



Manual Notice 98-1

To: Recipients of Subject Manual

From: Charles W. Heald
Executive Director

Manual: *Highway Operations Volume*
of the *Traffic Operations Manual*

Date: September 9, 1998

Purpose

This volume of the *Traffic Operations Manual* provides information on all aspects of TxDOT's highway operations.

Supersedes

This volume supersedes the *Texas Highway Operations Manual*.

Contents

This distribution of the *Highway Operations Volume* contains:

- ◆ this manual notice
- ◆ Table of Contents
- ◆ Chapters 1 through 12
- ◆ Appendix A through F
- ◆ Index
- ◆ divider tabs
- ◆ a front cover insert
- ◆ a spine insert.

Instructions

This is a new volume. Insert these chapters and related matter with tabs into a three-ring binder.

Effective Date

This manual notice is effective as of August 1, 1998.

Contact

Address questions concerning information contained in this manual notice to Al Kosik, P.E., Traffic Operations Division (TRF), 512/416-3248 or fax 512/416-3299.

To obtain additional copies of this volume, contact Lois Young of the General Services Division (GSD) at (512) 451-6206.

1. Report No. FHWA/TX-98/1467-6F	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle HIGHWAY OPERATIONS		5. Report Date August 1998	
		6. Performing Organization Code	
7. Author(s)		8. Performing Organization Report No. Research Report 1467-6F	
9. Performing Organization Name and Address Texas Transportation Institute The Texas A&M University System College Station, Texas 77843-3135		10. Work Unit No. (TRAIS)	
		11. Contract or Grant No. Study No. 0-1467	
12. Sponsoring Agency Name and Address Texas Department of Transportation Research and Technology Transfer Office P. O. Box 5080 Austin, Texas 78763-5080		13. Type of Report and Period Covered Final: September 1995-August 1997	
		14. Sponsoring Agency Code	
15. Supplementary Notes Research performed in cooperation with the Texas Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration. Research Study Title: Urban Highway Operations Research and Implementation Program			
16. Abstract <p style="text-align: center;"> This document replaces the <i>Texas Highway Operations Manual</i> which was issued in August 1992. This edition provides a means of implementing the results of research tasks performed as part of this study and completed since the publication of that manual. </p> <p style="text-align: center;"> The <i>Highway Operations Volume</i> of the <i>Traffic Operations Manual</i> was developed for the Texas Department of Transportation to serve as a Department manual addressing highway operations. The information in this volume covers a wide range of operational issues related to the planning, design, construction, maintenance, and management of highways. Part I of this volume serves as an introduction of the concept of highway operations. Part II addresses operational considerations for project development, design, and scheduled activities. Part III addresses systems management, data collection, operational analysis, incident management, control strategies, information systems, and control centers. Part IV contains the appendices, abbreviations and definitions, annotated bibliography, and index. </p>			
17. Key Words Traffic Operations, Freeway Analysis, Highway Capacity, Freeways, Highway Systems, Traffic Management		18. Distribution Statement No restrictions. This document is available to the public through NTIS: National Technical Information Service 5285 Port Royal Road Springfield, Virginia 22161	
19. Security Classif.(of this report) Unclassified	20. Security Classif.(of this page) Unclassified	21. No. of Pages 424	22. Price

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HIGHWAY OPERATIONS

Traffic Operations Division

Austin, Texas

Manual No. _____

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OVERVIEW

Traditionally, traffic operations have been concerned primarily with the mechanics of traffic control devices in order to make the most effective use of existing highways. The assumption was that with enough signs, signals, and markings, any highway design could be made to operate satisfactorily. As a result, the design and construction of a highway were sometimes completed before due consideration was given to the operating characteristics of that facility.

Over the years, experience has shown that highway designs that consider operational issues can be operated with a minimum number of traffic control devices, but highway designs based only on minimum geometric standards may not operate satisfactorily under higher traffic volumes, regardless of how many traffic control devices are used. An effective design process requires all highway factors to be considered so that a balanced facility can be achieved.

The *Highway Operations Volume* of the *Traffic Operations Manual* promotes the concept that highway operations is a partner with planning, design, construction, maintenance, finance, and administration. The volume also intends to show how various highway factors can be combined to provide the best possible operations under the prevailing conditions.

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HIGHWAY OPERATIONS

The term highway operations is used to describe the interaction of vehicles within the traffic stream, given the limitations controlling that interaction, such as geometric design, traffic control, vehicle characteristics, and driver characteristics. Highway operations are also the yardstick by which the user measures the quality of the facility. The highway characteristics which matter most to the driver are **speed of travel, safety, comfort, and convenience**. Drivers have been conditioned to expect a certain standard of excellence on Texas highways. The engineer's challenge is to provide the best possible level of service within budget constraints and the limitations of the design process.

1.0 Need for Addressing Operations

The need for considering highway operations has become more evident in recent years as the demand for highway facilities has increased faster than the supply of urban highway lane-kilometers (miles). The result has been an increase in traffic congestion and motorists' delay together with a reduction in operational efficiency. Congestion in Texas now costs billions of dollars each year in excessive delays, fuel consumption, and air pollution.

This manual provides engineers with the operational concepts and tools needed to accomplish the Department's mission of providing a safe, economical, effective, and efficient highway transportation network. Improving highway operations provides a more cost effective means of addressing highway needs in the state. An aggressive program to address congestion through a highway operations program will pay dividends in improved operations and better motorist satisfaction.

2.0 Benefits of Improved Operations

Improving highway operations results in improved safety, better utilization of available capacity, reduced fuel costs, improved air quality, greater trip reliability, and reduced travel time. Projects that improve operations have produced benefit/cost ratios of 10:1 or more. Improved highway operations helps develop public support for other highway activities.

3.0 Purpose and Objectives of the Highway Operations Volume

The overall purpose of this *Highway Operations Volume* is to provide, in one comprehensive document, the means by which department engineers can obtain the knowledge needed to improve highway operations. The volume intends to satisfy the following requirements and objectives:

continued

3.0 Purpose and Objectives of the Highway Operations Volume (continued)

- ◆ Have application to all aspects of highway planning, design, construction, maintenance, and administration.
- ◆ Be useful in congested urban areas, as well as suburban and rural areas.
- ◆ Serve as a primary tool for implementing the findings of operations research.
- ◆ Be compatible with other Department manuals.
- ◆ Contain state-of-the-art information which can be updated and revised as needed.

4.0 Institutional Considerations

Improving highway operations requires cooperation between the appropriate agencies and jurisdictions in all phases of highway operations. In addition to the Texas Department of Transportation, other agencies which may be involved in operations include city or county transportation or public works departments, state, city and county law enforcement agencies, transit agencies, emergency services, and others. The Traffic Management Team (TMT) provides a means for communications between these various agencies. Chapter 6 contains additional information about the TMT.

5.0 Use of the Highway Operations Volume

This volume is intended for use at all levels in many different areas including, planning, design, traffic engineering, construction, and maintenance. It describes operational concepts that have application to all situations, rural as well as urban. These concepts will be of greatest benefit when applied at the beginning of a project and followed throughout the project's life. However, these concepts may also be used to evaluate congested areas and the impacts of proposed improvements and/or reconstruction.

The practices in this volume are advisory in nature and are recommended but not mandatory. Nevertheless, operational considerations should be given equal weight when compared to other considerations in developing a project.

continued

5.0 Use of the Highway Operations Volume (continued)

The volume is organized in the following manner:

- ◆ Part I - Background
 - Chapter 1 - Introduction to Highway Operations
- ◆ Part II - Fundamental Operational Practices
 - Chapter 2 - Operational Considerations in Project Development
 - Chapter 3 - Operational Considerations in Design
 - Chapter 4 - Design Considerations to Improve Operations
 - Chapter 5 - Operational Considerations for Scheduled Activities
- ◆ Part III - System Management
 - Chapter 6 - System Management
 - Chapter 7 - Data Collection
 - Chapter 8 - Traffic Operations Analysis
 - Chapter 9 - Incident Management
 - Chapter 10 - Control Strategies
 - Chapter 11 - Information Systems
 - Chapter 12 - Control Centers
- ◆ Part IV - Supporting Material
 - Appendix
 - Abbreviations and Definitions
 - Annotated Bibliography
 - Index

Various publications are referred to throughout the text of this volume. The annotated bibliography provides a brief description of these publications and locations from which they may be obtained.

6.0 Relationship Between the Highway Operations Volume and Other TxDOT Manuals

This volume provides operational information which supplements other departmental manuals. This volume will help the highway designer understand how the interactions of various design elements affect operations so that an appropriate balance of elements can be achieved. The *Highway Operations Volume* is not intended to reproduce every detail in other manuals, therefore, it may be appropriate to refer to other manuals for additional details.

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OPERATIONAL OBJECTIVES OF DESIGN

Throughout the design process, the highway designer should strive to meet several objectives which will impact the quality of the highway design in its current form and in future redesigns.

1.0 Operations and Design Quality

The engineer should strive to obtain the highest quality highway design possible. A high quality design provides:

- ◆ operational flexibility to meet unanticipated traffic conditions;
- ◆ expansion potential to adapt to changes in design requirements; and
- ◆ maintainability to reduce maintenance requirements, including the performance of maintenance activities.

Quality design emphasizes the importance of evaluating a highway facility over its entire life (including reconstruction), as opposed to the design life, such that it has the lowest cost over its entire life.

The design or redesign process for a highway requires the balancing of needs such as access, operations, cost, constructability, maintenance, and others. In some cases, the optimal operational solution may be limited by the requirements of other needs. This is particularly true in the reconstruction of existing facilities. In these cases, the concepts described in this manual can be used to provide the best possible operations under the prevailing conditions. Figure 1-1 illustrates that operations is only one spoke on a wheel containing many other spokes. Each of these areas are necessary to provide an effective highway system.

2.0 Operational Flexibility

Highway design is predicated on developments which are forecast to take place 20 to 30 years in the future. Even when the future land use and travel materialize as forecasted, there is no assurance that local traffic will develop as predicted. Consequently, some highways or sections of highways may have inadequate capacity or be out of balance with adjoining facilities before the design life is reached. Even when peak hour volumes are forecasted with reasonable accuracy, unanticipated development patterns, accidents, or other incidents may cause overloading of specific highway segments. These negative impacts can be offset by providing operational flexibility in the highway design.

Flexibility of operation can be achieved by providing added capacity through judicious lane arrangements, lane balance, and alternative routes. Providing alternative routes, patterned locally and system wide, permits traffic to seek an acceptable level of service by distributing traffic. In all cases, the designer should strive to obtain the maximum practical capacity that can be economically achieved, consistent with other elements of system configuration. The highway design should be carefully selected with consideration for maintaining the ability to choose from multiple design alternatives for future changes.

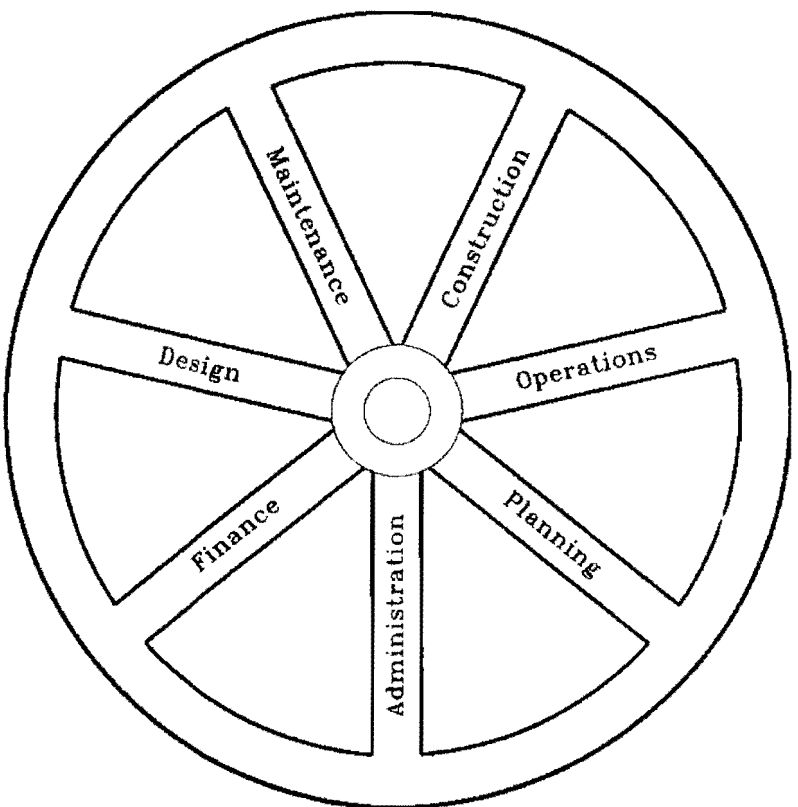


Figure 1-1. Spokes of Effective Highway System

3.0 Future Expansion

Although highway elements normally have a design life of 20 years to 30 years, the highway environment does not always mature in the manner in which planners envisioned. Future highway changes are often needed to accommodate unanticipated development. In the preliminary design phase, the flexibility of the highway to adapt to changing operational conditions should be evaluated. This evaluation should be done independently of existing and expected traffic volumes or current design policies. Some of the future changes which deserve consideration in preliminary design include: reduction of lane widths to add lanes, implementing high-occupancy vehicle lanes in median or outer separation, ramp and highway widening, future use of shoulders as lanes, and structure widening. Innovative engineering in preliminary design can greatly increase the flexibility of a facility to adjust to changing operational conditions. Some engineering considerations include: placement of bridge columns to permit pavement widening, extra width of pavement to permit restriping for narrow lanes, and drainage structures located away from potential future wheel paths.

4.0 Maintainability

Highway maintenance activities can have a detrimental effect on capacity. Therefore, future maintenance requirements of a facility should be carefully considered in preliminary design. Wherever practical, highway elements should be designed to reduce maintenance requirements. Potential maintenance considerations include increased pavement width, shoulder pavement thickness, reduction of sign supports on roadside and median, shoulders on both sides for parking maintenance vehicles, and others. When it is impractical to reduce maintenance requirements, highway elements should be designed to minimize the cost of the maintenance activities.

5.0 New Construction and Reconstruction

Much of the design and operational activities currently being performed by the Texas Department of Transportation are related to the reconstruction of existing highways, as opposed to the construction of new highways on new alignment. The redesign and reconstruction of an existing highway facility presents many limitations on the selection of operational alternatives. Restricted right-of-way, access requirements, environmental concerns, and public opposition may prevent the implementation of optimal operational conditions and require that compromises be made in all areas in order to provide the best possible operations given the restrictions on the design process.

Many of the operational concepts described in this manual address desirable operational conditions that are more easily implemented on new highway facilities. When the user of this manual is applying these concepts to the reconstruction of an existing facility, he or she must identify the operational limitations of the project and operational strategies that achieve the best possible operations given those limitations.

6.0 Public Involvement Process

Operational deficiencies are more difficult to address after design commitments have been made in the public involvement process. Therefore, it is important to consider the operational principles addressed in this volume during the earliest phases of the design process in order to obtain effective highway operations. The *Highway Design Division Operation and Procedures Manual* addresses the public involvement process in greater detail.

FUNCTION AND HISTORY OF THE HIGHWAY SYSTEM

The highway system in Texas and the United States serves a variety of functions, but primarily the movement of people and goods. Travel to and from work, services, social, and recreational purposes, and many other activities are necessary functions of our complex society. These functions have developed in a span of less than a hundred years, during which we have moved from horse-drawn vehicles on dirt roads to motor vehicles operating on an extensive network of high-quality highways. The next hundred years may see the development of automated vehicles, computerized navigation, and other technological advances.

1.0 Movement and Access

Highways serve two competing functions: movement and access. The highest quality of service is provided when access is controlled. Careful control of access ultimately provides the highest level of service to all system users. Access, once provided, is difficult to limit. All access decisions should be made with due consideration to the possibility of significant future traffic growth.

2.0 Historical Development

Our highway system has achieved its present level of maturity in a relatively short period of time. Highway construction for motor vehicles began in the early part of the 20th century. The post World War II era experienced a phenomenal growth in highway construction, including the construction of the Interstate Highway System. Presently, the focus has shifted from the construction of new facilities to the maintenance, operation, and rehabilitation of existing highways.

Prior to the turn of the century, highways in the United States were primarily narrow toll roads and turnpikes, often little more than cleared paths through the wilderness. The early roads were largely natural earth, although timber, cobblestone, macadam, and crushed stone were sometimes used as surfaces. The first state-aid highway law was enacted in 1891, and by 1900, six states had enacted similar legislation. In 1916, the Federal Aid Road Act was passed to aid the states in the construction of rural roads. A key feature of the act required all construction to be under the supervision of an organized state highway department. Texas became the 45th state to set up a highway department on April 4, 1917. Early Texas Highway Department efforts concentrated on registering vehicles (which provided the funding for Department activities) and organizing the Department.

World War I heralded a new era in highway construction in the United States. State and federal agencies recognized their responsibilities in the transportation field and began major construction efforts in many areas. As the highway system improved in quality, so too did the operating capabilities of the automobile. The improved operating characteristics of the automobile created a need for an even higher level of highway design, i.e., the freeway.

continued

2.0 Historical Development (continued)

The first access-controlled motor highway in the United States was the 64-kilometer (40-mile) Long Island Motor Parkway, built as a race course, but opened to the public in 1908. In 1923, construction began on a high-speed toll road in Italy. This was the first motor road of any considerable length to be built with full access control which is the vital principle of modern freeways. These roads were laid out as a series of long tangents, joined by superelevated curves of 500 meters (1640 feet) minimum radius. The first German autobahn began construction in 1933. These were the first highways with a design based on the concept of tying horizontal and vertical curvature and sight distance to speed. The design speed was 179 kmph (112 mph) in flat areas, and was reduced to 139 kmph (87 mph) in rolling and mountainous areas.

The first modern highway in the United States was the 100-kilometer (60-mile) long Pennsylvania Turnpike, opened in October of 1940. All curves of less than 1000 meter (3,300 feet) radius were spiraled and sight distance was provided for a speed of 110 kmph (70 mph) (96 kmph [60 mph] in eight cases). The first freeway in Texas was a 5.9-kilometer (3.7-mile) long section of the Gulf Freeway in Houston, opened in 1948. By mid-1951, four Texas cities had begun development of a freeway system. The Gulf Freeway was 13 kilometers (8 miles) long and the daily traffic volume was almost 67,000 vehicles. The Central Expressway in Dallas was 7 kilometers (4.4 miles) long, San Antonio had a 5-kilometer (3-mile) segment of freeway, and Fort Worth had constructed two freeway segments, totaling 10 kilometers (6 miles) in length. In 1963, there were 1526 kilometers (954 miles) of full access controlled freeways on the state highway system in Texas. In 1989, there were 6,395 kilometers (3,997 miles) of full access controlled freeways on the state system in Texas. Daily travel on these highways exceeded 195 million vehicle-kilometers (122 million vehicle-miles) in 1989.

The early Texas freeways differed in many ways from today's freeways, although the basic concept of the freeway has not changed over the years. The original Gulf Freeway was built on new alignment, designated as the new U.S. 75 highway (the interstate system had not yet been funded). The freeway cross-section consisted of six 3.7-meter (12-foot) traffic lanes and a 1.2-meter (4-foot) raised median with no barrier. One-way frontage roads were provided on each side of the freeway, although they were not continuous. The 24-hour traffic volume was approximately 28,000 (approximately 10 percent on frontage roads) just after the freeway first opened on September 30, 1948. By the middle of June 1949, the 24-hour volume was over 50,000 vehicles. The speed limit on the freeway was 70 kmph (45 mph) and 50 kmph (30 mph) on the frontage roads. However, the actual freeway speeds ranged between 54 and 106 kmph (34 mph and 66 mph), with an 85th percentile speed of 83 kmph (52 mph). Today, the same section of the Gulf Freeway serves more than 150,000 vehicles per day.

3.0 Current Challenges

Although freeway and highway design has made tremendous advances in the last 40 years, these advances have not eliminated all the problems associated with such systems. The major challenges at the present time include the high levels of demand which have developed over recent years in urban areas and the difficulty of adding lanes to increase capacity. Other challenges include aging of highway infrastructure, reconstructing existing facilities while maintaining traffic flow, changing travel patterns, updating design standards, and differing vehicle characteristics.

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FUTURE DIRECTIONS IN HIGHWAY MANAGEMENT AND INTELLIGENT TRANSPORTATION SYSTEMS (ITS)

The future in highway operations will involve more efficient management of the transportation system and may include the development of automated vehicles, computerized navigation, and other technological advances. Efforts are already underway in the United States and in Texas to develop the Intelligent Transportation Systems (ITS) concept. ITS was initially known as Intelligent Vehicle Highway Systems (IVHS).

1.0 Intelligent Transportation Systems (ITS)

Originally, IVHS research and activities were concentrated in six areas: Advanced Traffic Management Systems (ATMS), Advanced Traveler Information Systems (ATIS), Advanced Public Transportation Systems (APTS), Commercial Vehicle Operations (CVO), Advanced Rural Transportation Systems (ARTS), and Advanced Vehicle Control Systems (AVCS). ITS is defined as the application of current and evolving technology to transportation systems and the careful integration of system functions to provide more efficient and effective solutions to multimodal transportation problems. A broad range of diverse technologies, which satisfy 30 defined user services, now collectively comprise ITS. Table 1-1 shows these user services. Although many of the initial applications of ITS were in urban areas, rural ITS applications are receiving increasing emphasis.

Although research on ITS has been going on for some time, the passage of the Intermodal Surface Transportation Efficiency Act (ISTEA) in 1991 formally established the ITS Program and encouraged its implementation. ITS relies on the following three layers of infrastructure:

- ◆ **TRANSPORTATION LAYER**—The physical ITS infrastructure,
- ◆ **COMMUNICATIONS LAYER**—The informational layer that connects all of the elements of the Transportation Layer, and
- ◆ **INSTITUTIONAL LAYER**—The socioeconomic infrastructure of organizations and social roles.

In order to successfully implement ITS as a smoothly coordinated system, an architecture or framework must be developed to promote national compatibility and a *core set* of capabilities must be designated to provide a defined starting point. The core set of capabilities is known as the Intelligent Transportation Infrastructure (ITI).

Table 1-1. ITS User Services

Broad Area	User Services	Description
Travel and Transportation Management	Enroute Driver Information	Includes driver advisories and in-vehicle signing to improve convenience and safety.
	Route Guidance	Provides drivers with simple instructions on how to reach their destinations.
	Travel Services Information	Provides a reference directory, or "yellow pages," of service information.
	Traffic Control	Manages the movement of traffic on streets and highways.
	Incident Management	Helps officials quickly identify incidents and implement a response to minimize their effects on traffic.
	Emissions Testing and Management	Identifies super-emitting vehicles and promotes vehicle maintenance.
	Rail Highway Grade Crossing	Includes innovative warning devices, train activated roadside message signs, in-vehicle advisory and emergency warnings, and automatic collision notification.
Travel Demand Management	Demand Management and Operations	Supports policies and regulations designed to mitigate the environmental and social impacts of traffic congestion.
	Pre-Trip Travel Information	Provides information for selecting the best departure times, transportation modes, and routes.
	Ride Matching and Reservation	Makes ride sharing more convenient.
Public Transportation Operations	Public Transportation Management	Automates operations, planning, and management functions of public transit systems.
	Enroute Transit Information	Provides information to travelers using public transportation after they begin their trips.
	Personalized Public Transit	Offers more convenient service to customers by providing flexibility.
	Public Travel Security	Creates a secure environment for public transportation patrons and operators.
Electronic Payment	Electronic Payment Services	Allows travelers to pay for transportation services electronically with "smart cards."

Table 1-1. ITS User Services (continued)

Broad Area	User Services	Description
Commercial Vehicle Operations	Commercial Vehicle Electronic Clearance	Facilitates domestic and international border clearance, minimizing stops.
	Automated Roadside Safety Inspection	Facilitates roadside inspections.
	Commercial Vehicle Administrative Processes	Provides electronic purchasing of credentials and automated mileage and fuel reporting.
	On-board Safety Monitoring	Senses the safety status of a commercial vehicle, cargo, and driver.
	Hazardous Material Incident Response	Provides immediate notification of an incident and immediate request for assistance.
	Freight Mobility	Provides communications between drivers, dispatchers, and intermodal transportation providers.
Emergency Management	Emergency Notification and Personnel Security	Provides immediate notification of an incident and an immediate request for assistance.
	Emergency Vehicle Management	Reduces the time it takes to respond to an incident once notified.
Advanced Vehicle Control and Safety Systems	Longitudinal Collision Avoidance	Helps prevent head-on and rear-end collisions between vehicles and other objects or pedestrians.
	Lateral Collision Avoidance	Helps prevent collisions when vehicles leave their lane of travel.
	Intersection Collision Avoidance	Helps prevent collisions at intersections.
	Vision Enhancement for Crash Avoidance	Improves the driver's ability to see the roadway and objects that are on or along the roadway.
	Safety Readiness	Provides warnings regarding the condition of the driver, the vehicle, and the roadway.
	Pre-crash Restraint Deployment	Anticipates an imminent collision and activates passenger safety systems prior to a collision.
	Automated Highway Systems	Provides fully automated, "hands off" operating environment.

2.0 Intelligent Transportation Infrastructure (ITI)

The ITI, previously known as the Core Infrastructure for ITS, is a set of nine basic components that have been identified as the necessary elements needed to get ITS deployment started. Once these components are deployed, they will serve as the foundation and building blocks for future ITS services. The ITI concentrates primarily on metropolitan or urban areas and refers to the portions of ITS related hardware, software, and services that manages and supports transportation related activities. The nine integrated components that comprise the ITI are:

- ◆ Traffic Signal Control,
- ◆ Freeway Management,
- ◆ Transit Management,
- ◆ Incident Management,
- ◆ Electronic Fare Payment,
- ◆ Electronic Toll Collection,
- ◆ Railroad Grade Crossings,
- ◆ Emergency Management Services, and
- ◆ Regional Multimodal Traveler Information.

It is envisioned that the ITI will primarily be led by efforts in the public sector; however, private sector participation is being strongly encouraged and active partnership opportunities are being sought at all levels. The concept of ITI is that it should be an integrated system rather than nine separate core components that function in autonomous manners. Each of the nine components must work smoothly with all of the other components to create an integrated system. In order to accomplish this integration, a framework is needed. The National ITS Architecture development programs define this framework. One intent of the architecture is to exploit the synergies between the components to ensure maximum capability with minimum investment.

3.0 National ITS Architecture

The National Architecture is the primary step needed to achieve a seamless, multimodal, national ITS system that will be consistent across the nation. An architecture is the framework that defines the rules of information management based upon user requirements. The architecture identifies basic subsystems, defines the functions performed by each system component, and identifies the data that must be transferred between the various elements. It provides the guidelines for developing standards that result in efficiency, economies of scale, and national interoperability.

The architecture provides a common starting point and guidelines. However, it does not provide the actual design. This allows flexibility and does not lock the user into rigid deployment options. At the most basic level, the architecture defines a series of functions through a Process Specification (P-spec). These are the broad activities that each particular ITS system carries out. At higher levels, functions are graphically depicted as Data Flow Diagrams (DFDs). Figure 1-2 illustrates the DFD for traffic data analysis of incidents, which comes from *The National Architecture for ITS: A Framework for Integrated Transportation Into the 21st Century*, published by FHWA in 1997.

The architecture can be thought of in both logical and physical terms. The Logical Architecture documentation depicts what has to be done through the use of DFDs and P-specs. The Physical Architecture then defines the subsystems, assigns P-spec functions to them, and documents the dataflow interfaces between the subsystems. Following the architecture provides the user with an evolutionary path and a common language for deployment. The architecture is also being used to develop ITS standards.

As ITS develops, the standards for the system are also being developed. The requirements for these standards are a major output of the architecture. The architecture has identified which interfaces require standardization and has developed the initial requirements for standardization. This standardization creates compatible systems and subsystems and allows future modifications to be accomplished in an efficient manner. The following areas have been identified for priority standards:

- ◆ Information Broadcast,
- ◆ Travel Information Messages,
- ◆ Traffic Management,
- ◆ Mayday Messages,
- ◆ Incident Messages,
- ◆ Dedicated Short Range Communications,
- ◆ Commercial Vehicle Operations,
- ◆ Border Crossings, and
- ◆ Map Databases.

The architecture does not force technological decisions, but merely provides the framework for thinking about the problem. Utilizing a predefined architecture minimizes the time and costs to design, upgrade, integrate, and evolve operational ITS.

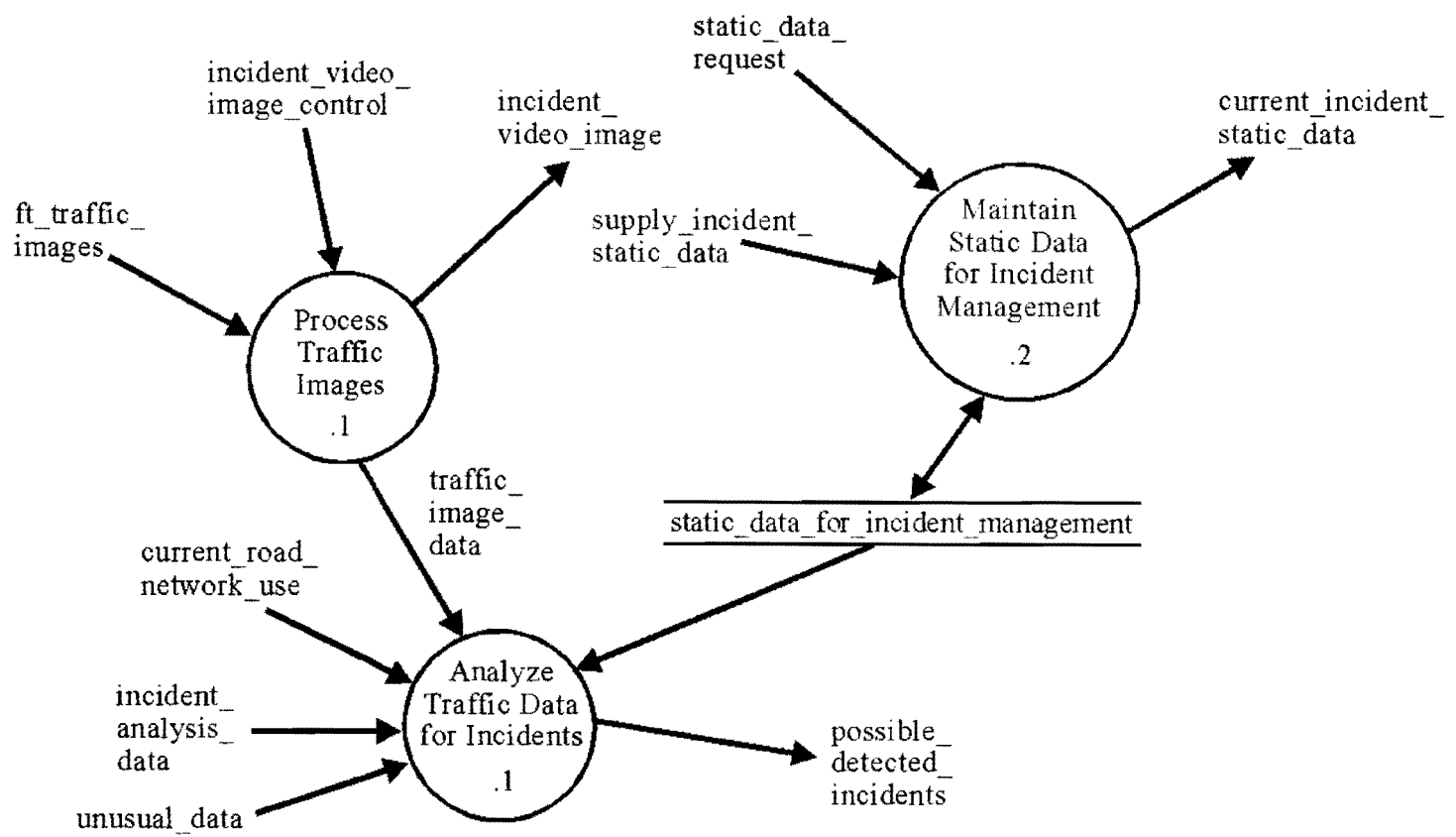


Figure 1-2. Example of a Data Flow Diagram: Traffic Data Analysis for Incidents

BASIC TRAFFIC FLOW CHARACTERISTICS

Understanding traffic operations requires a basic understanding of various factors which influence the traffic stream. The following subsections provide a brief description of the major traffic stream factors.

1.0 Driver Characteristics

A number of human factors have a direct influence on driver performance, particularly vision and response time. Those visual factors of concern to the engineer are visual acuity, the cone of vision, peripheral vision, and driver response to glare.

Visual acuity is the ability of a driver to discern objects. The test used to determine a driver's visual acuity measures the ability to see a non-moving object under ideal illumination. Therefore, care should be exercised when sizing various elements of the highway environment, keeping in mind the importance and complexity of the elements which must be observed and understood by the driver.

The cone of vision is that area in front of a driver where the driver focuses his visual attention. The sharpest vision occurs within a cone of 3° , clear vision occurs within a cone of 10° , and satisfactory vision within 20° . For reading purposes, the visual field is 10° or less. The ability of a driver to observe and react to information outside the cone of vision drops rapidly outside this limit.

However, objects outside the cone of vision can be detected in peripheral vision. When stationary, peripheral vision is nearly 180° . As speed increases, the driver's ability to detect objects at the limits of the peripheral vision decreases. At 32 kmph (20 mph), the effective peripheral vision is about 100° , and at 96 kmph (60 mph) it reduces to about 40° . When an object is detected with peripheral vision, the driver will focus attention on the object in order to evaluate it and determine the proper course of action.

Figure 1-3 illustrates the visual field. Note that the field of sharpest vision is only 2.4 meters (8 feet) wide at a distance of 45 meters (150 feet) from the driver. Whenever possible, pertinent information should be placed within the 10° cone of vision to facilitate its observation and understanding.

The 10° cone of vision has a significant impact on the placement of information, particularly signing. Figure 1-4 illustrates an example where a 2.4-meter (8-foot) wide sign is located 9 meters (30 feet) from the travel lane. If three seconds are required for the driver in the outside lane to read the sign, then it should be placed 152 meters (498 feet) in front of the driver. Therefore, the sign lettering should be large enough to be read from 152 meters (498 feet). This distance is longer for vehicles in the inside lanes. In some cases, it may be necessary to locate the sign over the lane in order to place it in the 20° cone of vision. Chapter 3, Section 3, Segment 7.0 contains additional information on sign design and location.

continued

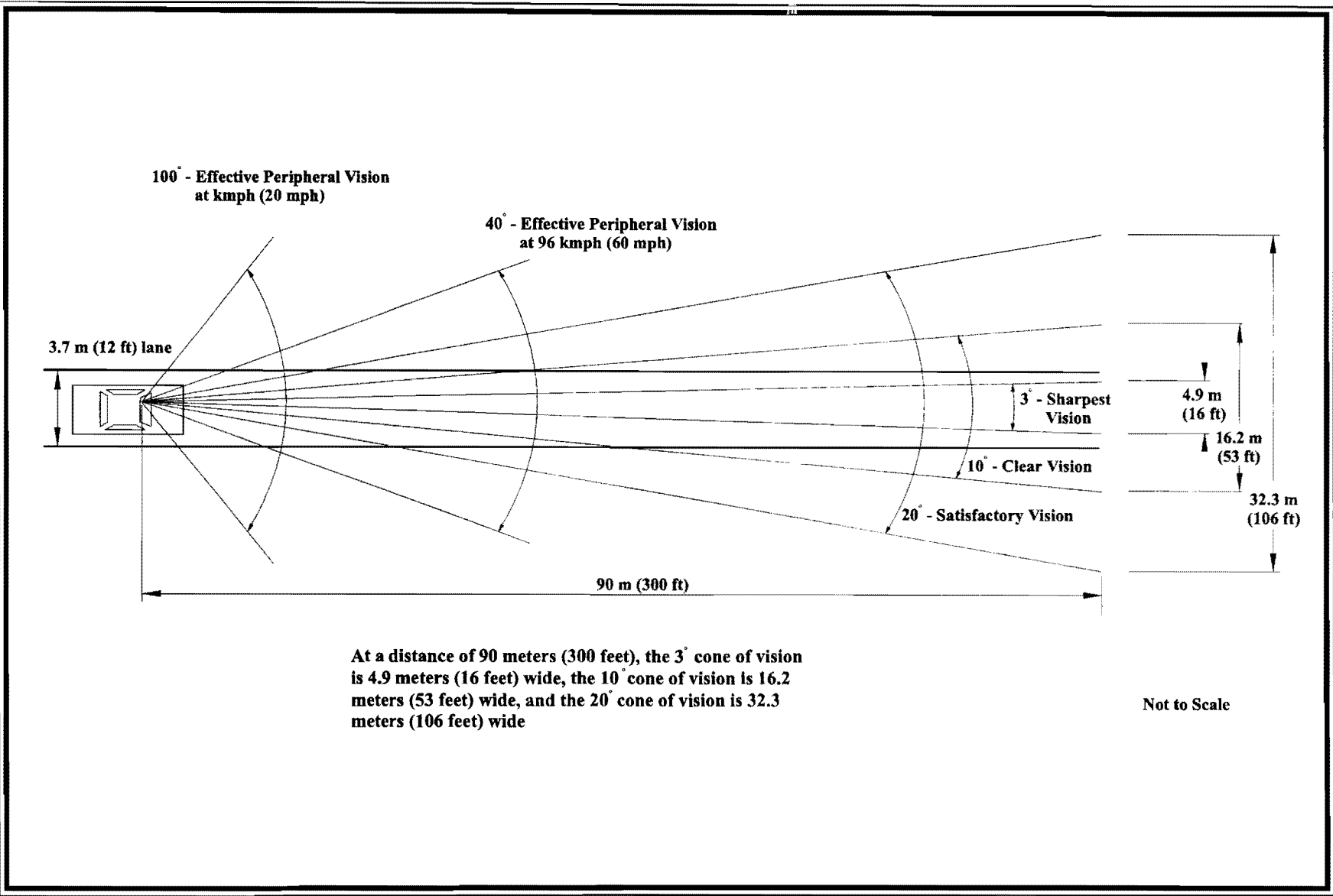


Figure 1-3. Visual Field

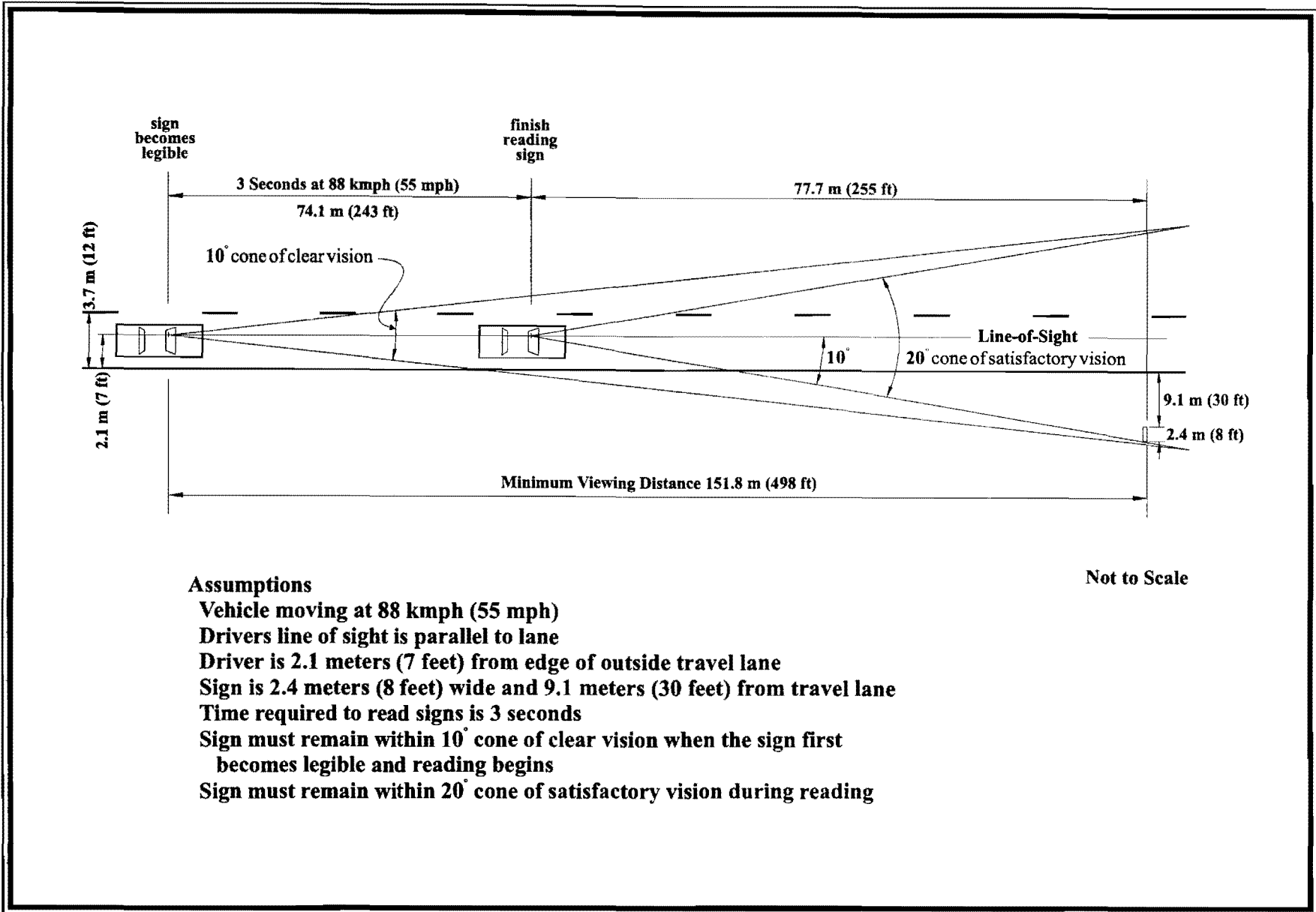


Figure 1-4. Sign Location and Cone of Vision

1.0 Driver Characteristics (continued)

Visual capability decreases in nighttime driving conditions, primarily due to reduced lighting levels. Visual capability is further decreased by the inability of the human eye to quickly adjust from bright to dark conditions and to discern between low contrast objects. When the driver is exposed to a higher lighting level, the pupil contracts in adjusting to the light. As the lighting level is reduced, the pupil dilates to allow more light to enter the eye. The time needed for the pupil to contract is only about 0.3 seconds, while it takes about six seconds for the pupil to dilate. When the pupil has contracted, the driver cannot easily see objects in the areas away from the area of the bright light. The term glare is used to describe the presence of bright lights or bright light reflection which interfere with the driver's vision. Glare sources include vehicle headlights, street lighting, advertising, and adjacent site lighting. The engineer should strive to reduce glare sources to an acceptable level.

Driving performance is also impacted by the time required for a driver to react to various situations which may occur in the highway environment. This time period is known as the response time and includes the time needed for a driver to see an object, identify the object, decide how to react to the object, and to carry out the desired action. The response time increases with the number of choices, complexity of the judgement, driver's age, degree of fatigue, level of alcohol consumption, and physical deficiencies. Typical response times range from 0.5 to 4.0 seconds. The stopping sight distance and passing sight distance are used to represent response times in most geometric design elements. In some cases, the decision sight distance (Chapter 2, Section 3, Segment 4.3) should be used due to the operational maneuver distances required in normal driving.

Many older drivers possess diminished visual and response capabilities from that of the general population. This is especially true in nighttime conditions. Additionally, older drivers are becoming an increasing proportion of the total driving population. The diminished capabilities of older drivers should be considered in the evaluation of highway operations and countermeasures should be taken where appropriate.

Good operations will most likely occur when drivers have good visibility and the largest practical response time. However, perception conditions are seldom ideal due to driver and environmental variability. Therefore, information should be placed for maximum visual perception given the prevailing conditions. The engineer must strive to achieve a compromise between driver demands and the limitations of other design factors.

