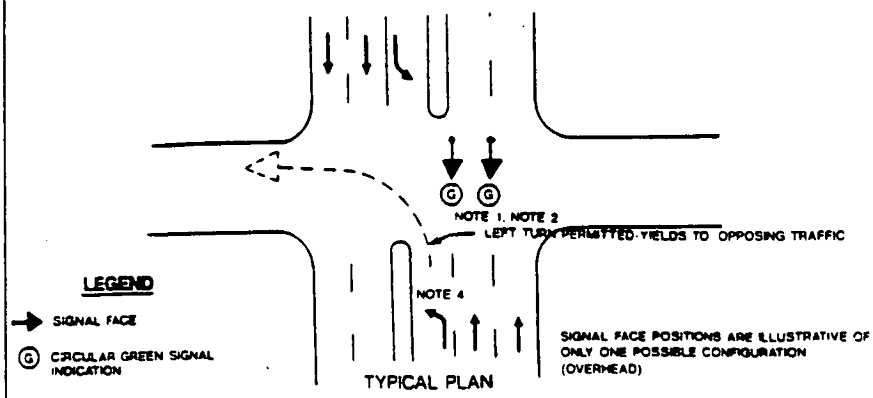


FIGURE 29 MUTCD typical arrangement of lenses in signal face. (*5*)

Permitted Only Mode (Figure 30)

This mode provides no separate protected signal indication for the left-turn movement and consequently, the left-turn arrow is not used for the left turn. The left-turn movement does not require a separate signal face but may operate off of the straight-through signal indications. The MUTCD provides that a separate left-turn signal face may be used but the signal indications must be identical to the primary signal faces for that approach, i.e. circular red-yellow-green. Some jurisdictions have reservations on providing a separate signal face for left turns on the permitted mode because drivers may perceive that it provides them an exclusive or protected left turn. No regulatory or information sign is required for this mode of



PERMITTED INTERVAL: CIRCULAR GREEN ALONE [SECTION 4B-6.3]
CHANGE INTERVAL: CIRCULAR YELLOW ALONE [SECTION 4B-6.2(a)]
PROHIBITED INTERVAL: CIRCULAR RED ALONE [SECTION 4B-6.1(a)]

1. **Separate signal face for left turns not required, but if used it shall be identical to the display for thru traffic (Section 4B-12.3[a]).**
2. **Lateral signal face position with regard to left turning motorists is not specified.**
3. **No type of regulatory "Left Turn" sign is required. Informational type signs; e.g., "Left Turn Yield on Green (symbolic green ball)" (R10-12) may be used, but are not required.**
4. **A dedicated left turn lane is desirable, but not required.**

FIGURE 30 MUTCD signal display for "permitted only" mode left turns. *(48)*

operation but if one is used it must be the LEFT TURN YIELD ON GREEN (symbolic green ball), R10-12. Additionally, a separate left-turn lane is not required because the left turns move at the same time as the through traffic, but must yield to the opposing traffic. The need for a dedicated left-turn lane depends on roadway geometrics, left-turn storage requirements, vehicle delay, visibility, and other considerations as addressed in Chapter 3.

Exclusive Only Mode (Figure 31)

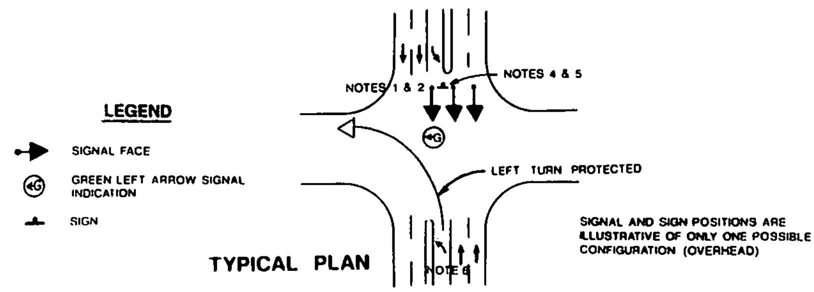
The left-turn movement is allowed only during the exclusive left turn interval with the display of a GREEN ARROW in a separate signal face for the left-turn movement. Note that the exclusive mode cannot be implemented by merely adding a green arrow indication to one of the primary or through-traffic signal faces. Two separate left-turn signal faces should be provided for approaches that have more than one exclusive left-turn lane.

The left-turn signal faces can consist of either (a) CIRCULAR RED, YELLOW ARROW, GREEN ARROW, or (b) RED ARROW, YELLOW ARROW, GREEN ARROW. A previous option of CIRCULAR YELLOW has been eliminated because the Manual mandates a yellow arrow change interval following a green arrow. Option (a) CIRCULAR RED, must be accompanied by a LEFT TURN SIGNAL sign (R10-10) unless the circular red indication is visually restricted from through traffic. A regulatory or information sign is not required with option (b) All Arrows but if one is used it must be LEFT ON GREEN ARROW ONLY (R10-5). Contrary to past practices in some jurisdictions, the red indication shall not be illuminated in conjunction with the green arrow indication.

Exclusive-Permitted Mode (Figure 32)

This mode of operation has an exclusive left turn during part of the signal cycle and a permitted left turn during another part of the cycle where the left turn must yield to opposing traffic during the circular green indication. A variety of signal sequences can be used for this mode, such as leading or lagging exclusive turn intervals with the adjacent through traffic stopped or moving concurrently with the left turn. This mode of operation is the most complex, has the greatest number of nonconforming signal displays, and can be the most confusing to inexperienced drivers.

The MUTCD (*5*) requires that all circular indications of the same color in all signal faces on each intersection approach must be simultaneously illuminated. This requires that the circular red for the left turn indications must be illuminated and terminated at the same interval as the circular red for the primary or through-traffic signal phases. The circular green for the left turn must also start and end at the same time for all signal indications on that intersection approach. This assures drivers of a uniform display between jurisdictions, avoids unexpected indications, and avoids some driver confusion from adjacent signal heads indicating conflicting messages. A



SEPARATE SIGNAL FACE FOR LEFT TURN

PROTECTED INTERVAL: GREEN LEFT ARROW ALONE [SECTION 4B-6.6]
CHANGE INTERVAL: YELLOW LEFT ARROW ALONE [SECTION 4B-6.5 (b)]
PROHIBITED INTERVAL: CIRCULAR RED ALONE [SECTION 4B-6.1]OR
: RED LEFT ARROW ALONE [SECTION 4B-6.4 (d)]

R Y G OR R Y G ONLY

NOTES

1. At least one separate signal face required to control the left turn in addition to the minimum two signal faces required for thru traffic (Section 4B-12.3[b]).
2. If two or more separately-controlled left turn lanes, two separate left turn signal faces should be provided (Section 4B-12.3[e]).
3. Position of separate left turn signal face should make it readily visible to those motorists (Section 4B-12.8).
4. If separate left turn signal face(s) consists entirelyy of arrow indications, no information sign is necessary, but if used it shall be "Left on Green Arrow Only" (R10-5).(Section 4B-12.3[b][1]).
5. If separate left turn signal face(s) contains a circular red indication, a "Left Turn Signal" sign (R10-10) located adjacent to the separate signal face(s) is required, unless the separate signal face(s) are shielded, hooded, louvered, positioned, or designed so that the conflicting indication (circular red) is not confusing to approaching drivers (Sections 4B-6.7 and 4B-12.3[b][2]).
6. A dedicated left turn lane(s) is necessary.

FIGURE 31 MUTCD signal display for "exclusive only" mode left turns. *(48)*

widely used application for this mode is to add a YELLOW ARROW and GREEN ARROW to a primary signal face with the signal head located between the left-turn and through lanes, as illustrated in Figure 29 "m" and "n".

No regulatory or information signs are required with the exclusive-permitted mode. If a sign is used, it must be LEFT TURN YIELD ON GREEN (symbolic green ball), (R10-12). Neither the LEFT ON GREEN ARROW (R10-5) nor LEFT TURN SIGNAL (R10-10) are appropriate signs for the exclusive-permitted signal mode.

Split Phase Operation (Figure 33)

Split phasing of the intersection approach movements may occur under various signal operation modes, as described in Figure 33. The split phasing of the intersection approaches is sometimes used for offset intersections (opposing traffic maneuvers conflict), for capacity reasons when left turns share a lane with through movements or when the opposing left turn is minor and left-turn accidents are a problem.

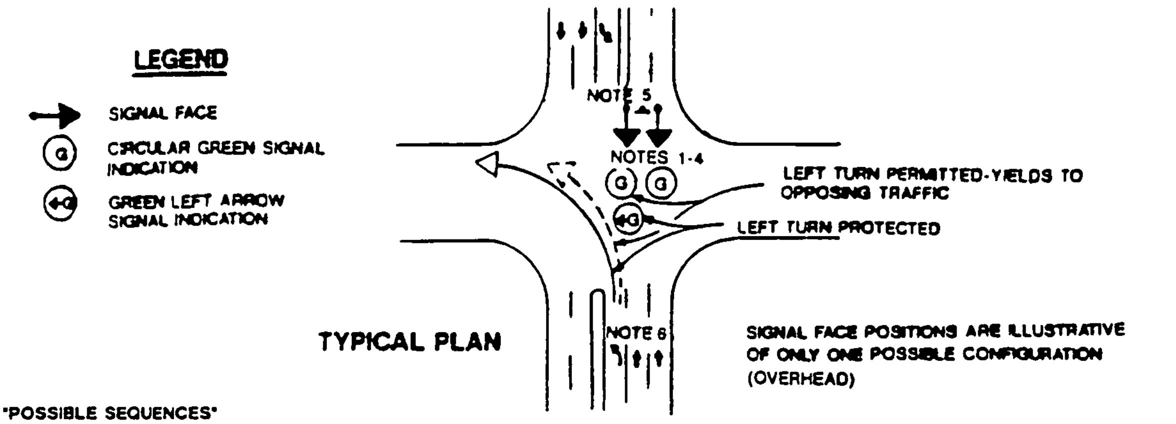
MUTCD Revisions

The MUTCD (*5*) is currently being rewritten with the above requirements to be incorporated in the new manual. The Federal Highway Administration provided an MUTCD Interpretation in 1993 ruling that if the five-section display for the left turn was shielded, hooded, louvered, positioned, or designed so that the left turn displays are not seen by through movement drivers, then the left-turn lane would not be considered to be the same approach as the through lanes. The MUTCD presently requires that circular displays for the left turn shall be illuminated concurrently and at the same intervals as the through lane traffic signal displays. As discussed in Chapter 7, research presently being implemented relative to traffic signal displays for protected-permitted left turns should resolve this issue.

CRITERIA FOR EXCLUSIVE LEFT-TURN PHASE

Traffic Studies

The requirement for separate left-turn traffic signal phasing at an intersection is based on the left-turning volumes, vehicle delay, visibility, and safety of the intersection. If there is not a separate left-turn lane and the left turns operate out of a shared lane, then the need for a separate left-turn phase is a function of the number of left turns, number of opposing vehicles and conflicting pedestrians that delay the left-turning vehicles, and



"POSSIBLE SEQUENCES"

CASE A. ADVANCE (LEADING) LEFT TURN - SAME DIRECTION THRU VEHICLES MOVING CONCURRENTLY WITH LEFT TURN (Opposing left turn is stopped, prohibited, or impractical during advance left turn.)

Protected interval: Green left arrow with circular green is required [Sections 4B-6.6(b) and 4B-12.3(c)(1)].

Change interval from protected to permitted: Yellow left arrow, concurrent with continuing circular green, is required [Sections 4B-6.5(c) and 4B-15] because thru motorists on the same approach are displayed a circular green and all signals are approach signals [Section 4B-12.3(c)(3)].

Permitted interval: Circular green [Sections 4B-6.3 and 4B-12.3(c)].

Change interval at termination of all movements on approach: Circular yellow [Sections 4B-6.2 and 4B-15].

Prohibited interval: Circular red [Section 4B-6.1(a)].

CASE B. ADVANCE (LEADING) LEFT TURN - SAME DIRECTION THRU VEHICLES ARE STOPPED (Opposing left turn, or other movements conflicting with thru vehicles, move concurrently with advance left turn).

Protected interval: Green left arrow with circular red is required [Sections 4B-6.1(b), 4B-6.6(b), and 4B-12.3(c)(1)].

Change interval at termination of protected interval: yellow left arrow, concurrent with circular red, is required [Section 4B-6.5(a)] because thru motorists on the same approach are displayed a circular red and all signals are approach signals [Section 4B-12.3(c)(3)].

Permitted interval: Circular green [Sections 4B-6.3 and 4B-12.3(c)].

Change interval at termination of all movements on approach: Circular yellow [Sections 4B-6.2 and 4B-15].

Prohibited interval(s): Circular red [Section 4B-6.1(a)].

CASE C. TRAILING (LAGGING) LEFT TURN - SAME DIRECTION THRU VEHICLES MOVING CONCURRENTLY WITH LEFT TURN (Opposing left turn is stopped, prohibited, or impractical during the trailing left turn).

Permitted interval: Circular green [Sections 4B-6.3 and 4B-12.3(c)].

Protected interval: Green left arrow with circular green is required [Sections 4B-6.6(b) and 4B-12.3(c)(1)].

Change interval at termination of protected interval:

If the protected left turn interval is terminated simultaneously with the termination of the circular green interval for thru vehicles in the same direction, circular yellow is required [Section 4B-6.2] and a yellow left arrow may also be displayed concurrently with the circular yellow.

If skipping of actuated phases results in the circular green for thru traffic continuing at the termination of the protected left turn interval, a yellow left arrow is required concurrent with the continuing circular green (as in Case A).

Prohibited interval: Circular red [Section 4B-6.1(a)].

CASE D. TRAILING (LAGGING) LEFT TURN - SAME DIRECTION THRU VEHICLES ARE STOPPED (Opposing left turn, or other movements conflicting with thru vehicles, move concurrently with trailing left turn).

Permitted interval: Circular green [Sections 4B-6.3 and 4B-12.3(c)].

Change interval from permitted to protected: Circular yellow is required [Section 4B-6.2] because all signals are approach signals.

Protected interval: Green left arrow concurrent with circular red is required [Sections 4B-6.1(b), 4B-6.6(b) and 4B-12.3(c)(1)].

Change interval at termination of protected interval: Yellow left turn arrow concurrent with circular red is required [Section 4B-6.5(a)] because thru motorists on the same approach are displayed a circular red and all signals are approach signals [Section 4B-12.3(c)(3)].

NOTES

1. All circular indications of the same color facing through motorists as well as left turning motorists shall be simultaneously illuminated; i.e., all are approach signal faces [Section 4B-12.3(c)(3)].
2. The green left arrow, and yellow left arrow intervals (except where not required) are timed independently of all circular indications.
3. Lateral signal face position with regard to left turning motorists is not specified.
4. A separate signal face for left turns in addition to the two for thru traffic is not required, but if provided it shall be an approach signal (See Note 1 above) [Section 4B-12.3(c)(3)].
5. "Left Turn Signal" or "Left on Green Arrow Only" signs shall not be used. "Left Turn Yield on Green" (symbolic green ball)" (R10-12) signs may be used, but are not required [Section 4B-12.3(c)(4)].
6. A dedicated left turn lane is necessary if the sequence has a green left arrow shown at any time when the approach signal faces are not green. Otherwise, a dedicated left turn lane is desirable but not necessary.

FIGURE 32 MUTCD signal display for "exclusive-permitted" mode left turns. *(48)*

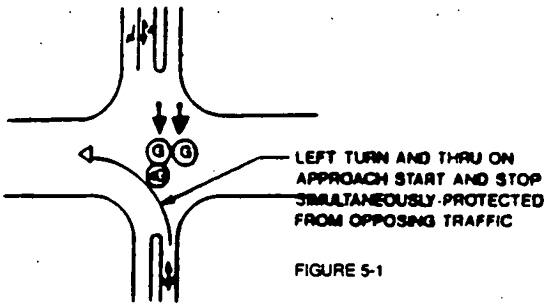


FIGURE 5-1

FIGURE 5-1 - DISPLAY AS CASE "C" OF "PERMITTED AND PROTECTED" MODE

- See Figure 3 - "Case C" for requirements. All signals are approach signals.
- Green left arrow with circular green is required during the protected right-of-way for the approach [Section 4B-6.6(b)], except that the green left turn arrow cannot be displayed if the left turn conflicts with pedestrians [Section 4B-6.6(a)].
- Yellow left arrow may be displayed concurrently with the circular yellow during the change interval at end of approach right-of-way if a green left arrow was displayed during the protected right-of-way.

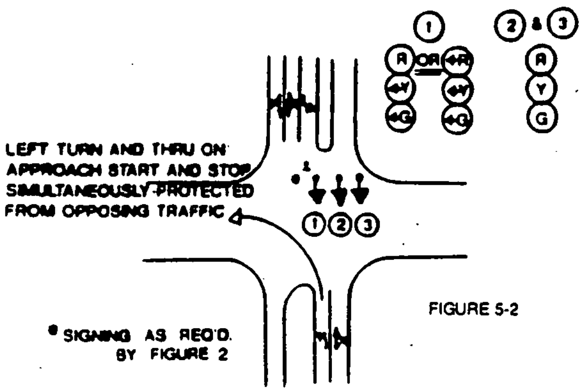


FIGURE 5-2

FIGURE 5-2 - DISPLAY AS "PROTECTED ONLY" MODE

- Separate left turn signal face or faces for the dedicated left turn lane(s).
- See Figure 2 for requirements.
- For change interval at termination of protected right-of-way for the approach, yellow left turn arrow is displayed in the left turn signal face(s) simultaneously with circular yellow in the thru signal faces.

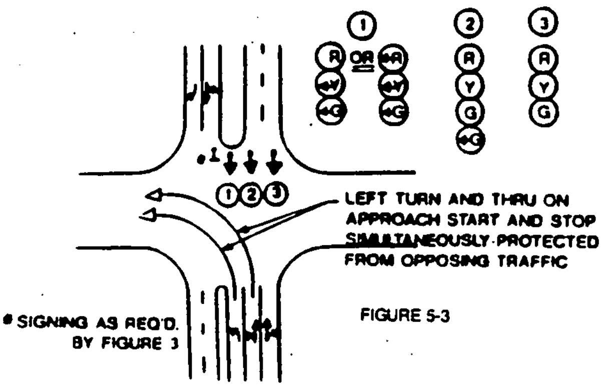


FIGURE 5-3

FIGURE 5-3 - COMBINATION OF DISPLAYS

- Separate left turn signal face(s) operated and signed as per Figure 2.
- For the change interval at the termination of the protected right-of-way for the approach, yellow left turn arrow is displayed in the separate left turn signal face(s).
- Control of the other lanes on the approach (including the shared thru/left lane) is by a minimum of two signal faces operated as per "Case C" of Figure 3, the left-most of these two faces must have a green left turn arrow displayed with the circular green during the protected right-of-way for the approach.
- Circular yellow change interval is required at the termination of the right-of-way for the approach (and a yellow arrow may also be displayed concurrent with the circular yellow). This change interval occurs simultaneously with the yellow left turn arrow change interval display in the separate left turn signal face(s).
- Signs such as "Left Turn Signal", "Left on Green Arrow Only", or "Left Turn Yield on (symbolic green ball)" are not appropriate to be displayed with these signal faces.

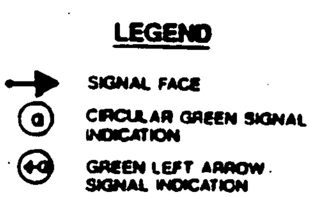


FIGURE 33 MUTCD signal display for "split phase" mode left turns. *(48)*

number of straight through vehicles that are delayed behind the left-turning vehicle, as addressed in Chapter 2. If a left-turn lane exists, then the need is a function of the number of left-turning vehicles, and opposing traffic and conflicting pedestrian movements that delay the left turn. At some intersections, limited visibility by the left-turning vehicles may require a separate left-turn signal phase to ensure an adequate gap in opposing traffic to make the left turn. It should be recognized that while a separate phase may reduce delay for left-turning traffic, it could result in more overall intersection delay because it takes traffic signal green time away from the heavier intersection movements. As noted in Chapter 2, the intersection should be observed in the field at least during peak hours with traffic data collected relative to the left-turn operations.

Representative examples of current values used by agencies to justify separate left-turn phasing are as follows (*49*):

- The product of left-turning vehicles and conflicting through vehicles during the peak hour is greater than 100,000 (or 50,000).
- Left-turn volumes greater than 100 (or 90) vehicles during the peak hour.
- Left turn peak period volumes greater than two vehicles per cycle per approach still waiting at the end of green (for pre-timed signals).

These criteria require that the left-turning traffic and through traffic be counted during the peak hours and during the off-peak periods. As noted, it is also desirable to know the number of delayed left-turn vehicles, the extent of their delay, and the number of pedestrian conflicts. Field observation also provides the opportunity to observe the intersection operations, noting those vehicle maneuvers that could be improved with a left-turn signal phase. Intersection traffic models described later can use the same data to simulate the intersection operations for determination of delay.

Geometrics

It is not desirable to provide an exclusive left-turn signal phase without a separate designated left-turn lane to store the left-turning traffic and to separate the left turns from the through traffic. Many jurisdictions, as a practice, will reconstruct the intersection to provide left-turn lanes in conjunction with any new traffic signal installation. Then the left-turn lane is available when an exclusive left-turn phase is needed. The minimum street width to accommodate a left-turn lane is 31 ft, providing 11-ft through lanes and a 9-ft left-turn lane (*25*). This width is not adequate if there is a significant amount of bus or truck traffic using the intersection. The desirable approach width would be 36 ft, providing three 12-ft traffic lanes for through movements and the left turn.

Safety Considerations

The improvement of an intersection to provide a traffic signal, left-turn lane or a separate left-turn signal phase can reduce some accidents but may increase others. Usually, right angle collisions are decreased with a signal installation, but there is an increase in rear-end accidents because of the vehicle queued at the signal. A left-turn lane will decrease the rear-end accidents involving turning vehicles but may increase the head-on or left-turn vehicle accidents depending on signal phasing for the left-turn maneuver. It may also increase accidents involving pedestrians who must cross a wider road. The intersection improvement may increase the accident frequency, but should reduce the accident severity.