2.0 Vehicular Characteristics

The vehicular characteristics related to operational concerns include size, weight, power, acceleration, and deceleration. The performance characteristics of trucks are lower than those of passenger cars. Vehicle size has an obvious impact on operations. The primary measurements of concern include vehicle length, width, height, turning radius, and weight. Larger vehicles such as trucks occupy more space, reducing the overall capacity of the highway. Heavier vehicles place a greater load on the pavement. The turning radius of vehicles impacts intersection design. Design vehicles are used to represent the physical characteristics of selected vehicle types. The design features of a particular highway are selected to accommodate a particular design vehicle. Both the *Highway Design Division Operations and Procedures Manual* and the American Association of State Highway and Transportation Officials *A Policy on Geometric Design of Highways and Streets* address the different design vehicles that use highway facilities.

3.0 Traffic Stream Characteristics

The parameters used to describe the traffic stream are a function of the driver, vehicle, and geometric characteristics found in the traffic stream. The most common parameters are flow, speed, and concentration. Level of service is used to provide a qualitative description of operational conditions.

Flow is a measure of the number of vehicles passing a point during a given time period. The most common units of measure for flow are Average Daily Traffic (ADT) measured in vehicles per day and Design Hour Volume (DHV) measured in vehicles per hour. Another unit of measure is the rate of flow or flow rate. Flow rates are actual counts of less than one hour (typically 15 minutes) expressed as an equivalent hourly volume. Flow rates are especially important in areas with short peak periods.

The rate of vehicular motion is described by speed. Speed can be measured at a point (time-mean speed) or over a length of roadway (space-mean speed). The most common unit of measure for speed is kilometers (miles) per hour, although meters (feet) per second is also used in some applications.

Vehicle spacing is represented by concentration. It is normally described by the density of traffic, but can also be described with lane occupancy (which represents the percent of time that a point in the highway is occupied). The units of measure for density and lane occupancy are vehicles per mile and percent occupancy, respectively. Density is not normally measured in the field due to the difficulty of performing the measurement.

Another variable used to describe the traffic stream is headway. Headway is the time separation between the same point of successive vehicles. Its most common unit of measure is seconds per vehicle. It can be measured from front bumper to front bumper or rear bumper to rear bumper. The inverse of the average vehicle headway provides a measure of flow.

continued

3.0 Traffic Stream Characteristics (continued)

A level of service definition generally describes operational conditions in terms of such factors as speed and travel time, freedom to maneuver, traffic interruptions, comfort and convenience, and safety. Six levels of service are defined for each type of facility for which analysis procedures are available. They are given letter designations, from A to F, with level-of-service A being the best and level-of-service F being the worst.

4.0 Congestion Characteristics

There are two types of congestion of concern to the engineer: recurring congestion and nonrecurring congestion. Recurring congestion occurs repeatedly at the same place (upstream of a bottleneck) and time as the result of insufficient capacity or increased demand at a specific location. Typically, the recurring congestion can be predicted with some reliability. Because recurring congestion can be predicted, steps can be taken to reduce the impact of the congestion. Recurring congestion normally occurs as the result of excessive demand due to peak period traffic volumes and special events, or reduced capacity caused by construction activities and scheduled maintenance activities.

Peak period recurring congestion results from increased demand during the primary commuting time in the morning and late afternoon. This is the so called "rush hour traffic." Part III of this manual addresses some of the options available to reduce the impacts of peak period congestion.

Some special events are such large traffic generators that congestion will always be present when the events take place. Athletic events and concerts are typical examples of special events which will create congestion that can be anticipated in advance of the activity. The congestion impacts of scheduled maintenance and construction activities can also be anticipated with a fair degree of accuracy. As a result, congestion resulting from these activities is considered recurring congestion. Chapter 5 also addresses recurring congestion for scheduled activities.

Nonrecurring congestion results from an increase in demand or decrease in capacity which cannot be anticipated in advance. Typical causes of nonrecurring congestion are crashes, vehicle breakdowns, adverse weather, inability of a highway component to fulfill its purpose in the intended manner, emergency (or unscheduled) maintenance, traffic diversions, and other situations. Chapter 9 addresses procedures for managing incidents on urban highways.

OPERATIONAL DEMANDS

The proper application of the principles described in this manual can result in improved highway operations. However, due to the multitude of factors which impact operations, it may not be possible to provide the optimal operational situation. In cases where the optimal situation is not possible, the operational factors described in the following paragraphs should be evaluated.

1.0 Driver Expectancy

Operations are improved when the actual highway environment agrees with what the driver expects it to be. This is because drivers tend to develop specific expectations about what the highway environment should be like and make driving judgements based on these expectations. Agreement between the drivers' expectations and the actual highway environment can result in a reduction of erratic vehicle maneuvers, driver frustration, driver errors, and reaction times.

The concept of driver expectancy has been developed to describe the preconceived notions and reactions to the highway environment. Driver expectancy is defined as an inclination to respond to a roadway or traffic situation in a set manner, based on previous experience. It should be stressed that the response is to the expected situation, rather than to the actual situation. In addition, the same circumstance may be perceived in several different ways, depending upon the situation, environment, and driver familiarity.

Drivers develop expectations about virtually all aspects of the highway environment, including the geometrics, signing, traffic flow, operational strategies, and others. As an example, drivers expect to exit a freeway from the right side. If the exit is on the left side, the driver may perform erratic maneuvers in order to position the vehicle to use the left exit, unless advance notice of the left exit is provided.

Distinctions can be made between the driver expectancy for familiar (or local) drivers and unfamiliar (or non-local) drivers. Familiar drivers develop expectations based on their prior knowledge of a highway and its environment. Unfamiliar drivers develop expectations based on their driving experiences on similar facilities and under similar conditions. Familiar drivers typically pay little attention to traffic control devices and react primarily to other vehicles in the traffic stream. For this reason, special attention should be given to alerting familiar drivers to changes in traffic control. Unfamiliar drivers rely on traffic control devices and their experiences in similar situations to make driving decisions.

Description and application of the driver expectancy concept is difficult. The primary reason is the inherent nature of the concept. Both local and non-local drivers are subject to expectancy problems. The following examples identify areas where addressing driver expectancy is especially critical.

1.1 Exit Location

Drivers have preconceived notions about how a highway facility should be laid out. For instance, freeway exits are normally located on the right side of the freeway. When an exit is located on the left side, it is contrary to what the unfamiliar driver expects and may cause driver expectancy difficulties in addition to merging and weaving problems, if the driver is not adequately warned. Left-hand entrances are similar in that drivers do not normally expect vehicles to merge into the traffic stream from the left side. The signing requirements are more complex in each case due to the need to modify driver expectancy.

1.2 Entrance and Exit Visibility

Turbulence is created whenever vehicles enter or leave the traffic stream. The design of these access points has an impact on the degree of turbulence created in the traffic stream. Ample visibility at access points improves the efficiency of traffic maneuvers, thereby reducing turbulence and congestion. Whenever practical, decision sight distance (Chapter 2, Section 2, Segment 4.3) should be provided for entrance and exit ramps. Providing decision sight distance will allow drivers to position their vehicles in a way that will provide the most efficient operation. If decision sight distance cannot be provided, then advance signing is needed to change the driver's expectancy and prepare them for the different conditions.

1.3 Merge and/or Diverge Maneuvers

Desirably, all merge and diverge maneuvers should occur in the outside lane or lanes to the right side of the through traffic lanes. Figure 1-5a shows one manner of locating merge maneuvers in the outside lane. If merge and diverge maneuvers cannot be accommodated in such a manner, then one or more of the following alternatives should be considered: providing additional sight distance, advance signing of merge conditions, or providing a recovery area. Merge/diverge maneuvers which do not occur in the outside lanes or on the right side may be unexpected by motorists.

Examples of unexpected merge/diverge maneuvers include interior lanes which end, left-hand entrances or exits, and lack of route continuity (Chapter 2, Section 2, Segment 1.0). Figure 1-5b illustrates an inside merge, where two interior lanes merge. In this situation, two lanes are merged into one lane, with one or more travel lanes on each side of the merge lanes. This typically occurs at freeway connections. The disadvantages of the inside merge include: both merging lanes are traveling at high speed leaving less time for choosing a gap, the right-of-way may not be clear creating uncertainty between drivers in the traffic streams, and there is no escape area (such as a shoulder) in case no gaps are available.

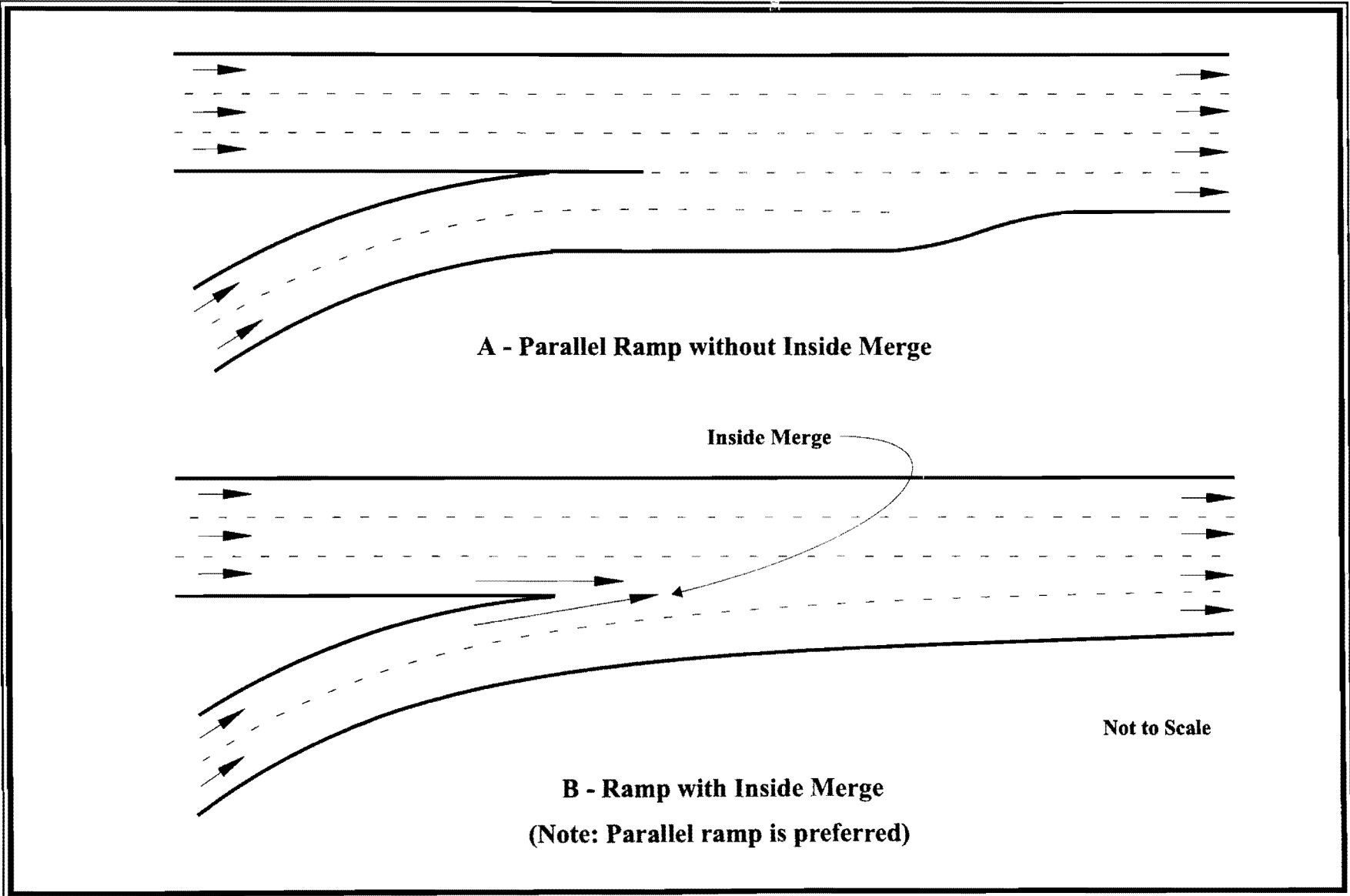


Figure 1-5. Inside Merge Illustration

1.4 Sight Distance

In a complex highway environment, the information processing demands of the driving task may overload the driver. Whenever possible, generous sight distance should be provided to reduce information processing demands. In addition, the part of the highway hidden from view should be the same as what the driver expects it to be from the portion of the highway visible to the driver.

It is desirable to provide decision sight distance (Chapter 2, Section 2, Segment 4.3) at locations such as freeway entrances and exits, freeway-to-freeway connectors, lane drops, roadside rest stops, and inspection stations. The additional time provided by decision sight distance allows drivers to maneuver into the proper position for the desired action in a manner which has a minimal impact on highway operations. Decision sight distance may not be obtainable in all situations. In these cases, it may be appropriate to provide advance warning for the motorist.

In some cases a motorist may make an improper interpretation of the highway environment. This situation occurs when a portion of the highway is hidden from the driver's view and a change in alignment or operations occurs in the hidden area. Figure 1-6 illustrates one example of this situation. A driver approaching the vertical curve in the outside lane observes four lanes at the crest of the vertical curve. This observation leads to the expectation that all four lanes are continuous and that the driver can remain in the outside lane. However, beyond the vertical curve, the outside lane drops at an exit ramp. During periods of light traffic volumes, the driver should be able to change lanes with little impact on operations. However, during heavy volume periods, the last minute lane changing may result in congestion.

1.5 Signing

Drivers will use signing to fill in their information gaps about the highway ahead. In order for the signing to have a positive impact on operations, the signing should fulfill an information need, be easily understood, and be consistent in application and use. Chapter 3, Section 3, Segment 7.0 contains information about the proper use and design of guide signs.

Examples of signing which may confuse drivers include signs which conflict with the visible geometrics at the point where the driver reads the sign, inconsistent reference to destinations, variation in sign messages between different cities, signs which do not provide sufficient distance to allow proper maneuvering, signs which do not apply to the current highway environment, and signing for a successive exit located immediately after the current exit point.

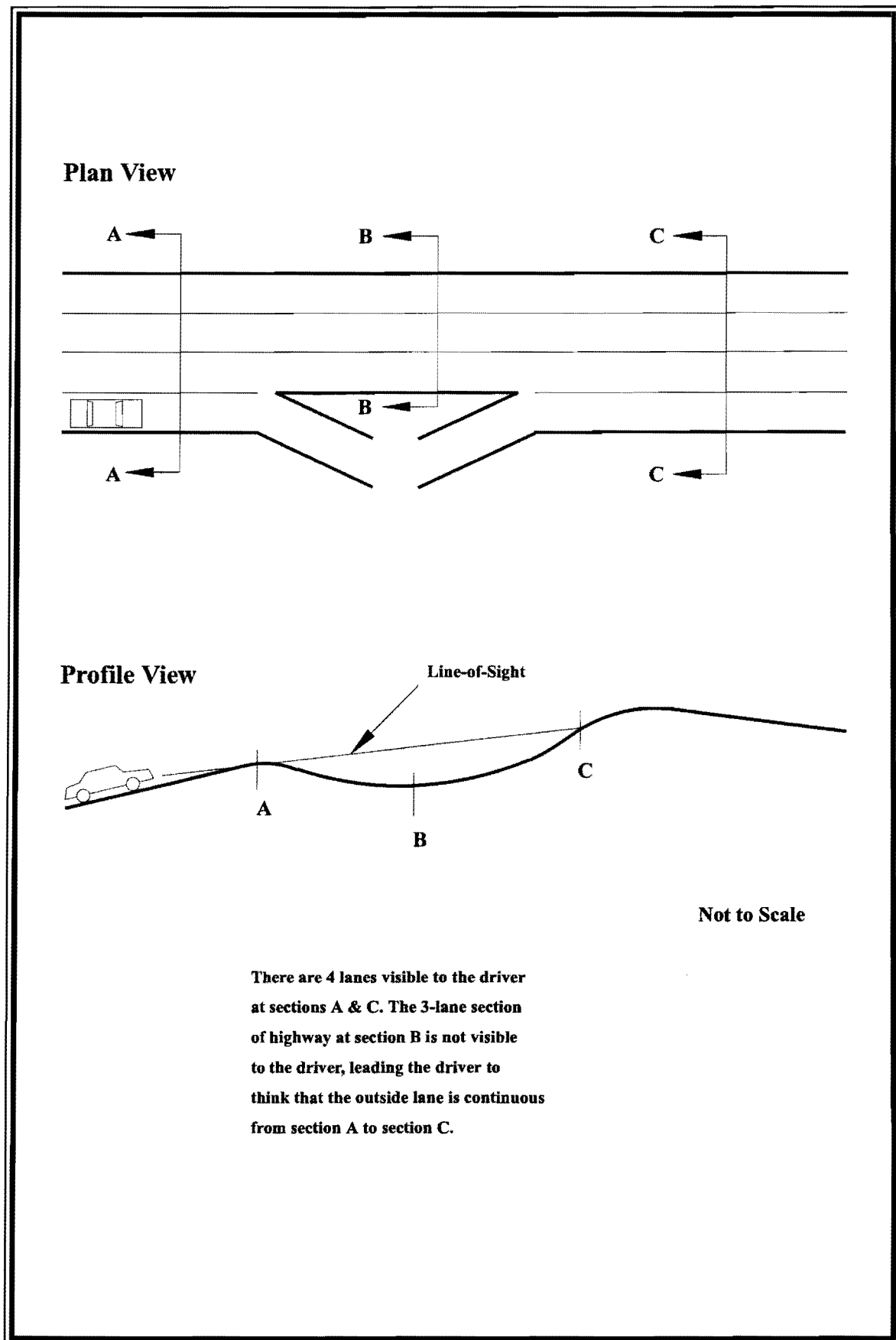


Figure 1-6. Deceiving Sight Distance Example

1.6 Peak Period Impacts

The impacts of driver expectancy vary according to the level of traffic demand on the highway. At low volumes, drivers may be able to react to an unexpected condition in a manner which has minimal impact on the other vehicles in the traffic stream. Even in the cases where turbulence is created by the maneuvering vehicle or vehicles, the lack of heavy traffic demand allows a quick recovery to normal operating conditions.

However, during periods of heavy traffic volumes, a highway may be operating at or near capacity conditions. In this case, the turbulence created by a forced merge or lane change may cause a reduction in the speed of the vehicle stream, resulting in a breakdown of smooth traffic flow. Once the traffic flow breaks down, a return to normal traffic flow will not take place until the demand is reduced and congestion is cleared.

2.0 Driver Workload Capacity

Drivers have limited capabilities for assimilating and digesting information from the highway environment. Sources of information can be described as formal or informal. Although there is some disagreement on the definitions, formal information sources are intended to communicate specific information to users which is consistent from one application to another. They include signs, markings, signals, vehicle taillights, and road maps. Informal information sources communicate varying information, depending upon the source, situation, and driver interpretation. Informal sources include roadway geometry, roadside appurtenances, landmarks, personal directions, roadside advertisements, other vehicles, and prior knowledge. Research has shown that control devices are **not** the primary source of information to the familiar driver. Therefore, highway design and operations should focus on meeting driver information needs through informal sources and insuring that formal and informal information sources are compatible.

When the environment provides more information than the driver can effectively process, the driver sheds certain information in order to satisfy driving demands. Driver information needs are arranged in accordance with a hierarchy where the driving tasks related to control are at the top of the hierarchy. Control tasks include starting, stopping, speed control, and steering. The next level of information needs are guidance tasks which include maneuvering the vehicle on the road in response to roadway elements, traffic, environmental factors, and legal requirements. Navigation tasks such as direction finding, trip planning, and route following are at the bottom of the hierarchy. Information needs at the top of the hierarchy have the highest priority and these needs should be satisfied before tasks lower in the hierarchy can be addressed by the driver.

Information should be presented in accordance with this hierarchy. As an example, critical directional signing should be located in an area which does not require complex control maneuvers. As an example, a driver negotiating a lane closure in a work zone will focus his or her attention on slowing down and changing lanes, and may miss directional information which is not critical to the driving task at hand.

continued

2.0 Driver Workload Capacity (continued)

Another example of driver information overload occurs when too much information is provided. Too many signs or too much information on an individual sign may force the driver to ignore information due to the lack of processing time. Chapter 3, Section 3, Segment 7.0 and Chapter 4, Section 2, Segment 3.0 provide information for the placement and design of signs.

3.0 Speed Reductions

Sudden reductions in vehicle speed can cause turbulence in the same manner as forced vehicle maneuvers. During heavy volume conditions when separation between vehicles is small, a reduction in the speed of one vehicle may propagate rearward resulting in a speed reduction for many vehicles. The speed reduction may spread to other lanes as well, resulting in a slowdown for the entire traffic stream.

Speed reductions can occur for numerous reasons. The most common is the presence of a hazard, obstruction, or congestion on the roadway. In this case, drastic speed changes may be reduced by providing generous sight distance, if it is available. Other causes for speed changes include adverse weather, isolated environmental conditions (such as water ponding, smoke or fog blowing across the highway, and blinding reflected sunlight), and geometric changes (such as a reduction in the design speed). The design speed should be constant over a substantial length of a given facility and the transition to a lower design speed should be gradual. The *Highway Design Division Operations and Procedures Manual* contains guidelines for the selection and application of design speed in the design of highway facilities.

4.0 Weaving

Weaving sections occur where one-way traffic streams cross by merging and diverging maneuvers. Weaving sections impose significant impacts on highway operations. The impact of the weaving section depends on the spacing between interchanges, the traffic volumes of the weaving and non-weaving movements, the speed of the weaving and non-weaving movements, and the number and type of lane changes required.

Whenever possible, weaving sections should be eliminated from the highway by increasing the distances between access points or moving the weaving movements to another facility such as a collector-distributor roadway. However, in situations where weaving sections cannot be eliminated, they should be designed to reduce the operational impacts of the weaving maneuvers as much as possible. Desirable attributes for weaving sections are included in Chapter 2, Section 2, Segment 3.4 and Chapter 3, Section 3, Segment 4.0. Following these principles will help to reduce the operational impacts of weaving sections. Chapter 8 includes information about analyzing weaving areas.

continued

4.0 Weaving (continued)

The factors which impact the operation of a weaving section are interrelated. For instance, during low-volume periods, a weaving section with less than desirable geometric characteristics may operate in an acceptable manner. However, during high-volume conditions, the same weaving section may experience congestion. The most desirable weaving section would be one with widely spaced access points, low weaving and non-weaving volumes, small differences in speeds between the weaving and non-weaving traffic, and geometrics which allow weaving maneuvers to be completed with a single lane change.

In cases where there are large volumes of weaving traffic, operations may be improved by redesigning the highway so that the weaving impacts are reduced. The closer the highway interchanges or ramp terminals are spaced, the less space there is available for weaving maneuvers. Desirably, the highway ramp terminals should be spaced more than 600 meters (2,000 feet) apart. However, this ramp spacing may not be practical in all situations. When the desirable ramp spacing cannot be achieved, operations should be evaluated to determine if the reduction in operational efficiency will be tolerable. Minor reductions in operational efficiency may be tolerated, especially if the frequency of occurrence is not high. The level of service of the weaving area should be consistent with the level of service for the remaining highway.

Entrance, exit, and connector ramps should be designed so that entering and exiting speeds at the gore are the same as the through lane speeds. Entrance ramps should be designed so that adequate length is provided between the upstream intersection or frontage road and the gore point for all vehicles to reach the highway speed limit. Likewise, an exiting vehicle should not begin decelerating until they have passed the gore point of the exit ramp. Adequate distance should be provided between the exit gore point and the downstream intersection or frontage road. Weaving sections should be arranged to allow weaving maneuvers to be made with as few lane changes as possible and so that no one lane is overloaded with vehicles.

OPERATIONAL ANALYSIS

An operational analysis is a set of procedures which can be used to estimate the traffic-carrying ability of a facility over a range of defined traffic conditions.

1.0 Purpose

A principle objective of operational analysis is estimating the maximum amount of traffic that can be accommodated by a given facility while maintaining prescribed operational qualities. Operational analysis also provides a mechanism for estimating the quality of traffic flow on a facility. A second objective is to insure that all components of a highway system are in balance. Ideally, when traffic volumes reach the capacity of a facility, all components should be equally loaded at the same time.

2.0 Analysis Periods

Operational analysis is typically based on flow rates from a peak 15-minute period. A 15-minute period is generally considered to be the shortest interval during which stable flow exists. Longer analysis periods can be misleading if large fluctuations in traffic occur during the peak period. Traffic counts during the peak period should generally be taken in 15-minute intervals to identify peaking factors. Table 1-2 illustrates the relationship between volumes and flow rates and the Peak Hour Factor (PHF).

Table 1-2. Volume, Flow Rate, and PHF Example

Time	Vehicle Count (vehicles)	Flow Rate (vehicles per hour)
7:00-7:14	400	1,600
7:15-7:29	300	1,200
7:30-7:44	350	1,400
7:45-7:59	250	1,000
7:00-7:59	1,300	
PHF = 1 hour volume / (4 × peak 15-minute volume) = 1,300 / (4 × 400) = 1,300 / 1,600 = 0.81		

A common error in collecting traffic volume data is measuring volumes upstream of a bottleneck in a highway section experiencing forced flow conditions. Forced flow conditions exist when traffic demand exceeds capacity. The volume of vehicles discharging from the bottleneck provides an estimate of the capacity of the bottleneck and can be obtained by measuring the volume just downstream of the bottleneck.

continued

2.0 Analysis Periods (continued)

Design of the typical cross section is normally based on the Design Hour Volume (DHV), which can be determined from the Average Daily Traffic using the K factor and the directional distribution, D. The calculation of DHV is described in the *Highway Design Division Operations and Procedures Manual*. Analysis based on a one-hour volume does not take into account peaking which may occur during that hour. The impact of the peaking effect varies by location and type of facility. In places where traffic flows are consistent throughout the day, the peaking effect is minimal. However, short-term demands in some locations may result in a short peak of high intensity. Design of individual roadway elements, such as auxiliary lanes (Chapter 3, Section 3, Segment 3.4) and weaving sections (Chapter 3, Section 3, Segment 4.0), should consider the use of flow rates for design.

Failure to account for peaks in demand may provide inadequate service on a facility during the periods of heaviest demand. The time needed to recover from a failure can be significant. A return to normal operation will not occur until demand has dropped to a level below the capacity of the facility and sufficient time has elapsed to remove the backlog of vehicles in the traffic queue.

The hourly volume can be adjusted for peaking with the use of a Peak Hour Factor (PHF). The PHF is calculated by dividing the hourly volume by the peak flow rate. Table 1-1 shows the relationship between the peak hour factor and the hourly volume. In large urban areas, the PHF ranges between 0.95 and 1.0. Small urban areas generally have a PHF less than 0.95. The DHV is divided by the PHF to determine a flow rate for use in an operational analysis.

3.0 Data Requirements

The most important data requirement is flow. Other data that are useful in analysis include: speed, vehicle classification, vehicle occupancy, lane distribution, origins and destinations, and geometric features. There is no substitute for regular and accurate field data collection. In particular, accurate data are needed to calibrate the analysis procedures to a specific location prior to analysis of an unknown or future situation.

The most useful flow data is a series of consecutive 15-minute volumes from which appropriate flow rates can be determined for analysis. Another important data type is the composition of the traffic stream, especially the percentage of heavy vehicles in the traffic stream. However, it may also be useful to collect data on other vehicle classifications (trailers, single unit trucks, etc.) as well.

4.0 Operational Precision

The human nature aspect of the traffic stream creates randomness that prevents precise analysis of operations. A traffic engineer cannot obtain the same precision when analyzing operations at a freeway interchange that a structural engineer can obtain when analyzing the structural components of the same interchange. Because operational analyses provide only an approximation of traffic flow conditions, the variability in individual drivers and traffic conditions should be recognized and adequate allowance should be provided in order to accommodate changes in conditions.

5.0 Basic Procedures

There are a multitude of different procedures for performing an operational analysis of a traffic stream. Many of these require intense data collection and input, while others are much less complicated. Some analysis procedures are applicable to specific situations of highway development or operation. These procedures are described in the appropriate chapters of this manual. Other procedures are more general or have wide application and are described in Chapter 8.

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CHAPTER 2
OPERATIONAL CONSIDERATIONS IN PROJECT DEVELOPMENT

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OVERVIEW

Design decisions made during the initial stages of project development have significant impacts on the eventual operational quality of a highway. This chapter describes operational fundamentals to be considered in the earliest phases of highway design. Failure to address these fundamental concepts in the project development stage may result in operational difficulties which cannot be economically corrected at a later time.

The operational concepts addressed in this chapter must be considered as part of a balanced highway design involving factors such as operations, access, safety, cost, and constructability. Some projects may present limitations which prevent the optimal operational solution from being utilized. In these cases, alternative solutions must be considered in light of those limitations.

The operational considerations described in this chapter are best utilized when applied to the design of a new highway facility. However, many of the considerations are also applicable to the redesign of an existing facility, although to a more limited extent. When an existing facility is being reconstructed, the considerations described in this chapter should be evaluated to determine if they apply to the reconstruction project and if they can be implemented within the limiting constraints of the project.

Many of the operational concepts considered in project development are, to some extent, independent or neutral of specific traffic volume data. However, traffic volume data should be used to evaluate the efficiency of traffic operations under the initial highway conceptual design whenever possible.

Data which are useful in project development include centerline alignment of the highway and cross streets, functional classification of the highway and cross streets, and an approximation of traffic volume.

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OPERATIONAL CONSIDERATIONS

A number of basic principles should be a part of the initial evaluation of a highway's alignment and its interaction with other facilities. Desirable operations in the future rely upon striving to adhere to these principles in the project development stage.

1.0 Route Continuity

The principle of route continuity requires that the through lanes serve the current route. Stated another way, a driver should not have to exit or change lanes to stay on the current route. In the process of maintaining route continuity, interchange configurations should always favor the through movement, not necessarily the heavy movement. Heavy turning movements may be accommodated with direct connections and auxiliary lanes.

The principle of route continuity simplifies the driving task in that it conforms to driver expectancy and therefore reduces lane changing, simplifies signing, delineates the through route, and reduces the driver's need for directional signing. Route continuity is highly interrelated with the concepts of interchange uniformity (Chapter 2, Section 2, Segment 3.1), ramp location (Chapter 2, Section 2, Segment 3.3), basic lanes (Chapter 3, Section 3, Segment 3.1), lane balance (Chapter 3, Section 3, Segment 3.2), and lane continuity (Chapter 3, Section 3, Segment 3.3).

If a highway facility is designed so that all exits are on the right-hand side (Chapter 2, Section 2, Segment 3.3), then providing route continuity would mean that a vehicle could remain on the designated route by staying in the inside (left) lane. Figure 2-1 illustrates the application of the principle of route continuity.

2.0 Concurrent Routes

Concurrent routes, also known as overlapping routes, exist when two or more highway routes occupy the same alignment within a corridor. Figure 2-2 is an example of concurrent routes, and illustrates that a continuous route designation is not required for concurrent routes. Concurrent routes, especially the short-distance type, should be avoided because of the problems they cause with route continuity (Chapter 2, Section 2, Segment 1.0), lane balance (Chapter 3, Section 3, Segment 3.2), and lane continuity (Chapter 3, Section 3, Segment 3.3), as well as decreasing highway capacity due to increased weaving traffic. Signing becomes more complicated and the decision process for the driver is more demanding. Concurrent routes may seem like effective use of roadways when traffic volumes are low. However, when traffic volumes increase towards the capacity of the two individual routes, the overlapping section tends to become a bottleneck.

continued

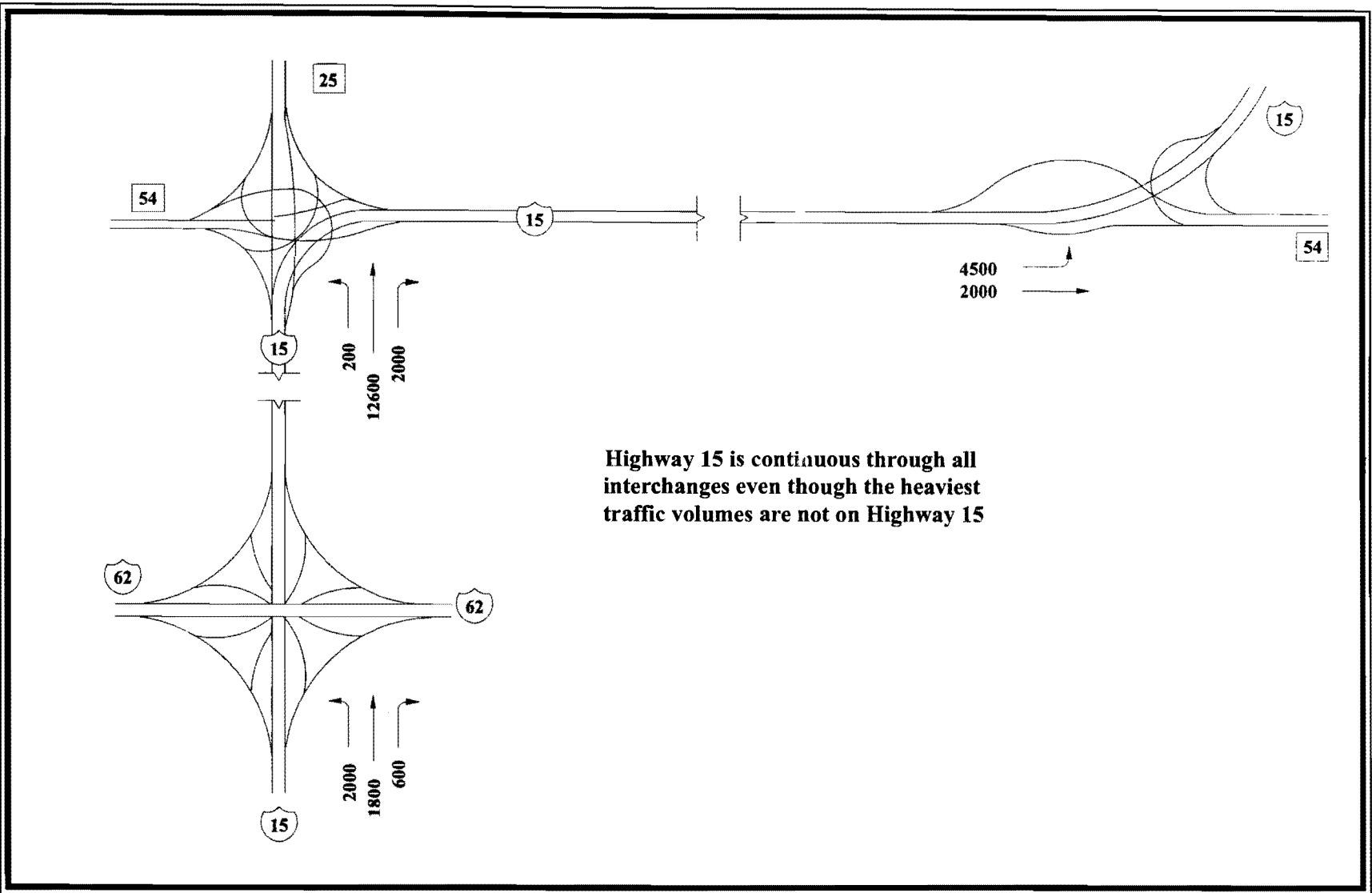


Figure 2-1. Application of the Principle of Route Continuity

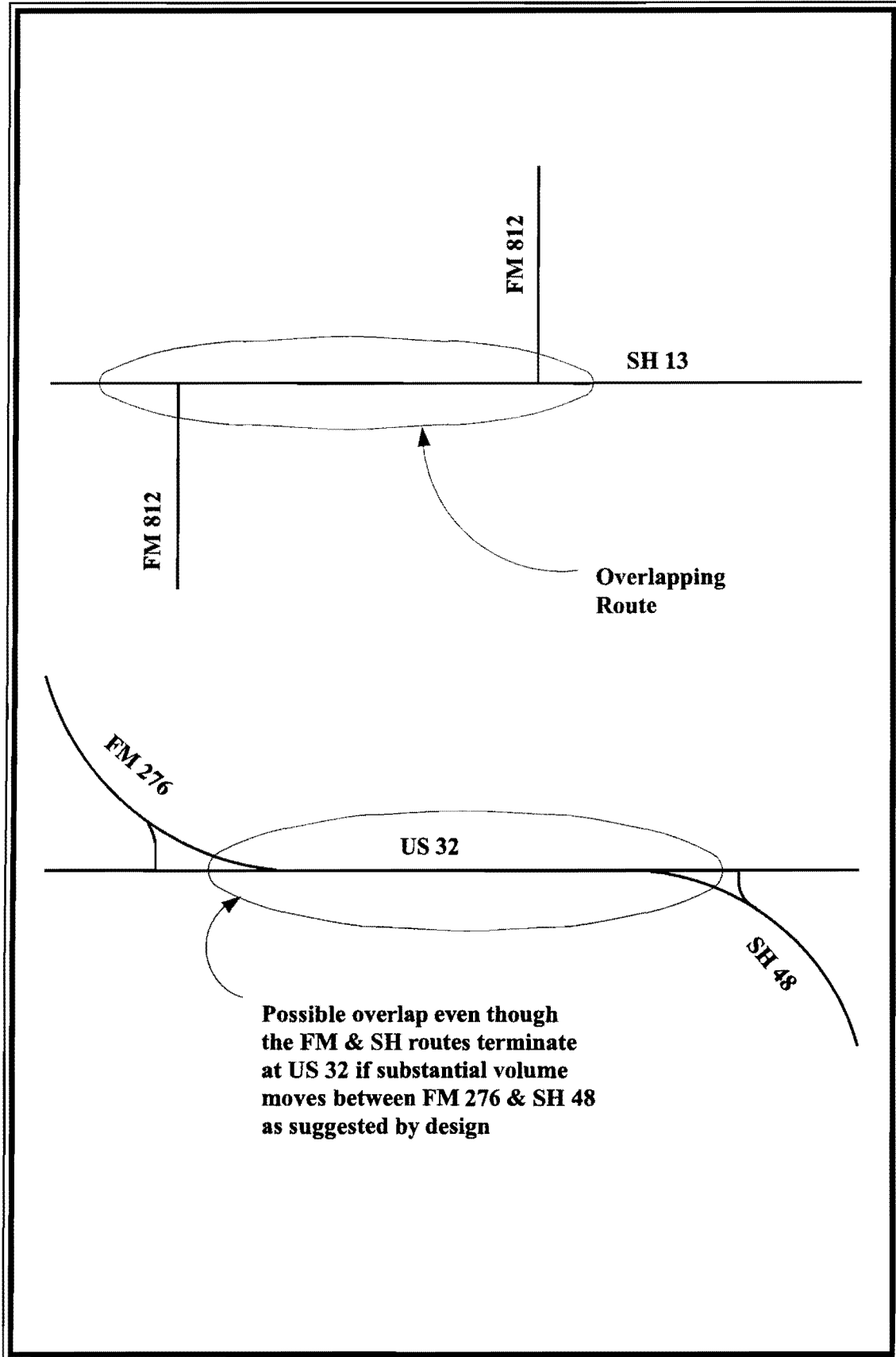


Figure 2-2. Concurrent Routes

2.0 Concurrent Routes (continued)

If it is necessary for two routes to occupy the same alignment, then the ideal operational solution would be to design the two routes as separate highways in a single right-of-way. This alternative is illustrated in Figure 2-3a. In this case, two distinct freeways maintain separate parallel alignments and connector ramps provide for movement between the two facilities. If the ideal solution is not practical, then an alternative solution would be to minimize the level of lane changing required between the two routes as illustrated in Figure 2-3b. Both of the examples in Figure 2-3 are appropriate for situations where the majority of the traffic remains on a single route. The example in Figure 2-3b may operate more efficiently when traffic patterns are such that a significant portion of the traffic moves between the two routes. When there are significant volumes of traffic moving between the two routes, it may be appropriate to evaluate other highway alignments for the most efficient operations. The operational requirements can then be balanced with the other design requirements of the project.

3.0 Interchanges

An interchange is a system of interconnecting roadways in conjunction with one or more grade separations that provides for the movement of traffic between two or more roadways. The basic function of an interchange is to separate conflicting through traffic lanes in order to accommodate high volumes of traffic safely and efficiently. Freeway interchanges include connections with another freeway or highway, and also connections between the freeway and frontage road, although connections with frontage roads are commonly known as ramps. Interchanges are a critical operational element as they define the locations where vehicles must maneuver within the traffic stream. These maneuvers create turbulence which reduces the operational efficiency of the highway and are also a potential source of driver error. Therefore, desirable interchange operations require the consideration of several basic operational elements early in the project development stage. These elements are discussed in the following subsections. Other elements which should be considered in the preliminary design stage are described in Chapter 3, Section 3, Segments 5.0 and 6.0.

3.1 Uniformity

Interchange uniformity requires that all interchanges along a route have similar appearance and operations characteristics. Desirably, all exits should be on the right side of the highway in advance of the cross street. Interchanges should utilize consistent design and operational characteristics such as design speed, number of exit lanes, and geometric design.

Interchange uniformity is vital in meeting driver expectation and can be achieved by giving consideration to interchanges as a system, as well as individually. Because interchanges are closely spaced in urban areas, shorter distances are available in which to inform drivers of the course to be followed in leaving the freeway or the side from which to expect merging traffic. Dissimilar arrangements of entrances and exits cause confusion resulting in slowing down on high-speed lanes and unexpected maneuvers. To the extent practicable, all interchanges along a freeway should be reasonably uniform in geometric layout and general appearance.

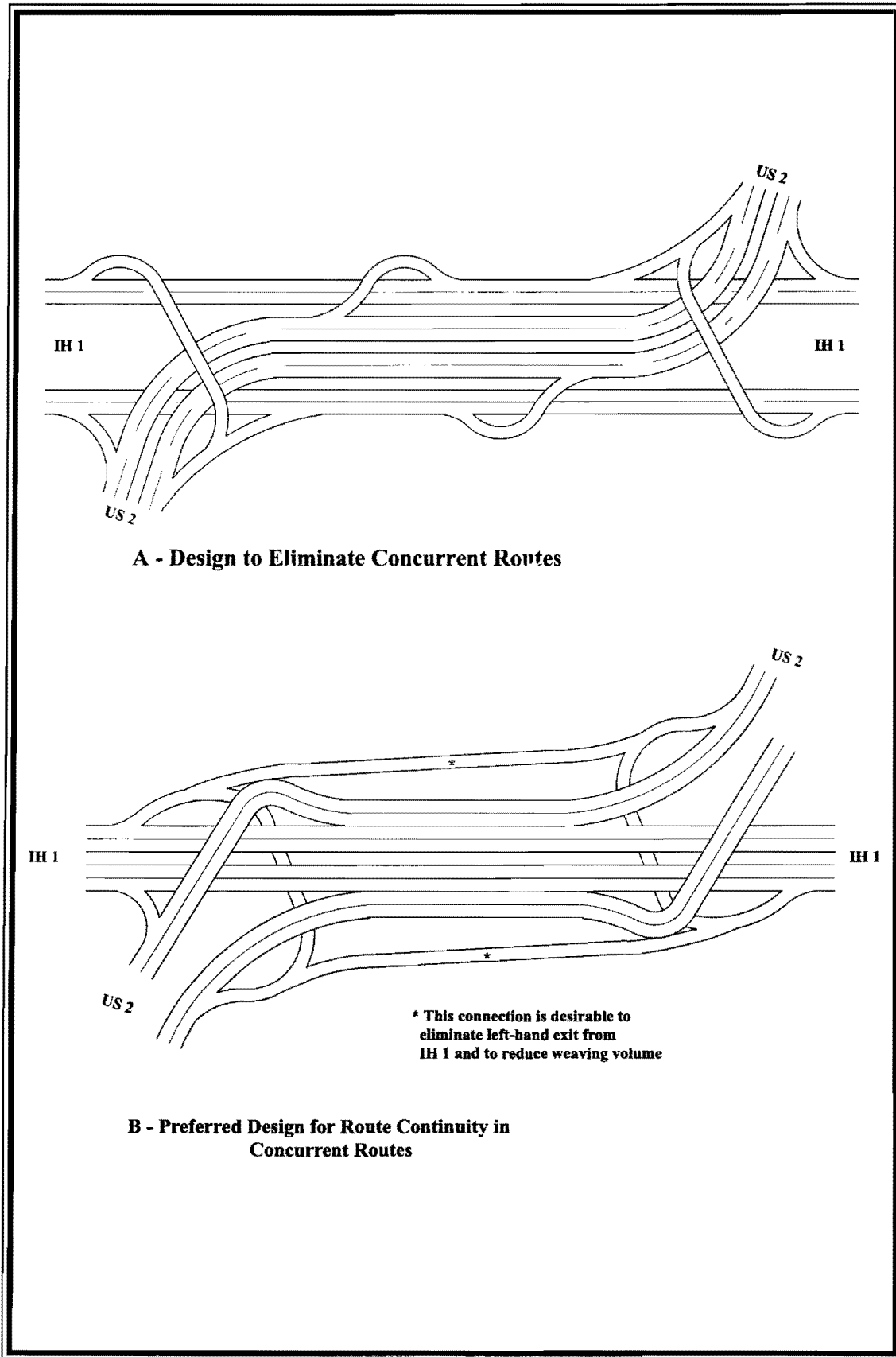


Figure 2-3. Design Alternatives for Concurrent Routes

3.2 Spacing

Generally, urban interchanges are so closely spaced that each interchange may be influenced directly by the preceding or following interchange. As a result, spacing of interchanges has a pronounced effect on the operation of freeways. A generalized rule-of-thumb for interchange spacing is a minimum of 1.6 kilometers (1 mile) separation between urban interchanges and 3.2 kilometers (2 miles) between rural interchanges.

The vehicle interactions at an interchange extend both upstream and downstream of the interchange. Therefore, interchanges less than 1.6 kilometers (1 mile) apart in urban areas will be influenced by the upstream and/or downstream interchanges. Chapter 2, Section 3, Segment 3.5 describes the areas of influence for entrance and exit ramps.

In areas of concentrated urban development, proper spacing usually is difficult to attain because of traffic demand for frequent access. Interchange spacing of less than 1.6 kilometers (1 mile) may be developed by grade-separated ramp pairs or by adding collector-distributor roads. However, these arrangements should be considered only under unusual circumstances such as existing arterials at close spacing.

3.3 Ramp Location

It is desirable to have all entrance and exit ramps on the right side of the through lanes due to the difficulty of left-entrance vehicles merging with high-speed through traffic and the requisite lane changing. Left-hand ramps reduce capacity, increase signing requirements, and increase vehicle conflicts. In some cases however, left-hand entrance or exits ramps may be necessary due to project limitations. When left-hand ramps are necessary, drivers must be adequately warned in order to change driver expectancy (Chapter 1, Section 6, Segment 1.0). Other accommodations which may be utilized include increasing sight distance, utilizing a higher design speed on the connections, or increasing spacing between access points.

Factors which influence the location of ramps in the vicinity of a cross street include sight distance, construction and right-of-way costs, circuitry of travel for left-turn movements, frontage road or cross street gradient at ramp intersections, storage requirements for left-turn movements at the cross street, and the proximity of other local road intersections.

3.4 Weaving

Weaving sections are one-way highway segments where the traffic patterns at access points cause vehicle paths to cross one another. Weaving sections have a detrimental effect on operational quality, and therefore, interchange designs that reduce weaving or remove it from the main facility are desirable. The simple weave consists of a single entrance followed by a single exit and has only two crossing traffic streams. The multiple weave consists of two or more overlapping weaving sections and has more than two crossing traffic streams. Multiple weaving sections typically consists of two closely spaced entrances followed by a single exit or a single entrance followed by two closely spaced exits.

Weaving maneuvers may not be addressed in detail in the project development stage. However, the detrimental impacts of weaving can be reduced by adhering to the principles of interchange spacing (Chapter 2, Section 3, Segment 3.2) and ramp location (Chapter 2, Section 2, Segment 3.3). Interchange spacings of 1.6 kilometers (1 mile) or greater will generally allow vehicles to find an acceptable gap and change lanes without having to reduce speed or force a merge. Placing all access on the right side eliminates the need to maneuver across all lanes in order to complete the desired maneuver.

Weaving maneuvers are discussed in Chapter 3, Section 3, Segment 4.0 and weaving analysis is described in Chapter 8.

3.5 Merging/Diverging

Traffic flow turbulence at interchanges is partly a result of the maneuvers made to enter or exit the highway facility, also known as merging or diverging. At the project development stage, merge/diverge operational considerations will be satisfactorily addressed if the other operational fundamentals are given sufficient consideration. These fundamentals include interchange uniformity, spacing, ramp location, and weaving.

A major concern of merging/diverging maneuvers at ramps is the area of influence of those maneuvers. When multiple entrances or exits are spaced closer than 900 meters (3000 feet), multiple weaving sections may result.

3.6 Design Considerations for Interchanges

Table 2-1 is a checklist of interchange items to consider in the project development stage. Parameters such as cost, environment, community values, traffic volumes, map reliability, and safety should all be considered in addition to the design considerations listed in Table 2-1.

Table 2-1. Interchange Design Considerations in Project Development

<ul style="list-style-type: none">◆ Route continuity◆ Uniformity of entrance and exit patterns◆ Single exits in advance of the separation structure◆ Degree of weaving◆ Potential for signing◆ Potential for staged construction◆ Compatibility with the environment
--

4.0 Sight Distance

Proper sight distance is an important part of any highway design. Sight distance also has an impact on highway operations. There are three types of sight distance which need to be considered: stopping sight distance, passing sight distance, and decision sight distance. Sight distances are impacted by the ability of drivers to see and respond to a stimulus in the environment. Chapter 1, Section 5, Segment 1.0 describes some of the driver characteristics which impact sight distances.

4.1 Stopping Sight Distance

The stopping sight distance is the distance required for a driver to see an object, identify the object, decide to stop the vehicle, step on the brake pedal, and for the vehicle to come to a stop. Stopping sight distance is an important element of geometric design and its application is described in the *Highway Design Division Operations and Procedures Manual*. The stopping sight distance can also impact highway operations. As the stopping sight distance approaches the minimum design values, drivers may tend to drive more conservatively, reducing the operational efficiency of the highway.

4.2 Passing Sight Distance

The passing distance is the distance required to safely perform a passing maneuver. It applies only to two-lane highways. Passing sight distance is also an important element of geometric design and its application is described in the *Highway Design Division Operations and Procedures Manual*. Highway operations generally improve as the availability of passing opportunities increases. Passing opportunities can be increased by increasing the availability of passing sight distance or by providing multilane highway sections at appropriate distances.

4.3 Decision Sight Distance

At some locations, stopping sight distance may not provide adequate time for drivers to make complex driving decisions and perform the appropriate traffic maneuver. At these locations, sight distance greater than stopping sight distance will provide drivers more time for decisions and avoid last minute maneuvers. This longer distance is known as decision sight distance. Decision sight distance should be considered in the very early design phase.

Decision sight distance is the distance at which a driver can detect a decision point in an environment of visual clutter, recognize its threat potential, select an appropriate speed and path, and perform the required action safely and efficiently. Its values are substantially greater than stopping sight distance. Decision sight distance is based on a 3.5-foot eye height and 0.5-foot object height. The decision sight distances in Table 2-2 provide values to be used by designers for sight distances at appropriate locations. Decision sight distance should be considered at freeway entrances and exits, freeway-to-freeway connectors, lane drops, roadside rest stops, inspection stations, and rural intersections.

If decision sight distance cannot be provided, special attention should be given to the use of suitable signing for providing advance warning of the conditions that are likely to be encountered. Guide signing is generally used for this purpose to position vehicles in the proper location for the desired maneuver.

Table 2-2. Decision Sight Distance

Design Speed, kmph (mph)	Decision Sight Distance, meters (feet)
80 (50)	312 (1,025)
96 (60)	388 (1,275)
112 (70)	442 (1,450)

5.0 Control of Access

Control of access is the condition where the rights of abutting owners to highway access are fully or partially controlled. Full control of access gives preference to through traffic by providing access connections only with selected roads (typically frontage roads) and by prohibiting crossings at-grade and direct private driveway connections. Freeways have full control of access. Partial control of access means that preference is given to through traffic to a degree that, in addition to access connections with selected public roads, there may be some crossings at-grade and limited private driveway connections.

The principal operational or functional difference between a highway with access control and one without is in the degree of interference with through traffic by vehicles and pedestrians entering, leaving, and crossing the highway. When access is controlled, the capacity of the highway is maintained at a high level and the crash hazard is kept low, regardless of the type and intensity of development of the roadside areas.

continued

5.0 Control of Access (continued)

The principle of full control of access is invaluable as a means for preserving the capacity of arterial highways and of minimizing crash hazards, but the principle does not have universal application. Highways without control of access are essential as land service facilities and the design features of these highways need to be carefully planned such that they will reduce conflicts and minimize the interference between vehicles to the maximum extent possible and still meet the needs of the highway users. Examples are the addition of right-turn lanes and left-turn lanes at major intersections.

Highway access should be provided only after careful consideration of current and future highway operations. **Once provided, access is very difficult to eliminate or reduce.**

6.0 Frontage Roads

Frontage roads serve numerous functions, including controlling access to the freeway, serving adjoining property, and maintaining circulation of traffic on each side of the freeway. Their primary purpose with freeways is to collect and distribute traffic between local streets and the freeway.

The operational considerations related to frontage roads in project development include the long-range use in urban or rural environment, the type of operation (one-way or two-way), the use of frontage roads as an alternative route for the freeway, the size of the outer separation and its effect on freeway access, the continuity of the frontage road, the type of frontage road intersections, the circuitry of travel on the frontage road, and frontage road traffic control. Generally, frontage roads should be continuous, even through major freeway-to-freeway interchanges. Frontage roads should be one-way in urban areas. If a highway is projected to be within an urban area during its design life, then consideration should be given to the frequency of grade crossings to facilitate one-way operations.

7.0 Alternative Routes

In urban areas, considerations should be given to potential alternative routes or travel paths for highway users. These alternative routes will be used when highway demand exceeds capacity, such as periods of peak demand, or in cases of temporarily reduced capacity, such as during maintenance operations, construction or incidents. Continuous frontage roads are one potential alternative route for freeways, especially during incidents.

8.0 High-Occupancy Vehicles

High-occupancy vehicle (HOV) lanes have become an important part of the overall transportation system. The effective implementation of HOV lanes requires consideration at the earliest stages of project development.

Although an HOV lane may not be a part of the initial operation of the highway facility, long range consideration should be given to the future implementation of HOV alternatives. Factors such as design of freeway, location of sign supports and luminaries, bridge columns in median, location of HOV lane, the types of access to be provided, and interface with other HOV facilities need to be considered and provided for during the project development stage. The *Revised Manual for Planning, Designing, and Operating Transitway Facilities in Texas* and the American Association of State Highway and Transportation Officials *Guide for the Design of High-Occupancy Vehicle Facilities* address the various considerations related to HOV lanes in the project development stage.

9.0 System Management

In urban areas, a highway facility can no longer be planned without giving consideration to the manner in which the highway interacts with other components of the urban transportation system. Such factors as relationships between system parts, future system control and management, and alternative transportation modes should be evaluated. Most of these factors are addressed in detail in Chapter 6 of this Manual.

10.0 Lighting

The lighting of an urban highway serves the principle function of improving driver visibility so that drivers can satisfactorily view the roadway, its appurtenances, and other traffic. The objectives of fixed lighting are to supplement vehicle headlights, improve visibility of roadway features, delineate the roadway, provide visibility of the environment, and reduce apprehension of those using the roadway.

Lighting systems for freeways are divided into two different types: continuous lighting and interchange lighting. Within each type, there are several different system configurations, dependent upon the characteristics of the facility to be lighted. Continuous lighting can take the form of median lighting, side-mounted lighting, high-mast lighting, and unidirectional lighting. Interchange lighting uses limited applications of the above-listed forms.

During the project development stage, the general type and location of lighting should be determined so that the relationship between design, operations, and lighting is determined early. As an example, a decision to provide for future implementation of a median high-occupancy vehicle lane may preclude the use of median lighting. Also, installing high-mast lighting before a major reconstruction project may help motorists identify and delineate the construction zone. Consideration should also be given to the maintenance requirements of the lighting system and the impact of the maintenance activities on highway operations.

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OPERATIONAL ANALYSIS

Operational decisions made in the project development stage are based on general principles, independent of traffic volume. Therefore, there are no analysis procedures for these decisions. The checklist in Table 2-3 summarizes the basic operational principles which should be accommodated in the project development stage.

**Table 2-3. Checklist of Operational Considerations
for Project Development**

- ◆ **Route Continuity** - Vehicles must exit to leave current route.
- ◆ **Concurrent Routes** - Routes or major traffic movements should not overlap within the same alignment.
- ◆ **Interchange Uniformity** - All interchanges should have similar appearance and operational characteristics.
- ◆ **Interchange Spacing** - Minimum spacing should be 1.6 kilometers (1 mile) between urban interchanges and 3.2 kilometers (2 miles) between rural interchanges.
- ◆ **Interchange Ramps** - Entrance and exit ramps should be located on the right-hand side whenever possible.
- ◆ **Interchange Maneuvering** - Weaving should be eliminated or reduced as much as possible.
- ◆ **Frontage Roads** - Frontage roads should be continuous and one-way in urban areas.
- ◆ **Alternative Routes** - Alternative route(s) should be available for traffic detours due to congestion or construction.
- ◆ **High-Occupancy Vehicle Lanes (HOV)** - Future location of HOV lanes should be anticipated.
- ◆ **System Management** - Highway design should be considered in context of overall transportation system.
- ◆ **Lighting** - Type and location should be compatible with usage.

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CHAPTER 3
OPERATIONAL CONSIDERATIONS IN DESIGN

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OVERVIEW

The preliminary design stage is distinguished by quantifying individual design features such as the number of lanes, horizontal and vertical alignment, placement of auxiliary lanes, and others. Operational analyses are used in this stage to evaluate the effectiveness of the geometric design under a variety of traffic conditions. The results of the analyses may lead to modifications of the geometric design in order to provide improved operations or to balance the operational needs with other design needs such as access, safety, cost, or constructability. The final product of the preliminary design stage is the preliminary design drawings showing the critical design elements in sufficient detail to begin the final design stage.

Many of the considerations addressed in this chapter can be best utilized when applied in the preliminary design of a new facility. When an existing facility is being reconstructed, project limitations may reduce the applicability of some of the operational considerations described in this chapter. In these cases, the operational considerations should be evaluated to determine the extent to which they can be utilized to improve the operational efficiency of the reconstructed facility within the limitations established by other design needs such as access, safety, cost, and constructability.

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DATA NEEDS

1.0 Traffic Volume

Average Daily Traffic (ADT) and Design Hour Volume (DHV) are generally used to size new facilities. However, if a more detailed analysis is required for reconstruction, or unusually complex geometrics are involved, 15-minute flow rates are often used in an operational analysis. These flow rates represent the equivalent hourly traffic volume passing a point during a given period of time, typically a peak 15-minute interval. A 15-minute period is used because it represents the shortest period during which stable flow typically exists. Chapter 1, Section 7, Segment 2.0 describes the procedure used to determine a peak hour flow rate from an hourly volume.

2.0 Other Traffic Data

Other traffic data are also useful in the preliminary design stage, including vehicle classifications, vehicle occupancies, and operating speed. Vehicle classifications include the number and types of heavy vehicles in the traffic stream. Vehicle occupancy classifies the traffic stream by the average number of people per vehicle and is useful when evaluating high-occupancy vehicle operations. Operating speed describes the movement of the traffic stream. Chapter 8 addresses each of these data types in greater detail.

3.0 Highway Drawings

At this stage of the project, large scale drawings of the highway can be very helpful in evaluating the basic operational principles of horizontal alignment. An appropriate scale would be 1"=100' or 1"=200'. Once the operational principles related to horizontal alignment have been satisfied, the drawings can be refined into preliminary design drawings which include the vertical alignment and other details.

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OPERATIONAL CONSIDERATIONS FOR GEOMETRIC DESIGN

The preliminary design stage is primarily an exercise in selecting the geometric design features appropriate to the highway facility. However, there are several operational principles which should be considered when selecting the geometric features.

1.0 Design Speed

The design speed influences most of the geometric features of a roadway. Sudden reductions in design speed introduce the element of surprise to the driver and should be avoided. Therefore, it is crucial that the design speed be selected so that all elements of a facility provide consistent operations. The *Highway Design Division Operations and Procedures Manual* discusses the selection and application of design speed.

Where project limitations cannot be overcome and it becomes necessary to use a lower design speed on a horizontal or vertical curve, it is desirable to have less than a 15 kmph (10 mph) change in design speed between successive curves, if possible. If the change in design speed is greater than 15 kmph (10 mph), then the motorists should be given appropriate warning of the condition. Introduction of a curve for a design speed lower than that of the project should be avoided at the end of a long tangent, a steep downgrade, or at other locations where high approach speeds may be anticipated, unless appropriate warning is given to the motorists.

Selection of low ramp design speeds may affect future operations by restricting the capacity of the ramp and impacting operations on the main lanes.

2.0 Volume-Capacity Relationships

Traditionally, the number of lanes has been determined primarily through capacity analyses based on the Design Hour Volume. This procedure is essential, but it should not be considered as the only criterion for establishing the number of lanes. There are other concerns just as important as the capacity per lane, including the arrangement of the lanes.

The number and arrangement of lanes should be established to avoid bottlenecks, to absorb fluctuations in traffic during the various peaks, and to provide a balanced facility. Providing operational flexibility in this manner may incur added costs, but the benefits can be significant in avoiding operational breakdowns and increasing the useful life of the highway.

The ratio of Design Hour Volume (DHV) to design capacity provides a general indication of the number of lanes required. Generally, a value of 1,500 vehicles per hour per lane should provide adequate capacity for through traffic in level terrain. This ratio should be determined for several separate highway elements, as shown in Figure 3-1. Basic freeway section flow capacity, ramp capacity at entrances and exits, and weaving capacity should all be evaluated to determine the number of lanes needed in a specific segment of highway. Segment 3.1 below and Chapter 8 describes more detailed procedures which can be used to perform operational evaluations if the above rule-of-thumb suggest potential operational problems or if other factors necessitate a more detailed evaluation.

3.0 Lane Considerations

The arrangement of highway lanes should be predicated on lane balance, basic number of lanes, and lane continuity. The need for auxiliary lanes can be determined from the arrangement of lanes and the need for additional capacity. When the number and arrangement of lanes have been determined, the manner in which lanes will be added or dropped can be determined along with the width of the lanes and shoulders.

3.1 Basic Lanes

The basic lanes concept refers to a constant number of lanes, exclusive of auxiliary lanes, which are maintained over a significant length of highway. The number of basic lanes is predicated on the general volume level of traffic over a substantial length of the facility. The number of basic lanes remains the same for this length, regardless of predicted changes in traffic volume at individual interchanges and requirements for lane balance. Figure 3-2 illustrates the use of the basic number of lanes.

The number of basic lanes may be determined from the procedures described in Segment 2.0 above or by using the procedures contained in the *1994 Highway Capacity Manual*. The number of basic lanes should be based on peak 15-minute flow rates or the DHV (Chapter 1, Section 7, Segment 2.0). A rule-of-thumb for approximating the number of lanes needed to provide adequate capacity is to divide the DHV by 1,500. This rule-of-thumb applies to through traffic on level terrain when trucks make up less than 5 percent of the traffic.

Localized variations in predicted traffic volume are ignored when determining the number of basic lanes. Therefore, sections with volumes below the basic level would theoretically have reserve capacity, and volumes on sections somewhat above the basic level would be compensated for by the addition of auxiliary lanes introduced within these sections (Chapter 3, Section 3, Segment 3.4). Again, if the increase or decrease in volume occurs over a substantial length, the number of basic lanes should be increased or decreased. The number of basic lanes should not be changed through a local interchange simply because there is a substantial volume of traffic leaving and/or entering at the interchange. At a freeway-to-freeway interchange with more than 50 percent turning traffic, the number of basic lanes may be reduced by one. If one basic lane is dropped, structure clearance beyond the freeway-to-freeway connection should be adequate to accommodate future construction of the dropped lane.

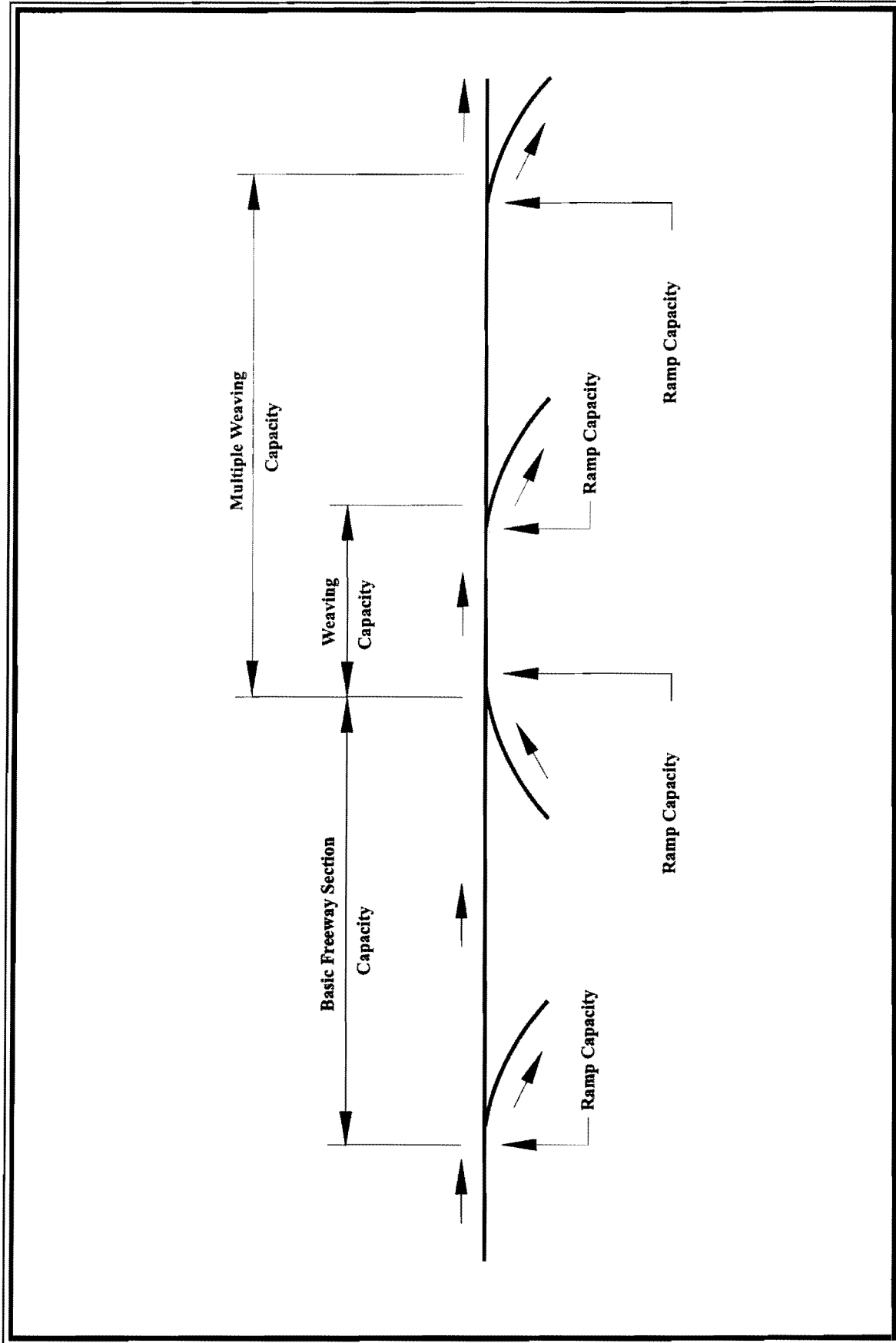


Figure 3-1. Elements of Freeway Capacity

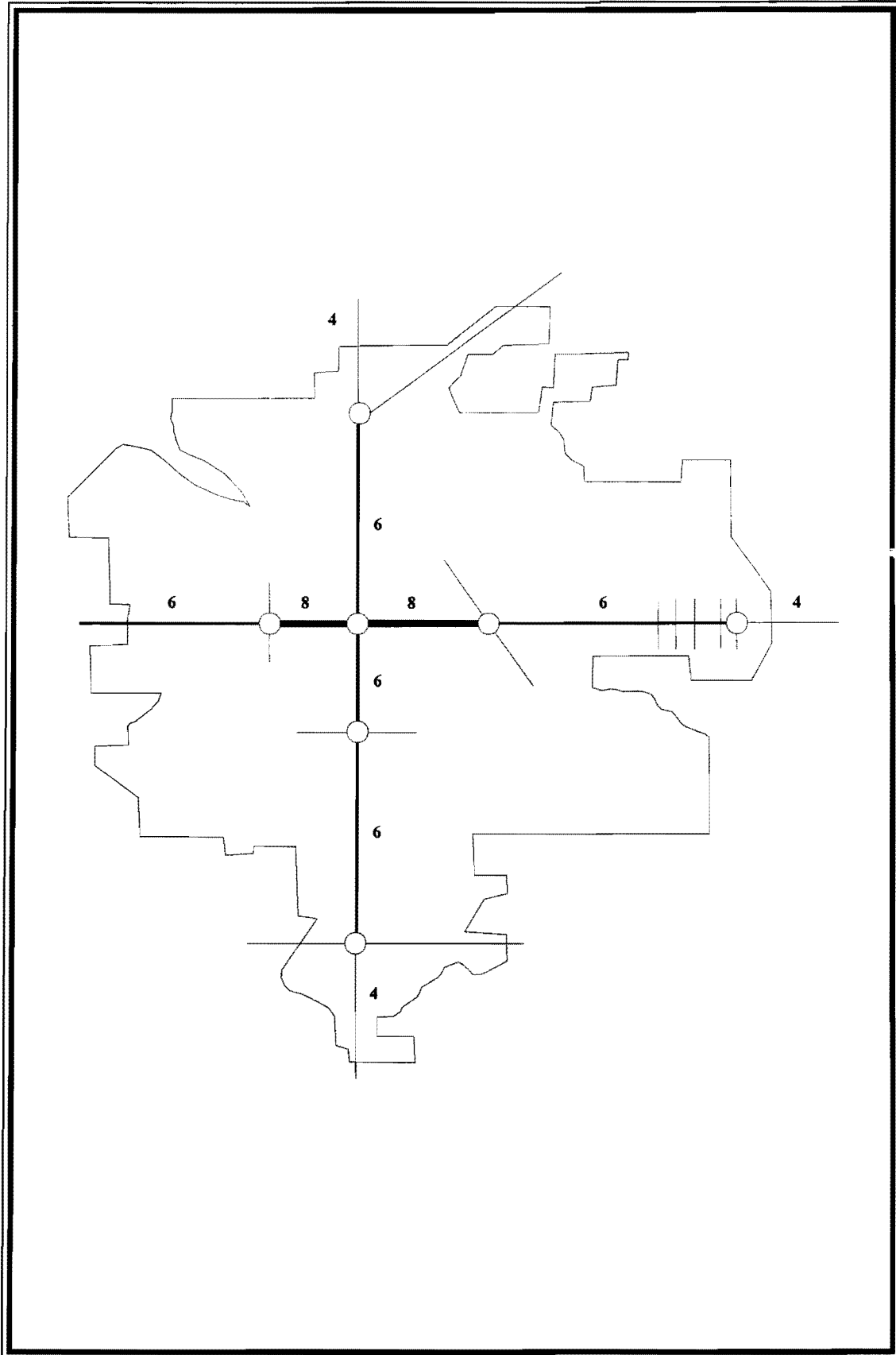


Figure 3-2. Basic Lanes Concept

3.2 Lane Balance

Smooth operation at an interchange is dependent on satisfying lane balance requirements. Lane balance principles define the relationship between the number of lanes approaching a merge/diverge point and the number of lanes leaving the same point.

The following principles should be followed to insure lane balance at interchanges:

1. **Entrances** - The number of lanes beyond the merge point should be equal to the sum of approach main lanes and entrance ramp lanes, **or** the sum of approach main lanes and entrance ramp lanes minus one. This principle of lane balance at entrances is illustrated in Figure 3-3.
2. **Exits** - The number of main lanes before the exit point must be equal to the sum of the departing main lanes and the number of exit ramp lanes minus one. This principle is illustrated in Figure 3-4.
3. The traveled way of the highway should be reduced by not more than one traffic lane at a time.

There is a definite relationship between capacity and lane balance at ramp entrances and exits. Capacity analysis determines the number of basic lanes (Chapter 3, Section 3, Segment 3.1) and the number of ramp lanes. Once these values are determined, the lane balance principles are used to determine the need for auxiliary lanes (Chapter 3, Section 3, Segment 3.4) and insure operational efficiency and flexibility. Three standard situations for entrance and exit ramps are illustrated in Figures 3-3 and 3-4, respectively. The determination of which arrangement to use should be based on the volume of ramp traffic and the volume of traffic in the outside lane of the freeway.

The lane balance and basic lanes concepts must be applied in coordination with one another. The basic number of lanes should be maintained through the interchange and auxiliary lanes (Chapter 3, Section 3, Segment 3.4) may be added to the basic lanes to achieve lane balance. Figure 3-5 illustrates the coordination of lane balance and basic lanes.

3.3 Lane Continuity

Drivers in through traffic lanes expect to be able to maintain their relative position without changing lanes. The principle of lane continuity provides that the basic lanes are continuous. Lane continuity provides that a vehicle in a basic lane will not have to change lanes to remain in the same basic lane relative to the other basic lanes. Figure 3-6 illustrates the examples of proper and improper application of lane continuity. In Figure 3-6a, there is a minimum of three lanes in the cross section at all points, but only one lane is continuous through the interchange. As a result of the discontinuity, the three lanes are not basic lanes. In Figure 3-6b, there is also a minimum of three lanes in the cross section at all points, but the three basic lanes are continuous through the interchange. Failure to maintain lane continuity results in lane shifting which reduces capacity. It is also contrary to driver expectancy.

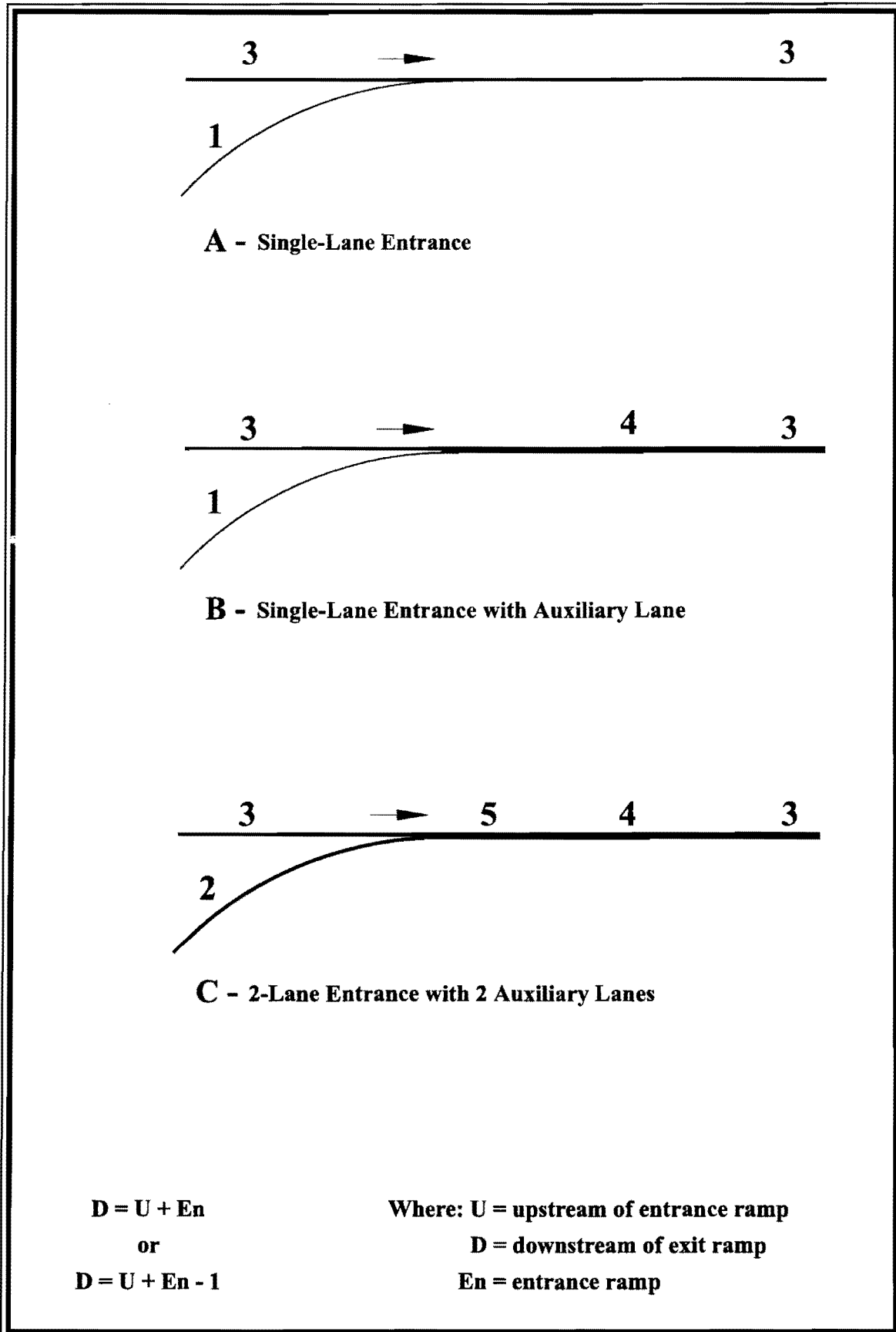


Figure 3-3. Lane Balance at Entrance Ramps

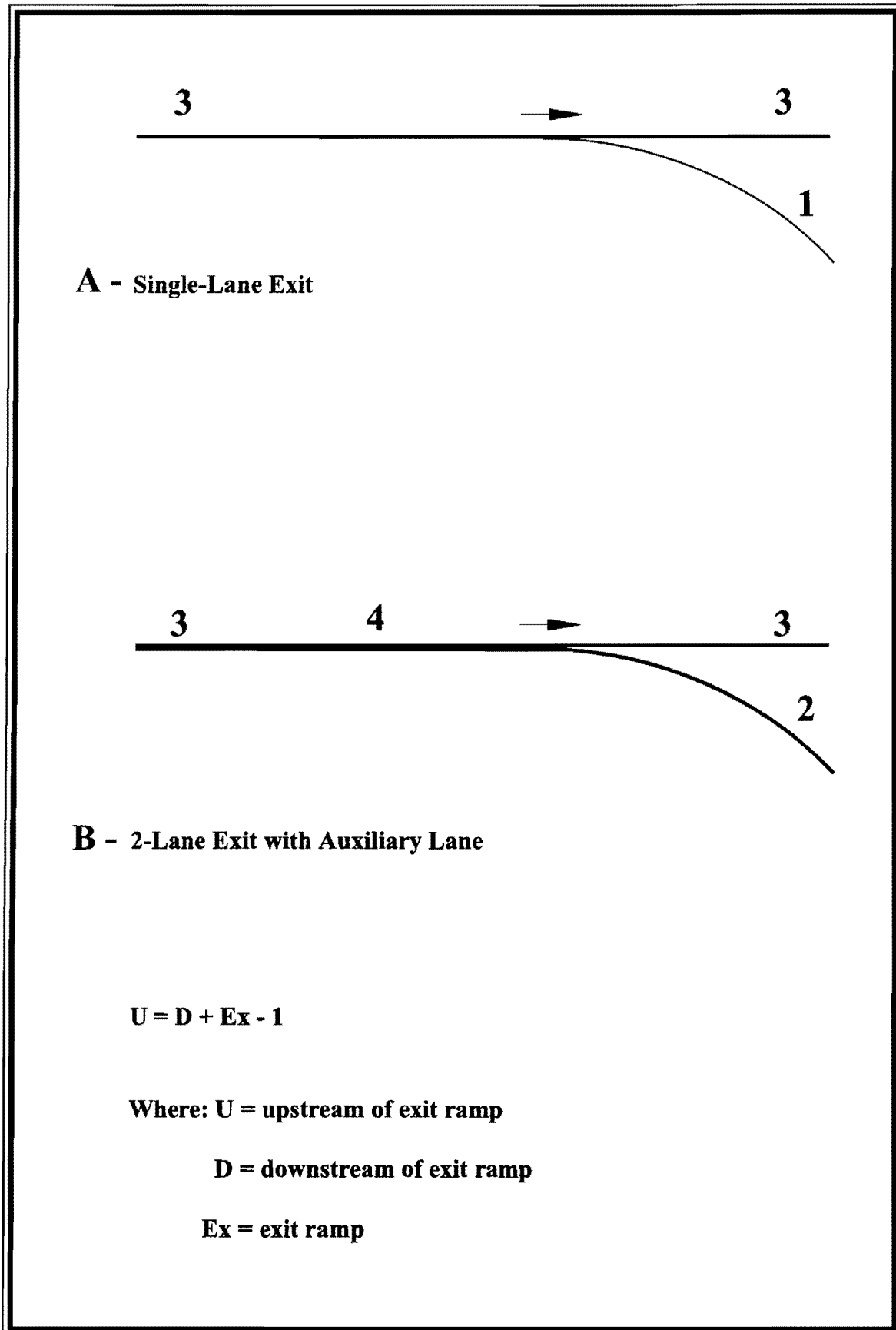


Figure 3-4. Lane Balance at Exit Ramps

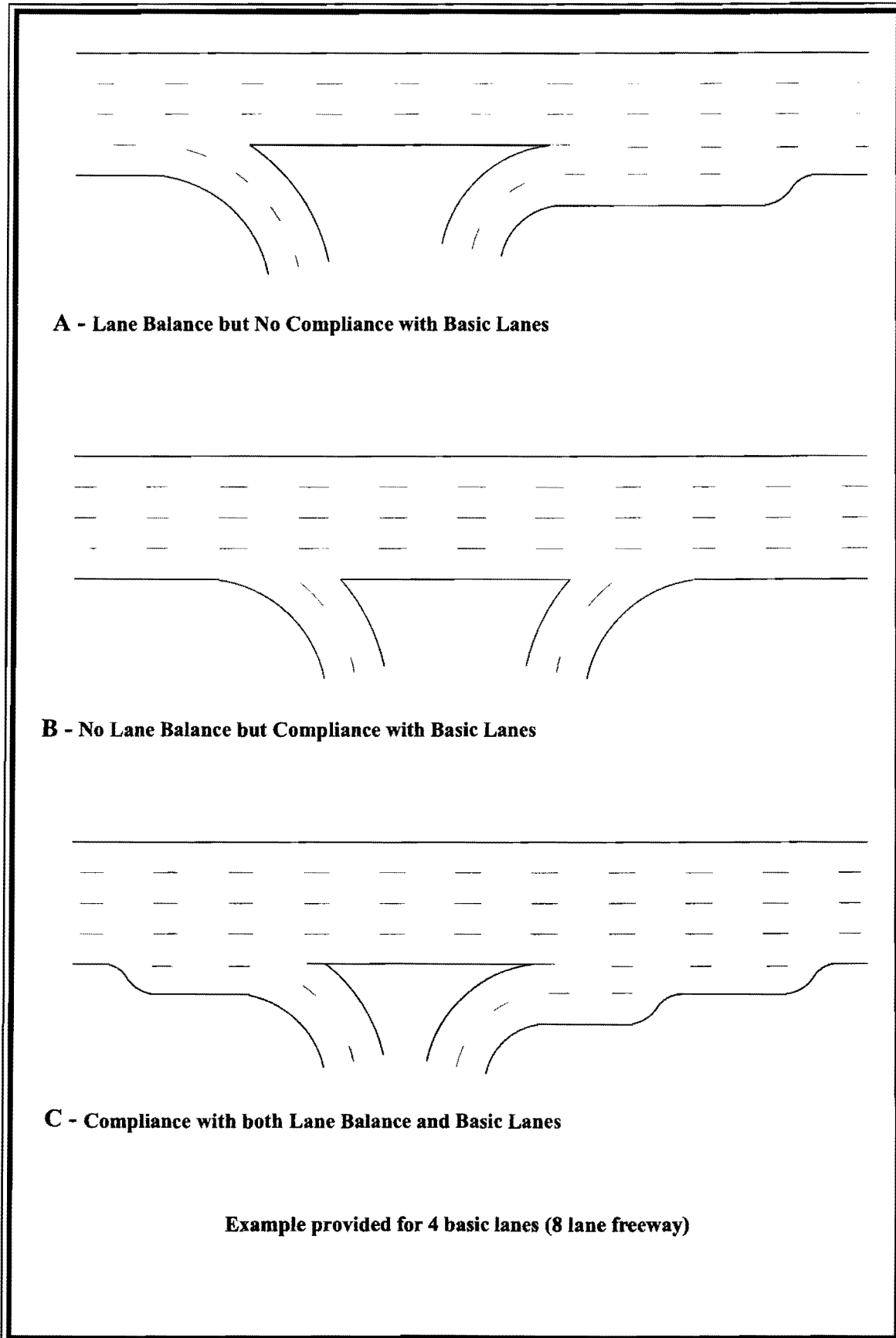


Figure 3-5. Coordination of Lane Balance and Basic Lanes

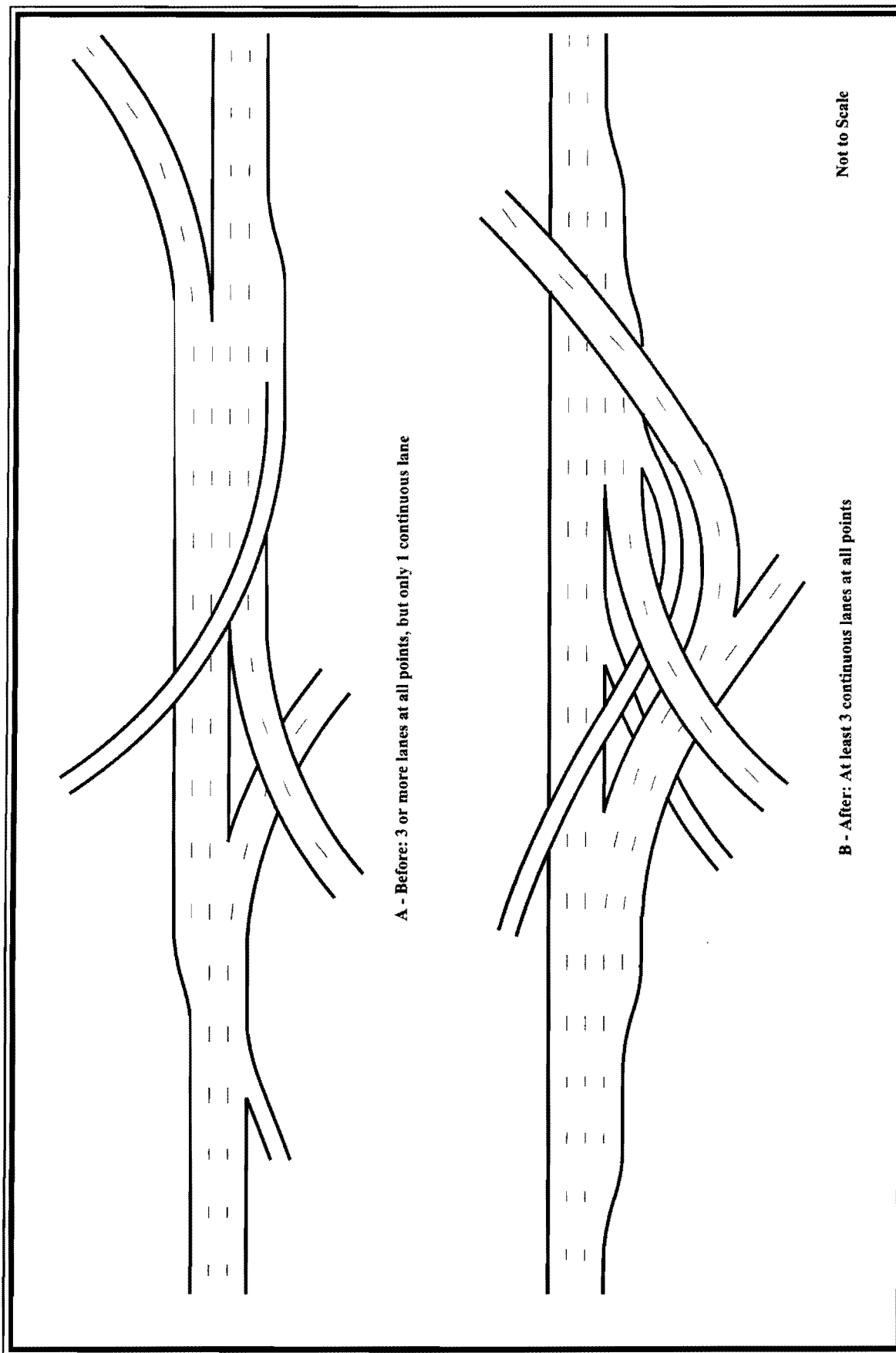


Figure 3-6. Lane Continuity Concept

3.4 Auxiliary Lanes

An auxiliary lane(s) is one or more lanes added to a highway to accommodate various operational demands supplementary to through traffic movement. An auxiliary lane may be provided to comply with the lane balance concept, to provide additional capacity beyond the basic lanes, to comply with capacity requirements in the case of adverse grades, or to accommodate speed changes, weaving, and maneuvering of entering and leaving traffic.