A study of newly installed traffic signals in Michigan (*50*) verified the above historical safety benefits of a traffic signal. The following were the findings when comparing before and after accident statistics where a left-turn lane was added coincident to the signal installation, the study found:

- The head-on, left-turn accident rate increased by 7 percent. This may be explained by the attraction of more left-turning traffic because of the left-turn lane and the practice in Michigan to rarely install an exclusive left-turn phase when the signal is initially installed.
- The total accident rate was reduced 31.7 percent which was statistically significant.
- Right angle and injury accident rates were reduced by 63.5 and 44.2 percent, respectively, and the differences between the before and after accident rates were statistically significant.
- The rate for other types of accidents was reduced significantly (by 33.1 percent) as it was for locations with and without a left-turn lane.

The California Department of Transportation (*4*) has found that left turn channelization will result in a 15 percent reduction in all accidents with no left-turn signal phase and a 35 percent reduction in all accidents with a left-turn signal phase.

SIGNAL DESIGN AND INSTALLATION

Signal Head Placement

The MUTCD (*5*) does not require a separate signal head for the left-turn movement in the permitted only mode yielding to conflicting opposing traffic. The left-turning vehicle operates with the through traffic signal indications, a circular green, which is terminated with a circular yellow and circular red. The signal head placement for this permitted left-turn maneuver can be retained in the same location as for the through lane, such as an overhead signal head in the center of the through-traffic lane. The MUTCD does require that each signal face be adjusted so that its indications will be of maximum effectiveness to the approaching traffic for which it is intended. Some jurisdictions relocate the traffic signal head to be on the lane line between the through-traffic lane and the left-turn lane for the permitted left turn with circular signal indications.

The placement of a five-section signal head on the lane line between the left-turn and through-traffic lanes for exclusive-permitted left-turn phasing was initially recommended by Agent (*35*) and later adopted by the Florida ITE Section (*36*). The basis for their recommendations can be summarized as follows:

- The shared traffic signal head for the left turn and through movement can serve as the second traffic signal indication required for the through-traffic movement.
- A supplemental sign adjacent to the signal head is not required and would not be recommended because of the confusion for through traffic.
- The shared traffic signal head connotes the shared intersection usage with the permitted left-turn signal operations.

Another study of 1,600 drivers in Nebraska (*34*) found that a five-section head centered over the left-turn lane had a statistically better driver understanding than the shared signal head on the lane line as noted above but the increased understanding was only 4 to 5 percent.

The exclusive (protected) left-turn signal phase requires a separate signal face to control the left-turn movement. This signal face is normally located in line with the center of the left-turn lane, either overhead on the far side of the intersection or median ground-mounted. Older signal installations have used the median ground-mounted installations because of the limited span of traffic mast arms. This application has decreased because of the exposure of the ground-mounted signals to collision and the availability of longer signal mast arms. In some cases, the separate signal for the left-turn lane has been mounted over the lane line between the left-turn and through lanes to reduce signal mast arm length. The MUTCD requirements of dual signal indications and 8 ft of horizontal separation between signal faces does not apply to left-turn signal indications. However, the MUTCD does require that the signal face mounted on a span wire or mast arm should be located as near as practical to the driver's normal line of sight. An additional far-left, left-turn signal that eliminates the need to look away from opposing traffic to see the signal has been suggested by McCoy (*51*) as a desirable feature for older drivers.

Supplemental signal faces may be used where an engineering study has shown they are needed to achieve both advance and intermediate intersection visibility. The MUTCD does not permit the display of left-turn arrows on near side right signal faces. Conversely, right turn arrows cannot be displayed in far-left installations or far-side median installations. Several jurisdictions always install a far-left, left-turn signal installation with multiple left-turn lanes.

Signal Display

The various possible arrangements of signal lenses are illustrated in Figure 29 showing both the horizontal and vertical mounting patterns. The usual display would be red, yellow, and green arrows as shown in Figure 29(c) which does not require the use of a supplemental sign, LEFT TURN SIGNAL (R10-10). If a circular red, yellow arrow, and green arrow configuration is used, then the supplemental sign is required (R10-10) unless the signal head is shielded, louvered, or visually restricted from the through traffic on that approach.

The exclusive-permitted left-turn signal display is more complicated in that the signal indication must provide for both exclusive and permitted left turns during the signal phase. The normal arrangement of signal displays is a five-section signal face vertical or horizontal and the "dog-house" arrangement shown in Figure 29(s). The signal display sequence for a lead-left turn is shown in Figure 36.

Vehicle Detection

Vehicle detectors in traffic signal installations have either recognized the presence of a moving or stopped vehicle, recognized passage of a moving vehicle by completing a circuit, or recognized changes in an electrical or magnetic field. When coupled with a signal controller unit, detectors are used to derive volume, vehicle speed, lane occupancy, and queue lengths and to infer congestion, incidents, stops, and delay. Detector types include: pressure (pads), magnetic, magnetometers, sonic, radar, microwave, and infrared; inductive loops are the most common. The manufacturers' literature on each type of detector and the FHWA Traffic Detector Handbook (*52*) provide detailed information on application, installation, and operation of vehicle detectors. Vehicle detection is required in the left-turn lane for actuated signal control if the left-turn lane is provided with a separate signal phase. Placement of the detector in the left-turn lane will depend on traffic speeds and mode of left-turn signal operation. Some jurisdictions use a small presence loop detector at the left-turn lane stop bar to detect the presence of a vehicle in the left-turn lane before calling the left-turn signal phase. Other jurisdictions use a detection loop located back from the stop bar so that three or four vehicles must be queued in the left-turn lane to detect presence and call the protected left-turn phase. A delayed call presence detector may also be used so that the protected left-turn phase is only called if the left turns are unable to make a permitted left turn and are delayed in the left-turn lane requiring a protected left-turn phase.

PHASE SEQUENCE

Options

There is a wide selection of signal phasing to accommodate the left-turn movement. The objective is to provide minimum delays to the heavier through-traffic volumes while accommodating left-turn maneuvers in relative safety without extensive delays. The special phasing of left-turn movements will always require the exercise of some engineering judgment since the provision for left-turn signal green time will detract from the through traffic green time, requiring some balance between signal phases for the total intersection.

A sample of the data needed to determine the best option for left-turn phasing has been suggested by Jonathan Upchurch (*53*) as follows:

- Left-turn volumes (hourly during peak hour),
- Cycle length,
- Opposing traffic during peak hour of highest left turn demand,
- Number of opposing traffic lanes,
- Speed of opposing traffic,
- Available sight distance, and
- Accident history including left-turn accidents.

Additionally, a time-space diagram showing traffic signal progression for adjacent signal installations should also be reviewed. A left-turn phasing decision tree is provided by Upchurch (Figure 34) to determine a recommended option. His recommended procedure is based on existing practice, vehicle delay, and safe intersection operations using the data collected above.

The University of Texas at Arlington (*39*) has developed guidelines for left-turn phasing based on research, actual field data, easy-to-use quantitative measures, and statistical analysis of most suitable left-turn options. The process favors the least restrictive, permitted left-turn option, unless traffic and geometrics warrant more restrictive control. The selection process recognizes the trade-off between operational efficiency and safety.

The decisions to be made are classified into three levels summarized as follows (Refer to Figure 35):

Level 1: Permissive Only versus Some Protection

- The permissive option should be used only if the plotted point of the peak-period left-turn volume and opposing traffic speed limit falls in the shaded portions of Figure 35, and

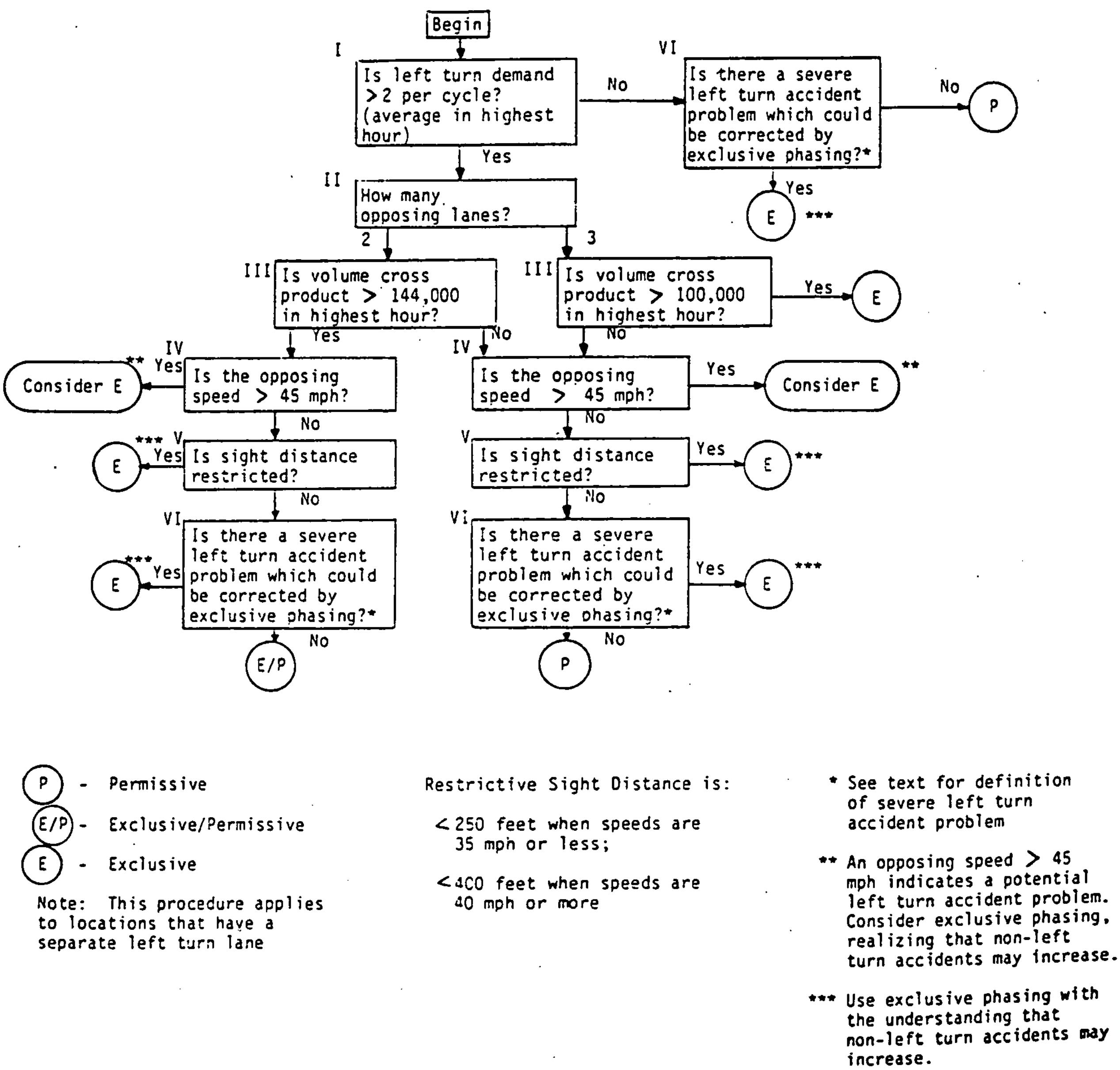


FIGURE 34 Recommended procedure for determining type of left-turn phasing. (*53*)

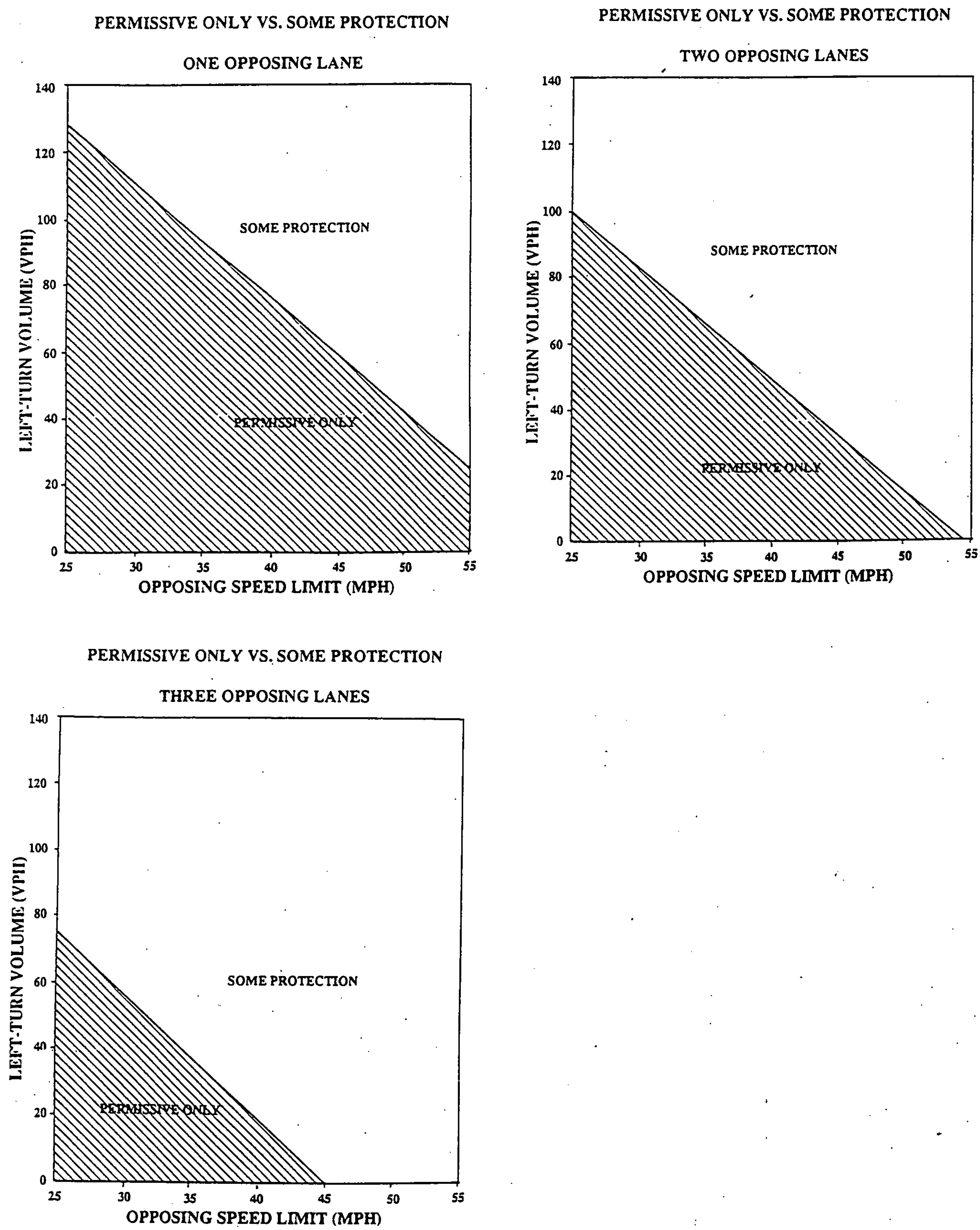


FIGURE 35 Selection criteria for left-turning phasing, University of Texas. *(39)*

• The sight distance for the left-turn vehicles shall not be restricted, and

• Fewer than eight left-turn related accidents have occurred within the last three years at any one approach with permissive only phasing, and

• Fewer than 450 left-turn related traffic conflicts per million entering squared vehicles (i.e. vphpl^2) are observed at an approach with permissive only phasing.

Level 2: Protected-Permitted versus Protected Only Phasing: Protected Phasing patterns are recommended under either of the following conditions:

• Approaches with restricted sight distance on the approach to the opposing traffic, or

• Where four or more lanes must be crossed by the left-turn movement.

Or use protected only phasing when any two of the following conditions are met:

• Peak 15-minute flow rate for the left-turning traffic is greater than 320 vph,

• Peak 15-minute flow rate for the opposing traffic is greater than 1100 vph,

• Opposing traffic speed limit is greater than or equal to 45 mph, or

• Two or more left-turn lanes.

Or use protected only phasing when any one of the following conditions is met:

• Three opposing traffic lanes and the opposing speed is 45 mph or greater, or

• Left-turn volume exceeds 320 vph and the percent of heavy vehicles exceeds 2.5, or

• Opposing volume exceeds 1,100 vph and the percent of heavy left-turn vehicles in the left-turn traffic exceeds 2.5, or

• Seven or more left-turn related accidents within 3 years for protected-permitted option, or

• More than 260 left-turn related conflicts per million squared vehicles for protected-permitted option, or

• The average stopped delay to left-turning traffic is acceptable for protected only phasing and it is the engineering judgment that more left-turn accidents would occur under the protected-permitted option.

Level 3: Sequence of Phasing: Lead or Lag? The following recommendations are made in deciding between a lead or a lag sequence for a single approach:

• A leading sequence is recommended when a protected-permitted or protected only phase has been selected provided it will not disrupt a traffic signal progression on either street.

• Dallas phasing (permitted lead-lag) is recommended where protected-permitted has been selected but level of service is not acceptable or where the 3-year left-turn accidents exceed seven but the protected only phase results in unacceptable delays.

• A lagging sequence is recommended where it is intended to improve the safety of an installed leading sequence with more than 190 conflicts per million squared vehicles or the lagging left-turn sequence is necessary to maintain a network or arterial progression plan.

• A lead-lag sequence is recommended for intersections where there is inadequate intersection space to safely accommodate dual left turns or it is necessary for signal progression.

Some of the options of phasing the traffic signal for left-turn movements are illustrated in Figure 36 (*54*) and are addressed below to assist in the exercise of reasonable engineering judgment. It should be noted that the Figure 36 (g) creates a "left turn trap", which will be explained later, and the "Dallas Phasing" has been retitled as Protective Lead-Lag (PLL) phasing.

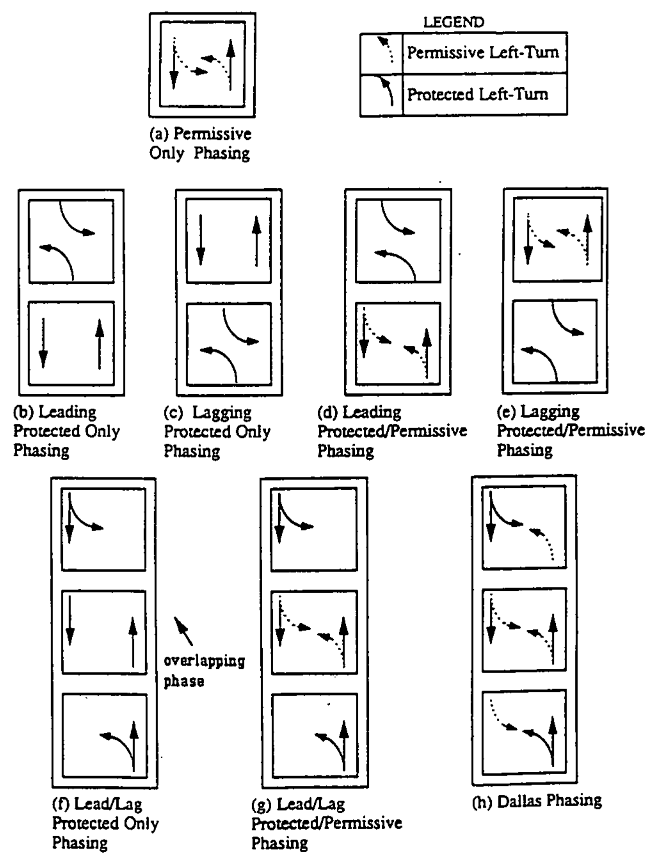


FIGURE 36 Left-turn phasing types. *(54)*

Permitted Left-Turn Phase—It is generally accepted that two vehicles can make the left turn and clear the intersection at the end of the circular green during the signal change interval for each intersection approach. However, if the opposing traffic does not fully use its available green time, then there is additional opportunity for the permitted left-turn movement. It has been the practice in some jurisdictions to operate an intersection with permitted left turns from a separate left-turn lane as the initial stage of signal operation when the traffic signal is first installed. After this initial operational experience, then the signalization for the left-turn movement can be upgraded to an exclusive or exclusive-permitted option. It is suggested that the traffic volumes be carefully reviewed in conjunction with intersection observations to determine if the left turns can be accommodated in the permitted only mode without unacceptable delays and vehicle conflicts.

Exclusive Left-Turn Phase—Previously, this phasing would have been defined as a protected left-turn phase. It is the mode of traffic control signal operation in which left turns may be made only when a left GREEN ARROW indication is displayed. The GREEN ARROW can only be displayed for the left turn when no other traffic movements are permitted to conflict with the left-turn movement. The through traffic movements are stopped and any signalized pedestrian movement across the side street and path of the left turn shall be held with a DON'T WALK pedestrian signal indication.

The exclusive left-turn phase is the highest level of left turn movement protection and is generally used after the trial of less restrictive control, such as permitted or exclusive-permitted control. Some jurisdictions, Michigan for example, do not install an exclusive left-turn phase for a single left-turn lane in new traffic signal installations as a matter of practice but do use exclusive-permitted phasing. The Florida ITE Section (*36*) recommends that exclusive only left-turn phasing should be provided for an intersection approach if any of the following conditions exist:

1. Double left-turn only lanes are operating.
2. Intersection geometrics force the traffic engineer to provide the left turn driver with an exclusive signal head that cannot be shared with adjacent through drivers.
3. Sight distance to opposing traffic is less than 250 ft when the opposing traffic is traveling at 35 mph or less, or less than 400 ft when the opposing traffic is traveling at 40 mph or more. This represents approximately 5-second gap size universally accepted by all left turn drivers in the California research project.
4. The approach is the lead portion of a leading intersection phasing sequence.