Auxiliary lanes are used to balance the traffic load and maintain a more uniform level of service on the highway. Such lanes facilitate the positioning of drivers at exits and bringing them onto the highway at entrances. Thus, the concept is very much related to signing (Chapter 3, Section 3, Segment 7.0) and route continuity (Chapter 2, Section 2, Segment 1.0). Careful attention should be given to the design treatment of an auxiliary lane because it may have the potential for trapping a driver at its termination point or the point where it is continued onto a ramp or turning roadway (Chapter 3, Section 3, Segment 3.5). Several different procedures for adding or dropping auxiliary lanes are illustrated in Figure 3-7.

Desirably, ramp terminals are spaced 750 to 900 meters (2,500 to 3,000 feet) apart. Occasionally, closer spacings may be necessary. In these situations, the operational efficiency may be improved by using a continuous auxiliary lane between the entrance and exit terminals. A more expensive alternative for high-volume locations is to provide a grade separation between the two ramps. Grade separated ramps should be considered when the volume on the auxiliary lane exceeds 1,500 vehicles per hour per lane. The impact of grade separated ramps on future widening should be considered.

3.5 Lane Additions and Reductions

The number of lanes on a facility may change as the result of an increase or decrease in basic lanes or auxiliary lanes. Lane additions are generally made at on-ramps. Parallel ramps (Chapter 1, Section 6, Segment 1.3) are preferred at lane additions. Lane drops should generally be made 600 to 900 meters (2,000 to 3,000 feet) beyond an interchange to allow for adequate signing. The lane reduction taper should be visible for 300 to 450 meters (1,000 to 1,500 feet) (Decision Sight Distance, Chapter 2, Section 2, Segment 4.3) to allow the motorist the opportunity to avoid a forced lane change. The change in the number of lanes should take place on a tangent section and prior to a crest vertical curve to provide adequate sight distance. For the same reasons that right-hand ramps are preferred (Chapter 2, Section 2, Segment 3.1), merges should be avoided on the left-hand side.

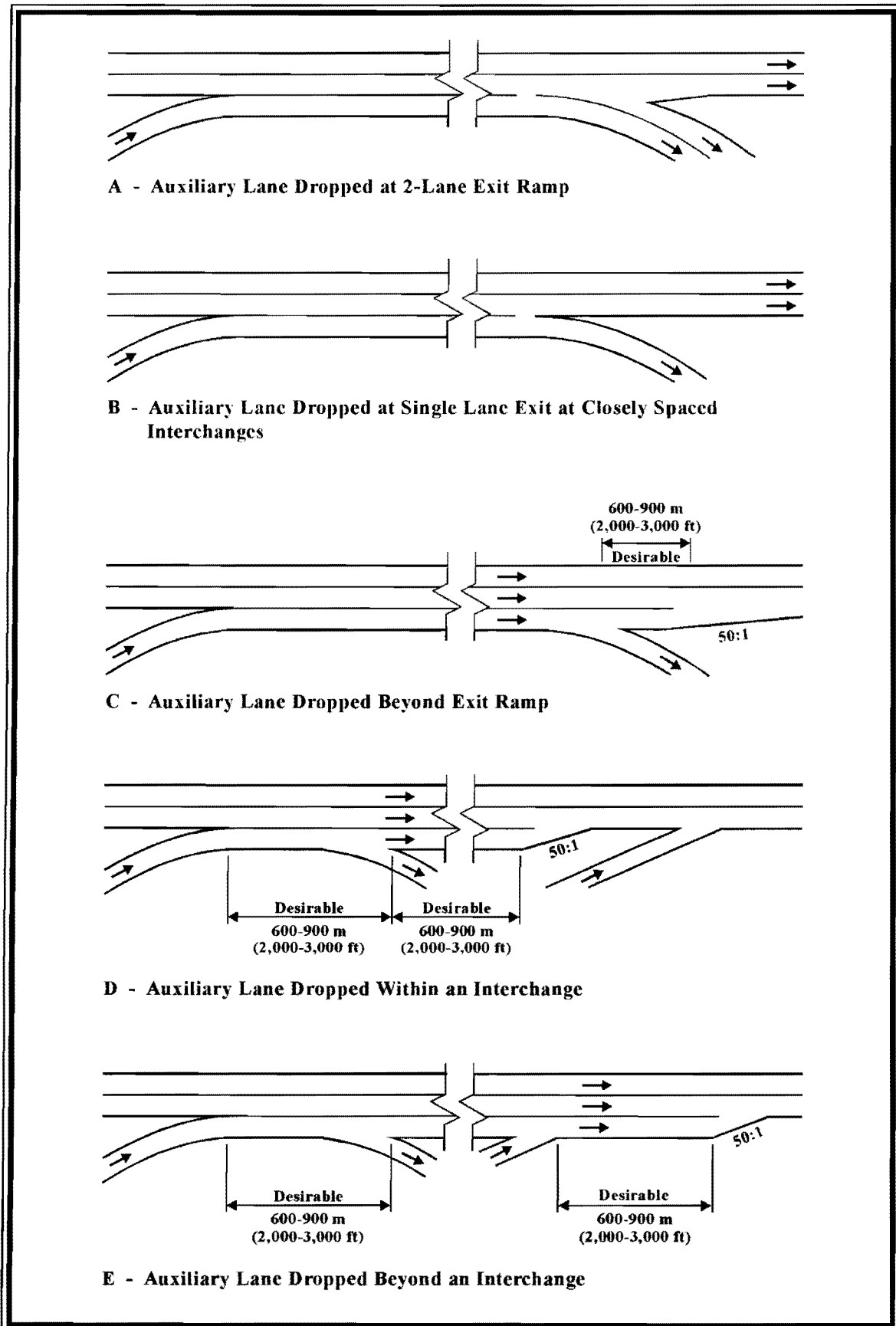


Figure 3-7. Alternatives for Dropping Auxiliary Lanes

3.6 Lane and Shoulder Widths

Generally, lane width is 3.7 meters (12 feet) and shoulder width is 3 meters (10 feet). In some cases, such as reconstruction or retrofit, it may be necessary to reduce lane and shoulder widths. Auxiliary lanes should be the same width as basic lanes.

Experience has shown that lane widths of 3.4 meters (11 feet) will result in operations which may be less than optimal for a particular lane, but which may be a marked improvement for the total facility if capacity can be increased by adding a lane as a result of narrowing the other lanes or shoulders. The use of narrow lanes should be considered when other alternatives are not feasible. The use of narrow lanes should be based on an operational analysis indicating that overall operations are improved. Future lane additions should be considered when determining the initial lane and shoulder widths, in order to provide the greatest flexibility for reallocating available pavement.

Figure 3-8 illustrates how the inside shoulder and narrow lanes can be used to add an additional travel lane in each direction. This type of treatment would typically be used for area congestion relief by the addition of an auxiliary lane.

Several principles can be used to select a cross section for reconstruction when full widths can not be achieved. First, a right shoulder (3 meters [10-foot]) should be provided. A left shoulder can be reduced to 0.6 to 1.2 meters (2 to 4 feet) in width. Shoulder widths greater than 1.2 meters (4 feet) and less than 2.4 meters (8 feet) are not preferred next to barriers because they encourage use where the space is insufficient for most vehicles. Lane widths can be reduced to 3.4 meters (11 feet) if needed and can be justified based on operational improvements that could not be obtained using full widths due to right-of-way or environmental limitations.

The drainage of the shoulder is another factor which should be considered. The type of drainage initially provided for the shoulder may impact the ability to use some or part of the shoulder as a travel lane at a later date. Not only should the drainage include consideration of the future use of the shoulder as a travel lane, but it should also consider temporary use of the shoulder to route traffic around an incident or maintenance activities.

3.7 Optional Lanes

Optional lanes permit a driver to choose between two alternative paths without merging into another lane. Figure 3-9 illustrates several different uses of optional lanes. Optional lanes are particularly useful at major forks (Chapter 3, Section 3, Segment 6.2) because of their inherent flexibility in handling fluctuations in traffic volumes between the possible vehicle paths.

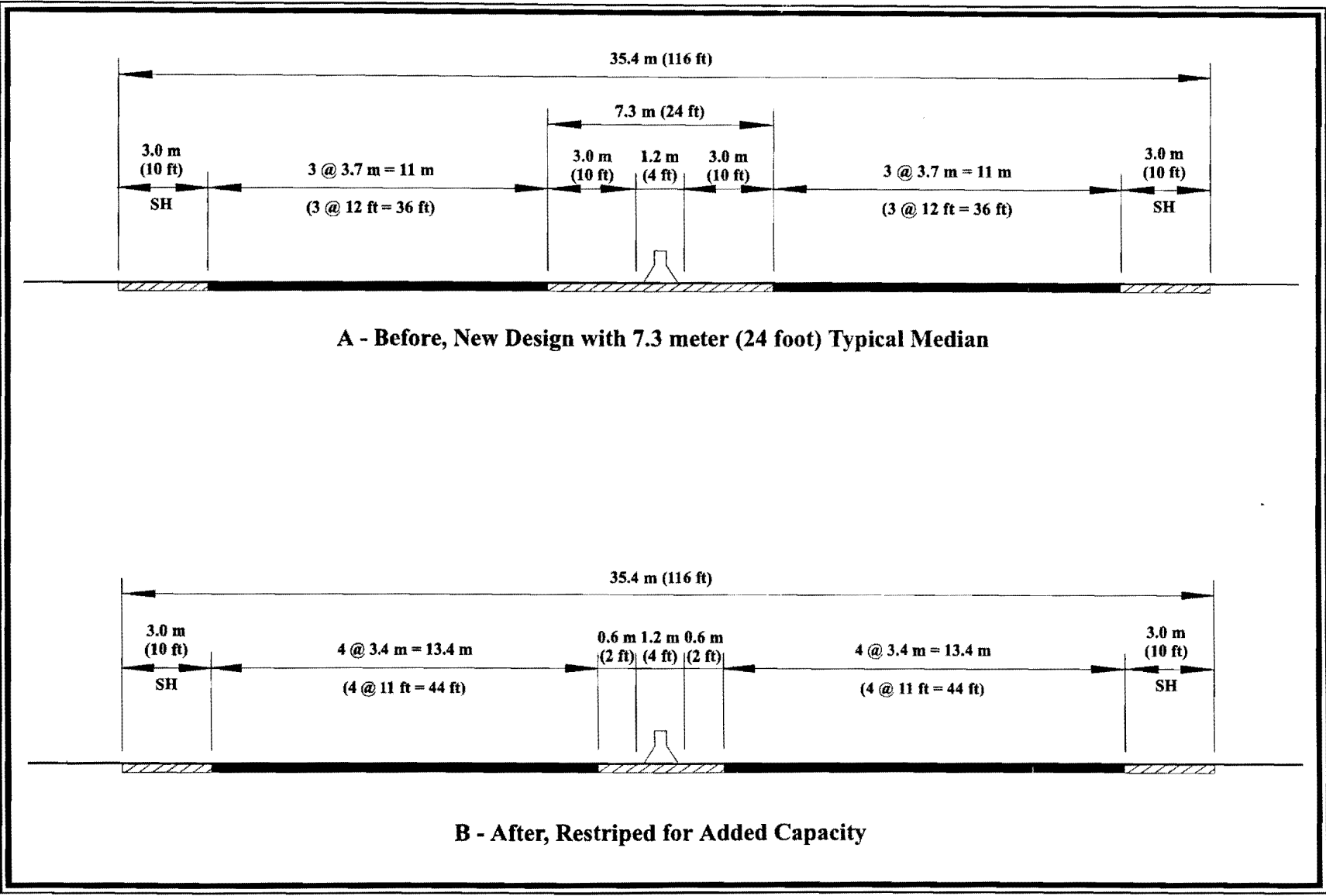


Figure 3-8. Cross-Section Flexibility

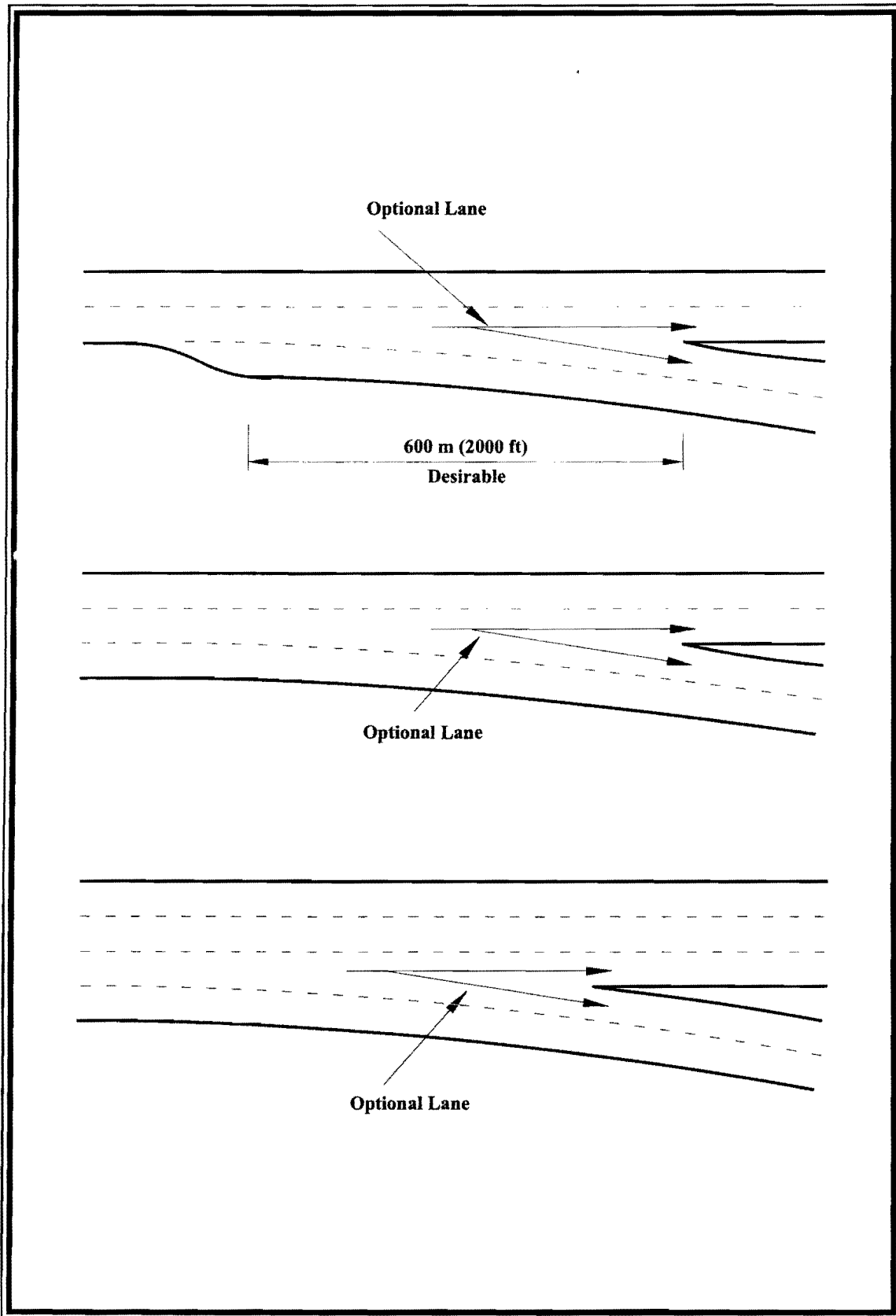


Figure 3-9. Optional Lanes

4.0 Weaving

Weaving maneuvers create turbulence in the traffic stream that causes a detrimental impact on operations. The amount of turbulence created by weaving is a function of ramp separation, lane arrangements, and traffic volumes. Figure 3-10 shows several different types of weaving sections, in order to illustrate some of the considerations related to weaving movements.

There is no ideal lane arrangement for weaving maneuvers. The design of a weaving area requires balancing the weaving needs with the limitations of the project. The following discussion of the illustrations in Figure 3-10 point out some of the operational impacts of various weaving arrangements. The highway designer should evaluate these impacts and use the most appropriate design, considering the traffic volumes of weaving and non-weaving traffic, the spacing between access points, the cross section, and the project limitations. Chapter 8 contains detailed analysis procedures for weaving sections.

Figures 3-10a, b, and c show weaving sections where both weaving movements are required to change lanes at least once. These arrangements may encounter operational difficulties under high volumes if acceptable gaps are limited. The weaving configuration in Figure 3-10a requires the non-weaving traffic to share the same lanes as the weaving traffic. In Figure 3-10b, the non-weaving movements have the option to stay out of the lanes where weaving is taking place. The weaving section of Figure 3-10b is normally preferable to that in Figure 3-10a, if there is room for the additional lanes. The weaving section in Figure 3-10c is created by adding an auxiliary lane between an entrance and an exit ramp. In this case, creating a weaving section by adding the auxiliary lane may be preferable to not having a weaving section. In situations with a high exiting volume, a 2-lane exit ramp may be used.

5.0 Interchange Types

There are several geometric patterns of ramps for turning movements at interchanges. Their application at a particular site is determined by the number of intersection legs, the expected volumes of through and turning movements, topography, design controls, proper signing, and policy. The selection of a particular interchange design is also affected by how that interchange relates to other interchanges in the system and across the state. Signing and operations are major considerations in the design of interchanges. Each design should be tested to determine if it can be signed to provide a smooth flow of traffic. The need to simplify interchange design from the standpoint of signing and driver understanding can not be overstated.

Fully directional interchanges, 3-level diamond interchanges, and diamond interchanges are the most widely used interchanges in Texas. Cloverleaf interchanges are found on some of the earlier highways in the state, but are not normally used in new construction. Each of these interchange types and the operational concerns of each type are briefly discussed and illustrated in the following subsections.

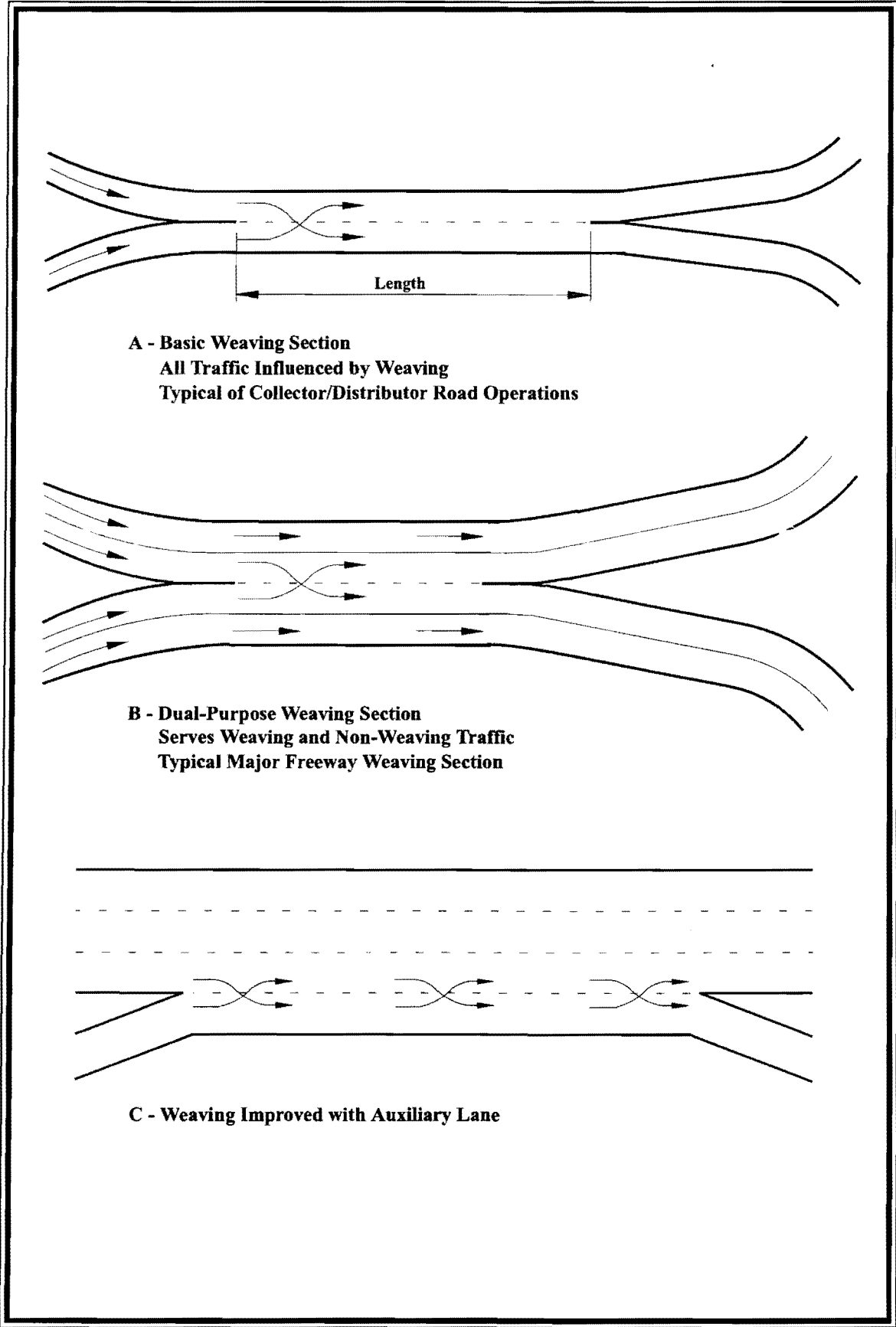


Figure 3-10. Typical Weaving Sections

5.1 Directional Interchange

Interchanges which provide a direct connection for the major turning movements are termed directional interchanges. When direct connections are provided for all turns, the interchange is a fully directional one. Fully directional interchanges provide the highest level of service. Figure 3-11 illustrates several different types of directional interchanges. The through lanes of a directional interchange typically should be located on the lower two levels. This may reduce the operational costs of the interchange by eliminating the need for large volumes of through vehicles to accelerate a steep grade. For some directional interchanges, it may be appropriate to locate the through lanes for one highway at the highest level in order to eliminate height restrictions on a truck route.

Some of the advantages of fully directional interchanges are that they require less right-of-way than cloverleaf interchanges, they can accommodate all movements, they are generally easier to sign than cloverleaf interchanges, they provide higher capacity, and they allow higher exiting and merging speeds. Fully directional interchanges are more expensive to build, due to the number of structures, and so are limited to interchanges of major routes.

Directional interchanges may utilize a single-exit or a two-exit design. The single-exit design illustrated in Figure 3-11a has several operational advantages. It is more consistent with driver expectancy, provides a single exit in advance of the separation structure, reduces weaving in the traffic stream, and simplifies providing interchange uniformity. A difficulty with the single-exit interchange design occurs under high-volume and high-speed conditions, at the fork following the single-exit from the freeway if the distance between the exit and fork is not adequate. There may also be some confusion at the second decision point, resulting in less than optimal operations. Signing may also be difficult to provide at the fork if minimum distances are used between diverge points.

Some designers prefer two exits on each approach of some directional interchanges with high-volume turning movements. Care should be exercised in these cases to insure that lane balance, weaving, and signing requirements are properly satisfied. Signing is more difficult if both exits are served from the same lane. Signing may also be confusing because the left-turn exit precedes the right-turn exit, which is the reverse of typical driver expectation.

Generally, the provision of single exits is more costly because of the added roadway, longer bridges, and in some cases, additional separation structures. Also, many of the benefits produced by the use of single exits are of such nature that their value will not show positively in a benefit-cost analysis.

Figures 3-11b through 3-11e illustrate three-leg directional interchanges. The three-leg interchange in Figure 3-11b is preferred to the loop ramp interchange shown in Figure 3-11c due to the lower speeds and limited capacity associated with loop ramps. The difference between Figures 3-11d and 3-11e is the primary route. In Figure 3-11d, the primary route curves to the right and minor route traffic must exit in order to continue straight ahead. In Figure 3-11e, the primary route continues along the tangent and the minor route must exit. The primary route should be determined on the basis of route continuity, not traffic volume.

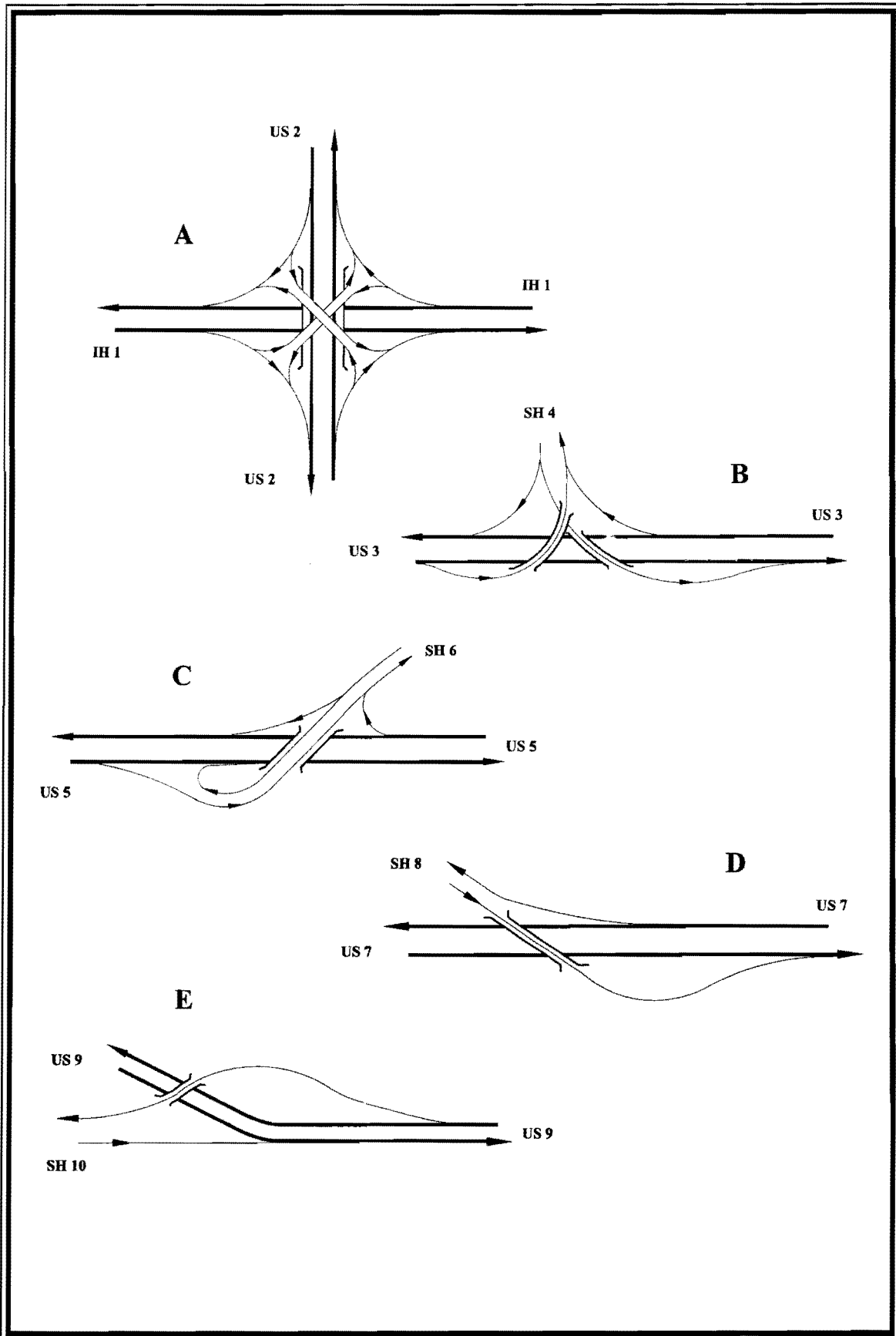


Figure 3-11. Typical Directional Interchanges

5.2 Three-Level Diamond Interchange

The three-level diamond interchange may be used when two high-volume roadways cross. Both routes should have a high volume of through traffic. This configuration provides uninterrupted through movement, but turning movements must maneuver through a series of intersections, which may be signalized or controlled with STOP or YIELD signs. A three-level diamond interchange is illustrated in the *Highway Design Division Operations and Procedures Manual*. This configuration may be used as an interim measure prior to the construction of a fully directional interchange if adequate right-of-way is available for future direct connections.

5.3 Diamond Interchange

The diamond interchange is the most common type of interchange found on a controlled access highway, and is especially prevalent in urban areas. The conventional diamond interchange derives its name from the shape of the access ramps, although the ramps may also take the form of a reverse diamond or X, where frontage roads exist. Figure 3-12 illustrates several different forms of diamond interchanges.

The conventional diamond form shown in Figures 3-12a and 3-12b is the most common application. The conventional diamond form has the advantages of having the exit ramp located near the cross street and the entrance ramp located to allow vehicles from the cross street quick access to the freeway. Its disadvantages include the possibility of exiting vehicles backing up onto the freeway when long queues form on the ramp or frontage road, and the requirement that most vehicles must go through the intersection to gain access to most frontage road property.

The reverse diamond or X interchange pattern shown in Figure 3-12c has application to locations with significant development on the frontage road. Its advantages are that access is provided to much of the property between interchanges and queues will not typically back onto the freeway. Its disadvantages are that entering vehicles may have to accelerate on an upgrade, exiting maneuvers occur just beyond a crest vertical curve where weaving will also take place, and queues at the interchange may block access to the entrance ramp. Another disadvantage of the X interchange pattern is that it encourages frontage road traffic to bypass the frontage road traffic signal and weave with the freeway traffic. This may disrupt the through traffic and under utilize the frontage road between the entrance and exit ramps. This disadvantage becomes a concern when interchanges are closely spaced.

The diamond interchange illustrated in Figure 3-12d has superior operational characteristics with signalized intersections due to the greater separation between intersections. However, the additional right-of-way needed for this interchange may limit its use.

The diamond interchanges illustrated in Figures 3-12e and 3-12f are appropriate for use with one-way arterial streets.

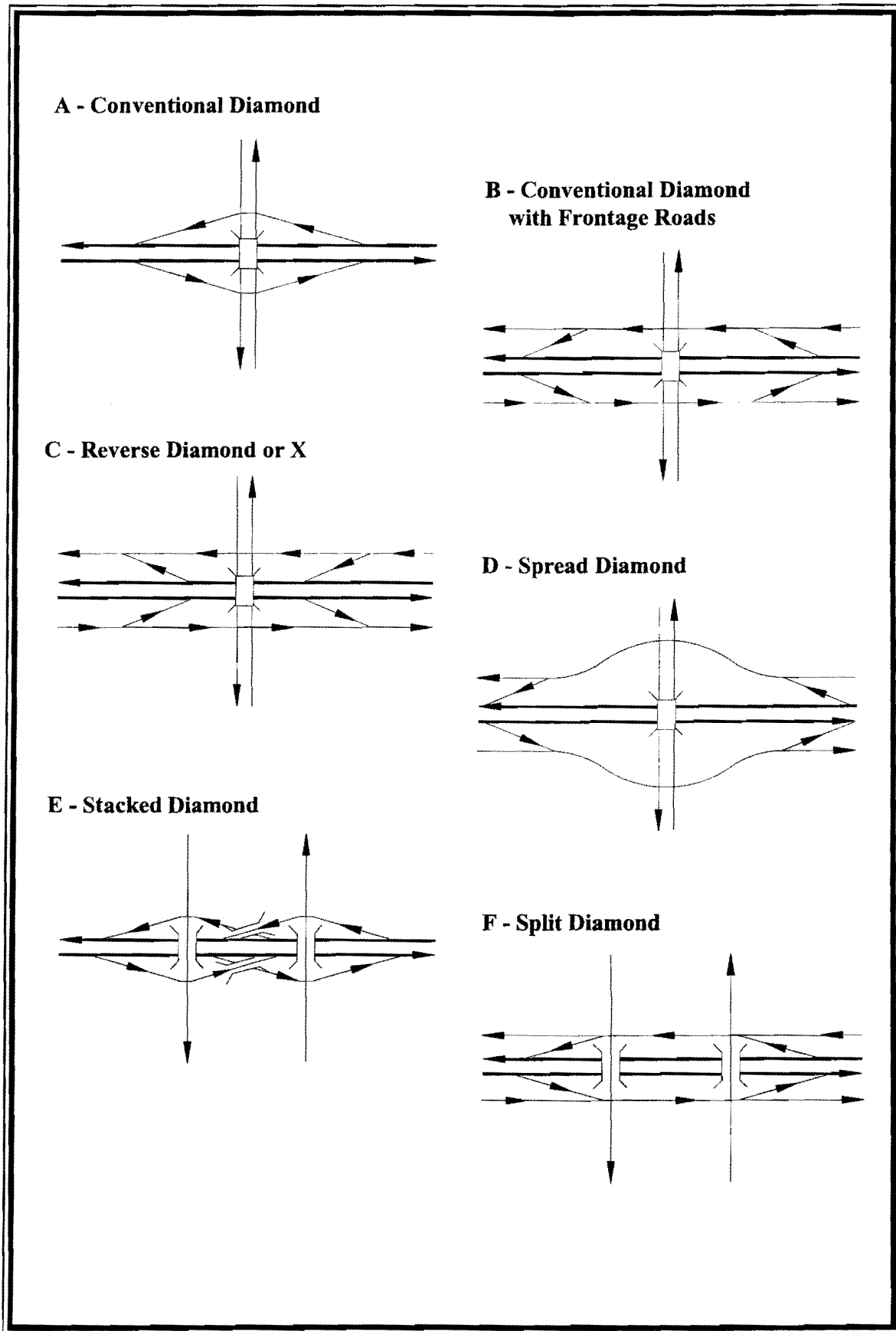


Figure 3-12. Typical Diamond Interchanges

5.4 Signalized Diamond Interchanges

Signalized diamond interchanges provide a majority of the access to freeways in urban areas. As a result, the traffic signal design and operation at a diamond interchange are critical to effective operation. Specific factors critical to design and operation include the number of approach lanes, the lane assignments, the distance between intersections, signal phasing, signal timing, and sight distance.

Generally, all lanes between the traffic signals should have a corresponding approach lane upstream of the traffic signal. Figure 3-13 illustrates a typical signalized diamond intersection on a cross-street having a center two-way left turn lane. The need for exclusive left- and right-turn lanes and U-turn lane should be evaluated on the basis of future traffic volumes and future travel patterns. Whenever possible, adequate clearance and right-of-way should be provided for future implementation of such improvements. Lane assignments at diamond intersections also have significant implications on capacity and operations. Signal operation should be evaluated for all peak periods to insure that operations are acceptable.

Signal operation improves as the distance between the intersections of a diamond interchange increases. The desirable distance for signal operation is 90 to 120 meters (300 to 400 feet). Distances less than 90 meters (300 feet) can be operated satisfactorily, however, there is less flexibility in the selection of traffic signal phasing. Even though the intersections of a diamond interchange may not be initially intended for signalized operation, consideration should be given to providing optimal intersection separation for future signalization.

5.5 Single-Point Urban Interchange

The single-point urban interchange (SPUI) is also a compact interchange utilizing a single intersection with highly channelized movements and 3-phase signal control (see Figure 3-13). Several design elements must be carefully considered in order to construct and use them efficiently. For instance, the vehicle paths within the large intersection region must be adequately marked. Also, SPUIs are more expensive to build because of the necessary increased bridge span width.

5.6 Cloverleaf Interchanges

A full cloverleaf interchange has a loop ramp in each of four quadrants to accommodate the left turn movements. An interchange with less than four loop ramps is referred to as a partial cloverleaf. Cloverleaf interchanges require more right-of-way than diamond interchanges and fully directional interchanges and, therefore, are less common in urban areas. Figure 3-14 illustrates two examples of full and partial cloverleaf interchanges.

continued

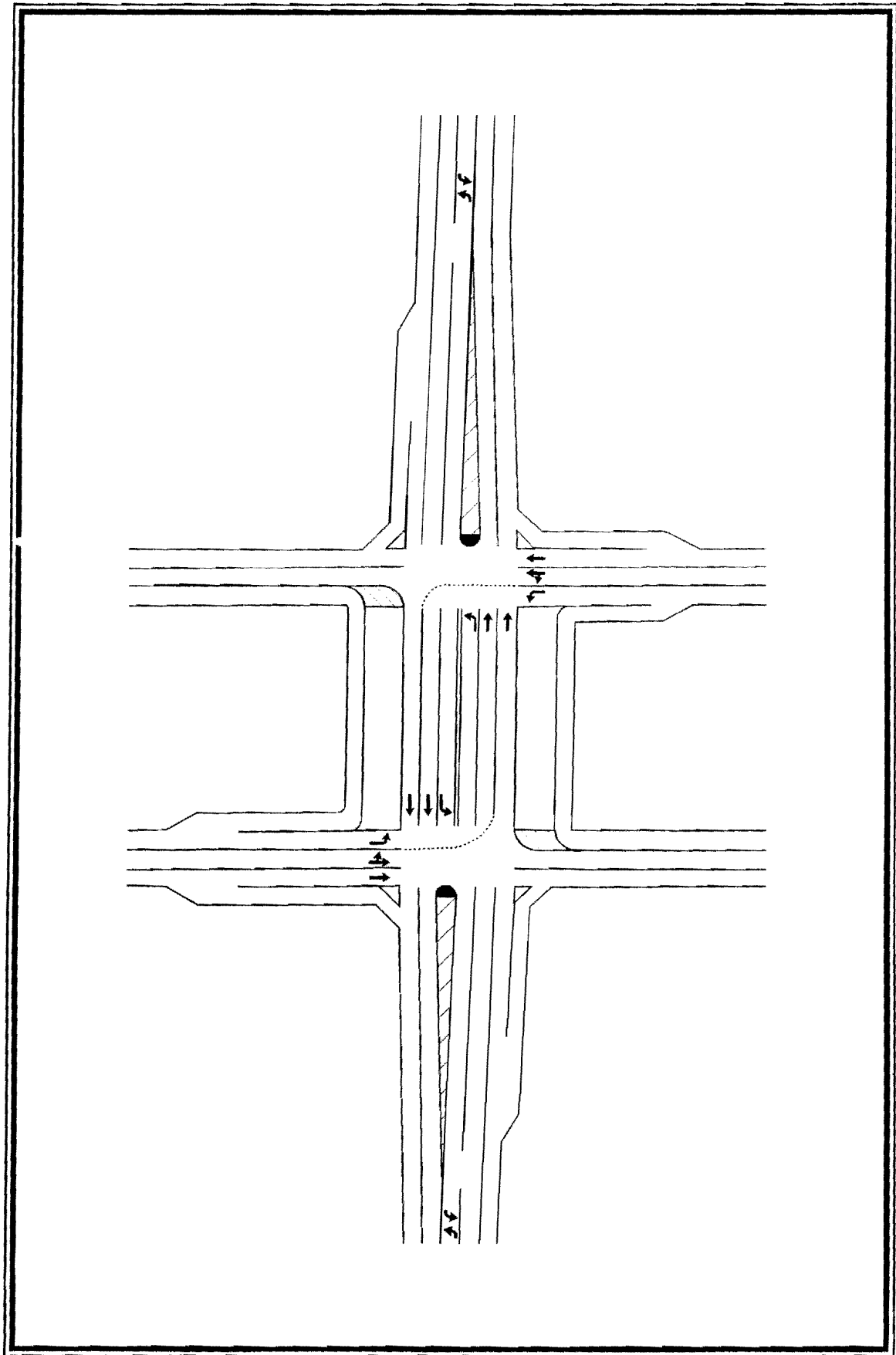


Figure 3-13. Typical Intersection for Diamond Interchange

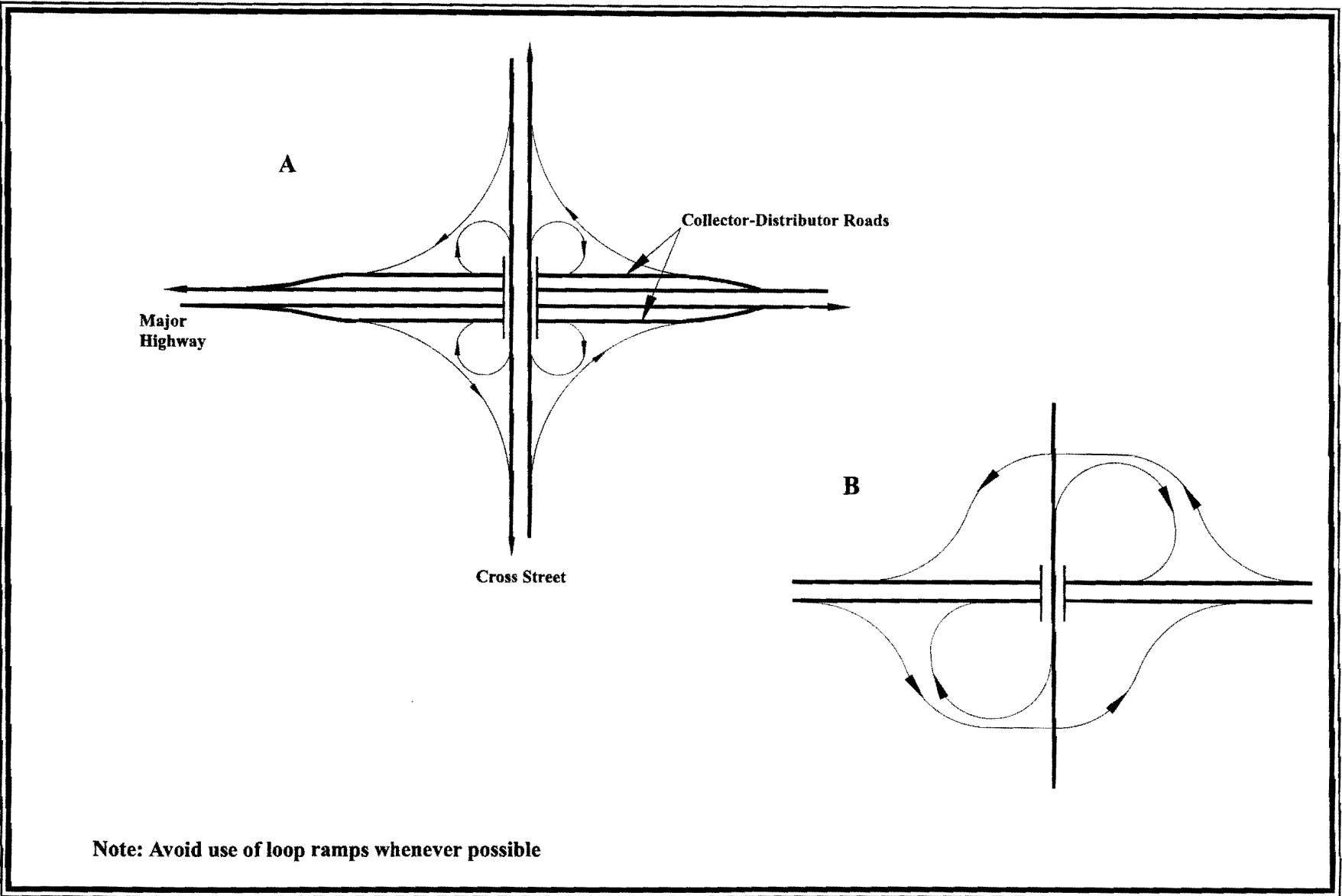


Figure 3-14. Full and Partial Cloverleaf Interchanges

5.6 Cloverleaf Interchanges (continued)

The advantage of the cloverleaf interchange is that it eliminates the need for a left-turn grade separation structure and allows left turns to be made without the need for control at an intersection. Disadvantages of cloverleaf interchanges are the extra travel distance required for left-turn traffic, the short weaving length available when two loops are in adjacent quadrants, the large reduction in speed for left turn movements, limited capacity of loop ramps, and the large right-of-way requirements. Locating the left-turn maneuver beyond the cross street may be unexpected by some drivers. Another disadvantage includes the difficulty of providing 2-lane ramps when volumes warrant 2 lanes.

The use of a separate collector-distributor road as shown in Figure 3-14a removes the weaving maneuvers from the freeway main lanes and places them on a lower speed roadway. If a collector-distributor road is not used, several other disadvantages include the double exit from and double entrance to the main lanes, the problems associated with signing a second exit, the speed differentials between the mainline traffic and the entering/exiting traffic, and the exit located after the crossing structure.

Figure 3-14b illustrates a partial cloverleaf with loop ramps that serve the two left turns from the cross street. This interchange is known as a Parclo-A interchange and may be an appropriate capacity enhancement for an existing diamond without frontage roads if adequate right-of-way exists. It may also be an appropriate conversion for an existing full cloverleaf that possesses operational problems if adequate capacity can be provided. The partial cloverleaf shown in Figure 3-14b has the advantages of no weaving problems and the loop ramp serving the lower speed arterial. The interchange has the appearance of a conventional diamond to freeway traffic, in that all exiting traffic uses the same ramp. The major limitation is the need to provide adequate arterial signing to inform the motorist that left turns are made from the right lane. More right-of-way is also required in the quadrants having the loop ramps as compared to the conventional diamond.

6.0 Interchange and Terminal Considerations

As most vehicle interactions occur in the vicinity of interchanges and terminals, their design is critical in terms of efficient operational performance. It is possible to provide an acceptable geometric design that results in less than optimal operational performance. The following subsections address significant considerations in the operational performance of interchanges and terminals.

6.1 Merging Capacity

The presence of any type of merge condition indicates a reduction in capacity. Whenever a merge is part of a highway design, the operating conditions should be carefully evaluated to insure that operations will be acceptable. The evaluation should not only examine the merge capacity at the specific point of the merge, but should also evaluate operations upstream and downstream of the merge.

Lanes located downstream of a merge may operate very close to capacity for a short distance downstream of the merge point. This is due to the mixing of two streams into one lane. As the traffic flows downstream, it will redistribute to other lanes. The capacity of lanes located upstream of a merge is restricted by the capacity of the merge itself.

6.2 Major Forks

The location where a highway or freeway splits into two major or separate flows is known as a bifurcation or major fork. Their design should follow all of the operational principles previously discussed, including lane balance. Invariably, operational difficulties will develop unless one of the interior lanes is an optional lane, where vehicles have the choice of taking either route.

Whenever possible, the approach to the fork should be on tangential alignment and one of the forks should continue the tangential alignment. The designated or continuous route is the obvious choice for the route to be located on the tangent. Figure 3-15 illustrates the comparison between alternative designs. The tangential alignment is operationally superior because an indecisive or inattentive driver will be able to continue on the route where the same driver might encroach the gore area with a "Y" design. The tangential alignment also eliminates superelevation transition problems. The diverge at a fork should be accomplished with a diverging tangent followed by a curve as shown in Figure 3-15. This allows each roadway to obtain its own identity with the existing cross-slope, with superelevation introduced after the roadways are separated.

6.3 Freeway-to-Freeway Connections

Freeway-to-freeway connections are formed by the convergence of two major traffic streams. The principles of route continuity (Chapter 2, Section 2, Segment 1.0) and concurrent routes (Chapter 2, Section 2, Segment 2.0) should be followed when considering their design. If possible, the use of inside merges should be avoided.

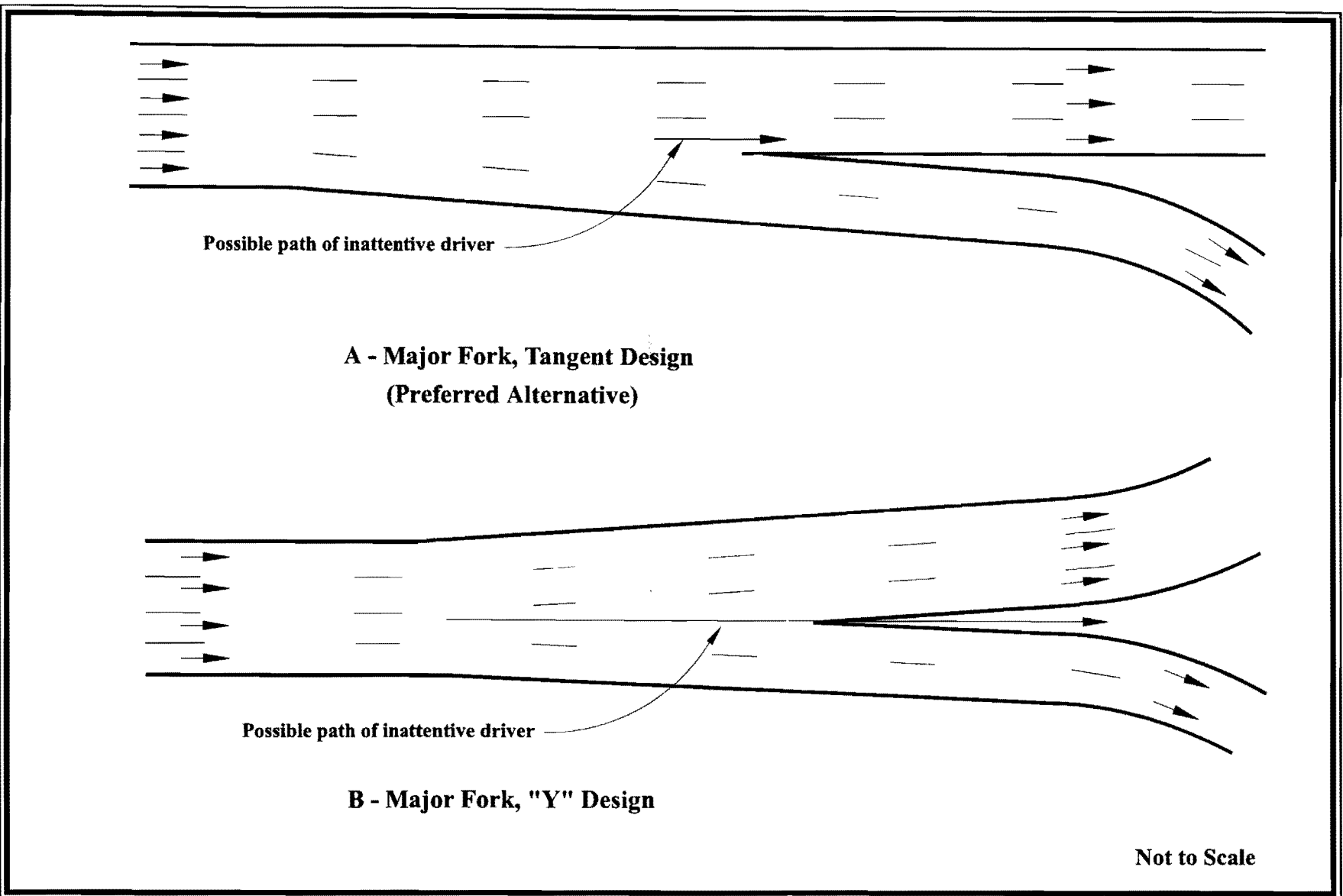


Figure 3-15. Major Fork Design Alternatives

6.4 Two-Lane Exit Ramps

Some situations may require a two-lane ramp at a point downstream from the exit gore. Reasons for a two-lane ramp include downstream capacity needs, future capacity needs, lane balance requirements at a downstream point, a wide structure for future highway widening, and others.

When a two-lane ramp is justified, lane balance requirements should be satisfied at the exit from the main lanes. An exit maneuver which can be made only from one main lane should have only one lane to exit onto. Figure 3-16 illustrates how lane balance requirements can be satisfied for a two-lane ramp served by a single freeway lane. This configuration has one lane of exiting capacity.

In some cases, capacity needs may require a two-lane exit. This can be done as shown in Figure 3-17 by adding a second lane and continuing the lane upstream as an auxiliary lane for an appropriate distance (desirably 600 meters [2,000 feet]). This configuration has two lanes of exiting capacity.

6.5 Ramp Design and Alignment

Freeway entrances and exits should be located on tangent sections wherever possible in order to provide maximum sight distance and desirable traffic operation. The location of exit ramps on a horizontal curve should be avoided wherever possible. If an exit ramp must be located on a curve, then the ramp should also utilize a curved horizontal alignment. A tangent alignment for an exit ramp located on a curved main lane segment may draw vehicles into the exit ramp. Locating an exit ramp on a curved main lane section also causes problems for superelevation transition.

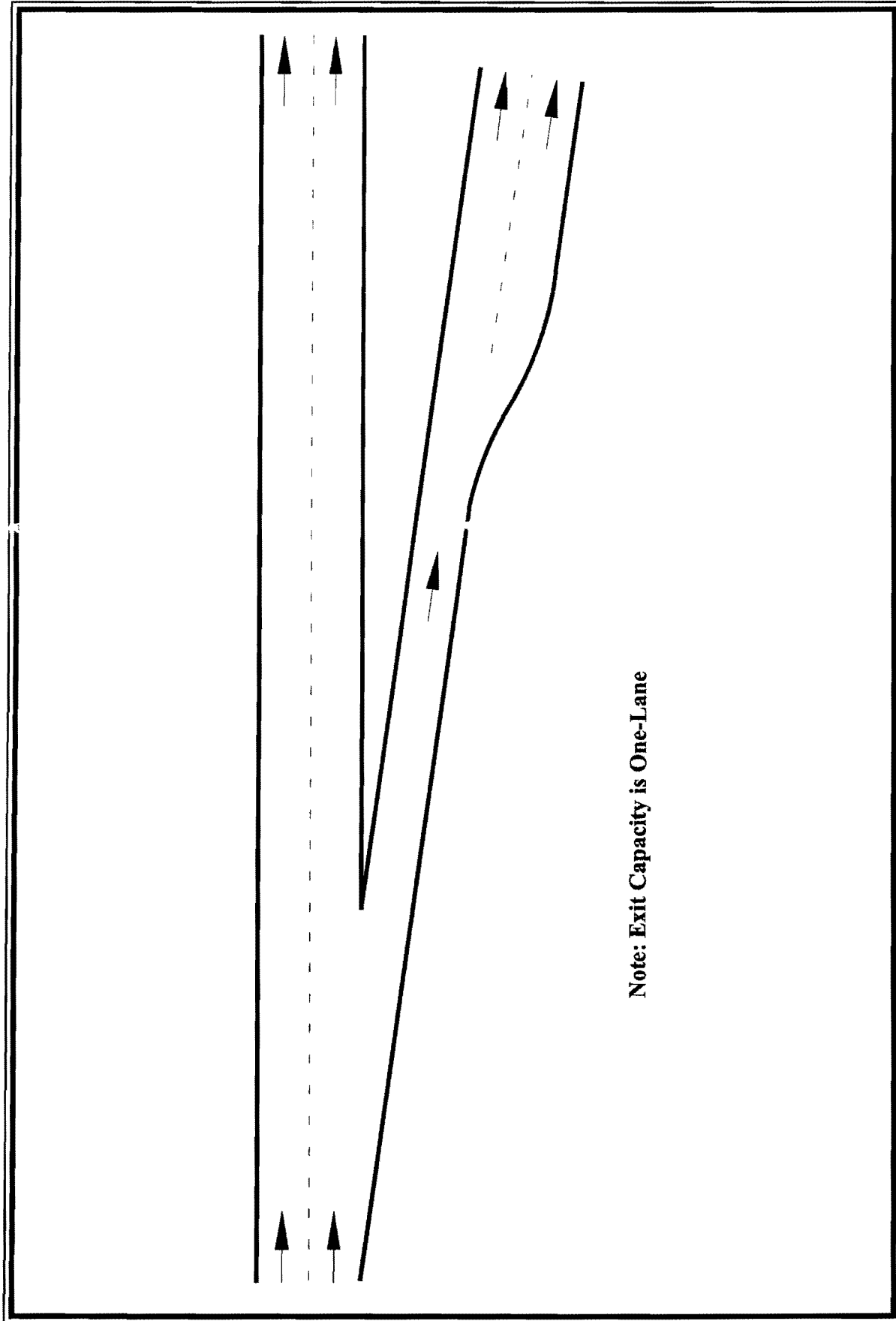


Figure 3-16. Lane Balance for Single Lane Transition to Two-Lane Exit Ramp

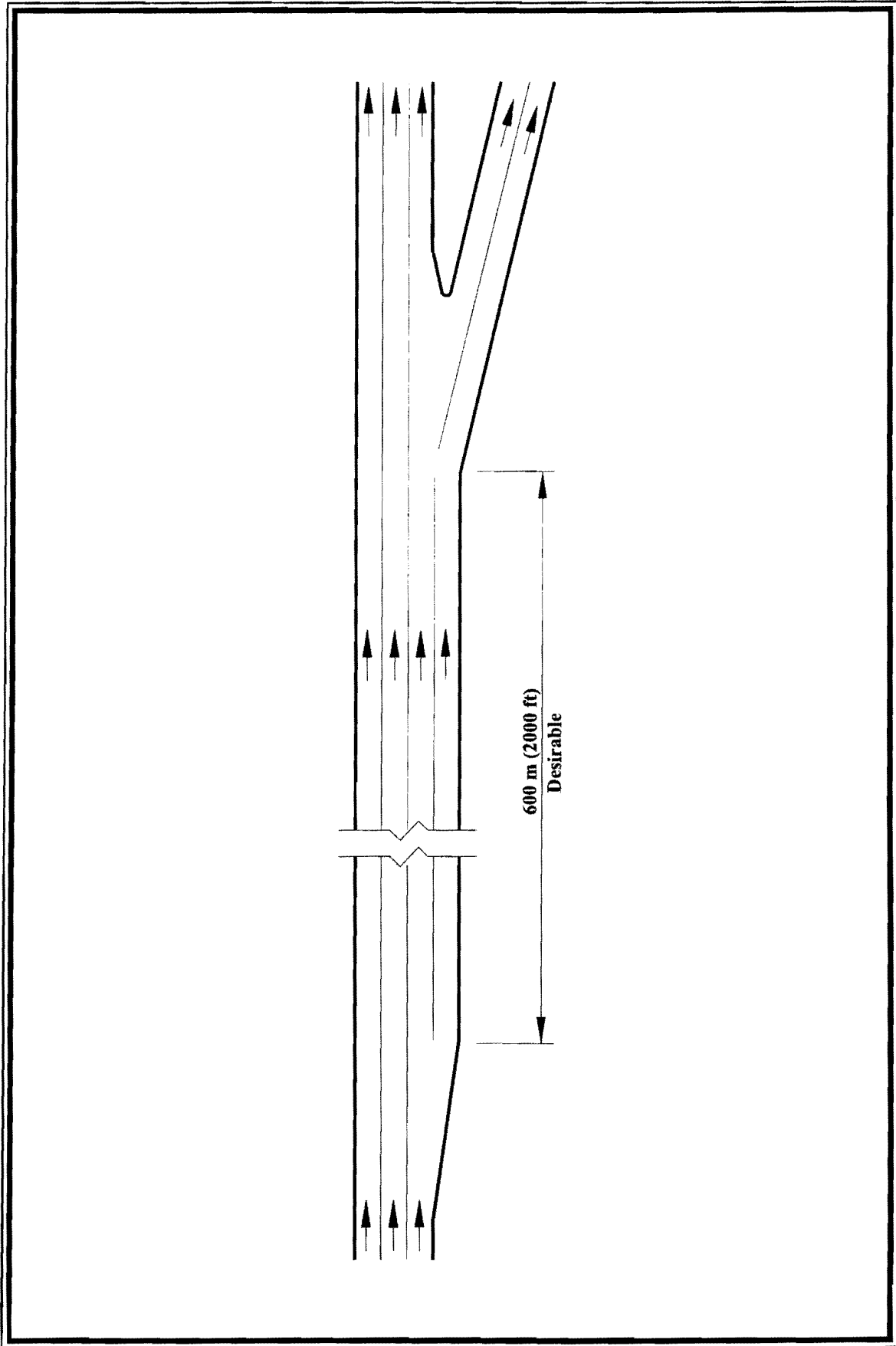


Figure 3-17. Two-Lane Exit Ramp

6.6 Truck Operation

Truck operations may be an important consideration for interchanges. The larger sizes and decreased performance capabilities of trucks should be considered when evaluating operations of interchanges, particularly on connecting ramps. The selection of horizontal and vertical alignment at interchanges must take into account the operational constraints of trucks and heavy vehicles. Heavy vehicles have different operational characteristics that can inhibit the merging and diverging activities of smaller vehicles. Larger gaps and longer distances are required. Table 3-1 describes specific areas related to truck operations at interchanges, which should be evaluated in the preliminary design stage. Whenever possible, the features described in Table 3-1 should be incorporated into interchanges which accommodate large volumes of truck traffic.

Table 3-1. Truck Operational Considerations at Interchanges

- ◆ **Transition to superelevation** - The proper transition to superelevation should be used to increase comfort and/or operational efficiency.
- ◆ **Compound curves** - Whenever possible, ramp curves of different radii should be separated by a tangent section to reduce demands on drivers and reduce the dependency on the side friction factor.
- ◆ **Deceleration lanes preceding an exit** - The deceleration lanes for exit ramps should be of sufficient length to allow trucks to slow down to the necessary speed to negotiate the ramp radius.
- ◆ **Sight distance** - Whenever possible, additional sight distance should be provided to allow truck drivers to maneuver the truck into the proper position for entering the ramp. The sight distance restrictions of overhead objects should also be considered for trucks.
- ◆ **Downgrade preceding a ramp exit** - Trucks may speed up on downgrades, requiring additional deceleration lane length.

6.7 Collector-Distributor Roads

A collector-distributor (C-D) road is an intermediate facility between the freeway and surface street or frontage road. It provides a buffer between the freeway mainlanes and the surface street or frontage road for accommodating weaving maneuvers. Figure 3-14a illustrates the use of a C-D road with a full cloverleaf interchange. The C-D road removes weaving maneuvers from the freeway, thereby improving traffic flow on the freeway. C-D roads can improve the operational characteristics of a corridor if the characteristics conducive to this type of facility are present. These characteristics include:

- ◆ sufficient right-of-way,
- ◆ significant separation between major cross streets,
- ◆ significant through and weaving movements on existing freeway mainlanes, and
- ◆ adequate intersection geometries for projected demand.

continued

6.7 Collector-Distributor Roads (continued)

The design of a collector-distributor freeway system should include the following elements:

- ◆ Ramp design should encompass one-lane entrances and two-lane exits.
- ◆ Provision should be made for a desirable distance of 900 meters (3,000 feet) between mainlane connector ramps and freeway-to-freeway interchanges.
- ◆ Mainlane to collector-distributor ramps should be designed to full freeway standards.
- ◆ Weaving areas on the collector-distributor roadway should be at least 300 meters (1,000 feet) long.

7.0 Signing

Good signing practices are essential to good operations. Specific guidelines for the use and design of regulatory, warning, and guide signs are set forth in the *Texas Manual on Uniform Traffic Control Devices (TMUTCD)* and *Standard Highway Sign Designs for Texas*. These publications also provide more general guidelines for the use of guide signs on conventional roads and freeways. Designing effective guide signing is a critical element in providing acceptable operations.

Enough information should be provided to guide motorists to their destinations without overloading them with so much information that they become confused. Irrelevant and ineffective signs are obstacles on the roadside and are costly to provide and maintain. Motorists should be given only the relevant information at the correct places and in a manner that will command attention. Table 3-2 provides guidelines on the desirable number of sign installations on a single sign bridge.

Signing and geometrics should be designed in concert with one another during the preliminary design stage. Highway guide signing should be consistent in appearance, unambiguous, and easily understood. Location and text of proposed guide signs should be determined. A simple axiom applies to the geometric design process: "If you can't sign it, don't build it." Chapter 4, Section 2, Segment 3.0 provides more detailed information on the design of guide signs.

Table 3-2. Desirable Sign Configurations

Number of Sign Panels on One Sign Bridge	Application
1	Frequently
2	Occasionally
3	Special Case
4	Avoid

continued

7.0 Signing (continued)

The major concerns of guide sign design should be addressed in the preliminary design stage. In the final design stage, features such as signage, design of sign supports, placement of supplementary and other minor signs, and other minor details are addressed. Seven basic principles have been found to be useful as a guide to be used in the design, installation, and maintenance of directional signing. These principles, which are also applicable to signing situations in other areas and on other types of highways, are listed in Table 3-3. Table 3-4 provides a checklist of questions which may be applied to a particular signing installation as a test to determine whether the signs comply with all the principles.

Table 3-3. Principles of Highway Signing

<ol style="list-style-type: none">1. Interpretation - All possible interpretations and misinterpretations should be considered in phrasing sign messages (words and symbols).2. Continuity - Each sign should be designed in context with those signs preceding and following it so that continuity is achieved through relatively long sections of highway.3. Advance Notice - Signing should prepare the driver in advance of each decision to be made.4. Relatability - Sign messages should be in the same terms as information available to the driver from other sources, such as touring maps and addresses given in tourists' information, advertising, and geometrics.5. Prominence - The size and position, as well as the number of times a sign or message is repeated, should be related to the competition from other demands on the driver's attention.6. Unusual Maneuvers - Signing should be specially designed at points where the driver has to make a movement which is unexpected or unnatural.7. Consistency - New signing should be consistent with existing signing in terminology and appearance. Existing signing beyond the project limits should be evaluated for consistency with geometric changes.

Source: Schoppert, D.N., K. Moskowitz, S.F. Hulbert, A. Burg, "Some Principles of Freeway Directional Signing Based on Motorists' Experiences," *HRB Bulletin* 244, 1960.

continued

7.0 Signing (continued)

Table 3-4. Compliance with Signing Principles

<ul style="list-style-type: none">◆ Is there enough information to prevent a motorist from being led astray by assumptions based on information that is not given?◆ If a motorist does exactly what the sign indicates, will the appropriate action be performed at the correct location?◆ Is the difference between alternatives clearly emphasized?◆ Is no more than one choice presented at one time?◆ Is the message too cryptic because of the use of symbols or words which are either ambiguous or meaningless to a certain portion of the motoring public?◆ Is the motorist confronted with too much information to comprehend at one location, either by having too much on one sign or too many signs?◆ Are the various items of information emphasized (by their size, position, color, etc.) in accordance with their importance to the motorist?◆ Is the signing sufficiently prominent to overcome the competition for the motorists' attention from other sources?◆ Does the information presented at this sign installation preserve the continuity established by previous signing?◆ Does the information presented relate to that available to motorists from other sources?◆ Is the information repeated often enough and far enough in advance to assure that motorists will see it and reach a decision well in advance of the position where action is required?◆ Has presentation of new information at the point of decision been avoided?◆ Is this sign installation the same as those used at other locations where similar conditions exist? The term "conditions" refers to alignment, permissible movements, decisions required, etc.◆ Do the conditions at this location demand custom-designed signing because unusual, unnatural, or unexpected maneuvers are required of motorists? This special signing need not result in bizarre treatment; it can be accomplished by the imaginative application of accepted practices.◆ Has signing upstream and downstream of the new signs been evaluated to insure consistency?◆ Do modifications to geometrics require changes to signing outside of the project limits?

continued

7.0 Signing (continued)

Signs are designed for legibility distances based on the speed of traffic. Freeway guide signs typically have 406-millimeter (16-inch) letters (minimum) which are designed to be read from a distance of 244 meters (800 feet). This distance is based on a legibility of 0.6 meters per millimeter (50 feet per inch) of letter height for series E letters. Typical reading times may be 3 seconds which translates into 74 meters (243 feet) of reading distance at 88 kmph (55 mph). If the sign is to remain within a 10° angle of the roadway centerline while being read, as shown in Figure 1-3, then the sign should be legible from a distance of 152 meters (498 feet). Therefore, a major guide sign should have at least 152 meters (500 feet) of unobstructed viewing. Figure 3-18 shows the sight triangle for a ground-mounted sign. No other signs should be installed in the viewing area of the sign. If other ground-mounted signs cannot be relocated, the guide sign should be mounted overhead for improved visibility.

Horizontal curves can cause viewing problems for signs. Arrows on overhead signs may point to the correct lane at the point of the sign, but, from a distance, the sign may appear to be pointing to a different lane. Overhead signs should not be installed in horizontal curves, if possible. If signs must be installed in horizontal curves, it may be appropriate to slightly offset the sign, moving the arrow from the center of the lane, to improve viewing from a distance. Horizontal curves to the right may be a problem for ground-mounted signs because of the increased viewing angle. It may be necessary to mount signs overhead to improve the visibility of the sign.

Lane assignment and advanced information signs are two closely related aspects of guide sign installations which should be carefully evaluated in order to reduce driver confusion. Drivers should be provided with enough advance information to position the vehicle in the proper lane so that last minute maneuvers can be avoided. Advance lane assignment information is especially important at locations with optional lanes, two-lanes exits, or exit only lanes.

Figure 3-19 illustrates advance lane assignment guide signing for a typical situation involving an optional lane, a two-lane exit, and an exit only lane. Lane assignment information is especially important if the exit from I.H. 100 and the north and south split of S.H. 1 are closely spaced. By indicating the proper lanes for S.H. 1 north and S.H. 1 south, the full capacity of each lane can be realized. Additionally, identifying the optional lane as such informs through drivers that they can use the lane, allowing the capacity capabilities to be used more effectively. The exit only information helps drivers from being trapped in the exiting lane.

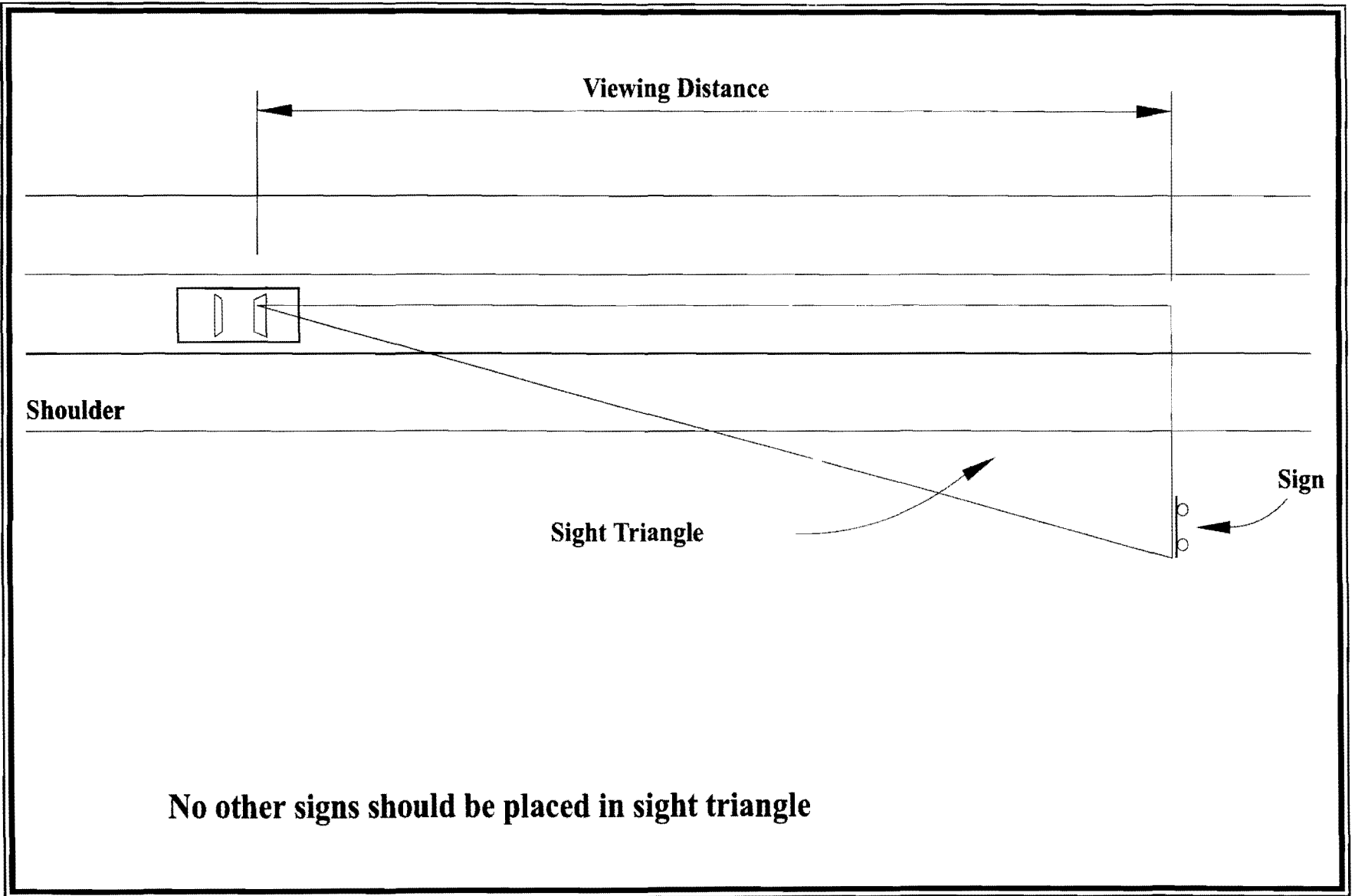


Figure 3-18. Sight Triangle for Ground Mounted Sign

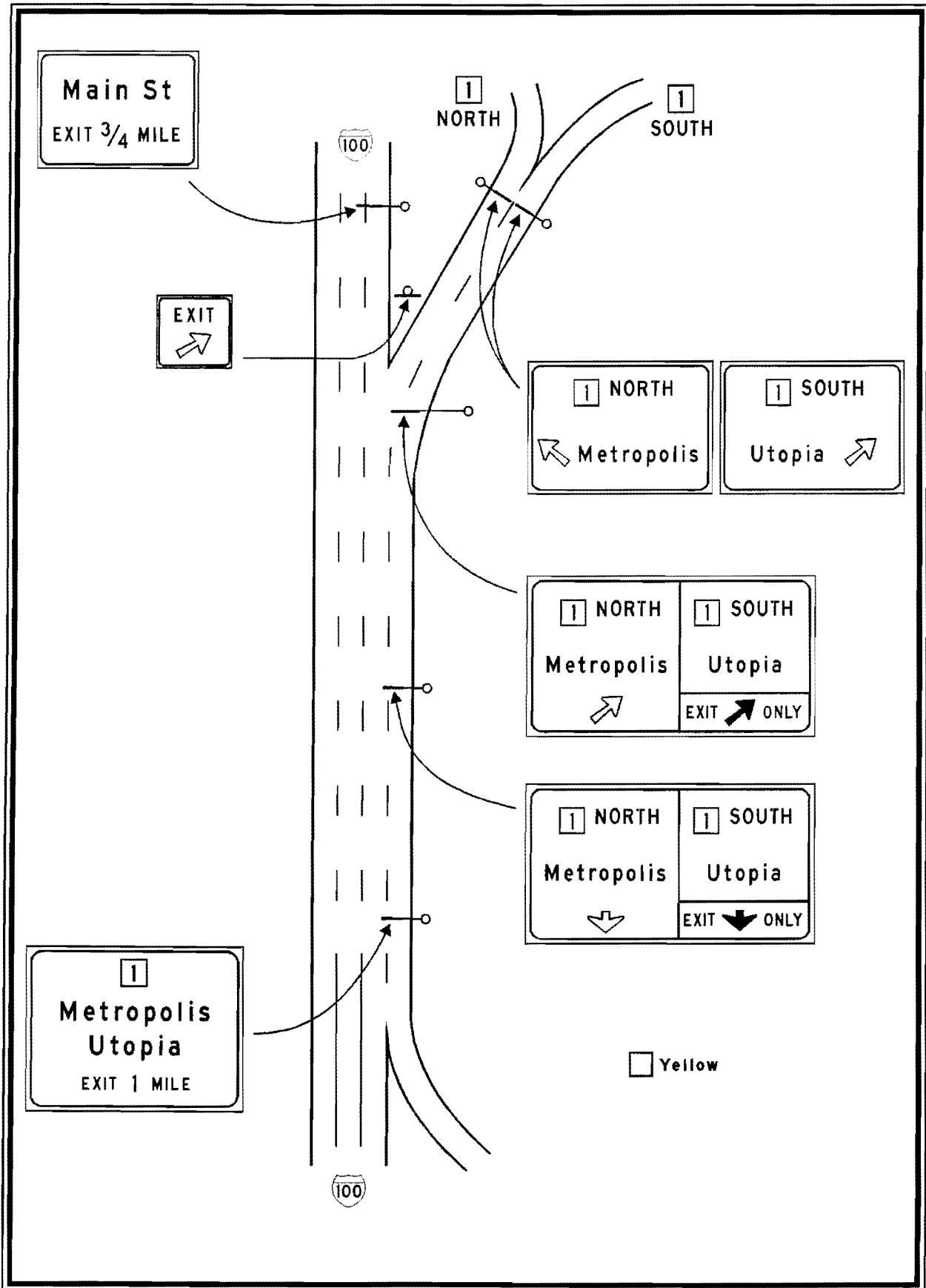


Figure 3-19. Advance Lane Assignment Guide Signing

8.0 Horizontal and Vertical Alignment

Horizontal and vertical alignments are permanent design elements which are important to the long-term safety, efficiency, and economic service of a highway. It may be difficult and costly to change alignment after the highway is constructed. Restrictive geometric alignment reduces the operational efficiency of a highway facility. The designer should provide generous geometrics whenever possible. The interaction between horizontal and vertical alignment and other design considerations, such as the location of signs, access, interchanges, and other elements should be carefully evaluated.

Vertical grade of ramps affects sight distance and vehicle acceleration/deceleration performance. Ramp grades near the terminal points should approximate the grade of the lanes with which they intersect.

Horizontal and vertical alignments should complement each other. However, coordination of alignment may not be possible on existing facilities and other measures such as signing or lighting may need to be considered. Coordination of horizontal and vertical alignment is obtained by engineering study and consideration of the general principles given in Table 3-5. These principles are illustrated in Figure 3-20.

Table 3-5. Coordination of Horizontal and Vertical Alignment

- ◆ **Curvature and grades should be in proper balance.** Tangent alignment or flat curvature at the expense of long steep grades or excessive curvature with flat grades should be avoided, whenever possible.
- ◆ **Vertical and horizontal curvature should be superimposed.** This generally results in a more pleasing design, but should be analyzed for the effect on traffic operations. The number of sight restrictions on the project is reduced.
- ◆ **Sharp horizontal curvature should not be introduced at or near the top of a pronounced crest vertical curve.** This allows the driver time to perceive the horizontal change in alignment, especially at night. Operational difficulties may be avoided if the horizontal curve leads the vertical curve (the horizontal curve is made longer than the vertical curve).
- ◆ **Sharp horizontal curvature should not be introduced at or near the low point of pronounced sag vertical curve.** This prevents the roadway from presenting a distorted appearance.

9.0 Pavement Considerations

Longitudinal pavement joints may be viewed as de facto lane lines when pavement markings are worn or pavement is wet at night. Whenever practical, longitudinal joints should be parallel to lane lines.

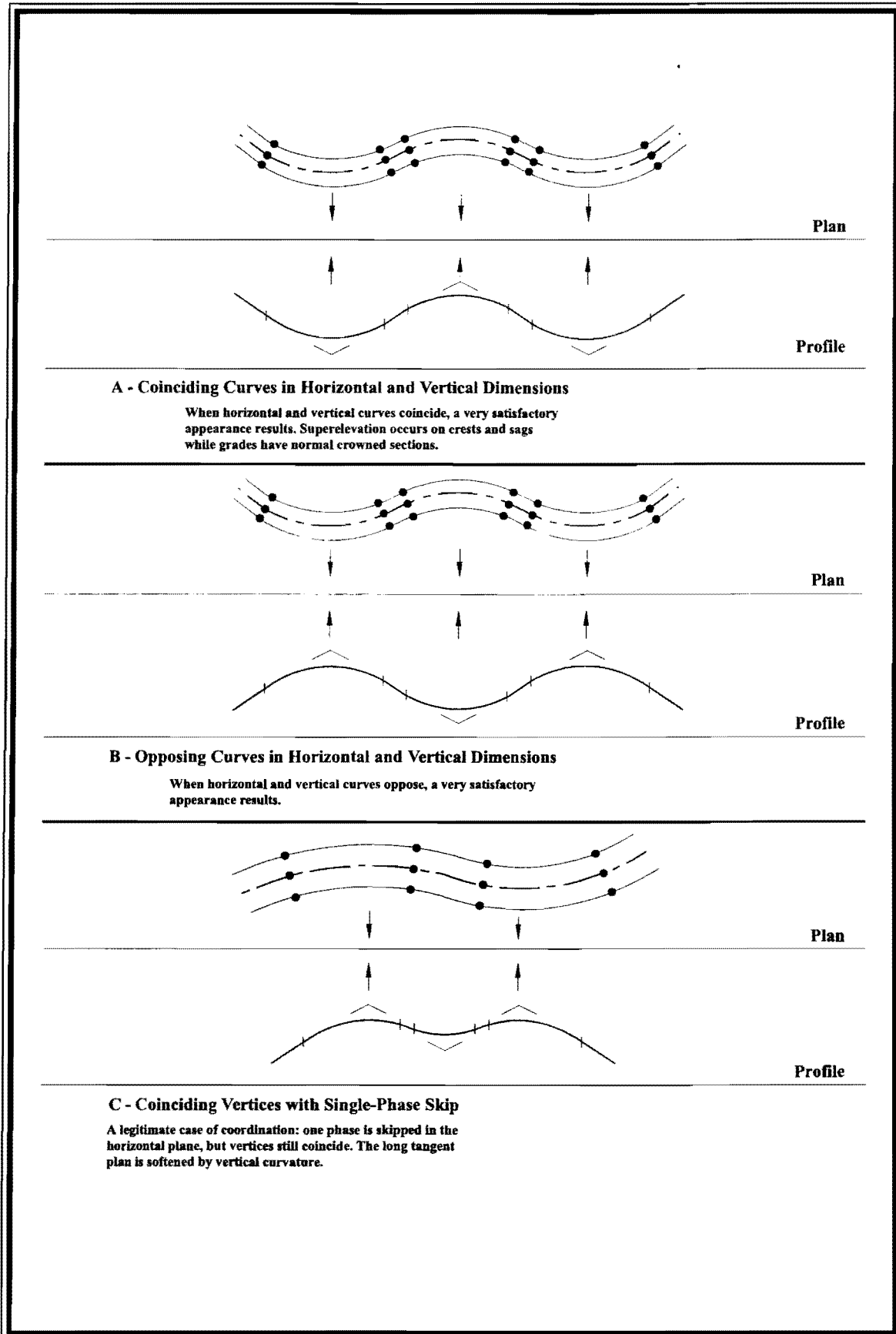


Figure 3-20. Coordination of Horizontal and Vertical Alignment

OPERATIONAL ANALYSIS

Operational analysis becomes possible early in the preliminary design stage. Traffic and geometric data are used to provide an indication of the level of service or quality of flow on the highway. Each section of highway should be evaluated for operational characteristics during the preliminary design stage. This evaluation should address all entrances, exits, and interchanges for their adaptability, capacity, and operational features from the driver's point of view.

1.0 Travel Path Analysis

The design should be tested for ease of operation by drawing or tracing separately the path for each principal origin and destination to permit studying those physical features that will be encountered by a driver. The designer can visualize exactly what the driver sees -- the road being traveled, the various points of ingress and egress, interactions with other vehicles, and the directional signs along the travel path -- and have a sense of the accompanying traffic.

Such an analysis indicates whether or not confusion may be likely because of exits and entrances too close together or interference that may occur because of weaving sections. It should show also whether or not the path is clearly defined, if it is feasible to sign the facility properly, and if roadside or overhead signs are required and where they may be placed. Major signing requirements spaced closer than 400 meters ($\frac{1}{4}$ mile) are indicative of potential operational problems.

2.0 Operational Efficiency

There are no definitive procedures for evaluating the operational efficiency of a facility. Engineering judgement should be used to determine if the driver can receive the appropriate messages and can respond in an acceptable manner. Table 3-6 addresses some of the major concerns related to providing operational efficiency.

3.0 Highway Capacity Manual Procedures

The *1994 Highway Capacity Manual* contains the most widely used capacity analysis procedures. It describes the theory and methods for manually determining the level of service, capacity, and service flow rates for basic freeway sections, weaving and ramp areas, two- and multi-lane highways, and signalized and unsignalized intersections. Microcomputer software is also available to automate these procedures. The minimum level of analysis would include separate analysis of basic freeway section capacity, ramp capacity, weaving sections, and signalized intersection capacity. In major urban areas, it may be appropriate to use other computer simulation models (Chapter 8) to analyze complex geometrics where it is likely that several parts of the system have major interactions.

Table 3-6. Operational Efficiency Concerns

<ul style="list-style-type: none">◆ Basic Lanes - The basic lanes should be continuous over a significant length and through interchanges.◆ Lane Balance - Merge and diverge areas should follow the lane balance principles.◆ Ramp Spacing - Ramps should be spaced so that the areas of influence do not overlap.◆ Freeway/Ramp Speed Relationship - Speeds of the merging freeway and ramp vehicles should be as nearly equal as possible.◆ Appropriate Interchange Type - Interchanges should accommodate necessary movements in an appropriate manner.◆ Single Exit Design - Single exits in advance of the cross street should be provided for all interchanges.◆ Decision Sight Distance - Adequate sight distance should be provided at all locations requiring complicated decision making and vehicle maneuvering.◆ Weaving within Interchange on Mainline - Weaving maneuvers should be eliminated from the vicinity of interchanges.◆ Signing - If you can not effectively sign it, you should not build it.

4.0 Highway Models

Analysis of complicated interchange designs may benefit from the construction of small scale interchange models to provide a three-dimensional tool for evaluation of geometric layout and for presentation of proposed improvements to the public. Three-dimensional computer graphics will eventually be an alternative to a physical model.

CHAPTER 4
DESIGN CONSIDERATIONS TO IMPROVE OPERATIONS

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OVERVIEW

With construction of the Interstate Highway System 99 percent complete, many freeways are reaching the end of their design life. In addition, many freeways are congested and are operating at levels below which they were intended. The redesign/reconstruction phase of freeway development offers the unique opportunity to address many current traffic operational problems in a cost-efficient manner. For instance, high-occupancy vehicle (HOV) lanes may be retrofitted onto the existing cross-section of freeways to help encourage a shift to more efficient travel modes. Modifications can be made to freeway geometric features to eliminate or reduce bottlenecks or to provide improved incident response capabilities. Finally, redesign/reconstruction can be coordinated with the design and eventual installation of traffic surveillance and control systems. These topics are discussed in this chapter.

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HIGH-OCCUPANCY VEHICLE LANES AND TRANSITWAY FACILITIES

High-occupancy vehicle (HOV) facilities can contribute significantly to the improvement of transportation efficiency in an urban freeway corridor or region. Factors such as design vehicles, geometric design features, HOV surveillance and control systems, enforcement, signing, and location and design of support facilities in the corridor all impact the ultimate efficiency of HOV utilization (and thus operations throughout the corridor or region). The *Revised Manual for Planning, Designing, and Operating Transitway Facilities in Texas* and the American Association of State Highway and Transportation Officials *Guide for the Design of High-Occupancy Vehicle Facilities* provide additional information about specific preliminary design considerations. Some of the basic characteristics of HOV facilities and their impact on operations are summarized below.

1.0 Advantages of the HOV Concept

The following advantages characterize high-occupancy vehicle projects.