Overlap Left-Turn Signal Phasing—The overlap left-turn phasing permits the left-turn movement and the adjacent through movement to be overlapped as shown in Figure 36. A lack of vehicles in one left turn permits that left turn to be terminated while the other left turn is continued in conjunction with the adjacent through movements. When left turns on both streets are overlapped with the through traffic movements it is termed "quad left-turn phasing." The overlap phasing permits compatible traffic movements, i.e. those that do not have traffic conflicts, to operate not only during their primary phase but also with a compatible overlap phase. These overlap provisions afford more flexibility for the traffic signal controller to accommodate fluctuations in traffic volumes, allow the signal to provide "green" time for the heavier traffic movements, and not provide a green indication for a traffic movement when there is no traffic to use the green, i.e. the terminated left turn. Overlapped left turns are particularly beneficial for directional peak hour movements on a street where the outbound or inbound traffic is heavier and the opposing traffic is lighter. The heavier left-turn movement and adjacent heavier through-traffic movement can be more efficiently accommodated while still accommodating the opposing left-turn and through movements.

Exclusive-Permitted Left-Turn Phase

The exclusive-permitted option is a combination of the exclusive phase where left-turn traffic moves on a protected turn with a green arrow and the permitted phase where the left turn is directed with a circular green requiring left-turning traffic to yield to the opposing through movement as illustrated in Figure 36. The intent is to accommodate light left-turning volumes during the permitted phase and use the exclusive phase when the left-turn traffic is heavier.

The application of lead-lag, exclusive-permitted signal phasing needs to avoid entrapment of left-turn drivers into wrong assumptions of signal indications for the opposing traffic commonly called the left-turn "trap" or "yellow trap." The left-turn trap is illustrated in Figure 37 (*40*). Drivers attempting to make a permitted left turn opposing the lagging, protected left-turn phase can be mislead by the display of the yellow for the adjacent through traffic assuming that the opposing through traffic movement is also being terminated. The "trap" situation can be avoided in lead-lag, exclusive-permitted operations by making the lead phase exclusive and the lag phase permitted.

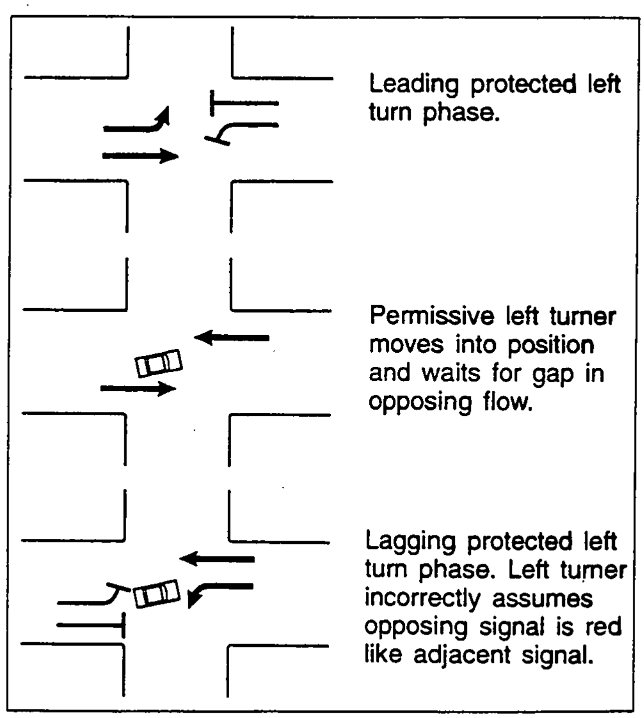


FIGURE 37 The trap problem with lead-lag protected-permissive left turns. (*40*)

Several Texas communities developed special signal phasing, commonly called the "Dallas" phasing, in 1987 to avoid the left-turn trap. This phasing has now been retitled as the permitted lead-lag (PLL) phasing. The PLL phasing as used in Dallas, Richardson, and Arlington, Texas, is illustrated in Figure 38.

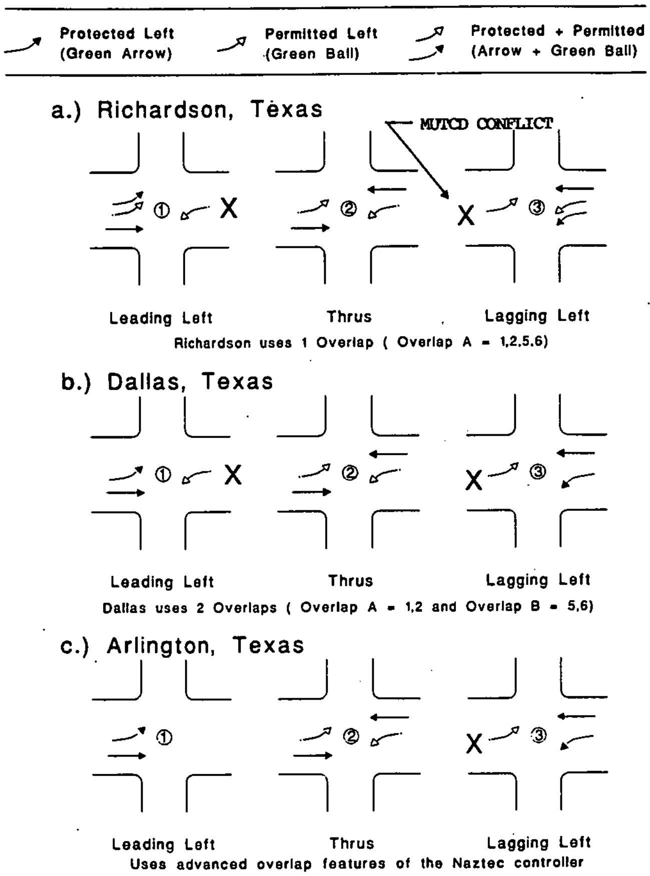


FIGURE 38 Texas permitted lead-lag phasing (PLL). *(40)*

Leading-Lagging Left-Turn Phases

The lead-lag left-turn phases are used to provide a left turn in one direction leading the through-traffic movement with a lag left turn in the other direction as a means of improving the traffic progression on an arterial. Several options of lead-lag left turns are illustrated in Figure 36. The advantages and disadvantages of this option as cited by the ITE *Traffic Signal Design Manual* are shown in Table 12 (*49*). One of the major pitfalls of coordinated signal timing noted by Buckholz (*55*) is the reluctance of traffic engineers to use lead-lag left-turn signal phasing. There is some assumption that it violates "driver expectations" and it is necessary to avoid the "yellow trap." The experience with traffic corridors where drivers have become used to signal variations shows that it can have a positive affect on the arterial progression.

The leading-lagging operations were evaluated in Indiana (*56*) with guidelines developed for the application of lead-lag left-turn phases as shown in Figure 39. The authors qualify the guidelines as appropriate to the following applications:

Three- or four-leg intersections on four-lane arterials;
Intersection angles of approximately 90 degrees;
Narrow or nonexistent medians;
Single left-turn lanes;
Adequate left-turn lane lengths (spillback is rare);
Relatively unaggressive driver population (gap-acceptance distribution about 0.5 to 1.0 sec more relaxed than drivers in Washington, D.C., no left-turn "jumpers", a maximum of two left-turn sneakers);
Light to medium-heavy volumes (still unsaturated);
Balanced flow between the directions on the street with left turn signals; and
Simple two- or three-phase signal control at diamond interchanges.

The city of Tucson (*57*) converted an arterial street from a leading left-turn operation to lagging left turns in the mid 1980s with positive signal synchronization results. An after study of the arterial signal conversion documented decreases of 38.3 percent in fuel consumption, 43.1 percent in air pollutants, 40.0 percent in traffic collision rate, and 42.2 percent in vehicle delay. Based on the positive results in Tucson, other Arizona cities converted to lagging protective left-turn operations or considered such a conversion. A 1991 Arizona study (*58*) performed a comparative analysis of leading and lagging left turns in Arizona with the following conclusions:

> Based on the field studies, it was found that intersection delay is significantly greater with the lagging left turn operations. No significant change in total delay was found with third car actuation of leading protected left turns. In addition, no significant differences were found in progression between the leading, lagging, and mixed operations. In terms of accident experience, no significant differences were found between the leading and lagging left turns. Finally, there was a mixed response from the motorist preference survey. Glendale drivers felt that leading left turns were better while Tempe drivers preferred the lagging left turns.

These studies would indicate that the benefits of lead-lag left-turn signal operations are contradictory. Accordingly, jurisdictions are encouraged to make their own study of arterial signal operations before a decision is made to convert the signals to lead-lag operation.

Flashing Red or Yellow Permitted Signal Indications

The permitted left-turn phase has led to other innovative left-turn indications by a number of jurisdictions. There is some concern that drivers do not understand the significant difference between the green arrow and the circular green for the left-turn movement. This concern is supported by a 1988 survey of Indiana State Fair participants (*41*) which found that

TABLE 12

ITE COMPARISON OF LEAD-LAG LEFT-TURN PHASE ALTERNATIVES *(49)*

Lead-Left-Turn Phase	
Advantages	**Disadvantages**
• Increases intersection capacity on one- or two-lane approaches without left-turn lanes when compared with two-phase traffic signal operation.	• Left turns may preëmpt the right of way from the opposing through movement when the green is exhibited to the stopped opposing movement.
• Minimizes conflicts between left-turn and opposing straight through vehicles by clearing the left-turn vehicles through the intersection first.	• Opposing movements may make a false start in an attempt to move with the leading green vehicle movement.
• Drivers tend to react quicker than with lag-left operations.	
Lag-Left-Turn Phase	
• Both directions of straight through traffic start at the same time.	• Left-turning vehicles can be trapped during the left-turn yellow change interval as the through traffic is not stopping as expected.
• Approximates the normal driving behavior of vehicle operators.	• Creates conflicts for opposing left turns at start of lag interval as opposing left-turn drivers expected both movements to stop at the same time.
• Provides for vehicle/pedestrian separation as pedestrian usually crosses at the beginning of straight through green.	• Where there is no left-turn lane, an obstruction to the through movement during the initial green interval is created.
• Where pedestrian signals are used, pedestrians have cleared the intersection by the beginning of the lag green interval.	• The hazards inherent in lag-left operations are such that they tend to restrict its use to pretimed operations or to a few specific situations in actuated control, such as "T" intersections.
• Cuts off only the platoon stragglers from adjacent interconnected intersections.	• A green arrow cannot be displayed during the circular yellow, therefore, a stop-start situation is necessary with simultaneously opposing left turns.

the circular green was the least understood of the left-turn indications with less than 50 percent fully understanding that it was for an unprotected permitted left-turn movement. It has been recommended that the display criteria for the permitted left-turn signal indication be distinctly different from the green arrow indication (personal communication from Glenn Grigg to William Savage, August 18, 1992) by requiring:

Change In Mode—Steady Indication to Flashing Indication
Change in Shape—Arrow to Circular Indication
Change in Position—Bottom of Signal Head up
Change in Color—Green to Red or Yellow.

In this way, the multiple signal indication message would provide additional clues for the driver to understand that the

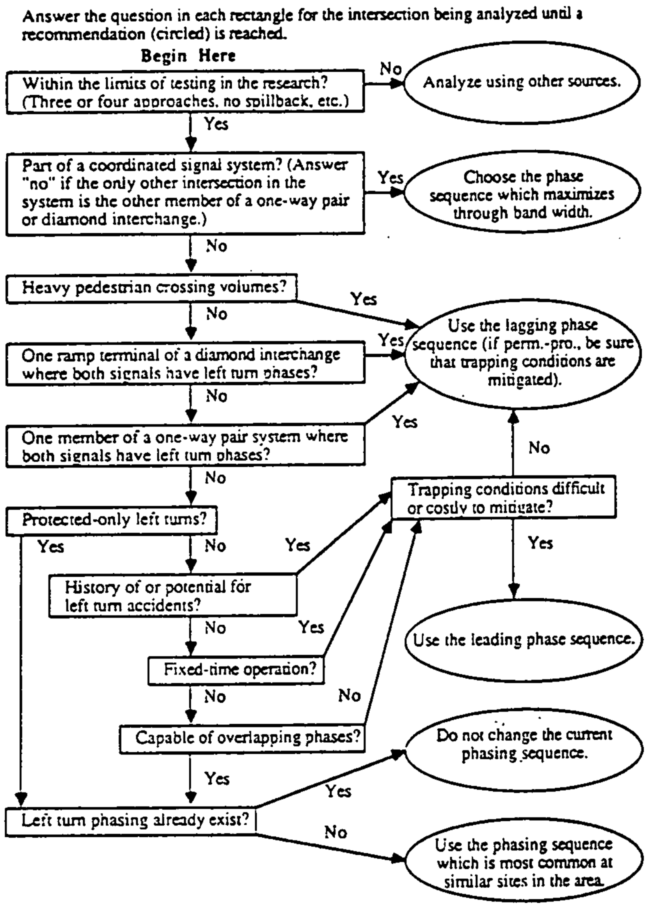


FIGURE 39 Flow chart for decisions on lead/lag phasing. *(56)*

left-turn operations and responsibility to yield to other traffic have changed.

The known applications of yellow or red permitted turn signal indications based on the questionnaire, literature search, and individual contacts are as follows:

FLASHING CIRCULAR RED—State of Michigan; Oakland and Wayne Counties in Michigan

FLASHING RED ARROW—States of Delaware and Maryland; Cupertino, California

FLASHING CIRCULAR YELLOW—Cities of Seattle, Everett, Tumwater, Longview, Kirkland, Vancouver, Tacoma, and Mountlake Terrace and King County; Washington

FLASHING YELLOW ARROW—Berne, Switzerland; Heidelberg, Germany; Strasbourg, France; and Reno, Nevada.

The Strasbourg application is a flashing right turn yield for pedestrian traffic; the Reno usage is a very recent application.

The state of Washington application of Flashing Circular Yellow was initially done in 1966 extending into the 1970s. The results of these applications were addressed by a Washington Section ITE Committee *(59)* citing the benefits noted in Table 13. Drivers' understanding of signal indications based on a 1988 study by Ketron for FHWA *(60)* in the cities of Philadelphia, Seattle, Dallas, and Lansing indicated the following correct responses for the permitted left-turn signal indications:

Green Ball (MUTCD)	76%
Flashing Yellow Ball (Seattle)	76%
Flashing Red Arrow (Delaware)	64%
Flashing Red Ball (Michigan)	64%

The researcher indicated that a large percentage of drivers did not understand the meaning of traffic signal displays for exclusive-permitted modes. They also were apprehensive about the above survey results and recommended that the study be redone under more controlled circumstances.

TABLE 13
BENEFITS OF FLASHING YELLOW PERMITTED LEFT-TURNS—WASHINGTON *(59)*

	Flashing Yellow	Circular Green
1. Average number of left-turn conflicts	3.14	5.00
2. Collisions per million vehicles	0.49	0.89
3. Percent of drivers that consider it safer	66%	34%

A 1980 FHWA study of left-turn phasing at traffic signals *(61)* found that the level of public understanding of the meaning of the circular green when used following the green arrow was unacceptably low. They also pointed out that the correct public understanding of the signal display was more important than the technical aspects of the exclusive-permitted technique and that uniformity of the display for exclusive-permitted is needed.

A limited study in Maryland *(62)* on the Flashing Red Arrow found that the driver compliance was only 62 percent with 38 percent of the left turns going through on the flashing red arrow. The Maryland law requires drivers to stop before proceeding with their left turn while yielding to other traffic. However, they did find that the collision rate decreased to 0.18 accidents per million entering vehicles with a flashing red arrow versus 0.78 accident rate per million entering vehicles at the control intersections although the percentage of left-turn accidents was nearly the same for the study and control locations.

The above discussion illustrates that there is no universally accepted method of operating, signalizing, or signing a permitted left-turn operation at an intersection. As a result, NCHRP Project 3-54, Uniform Traffic Signal Displays for Protected-Permissive Left-Turn Control, has been approved with the initial objective of developing a research plan to evaluate the safety and effectiveness of different signal displays and phasing for exclusive-permitted left-turn control. It is intended that the research will look at the current MUTCD criteria, Dallas Phasing, Flashing Red, and Flashing Yellow applications. The goal would be to obtain the field data needed to establish a national uniform system of traffic control for exclusive-permitted signal control.

CHANGE INTERVALS

There is currently no established practice for determining vehicle signal change (clearance) intervals, although ITE has a proposed Recommended Practice (*63*) under consideration. It proposes an initial yellow interval based on a 1.0 second perception-reaction time and a deceleration rate of 10 ft/sec^2 with adjustments for roadway grade. The method for determining a red clearance interval is based on vehicle speed, width of intersection, and length of vehicle. The discussion evolves around application of the determination formulas for specific intersections. The proposal does not specifically address left-turn signal change intervals other than the need to recognize the distance the left-turning vehicle must travel to clear the intersection area.

The responses to the synthesis questionnaire indicated that yellow change intervals for left turns varied from 3.0 to 5.0 seconds with All Red Indications from 0 to 2.0 seconds. Among the factors considered for increasing the change intervals are length of left turns, larger vehicles, geometric width, approach speed, grade, accidents, complaints, field observations and engineering judgment. The MUTCD provides that a yellow change interval should have a range of approximately 3.0 to 6.0 seconds. The yellow change interval may be followed by a red clearance interval, of sufficient duration to permit traffic to clear the intersection before conflicting traffic movements are released.

A 1985 survey of 300 jurisdictions by the Colorado/Wyoming Section ITE (*64*) on techniques to establish left-turn change intervals was quite varied and did not represent any widely accepted method. Most of the responses favored a national technique but used a number of variations summarized as follows:

1. The through-movement technique in the 1982 ITE Handbook.
2. A minimum of 3.0 second amber with an additional 1 to 3-second amber or "all red" depending on local intersection geometrics, speeds and operational conditions.
3. The ITE formula using a 20 mph left-turn speed, deceleration of 12 ft/sec^2, 20-ft vehicle length, and travel distance turning into the nearest lane.
4. Table 11-1, page 143, ITE *Manual of Traffic Signal Design.*
5. The California Transportation method that uses the ITE formula with 1.0 second reaction time, approach speed, and deceleration rate of 12 ft/sec.^{2}

An ITE Committee (*65*) is currently evaluating the above proposed ITE Recommended Practice attempting to resolve some of the issues so that an acceptable national technique can be adopted. This committee has made the following points to be considered for left-turn change intervals:

- The kinematic ITE Formula for yellow change interval may not be applicable for protected left-turn phases because of the variety of approach speeds for turning vehicles.
- Recent research found that a constant uniform deceleration rate does not exist in practice and that a uniform yellow change interval of approximately 4.0 seconds satisfies most conditions.
- A primary measure of effectiveness for the yellow change interval is the percentage of vehicles entering the intersection after the termination of the yellow indication.
- Physical conditions such as signal visibility, grade, vehicle mix, railroad crossing, and intersection geometrics contribute to the likelihood of vehicles entering on red indication and may influence the yellow change interval length.
- Some jurisdictions use a red clearance interval at all intersections while some choose not to use a red clearance at any intersection; the issue is hotly debated.
- Some jurisdictions subtract 1.0 seconds of the calculated red clearance interval to recognize the fact that most drivers do not use the last portion of the yellow change interval.
- In case of turning vehicles, intersection width is measured along the curved path traveled by the vehicle from the near stop line to the far edge of the area of conflict.
- To provide a reasonable red clearance interval, the use of the same value for vehicle speeds in the intersection is not always valid.
- The measure of effectiveness for the red clearance interval is whether the desired result of the red clearance interval is obtained.

Time-of-Day Variability

The traffic signal control equipment provides the opportunity to vary the type of left-turn traffic control during the day based on time clock control so that left turns can be handled one way during the peak hours and another way in the off-peak periods. It allows the minimum needed control of the left-turn movement that permits increased efficiency of the intersection. In response to the questionnaire for this synthesis, 17 states, 14 local agencies and 1 other agency indicated that they have used time-of-day special phasing for the left turns. The most common application is to have an exclusive left turn during the peak hour with permitted phasing in the off-peak periods. Several locations switch the left-turn traffic control between lead and lagging left turns. The city of Tucson uses a reversible center lane operation during the peak hour and accordingly, prohibits left turns during the periods that the center lane is used for reversible traffic operations. The state of California has omitted the exclusive left turns during peak hours to increase the major street green times. One jurisdiction provides a peak hour double left turn with activated signing. In all cases, the responses indicated that they had good compliance with the time-of-day variations.

TIMING OPTIMIZATION

Models

The following traffic signal models can be used to evaluate signal installations and in some cases to optimize the signal timing. These computer analysis software packages are available from the Center for Microcomputers in Transportation (McTrans) at the University of Florida and PC Trans, University of Kansas. However, at existing intersections, it is desirable to make field reviews and collect any necessary data for existing situations to refine the traffic signal timing to obtain the most efficient traffic operations in both the peak and off-peak periods.

Highway Capacity Manual Software—A variety of software products has been developed to implement the signalized and unsignalized intersection analysis procedures of the *Highway Capacity Manual.* The most commonly used program is the Highway Capacity Software (HCS), the current version of which has been developed by McTrans at the University of Florida. Several other products, most of which include analytical extensions, advanced computational features, graphic displays, etc., are also available.

Signal Operations Analysis Package (SOAP)—The University of Florida also developed SOAP for the Federal Highway Administration to analyze and optimize signal timing at isolated intersections. The model will analyze pretimed and actuated control and permitted left turns. The program determines optimum cycle lengths but multiple runs are necessary for phase sequence optimization.

Signalised-Unsignalised Intersection Design & Research Aid (SIDRA)—SIDRA was developed by the Australian Road Research Board and is extensively used internationally. It models traffic operations at signalized intersections, stop-controlled intersections, and roundabouts. Its analysis procedures are considerably more complex than the HCS and are generally considered to produce more accurate results. SIDRA's treatment of left turns in shared lanes incorporates a unique feature that recognizes that it may be possible for one or more permitted left turns to wait for gaps in the opposing traffic without blocking the through vehicles in the same lane.

TEXAS Mode—The Center for Transportation Research at the University of Texas developed the TEXAS Model to evaluate and simulate existing or proposed conditions. A graphics display illustrates speed, location, and time relationship for every simulated vehicle. The program is used for evaluation and not optimization.