- ◆ *Implementation Cost.* While actual implementation costs are site specific, bus/carpool HOV lanes often represent the least costly fixed transit facility. This is particularly true when the priority HOV lanes are developed in existing freeway right-of-way.
- ◆ *Implementation Time.* High-occupancy vehicle facilities have been planned, designed, and constructed in a 3- to 8-year time frame. The construction involves well-known highway technology.
- ◆ *Staged Opening.* High-occupancy vehicle lanes can be opened as each section is completed.
- ◆ *Limited Risk.* If the HOV facility is not sufficiently utilized, it can be converted to other useful highway-related functions such as additional mixed-flow lanes or emergency shoulders.
- ◆ *Cost Effectiveness.* Evaluation of HOV priority lanes on congested highways has shown that the benefit/cost ratios for such projects are frequently in excess of 6.
- ◆ *Multi-Agency Funding.* High-occupancy vehicle facilities are eligible for local, state, and federal funding from both highway and transit agencies.
- ◆ *Multiple User Groups.* In addition to transit vehicles, vanpools and carpools can often utilize the HOV lane, thereby increasing potential total person movement.
- ◆ *Operating Speed.* Transit service on priority lanes is often express and non-stop. Many HOV facilities are intended to operate at speeds greater than 80 kmph (50 mph).
- ◆ *Flexibility.* The high-occupancy vehicles can use the existing street system for the collection distribution function. Also, necessary support facilities, such as park-and-ride lots and bus transfer facilities, can be located remote from the HOV lane on relatively inexpensive land without requiring a transfer at the line-haul transitway.
- ◆ *Time Adjustable Operation.* On some priority facilities, the lane used by priority vehicles during peak periods can be used for other beneficial purposes (e.g., emergency shoulder, extra general use freeway lane) during non-peak-period operation.

2.0 Types of HOV Lanes

Four different types of high-occupancy vehicle (HOV) lanes are used on freeways.

- ◆ *Exclusive HOV Facility: Separate Right-of-Way* -- A roadway or lane(s) developed in a separate and distinct right-of-way and designated for the exclusive use of HOVs.
- ◆ *Exclusive HOV Facility: Freeway Right-of-Way* -- Roadways or lanes built within the freeway right-of-way which are physically separated from the other freeway lanes but reserved for exclusive use by HOVs, at least during portions of the day.
- ◆ *Concurrent Flow Lane* -- A freeway lane in the peak direction of flow (normally the inside lane) that is not physically separated from the other freeway lanes but is designated for use by HOVs at least for a portion of the day.
- ◆ *Contraflow Lane* -- A freeway lane in the off-peak direction of flow (normally adjacent to the median) that is designated for use by HOVs traveling in the direction of peak flow for at least a portion of the day. Normally, the contraflow lane is “separated” from the off-peak (or opposite) flow by insertable cones or pylons.

3.0 Ramps/Merge Areas

The decision of how to interface high-occupancy vehicles with general purpose vehicles on and off the freeway has a significant impact on operations on both HOV and regular traffic lanes. Several options are available. One option is to connect the HOV facility directly to the freeway with the use of elevated flyover ramps or at-grade slip ramps. Another option is to link the HOV facility directly to the frontage road or surface street system. Transition treatments must be provided in some manner at both ends of the roadway.

If feasible, the terminal connections to HOV facilities from the adjacent freeway mainline should be made with flyover ramps at both terminal end connections. This allows buses and other vehicles using the HOV facilities to exit and enter the freeway mainline on the right instead of the inner high-speed lanes. This eliminates the high speed lane merge, which is inherently more difficult to execute, especially for HOV traffic such as buses and vans. Depending on the interchange spacing, it could also eliminate the need for the HOVs to make several rapid lane changes in order to access the HOV lane or exit the freeway.

Where limited right-of-way and/or high costs prohibit the use of elevated flyover ramps, at-grade slip ramps can be used. At-grade slip ramps are also appropriate where the HOV facilities are reversible, and are particularly applicable to temporary or phased HOV lane implementation. If traffic patterns warrant, separated HOV facilities should tie to the existing street system within the central business district.

All terminal and intermediate access connections should have high design standards. Tapers on entrance and exit ramps should consider the different acceleration and deceleration characteristics of loaded buses, especially where ramp grades are significant. Very long, gradual tapers should be avoided on exit ramps as traffic may inadvertently follow the taper assuming it is the main roadway. Ramps that connect to adjacent facilities should be designed to the same standards as comparable facilities that connect freeways to cross roads.

4.0 Park-and-Ride Facilities

Park-and-Ride lots collect automobiles at outlying locations along transitway corridors. In order to maximize the number of patrons, park-and-ride facilities must be strategically located. The following is a checklist for a well-placed, successful park-and-ride facility.

- ◆ The park-and-ride facility should be located in advance of intense traffic congestion along the corridor which experiences approximately 20,000 vehicles per lane per day.
- ◆ Lots should be located at least six to eight kilometers (four to five miles) from the activity center and from another park-and-ride lot.
- ◆ The park-and-ride facility should be located downstream of but in the immediate area of sufficient traffic demand to the activity center being served.
- ◆ The park-and-ride lot must have both good accessibility and access.
- ◆ Park-and-ride patrons should not be charged for parking.
- ◆ Space should be reserved for future expansion.
- ◆ Park-and-ride lots located on the right-hand side of the inbound roadway may attract more patrons due to its convenience to the inbound traffic.

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BOTTLENECK REMOVAL

A freeway bottleneck can generally be defined as a segment of highway with lower capacity than the previous portion of highway. Queues develop upstream of bottlenecks and volumes downstream do not represent actual traffic demand. Bottlenecks can occur due to unanticipated changes in travel patterns or unforeseen urban land development. A frequent cause of bottlenecks is a high-volume entrance ramp. However, bottlenecks can also occur as a result of weaving sections, lane drops, exit ramp queues, ramp design, horizontal curvature, vertical alignment, or other physical or operational characteristics.

Bottleneck improvements are relatively low-cost and designed to alleviate congestion at a concentrated segment of highway. Bottleneck relief can be found by restriping lanes, modifying weaving areas, or by converting a shoulder to a driving lane in short sections. These options are discussed in Chapter 3, Section 3. Traffic operations analyses should be performed to determine whether the improvement will yield significant benefits in operations. Methods for analyzing bottleneck sections and improvement alternatives are discussed in Chapter 8, Sections 5 through 7.

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INCIDENT RESPONSE

The ability to facilitate emergency vehicle travel time and access to an incident location can dramatically affect congestion levels in a freeway corridor, particularly in peak travel periods. Also, the ability to quickly remove an incident from the freeway can significantly improve traffic conditions within the freeway corridor. Crash investigation sites and median barrier gates are two freeway design features that can aid in the quick removal of incidents from the freeway.

1.0 Crash Investigation Sites

Crash investigation sites must be easily accessible from the freeway, requiring a minimum number of turns and travel distance after leaving the freeway. The sites can be constructed in the following locations:

- ◆ on the freeway right-of-way in the separation between the freeway and frontage road or underneath a bridge structure,
- ◆ in the outer separation between the frontage road and the right-of-way line,
- ◆ on existing parking facilities on property abutting the freeway right-of-way, or
- ◆ in public curb parking spaces on local streets or frontage roads near the freeway.

If crash investigation sites are to be included in a freeway reconstruction project, it will be beneficial if an entire system of sites can be installed. Incomplete systems make it difficult for drivers to remember that crash investigation sites are available, to know whether or not a site is available in a particular area, and where such sites are located.

Additional guidelines are available in the FHWA report *Promotional Issues Related to Off-Site Crash Investigation*.

2.0 Median Barrier Gates

Another freeway design feature that facilitates incident response and management is the provision of access gates periodically in the concrete median barrier. These gates allow emergency vehicles to gain access to an incident site from the opposite direction of travel. In addition, they can allow freeway traffic trapped upstream of an incident to be cleared. Since they remain closed when traffic conditions are normal, there is no break in the barrier where drivers might try to make an illegal U-turn or strike an exposed barrier end.

In the past, some agencies have expressed concern over the crash worthiness of barrier gates. At least one manufacturer has developed a motorized gate that passes concrete barrier crash tests. These gates have successfully been installed at several locations in Houston. The gate can be operated from the site or remotely from a traffic management center. In the event of power loss, the gate can be cranked opened manually.

3.0 Incident Response Vehicle and Equipment Staging Areas

Another incident management strategy identified that has freeway design implications is the provision of special staging areas at selected points along the freeway where certain types of equipment and materials (such as sand to spread over truck spills, special traffic control devices for management of major incidents, etc.) can be stored and where vehicles and personnel can coordinate response activities. These areas can help facilitate incident response actions and lead to a shorter total incident duration.

Major freeway incidents are three to four times more likely to occur within freeway-to-freeway interchanges than between them, and so staging areas should be located at or near such interchanges. Fortunately, most freeway interchange designs have space available within the interchange right-of-way itself to establish a special staging area. If such areas are included in the redesign, access to and from the site must be considered, and design criteria for larger trucks (i.e., curb radii, median openings, etc.) must be used to allow access by specialized response equipment.

TRAFFIC SURVEILLANCE, COMMUNICATIONS, AND CONTROL SYSTEMS

As stated previously, freeway construction and reconstruction offers an excellent opportunity for transportation agencies to incorporate traffic management system components into freeway design decisions. In general, synergism between freeway design decisions, traffic surveillance, and control system components is maximized if the system design itself occurs simultaneously with the design for general freeway reconstruction. The sections that follow outline some of the more critical surveillance and control system considerations that can be enhanced through proper freeway design or redesign practices.

1.0 Surveillance and Control Data Communication Trunk Lines

Past experiences of several transportation agencies suggest that provisions for a communications trunk line should be included in urban freeway reconstruction design plans if a computerized traffic management system is to be implemented within the reconstructed section at any point within a 10-year time frame. Key decisions that need to be made as part of the freeway redesign process include where the trunk line will be placed within the reconstructed freeway cross-section, and which type of trunk line protection will be used.

1.1 Trunk Line Location

Locating the trunk line within the freeway median allows equal access to the line for traffic management components on both sides of the freeway. This approach is appropriate only if the various components themselves can connect directly to the trunk line in the median. For example, dynamic message signs and closed-circuit television cameras can be mounted on overhead sign bridges that are supported in the median, and these can be easily connected to the trunk line by running the cable up the structure and over to the sign or camera. A median trunk line is usually not appropriate if the components are only accessible from the outer shoulders of the freeway. The more common placement practice is to bury the trunk line within the separation between the freeway and the frontage road. In some instances, the trunk line can be located under the freeway shoulder.

If the trunk is installed in the freeway median, another alternative to burying the trunk line is to place it in a metal tray or rail mounted on top of the median concrete traffic barrier. This above-ground alternative is cheaper to construct than buried conduit and is easier to maintain. However, some breaks will likely occur in the line when the traffic barrier sustains major damage by impacts with heavy vehicles. Consequently, redundancy in the trunk line network is critical when it is mounted on top of a median barrier. Chapter 7, Section 4 discusses data communications in greater detail.

1.2 Buried Trunk Line Conduit

It is common practice in Texas to install a PVC conduit system as part of a regular roadway construction contract, and let a separate traffic management system contractor with more understanding and experience with the installation of these systems come in later and run the actual cabling. If this approach is followed, inspection of hardware details (i.e., proper grounding of junction boxes, adequate seals against moisture, proper top plate thicknesses, etc.) must be stressed during construction to avoid problems in this equipment that will not be detected otherwise until it is time to install the cable and other components of the system. This can be particularly important if the design calls for the conduit to be encased in concrete to protect it from accidental breakage due to utility work or other maintenance efforts.

The location of buried conduit should be adequately marked to reduce the potential of accidental breakage due to trenching or digging for utilities, roadway maintenance, etc. In one TxDOT district, warning signs are placed above ground over the conduit, and the conduit's location is also marked with a metalized mylar tape placed in the ground 0.3 meter (1 foot) above the conduit. The agency's name, contact telephone number, and a fiberoptic cable warning are imprinted on the tape.

Attempting to run a second or third cable through a conduit already having a cable in place can cause significant binding and other problems. To avoid this, it is beneficial to use a larger conduit that is fitted with several smaller innerducts. Each cable can then easily be pulled through a separate innerduct.

2.0 Closed-Circuit Television (CCTV)

Implementation of closed-circuit television (CCTV), whether as a traffic monitoring and incident verification tool or for video imaging purposes, interacts significantly with freeway design decisions. Commonly, it is desirable to have CCTV line-of-sight capabilities for at least 0.8 kilometers (0.5 miles) in both directions of travel. Furthermore, it is advantageous to be able to view conditions along the adjacent frontage roads (where they exist) because traffic conditions along them can influence ramp operations and thus freeway flow characteristics.

Fitting CCTV cameras into an existing freeway environment is more difficult than fitting them onto a new freeway facility. Assorted geometric features, traffic control devices, and adjacent roadside development can cause visual obstructions. Roadside development can be particularly troublesome because it can occur years after the selection and installation of camera locations. Trees and shrubbery can cause problems as they grow. In addition, other freeway design practices unrelated to CCTV can cause geometric obstructions. For these reasons, it is sometimes difficult to find CCTV mounting locations that offer good visibility over the camera's entire operating range. Fortunately, some of these problems can be reduced if CCTV placement is considered in conjunction with freeway design activities.

continued

2.0 Closed-Circuit Television (CCTV) (continued)

Depressed freeway sections tend to provide the best viewing conditions for CCTV. Because the height differential is greater between the cameras and the various freeway obstructions (guide sign structures, cross-street overpasses, etc.). Another advantage is that the frontage road intersections of a diamond interchange are elevated, making it easier to locate a single camera where both intersections of an interchange can be monitored. Finally, depressed freeways do not rise and fall in order to pass over cross-street diamond interchanges and are less likely to generate a “roller-coaster” freeway alignment perspective that tends to hide sections of the freeway travel lanes from CCTV view.

2.1 Camera Mounting Design Considerations

CCTV cameras should be mounted as high as practical to provide the greatest viewing distance and to minimize the number of obstructions caused by overpasses, sign structures, etc. For this reason, it is advantageous to mount cameras on fill sections within the freeway right-of-way (such as at frontage road intersections where the cross-street passes over the freeway) in order to increase the effective height of the camera above the freeway. However, adequate support must be designed into the fill material to provide a stable camera mount.

On elevated freeway sections, cameras should not be mounted on overhead sign structures that are attached to the freeway deck; rather, the structure itself should have supports that reach all the way to the ground. In all cases, camera mounts must be extremely solid so as to minimize vibration and provide a stable picture to system operators.

2.2 Design Consideration Affecting Camera Location Decisions

Several design features affect the viewing capabilities of CCTV. The coordination of CCTV camera locations and freeway design decisions cannot be described as a simple step-by-step process. However, the following design elements affect camera placement options for surveillance and control systems.

- ◆ *Fixed Objects* -- Cross-street bridges, pedestrian overpasses, HOV and braided ramp designs, and freeway-to-freeway interchanges all create obstacles to CCTV visibility. The more frequent such objects are located along the freeway, the closer CCTV cameras will have to be placed in order to achieve full viewing coverage.
- ◆ *Horizontal Curves* -- Horizontal curves can create blind spots when billboards or large buildings are constructed close to the freeway right-of-way line. These objects can be constructed even after the cameras have been installed. The greater the length of curve and the degree of curvature, the greater the potential for roadside obstructions.

continued

2.2 Design Consideration Affecting Camera Location Decisions (continued)

- ◆ *Vertical Curves* -- Vertical curves can also create blind spots for cameras. This is especially for freeways of older design that utilize shorter vertical curve lengths over the cross-street arterials, creating a roller-coaster type of alignment. Newer freeway designs that use longer curve lengths reduce the effect of vertical curvature upon CCTV visibility.
- ◆ *Overhead Guide Signs* -- The effect of freeway guide signs upon CCTV visibility is minimized if the height differential between cameras and signs is as great as possible. Also, increasing the lateral offset between cameras and signs reduces their obstruction potential. This means that cameras mounted between the freeway and the frontage road will be less affected by guide signs mounted from, and displayed over, the freeway median. Likewise, signs and sign structures located on the right side of the freeway will have less of an effect upon CCTV visibility if the camera is mounted on or near the median of the freeway.

3.0 Maintenance Access to Surveillance and Control System Components

Maintenance access is another design concern affecting surveillance and control system components. It may be necessary to specify a special concrete or gravel pad adjacent to the mounting location of a CCTV camera or dynamic message sign in order to provide a stable base for the bucket truck outriggers that will be needed. If the camera or sign is intended to be accessed by the maintenance vehicle while on the shoulder, enough lateral clearance should be provided so that the outriggers can be put down without impinging upon the freeway travel lanes and necessitating a lane closure.

CHAPTER 5
OPERATIONAL CONSIDERATIONS FOR SCHEDULED ACTIVITIES

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OVERVIEW

Construction activities, maintenance activities, and special events have significant impacts on highway traffic operations which can be minimized through careful planning and appropriate traffic management. Because many of these activities are generally scheduled in advance, their impacts on highway operations can be anticipated and appropriate operational measures can be taken. In most situations, there is ample opportunity to select a strategy that will minimize the operational impacts while fulfilling the needs of the activity. The selection of a particular traffic management strategy depends upon the anticipated impacts. This chapter discusses the operational considerations, management strategies, and analysis procedures related to scheduled activities.

It should be noted that operations are only one of the considerations that impacts the selection of a traffic management strategy for scheduled activities. Other considerations include access, safety, cost, and public acceptance. When selecting the most appropriate management strategy, the individual should strive to obtain a balance between the various considerations.

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TYPES OF ACTIVITIES

Scheduled activities are typically classified by the type of activity that is being performed. Construction/maintenance activities (or work zone activities) and special events have different characteristics, but both types of activities can impact traffic. The location of the activity and the time required to perform the activity will also determine the degree of the operational impacts.

1.0 Work Zones

The type of work being performed dictates the extent to which the highway will be occupied and closed to normal traffic. Work zone activities are most commonly categorized in terms of the type, duration, and location of the project.

1.1 Type

Work zones may be classified as either construction activities or maintenance activities. Construction activities involve upgrading an existing facility (lane additions, bridge replacement, etc.), whereas maintenance activities are performed periodically either to prevent a failure in the system or to correct physical defects in the roadway, roadside, or supporting structures (maintaining traffic control devices, safety structures, pavement, and other roadway-related features). Typical construction and maintenance activities are listed in Table 5-1.

Most construction activities are longer in duration and may require more extensive traffic control and traffic management than maintenance activities. Construction activities usually require a minimum of several weeks or months to complete, although some last longer than a year. These activities typically require semi-permanent traffic control devices and facilities, such as concrete traffic barriers and temporary roadways for detours. Construction activities typically impact operations through reductions in the number of lanes, environmental factors such as dust or water, reduced lane widths, elimination of shoulders, reduced clearances, heavy truck traffic, temporary detours, visual distractions, and others.

Table 5-1. Typical Work Zone Activities

Construction	Maintenance
◆ Interchange construction	◆ Pothole patching
◆ Curb and gutter construction	◆ Litter pickup
◆ Traffic lane/High-Occupancy Vehicle lane additions	◆ Lane striping
◆ Bridge replacement	◆ RPM replacement
◆ Drainage system installations	◆ Guardrail/barrier repair
	◆ Luminaire relamping
	◆ Hot mix asphalt application

continued

1.1 Type (continued)

Although maintenance activities are generally completed more rapidly, they can have significant operational impacts. Most maintenance activities are performed during one day as either a daytime or nighttime operation, and may require the closure of one or more traffic lanes. Some maintenance activities, however, involve extensive rehabilitation and take on the basic properties of a construction activity. The operational impacts of maintenance activities are typically due to lane closures, slow-moving maintenance vehicles, lane shifting, visual distractions, and other factors.

Regular maintenance activities are typically scheduled in advance and the operational impacts can be minimized with planning. However, not all maintenance needs can be planned, and emergency maintenance activities will occur. Emergency maintenance activities do not provide as much opportunity to minimize operational impacts, due to the need for prompt action. In emergencies, the operational impacts of maintenance activities can be classified as nonrecurring congestion. The concepts in Chapter 9 can be used in addressing emergency maintenance.

1.2 Duration

The *Texas Manual on Uniform Traffic Control Devices (TMUTCD)* classifies work zones based upon the duration and location of the work. Work duration is a major factor in determining the number and types of devices used. The five categories of work duration and their time at a location are as follows:

- ◆ Long-term stationary -- Work that occupies a location more than 3 days.
- ◆ Intermediate-term stationary -- Work that occupies a location from overnight to 3 days.
- ◆ Short-term stationary -- Daytime work that occupies a location from 1 to 12 hours.
- ◆ Short duration -- Work that occupies a location up to 1 hour;
- ◆ Mobile -- Work that moves intermittently or continuously.

1.3 Location

The choice of traffic control needed for a temporary traffic control zone depends upon where the work is located. As a general rule, the closer the work is to traffic, the more control devices are needed.

Work can take place in the following locations:

- ◆ Outside of the shoulder edge -- Devices may not be needed if the work is confined to an area 4.5 meters (15 feet) or more from the edge of the shoulder. Consideration should be given to roadway characteristics, roadway geometrics, and vehicle speed. A general warning sign like ROAD MACHINERY AHEAD should be used if workers and equipment must occasionally move closer to the roadway.
- ◆ On or near the shoulder edge -- The shoulder should be signed as if work were on the road itself, since it is part of the drivers' "recovery area." Advance warning signs are needed. Channelizing devices are used to close the shoulder, direct traffic, and keep the work space visible to the motorist. Portable barriers may be needed to prevent encroachment of errant vehicles into the work space and to protect workers.
- ◆ On the median of a divided highway -- Work in the median may require traffic control for both directions of traffic, through the use of advance warning signs and channelization devices. If the median is narrow, with a significant chance for vehicle intrusion into long-term work sites and/or crossover crashes, portable barriers should be used.
- ◆ On the traveled way -- Work on the traveled way demands optimum protection for workers and maximum advance warning for drivers. Advance warning must provide a general message that work is taking place, information about specific hazards, and actions the driver must take to drive through the temporary traffic control zone.

2.0 Special Events

Another scheduled activity that can have significant impacts on highway traffic operations is special events such as sporting events, parades, motorcades, major concerts, conventions, and grand openings. These activities require traffic control plans much like those required for work zones. Managing traffic during special events can result in reduced congestion and delay. Special events usually generate large volumes of traffic, and congestion generally occurs on highway segments at or near the generator. In many cases, the effects of special events can be predicted from historical data.

There are many types of special events and each has its own characteristics; therefore, a wide variety of traffic control measures (e.g., lane closures, traffic signal retiming, special signing to the event, etc.) may be required. Alternative traffic management strategies can be evaluated during the planning stages so that the strategy that minimizes the operational impacts may be implemented. Traffic Management Teams (TMT) provide a means of establishing communication and cooperation between various agencies and organizations which may be impacted by special events. Chapter 6 provides additional information about TMT.

DATA NEEDS

The data needed to adequately evaluate alternative traffic management strategies should be assembled during the early stages of the traffic control planning process. Each activity type influences traffic operations differently due to its duration and location relative to the travel lanes. Therefore, each activity may require a different level of data collection. The three basic categories of data include a description of the scheduled activity, the existing or anticipated traffic conditions, and a description of the roadway and related features. The data needs for most activities are summarized in Table 5-2.

Table 5-2. Potential Data Needs

Scheduled Activity Description	Existing Traffic Conditions	Roadway and Related Features
<ul style="list-style-type: none"> ◆ Type of work ◆ Amount of roadway encroachment required ◆ Limits of work ◆ Tentative schedule ◆ Estimated cost 	<ul style="list-style-type: none"> ◆ 24-hour volume counts ◆ Daily and seasonal volume variations ◆ Hourly volume counts ◆ Intersection and interchange turning movement counts ◆ Volume of trucks ◆ Travel time and speed data ◆ Crash history ◆ Signal timing data 	<ul style="list-style-type: none"> ◆ Right-of-Way limitations ◆ Cross-section ◆ Horizontal and vertical profiles ◆ Type and location of traffic control devices ◆ Adjacent land use ◆ Description of potential detour routes

1.0 Scheduled Activity Description

A complete description of the work to be performed is basic to the evaluation of alternative traffic management strategies. The description should include the type, location, limits, and cost of the activity. The space needed by the work activities and equipment, the safety buffer required for adequate site protection, and the physical space occupied by traffic control devices should be included in the description. The project limits can be described by the number of traffic lanes to be occupied, the length of the work zone, and the duration of the activity.

2.0 Existing Traffic Conditions

Existing traffic conditions are an important data component in the planning process. Traffic volumes, travel time and speeds, crash history, and signal timings on a given section of highway influence the selection of a traffic management strategy.

Traffic volumes are one of the most important data needs for work zone traffic management planning. The hourly, daily, and seasonal volume information can be very useful in determining the best time period to perform the activity. Anticipated demand volumes at a work zone can be estimated from recent traffic counts or from automatic traffic counter data. Permanent count data may not provide an accurate estimate of traffic volumes if the work zone is a considerable distance away.

A problem with estimating traffic volumes at work zones is the amount of diversion that naturally occurs at work zones. When encountering unusual congestion, many motorists familiar with the area will seek alternative routes to their destinations to avoid the congestion. The extent of this diversion is difficult to predict.

Travel time and speed data may be necessary to measure delays to motorists traveling through or around the activity, especially where a detour must be considered. These data may also be needed for speed control, determining sign placement, and/or changing existing signal timing.

Crash data can be used to indicate the need for specific traffic control measures to address crash concerns such as crash types, locations, and times. Historical crash data can also be used as a basis of comparison when evaluating crashes within work zones.

Traffic signal timing data is needed to assess how work zones will impact operations at signalized intersections and whether changes in signal timing will be needed.

3.0 Roadway and Related Features

The description of the roadway and the surrounding area is another data component needed to evaluate potential alternative traffic management strategies. In most cases, roadway geometrics, such as right-of-way limits, cross-sectional elements, and horizontal and vertical profiles, will dictate which strategies are feasible alternatives.

The data should include information about adjacent roadways where detour of traffic to alternative routes is possible. Special land uses (e.g., schools, hospitals, etc.) that may be sensitive to additional traffic should be identified when planning detour routes. In addition, potential conflicts between diverted traffic and pedestrian activity on the alternative route should be identified and planned for appropriately.

OPERATIONAL CONSIDERATIONS

All scheduled activities should be planned and conducted with due consideration for the safety of the motorists, pedestrians, and workers. The basic principles that govern the design of permanent roadways and roadsides should also govern the design of construction and maintenance sites. Frequent and abrupt changes in geometrics should be avoided. Adequate warning, delineation, and channelization should be provided to ensure that motorists are provided with guidance in advance of and through the work area.

There are several specific considerations for planning scheduled activities, including speed changes, driver expectancy, driver workload capacity, traffic control plan, signing requirements, and activity periods.

1.0 Speed Changes

Both excessive and low speeds are frequently cited as factors in many highway work zone crashes. Speed affects the distance required to physically stop a vehicle. Drivers do not expect to encounter drastic speed reductions without adequate warning (Chapter 1, Section 6, Segment 3.0) and tend not to reduce their speeds unless they perceive a clear and present need to do so. Reducing vehicle speeds below the normal operating speed of a facility is difficult to accomplish in most work zones, even when adequate warning is provided. Work zone speed control methods have been found to be only moderately successful. The *Texas Manual on Uniform Traffic Control Devices* recommends that work zones be designed to maintain the normal operating speed of a facility, whenever practical.

2.0 Driver Expectancy

Driver expectancy (Chapter 1, Section 6, Segment 1.0) is an important consideration when addressing the operational improvements of scheduled activities. It affects how drivers react to and handle information about the work zone, how decisions are made, and how these decisions are translated into control actions and driving strategies. Since motorists have come to expect a high level of traffic operations on highway and freeway facilities, scheduled activities often represent unexpected situations. Local motorists may be surprised the most by scheduled activities.

Drivers must be provided with advance information about the activity. This may be done with advance warning signs, dynamic message signs (CMS), and/or public relations efforts, depending on the location and duration of the activity. The point where drivers are informed of the activity is critical. Drivers should be given the opportunity to select alternate routes. Alternate routes suggestions may be appropriate if permission is obtained from agencies responsible for operations on these routes.

Within the vicinity of the scheduled activity, the highway environment should conform to the expectations a driver would have in that situation. Driver expectancy should be considered in the selection of geometrics, speeds, detours, signs, signals, and markings.

3.0 Driver Workload Capacity

The ability to identify and comprehend traffic control devices while maneuvering a vehicle through a scheduled activity should be considered when evaluating the type, number, and location of the traffic control devices to be used. Chapter 1, Section 6, Segment 2.0 addresses driver information needs and the related hierarchy. Traffic control devices in a work zone should be placed according to the information hierarchy so that the driver will not miss important information.

4.0 Traffic Control Plan

The traffic control plan (TCP) is a strategy for safely moving traffic through a work zone. TCPs typically provide specific information about placement and maintenance of traffic control devices, methods and devices for delineation and channelization, construction scheduling, application and removal of pavement markings, roadway lighting requirements, traffic regulations, and surveillance and inspection procedures. Some form of a TCP should be developed for all scheduled activities (construction, maintenance, and special events). Texas Department of Transportation policies require a TCP for all construction projects and states that it should be used on all maintenance activities.

The TCP should be developed during the initial planning stages of any scheduled activity and should be considered in all decisions related to the activity. Table 5-3 lists some of the major questions which must be considered in the development of a TCP.

Table 5-3. Traffic Control Plan Elements

- ◆ What type of activity is involved, and how does the activity impact traffic flow?
- ◆ Will capacity be restricted, and how can the impacts of a restriction be reduced?
- ◆ Will traffic be detoured, where will it go, and what organizations or agencies need to be informed?
- ◆ What traffic control responsibilities will be fulfilled by the activity sponsor or contractor?
- ◆ Who will be responsible for making traffic control decisions during the activity?
- ◆ How will the activity schedule impact traffic flow and will time restrictions be needed?
- ◆ How will weather and environmental conditions affect the activity and traffic flow?
- ◆ What type of traffic control devices and arrowboards will be required?
- ◆ Will barriers or crash cushions be needed?
- ◆ Can dynamic message signs be effectively utilized?
- ◆ Will lighting improve traffic flow?
- ◆ Are flaggers needed for traffic control and do the flaggers need to be trained?
- ◆ Can traffic flow be improved by providing additional traffic control devices, dynamic message signs, or barriers?
- ◆ Will advance publicity help mitigate the operational impacts of the activity?
- ◆ Have the appropriate local jurisdictions been notified?

5.0 Signing

The purpose of work zone signing is to provide drivers with the information needed to safely and efficiently navigate through the scheduled activity. Both message content and placement are extremely important in fulfilling a driver's informational needs and should be carefully considered. Inappropriate messages and/or incorrect placement of devices can mislead and confuse drivers.

The *Texas Manual on Uniform Traffic Control Devices (TMUTCD)* contains specific requirements for the use of traffic control devices, including those used with scheduled activities. Part VI of the *TMUTCD* is specifically oriented to traffic control devices for construction and maintenance areas. However, the *TMUTCD* does not and can not address all situations related to scheduled activities. In these situations, the engineer must utilize judgement in applying the requirements of the *TMUTCD* to scheduled activities.

The Traffic Control Plan must meet the *TMUTCD* requirements for signs, signals, markings, and channelizing devices. However, it may also be appropriate to pursue additional measures beyond those required in the *TMUTCD* in order to improve highway operations. Typically, these measures involve the use of additional signing. In particular, dynamic message signs, destination signs, and informational signs may help improve traffic operations by providing needed directional information and choices for alternate routes.

Most work zone signs are static in terms of the information they provide. However, the development of changeable or dynamic motorist information signing devices such as dynamic message signs and advance warning arrow panels (arrowboards) has greatly improved the amount and type of information that can be provided motorists in work zones. These devices are effective at providing warning, guidance, and navigational information that is readily understood by drivers. They are not intended to be used as replacements to any of the standard work zone traffic control devices, but as supplements.

The applicability of signing to the current situation should also be monitored. Signs should not be placed until required, and should be removed if not needed. This principle applies to both short-term and long-term situations.

6.0 Activity Periods

Traffic flow exhibits definite peaking characteristics. These peaks can occur during different months, days, hours, and within a single hour (Chapter 1, Section 7, Segment 2.0). Scheduled activities should be planned to reduce operational impacts during traffic peaks. Examples of typical traffic peaks are provided in Table 5-4.

Most scheduled activities take place during daylight hours. However, some activities may be scheduled for nighttime, in order to mitigate the traffic impacts. Many safety and operational factors must be considered when scheduling work at night, some of which are listed in Table 5-5.

Table 5-4. Examples of Traffic Peaks

<p>Monthly or seasonal peaks</p> <p><i>Christmas</i> - Higher traffic volumes before and after Christmas in urban retail areas due to shopping. Volumes generally show increases around Thanksgiving.</p> <p><i>Recreational and vacation traveling</i> - Higher traffic volumes in recreational and tourist areas during the summer months.</p> <p><i>Winter weather</i> - Severe weather typically reduces the traffic volume to some extent, depending on location and severity of weather.</p> <p><i>Harvest time</i> - Periods of major crop harvest may create higher volumes on some highways, in both rural and urban areas.</p>
<p>Daily peaks</p> <p><i>Friday</i> - Traffic volumes on this day are normally higher than the weekday average.</p> <p><i>Weekends</i> - Traffic volumes generally lower than average daily traffic. Localized increases in congestion may result from recreational and shopping traffic.</p> <p><i>Holidays</i> - Varied volume effects depending on area and holiday.</p>
<p>Hourly peaks</p> <p><i>Peak periods</i> - Traffic volumes are higher during morning and evening peaks. The morning peak typically exists from 6:00 a.m. to 9:00 a.m. and evening peaks from 3:30 p.m. to 6:30 p.m. The traffic volume and length of the peak is a function of the location. The evening peak usually has worse congestion.</p> <p><i>Lunch</i> - Volumes during the noon hour may near those of the peak periods in some areas. There may not be a distinct directional movement.</p>

Table 5-5. Factors Influencing the Scheduling of Work Activities at Night

<ul style="list-style-type: none">◆ The cost of increased traffic control and lighting requirements.◆ The impacts of noise on surrounding residential communities.◆ The impacts of reduced visibility on driver safety.◆ The added risks for construction workers exposed to a greater number of impaired drivers.◆ The impacts of non-standard work hours on the quality of work.◆ The availability of construction materials such as sand, gravel, concrete, or asphalt.◆ The increased costs of nighttime construction.
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MANAGEMENT STRATEGIES

Several management strategies can be taken to reduce the operational impacts of scheduled activities. Some may be appropriate only for specific types of activities or circumstances and the use of a particular strategy will depend on the characteristics of the work activity, prevailing traffic conditions, and the physical characteristics of the roadway. Some of the management strategies include lane constriction, lane/ramp closure, detour/alternative route, crossover, shoulder utilization, frontage road utilization, High-Occupancy Vehicle utilization, speed control, and public information.

1.0 Lane Constriction

Lane and shoulder widths may be reduced slightly in order to maintain a given number of lanes through a work area. This scheme is the least disruptive of all work zone strategies since the same number of lanes are retained and narrow lanes, while reducing speeds, have minimal effect on capacity. Lane widths as narrow as 3 meters (10 feet) have been used on urban freeway reconstruction projects in Texas. Figure 5-1 illustrates this type of work zone.

The lane constriction strategy is generally used in combination with other strategies. In the case where the work area is mostly outside the normal traffic lanes, narrowed traffic lanes may be the only strategy necessary to perform work activities. However, if the work area occupies a traffic lane, a method known as "traffic shifting," where traffic is shifted so that a portion of traffic utilizes the shoulder as a traffic lane, may be used in combination with reduced lane widths. Thus, the use of the lane constriction strategy may depend upon the availability and width of shoulders.

The new lanes must be well defined, through the use of lane markings for long-term lane constrictions or cones for short-term restrictions. If new lane markings are used, the previous markings must be obliterated.

2.0 Lane Closure

Lane and/or ramp closures may be necessary when a portion of the roadway is needed for the exclusive use of construction or maintenance activities. The lane closure strategy is implemented by closing off one or more normal traffic lanes. The most obvious impact of lane closures is the reduction in roadway capacity. An analysis may be necessary to determine whether congestion will result from the closure. The capacity of the remaining travel lanes will be less than normal due to the operational turbulence caused by the lane closures. Lane changing in the transition area will be higher and speeds may be lower. In most cases, an alternate strategy that would retain the same number of lanes would be operationally preferable to reducing the number of lanes.

Lane closures can take several different forms including single-lane, multilane, traffic splitting, shared right-of-way, temporary bypass, and intermittent. These forms of lane closures are illustrated in Figure 5-2.

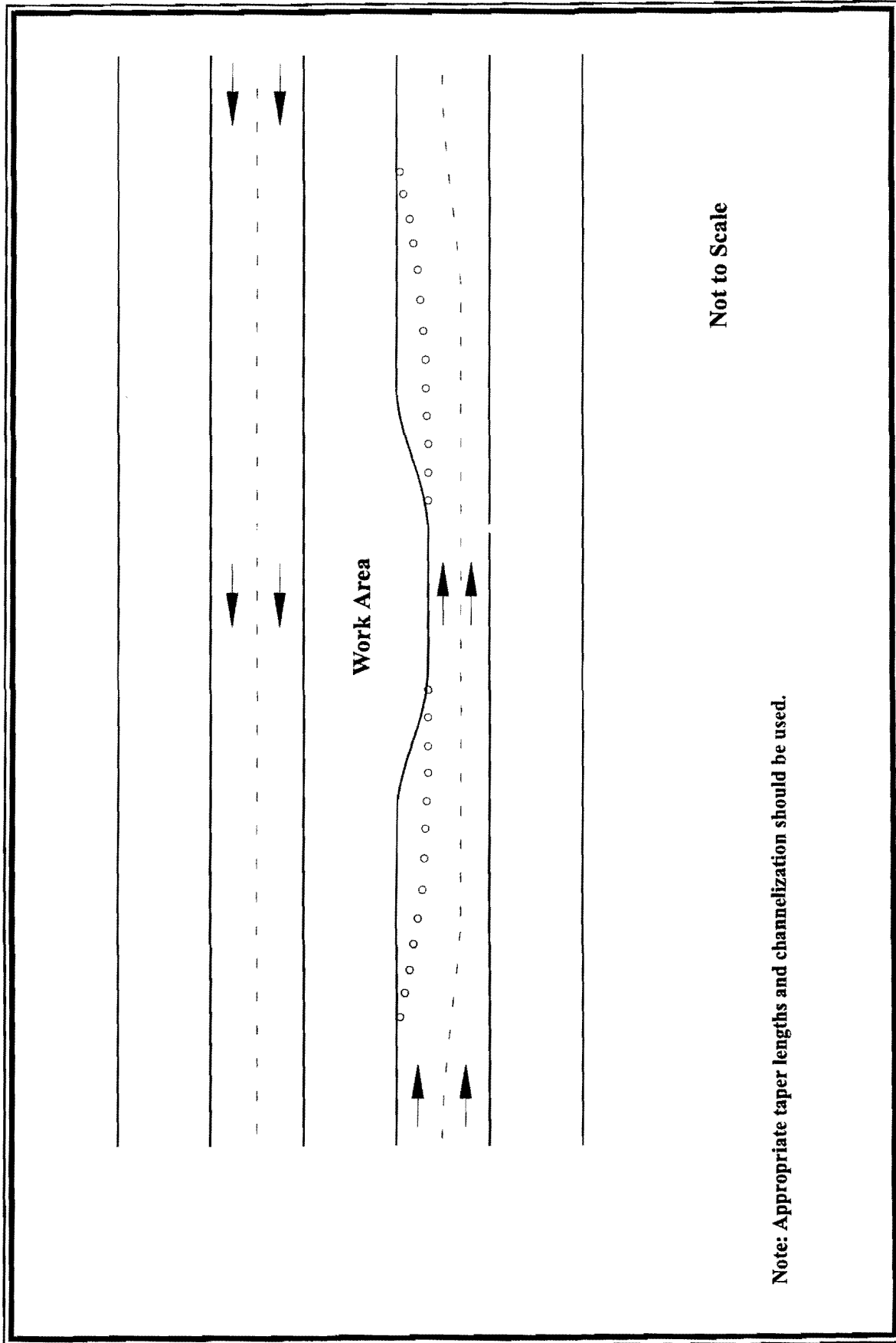


Figure 5-1. Lane Constriction Strategy

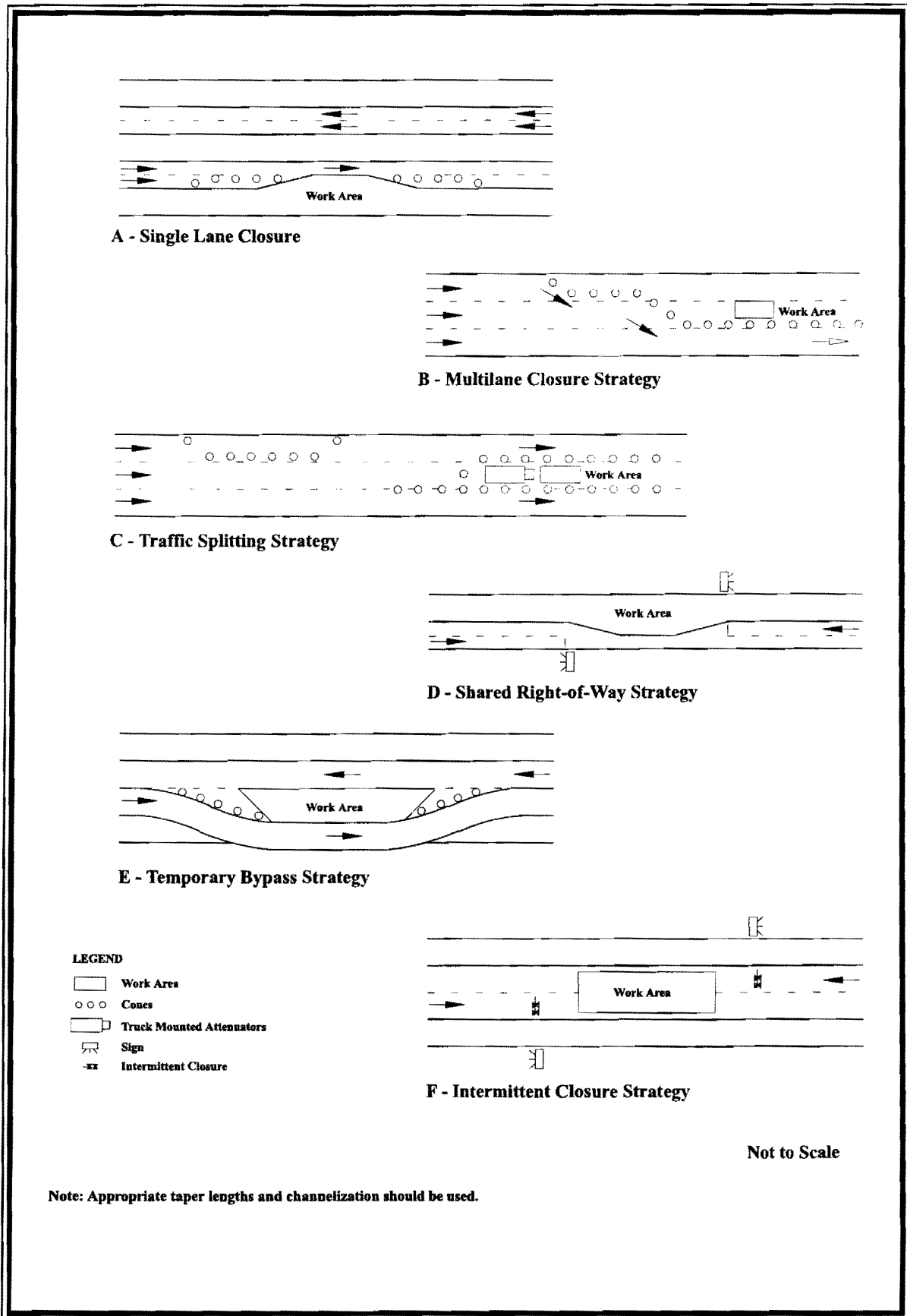


Figure 5-2. Lane Closure Strategies

2.1 Single-Lane Closure

This strategy involves closing a lane in such a manner that traffic is forced to merge from the closed lane into another lane. Adequate advance warning must be provided far enough upstream of the closure so that drivers in the closed lane have enough time and distance to merge safely into the adjacent open lane. A typical closure of an exterior lane on a multilane highway is illustrated in Figure 5-2a.

2.2 Multilane Closure

Closing more than one lane may be necessary when the work area encompasses more than one lane or when the work area is in a center lane. In these cases, a multiple lane closure may be utilized if the remaining open lanes can accommodate the traffic volumes. A multilane closure avoids an isolated work area when work is required in an interior lane. When implementing a double-lane closure, the lanes should be closed one at a time and separated by a transition distance. Advance signing and a merging taper should be provided for each individual lane closure. Figure 5-2b is an example of a typical multilane closure.

2.3 Traffic Splitting

Traffic splitting is sometimes used as an alternative to closing both the outside and middle lanes when work is required in the middle lane of a multilane highway. Only the middle lane is closed and traffic is permitted to move on both sides of the work area. This approach, if not carefully implemented, may result in operational and safety problems due to drivers in the middle lane merging into exterior lanes too close to the work area. In addition, such an operation may be confusing to drivers if it is not properly planned. Figure 5-2c illustrates a typical application of traffic splitting.

Traffic splitting is a useful strategy for managing traffic at middle lane work sites which are relatively short in length. It should not be used immediately upstream of high-volume exit ramps because drivers desiring to exit could be trapped in the inside lane, thereby, causing erratic maneuvers to occur. Traffic splitting is typically accomplished by closing an exterior lane 300 to 450 meters (1,000 to 1,500 feet) upstream of the work area, then routing the remaining open lanes around the work area with no further merging. This removes merging maneuvers from the immediate vicinity of the work area.

2.4 Shared Right-of-Way

Shared right-of-way is the use of one lane for both directions of traffic. The operational effects of the shared right-of-way strategy should be analyzed to determine whether another option which permits two-way operation, such as lane constriction (Chapter 5, Section 5, Segment 1.0) or a temporary bypass (Chapter 5, Section 5, Segment 2.5), would be more appropriate. A two-lane highway application of shared right-of-way is illustrated in Figure 5-2d.

Traffic control at shared right-of-way locations may take several different forms, including self-regulating (only at spot locations with good sight distance), flagger control, flag-carrying or official vehicle control, pilot-vehicle control, yield control, and traffic signal control. Several factors should be considered in selecting the best type of control, including the capacity of the one-lane section, sight distance, motorist delays, and costs.

In general, flagger and flag-carrying or pilot-vehicle control are more conducive to short-term activities. Because these methods require continuous manpower, they typically are not feasible for a long-term lane closure, for which yield or traffic signal control are more favorable. However, the potential for vehicle crashes within the work zone may be higher when devices are used, especially under low-volume conditions, when driver noncompliance with controls is higher.

2.5 Temporary Bypass

A temporary bypass is used when the roadway is totally closed in one or both directions and traffic is rerouted to a temporary roadway. This type of work zone is also referred to as an on-site detour. Generally, a bypass requires extensive preparation of the temporary roadway to withstand the traffic loads. Frequent maintenance may also be required to ensure a safe roadway surface is maintained. An example of a temporary bypass is shown in Figure 5-2e.

2.6 Intermittent Closure

Intermittent closures stop all traffic in one or both directions for a relatively short period of time to allow the work to be accomplished. After a certain time, depending on traffic volume, the roadway is again opened and all vehicles are allowed to travel through the work area. This strategy is normally applicable only for maintenance activities on low-volume roadways. Figure 5-2f illustrates a typical intermittent closure.

3.0 Ramp Closure

It may be necessary to close exit and/or entrance ramps in a freeway work zone to protect the work crew and facilitate the work activity. Whenever possible, motorists should be given advance notification of the closure through newspaper releases, radio and television reports, and special signing when ramps are closed. Advance notification will allow informed motorists to adjust their travel patterns, and thus lessen the impacts of the closure.

Entrance ramps in or upstream of a work zone may be closed to reduce traffic demands through the work area. This strategy is particularly applicable at work zones having insufficient capacity for handling estimated traffic volumes. However, when entrance ramps are closed, it is important to evaluate the operational impacts of the diverted ramp traffic on the alternative routes in the freeway corridor. This strategy may be used independently or in combination with other strategies.

4.0 Detour/Alternative Route

Detours and alternative routes are used to reroute traffic when the roadway is totally closed in one or both directions. Detours reroute some or all of the traffic approaching an activity area to bypass the area. Alternative routes provide an optional travel path that an individual driver may choose in order to avoid congestion near the activity area. These strategies are applicable in cases where the detour or alternative route has sufficient capacity to handle the additional traffic. They also have the advantage of removing traffic from the work site, thereby minimizing the conflicts between traffic and the work activity. An example of the detour strategy is shown in Figure 5-3a.

Some of the potential disadvantages of detours and alternative routes include longer driving time, higher operating costs, lower service level, congestion and/or deterioration of alternative route, higher crash rates on the alternative routes than at the work zone itself, and driver confusion.

Traffic detours require substantial traffic control, especially with high-speed freeway traffic. Sufficient driver information must be provided in advance of and throughout the detour. Adequate signing must be provided on the detour or alternative route to guide motorists around the work activity and to assure motorists that the detour will return them to their previous route. Signing must also be provided far enough in advance to allow the driver to make the decision in a timely manner. Additional information should be provided including the reason for using the alternative route, the expected delay or time savings, and a description of the route.

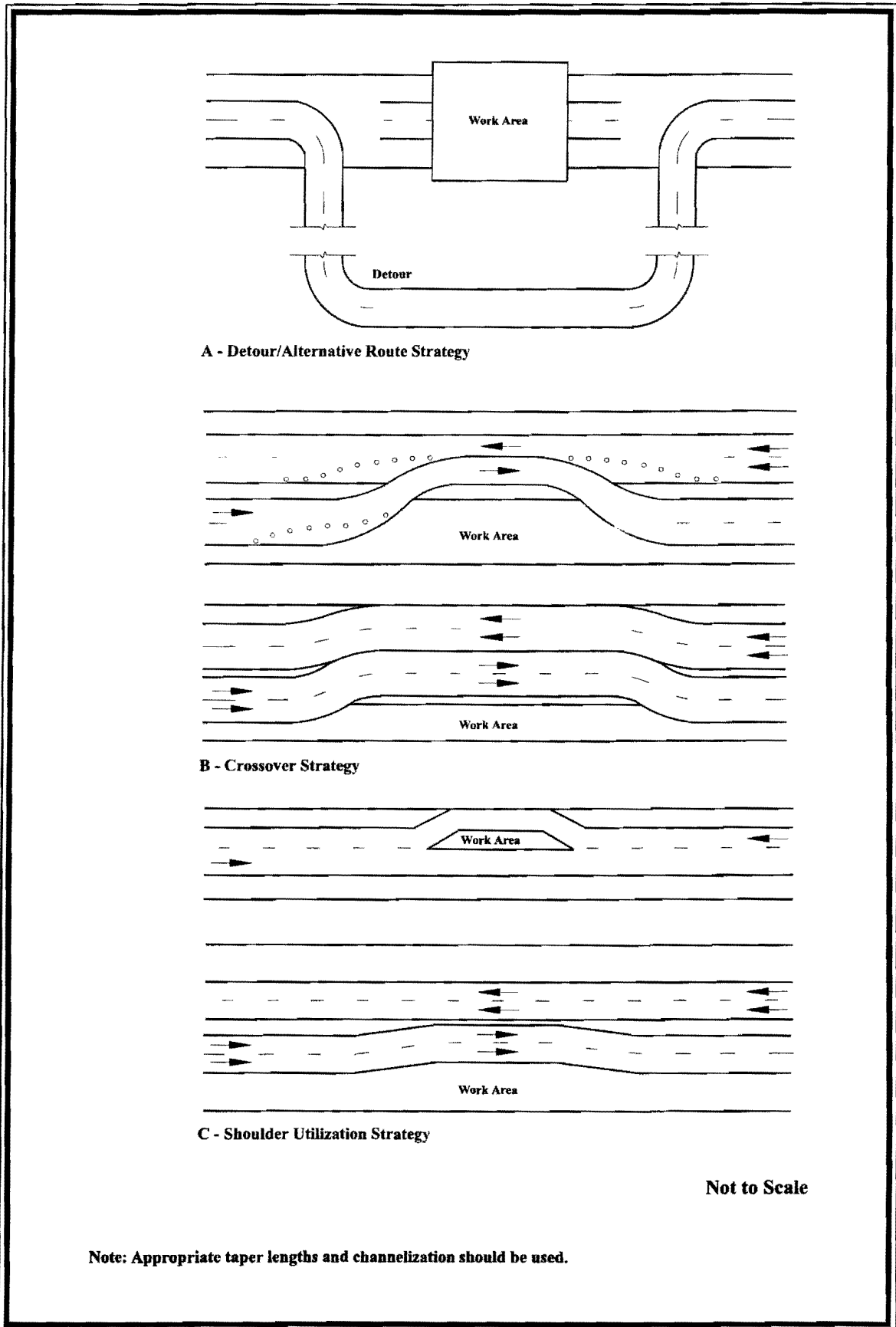


Figure 5-3. Other Management Strategies

5.0 Crossover

This strategy involves routing a portion or all of one direction of the traffic stream across the median to the opposite traffic lanes. The crossover may also incorporate the use of shoulder and/or lane constriction to maintain the same number of lanes. Figure 5-3b illustrates two cases of the use of crossovers.

When this strategy is used, the transition roadways should be constructed to equal or better geometric standards than the permanent roadway. Federal Highway Administration directives restrict the use of this strategy on federal-aid funded projects unless other methods of traffic control are determined to be unfeasible. If crossovers are used, the opposing traffic should be separated with positive barriers, drums, cones, or vertical panels throughout the length of the two-way operation. Drums, cones, or vertical panels should be used only for short durations. Delineation should be provided in the transition area to improve operations and safety.

6.0 Shoulder Utilization

The outside or median shoulder may be used in many situations as a temporary traffic lane in order to maintain the same number of lanes. Shoulder utilization requires that the shoulder pavement be able to adequately support the anticipated traffic loads. In addition, traffic must be safely transitioned to the temporary shoulder lane. Some applications of this strategy may be similar to the temporary bypass (Chapter 5, Section 5, Segment 2.5). This strategy may be used in combination with others or as a separate strategy. Two examples of this shoulder utilization are shown in Figure 5-3c.

7.0 Frontage Road Utilization

Frontage roads may be used as alternative routes in cases where the freeway is partially or totally closed and the freeway traffic is rerouted to the frontage road in order to bypass the work area. Diversion to the frontage road may also occur naturally as drivers seek the best travel route past a congested work area. In either case, an analysis should be performed to determine the availability of capacity on the frontage road and to evaluate the impacts of the diverted traffic on frontage road operations.

One advantage of using the frontage road as an alternative route is that construction time may be reduced by allowing work to proceed on a larger portion of the roadway. This strategy may also alleviate the interference between work zone activities and freeway traffic.

When frontage roads are used as alternative routes, improvements may be necessary to accommodate the diverted traffic volumes. Traffic control at frontage road intersections may need to be modified to obtain additional capacity. Specifically, modifications to traffic signal timing may be needed. Frontage road traffic should be notified in advance of a work activity using signing or other methods. Public information is particularly critical when traffic conditions on a frontage road will be drastically altered.

One problem that has been observed where traffic has been detoured to the frontage road is that the outside traffic lane of the frontage road is not effectively used. Many drivers fear that if they use the outside lane they may be trapped and unable to reach the open entrance ramp. Proper signing should be placed along the frontage road to inform drivers where they may reenter the freeway so that the capacity of the frontage road may be utilized more effectively.

8.0 High-Occupancy Vehicle Utilization

High-occupancy vehicle (HOV) facilities provide another strategy for managing traffic during construction and maintenance activities being performed on the general purpose lanes. One limitation to this strategy is that ingress/egress points to the HOV traffic lanes are usually located some distance apart making it less feasible to use that facility to bypass a short closure.

HOV treatments may be implemented during construction to reduce traffic demand on the freeway. Ridesharing should be promoted during major urban freeway reconstruction projects in an attempt to maximize traffic flow by reducing the number of vehicles traveling through the work area. Restricting some ramps to HOV usage is another treatment that can be used to reduce traffic demand on the freeway. However, a travel time savings must be realized by the users of the HOV-only ramps for these ramps to be utilized effectively. The selection of ramps to be restricted to HOVs should be based upon the location of the expected congestion and whether HOV-only ramp users can bypass this congestion. The principal costs associated with HOV-only ramp restrictions are for informing the public that the ramp is restricted and for enforcement.

9.0 Speed Control

It is extremely difficult to reduce speeds in work zones below the normal operating speed of a facility. Therefore, it is recommended that traffic control should be designed to accommodate normal operating speeds whenever possible. When it is impossible or impractical to accommodate normal operating speeds, methods for reducing speeds should be considered. Although some methods of controlling speeds have been moderately successful, they are costly and sometimes difficult to implement. Table 5-6 lists some of the techniques that have been tried to reduce speeds in work zones. Several elements that demand consideration in order to implement speed control in work zones include: determining the need for speed reduction, selecting a reasonable speed, selecting a location for treatment implementation, and selecting a treatment based on effectiveness.

Table 5-6. Speed Control Techniques

- | |
|--|
| <ul style="list-style-type: none">◆ Regulatory and Advisory Speed Limit Signing◆ Dynamic Message Signing◆ Transverse Striping◆ Lane Width Reductions◆ Flagging◆ Enforcement◆ Unmanned Radar Transmitters◆ Utilization of a Traffic Queue (congestion) |
|--|

9.1 Need for Speed Reduction

Speed control abuse and misuse can render a speed reduction attempt ineffective and damage the credibility of traffic control efforts in general. Using unreasonably low speed limits and leaving reduced speed limits in place after the activity is concluded are abusive practices that should be avoided.

Several important considerations should be recognized when determining whether to reduce speeds for a special activity. The need to reduce speeds should be identified. Speed reduction should be aimed at decreasing the number and/or severity of crashes or the potential for crashes at sites where speed-related potential hazards exist. Also, consideration should be given to other traffic control strategies (e.g., the use of a buffer area or portable barriers) that may provide a safer environment and alleviate the need for speed reduction. Speed-related potential hazards are those which exist because traffic is traveling too fast for conditions. Examples of speed-related potential hazards include insufficient sight distance, hidden or obscure features, reduced design speed, and unprotected work space.

continued

9.1 Need for Speed Reduction (continued)

Passive speed control utilizes static signing (regulatory and advisory) to post the reduced speed limit and is appropriate where reduced speeds are desired in the interest of safety or where lower travel speeds are expected. Active speed control refers to methods which restrict movement, display real-time dynamic information, or enforce compliance to a passive control. These methods include: flagging, law enforcement, dynamic message signs, lane constriction, weave sections, and others. Active control is needed in situations where drivers are unable or unwilling to drive the appropriate safe speed. If a particular work activity will be in progress for an extended period of time, active speed control is not recommended for the entire duration of the project. In this case, the active speed control would be too costly and most drivers would eventually become familiar with work zone conditions and drive at their own comfortable speed.

9.2 Selecting a Reasonable Speed

A safe and reasonable speed should be selected after it has been determined that reduced speeds are desirable and practical. The selected speed should not be unreasonably low. Several factors influence what is a safe and reasonable speed for a given situation. First, drivers will only slow to a certain level regardless of the presence of a speed control treatment. Second, it is very important that the speed is not significantly lower than drivers reasonably expect or will tolerate. Finally, an appropriate speed for the particular set of conditions should be selected. If an unreasonably low speed is established, drivers will quickly lose respect for the speed control treatment. The loss of credibility and respect will result in reduced effectiveness of the speed control treatment at the site and possibly at other sites. Table 5-7 presents the suggested speed reductions to be used in work zones on different types of roadways.

Table 5-7. Suggested Speed Reductions by Type of Roadway

Roadway Type	Speed Reduction, kmph (mph)
Rural Two-Lane Highway	16-24 (10-15)
Rural Freeway	8-24 (5-15)
Urban Freeway	8-16 (5-10)
Urban Arterial	16-32 (10-20)

9.3 Location of Speed Reduction

A speed control treatment should be introduced 150 to 300 meters (500 to 1,000 feet) upstream of the desired speed reduction location to insure that drivers have adequate time to react. Speed control should be initiated after the first advanced warning sign in a section which is relatively free of other signs. Additional speed control treatments may be needed downstream in long sections or when drivers do not slow down on their own.

10.0 Public Information

Public information is an important component of traffic management plans for scheduled activities. The adverse effects of the activity may be minimized by providing information to the traveling public prior to and throughout the life of the project. Public information efforts are necessary for increasing the public knowledge and acceptance of the project. These efforts can also encourage the use of alternative routes and modes to assist in reducing traffic demand through the area.

The type and amount of information depends upon the type of activity and the anticipated impacts of the activity. Advance notification is desirable for all activities; however, it is most critical for those that may result in considerable traffic disruptions. In addition, information should be provided to motorists for activities that require ramp closures and detours or activities which occur at unusual times.

Although the level of effort for different activities may vary, the basic steps in developing the public information program include 1) identify the various audiences affected by the activity, 2) specify the needs of each audience in terms of the type and amount of information required, 3) select and implement methods for disseminating the required information, and 4) monitor the effectiveness of the methods and adjust the information and/or method. The audiences that may be targeted in a public information program include motorists using the highway, residents living adjacent to the highway, and nearby businesses.

Some of the methods that may be used to disseminate information to the traveling public include radio and television news broadcasts, news releases and newspaper articles, press conferences, special signing and billboards, public service announcements, paid advertising, special publications, interviews, public meetings and presentations, toll-free hotlines, and highway advisory radio.

OPERATIONAL ANALYSIS

In planning traffic control for scheduled activities, it is desirable to identify all of the feasible traffic management strategies and assess the impacts of the most promising strategies. Both the identification and assessment of strategies require an evaluation of the roadway capacity (the maximum number of vehicles expected to be able to use the roadway in a given time period) during the scheduled activity. The relationship between capacity and traffic demand influences how a work zone impacts travel efficiency.

1.0 Evaluation Process

A basic planning process that leads to the selection of an appropriate traffic management strategy for a given activity begins with the identification of alternatives and constraints, followed by an evaluation of costs and impacts. The end result of this process is the selection of the best traffic control alternative for the proposed activity. The nine step process is illustrated in Figure 5-4 and includes a feedback loop whereby the original project design and/or construction procedure can be revised if it is determined that severe constraints are imposed on the traffic control strategies by the original project design. These constraints may be relieved by design changes which still meet the project objectives. The individual steps in the design process are described in Table 5-8 (this table makes reference to Tables 5-9, 5-10, and Figure 5-5 as well).

2.0 Traffic Control Zone Capacity

An assessment of capacity is a necessary part of the planning of traffic management strategies during scheduled activity. Capacities vary depending upon the nature of the activity being performed, the number and size of the equipment used, and the exact location of the equipment and crews with respect to moving lanes of traffic. One of the major considerations for traffic control planning is the formation and length of queues. The *1994 Highway Capacity Manual* and Chapter 8 contain additional information on capacity and queue length analysis.

Table 5-8. Planning Process for Scheduled Activity Traffic Management

Step	Task	Description
1	Assemble Data	See Chapter 5, Section 3 and Table 5-2.
2	Determine Extent of Roadway Occupancy	See Table 5-9 (page 5-30).
3	Identify Feasible Alternatives	See Figure 5-5 (page 5-32).
4	Analyze Volume/Capacity Relationships	See Chapter 5, Section 6, Segment 2.0.
-	Are There Capacity Deficiencies?	If Yes - Go to Step 5, If No - Go to Step 6.
5	Analyze Capacity Improvement Techniques	See Table 5-10.
6	Define Alternatives	Eliminate impractical or unacceptable alternatives from consideration and prepare TCPs sketches.
7	Quantify Impacts	Evaluate safety, traffic, environmental, and economic impacts and select initial strategy.
8	Modify Procedures	Review original plans for alternative construction or design methods.
9	Select Preferred Alternatives	Select preferred strategy on the basis of impacts and trade-off analysis.

Table 5-9. Factors Needed to Define Extent of Roadway Occupancy

- ◆ The total project length and the beginning/ending points of the project.
- ◆ The length of the occupied roadway at any one time and during a particular 24-hour period.
- ◆ The portion of the roadway that will be prohibited to normal traffic.
- ◆ The expected number of working days to complete the project.
- ◆ The number of hours each day during which the roadway will be occupied.

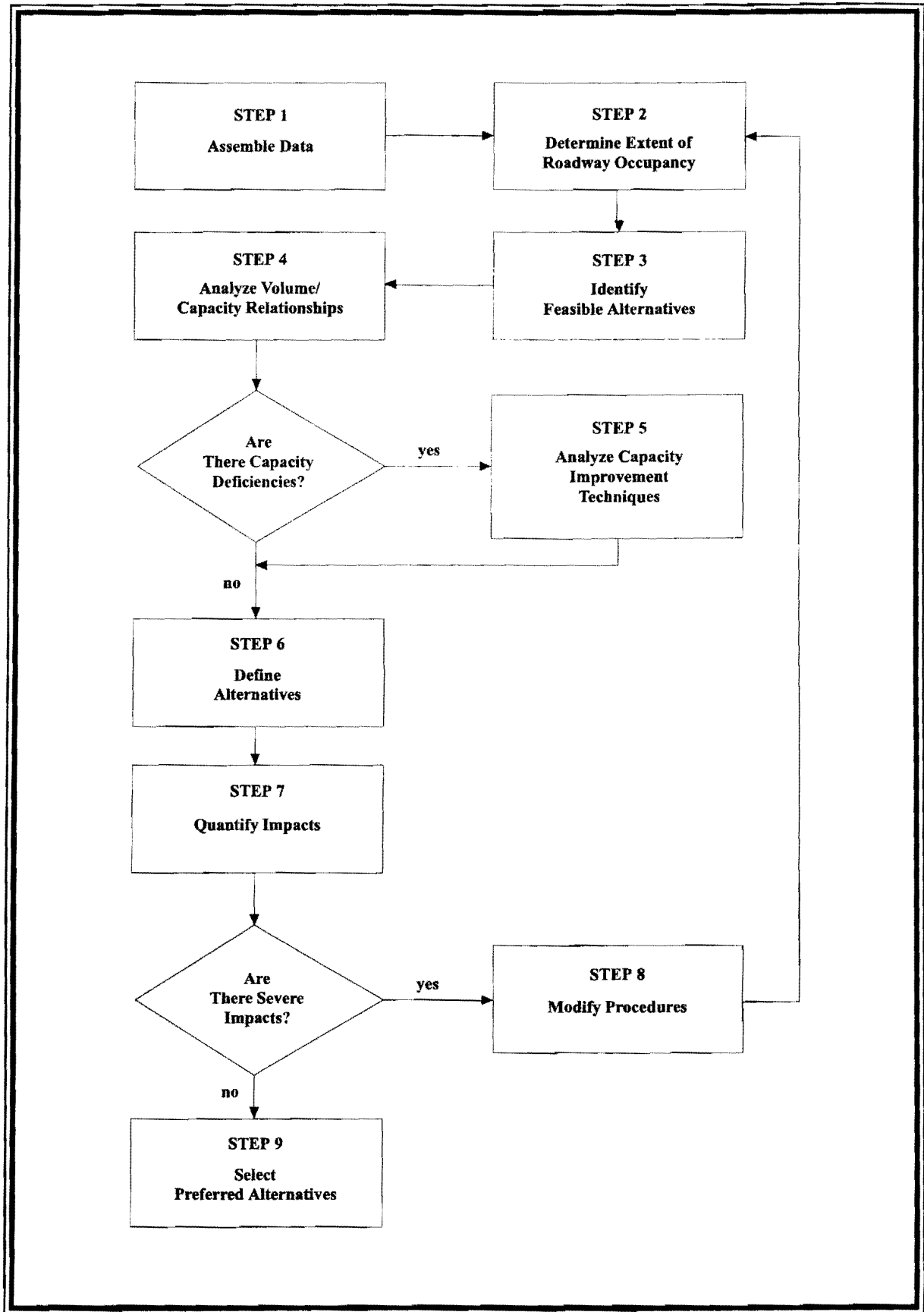


Figure 5-4. Basic Planning Process

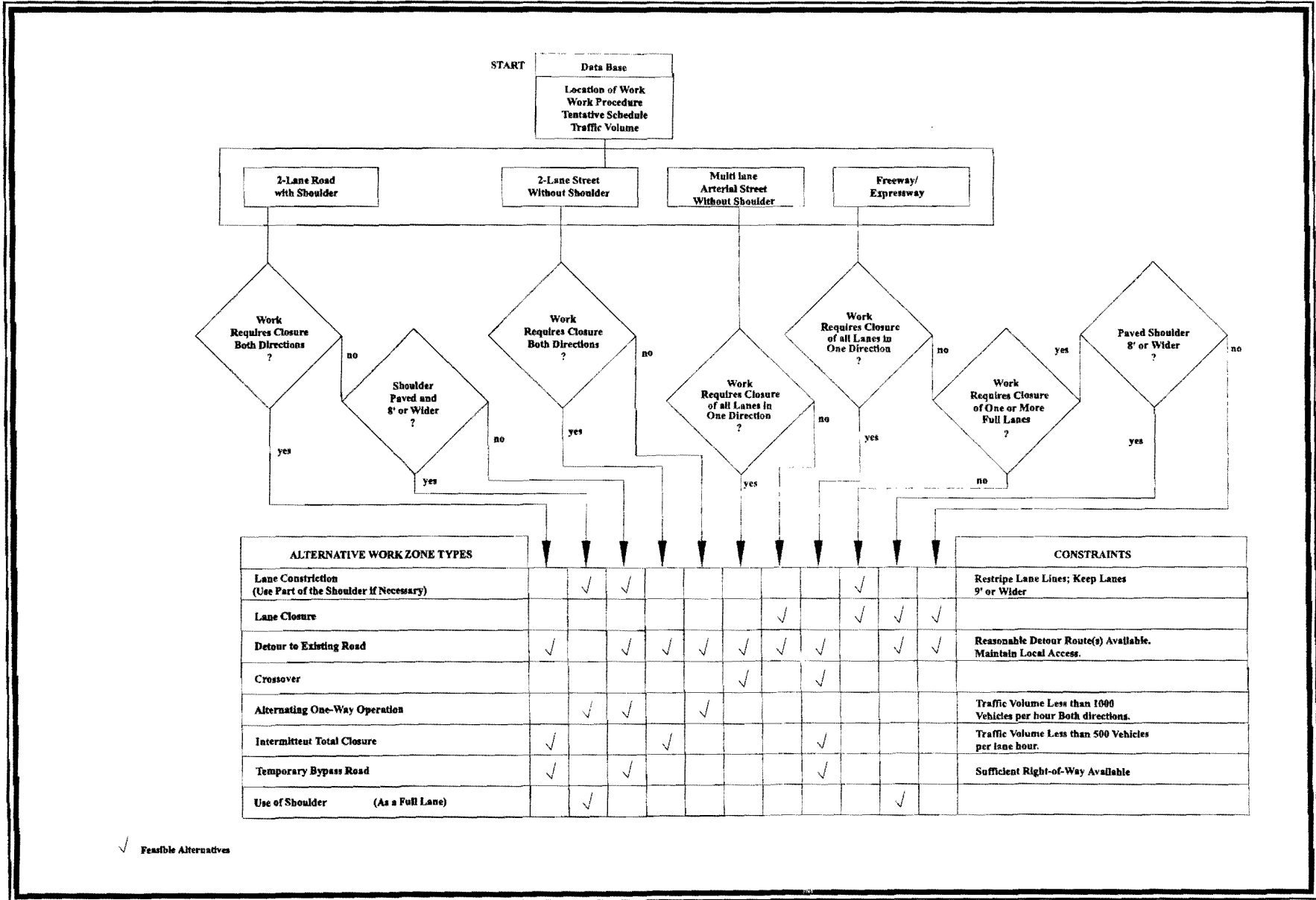


Figure 5-5. Identification of Feasible Work Zone Types

Table 5-10. Capacity Improvement Techniques

Technique	Applicable Roadway Type	Necessary Conditions
Restrict work to off-peak hours only	All types	Roadway occupancy duration can be reduced to less than 8 hours. Volume exceeds capacity during peak hours only.
Nighttime work	Multilane highways in non-residential area and freeways	Roadway occupancy duration can be reduced to less than 8 hours. Work does not require coordination between contractors.
Remove parking	Urban streets	Off-street parking available.
Postpone work to off-season	All types	Significant volume reduction during off-season period.
Work only on weekends	All types	Work does not require coordination between contractors.
Selective ramp closure	Freeways/Expressways	Reasonable detour routes available.
Use reversible lanes	Multilane roads	Significant peak hour directional imbalance.
Restrict turns at signals	Urban streets	Effective signing possible.
Modify signal timing	Urban streets	Good parallel route available.

3.0 Operational Impacts

An assessment of the safety, operational, economic, and environmental impacts is critical in determining the appropriate traffic management strategy to be used at a scheduled activity. Several measures can be used to quantify the impacts of a scheduled activity including crashes, vehicle delays, vehicle stops, project costs, business costs, vehicle operating costs, fuel consumption, and air quality.

An estimate of the number and cost of crashes can be helpful in selecting between alternative management strategies. Crash costs can be calculated from the anticipated crash rate for the construction period, which is a function of the traffic volumes, activity duration, traffic management strategy, and length.

The difference between the normal travel time and the estimated travel time when the traffic control is in place can be considered to be the vehicular delay that is experienced by motorists in a particular section of freeway. Vehicle delays may be caused by any of the following (alone or in combination with another): increased travel distance and/or a reduced speed, insufficient capacity, and temporary stoppages of traffic flow. The number of vehicle stops is another important measure of the impacts of a scheduled activity. For freeway work zones, stops typically occur when the demand volume exceeds the capacity of the traffic control zone. Therefore, the cost of these stops is included when calculating delay costs. Calculating increased vehicle delay, stops, and operating costs for a work zone can be time-consuming and laborious. Fortunately, software does exist to assist with this analysis (see FHWA/TX-92/1108-7, *User's Manual for QUEWZ-92*, for example).

The traffic control strategy chosen to be implemented impacts the total cost of a project. Therefore, the costs of the traffic control and the impacts of the traffic control should be evaluated for each alternative strategy considered. Traffic control costs include the costs of devices and manpower to warn and guide traffic. The cost of any temporary construction that is needed to implement a strategy but destroyed upon completion of the activity should be included as part of the traffic control cost.

The impacts of a traffic control strategy should also be evaluated. Some traffic control strategies may result in a shorter activity duration. However, traffic control strategies that increase efficiency typically increase traffic control costs. Therefore, a case-by-case assessment of the impacts of each traffic control strategy on construction efficiency should be performed as well.

There is wide variability in the impacts on different types of businesses and quantifying the impacts on local businesses is difficult. The designer should keep in mind the need for providing access to all property owners.

CHAPTER 6 SYSTEM MANAGEMENT

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OVERVIEW

Many urban areas in Texas are experiencing congestion throughout the day, creating delay in major corridors. In years past, the typical approach to lessening the impacts of congestion has been to add more freeway lanes. Today, however, this option is not always practical or available. System management provides a means of improving operations and minimizing congestion.

System management combines multiple congestion-reducing strategies into a total system. A comprehensive system management process includes provision for collecting data, analyzing traffic operations, managing incidents, controlling traffic, and providing information to travelers.

This chapter serves as an overview to Part III of the *Highway Operations Volume*. It describes the general concepts of system management and ties together the individual components of a system management process. These components are addressed in detail in the other chapters of Part III.

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SYSTEM MANAGEMENT

1.0 Description

The general concept of system management is the integration of control and management strategies to perform various tasks in the most efficient manner possible.

A management system consists of one or more of the components illustrated in Figure 6-1. Each of these components are discussed further in Topic 5 of this section and in separate chapters of this manual. The components influence the type of data collected, the congestion control strategies selected, and the methods for informing motorists and travelers about traffic conditions. System management components have the capability to adjust system responses to match demand on the system. This is accomplished by:

- ◆ monitoring traffic flow (Chapter 7 - Data Collection),
- ◆ analyzing operations and detecting congestion (Chapter 8 - Traffic Operations Analysis),
- ◆ quickly responding to and removing incidents (Chapter 9 - Incident Management),
- ◆ controlling system operation (Chapter 10 - Control Strategies),
- ◆ diverting traffic demand (Chapter 10 - Control Strategies),
- ◆ providing information to travelers (Chapter 11 - Information Systems), and
- ◆ coordinating through a control center, which serves as the nerve center of the system (Chapter 12 - Control Centers).

System management responds to the impacts of incidents, special events, rehabilitation work, and other conditions on the traffic operations on a freeway or throughout an entire corridor. **Freeway management** emphasizes monitoring and controlling the actual conditions on a freeway. Control is primarily accomplished by entrance ramp controls, lane control signals, frontage road signal monitoring, and dynamic message signing. Freeway management also gives special consideration to managing the freeway for a specific purpose, such as maximizing person movement through the use of high-occupancy vehicle lanes. **Corridor management** is concerned with the management of one or more freeways and the related surface streets as an integrated system.

2.0 Objectives

The objective of system management is to make the best use of the highway system in order to minimize congestion. This is accomplished by managing demand when it exceeds capacity and quickly restoring full capacity whenever there is a temporary reduction in capacity. The primary benefits of system management are the maintenance of an acceptable level of service and the early detection of traffic problems.

continued

2.0 Objectives (continued)

System management is a continuous responsibility. Previously, projects to improve operations were reactionary processes. When a system breakdown was identified, a solution to the breakdown was selected and implemented. With system management, the roadway system is continuously monitored to identify potential problems prior to breakdown conditions. Appropriate responses are then implemented. The monitoring and adjusting process is not as capital intensive as a major roadway building program; however, trained personnel and constant attention are required to make the best use of the highway system.

3.0 Institutional and Managerial Considerations

Special efforts are required when two or more jurisdictions or agencies are involved in a condition which must be solved. One function of system management is to improve the overall traffic operation and safety in an urban area by improving the coordination of the activities of the principal operational agencies in an area. Activities that need to be coordinated include work zones, route improvements, normal operations, incident response, emergency planning, high-occupancy vehicle services, and special-event traffic handling. Pre-planning the management of these activities is highly important for successful coordination between agencies. Forming a team of agency representatives is one successful way to address agency responsibility and jurisdictional issues.

4.0 Traffic Management Team

A Traffic Management Team (TMT) composed of city, county, state, transit, and law enforcement representatives may be able to address interjurisdictional transportation operational problems more efficiently than each agency working independently. The responsibilities of the team vary depending upon the needs in the metropolitan area. Possible areas of responsibility for the TMT are designing, maintaining, enforcing, and operating a management system in a metropolitan area. These responsibilities are discussed in the following segments.

4.1 Design

The TMT can serve as a forum for discussing the design of various projects that will make up the areawide management system. Such discussion can contribute to a more efficient operation by identifying how different agencies will interact, coordinate, and communicate between themselves.

4.2 Maintenance

The TMT can serve as a means of identifying maintenance needs and potential maintenance problem areas so that agencies responsible for specific equipment will be aware of future maintenance needs.

4.3 Enforcement

The Traffic Management Team (TMT) can serve as a forum for identifying the areawide enforcement needs of a highway system. This can be particularly useful in identifying how a consistent level of enforcement can be provided throughout the system. The TMT may also help to coordinate the response of enforcement personnel to incidents.

4.4 Operations

The TMT can help to coordinate the operational activities of the various system management components that involve multiple agencies in a metropolitan area or cross jurisdictional boundaries. Operational activities which the TMT may help to coordinate include: traffic signal systems, information to be displayed on dynamic message signs, and responses to incidents.

5.0 System Components

There are several components to a management system. These components included some means for making management decisions, collecting data, analyzing the operations of the system, managing incidents that occur in the system, controlling input to the system, and providing useful information to the users of the system. These components are discussed in the following segments.

5.1 Decisions

System management begins with the decision and commitment to implement a system and the selection of the system components. There are many parts to an effective management system. These parts must work within the constraints of an existing administrative structure. When a new or different plan is proposed to address a specific issue such as highway operations, it is appropriate to evaluate whether institutional management, procedural structures, and current staff are adequate to accomplish the stated goals in an effective and timely manner. It is also necessary to determine the technological shortfalls in developing a comprehensive management system. Lastly, a comprehensive system overlaps jurisdictional boundaries of enforcement, highway, and transit agencies. A system implementation strategy is required to assure success of an integrated system. Section 3 of Chapter 6 discusses the system management analysis and selection process.

5.2 Data Collection

The initial step in system management operation is to collect data in a usable format. A data collection (or surveillance) system is a means of monitoring demand to determine when and where the system is not operating properly. One function of the surveillance system is to gather data into a format that can be used in other areas of the management system; for example, in analyzing operations and operating traffic control devices. Surveillance systems are used to detect and locate incidents and to continually monitor traffic so that decisions to implement congestion reduction strategies can be made. Chapter 7 discusses the importance of data collection, types of collection and communication equipment, and uses of data.

5.3 Operational Analysis

Traffic operations analysis provides a means of analyzing traffic flow so that alternative strategies can be evaluated. Various analysis procedures can be used to evaluate a range of operational conditions such as weaving areas, ramp control, lane blockage, geometric improvements, and lane arrangements. Chapter 8 addresses these analysis procedures and provides a foundation of operations knowledge. The results of the analyses will assist in making decisions concerning changes to the management system.

5.4 Incident Management

Incident management provides a means of responding to incidents so that impacts on traffic operations are minimized. Incident management includes the evaluation of incidents, the allocation of resources, the actual response to and removal of the incident, and the traffic management responses to lessen the impacts on traffic flow and safety. Chapter 9 addresses incident management considerations in detail, including incident description and characteristics, response process, and management techniques.

5.5 Control Strategies

The management of congestion both at specific locations and over the entire system is addressed in Chapter 10. Strategies include ramp closure or metering, traffic diversion, lane control signals, HOV lanes, and alternatives for managing demand.

5.6 Information Systems

Information systems provide travelers with information that can minimize travel time by avoiding congestion. This type of information includes advance notification of congestion (while at home or office), advice on alternative routes and commuter modes, and in-vehicle information about traffic conditions (through the use of signing, radio, or other means). Chapter 11 addresses the information needs of travelers and how those needs can be met.

5.7 Control Centers

The control center is where information about the highway system is collected, processed, and fused with other operational and control data. It is also the location where decisions about what control strategies to implement are made, where the coordination with other agencies occurs, and where operational measures are implemented and monitored. Information dissemination to motorists and the media is also typically coordinated and implemented from the control center.

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SYSTEMS ENGINEERING APPROACH

The term *systems engineering* may be used to describe an integrated approach to the synthesis (i.e., the combination of parts, elements, etc. to form a working and coherent whole) of entire systems to perform various tasks in the most efficient manner. Thus, the term systems engineering is used to describe an approach that views an entire system of components as an entity rather than simply as an assembly of individual parts.

As illustrated in Figure 6-2, the systems engineering approach is an iterative process that lasts throughout the life of the system. After first identifying specific problems a system is developed to address these problems. Continuous evaluation of the performance of the system allows new problems and opportunities to be defined. By using this iterative process, continuous improvement to the system can be identified and implemented. Each of the elements of this approach are discussed in detail below.

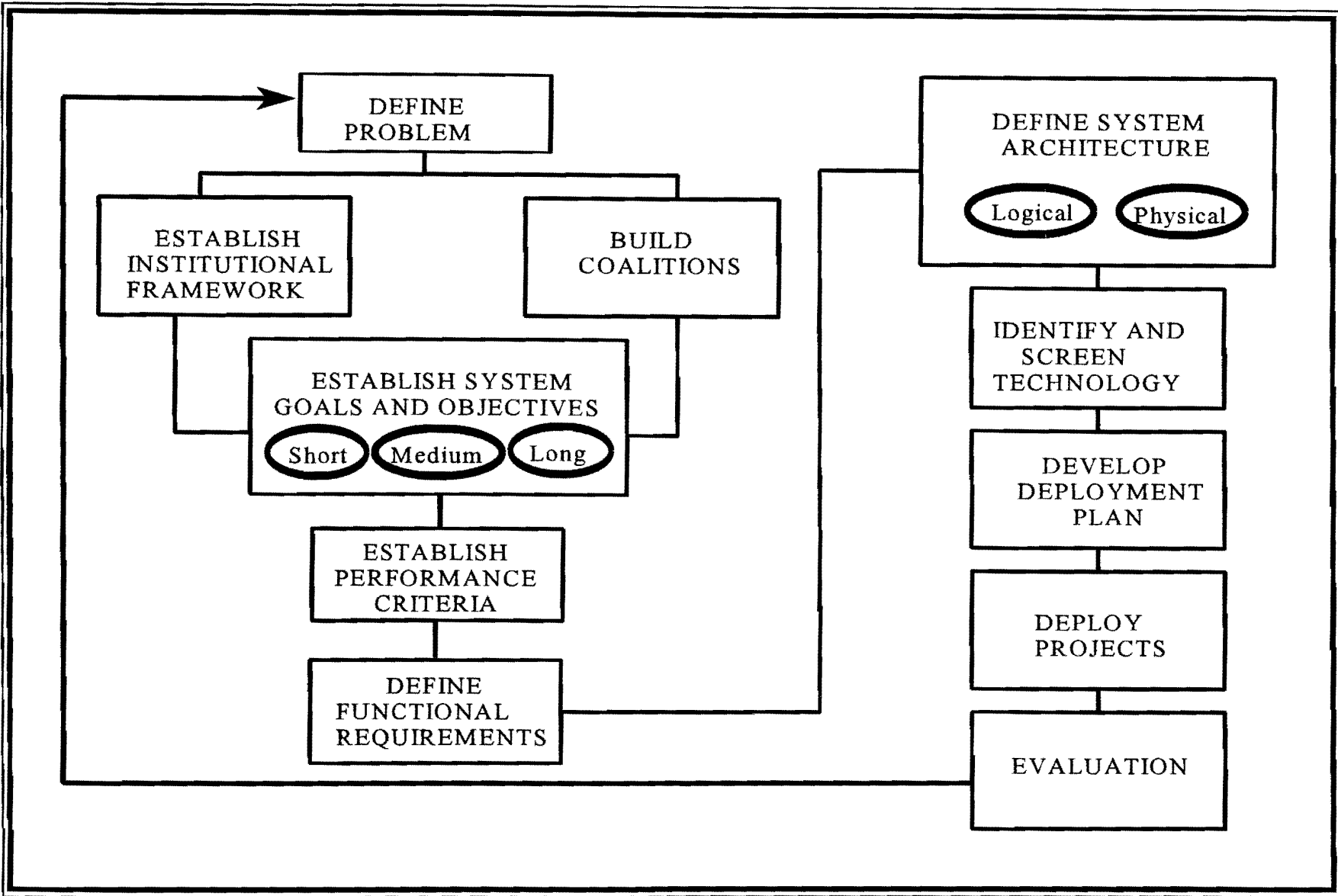


Figure 6-2. Systems Engineering Process Diagram

1.0 Define Problem

The first step in the systems engineering approach is to define the problems to be addressed by the system. Problems can vary in breadth from being operational in nature (e.g., congested areas or times of days, high crash frequencies, poor air quality or non-attainment with air quality standards) to institutional (e.g., better coordination between and within agencies, underutilization of transit facilities, etc.).

Several methods are available to help with defining problems that can be addressed by a traffic management system. Traditional operational studies such as traffic flow and capacity analyses, travel time and delay studies, and crash studies are often used to identify operational problems that can be addressed. Other sources of information include:

- ◆ regional transportation and land use planning studies,
- ◆ site impact analyses, and
- ◆ air quality assessments.

It is important not to overlook the importance of coordinating with other transportation-related agencies to identify problems to be addressed. For example, long-range transit plans can provide an indication of when high-occupancy vehicle facilities may be needed in the freeway system. Input from commercial industries can also be valuable in identifying specific areas of concerns or needs. Finally, and perhaps most importantly, input from local politicians could also provide insight into the public's perception of problems with the roadway system.