EVIPAS—The University of Pittsburgh developed EVIPAS as an optimization simulation model for isolated intersections under actuated control for the Pennsylvania DOT. EVIPAS can analyze and develop almost any phasing pattern available in the standard NEMA or Type 170 signal controllers. Users can select a variety of measures of effectiveness to determine optimal signal timing settings for pretimed, semi-actuated, or volume density control with or without pedestrian actuations.

Passer II-90 (Progression Analysis and Signal System Evaluation Routine—The Texas Transportation Institute developed Passer II-90 for the Texas DOT to analyze both isolated intersections and arterial streets. The model varies signal phasing and the green time splits according to user-specified cycle lengths and minimum phase lengths to arrive at the optimal timing plan. It includes provisions for actuated and pretimed control, saturation flow rates, and the modeling of permitted left turns.

TRANSYT-7F—Dennis Robertson of the Transport and Road Research Laboratory in England developed the Traffic Network Study Tool with version 7 modified by the University of Florida to reflect North American nomenclature. The program can be used for the analysis and optimization of signal timing on coordinated arterial and grid networks. It includes provisions for pretimed and actuated control, modeling permitted left turns, and provisions for stop-controlled intersections within the network. TRANSYT will graphically illustrate the traffic flow profiles of the through and left-turn movements along the arterial.

TRAF NETSIM Mode—This model was developed by the Federal Highway Administration to simulate traffic control systems in great detail. It will handle both isolated intersections and coordinated signal networks but cannot be used to optimize signal timing.

Traffic Model Integrators—The traffic models above require similar input data and generate similar measures of effectiveness. This creates some duplication in computational methodology but each model offers unique features and a combination of models offers a broader capability for design and analysis. Several traffic model integrators have been developed to facilitate access to multiple models from the same input data. A partial summary of model integrators that have direct application to left-turn treatment selection is provided in Table 14. Work on traffic model integrators is proceeding and their capabilities are expanding rapidly.

Parameters

The Texas Transportation Institute (TTI) (*66*) collected field data and modeled intersection operations using PASSER II to compare the Dallas and conventional exclusive-permitted left-turn phasing. Based on this information, TTI recommends that the following left-turn parameters be used when modeling exclusive-permitted left turns on high type arterials with two or three opposing lanes:

Critical gap	=	5.1 seconds
Left-turn headway	=	2.5 seconds
Number of left-turn sneakers	=	1 per cycle

FLASHING OPERATION

The MUTCD (*5*) makes provisions for the flashing operation of traffic signals by a manual switch or automatic conversion. The automatic conversion to flashing can be activated by the controller conflict monitor detecting an inappropriate signal indication or by time of day. The turn lane signal shall flash the same color as the approach through lanes with circular lens flashed versus arrow indications if the signal head contains the appropriate circular indications. If the turn lane signal is flashed a different color than the through lanes then the turn lane signal shall be louvered or shielded so that the flashing turn lane indication is not visible to the through traffic

TABLE 14

TRAFFIC MODEL INTEGRATORS

	Integrators			
Traffic Models	AAP[1]	WHICH[1]	EXPERT SIGNAL	TEAPAC
SOAP		X		
HCM Chapter 9		HCS-Signalized & Unsignalized Intersections	HCS-Signalized Intersections	Signal 94
SIDRA		Signalized Unsignalized & Roundabouts		
NETSIM	See Note [2]	Signalized & Unsignalized Intersections	Signalized Intersections	X
PASSER II	X			X
TRANSYT-7F	X			X
EVIPAS		X	X	

NOTE: "X" indicates fully implemented Integrators

[1] Data may be transferred for any intersection on an arterial street between WHICH and AAP.

[2] The AAP can provide access to TRAF-NETSIM through a program called TRANNET that converts a TRANSYT-7F data set to a TRAF-NETSIM data set.

lanes. The MUTCD does not indicate any guidelines or recommendations as to when flashing operations should be used.

The synthesis questionnaire included one question on signal flashing operations but the response indicated that there was some confusion on the appropriate answer. The question requested the left-turn indication for signal turn-ons, emergency operations, and signal flashing operations. The responses were as follows:

Left Turn flashes the same as adjacent through lanes—8 jurisdictions

Flashing Circular Red—20, Only on Protected Left Turn—7, For Shared Lane—1

Flashing Red Arrow—13, Only on Protected Left Turn—6

Flashing Circular Yellow—3, Only on Protected-Permissive—6

Flashing Yellow Arrow—3, Protected 3-Section Head Only—1

It would be expected that most of the answers should be the same as the adjacent through lanes or Flashing Circular Yellow or Arrow. Therefore, the above data are viewed as suspect and should be substantiated from another data source or survey.

A recent TTI study (*67*) reviewed the practice and need for guidelines for the use of flashing operation at signalized intersections. The study found a lack of adequate guidelines for implementing flashing operations and that the decision to implement flashing operations varies widely from one locale to another. The research found it was difficult to develop definitive guidelines for flashing operations and concluded that engineering judgment would continue to be the basis for decisions to use them. The suggested considerations do not contain any specific references for the flashing operation of turn lanes. However, it is recommended that the report be reviewed for guidance in establishing signal flashing policies.

LANE-USE CONTROL SIGNALS

The MUTCD provides lane-use control signals as special overhead signals having indications used to permit or prohibit the use of specific lanes of a street or highway or to indicate the impending prohibitions of use. The older lane-use signals applied symbolic green arrows, yellow "X" and red "X" to signalize the directional changes for a traffic lane. New MUTCD requirements have added the symbolic left-turn arrows, Figure 40, for lane-use control signals where left turns are permitted under reversible lane operations (reference Chapter 4).

The MUTCD will now recommend lane-use control signals for use under the following conditions (*5*):

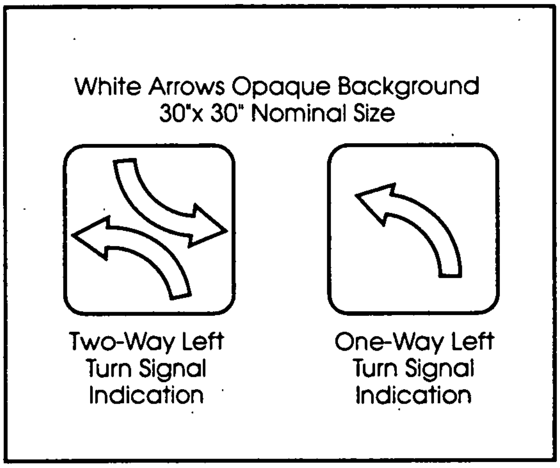


FIGURE 40 MUTCD new symbolic lane-use control signal indications (approved by NCUTCD, but not in MUTCD).

- More than one lane is reversed in direction.
- Two-way or single left turns are allowed during peak period reversible operations, but those turns are from a different lane than during off-peak periods.
- Other unusual or complex operations are included in the reversible lane pattern.
- There is demonstrated accident experience with reversible lane operation using static signs which is correctable by the positive indications provided by lane use control signals at the time of transition between peak and off-peak periods.
- An engineering study indicates that safer and more efficient operation of a reversible lane system would be provided by lane-use control signals.

The Lane-Use Control Signals will have the following indications and meanings in the MUTCD (*5*):

1. Steady DOWNWARD GREEN ARROW—Driver permitted to drive in this lane.
2. Steady YELLOW X—Driver should vacate the lane because a lane change is occurring.
3. Steady WHITE TWO-WAY LEFT TURN ARROW—Driver permitted to use lane for a left turn in both directions but not for through travel. (refer to Figure 40)
4. Steady WHITE SINGLE LEFT TURN ARROW—Driver is permitted to use the lane for left turns in the direction indicated without opposing left turns but not for through travel. (Refer to Figure 40)
5. Steady RED X—A driver shall not drive in this lane.

The lane-use control signals are installed overhead above the traffic lanes that change as part of the reversible lane operations and should be located at about every one-quarter mile. These new lane-use control signal recommendations have been approved by the NCUTCD but have not been incorporated in the current edition of the MUTCD.

The city of San Antonio, Texas, has FHWA approval to experiment with a YELLOW ARROW pointing down or diagonally in lieu of the YELLOW X for freeway reversible lane signal change intervals. Preliminary testing has indicated good driver understanding of the YELLOW ARROW.

RAILROAD PRE-EMPTION

The MUTCD provides that traffic signal installations within 200 ft of a railroad grade crossing should be interconnected with the railroad grade crossing signals. Railroad pre-emption permits the railroad crossing to be cleared of vehicles prior to the arrival of the train and restricts the traffic signal from allowing traffic to enter the railroad crossing approach when it would cause conflicts with the train. Left-turn movements are an integral part of the pre-emption operations so that turning vehicles should not be permitted to turn onto the railroad grade crossing. The major disadvantage with railroad pre-emption is the time required to clear the crossing prior to activation of the railroad signals. The left-turn signal operations under railroad pre-emption should be reviewed to ensure that the pre-emption does not create a left-turn trap. The NCUTCD devices is currently reviewing the traffic signal-railroad pre-emption requirements to establish a more realistic approach.

A similar problem exists for light-rail transit operations where the frequent arrival of rail transit vehicles creates significant conflicts with signalized intersection traffic movements. Traffic control device guidelines are now being developed for light-rail transit operations. It is expected that these guidelines will be available and incorporated in the next edition of the MUTCD.

CHAPTER SIX

PERFORMANCE MEASURES

MEASURES OF EFFECTIVENESS

The Highway Capacity Manual (HCM) (*6*) defines measures of effectiveness as parameters describing the quality of service provided by a traffic facility to drivers, passengers, or pedestrians. Examples include speed, density, delay, and similar measures. For left-turn treatments at intersections, measures of effectiveness would be those parameters that describe the capability of the intersection and intersection traffic control to accommodate left-turn movements as well as the other intersection traffic movements. The HCM uses average individual vehicle stopped delay as a measure of effectiveness for signalized and unsignalized intersections. Left turns are only a portion of the intersection traffic movements but the availability of turn lanes, intersection traffic control, signal phasing, and type of left-turn signal phasing will have an impact on the other intersection traffic and the intersection level of service. Therefore, any measures of effectiveness should reflect improvements in not only the left-turn movement but also other intersection movements.

The questionnaire response from governmental jurisdictions (Appendix B) indicated that 15 agencies have measures of effectiveness for left-turn operations. These positive responses represented only 3 states, 10 local agencies and 2 other agencies. It is suspected that more jurisdictions do measure the effectiveness of their left-turn operations, but because they lack a formal process for evaluation, they responded negatively. The primary measures used by respondents were field observations, accidents, and delay studies. The traffic models in previous chapters were mentioned as several methods for analysis. The left-turn operations will probably be reviewed in conjunction with the other intersection traffic operations on an as-needed basis. The initiative to review the intersection operations normally would be triggered by a public complaint, enforcement inquiry, increasing accident patterns, long traffic queues, or other unacceptable operational considerations. It is desirable for a governmental agency to have the resources to make periodic operational analyses of intersections as a standing practice.

A variety of traffic characteristics and intersection operational situations can be used to measure the effectiveness of left-turn treatments. The information needed for measurement depends on the left-turn problem, the type of left-turn improvement, and the characteristics of the left-turn movement. The analysis of the left-turn operations may involve field observations, collection of limited field data, or full-scale traffic studies or computer analyses. The degree of data collection, study, and analysis is subject to engineering judgment based on intersection problems, purpose of evaluation, and documentation requirements. The left-turn evaluation considerations have been summarized in Table 15 to outline possible characteristics for evaluating left turns. The information has been formulated into type of left-turn lane, traffic control, and signal phasing, recognizing that the data vary with the left-turn operations. These data are not all-inclusive but represent some of the data resources, identified problems, and left-turn issues addressed elsewhere in this synthesis.

A 1990 study by the University of Texas at Austin (*68*) for the Texas Department of Transportation analyzed the intersection impacts of left turns and developed a microcomputer program to analyze left-turn movements. The study selected three left-turn performance measures for the implementation package of the microcomputer program. The first measure was cycle failure based on Drew's Method (*69*), defined as any cycle during which approach arrivals exceed the capacity for departures. Using Drew's equation, they selected a 30 percent probability of cycle failure given the peak 15-minute volume, the signal timing, and the average minimum headway. The second measure of performance was the relationship between traffic demand and capacity where it was shown that intersection delay increases dramatically as a volume-to-capacity (v/c) ratio exceeds 0.90. The fourth-order polynomials in Figure 41 were plotted based on a series of TEXAS Model simulations to describe the relationship between delay and v/c ratio. It should be noted that the inflection point remains at 0.90 with a change in the cycle length from 60 seconds to 120 seconds. The last performance measure was amount of delay based on Lin's study (*70*), showing that a queue-delay value of 35 seconds can be experienced before drivers become impatient and thus potentially dangerous. Note that in Figure 41(a), the horizontal line for 35 seconds intersects the curve at the 0.90 v/c ratio where the left-turn operations become critical. In Figure 41(b), the points fall above the line and inflection point indicating that the 120-second cycle length is inappropriately long with respect to queue delay. The same measures of performance were also found applicable to dual left-turn lanes with the assumption that each dual lane functioned essentially the same as a single left-turn lane. The only variation for dual left-turn lanes was the saturation flow rate for the left turn. A saturation flow rate at 95 percent of the through lane was used for single left turns and a saturation flow rate at 90 percent of the through lanes was used for the dual left turns. It appears that all three of these measures could readily be used to measure the relationship of performance of left turns to the full left-turn capabilities.

TTI has developed *Implementation Guidelines for Retiming Isolated Intersections* (*71*) for the Texas Department of Transportation. The measures of effectiveness for retiming isolated intersections selected by the TTI study are summarized as follows:

TABLE 15

LEFT TURN EVALUATION CONSIDERATIONS

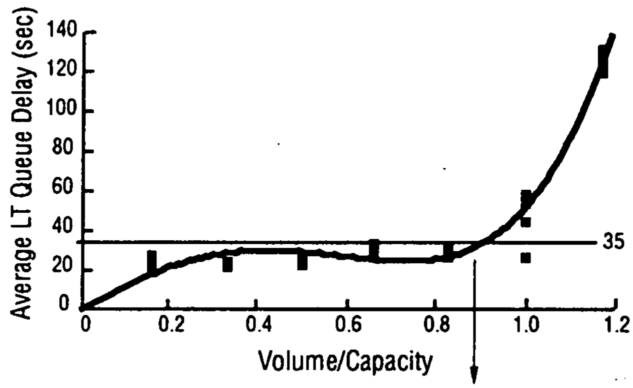
		SHARED LEFT TURN LANE		SEPARATE LEFT TURN LANE		
TRAFFIC CONTROL		NONE	SIGNAL	NONE	SIGNAL*	SIGNAL*
TRAFFIC SIGNAL PHASE		NONE	NONE	NONE	PERMISSIVE	EXCLUSIVE
SAFETY						
	Accidents and Traffic Conflicts	Number of accidents and traffic conflicts involving left turn vehicles, i.e., turning movement, rear end, pedestrian & bicycle				
GEOMETRICS						
	Blockage	Through Traffic		Left turn spillback to through lanes		
	Sight Distance	For left turns vs. opposing traffic speed and sight distance blockage by opposing left turn				NO
	Approach Grade	Plus/minus starting delay and signal change interval				
	Intersection Angle	Left turn travel distance and conflicts with other maneuvers				
	Traffic Lanes	Number of traffic lanes opposing left turn				NO
TRAFFIC VOLUMES						
	Left Turns & Opposing Traffic	Number of vehicles in 15-minute intervals for a.m. peak, p.m. peak and off-peak periods				
	Trucks	Percentage of trucks in left turn traffic				
	Pedestrians	Number of pedestrians crossing left turn movement				
	No. of Sneakers**	NO	YES	NO	YES	NO
TRAFFIC FLOW						
	Queue Length	NO	NO	LEFT TURNS	LEFT TURNS	LEFT TURNS
	Vehicle Delay	Thru Traffic	Thru Traffic	Left Turns	Left Turns	Left Turns
	Traffic Gaps	Adequate in the traffic opposing left turn				NO
SIGNAL TIMING						
	Green Intervals & Change Interval	NO	SHORT/LONG	NO	Adequate or excessive left turns & others	

*Exclusive/Permissive Left Turn: Look at each column relative to the exclusive and permissive portion of the left turn signal phasing.
**Sneakers = Maximum number of vehicles that complete the left turn during the signal change interval for that approach.

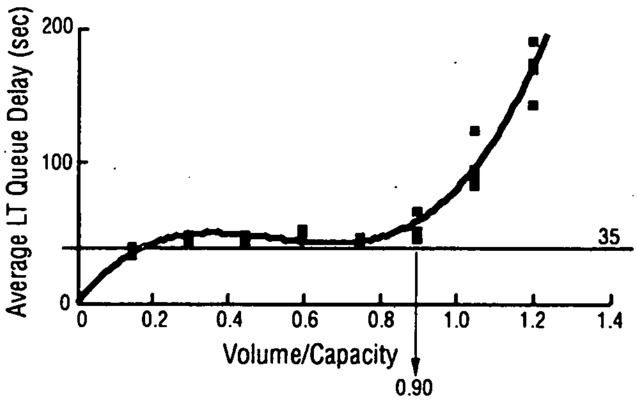
Volume-to-Capacity Ratio (v/c): represents the actual or projected rate of flow on an approach or designated group of lanes during a peak 15-minute interval divided by the capacity of the approach or designated lane group during the same time interval. The HCM (*6*) defines the v/c ratio as measure of capacity sufficiency, that is, whether or not the physical geometry and signal design provide sufficient capacity for the subject movements. For signalized intersections, a v/c ratio of 1.0 does not necessarily define level of service E, since for near saturation lane groups the cycle lengths, signal timing, or signal progression for that lane group may be poor. Therefore, it is necessary to review both the v/c ratio and delay to fully understand the intersection operational characteristics.

Delay: is a measure of quality of service to the road user. Delay can be reflected as average stopped delay per vehicle for a particular movement, e.g., left turn, or the total intersection stopped delay for all vehicles using the intersection. The delay can be tabulated in the field or calculated based on traffic, geometric features, and signal timing parameters. The HCM contains the most widely used model to compute stopped delay. PASSER II-90, SOAP-84, and TRANSYT-7F are other software packages commonly used for the analysis of intersections and can be used to determine delay at intersections.

Level of Service: indicates a range of operating conditions as a qualitative measure of the intersection operations. Level of service for an intersection is defined in terms of stopped



a. Fourth-order curve showing relationship between V/c and delay for C=60 sec. and Ge/C = 0.3.



b. Fourth-order curve showing relationship between V/c and delay for C = 120 sec. and Ge/C = 0.3.

FIGURE 41 Relationship of v/c ratio vs queue delay. *(68)*

delay per vehicle. Delay represents a measure of driver discomfort, frustration, fuel consumption, and lost travel time. Level of service ranging from A to F is readily recognized as a general description of intersection operations for discussion purposes.

Queue Length: is another measure of effectiveness, particularily where the queue storage length is limited. A heavy left-turn demand can exceed the left-turn lane storage, blocking the through traffic movement, or the backup in the through lanes can block the entrance into the left-turn lanes. The queue length can be estimated from formula or observed in the field.

Stops: The number of vehicle stops is another basic measure of intersection performance. The stop rate is the number of stops per movement divided by the demand volume in vehicles per hour.

Fuel Consumption: The amount of fuel consumption has been a measure of effectiveness because the interest in energy conservation has become a public issue. The fuel consumption can be calculated from both the TRANSYT-7F and PASSER II-90 programs. Note that the traffic models discussed in the previous chapter can also be used to evaluate left-turn performance.

EVALUATION METHODOLOGY

Evaluation of left turns can be based on field observations, as noted previously, or can include the collection of data. Although the evaluation is based only on observation, it is advisable to note the left turn problems and a quantitative number of those problems. Table 15 provides several items that can be reviewed in the field for various types of left-turn operation. If the decision is made to collect field data, several approaches can be taken. The first approach would be the collection of traffic characteristics and field measurements to document the left-turn operations outlined in Table 15. The second approach would be to collect traffic characteristics, signalization, and geometric data necessary to run one or more of the traffic models to identify the left-turn problem, compare before and after evaluations, assess left-turn improvements, or project left-turn operations for future conditions. The third approach would be to collect the necessary input data for the traffic models plus those existing traffic characteristics of left-turn operations that are to be determined by traffic model simulation. This will provide current data to support computer model computations of existing conditions for comparison, which will add to the credibility of computations for left-turn modifications or projections.

The TTI *Guidelines for Retiming Isolated Intersections* (*71*) recommends the following evaluation of an isolated intersection:

Field Evaluation

1. Check that the green intervals are long enough to clear the stopped queues during most time periods. Although this objective may not be a desirable strategy with actuated control and oversaturated conditions, cycle failure over an extended period of time indicates signal timing or geometric problems. Such problems result in long delays and queue lengths with excess fuel consumption.

2. Check that the green intervals are short enough that no period of time exists when vehicles are not moving through the intersection. Longer than necessary green intervals create wasted time and result in unnecessary delay and longer queues for other movements.

3. Check that the left-turn queue does not exceed the left-turn storage. If so, the left-turning vehicles may block the through lane and reduce its saturation flow-rate; i.e., the available through capacity cannot be fully used. The opposite condition, long through queues blocking access to a left-turn lane, has a similar effect on left-turn capacity. Neither condition is desirable.

Computer Analysis

1. Check that individual movements are not delayed disproportionately to one another. If so, green splits need adjustments and/or geometric modifications may be required.

2. Check that volume-to-capacity ratios for individual movements do not exceed 1:2. If so, the input data (usually

capacity estimates) are probably in error, and should be corrected. If not, the green splits and/or cycle lengths may be too short and require lengthening.

3. Check that levels of service for volume-to-capacity ratios are not more than one letter grade below the levels of service for delay. If so, the green splits and/or cycle length are probably too long (wasted green time), and may require shortening.

4. Check that the estimated queue lengths do not exceed the available storage. If so, the intersection cannot operate at its full potential for moving traffic. Signal timing or geometric modifications may increase the intersection's operational efficiency.

The more extensive evaluation of left-turn operations as outlined in Table 15 can involve either notation of field observations, review and evaluation of existing available data, or detailed field studies. The methodology and procedures for detailed traffic studies are thoroughly addressed in the ITE *Manual of Transportation Studies* (*10*), which provides a good resource for planning, study procedures, data formats, analysis, and data presentation. The detailed traffic studies contained in that publication that would be of interest for left-turn evaluation include:

Traffic Volumes
Intersection Stopped Delay
Saturation Flow Rate
Lost Time Studies
Gaps and Gap Acceptance
Intersection Sight Distance
Traffic Accident Studies
Traffic Conflict Studies
Evaluating Safety Improvements
Queuing Studies
Experiment Design and Statistical Analyses
Data Presentation, Reports and Presentations

The intersection evaluation can also be performed through computer analysis of traffic models, which requires collection of field data. It is important to know the computer analysis package prior to field data collection so the necessary information can be collected without additional trips to the intersection. The information requirements suggested by the Texas Transportation Institute (*71*) for analyzing an existing intersection timing plan or developing an optimal plan are summarized as follows:

Traffic Data

- Traffic Volumes—Traffic counts of all intersection movements in 15-minute intervals for the a.m., p.m., and off-peak periods.
- Peak Hour Factor—Is used to make adjustments of the peak flow rates to the hourly volume. Peak hour factor is the ratio of the total hourly volume to the maximum 15-minute flow rate within that hour.
- Saturation Flow Rate—Is the maximum flow rate of vehicles entering the intersection expressed in terms of vehicles per hour of green per lane, under prevailing roadway conditions during the peak demand.

Signal Data

- Cycle Length—Traffic signal cycle lengths for the various periods of the day. With actuated traffic control equipment the cycle lengths will be variable so the average cycle length for the study period should be determined from the timing plans, controller, or field measurement.
- Green Splits—These are the green time plus yellow and all-red clearance times for each phase of the signal. It is constant for pre-timed equipment but variable for actuated controllers. An average time can be obtained by taking several field measurements during the period of study and averaging the data.
- Phasing—Record the existing phasing including the sequencing of the phases. The traffic signal plans can be an initial source of information but they must be verified in the field.
- Type of Controller and Signal Hardware—The type of equipment can have a bearing on the intersection operations and the available options for improvement without replacing or adding to the traffic signal installation.

Geometric Data

- Number of Lanes per Approach—This should be the number of lanes at the intersection stop bar with verification of exclusive turning lanes or shared lanes. If there is an exclusive turn lane or roadway transition to added intersection lanes, the storage length for each traffic lane should be noted.
- Lane Widths—Normal lane widths of 12 ft or more will not affect the capacity. However, if lane widths are less than 12 ft, they should be noted so the available capacity can be adjusted.
- Percent Grade—Any significant grade on an intersection approach should be determined and recorded. Approach grade will affect vehicle starting times, signal change intervals, and vehicle stopping capabilities.
- Location—The general location of the intersection relative to the surrounding area and business activities, such as business districts, schools, shopping areas, and rural areas, has an impact on the signal operation considerations.

The Left-Turning Movement Analysis Program (LTMAP) (*68*) is an IBM-compatible Turbo Pascal program developed by the Center for Transportation Research at the University of Texas at Austin to assist in analyzing existing or proposed left-turning movements at urban intersections. The program operates with the TEXAS Model simulation results that are based on user-specified inputs. The program allows for the determination of cycle failures, volume-to-capacity relationships, average delays, and queue lengths for single and dual left-turn lanes. LTMAP provides a relatively user-friendly program with interactive intersection design to evaluate left turns.

The traffic models described in Chapter 5 also provide methodology and procedures to evaluate and measure the effectiveness of left-turn treatments. Each referenced model has particular applications and use of a combination of models to measure the performance of left-turn treatments may be desirable using the Traffic Model Integrators.

CHAPTER SEVEN

SPECIAL APPLICATIONS

INTRODUCTION

The special and unique applications of left-turn treatments in several local jurisdictions are reviewed in this chapter. Most jurisdictions have the practice of prohibiting or relocating left turns at major intersections where necessary. The basis for decisions on turn prohibition and several examples of left-turn relocations are provided under the sections on regional and local practice. The methods of accommodating pedestrians and bicyclists at intersections in conjunction with left turns are addressed as a consideration in the left-turn treatments. Several jurisdictions have developed public information material that is discussed in this chapter and reproduced in Appendix C. A number of research projects are planned and underway to provide answers to questions on left-turn treatments. The relationship of the research to left turns, responsible agency, and current status are provided.

REGIONAL AND LOCAL PRACTICES

City of Indianapolis (*72*), Intersection Improvements

In the mid 1980s the city of Indianapolis, Indiana, implemented an aggressive intersection management program to minimize delay, increase capacity, optimize signal timing, and significantly reduce accidents. The primary data used were accident records, traffic volumes, location files, and intersection condition diagrams. The types of improvements and benefits are summarized as follows:

1. Restriping to provide left-turn lanes—Resulted in a 62 percent reduction of left-turn accidents and 58 percent decrease in all intersection accidents. It also provided increased capacity, fewer vehicle stops, and intersection delay reduction.
2. Split signal phasing to separate left-turn movements—Used as an interim improvement for intersections with a high rate of left-turn accidents. The left-turn accidents were reduced by 78 percent.
3. Removal of unwarranted exclusive left-turn signal arrows—The left-turn signal was removed at intersections where it was not needed because of low volumes, land use changes, or other intersection considerations. The accident reduction for all intersections was not significant, some intersections had a reduction and others an increase.
4. Add left-turn lanes and modernized traffic signals—This type of improvement had the greatest capital investment but produced the highest return. There was a reduction of 78 percent in left-turn accidents, 85 percent in right-angle accidents, and 67 percent in all intersection accidents.

The safety and operational improvements of the intersections have resulted in significant benefits to the Indianapolis street system.

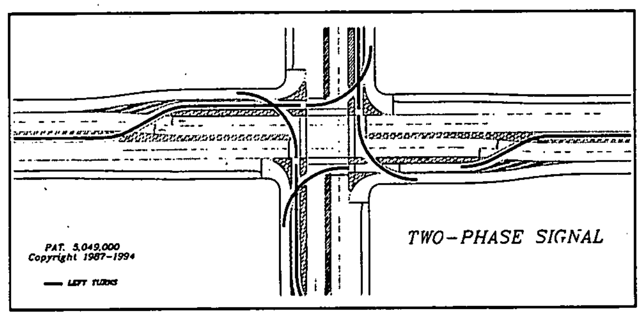


FIGURE 42 Continuous flow intersection (CFI), New York City. *(73)*

New York City (*73*), Continuous Flow Intersections

The New York City Department of Transportation and Public Development Corporation have developed a new intersection concept to improve intersection capacity and avoid a grade separation alternative in the Tillary Street Corridor on Staten Island. The continuous flow intersection (CFI) is conceptually depicted in Figure 42. Left turns are crossed over at midblock prior to the intersection under signal control during the cross street traffic movement and stored at the intersection. They are then released and complete their left turn with the arterial street green. The concept would require some education of left-turning drivers who must begin the turn manueuver prior to the intersection and are stored in a lane that has opposing traffic on both sides. The CFI requires only a two-phase signal at the major intersection to separate the major street and cross street traffic. A more detailed plan for the Tillary-Adams intersection is illustrated in Figure 43. Note that the right turns are also separated from the through-traffic movements and would be coordinated with the left-turn movement and pedestrian crossings. The plan would require the pedestrians to cross in separate, progressively signalized crossings with short hold periods on intermediate intersection islands. The pedestrian movements are fully signalized so there is no conflict with turning traffic. The design would have the following features:

1. Substantial channelizing islands to guide vehicles and provide pedestrian refuge.

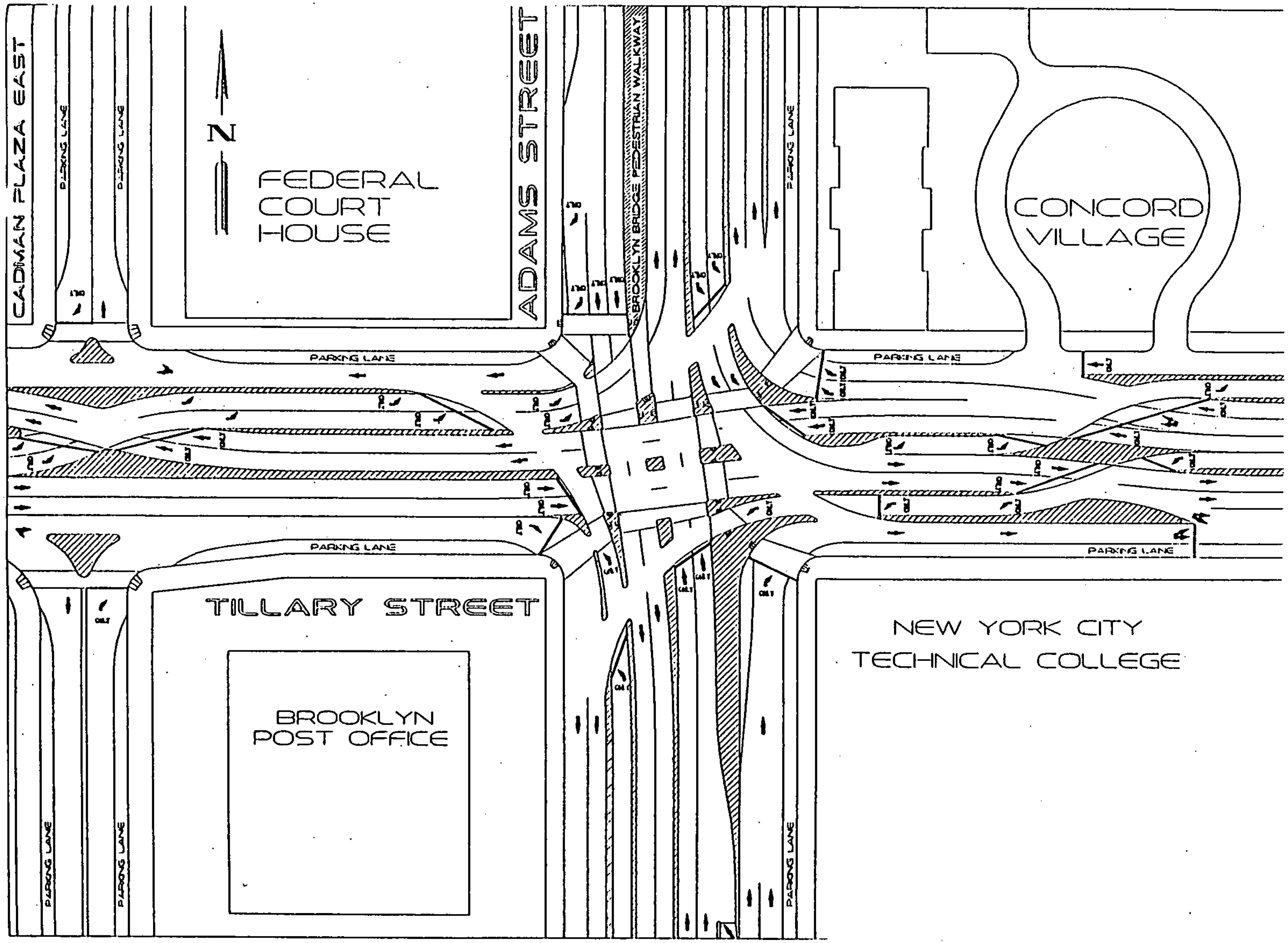
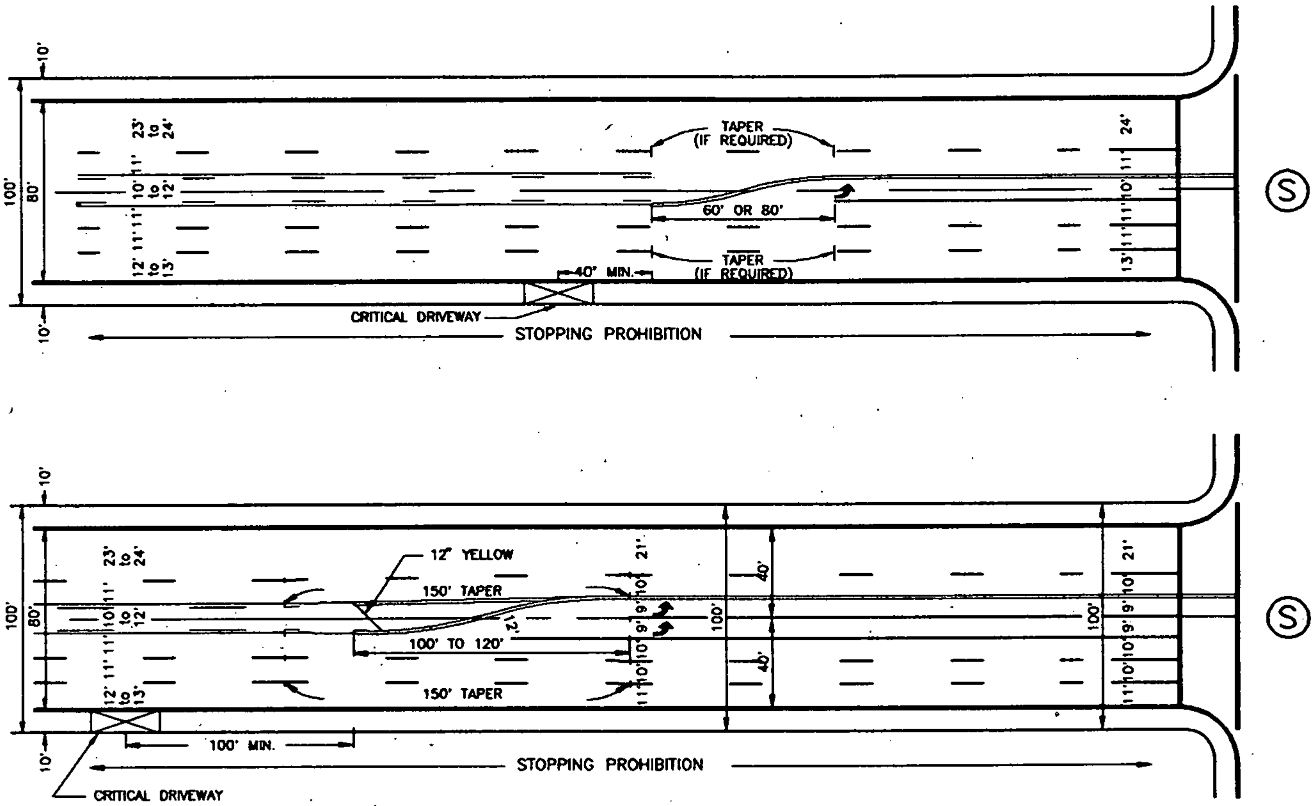


FIGURE 43 CFI concept plan—Tillary/Adams Intersection, New York City.



NOTES:

1. SELECTION OF LENGTH OF LEFT TURN POCKET LANE DEPENDS ON DEMAND, SPACING BETWEEN INTERSECTIONS AND LOCATION OF CRITICAL DRIVEWAYS TO BE SERVED BY TWO-WAY LEFT TURN LANES (2WLTL). THE DESIRABLE LENGTH AT SIGNALIZED INTERSECTIONS IS AT LEAST 40' OF STORAGE PER VEHICLE PER SIGNAL CYCLE AVERAGED DURING THE PEAK HOUR. HOWEVER, THIS DESIRABLE LENGTH OFTEN MAY NOT BE FEASIBLE. MINIMUM LENGTHS AT SIGNALIZED INTERSECTIONS ARE:
   - 100' AT MAJOR HIGHWAYS
   - 100' AT SECONDARY HIGHWAYS
   - 60' AT COLLECTOR STREETS
   - 40' AT LOCAL STREETS
2. SELECTION OF WIDTH OF 2WLTL (10'-12') IS DEPENDENT ON DEGREE OF ACTIVITY INTO DRIVEWAYS VERSUS THE USAGE OF CURB LANES.
3. UTILIZE 60' REVERSALS FOR POSTED SPEED LIMITS OF 35 MPH AND LESS, AND 80' REVERSALS FOR POSTED SPEED LIMITS OF 40 MPH AND GREATER.
4. SELECTION OF AN OPEN-ENDED (AS SHOWN IN TOP DRAWING) VERSES CLOSED ENDED (AS SHOWN IN MIDDLE DRAWING) 2WLTL IS DEPENDENT, IN PART, ON THE PROXIMITY OF A CRITICAL DRIVEWAY WHERE IT IS DESIRED TO SERVE IT BY A 2WLTL. MINIMUM DISTANCES TO CRITICAL DRIVEWAYS ARE SHOWN.
5. THE PAINTED REVERSAL FOR A SINGLE LEFT TURN LANE MAY BE ELIMINATED AT A SIGNALIZED INTERSECTION ON A SELECTIVE BASIS IF SPILLOVER IS RECURRENT AND IF IT IS NOT FEASIBLE TO LENGTHEN THE LEFT-TURN POCKET.

FIGURE 44 Typical striping treatment, City of Los Angeles.

2. Overhead lane controls to designate appropriate lanes.
3. Raised pavement markings for lane delineation and separation of traffic flows.
4. Colored roadways to better define directional travel paths.

The CFI concept is still in the planning stage, and requires community and business approval for implementation in the next few years.

State of California, Crossing Double Stripes

The California Vehicle Code permits a left turn across double yellow pavement stripe to access adjacent businesses. However, the California code prohibits left turns across a median area defined by double yellow stripes with an intervening space of at least 2 ft. Therefore, left turns to access adjacent properties cannot be made across painted medians including those for left-turn bays. Accordingly, officials must carefully review the left-turn bay design and median striping in relationship to critical driveways. Several examples of typical highway striping in Los Angeles to compensate for this left-turn prohibition are illustrated in Figure 44. The more liberal approach in most states recognizes that painted lines are not a barrier, and accordingly, a driver can turn left to access property while yielding to all other traffic.

LEFT-TURN PROHIBITIONS

The questionnaire to governmental jurisdictions, Appendix A, included two questions on the prohibition of left turns and the deletion of left-turn signal phasing. Responses to the question on prohibition of left-turn maneuvers are summarized below:

1. Left turns have been prohibited by 27 states, 28 local agencies and 2 other jurisdictions, indicating that most agencies at one time or another have prohibited left turns.

2. The items considered for the prohibition of left turns were:
   Accidents (18)
   Operational and Geometrical Reasons (16)
   Volume/Capacity Deficiencies (13)
   High Traffic Volumes with a Shared Left-Turn Lane (9)
   Limited Sight Distance (4)
   Other reasons were a minor street served by alternative access, prohibition only during peak hours, special events, short street spacing, reversible lane operations, and one-way streets.

3. The methods of left-turn prohibition were:
   Signing (59)
   Raised Islands (15)
   Pavement Markings (2)
   Enforcement (2)

4. The cited operational benefits were:
   Reduced Accidents (26)
   Increased Intersection Efficiency (27)
   Reduced Delay (9)
   Reduced Conflicts (6)
   Improved Traffic Flow (9).

The questionnaire response also indicated that 15 states, 16 local agencies, and 1 other agency have deleted a protected (exclusive) left-turn signal phase or removed the left-turn signal indication. The basis for the removal was limited intersection geometrics, traffic delay, traffic accidents, low volumes making the left turn, and changing traffic patterns making the left turn unnecessary.

In 1981, ITE Committee 4N-M (*74*) surveyed the governmental agencies throughout the United States to determine if a practice or guidelines could be established for prohibition of left turns at traffic signals. They received responses from 216 jurisdictions indicating that they did have criteria to consider prohibition of left turns, but that the decision was based on engineering judgment for each location. The Committee prepared an informational report of its survey results indicating that warrants or guidelines may be desirable but resources were not available to develop quantitative data to support a recommended practice. It is noteworthy that the responses to the Committee's survey were consistent among governmental units in ranking the factors important in the prohibition of left turns (Table 16). Traffic signs were used in most cases (Table 17) to prohibit the left turns along with other devices as noted. Table 18 indicates the general location of the NO LEFT TURN sign but does not indicate a strong preference for the "over left lane" and "far left corner" as required by the MUTCD.

In 1990, the Georgia DOT constructed a 4.34 mile Memorial Drive arterial improvement project in Atlanta that eliminated a two-way left-turn lane, installed a median barrier, restricted left turns except at the more important intersections, and provided signalization at all the median openings. A report on the project (*75*) by Parsonson indicated that the project was done over objection from the adjacent businesses because of restricted access and the need for indirect travel to reach the business activites. All intersections were designed with turn lanes and U-turn capabilities. The traffic signals were fully traffic-responsive, timed, and integrated to promote uniform and efficient traffic flow. In the first year of operation after construction, the project prevented 300 accidents and 150 injuries based on previous accident history. There was a 37 percent reduction in total accidents and a 48 percent drop in injury rate. The redesign of this arterial with the prohibition of left turns and upgrading of the intersections was effective in moving traffic with significant safety benefits. Left-turn accidents within the intersection were virtually eliminated.

LEFT-TURN RELOCATIONS

The volume of traffic using an intersection may require that left turns be prohibited or be moved to another location where

TABLE 16

FACTORS IMPORTANT IN THE PROHIBITION OF LEFT TURNS *(74)*

	Rank			
Factor	Combined	State	County	City
Accidents	1	1	3	1
Left Turn Volumes	2	2	1	2
Vehicle Delay	3	4	4	3
Opposing Volumes	4	5	2	4
Alternate Locations	5	3	6	5
Geometrics	6	6	5	7
Number of Approach Lanes	7	7	7	6
Number of Opposing Lanes	8	8	8	8
Pedestrians	9	9	9	9
Others	10	10	10	10

TABLE 17

TRAFFIC CONTROL DEVICES USED TO PROHIBIT LEFT TURNS *(74)*

	Number of Times Checked on Questionnaires and Percentage of Total Questionnaires Evaluated					
	City	%	State	%	County	%
Signs	126	97	38	100	19	100
Signals	46	35	12	32	8	42
Markings	39	30	11	29	8	42
Blank Out Signs	31	24	13	34	7	37
Other (geometrics, cones, etc.)	2	2	0	0	2	11
Questionnaires Evaluated	130	--	38	--	19	--

TABLE 18

LOCATION OF NO LEFT TURN SIGNS *(74)*

	Number of Times Checked on Questionnaires and Percentage of Total Questionnaires Evaluated					
Location	City	%	State	%	County	%
Over Left Lane	63	48	27	71	10	53
Near Left Median	33	25	10	26	7	37
Far Left Median	43	33	13	34	8	42
Far Left Corner	75	58	22	58	10	53
Near Right Corner	24	18	10	26	7	37
Far Right Corner	18	14	3	8	1	5
Overhead	19	15	--	--	--	--
Other	15	12	1	3	1	5
Questionnaires Evaluated	130	--	38	--	19	--

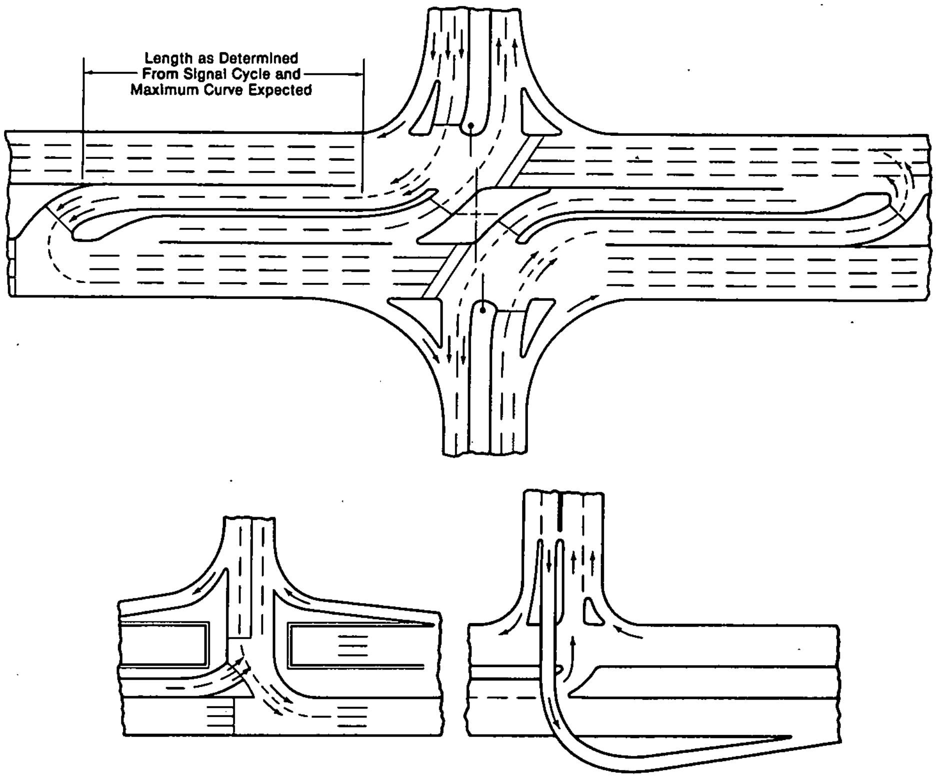


FIGURE 45 Indirect left turns and partial grade separations. *(14)*

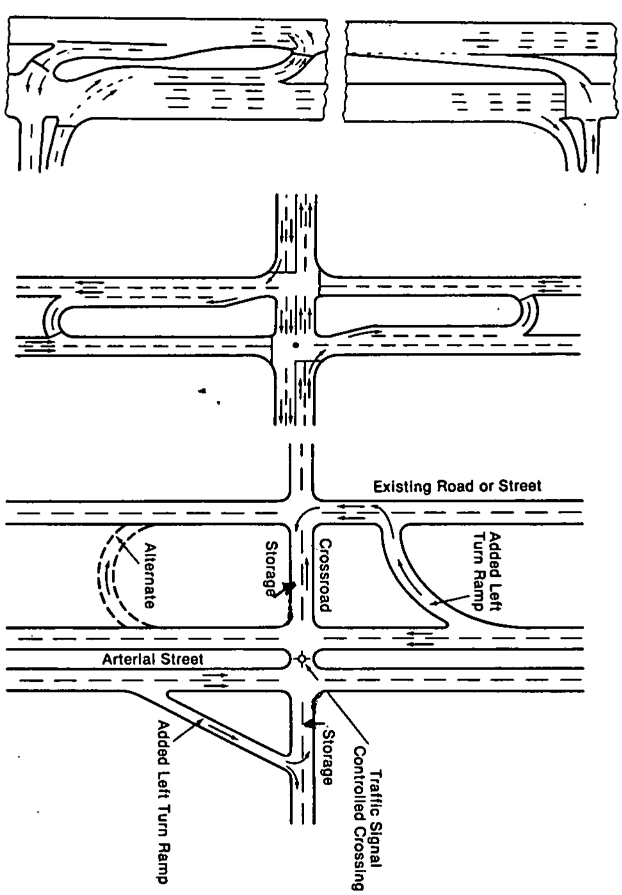


FIGURE 46 Left-turn relocations. *(14)*

they can safely be completed without detracting from the larger number of vehicle maneuvers at the intersection. Some jurisdictions have relocated the left-turn movement to require indirect left turns, as illustrated in Figures 45 and 46. Other possible indirect left-turn designs are used in Michigan and shown in Figure 47. The questionnaire response (Appendix B) indicated that 16 agencies use the "jughandle" design, Figure 48, while others indicate that jughandles confuse drivers and are not an effective solution. The jughandle is most effective for drivers acquainted with the design, because drivers must make an advance right exit to negotiate the jughandle in making their left turn. A total of 26 agencies use the indirect left turn, although there is an initial lack of public acceptance and business properties prefer the more direct left turn such as two-way left-turn lane.

A new indirect left-turn concept has been suggested by North Carolina State University *(76)*. The Bowtie intersection, shown in Figure 49, requires vehicles to negotiate a side street roundabout in lieu of an arterial left turn. It requires a vehicle to make a right turn from the arterial, circle the roundabout and make a 90-degree crossing of the arterial. The concept requires a circuitous route for left turns and drivers must be made aware in advance on the arterial that right turn is required rather than the normal left turn.

U-TURN CONTROL

A raised median on an arterial roadway does increase the need for U-turns at intersections and indirect left turns to

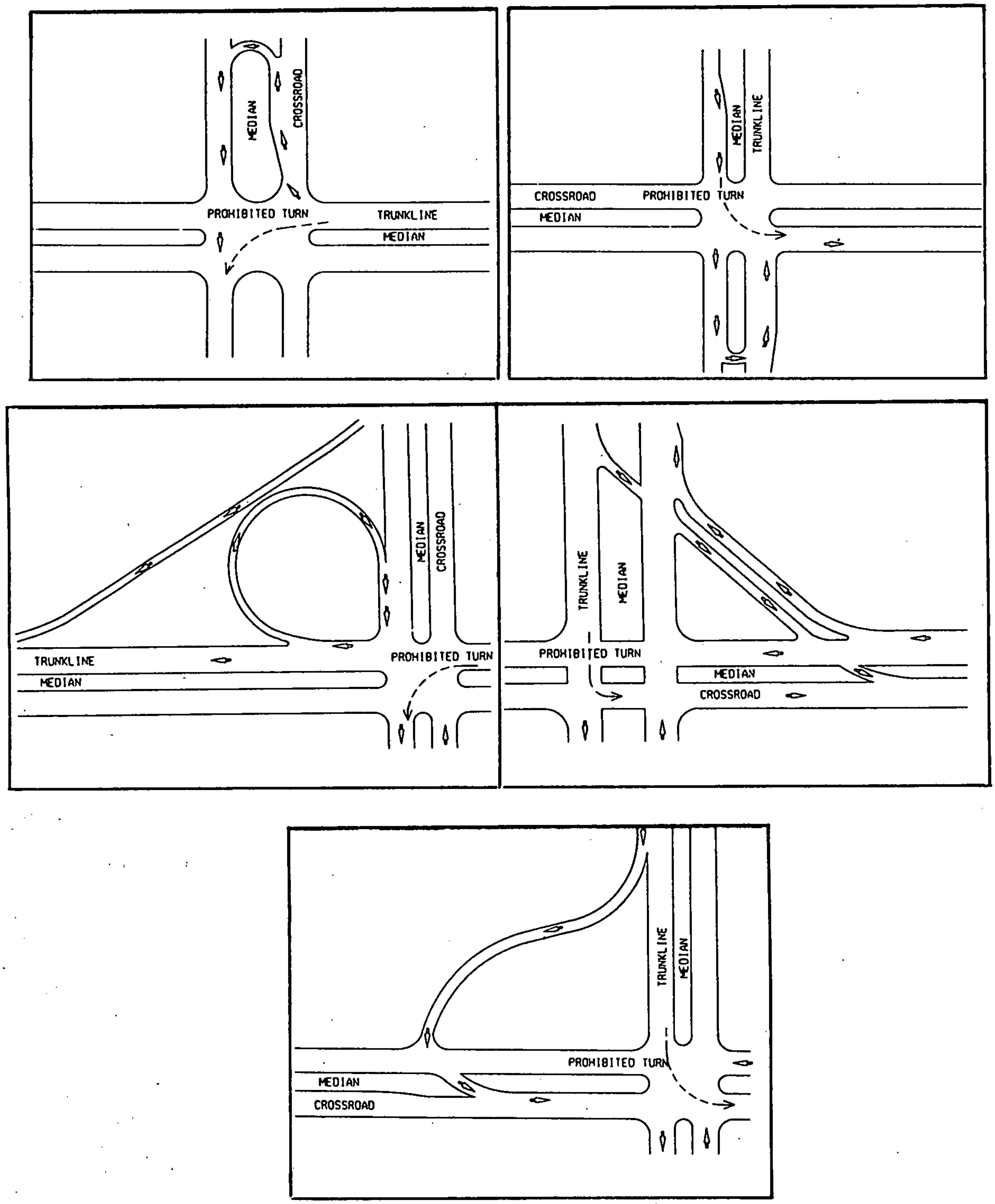


FIGURE 47 Michigan—alternative left-turn treatments. *(4)*

access properties or minor streets on the opposite side of the median. It was noted in the questionnaire responses that 6 states, 3 local agencies, and 3 others restrict U-turns from left-turn lanes as a general practice. Several jurisdictions prohibit U-turns where there are conflicting heavy right turns, during signalized right turns, and where turning width is restricted. In Florida (77), the Median Revision U-Turn concept depicted in Figure 50 has been implemented for high accident locations with narrow medians and strip development. The concept decreases the intersection conflicts from 16 to 4, which has reduced intersection accidents approximately 22 percent and is reasonably accepted by the public. However, this concept also requires motorists to make U-turns and indirect left turns to reach their destination because the side streets have right-only turns for exiting vehicles.

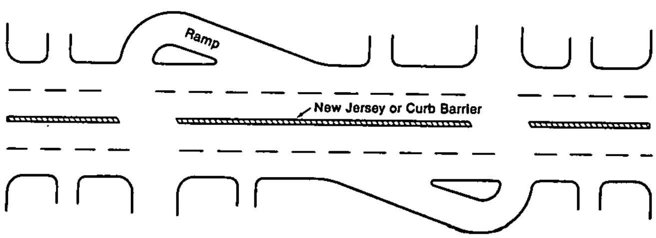


FIGURE 48 Median barrier with indirect left-turn ramps (jughandles). *(14)*

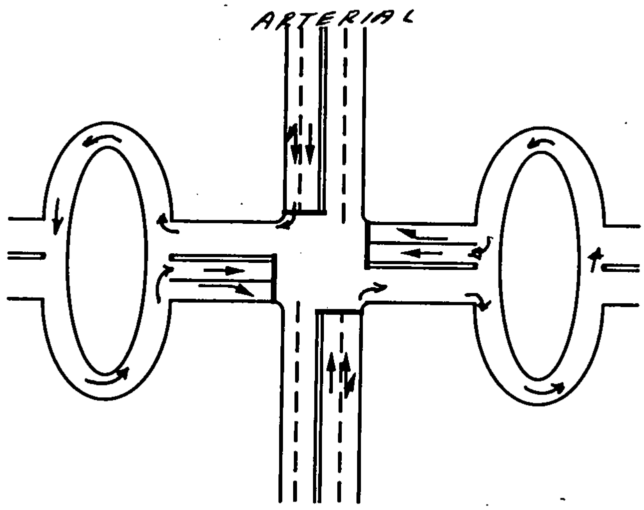


FIGURE 49 Bowtie intersection concept, North Carolina State University. *(76)*

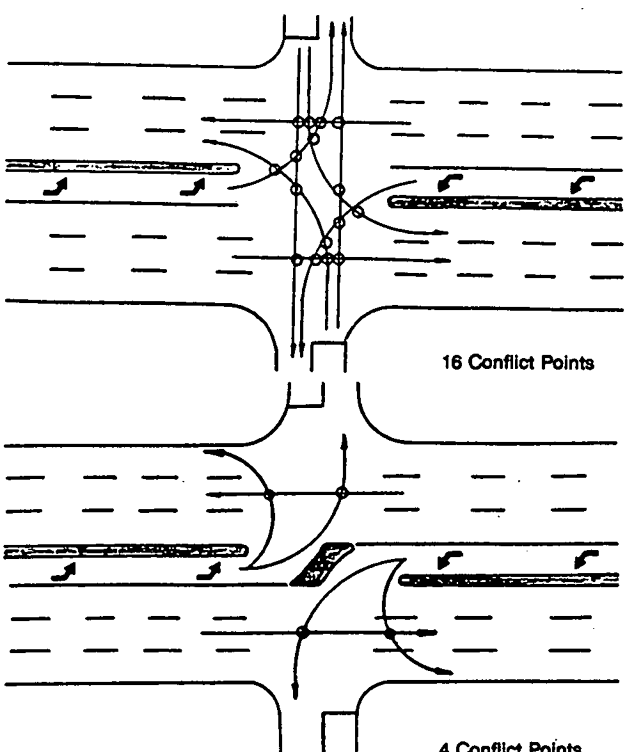


FIGURE 50 Florida—median U-turn concept. *(77)*

PEDESTRIANS

The conflict between vehicles and pedestrians at an intersection is an important safety problem. On average, only about 15 percent of the vehicles turn left at an intersection but 30 percent of the collisions with pedestrians involve left-turning vehicles (*78*). Contributing factors to the problem include in-vehicle visibility limited by the corner post, driver attention to opposing traffic, and greater concern for the conflicting traffic. The problem can be alleviated at signal-controlled intersections by separating the left-turn movement and pedestrian movement with pedestrian control signals. If pedestrians are not controlled by a signal, then a far left vehicle signal head can be installed so that the left-turn signal indication, other traffic, and pedestrians are all within the field of view or peripheral vision of the left-turning driver as suggested by Habib in 1980 (*79*).

The current MUTCD only indicates that pedestrian signal indications may be installed under the following conditions:

1. When any volume of pedestrian activity requires use of a pedestrian clearance interval to minimize vehicle-pedestrian conflicts or when it is necessary to assist pedestrians in making safe crossings.
2. When multi-phase indications would tend to confuse pedestrians guided by vehicle signal indications.
3. When pedestrians cross part of the street, to and from an island, during a particular interval.

The proposed revisions to the MUTCD will clarify that no movement that may involve an unexpected crossing of pathways of moving vehicles or pedestrians should be allowed during any green or yellow interval except when:

1. The movement involves only slight hazard, and
2. Serious traffic delays are materially reduced by permitting the conflicting movement, and
3. Drivers and pedestrians subjected to the unexpected conflicts are effectively warned thereof by a sign.

These requirements indicate that pedestrian signal control requires more attention than has been the case in the past. It also supports a recommendation that left-turning vehicles and conflicting pedestrian movements should be separated by respective signal indications when the left-turn maneuver is signalized. It would be one of the countermeasures to reduce the pedestrian accident problems, particularly among older pedestrians as noted by Hauer (*3*). The signalization of left-turn movements and the optional phasing of the left turns can present a confusing traffic pattern to pedestrians attempting to use a crosswalk controlled only by the vehicle signal indications.

LIGHT RAIL TRANSIT

The city of Los Angeles has evaluated and implemented a light rail transit (LRT) system running on existing city streets (*80*). The LRT operates on Washington Boulevard in the downtown area with two tracks occupying the center lane, which formerly accommodated the median turn lanes on a seven-lane roadway. The Boulevard now has two through lanes in each direction and left-turn lanes adjacent to the LRT facilities. The Boulevard operates essentially as a divided roadway with several minor streets closed to cross traffic and all intersections signalized. Left turns and U-turns across the LRT tracks are restricted to the signalized intersections. The left turn pockets vary from only 100 ft in length, because of short intersection spacing, up to 200 ft where spacing permits. A yellow half-moon median island was painted at the cross streets and entrance to the left-turn lanes to prevent left turns from the cross streets from entering the LRT tracks. Property access driveways are restricted to right turn entering and right turn exiting the property with no backing out of driveways onto Washington Boulevard.

The intersection traffic controls were designed and operate to reduce the conflict between LRT trains, vehicles, and pedestrians. The intersection traffic controls include signals for the LRT, left turns, through lanes, cross street traffic, and pedestrians. Two left-turn signal indications are provided, one on a mast arm over the left-turn lane and the other on the far left of the intersection. A sign, LEFT TURN ON GREEN ARROW has been installed adjacent to the left-turn signal head to increase safety and to inform motorists that a turn is not permitted on the red arrow signal indication. All left-turn movements operate in a fully protected signal mode to prevent left turns in front of an LRT vehicle approaching from behind and immediately to the left of the vehicle left-turn lane. Initially, the decision was made to use all "lagging" left-turn phasing because, in San Jose, when the left-turn phase was omitted during the LRT priority operation, drivers could not understand why their signal phase was skipped and they attempted to make a turn in front of the train against the signal indication. The "lagging" phase would allow the train to pass and the left-turn phase would not be skipped in the LRT priority operation as the train would already have cleared the intersection. After the initial installation it was found that three intersections had to be converted to lead-lag left turns because of "interlock" problems from two simultaneous opposing left turns. A year later, the left turns at four other intersections were converted to lead-lag operation to improve the signal progression "band width" along the Boulevard. At all seven intersections, the lower volume left turn was converted to the "lead" left turn and the heavier left-turn volume retained as a "lag" left turn. To date, no problem with drivers attempting to turn left across the LRT tracks in front of the trains at the "lead" left turn locations has been reported. The remaining eight intersections operate with "lag" left turns in both directions as originally planned.

The number of accidents involving LRT trains has varied from 15 to 31 per year, averaging 4 accidents per 100,000 train miles of operation. Illegal left turns account for 51 percent of the LRT accidents. Among the negative impacts that still exist are the special signs and signals needed to operate the system and the permanent turn conflicts that need continual monitoring for safety.

BICYCLES

The increase in bicycle usage has promoted the designation of more bicycle facilities, such as designated bicycle lanes. However, the limited amount of bicycle usage in the United States does not encourage the bicycle signals, advance bicycle stop lines, and separate bicycle facilities common in Europe.

Normally, bicyclists are encouraged to merge with left-turn traffic when making a left turn. Some jurisdictions in California have provided separate bicycle left-turn lanes, as shown in Figure 51 (*81*), to accommodate bicycle left turns serving bike lane facilities. If this is done at signalized intersections, then bicycle-sensitive detectors are needed in the designated bicycle left-turn lane.

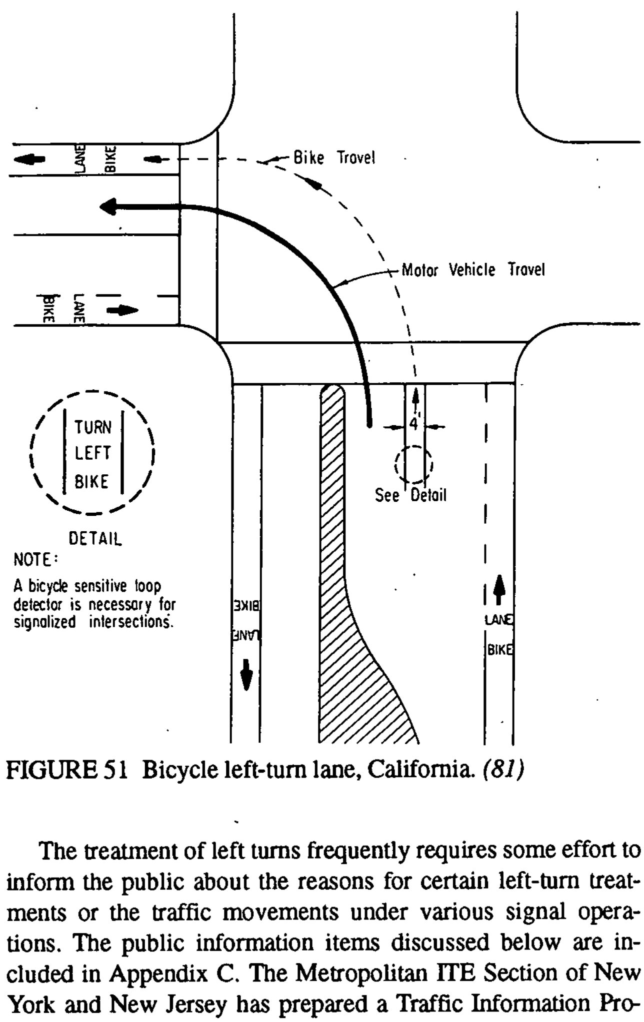


FIGURE 51 Bicycle left-turn lane, California. (*81*)

The treatment of left turns frequently requires some effort to inform the public about the reasons for certain left-turn treatments or the traffic movements under various signal operations. The public information items discussed below are included in Appendix C. The Metropolitan ITE Section of New York and New Jersey has prepared a Traffic Information Program "TIPS" Series (*82*) on various traffic features including TURN LANES and LEFT-TURN PHASING WARRANTS. The Idaho Transportation Department recently installed an exclusive-permitted left-turn signal phasing system in Moscow, Idaho, the first for that community, with an illustration to define the traffic operations for each signal indication. As a result, the new signals reduced intersection delay, have resulted in no increase or change in the accident patterns, and were readily accepted by the public. The city of San Buenaventura has prepared a complete series of public information brochures that can be hand distributed or mailed in response to an inquiry. Their brochure on left-turn traffic signals is provided in Appendix C.

CURRENT RESEARCH

Research is currently underway that will add to the knowledge of driver operations and left-turn treatments. The Federal Highway Administration (*83*) has been sponsoring a number of research projects of which the following could have a bearing on left-turn treatments:

"Older Driver Perception-Reaction Time for Intersection Sight Distance and Object Detection," being published as FHWA-RD-93-168.
"Traffic Maneuver Problems of Older Drivers," being published as FHWA-RD-93-092.
"Traffic Operations Control for Older Drivers," 1994
"Intersection Geometric Design for Older Drivers and Pedestrians," 1995
"Capacity Analysis of Permitted Left Turns," University of Maryland.

Additionally, the state of Texas, under cooperative sponsorship by FHWA, is preparing the following traffic signal studies:

"Criteria for Left-Turn Phasing, Indication Sequence, and Auxiliary Signing"
"Evaluation of Flashing Traffic Signal Operations"

The Transportation Research Board has a number of National Cooperative Highway Research Projects (*84*) underway that will add to the knowledge of left-turn operations and treatment. These studies include:

NCHRP 25-4 "Determining Economic Impacts on Adjacent Businesses Due to Restricting Left Turns;" Cambridge Systematics, Inc.; Glen E. Weisbrod, Principal Investigator; completion and publication in 1995.

Objective: to determine the economic impacts on adjacent businesses and property owners due to restricting left-turn movements. Based on a status report at the National Conference on Access Management, Cambridge Systematics (*85*) reports that:

1. The literature search on the subject offers very little on economic impacts.
2. The impacts on businesses have been mixed and varied, some have experienced losses and some have had economic gain. Any negative impacts appear to be transitory.
3. There is evidence that businesses that rely on "passby" traffic such as service stations and convenience stores tend to be negatively affected more than "destination-oriented" businesses.
4. The literature indicates that transportation access is only one of a number of factors that affect business location and the success of the business. Other factors such as type of business, the location and nature of the competition, the overall economic climate, sensitivity to price and quality, among others, along with left-turn restriction may have a relationship to sales loss.

NCHRP 15-14(2), Median Intersection Design; Midwest Research Institute; Douglas W. Harwood, Principal Investigator; completion in 1995.

Objective: to develop and recommend median-width parameters and design criteria for intersections on rural and suburban highways with partial or no access control. Median width on these facilities may pose operational problems in the vicinity of intersections for left-turning traffic from both the main roadway and the crossroad.

NCHRP 15-14(1), Intersection Sight Distance; Midwest Research Institute; Douglas W. Harwood, Principal Investigator; completion in 1995.

Objective: to evaluate current AASHTO methodology for Cases I, II, III, and IV intersection sight distance and where appropriate recommend new and revised models. There is some concern that sight distance is not addressed for the left-turn maneuver off a main roadway.

NCHRP 3-44, Improved Traffic Control Device Design and Placement to Aid the Older Driver; Michigan State University; Dr. Richard Lyles, Principal Investigator; completion in 1995.

Objective: to determine which traffic control device improvements enhance driver performance with particular emphasis on older drivers. Left-turn movements are a targeted portion of this research because many older drivers have difficulty with left turns.

NCHRP 3-49, Capacity and Operational Effects of Midblock Left-Turn Lanes; University of Nebraska-Lincoln; Dr. Patrick T. McCoy, Principal Investigator; Completion in 1996.

Objective: to develop a quantitative methodology for evaluating alternative midblock left-turn treatments on urban and suburban arterials. The research will produce a guide that allows the transportation practitioner to make decisions based on commonly available data and to provide a better understanding of the relationship between businesses, midblock left-turn treatments, and arterial operations.

NCHRP 3-54, Uniform Traffic Signal Displays for Protected/Permissive Left-Turn Control, proposed phase 2 to begin in 1996.

Objective: to evaluate the safety and effectiveness of different signal displays and phasing for protected (exclusive)-permissive (permitted) left-turn control. It is expected that the outcome of this evaluation will be recommendations for uniform signal displays for exclusive-permitted turn control. The first phase of the project will be to formulate a detailed plan for the research needed to accomplish the overall objective. The second phase would be to conduct the field research and prepare the final recommendations. It is intended that the research would look at the "Dallas" phasing, red and yellow indications mentioned previously in this synthesis.

NCHRP 3-46, Capacity and Level of Service at Unsignalized Intersections; University of Idaho; Dr. Michael Kyte, Principal Investigator; completion in 1995.

Objective: to develop and validate capacity analysis procedures for all-way stop control and two-way stop control intersections that can replace the existing procedures in Chapter 10 of the 1985 *Highway Capacity Manual,* and to correlate these capacity procedures with the MUTCD warrants for installation of signals and all-way stop control to provide consistency between the HCM and the MUTCD.

NCHRP 3-48, Capacity Analysis for Actuated Intersections; University of Florida; Dr. Kenneth Courage, Principal Investigator; completion in 1996.

Objective: to develop a capacity and level-of-service analysis methodology for intersections with actuated control to augment or replace the existing procedures in HCM Chapter 9. The procedure will be calibrated and validated through limited new field data, supplemented by existing field data, and data from simulation/optimization programs.

CHAPTER EIGHT

CONCLUSIONS

Vehicle left turns significantly influence intersection operations. Left-turning vehicles can be delayed while they are waiting for an opportunity to complete the turn and they, in turn, may delay through traffic if separate left-turn lanes are not provided. Older drivers have particular difficulty with left-turn maneuvers, as evidenced by a higher potential for accident involvement. The problem has been identified with greater difficulty in gauging the speed of opposing traffic; selecting available gaps for turns; and the need to view other traffic, pedestrian movement, and traffic control concurrently under dynamic traffic patterns while operating and positioning their vehicles for a left turn. The number of accidents involving left-turn maneuvers supports the degree of difficulty of this traffic maneuver and the need for left-turn treatment consideration.

The treatment of left turns progresses through various stages of intersection facilities and traffic control features as the left-turn and intersection volumes increase. A minor left turn at a low-volume intersection can easily operate from a traffic lane shared with other traffic and without any specific traffic control. As the traffic volumes and number of left turns increase, it becomes necessary to widen the roadway approach to provide a left-turn lane separating the turn from other traffic and providing storage for the left-turning vehicles. Further traffic increases reduce the gaps in opposing traffic with a greater number of left turns, causing an unacceptable left-turn queue that requires traffic signal control. The synthesis provides some criteria and guidelines to assist in making a decision on geometric and traffic control left-turn treatments.

A survey of state and local transportation agencies in the United States and Canada was conducted to obtain information on current practices and to identify any special or innovative practices. Of the 69 responses received, 69 percent of states use the AASHTO geometric design guidelines to determine left-turn requirements, and 64 percent of the responding local agencies use these criteria.

Survey responses further show that only a few state or local agencies use design criteria that differ from AASHTO; these agencies note that the AASHTO criteria are primarily for new construction and do not necessarily apply to existing urban arterials or certain local conditions. Some agencies have developed additional design procedures that clarify the AASHTO policies or provide a more reasonable approach to application of these policies. It is important that the needed sight distance of left-turning drivers be recognized and evaluated. A lack of adequate sight distance may require a separate left-turn lane or left-turn traffic signal control so that the left turn can be safely completed. The sight distance restrictions created by geometrics or by opposing left-turn vehicles should not be overlooked in the design and operation of left-turn facilities.

The MUTCD provides the authoritative, nationally accepted guidelines for signing, pavement markings, and traffic signal control of left turns. A number of research studies and field applications tend to support the validity of the MUTCD provisions. The pavement markings for left-turn treatment are clearly outlined and uniformly applied by most jurisdictions. There is some limited driver understanding of signing and traffic signal application because of a lack of national uniformity, driver education, and subtle variations in the applications. Reliable field data on traffic operations for some traffic control device applications are needed to assist in the expansion and clarification of MUTCD provisions.

Various traffic signal phasing and signal indications have been used for left-turn treatments. There has been a tendency to provide more traffic signal control for left-turn movements and greater left-turn protection than may always be necessary. The current approach is to provide the minimum left-turn control that will accommodate the left-turn maneuver with the least impact on other intersection movements. This has resulted in left-turn signal phasing, providing permitted, exclusive (protected), lead-lag, and various combinations during peak and off-peak hours of operation. The type of operation has varied some from the MUTCD provisions throughout the country with questionable driver understanding of the permitted signal indications. A current research study aims to develop the necessary study plan and data collection methodology to resolve these questions and establish a single method of signalizing permitted left turns.

The accommodation of left turns has resulted in a number of special applications limited only by the innovative approach of the traffic engineering profession. These have included the continuous flow and bowtie intersection concepts. Jurisdictions have prohibited left turns or relocated them by providing indirect left turns when they cannot be safely and effectively permitted at the intersection. Special accommodation of left turns has been incorporated into reversible traffic lane operations with signing and lane control signals to implement these traffic operations. The number of left-turn lanes has increased with triple left-turn lanes becoming more common. The application of design, traffic control, and operational criteria for multiple left-turn lanes requires special consideration. Pedestrian and bicycle activities in the intersection conflict with left-turn maneuvers and require special attention to reduce the accident potential.

The adequacy of left-turn treatments can be evaluated through field observations, traffic studies, and computer traffic models. The initial evaluation of left turns should include a field review of the intersection and left-turn operations. This field review identifies left-turn operational problems and provides insight into the field data collection requirements to fully evaluate the intersection operations and possible improvements. Various computer traffic models are available using the same geometric and traffic characteristics as a detailed operational study that will permit not only the evaluation of left-turn performance but also provide the means to measure the effectiveness of left-turn improvement alternatives.

Research is proceeding on several issues that will address some of the questions on left-turn treatments. A critical gap in data exists where innovative applications by local jurisdictions are not documented. Much can be learned about the effectiveness of a design or traffic control feature when traffic characteristics are collected. Before and after data, however limited, that can be used to consider future applications of the tested left-turn treatment would be helpful.

Future research on left-turn treatments would be useful in the following areas:

- Traffic control and channelization to assist older drivers in making left turns.
- Traffic characteristics and accident data to clarify and strengthen MUTCD provisions.
- Traffic data and engineering analysis supporting definitive guidelines on when specific levels of left-turn treatment are appropriate.
- Research to provide acceptable national guidelines for left-turn signalization covering the range from no control to permitted and exclusive protection with time-of-day variations to reduce the intersection operational impacts.

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GLOSSARY OF ACRONYMS AND ABBREVIATIONS

AADT	Average Annual Daily Traffic
AAP	Arterial Analysis Package
AASHTO	American Association of State Highway and Transportation Officials
ADT	Average Daily Traffic
CALTRANS	California Department of Transportation
CFI	Continuous Flow Intersection
DHV	Design Hourly Volume
DOT	Department of Transportation
FHWA	Federal Highway Administration
ft/sec^2	feet per second squared
HCM	Highway Capacity Manual
HCS	Highway Capacity Manual Software
IBM	International Business Machines
ITE	Institute of Transportation Engineers
LRT	Light Rail Transit
LTMAP	Left Turning Movement Analysis Program
LUF	Lane Utilization Factor
mph	miles per hour
MUTCD	Manual on Uniform Traffic Control Devices for Streets and Highways
mvm	million vehicle miles
NCHRP	National Cooperative Highway Research Program
NCUTCD	National Committee on Uniform Traffic Control Devices
NEMA	National Electrical Manufacturers Association
NETSIM	Traffic Network Simulation Program
PASSER II	Progression Analysis and Signal System Evaluation Routine
PHF	Peak Hour Factor
PLL	Permitted Lead-Lag
sec/veh	seconds per vehicle
SOAP	Signal Operations Analysis Package
TIPS	Traffic Information Program
TRANSYT	Traffic Network Study Tool
TWLTL	Two-Way Left-Turn Lane
UVC	Uniform Vehicle Code
v/c	volume to capacity
vpd	vehicles per day
vph	vehicles per hour
vphgpl	vehicles per hour green per lane
vphpl	vehicles per hour per lane

APPENDIX A

1994 Survey Questionnaire

NCHRP Project 20-5, Synthesis Topic 25-03
SURVEY OF LEFT TURN TREATMENTS AT INTERSECTIONS
March 1994

Dear State or Local Traffic Engineer:

As part of the National Cooperative Highway Research Program (NCHRP), the Transportation Research Board (TRB) is looking for different and innovative ways for accommodating left turning traffic at intersections. It would be appreciated if you would take a few minutes of your time to complete the following questionnaire. The survey is divided into five parts: DESIGN, TRAFFIC CONTROL DEVICES, TRAFFIC SIGNALS, PERFORMANCE MEASURES, SPECIAL USERS, and SPECIAL APPLICATIONS. Thank you for your assistance.

Please provide the name of the person completing this questionnaire, or who may be contacted in your agency to obtain follow up information:

Name______________________________
Title______________________________
Agency______________________________
Address______________________________

Telephone (____)________________
Fax (____)________________

DESIGN

The AASHTO Policy on Geometric Design (1990) provides recommended guidelines for left turn lane usage and design.

1. What guidelines does your agency use to determine left turn lane requirements?:
AASHTO Policy____ Agency Criteria____ If an agency guide is used, please enclose a copy.

2. What special considerations are used other than traffic volumes to justify a left turn lane?

Accidents ☐
Other _________ ☐

Comments______________________________

3. Have you relocated left turn movements by providing indirect left turns, such as:

Jughandles ☐
Median U-Turns ☐
Other _________ ☐

What has been your experience and the public acceptance of these actions? Please comment:

Please provide any studies or reports on advantages and disadvantages.

4. Does your agency have left turn lane design criteria that vary from the AASHTO Policies? YES___NO___ If yes, please enclose a copy.

What has been the basis for your own design criteria?

TRAFFIC CONTROL DEVICES

The Manual on Uniform Traffic Control Devices for Streets and Highways(MUTCD) provides recommended standards for marking and signing left turn lanes.

5. Have you installed any innovative signing or pavement markings for left turn lanes at intersections? YES__NO__ If yes,please enclose picture or diagram.

6. What were the reasons for the special design and what has been your operational experience with this design? Please comment:

7. Are there revisions or changes you would like to see in the MUTCD requirements to make these devices more effective? YES__NO___
Explain:______________________________

TRAFFIC SIGNALS

The MUTCD provides recommended standards for left turn traffic signal design, displays and phasing.

8. Does your agency have special vehicle detection requirements for the left turn lanes? YES___NO___
What are they? Please comment:

9. Does your agency have left turn display arrangements that vary from the MUTCD requirements? YES___NO___ If yes, please enclose a diagram or sketch.
Comment on reasons for their application:

10. If you have a flashing left turn signal indication for signal turn-on, flashing operations, or emergency conditions, the left turn signal is:

	Under What Conditions or Displays?
Unilluminated______	______
Flashing Red, Circular______	______
Arrow______	______
Flashing Yellow, Circular______	______
Arrow______	______

11. The left turn signal phase may be protected, overlapped with other phases, protected/permissive, split approach phasing, etc. What traffic data, roadway limitations and operational characteristics do you consider in the left turn signal phasing requirements?

12. Have you applied different variations from the MUTCD provisions for:
a. Protected/Permissive Left Turns, YES___NO___
b. Leading/Lagging Left Turns, YES___NO___

Please comment on the variations and reasons for their application______

13. Have you operated special left turn phasing during peak hours and other phasing during off peak periods? YES___NO___
Comment on type of operation and driver compliance______

14. What criteria are used to determine left turn signal change intervals?
Yellow indication: Standard___seconds or Yellow plus ___seconds

All red or yellow and all red timing increased under following conditions:
Length of Left Turn? YES___NO___ Larger Vehicles? YES___NO___
Other Reasons______

PERFORMANCE MEASURES

15. Does your agency have methods or procedures for measuring the effectiveness of left turn operations? YES___NO___ If yes, please provide a copy of the procedure or a performance evaluation.

SPECIAL USERS

16. Does your agency apply special design considerations for special vehicles or users? Check and explain special considerations.
Large Vehicles___ ______
Transit___ ______
Bicycles___ ______
Light Rail___ ______

SPECIAL APPLICATIONS

17. Do you restrict U-Turns from left turn lanes? As a general practice___
Only for operational requirements___, Other circumstances, explain______

18. Have you prohibited left turn maneuvers? YES___ NO___ If yes, what were the circumstances? ______

Method of prohibition?

What were the operational benefits? ______

19. Have you deleted protected left turn signal phasing and/or removed left turn signal indications? YES___NO___What were the circumstances and was it effective?
Comment______

20. Are there other provisions, criteria, requirements or experience relative to left turns at intersections that you would like to report?

Please Mail Completed Questionnaire to:
Mr. James L. Pline, P.E.
Pline Engineering, Inc.
2520 Fry Circle, Boise, ID 83704

If you have questions or additional comments, please feel free to call at (208) 375-3026

THANK YOU FOR YOUR ASSISTANCE

APPENDIX B

Survey Responses

A survey of state and local highway agencies and toll road and turnpike authorities was conducted to obtain information on left turn treatments at intersections. The major objective of the survey was to obtain information on current practices and to identify any special or innovative practices. The survey was conducted by means of the attached mail questionnaire.

The questionnaire was mailed to the AASHTO Highway Subcommittee on Traffic Engineering that includes the 50 member states, Puerto Rico, District of Columbia, Canadian Provinces, New Jersey Turnpike Authority, Massachusetts Metro District and Military Traffic Management Command. A selected list of 68 cities and seven counties also received the questionnaire using the Institute of Transportation Engineer's (ITE) directory of Urban Traffic Engineers Council (UTEC).

RESPONSE RATE: The response rate on the questionnaire was as follows;

AGENCY	MAILING	RESPONSES	PERCENTAGE
State	50	33	66%
Cities	70	28	40%
Counties	7	4	57%
Provinces	7	1	14%
Other	5	3	60%
Total	139	69	50%

DESIGN

Question 1 Guidelines that agency uses to determine left turn lane requirements.

	AASHTO Policy	Agency Criteria
States	69%	31%
Local Agencies	64%	26%

Question 2 Special considerations used other then traffic volumes to justify a a left turn lane. Number of responses

Accidents 63 Level of Service 17 At major Intersections 7

Sight Distance 5 Traffic Operations 5

Other considerations: At all signals, engineering judgement, turning movements, speeds, location and land use, intersection geometrics.

Question 3 Have left turns been relocated by providing indirect left turns, such as: Jughandles 16 responses Median U-Turns 26 responses

Other: Leading U-Turns so traffic does not enter intersection

Move left turns and U-turns to another signal

Provide two way left turn lanes to relieve intersections

Comments: The comments on "Jughandles" varied from they work well, favored by the public, to drivers do not understand usage, confuse drivers, not an effective solution. Median U-Turns are favored over intersection U-Turns, median U-Turns used for years without problems, public thinks U-Turns are more dangerous than left turns, public acceptance of median U-Turns after some initial problems, businesses prefer direct left turns to indirect median U-Turns, raised medians and median U-Turns installed to control indiscriminate left turns and U-Turns.

Question 4 Does left turn design criteria vary from AASHTO Policies?

NO	States 27 responses	Local Agencies 22	Other 4
YES	States 7	Local Agencies 8	Other 0

Comments:

1. AASHTO is general and oriented to highways and new construction not existing urban arterials.

2. The California local agencies generally use the CALTRANS design criteria.

3. AASHTO design is deficient in addressing urban arterials, existing streets, lower speeds, and taper design for an added lane at an intersection

TRAFFIC CONTROL DEVICES

Question 5 Are innovative signing or pavement used for left turns at intersections? States 5 responses Local Agencies 8 responses

Question 6 Reasons for the special design and operational experience with this design.

New York: Uses a "Wait for Green Light" and "Wait for Green Arrow" signs.

Amarillo, Texas: The R10-9 sign at 12" X 18" is not readable, enlarged to 18" X 24".

Albuquerque, New Mexico: Uses a temporary dual left turn lane for construction signing.

Cincinnati, Ohio: Drivers pay more attention to "Left On Arrow Only" which is not a mandatory sign.

Chattanooga, Tennessee: Reduces the pavement widening for an added lane to minimize pavement markings.

Los Angeles, California: Clearly terminates Two Way Left Turn Lane, provides single entry into dual lane to eliminate excessive pavement markings.

Nevada: Uses overhead signing for triple left turn lanes to give left turn lane destinations.

Reno, Nevada: The use of "Left Turn Yield When Flashing" with a flashing yellow arrow is unnecessary since drivers understand the flashing arrow signal indication.

Illinois: Have used a fiber optics permissive left turn sign but the effectiveness is inconclusive.

Minnesota: Uses a R10-12 sign, "Left Turn Yield on Green Ball", adjacent to signal head for protected/permissive operations. The R10-10 sign, "Left Turn Signal", is not necessary and is not used for protected left turn indications.

Overland Park, Kansas: Uses a diagrammatic arrow showing Left and U-Turns with legend, "On Left Arrow Only". Eliminates need for added median openings and driver experience has been good.

Buenaventura, CA: Uses a dual left turn lane, left lane U-Turn and other lane Left Turn, where there are heavy U-Turns and cross street can not handle dual left turn movements.

Georgia: Uses a U-Turn arrow symbol for permitted U-Turns at T-Intersections.

Question 7 Are there revisions or changes in the MUTCD requirements to make these devices more effective. Only 7 responses

Comments:

Alabama: Left turn lanes should be required with all median openings before signal installations.

Amarillo, TX: Increase size of R10-9 sign.

Los Angeles, CA: Adopt specific distances for left turns to serve driveways and specific criteria for not using a reverse curve entry into left turn lanes.

Cincinnati, OH: When a turn arrow is used, the R10-5 sign, "Left On Green Arrow Only" is more effective than R10-10, "Left Turn Signal" sign.

Overland Park, KS: Ensure that diagrammatic left turn and U-turn sign is permissible.

Chattanooga, TN: The MUTCD does not address taper transitions for Left Turn lanes when lane is added.

Gwinnett County, GA: The MUTCD is not detailed on Protected/Permissive traffic signal indications.

MUTCD needs to provide better guidance on overhead signs and to be effective for left turns signs have to be mounted overhead.

TRAFFIC SIGNALS

Question 8 Is there special vehicle detection requirements for left turn lanes?

11 States and 12 Local Agencies responded with a YES

Comments; Many jurisdictions use multiple loops separate from the through traffic lanes. Several use a loop back from the STOP bar that requires 3 to 4 vehicles before actuation under protective operation for protected/permissive signal operations. Some use a presence detector at the STOP bar that is not activated under permissive left turn operations. It was noted that loops should include a header to detect motorcycles. Also, noted that loops must detect bicycles.

Question 9 Does agency have left turn display arrangements that vary from MUTCD requirements? 10 States and 2 Local Agencies responded YES

Comments:

Michigan: Experimented under FHWA project with flashing Circular Red in left turn signal for permissive left turn operations.

Nebraska: Use a five section signal head protected/permissive, red ball with green arrow, ie. Bonneson/McCoy University of Nebraska 1993 Study of Left Turn Signal Displays

Pleasanton,CA: Use a mast arm and a far left turn arrow, sometimes near side median turn arrow.

Dade County,FL: Horizontal signal mounting with Green Arrow pointing at illuminated Red Ball.

Arkansas: Do not allow the use of yellow and red arrows for safety reasons.

Delaware: Uses a flashing red arrow during the permissive left turn phase.

Connecticut: They have not yet updated the older signals to current MUTCD requirements.

Nevada: Prefer a far left traffic signal for left turn phasing. Eliminates signal blocking by trucks.

Reno, NV: Uses	Red Arrow	Steady	All other Intervals
	Yellow Arrow	Steady	Clearance Green Arrow
	Yellow Arrow	Flashing	Permissive Left Turn
	Green Arrow	Steady	Protected Left Turn

Avoids the left turn trap, excellent driver comprehension, and improved operations.

Illinois: Experimented with an activated "Left Turn Yield" sign. Effectiveness has been inconclusive. IL DOT does not recommend future installations.

Minnesota: Always uses a far side left turn signal for dual left turns and sometimes near median mounted signal.

Question 10 What is the left turn indication for signal turn-ons, emergency operations or signal flashing operations?

Flashing the same as adjacent through lanes - 8

Flashing circular red - 20 Unqualified, Protected Left Turn - 7, For Shared Lane - 1

Flashing Red Arrow - 13 Unqualified, Protected Left Turn - 6

Flashing Circular Yellow - 3 Unqualified, Protected/Permissive - 6

Flashing Yellow Arrow - 3 Unqualified, Protected 3 section Head only - 1

Question 11 What traffic data, roadway limitations and operational characteristics do you consider in the left turn signal phasing requirements?

Traffic Volumes	49	Accidents	30
Geometrics	30	Sight Distance	15
Signal Coordination	14	No. of Opposing Lanes	13
Vehicle Delay	11	Capacity	9
Opposing Speed	9		

Other items noted where wide medians, driver expectancy, operational characteristics, number of left turn lanes, percent of trucks on grade, gap studies, public feedback, and commercial vehicles. Hawaii requires a left turn lane for left turn signal phasing.

Question 12 Have different variations from MUTCD been applied for -

Protected/Permissive Left Turns: 5 States and 3 Local Agencies responded YES

Leading/Lagging Left Turns: 1 State and 2 Local Agencies responded YES

Comments:

Maryland: Use flashing red arrow at night for Protected/Permissive with sign, "Left Turn on Flashing Red After Stop".

Michigan: Flashing Circular Red for permissive left turns.

Nebraska:Use a five section head, Circular red with green arrow.

Texas: Several cities use the "Dallas Phasing" for Protective/Permissive, Lead/Lag, operation.

Delaware & Cupertino, CA: Flashing Red Arrow for permissive left turns.

Connecticut: Use older MUTCD interpretations are still used.

Tallahassee, FL: Only 1 in 160 installations has a lagging left turn for signal progression purposes.

Illinois: Would like to obtain more information on "Dallas Phasing" for application consideration.

Question 13 Have you operated special left turn phasing during peak hours and other phasing during off peak periods?

17 States, 14 Local Agencies and 1 Other Agency responded YES

Comments: Most of the response related to protected left turn peak hour to permissive in off peak. Several locations switch between lead and lagging left turns. Tucson prohibit left turns during reversible lane operations during peak hours. California omits protected left turns during peak hours to increase major green times. One location provides a peak hour double left turn. All indicate good compliance with these special phasing operations.

Question 14 Criteria used for left signal change intervals.

Yellow Indication, 3.0 seconds(27), 3.5 seconds(6), 4.0 seconds(11), 5.0 seconds(1)

All Red Indication, 0.5 seconds(1), 1.0 seconds(8), 0 to 2.0 seconds(5)

Comments: Use Traffic Control Handbook to determine timing, five use ITE formula, one agency uses 0.5 seconds of All Red for every 5 mph increase in approach speed.

Timing for change intervals increased under following conditions:

Length of Left Turn: 17 States, 13 Local Agencies and 2 Other Agencies responded YES.

Larger Vehicles: 13 States, 8 Local Agencies and 2 Other Agencies responded YES

Other Reasons: Geometric width(16), Approach Speeds(15), Down Grade(6), Engineering Judgement, Field Observations, Intersection Angle, Complaints, Sight Distance, Accidents, and apply procedures from Parsonson ITE article(July 1989).

PERFORMANCE MEASURES

Question 15 Methods or procedures for measuring the effectiveness of left turn operations: 3 States, 10 Local Agencies and 2 Other Agencies responded YES.

Comments:

Texas & Idaho: Field observations, accident data, and operational data.

Florida: Intersection delay studies for left turns.

Minnesota: Visual Observations

Washington: Nothing formal, field reviews and operational analysis periodically.

Pleasanton, CA: Annual V/C measurements for peak hours and field observations.

Beaumont, TX: Passer II, Left Turn Analysis Program

Cupertino, CA: Delay based optimum LOS analysis.

Dade County, FL: Field observations and accidents.

Reno, NV: Capacity Analysis, Arterial Analysis Program.

Los Angeles,CA: Accidents, Delay, Volume, and Geometry.

Gwinnett County, GA:Delay studies based on Bretherton Study, 1991 ITE Meeting Compendium.

Cincinnati, OH: Before and After observations and accidents.

Charlotte, NC: Monitor left turn accidents.

SPECIAL USERS

Question 16 Are there special design considerations for special vehicles or users.

Large Vehicles: 12 States, 8 Local Agencies and 2 Other Agencies

Transit: 6 States and 4 Local Agencies

Bicycles: 5 States and 10 Local Agencies

Light Rail: 2 States and 2 Local Agencies

Other Considerations: Elderly, School Children, Location, Geometrics, Signal Progression.

Comments: Bicycles need accessible push buttons or special detection, use bicycle turn lanes, Maryland uses Opticom for transit buses.

SPECIAL APPLICATIONS

Question 17 Are U-Turns restricted from left turn lanes?

As a general Practice: 6 States, 3 Local Agencies and 2 Other Agencies.

Only for operational Requirements: 25 States, 19 Local Agencies and 1 Other Agency.

Other Circumstances:

Canada & Washington,D.C.: U-Turns are illegal at traffic signals.

Limited roadway width or restrictive geometrics reported by several agencies.

Prohibited where the U-Turn and Right Turn Arrow would overlap into same space.

Conflict with a heavy right turn or at heavy volume intersections.

Question 18 Have left turns maneuvers been prohibited?

27 States, 28 Local Agencies and 2 Other Agencies responded YES.

CIRCUMSTANCES: Accidents (18), Operational & geometric reasons(16), V/C deficiencies(13), High volume & shared traffic lane(9), Limited Sight Distance(4), Minor Street & alternate access, during peak periods, for special events, short street spacing, reversible lane operations, and one way streets,

METHOD OF PROHIBITION: Signing(59), Raised Island(15), Markings(2) Enforcement (2)

OPERATIONAL BENEFITS: Reduced accidents(26), Increased Efficiency(27), Reduced Delay(9), Reduced Conflicts(6), Improved traffic flow(9).

Question 19 Has protected left turn signal phasing been deleted and/or left turn signal indications been removed?

15 States, 16 Local Agencies and 1 Other Agency responded YES

Comments:

Georgia: Very rarely and only with intersection geometric changes.

Mississippi: At congested area with no room for more lanes, reduced the delay.

Alabama: Only base on accidents and traffic operational considerations.

North Dakota: At an isolated intersection with low volumes.

Nebraska: Added a left turn lane and deleted the left turn signal phase.

Texas, New York,Phoenix: For changing traffic patterns and lower volumes.

Tucson & Pleasanton: Signals installed for future traffic volumes and left runs not required now.

Chattanooga: Low left turn volumes in CBD intersections.

Question 20 Other provisions, criteria, requirements or experience to be reported.

Rhode Island: Ohio has developed reasonable evaluation procedures in FHWA/OH-83/003 report.

Wyoming: Operating a dual left protected/permissive left turn

South Dakota: Left turn lanes at signalized intersections even without left turn phasing reduces accidents.

Ohio: The painted median on right for offset left turns is a problem.

Nevada: Would like some research on clearance intervals for very wide and/or skewed intersections.

Illinois: The AASHTO Greenbook should the need to offset left turn lanes in design.

Beaumont,TX: Has had good luck using all signal arrows for protected only signals.

Buenaventura,CA: Does not like CALTRANS warrant for left turn signalization but has no better ideas at this time.

Dade County, FL: Tried one left turn lane protected and other left turn lane protected/permissive but was not successful. May try again.

Los Angeles, CA: Unless safety is a problem, the left turn signal phasing should always start as protected/permissive operation before going to a protected only phasing.

New York City: Developing a "Continuous Flow Intersection" design, reported in body of synthesis.

Phoenix, AZ: The combination of lead/lag, Protected/permissive needs to be applied more.

APPENDIX C

Public Information Brochures

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LEFT-TURN PHASING WARRANTS

-NEW YORK CITY-

Nationally accepted warrants do not exist to assist traffic engineers in the use of the protected/permissive left-turn phasing technique. For this reason the Bureau of Traffic (N.Y.C.D.O.T.)has developed it's own warrants. The warrants used for approving a left-turn phasing at signalized intersections are based on accident experience and left-turn capacity.

The following two warrants are utilized by the Bureau before recommending the implementation of a Left-Turn phase:

> WARRANT 1 (Accident Experience): This Warrant is satisfied when a minimum of 5 related left-turn accidents exist in a 12 month period. If accidents can not be obtained for the latest 12 month period, then accident information for previous periods may be used for the analysis.
>
> WARRANT 2 (Left-Turn Capacity): This warrant is satisfied when for the analyzed direction the left-turn flow rate exceeds the left-turn capacity. The left-turn capacity is the maximum flow rate that may be assigned to the designated phase.
>
> The warrant allows the engineer to analyze approaches with exclusive left-turn bays and approaches with shared left-turn and through vehicles.
>
> The Bureau of Traffic requires the completion of the 5 page "Left-Turn Phasing" warrant study. The study includes the field survey page (geometrics, signal phasing, timing, turning movements, etc.) and the Warrant 1/Warrant 2 calculation pages.
>
> Copies of the study may be obtained by notifying the Bureau of Traffic Operations.

The following definitions are used with the left-turn phasing analysis:

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Protected-Only (Exclusive) Left-Turn: The left-turn driver is directed to turn left in a protected manner through the display of a green arrow, and then directed by the display of a circular red to wait for the next traffic signal cycle and its corresponding green arrow.

Permissive Left-Turn: The left-turn driver is not directed to turn left in a protected manner during the circular green in a traffic signal cycle and may only turn left when the gap in the opposing through traffic is adequate to ensure a safe left-turn or turn left at signal's yellow clearance period.

Protected-Permissive (Leading) Left-Turn: The left-turn driver is first directed to turn left in a protected manner through the display of a green arrow, then given the opportunity to turn permissively when adequate gaps appear in opposing traffic through the display of a circular green.

Permissive-Protective (Lagging) Left-Turn: The left-turn driver is first given the opportunity to turn permissively when adequate gaps appear in opposing traffic through the display of a circular green, then directed to turn left in a protected manner through the display of a green arrow.

TURN LANES
"Why are 'turn lanes' used?"

Turn lanes at intersections are designed primarily to separate turning traffic from through traffic. With turn lanes, through traffic is not delayed by vehicles waiting to turn. By removing the turning vehicles from a through lane, traffic flow and safety are improved. Turn lanes may also be used to enable vehicles to slow down when leaving the major street.

Accident studies have shown that channelization of intersections, with turn lanes, produced an average of 32.4 percent reduction in all types of accidents. Accidents involving personal injuries decreased by over 50 percent. One study showed that intersection channelization projects had produced an average benefit/ cost ratio of 2.31. Turn lanes at major driveways can also improve efficiency and safety, especially on high volume or high speed roadways. When turn lanes are added, studies have shown a 52% decrease in rear end accidents as well as 6% decrease in left turn accidents.

One of the most significant features affecting an intersection's operation is the treatment of left-turning vehicles. Accommodation of left turns can be one of the most critical intersection design factors since safety and the level of service are greatly influenced.

A left turning vehicle (from a major street) can conflict with: a) Opposing through traffic; b) Crossing traffic; c) Through traffic in the same direction.

The major accident types involved with left turning vehicles are rear end, angle and sideswipe accidents in the same direction. Accident studies have shown the beneficial effect of left-turn lanes on accident rates at intersections. The results of one study is shown below:

Intersection Type	Accidents Per Million Entering Vehicles
Unsignalized - without left turn lanes	4.3
Unsignalized - with left turn lanes	1.1
Signalized - without left turn lanes	2.5
Signalized - with left turn lanes	1.6

Accidents types associated with right-turning vehicles are rear-end, side-swipe pedestrian. An accident study of driveway accident types related to turning movement is shown below:

MOVEMENT	NUMBER OF ACCIDENTS	% OF TOTAL
Entering driveway by left turn	246	43
Entering driveway by right turn	26	15
Leaving driveway by left turn	65	27
Leaving driveway by right turn	35	15

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The use of right-turn lanes at intersections can significantly affect operations. At signalized intersections, decrease in total approach delay can be provided by an addition of a separate right-turn lane. At unsignalized intersections, right-turn lanes can serve to safely remove turning vehicles that are decelerating from the through traffic.

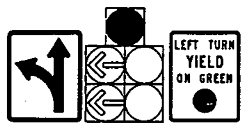
In general, the treatment of right-turning vehicles is less critical than left-turning vehicles due to the fact that right-turning vehicles must yield the right-of-way to fewer conflicting movements than left-turning vehicles.

TIPS TRAFFIC INFORMATION PROGRAM SERIES - Revision 5/5/93

City of San Buenaventura, California

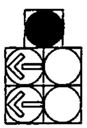
3RD STREET
WESTBOUND AT JACKSON STREET
EASTBOUND AT WASHINGTON STREET

The new "protected/permissive" signal operation to be installed at the intersections of 3rd Street with Jackson and Washington Streets will consist of a basic six step (phase) signal sequence for traffic in the left lane of 3rd Street (westbound to southbound at Jackson and eastbound to northbound at Washington) as indicated below. Although the signal operation will be the same as at 6th and Jackson and 6th and Washington, the allowable traffic movements are somewhat different because of the difference in the lane configurations. Note the additional sign that will be used at these locations.



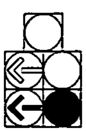
Left lane signal display with signs.

Signal Operation Sequence



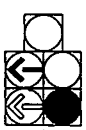
1

Red light. All traffic in this lane must stop. Cross street traffic is proceeding.



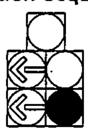
2

Green arrow with green ball. Traffic in the left lane may either turn left or continue straight across the intersection. The green arrow indicates that the left turn is "protected," that is, both the oncoming traffic and cross street traffic are stopped.



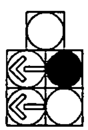
3

Yellow arrow with green ball. The yellow arrow indicates that the "protected" left turn is terminating, and oncoming traffic is about to receive a green light. Traffic in the left lane may continue to go straight across the intersection, but left-turners must now prepare to yield to oncoming traffic.



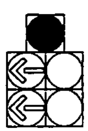
4

Green ball. Oncoming traffic now has a green light. Traffic in this lane may continue to go straight across the intersection. However, as indicated by the sign, traffic in this lane must now yield to oncoming traffic before turning left.



5

Yellow ball. Prepare to stop. The light is about to change to red. Cross street traffic is about to start proceeding.

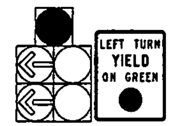


6

Red light. All traffic in this lane must stop. Cross street traffic is proceeding.

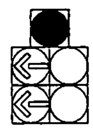
6TH STREET
WESTBOUND AT JACKSON STREET
EASTBOUND AT WASHINGTON STREET

The new "protected/permissive" signal operation to be installed at the intersections of 6th Street with Jackson and Washington Streets will consist of a basic six step (phase) signal sequence for traffic turning left (westbound to southbound at Jackson and eastbound to northbound at Washington) as indicated below. Traffic in the through lanes will not notice any significant change in signal operation.



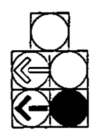
Left turn lane signal display with sign.

Signal Operation Sequence



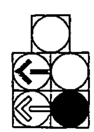
1

Red light. All traffic in this lane must stop. Cross street traffic is proceeding.



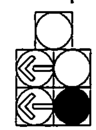
2

Green arrow with green ball. Traffic in this lane may turn left. The green arrow indicates that the left turn is "protected," that is, both the oncoming traffic and cross street traffic are stopped.



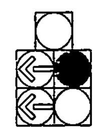
3

Yellow arrow with green ball. The yellow arrow indicates that the "protected" left turn is terminating, and oncoming traffic is about to receive a green light. Left-turners must now prepare to yield to oncoming traffic.



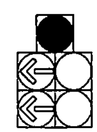
4

Green ball. Oncoming traffic now has a green light. As indicated by the sign, traffic in this lane must now yield to oncoming traffic before turning left. This is the "permissive" part of the operation.



5

Yellow ball. Prepare to stop. The light is about to change to red. Cross street traffic is about to start proceeding.



6

Red light. All traffic in this lane must stop. Cross street traffic is proceeding.

Other Traffic Information Brochures Available

- *Speed Zones & Speed Bumps*
- *Stop Signs & Traffic Signals*
- *Marked Crosswalks*
- *Pedestrian Signals*
- *Traffic Signal Systems*
- *Adult School Crossing Guards*
- *Flashing Beacons*
- *Parking Pointers*
- *Avoiding Parking Tickets*
- *Traffic Safety Tips*

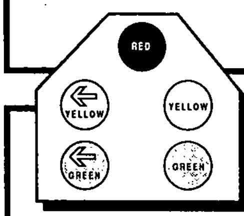
If you have questions, requests or suggestions concerning traffic, please call the Engineering Division at 654-7887.

In compliance with the Americans with Disabilities Act, this document is available in alternate formats by calling 654-7887 or through the California Relay Service.

Printed on recycled paper

City of San Buenaventura
Engineering Division
501 Poli Street
P.O. Box 99
Ventura, CA 93002-0099

Left Turn Traffic Signals



Engineering Division
City of San Buenaventura

Left Turn Traffic Signals

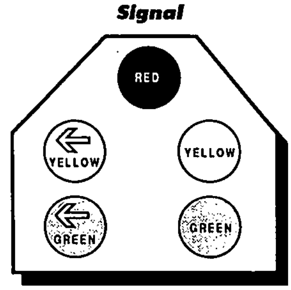
Until recently, drivers have been accustomed to seeing left turn signals where there is initially a green arrow followed by an amber arrow followed by a red arrow. On the green arrow drivers are given the right-of-way to complete left turns free of any other traffic conflicts. The amber arrow warns drivers that the left turn signal is ending. On the red arrow, left turns are not permitted. These type of arrows are helpful but when there is no opposing traffic they can cause unnecessary delays.

Protective/Permissive Left Turn Signals

Over the last several years, a different type of left turn signal has been implemented at intersections in the city. Under this new arrangement, left turn signals provide the usual green arrow which is usually followed by the normal amber arrow. After the amber arrow has terminated, drivers are now faced with a solid green ball signal.

During the display of the solid green ball, left turns can be made when there are adequate gaps in opposing traffic to complete left turns safely. This new type of left turn phasing is designed to help minimize delay by eliminating the need for the red arrow and allowing vehicles to turn on the green ball after opposing traffic has cleared. By not having the red arrow, motorists do not have to sit and wait to turn left even when there is no opposing traffic, a situation that often occurs during periods of low traffic volumes. The signal still provides a green left turn arrow during rush hours when traffic is heavy, but during off-peak hours, left turning vehicles are not delayed by a red arrow.

Protective/Permissive Signal



Why Doesn't the City Use Protected/Permissive Left Turn Signals Everywhere?

The City is using protective/permissive left turn signals where drivers can turn left safely because there are gaps in approaching traffic and drivers can clearly see oncoming vehicles. Examples of recent protected/permissive installations are at the intersections of Victoria/Loma Vista, Telephone/Portola, Telephone/Market, Telephone/Transport and Bristol/Ramelli. In order to provide for good signal coordination, protected/permissive signals will not be available at all intersections. Special left turn sequencing is used to improve signal coordination and provide smooth through traffic flow at selected intersections. Some of these locations included Victoria/Telephone, Telephone/Lark, Victoria/Portola, and Telegraph/Ashwood where one arrow comes up at the beginning of green and the opposing left turn arrow comes up at the end of green. At these locations, protected/permissive operation would be dangerous for drivers. There are some intersections where the City could install protective/permissive left turns. However, this requires lengthening mast arms and installing new signal heads on the end of the longer mast arms which costs $60,000 per intersection. The City does not have funds to convert all these intersections to protective/permissive left turns. The City plans to use protective/ permissive signals wherever possible as signals are modernized and new signals are installed.

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