Another critical element in defining the problems that exist is to obtain an accurate and complete inventory of the entire existing transportation system. This inventory should include both physical and organizational components. Examples of physical components that should be identified in the inventory include:

- ◆ roadway network,
- ◆ existing surveillance and control systems, and
- ◆ existing information dissemination systems.

Examples of the organizational components that might influence the design of a traffic management system and, thus, must be identified in an inventory include:

- ◆ operating agencies,
- ◆ funding sources, and
- ◆ political and agency jurisdictions.

2.0 Establish Institutional Frameworks and Build Coalitions

Another critical step in implementing a successful traffic management system is to build critical coalitions and institutional frameworks. Institutional frameworks and coalitions need to be established at the beginning of the planning and design process. These coalitions and institutional frameworks need to be established at three levels: between agencies (interagency), within agencies (intra-agency), and with other stakeholders affected by traffic operations.

Traffic congestion is not restricted by jurisdictional boundaries. When one part of the transportation system (e.g., the freeway network) is not functioning properly, it affects the operations of other parts of the system (e.g., the surface streets, the high-occupancy vehicle lanes, etc.). Therefore, there is a strong need to develop good working relationships and build coalitions between agencies responsible for managing traffic in an area. Examples of the types of agencies where strong coalitions would help in implementing a traffic management system include the following:

- ◆ metropolitan planning organizations (MPOs),
- ◆ highway and public works agencies,
- ◆ transit agencies,
- ◆ law enforcement,
- ◆ emergency services (fire, ambulance),
- ◆ turnpike / toll road authorities,
- ◆ port authorities, and
- ◆ state and federal emergency management authorities.

Cooperation and coalitions within an agency are also essential in establishing an effective freeway management system. Often, this type of cooperation is the hardest to obtain. Some sections within an agency may view a traffic management system as usurping some of their responsibilities and power. It is essential that all elements within an agency (e.g. planning, administrative, construction, design, operations, and maintenance) are committed to constructing, operating, and maintaining the system.

Finally, there may be others in the community that may be important allies when implementing traffic management systems. Perhaps the biggest of these is the general public. Without the support of the general public, it will be extremely difficult to implement a traffic management system. Extensive public relations and media campaigns may be required to show the public how a traffic management system will have a direct benefit to them. Strong public support makes it easier to secure funding and political support. Without public support, it will be extremely difficult to generate political and agency interest and support for traffic management.

continued

2.0 Establish Institutional Frameworks and Build Coalitions (continued)

Others stakeholders that may be useful in implementing traffic management systems include:

- ◆ major traffic generators,
- ◆ utility companies,
- ◆ politicians,
- ◆ the media, and
- ◆ private transportation providers.

Establishing institutional frameworks and coalitions can be difficult at times. The first step in building effective coalitions is to identify “champions” in those agencies responsible for transportation in a community (e.g., state highway agencies, MPOs, transit authorities, etc.). These individuals are likely to be top administrative officials in these organizations. Since traffic management systems often compete with other “traditional” agency activities and expenditures (e.g., pot-hole patching, construction, etc.), the support of top management is essential if agency resources are to be allocated to the operation and maintenance of the system. If congestion is widely recognized as a major issue in a community, upper management support may already exist within many organizations and propagate through the agencies in a “top-down” fashion; however, if it is not, support must be generated from the bottom up. One way to achieve “bottom-up” support is to implement components of the system one at a time so that the benefits of the system can be quickly and easily demonstrated.

In addition to identifying “champions” for the system, it is also important to identify those individuals that will be critical for the success of the systems (e.g., the public, politicians, major employers, etc.). The support of one or more local politicians can be highly effective in securing funding for the system. Often this support is automatic if conditions have already deteriorated or if the potential for major traffic problems looms on the near-term horizon.

Another effective way of building strong coalitions between and within agencies is to take advantage of institutional frameworks that already exist. Many locales have institutional frameworks to address freeway management concerns. For example, many locations use Traffic Management Teams and Incident Management Teams to address problems on freeways. Often these teams are a coalition between state and local transportation agencies, and law enforcement personnel. These coalitions can be expanded to encompass additional functions of a traffic management system.

Finally, in building effective coalitions, it is important to identify key individuals within organizations that have the appropriate level of knowledge and experience. These individuals must have the level of authority that is appropriate of the type and level of responsibilities that will be performed by the agency. In addition, it is also important to identify individuals who are likely to be present throughout the entire planning and design process for a traffic management system. A common thread among past successful traffic management systems is that key personnel committed to the system have remained with the agencies throughout the planning, implementation, and ongoing operation of the system.

3.0 Establish System Goals and Objectives

Once coalitions have been formed, agencies should work together to define the goals and objectives of the system. The system goals and objectives should describe what it is the system is supposed to accomplish. The goals and objectives should be directly related to the specific problems to be addressed by the system.

Generally, system goals are used to define the long-range desires of the system. System goals also tend to be broad in terms of their scope. System objectives, on the other hand, define the level of performance that is expected to be obtained in the future. As such, system objectives are measurable. Often, more than one system objective is required to fulfill a system goal. Likewise, more than one system goal may be required to address an identified problem in a system.

It is also important to note that system objectives are defined in terms of what services and functions that a system is to provide -- not in terms of technology. Focusing on what the system is to achieve instead of on how it is to achieve it gives the designers flexibility in the way that components can be combined to build a system to achieve a desired outcome.

4.0 Establish Performance Criteria

After establishing the system goals, the next step in the systems engineering approach is to establish the criteria for judging the performance of the system. The performance criteria is used to determine whether the system objectives are being achieved. The criterion include both qualitative and quantitative measures of performance for the system. It also forms the basis for evaluating the design and operations of the system. The criteria used to measure the performance of the system should correspond directly to the objectives of the system.

5.0 Define Functional Requirements

The next step in the systems engineering approach in designing a system is to define all of the features or activities (commonly called functions) of the system that are necessary to achieve the identified objectives. The system functions need to be described, at least initially, independent of the technology or architecture to be employed in the system. In other words, this step focuses on describing *what* the system will be designed to do, not *how* the system will be doing it.

The functional requirements needed to achieve a system objective can often be outlined in hierarchical order. For example, the functional requirements of an incident management program might be described as shown below. Note that each of the functional requirements defines an action or activity that is to be performed by the system and is independent of technology.

Example of Functional Requirements of an Incident Management System

- ◆ Identify incidents
 - Identify location of incident
 - Identify impacts of incident
 - Identify characteristics of incident
- ◆ Formulate response actions
 - Identify necessary emergency vehicle response
 - Select incident information for dissemination to travelers
 - Identify traffic control strategies
- ◆ Initiate and monitor response
 - Provide response procedures to agencies
 - Implement emergency vehicle response
 - Provide incident information to travelers
 - Implement traffic control strategies
 - Monitor response
 - Arrival of emergency vehicles
 - Implementation of traffic control
 - Clearance of incidents
 - Clearance of congestion

6.0 Define System Architecture

After defining *what* the system is supposed to accomplish, the next step in the system approach is to define the system architecture. System architecture is a framework within which the system carries out the functions required to support the desired objectives. It describes the system elements and their relationship to one another.

The system architecture of many freeway management systems in operation today tends to have evolved as new functions were added to the system. However, there are real benefits to be achieved in planning the system architecture in advance, even if the system will not be fully implemented at one time. Planning the system architecture minimizes the number of redundant functions and efforts performed by the system. Planning the system architecture also promotes the efficient use of equipment, staff, and resources. A well-planned system architecture permits easy expansion and modernization of the system in the future. How the system architecture is defined also facilitates the sharing of information between jurisdictions and leads to cost savings throughout the design, implementation, and operation of the system. The system architecture consists of three elements: the functional requirements, the logical architecture, and the physical architecture. As discussed above, the functional requirements define what the system is supposed to do. The logical architecture identifies what information flows between the functions. The physical architecture identifies where functions occur and who is responsible for performing the function. The physical architecture permits like functions to be grouped into subsystems.

It is extremely important when defining the system architecture that it remain as open as possible. An “open” architecture is a system that has been designed with standard data interfaces so that equipment from multiple vendors can be used throughout the system. In addition, an open architecture helps to keep the system from becoming obsolete because new functions and technologies can be easily added as they become available. Furthermore, an open architecture will make systems being developed today compatible with the national ITS architecture as it emerges. Chapter 1, Section 5 contains additional information on ITS architectures.

7.0 Identify and Screen Technologies

Once the system architecture has been defined, the next step in the systems engineering process is to identify alternative technologies whose performance and reliability meet the defined functional requirements. This can be accomplished by conducting a state-of-the-art review of the available technologies. Evaluation studies, vendor brochures, and demonstrations from manufacturers are excellent sources of information of the state-of-the-art of specific technologies. Site visits to existing systems that use specific types of technologies can also be an excellent tool for evaluating different technologies.

The interaction between alternative technologies and other elements within the system should be considered when evaluating different technologies. How the systems work together and what functions they perform can greatly influence how different technologies perform in a system. The impacts of different technologies on the physical configuration of the system and on the performance of other technologies and components in the system should also be considered. The expandability and flexibility of the technologies should also be considered.

Cost is another factor that should be considered when identifying and screening different technologies. The engineer should consider the life-cycle costs of each alternative technology. Life-cycle costs include:

- ◆ procurement, installation, and construction costs,
- ◆ the costs associated with operating and maintaining each technology,
- ◆ replacement costs during the system's life-cycle, and
- ◆ the costs associated with expanding the system.

Operations and maintenance are other important factors that must be considered when evaluating different technologies for use in a management system. Often, each technology requires unique operating and maintenance activities. The resource requirements, in terms of the number and qualifications of the personnel, the equipment and facility needs, and the operating and maintenance costs, should be factored into the evaluation.

The process of identifying and screening different technologies for inclusion in a system is often iterative. There are multiple ways that different technologies can be combined to achieve an objective. Because the ways that different technologies interact with one another can affect system performance, each combination must be evaluated in an iterative fashion.

8.0 Develop Implementation Plan

After the technologies that will be used in the system have been selected, the next step in the process is to develop a plan for implementing the system. The implementation plan documents the results of the previous steps and identifies how the system will be implemented in the field. Most implementation plans include the following:

- ◆ the transportation system problems and opportunities to be addressed by the system,
- ◆ the institutional arrangements (i.e, who, what, when, where, why, and how) needed to make the system work,
- ◆ the goals and objectives of the system,
- ◆ the functional requirements and architecture of the entire system, and
- ◆ the technology options to be used in the system.

The implementation plan should also assess the phasing, procurement, and funding options available for implementing the systems.

The purpose of an implementation plan is “to ensure that the system is designed, built, operated, and maintained so that it accomplishes its purpose in the most efficient manner possible, considering performance, cost, and schedule.” An implementation plan is required when either a new traffic control system or an expansion of an existing system uses federal funds (see Title 23, Section 655.409 of the *Code of Federal Regulations*). Because it completely describes how the system is going to be designed, operated, and maintained, it is highly recommended that an implementation plan be developed as well for those systems that do not use federal funds. Figure 6-3 lists the elements of a typical implementation plan.

- ◆ Needed Legislation
- ◆ System Design
 - System Designer
 - System Design Life
 - System Coverage
 - System Design and Operations/Maintenance Philosophies
 - System Architecture
 - Integration of Other Functions
 - System Components and Functions
 - Communication Subsystem Design Approach
 - Traffic Operations Center Design Features
 - Project Phasing/Scheduling
 - Design Review
- ◆ Procurement Methods
- ◆ Construction Management Procedures
 - Division of Responsibilities
 - Scheduling and Establishing Mileposts
 - Conflict Mitigation
 - Coordination with Other Projects
- ◆ System Start-up Plan
 - Software and System Acceptance Tests
 - Partial Acceptance
 - Documentation
 - Transition from Old to New Control
 - Operational Support and Warranty Period
 - Training
 - Coordination with Media
- ◆ Operations and Maintenance Plan
 - Evaluation
 - System evaluator
 - Method of evaluation
 - Cost of evaluation
 - Maintenance Plan
 - Maintenance policies for preventative maintenance, system malfunctions, etc.
 - Formal maintenance management programs
 - Initial inventory of spare parts and all necessary test equipment
 - Training in providing limited maintenance to software and equipment
- ◆ Institutional Arrangements
 - Contact Person/Project Liaison Within each Organization
 - Delineation of Organizational Responsibilities
 - Provisions for Periodic Project Updates
 - Utility Arrangements
 - Written Cooperative Agreements for Personnel- and Cost-sharing, Metering, Traffic Diversion, etc.
- ◆ Personnel and Budget Resources
 - Staffing Plan (including the number of persons and their functions per shift)
 - Contract Operations Staff Agreements (if used)
 - Provisions for Training New Staff
 - Sources of Budgetary Resources
 - Estimates of Annual Expenses by Category
 - Signatures of the Head of the Operating Agency, Head of State Highway Agency, and the FHWA Division Administrator

Figure 6-3. Elements of a Typical Implementation Plan

9.0 Deploy Projects

There are a number of approaches that are commonly used by agencies to deploy individual projects or systems. Not all agencies have statutory authority to implement all possible approaches. Each agency must verify the types of procurement procedures they are legally allowed to employ. The more common types of procurement approaches include:

- ◆ sole-source,
- ◆ engineer/contractor,
- ◆ two-step approach,
- ◆ system management, and
- ◆ design-build.

With a sole-source project, a contract is awarded to a named supplier without any competition for the project. This type of procurement approach typically involves a standard off-the-shelf product that can only be made by one manufacturer. It should only be used if it can be justified to be more cost-effective than a competitive low-bid process.

With an engineer/contractor approach, a single contract is awarded to the lowest responsive bidder to a specific request by the highway agency. The contractor is then responsible for providing a complete and fully operational system. In designing and deploying the system, the contractor may elect to subcontract much of the work that is outside the area of expertise of the contractor. The highway agency should specify the appropriate level of qualifications for the prime contractor to avoid getting a contractor who is unable to complete the job.

A two-step procurement process helps to eliminate some of the problems associated with the standard engineer/contractor approach. With a two-step procurement approach, a formal technical prequalification process is added to the engineer/contractor approach. This helps insure that the contract team has the appropriate skills and expertise in implementing the desired types of system.

A systems management approach is commonly used by many highway agencies to implement freeway management systems. With this approach, a system manager is hired to perform the system design, software development, and system integration activities. Separate contracts are then prepared and awarded for implementing the various subsystems as dictated by the design.

A design-build type of procurement approach is another common way that highway agencies deploy freeway management projects. In a design-build approach, a single entity is responsible for all of the work associated with deploying a system. This includes the system design, the contracts for and the construction of the system components, and the integration of the system elements. Upon completion of the project, the design-builder turns over the system to the agency for operations and maintenance. This process is often used to fast-track projects since it can significantly reduce the process time. Agency supervision is required, however, to ensure the quality of the product that is provided by the contractor.

10.0 Evaluation

Evaluation is an ongoing process that occurs at all stages of system development and continues for the entire life of the system. Through the evaluation process, the system designers and operators are able to determine how well individual projects meet the previously established system objectives. The evaluation process also allows engineers to identify possible enhancements to the system. These enhancements can be made to correct operational or design problems, to expand the system either functionally or geographically, or to include additional systems into a regional architecture.

Also, one of the most critical parts of the evaluation process is to document the lessons learned during the development and operations of the system. These lessons learned provide critical information to others that may be considering implementing a similar type of system. The lessons learned should not focus solely on the problems that were encountered during the development or operation of the system, but also describe the positive elements of a particular system architecture or technology.

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DATA COLLECTION

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OVERVIEW

Data collection is the process of gathering the information needed to develop traffic control strategies, to identify and locate traffic problems and incidents, and to evaluate existing traffic operations. Data collection is often referred to as “surveillance” and represents one component of a management system developed to meet the demands of congested urban corridors. Data collection activities are the “eyes” that provide the information needed by the other components of the system. The components include incident management (Chapter 9), control strategies (Chapter 10), and information systems (Chapter 11). Without the information provided from data collection activities, the efforts of related components would not be effective.

This chapter describes the various considerations related to data collection. It includes descriptions of the general types of data that can be collected, the technologies that are available for collecting the data, the technologies that are available for transmitting and communicating the data, and some of the general uses of the data. These descriptions include both current and emerging technologies which can be used to collect data.

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DATA MEASUREMENT

Data collection or surveillance provides the cornerstone for a corridor management system, for without accurate and timely data, it is not possible to manage the system in an efficient manner. Data collection provides the information used in the decision process of control strategies, incident management procedures, motorist information displays, and a number of other activities that contribute to the safety and efficiency of streets, highways, and freeways. Data collection includes measurement of traffic conditions. The data can then be used in real-time to make management decisions, or stored to provide a historical record of traffic conditions. The speed with which the data is made available has a significant impact on the way that the data can be used.

1.0 Measures of Traffic Conditions

The most common traffic characteristics which are measured in surveillance activities include flow, speed, and concentration. **Flow** measurements are used to describe the quantity of traffic. Flow is usually measured by counting the number of vehicles or axles that pass a given point on the highway. Increasing flow rates may indicate conditions which may result in congestion. **Speed** measurements are used to provide an indication of the quality of traffic flow. Reduction in speed often indicates the presence of congestion or the formation of congestion creating conditions. **Concentration** represents vehicle spacing and is normally described by density or lane occupancy. Density is also a measure of the quality of traffic flow. It is difficult to obtain and is usually derived from flow and speed. Data collection methods normally measure lane occupancy to provide an indication of density. Occupancy is the percent of time that a point in the road is occupied by vehicles. Additional details on traffic measurements are included in Chapter 1, Section 5 and Chapter 8, Section 2.

2.0 Historical and Real-Time Data

Data is generally either historical or real-time. Historical data is defined as information related to past events. Its major uses are providing a measure against which real-time data can be compared or to indicate trends which can be used to predict future traffic conditions. Since traffic conditions are constantly changing, almost all data can be considered historical.

Real-time data describes events as they occur. Real-time data is typically used to make traffic management decisions in such a manner that the decisions have an impact on current traffic conditions. Therefore, by definition, real-time data must be processed in a sufficiently rapid manner so that the results of the processing are available in time to influence the process being monitored or controlled.

3.0 Speed of Data Collection

The acceptable time frame needed to provide traffic data is dependent on the function being served. For example, when the surveillance of traffic approaching a signalized intersection is used to adjust timing patterns or to call for specific signal phasing, the adjustments may be implemented on a cycle-by-cycle basis, or at time intervals that can range from one to fifteen minutes. Data collection systems used to measure traffic operation conditions on urban freeways for adjustments in management strategies must provide information at very short intervals to be effective in reducing or preventing the formation of congestion.

The faster the data collection devices can provide accurate information, the greater the benefits that can be achieved. However, fast data collection systems typically cost more. Some operational functions can best be served by systems composed of vehicle sensors connected to processors, some require visual evaluation by traffic observers, while others use combinations of these and still other concepts. **There is no one data collection system design that is considered ideal for all applications.** Decisions on a data collection system must balance accuracy, benefits, and costs.

Information provided by data collection systems can also be used to calculate the impacts of system management strategies in order to quantify the benefits of the system.

DATA COLLECTION EQUIPMENT

There are many technologies available for collecting data. Most of these can be divided into site specific, variable location, and vehicle-based detection methods. In addition, new technologies in all three areas continue to be developed for data collection purposes.

1.0 Site Specific Equipment

Site specific equipment includes all detectors which collect data at a specific location on the roadway. Typical site specific data collection equipment includes embedded, on-pavement, and above-pavement detectors.

There are three modes of detection for site specific detectors--pulse, presence, and mechanical stress. In pulse detection, a short signal is sent when a vehicle passes the detection area. In presence detection, a signal is continually sent while the vehicle is occupying the detection area. Presence detectors can be modified to operate as pulse detectors. Mechanical stress sensors produce a charge at their terminal when subjected to an applied load.

Embedded detectors are the most common type of site specific data collection equipment. Of these, the inductive loop detector is the most widely used, although magnetometers and magnetic detectors are used in special situations. Loop detectors measure changes in the energy field as the vehicle passes through the detection zone. They are typically embedded in the pavement to form permanent data collection stations.

Site specific detectors can also be installed directly on the pavement. The three most common types of on-ground detectors are temporary inductive loop detectors, pneumatic tubes, and tapeswitches. Most on-ground detectors are temporary and function only for a short period of time relative to embedded detectors.

Site specific detectors located above the pavement are an area of changing technology. They include equipment such as infrared, ultrasonic, and radar detectors mounted off of the pavement. Typical mountings include posts or barriers on the side of the road and bridges or mast arms above the road. This type of detector equipment is described in Section 3, Segment 4.0.

1.1 Inductive Loop Detectors (embedded or on-pavement, pulse or presence)

The inductive loop detector is the most commonly used form of detector. A loop detector system contains three parts: the loop itself, the lead-in cable, and the detector unit.

- ◆ The **loop** consists of a coil of cable placed below, in, or on the pavement surface. The number of times the cable circles the loop is known as the number of turns. Loop cable is usually placed in saw cuts made in the pavement surface, although it may be placed below the pavement when the roadway is constructed or on the pavement for temporary installations. Loop sizes can vary greatly, although loops for 3.7-meter (12-foot) wide lanes are typically 1.8 meters (6 feet) wide and vary in length from 1.8 to 30.5 meters (6 to 100 feet).
- ◆ The **lead-in cable** is used to connect the loop to the detector unit. It normally consists of two types of cable. The portion of the lead-in cable between the loop and the pull box is the loop cable. It is the same cable used to form the loop and is usually placed in a saw cut in the pavement. The portion of the lead-in cable between the pull box and the detector unit is a shielded cable. The total length of the lead-in cable is the distance from the loop to the detector unit.
- ◆ The **detector unit** is sometimes referred to as the **detector amplifier**. It consists of electronic circuitry which interprets the changes in the electrical properties of the loop when a vehicle passes over the loop. The detector unit is typically located in a cabinet off the roadway, away from the loop.

A loop system becomes active when the detector unit sends an electrical current through the cable, creating a magnetic field at the loop. When a vehicle passes through the loop's magnetic field, the ferrous material in the vehicle causes a decrease in the inductance of the circuit and an increase in the frequency of oscillation which is sensed by the loop detector unit electronics.

Loop detectors can operate in either a pulse or presence mode. In the pulse mode, a signal of a very short duration (typically about 0.125 seconds) is sent by the detector unit when activated. In the presence mode, the signal sent by the detector unit lasts as long as a vehicle is over the detection area. Presence mode is used for most detector applications, and is the preferred mode for system management purposes.

There are several properties of loop systems which have a significant influence on the effectiveness of its operation. These properties include the sensitivity, the efficiency, and the response time.

- ◆ The **sensitivity** of a loop system defines its ability to detect a given vehicle. It establishes a threshold value for the required change in system inductance (i.e., frequency shift) before a given vehicle is detected. The sensitivity is the ratio of the change in inductance to the total system inductance expressed as a percentage. The sensitivity is set in the detector unit. Most detector units have several different sensitivity settings.

continued

1.1 Inductive Loop Detectors (continued)

- ◆ The **efficiency** of a loop system is the ratio of the loop inductance to the total system inductance, expressed as a percentage. It determines how well the loop system can detect various types and sizes of vehicles. The efficiency is a function of the size of the loop, the number of turns of cable in the loop, and the length of the lead-in cable. If the loop cable was connected directly to the detector unit, the efficiency would be 100 percent and the loop size or the number of turns would not matter. As the length of lead-in cable increases, the efficiency of the loop system decreases, and the number of turns of cable in a given loop must be increased to bring the efficiency back to an acceptable level. Appendix B contains formulas for calculating the inductance of the loop system components and the system efficiency.
- ◆ The **response time** of a loop system is the time period from when a vehicle enters a detection zone to the time the detector unit determines the presence of the vehicle. Response time is linked directly to the sensitivity of the detector unit. A longer response time is needed to recognize smaller vehicles.

Loops can be used to detect vehicle speeds by placing two loops a short distance apart. The distance between the loops divided by the time required for a vehicle to travel between the loops provides the speed of the vehicle. Loops used to measure speeds must have similar configurations (yielding nearly identical response times) in order to provide an accurate measure of speeds.

Short loops have been shown to be more effective at detecting vehicles, therefore, they are normally used for detection purposes as part of a management system. Short loops are generally 1.8 meters by 1.8 meters (6 feet by 6 feet). The maximum length of a short loop should be 3 meters (10 feet), as loops longer than one-half a car length maximize the possibility of spillover detection from adjacent lanes.

Crosstalk between loops is common when detector lead pairs are located in the same bundle or when detectors are closely spaced. Combining a variable number of turns of cable with carefully selected applications of capacitors or inductors can insure satisfactory operations without crosstalk.

The *Texas Traffic Signal Detector Manual* describes the operational basis of inductive loop and microloop detectors, particularly as they are used in a traffic signal system. Installation principles, treatments of commonly encountered field problems, suggestions on reducing the amount of time a lane is closed for loop installation, and procedures for cutting pavements are also discussed. The sealants that have proven successful are listed in the manual.

The quality of the loop installation has a significant impact on the performance and life of the loop itself. In addition, loops cannot be repaired or replaced without disrupting traffic. Therefore, special care should be taken during the installation of a loop to insure that a high level of quality is maintained.

1.2 Magnetometers (embedded, pulse or presence)

Magnetometers are small cylinders containing sensor coils that operate in a manner similar to inductive loops. These coils are installed in a small circular hole in the center of each lane. Wires or a radio link connect the magnetometer to the electronic interface located on the roadside. Magnetometers function by detecting increased density of vertical flux lines of the earth's magnetic field caused by passage of the ferrous material in a vehicle. They operate in either the presence or pulse modes and are embedded in or under the pavement. Magnetometers are more durable than loop sensors, require less sawing of the pavement, and can be installed on bridges without damage to the deck.

1.3 Magnetic (embedded, pulse or presence)

A magnetic detector consists of several dense coils of wire wound around a magnetic core. This tubular device is either placed in a nonferrous conduit or directly buried under or in the pavement. Magnetic detectors, which can operate in either the pulse or presence mode, detect distortions in the earth's magnetic field caused by ferrous material in vehicles. A vehicle moving in the sensor detection area causes a change in the lines of the earth's magnetic flux. This change triggers a voltage output signal. These devices cannot detect vehicles traveling at less than 5 kmph (3 mph). They also have a large detection zone which can result in detection of vehicles in adjacent lanes.

1.4 Piezoelectric Axle Sensors (embedded or on-pavement, mechanical stress)

Piezoelectric axle sensors are used at permanent count locations to obtain vehicle classification information. A charge is produced at their terminals whenever they are subjected to mechanical stress. The greater the stress and the faster it is applied, the greater the output level. A piezoelectric axle sensor can either be a piezoelectric cable or a piezoelectric film. Piezoelectric cable consists of a piezoelectric ceramic material that is packaged in rubber, urethane, or possibly a steel or aluminum channel for installation in a cut in the pavement. The piezoelectric film axle sensor is constructed with urethane in an aluminum channel. Piezoelectric sensors that are not packaged in a steel or aluminum channel can be placed on the pavement for use as a temporary detector. Piezoelectric sensors offer the capability to emit signals that have an amplitude that is proportional to the force applied to them, therefore allowing the discrimination between a passenger car axle and a truck axle. Since piezoelectric axle sensors are a relatively new technology, extensive field experience does not exist and most technical staffs are unfamiliar with the technology.

1.5 Pneumatic Tubes (on-pavement, pulse)

Pneumatic tubes are hollow rubber tubes and are stretched over the roadway pavement. They are the most widely used axle sensor technology. One end of the tube is plugged and the other is connected to an air pressure transducer usually located in a traffic counter. When a wheel passes over a pneumatic tube, the internal air pressure increases. The pressure change is detected by an air pressure transducer which creates a pulse signal. Therefore, pneumatic tubes operate in the pulse mode only. Tubes are typically about ½ inch in diameter and are available in various lengths. Tubes are inexpensive and relatively accurate for light traffic flows. However, they cannot easily measure adjoining lanes independently and so are not feasible for vehicle counts in more than one lane. Tubes are limited to counting axles and can be destroyed relatively easily by vehicles or vandals.

1.6 Tapeswitches (on-pavement, pulse)

Tapeswitches consist of two steel strips separated on the edges by rubber spacers. When a vehicle passes over the tapeswitch, the two steel strips make contact, resulting in an electrical contact closure which is interpreted as an actuation. Tapeswitches operate in the pulse mode only. They are about 25 millimeters (1-inch) wide, relatively flat, and are available in various lengths. Tapeswitches can produce very accurate speed and axle spacing measurements and can sense traffic in several lanes independently of the adjoining lanes. They are not suitable for use in areas with heavy rainfall and they wear out in a comparatively short period of time.

2.0 Variable Location Equipment

Variable location equipment includes all detection methods which have the ability to change the specific location where data is collected. Therefore, variable location detectors have the capability to focus their attention on specific points of concern in the traffic stream. Cameras and aircraft provide the primary surveillance methods which have the ability to direct attention to different areas. Vehicle-based equipment can also provide information from variable locations. However, due to the many uses of vehicle-based equipment, they are described separately in Section 3, Segment 3.

2.1 Camera Surveillance

A closed-circuit television (CCTV) system consists of one or more cameras located above a roadway, a data transmission link, and monitors in a central control room. Operators in the control room monitor the traffic conditions at locations where cameras are placed or use the image to verify the type of traffic conditions indicated by another surveillance system. The cameras have pan, tilt, and zoom capability so that the operators can view images from different locations.

The locations for cameras should be selected to provide good coverage of critical operational features, such as ramps and connecting roadways, weaving areas, and high-occupancy vehicle (HOV) facility terminals. An additional consideration in locating cameras is the location of other driver information and control devices that are monitored from the central control center. The camera platform and the equipment cabinets should be protected from damage by vehicles, and should be accessible by a maintenance vehicle without causing a disruption to traffic flow.

Advantages of a CCTV system are that it allows the operator to monitor a section of roadway in real-time, to visually confirm traffic operations, and to observe traffic at a variety of locations. The high cost to install and maintain the system is a disadvantage. Also, without an electronic surveillance system, continuous monitoring of the video displays by qualified technicians is a costly and tedious task. Operators tend to lose interest and fail to notice incidents immediately. CCTV systems are also sensitive to lighting and environmental changes; however several systems are available with differing light sensitivity.

2.2 Aerial Surveillance

Aerial surveillance from helicopters or light airplanes is used by police and commercial traffic reporting services to monitor traffic flow, detect incidents, and provide alternate route information to motorists. Information is typically provided to drivers through traffic reports on commercial radio. It is not normally used by agencies responsible for system management, although it can be used for this purpose.

The primary advantage of aerial surveillance is that an overall picture of an incident can be obtained and conditions on several alternate routes can be determined almost simultaneously by visual methods. Because it is expensive to operate, aerial surveillance is often used to cover a wide geographical area. This often results in considerable time delays in identifying and removing incidents. Furthermore, the effectiveness of this system is limited by weather conditions. Although aerial surveillance has been shown to be cost-effective as a tool for rerouting traffic in response to an incident, it has not yet been shown conclusively to be economically feasible as a method for detecting incidents.

3.0 Vehicle-Based Equipment

Vehicles operating in the traffic stream can be used to provide information on traffic conditions in a variety of ways. Equipment located in a vehicle can be used to measure the speed of the traffic stream. These speed measurements can be classified as time-mean speeds or space-mean speeds (Chapter 8, Section 3, Segment 2.0). The speed may be recorded in some form for subsequent use, or may be transmitted from the vehicle to the control center for application to the surveillance system in real-time. The speeds may be transmitted through electronic means or by a human operator in the vehicle as described in Section 4, Segment 4. The most common speed measuring equipment based in vehicles includes radar, the speedometer, and the odometer/clock combination.

3.1 Radar

Vehicle mounted radar units can be used to measure the time-mean speed of other vehicles in the traffic stream. The radar-based vehicle can be moving or stopped. This method is commonly used by law enforcement agencies to identify vehicles exceeding the speed limit.

3.2 Speedometer

A speedometer can be used to measure the time-mean speed of the traffic stream that the vehicle is in. The measuring vehicle paces itself so that it provides a reasonable representation of movement. There are three methods of pacing the vehicle:

- ◆ *Floating-car technique*—Driver floats with the traffic by passing as many vehicles as pass the test car.
- ◆ *Average-car technique*—Vehicle travels according to the driver's judgement of the average speed of the traffic stream.
- ◆ *Maximum-car technique*—Vehicle is driven at the posted speed limit unless impeded by actual traffic conditions.

3.3 Odometer/Clock

A space-mean speed is calculated by dividing a known distance by the time to travel the distance. The distance may be determined from maps or the vehicle odometer. The driver paces the vehicle in the traffic stream to provide a reasonable representation of traffic using one of the three methods described above.

4.0 Emerging Technologies

Several types of detectors are being developed to improve the collection of data for surveillance needs. Following are brief discussions on several of these devices.

4.1 Conductive Plastic Inductive Loop

Conductive plastic inductive loops are being developed to provide a solution to two serious problems commonly experienced with copper wire inductive loops: the susceptibility to breakage by pavement stresses and the deterioration of the copper wire's insulation caused by moisture or chemicals. Conductive plastic inductive loops have been designed to take advantage of the unique characteristics of a plastic (polymer) known as Polyvinylidene Fluoride (PVDF). The loops consist of a layer of conductive ink applied to a cable fabricated from PVDF. PVDF and conductive ink have been shown to be very durable, tough, and flexible even in extremely harsh environments. Testing of conductive plastic loops has shown that the signal will likely require modification for use with a commercially available vehicle classifier.

4.2 Infrared

Active infrared sensors operate by focusing a narrow beam of energy onto an infrared-sensitive cell. Vehicles are detected when they pass through this beam, interrupting the signal. The infrared beam can be transmitted from one side of the road to the other, or from an overhead or roadside position to a device in the pavement surface. Because infrared sensors are mounted either above the pavement surface or at the roadside, disruption to the flow of traffic is minimized for their installation or maintenance. The infrared system provides information on vehicle height and length, more accurately monitors vehicles changing lanes near the sensors than the pavement based systems. The infrared system is also a relatively low-cost system. Active infrared sensors can be used as a presence or pulse sensor. The disadvantages of infrared detectors include: inconsistent beam patterns due to passing clouds, shadows, fog, and precipitation; infrared lens sensitivity to moisture, dust, or other contaminants; beam alignment difficulties on structures where vibrations are a problem; limitations to single-lane across-road use when collecting speed and volume data (such as the case for transitways); and possible unreliability under high-volume conditions. For multilane applications, infrared detectors should be mounted overhead for both speed and volume measurements.

4.3 Ultrasonic

Ultrasonic detectors consist of compact electronic signal generation and receiver units that are mounted either over or to the side of the roadway. A vehicle is detected when the energy burst that is directed at a target point is reflected faster than expected. Ultrasonic detectors can be used for both presence and pulse applications. Because the ultrasonic devices are not mounted in the pavement, there is little or no disruption to traffic during installation or maintenance. However, environmental conditions can affect their operation and require a very high level of special maintenance capability. This technology has been used successfully and extensively on freeways in Japan.

4.4 Microwave and Radar

Microwave and radar sensors direct a beam of microwave energy onto a detection area from an antenna mounted either above the lane or on the roadside. Vehicle sensing is accomplished through detection of a Doppler phase shift. Microwave and radar sensors are not capable of detecting vehicles moving at less than 5 kmph (3 mph). They are expensive to operate, mainly because they must be serviced by technicians with Federal Communication Commission (FCC) licenses.

4.5 Laser

Lasers, an acronym for “light amplification by stimulated emission of radiation,” are devices which contain a crystal, gas, or other material in which atoms are stimulated by focused light waves. The unit is mounted either above or at the side of the road. The receiver is built into the transmitter and actuations are detected by changes in the characteristics of the laser beam. The very narrow beam can be more precisely aimed than the infrared or ultrasonic devices, thereby avoiding false actuations from vehicles in adjoining lanes. However, small vehicles, such as motorcycles, that are traveling on the edge of the lane may be missed when using a narrow beam.

4.6 Video Image Processing Systems

Video image processing research evolved during the mid 1970s. Early systems used “fixed geometry” sensors, meaning that points on the roadway being monitored could not be changed unless the camera was physically moved. This was undesirable, so subsequent generations of systems allowed the detection area within the camera’s field-of-view to be altered. Advanced video image processing systems can collect, analyze and record traditional traffic data, detect and verify incidents, classify vehicle types, and monitor intersections.

A video image processing system consists of one or more cameras providing a clear view of the area, a microprocessor-based system to process the video image, and a module to interpret the processed images. Several steps are required to acquire, process, and interpret a video image. The first step is image acquisition through the camera system. The second step requires an analog-to-digital converter to transform the analog signal into a digital form for use by the computer. The third step involves processing the image to eliminate unwanted noise and enhance edges, contrast, and motion.

The resolution of the image limits video image processing. The resolution is represented by the number of pixels within the image view. Pixel is short for “picture element” and represents the smallest area of a television picture capable of being delineated by an electrical signal passed through the system. A pixel is a two-dimensional element representing a three-dimensional image. The actual dimensions a pixel represents is a function of the pixel’s location within the image. Pixels representing a portion of the image far from the camera may represent several meters, while pixels representing the portion of the image close to the camera may represent less than 0.3 meters (1 foot).

continued

4.6 Video Image Processing Systems (continued)

Video image processing systems view an image as a set of pixels belonging to one of two categories. The first pixel category is *figure pixels*. Figure pixels are pixels that belong to the object of interest, such as a vehicle. The other category is the *ground pixel*. Ground pixels belong to the object's environment, or background. Video image processing systems "learn" the pixel intensity of the background, the part of the image that does not change or changes very little over time. When an object passes through the image, the system reacts to the changes in pixel intensity.

"Noise" refers to the electronic noise transmitted through the system. "Point noise" is the most common form of noise, where a single pixel has an unusually high or low value. Analyzing surrounding pixels and averaging the pixels as a group reduces this type of noise. Edge detection and enhancement find areas in an image where the pixel values change abruptly. These abrupt changes generally occur at the boundaries of the image, such as a white car against a black pavement surface. Vehicle colors that are similar to their background cause problems with edge detection and enhancement techniques.

Contrast enhancement increases the dynamic range of the gray value in the image. Motion detection analyzes multiple images. Two images are compared pixel-by-pixel to find differences between them. Generally, the two images are divided, one image represents the background picture and the other image has vehicles in the image. Processing speed of the image system becomes a concern when utilizing these processes. The more enhancement desired, the longer the time to process the image in the system. Limitations of the processing hardware must be considered when very high levels of accuracy and process ability are desired.

Two basic video image processing systems exist. The first type is classified as a "trip-wire" system. Trip-wire systems use a narrow line of pixels across a traffic image to detect passing vehicles. The second type of video image processing system is classified as a "tracking" system. Tracking systems identify individual vehicles in an image and track the vehicles through that image.

4.6.1 Trip-Wire Systems

Trip-wire systems focus on movement in only a specific location within the image field-of-view. These specific locations are called "detection zones." The rest of the image is ignored. Vehicles are detected when they pass through a detection zone. Movement is detected by the pixel intensity change within the detection zone. Vehicle presence is registered if the intensity change in the pixel is above a set threshold limit.

A trip-wire system can measure vehicle speed. Trip-wire systems determine speed in the same manner inductive loop detectors determine speed. Speed determinations require two detection zones at a known distance apart. Trip-wire systems calculate speed by knowing the distance between detectors and the time taken for a vehicle to cross the two detectors.

continued

4.6.1 Trip-Wire Systems (continued)

The advantages of trip-wire systems are:

- ◆ trip-wire systems are able to operate in a multitude of directions,
- ◆ vibrations are not detrimental,
- ◆ setup is generally easier, and
- ◆ limited processing power is required.

The disadvantages of trip-wire systems include:

- ◆ dependence on glare, and
- ◆ headlight association between vehicles.

4.6.2 Tracking Systems

Tracking systems determine the location of a vehicle from pixel intensity changes that occur from frame to frame in a video image. Moving vehicles are represented by groups of changing pixels. Tracking systems must associate these pixel groups and determine if the group is one vehicle or more than one vehicle. "State Estimation" and "Data Association" are two important processes in this determination. Vehicle state estimation determines which pixel groups in successive frames represent the same vehicle as the vehicle moves through the image. Tracking algorithms utilize a variety of filtering techniques to solve the problem of estimation. Data association is the process of choosing which pixel groups to use for vehicle state estimates. A tracking video image processing system must include an algorithm to determine if a pixel group is a separate vehicle. Tracking video image processing systems require the user to enter several parameters including: minimum distance between vehicles, minimum vehicle length and width, and maximum vehicle length and width.

The advantages of a tracking system are:

- ◆ ability to handle shadows,
- ◆ ability to handle lane changes,
- ◆ ability to associate headlights with vehicles, and
- ◆ ability to ignore visual noise.

The disadvantages of tracking systems are:

- ◆ the large number of variable input requirements,
- ◆ tracking aerodynamic cars,
- ◆ sensitivity to vibrations, and
- ◆ significant processing power required.

Both types of video image processing systems have flexibility and ability to detect traffic in multiple locations within the camera's field-of-view. The detection zones do not physically exist on the pavement, allowing them to be removed or adjusted to improve detection. Additionally, a single camera can replace many loops, thereby becoming cost-effective.

4.6.3 Phenomena Affecting Video Image Processing Systems

Phenomena which can compromise the accuracy of video image processing systems include: reflections, shadows, occlusion, darkness, and transitional lighting. Reflections can be useful in detecting vehicles, especially in poor illumination, because they can enhance the contrast between the object and the background. However, reflections also have a negative side. Especially at night or on wet pavement, reflections can trigger changes in a pixel's value resulting in erroneous detection as a moving vehicle. Most video image processing systems utilize a nighttime detection algorithm to minimize these problems.

Shadows, like reflections, are both useful and detrimental. Useful shadows exist under and to the side of a vehicle on bright days. Small, dark shadows beneath a moving vehicle provide increased contrast between the vehicle and the road surface, making the vehicle easier to detect. Long vehicular shadows extending across more than one lane of traffic pose a disadvantage. Slow moving shadows from tall stationary objects, such as luminaries or traffic signal poles, are also difficult to interpret. Changing shadows are problematic for both trip-wire and vehicle tracking systems.

Nighttime conditions affect video imaging systems. In some situations, vehicle detection at night is easier than during daylight due to greater contrast by vehicles' headlights. However, the reflection effects of headlights need further attention to avoid double counting. Either dawn or dusk transitional lighting causes problems for video image processing systems. Some systems utilize two separate detection schemes, one for daytime and another for night, to process the video image. Transitional lighting can confuse the system, partly because some headlights are on and some are off.

Occlusion occurs when one or more vehicles obstruct the view of another vehicle. Occlusion has a major impact on detection when one vehicle "hides" a horizontal edge of another vehicle, thus making the appearance of one larger vehicle. Vehicles can occlude vehicles in other lanes or in the same lane. Occlusion can occur in both trip-wire and tracking systems. The most practical solution to overcome occlusion is improved camera position.

4.6.4 Video Imaging Design Considerations

- ◆ Generally, no more than four adjacent freeway lanes can be “accurately” counted with one camera mounted not more than 4.6 meters (15 feet) off the shoulder. Count accuracy in heavy flows will be reduced in lanes farther from the camera. Count accuracy by lane may be consistently as high as 90 to 95 percent for some lanes in ideal lighting and weather conditions and with the correct camera height and aim. However, count accuracy can suffer drastically in inclement weather, dropping well below 90 percent.
- ◆ The horizontal angle of the camera (as measured with the direction of traffic) depends upon its focal length, imager size, and the number of lanes in the detection zone. However, an appropriate beginning point for aiming the camera based on the 4.6 m (15 ft) offset noted above is 30 degrees. To achieve this angle, the camera should be aimed at a point 24 meters (80 feet) away from the base of its support and centered on the four lanes.
- ◆ The camera’s vertical angle with the horizontal plane should be at least 30 degrees.
- ◆ Increasing camera height reduces occlusion; however, sway and vibration may become problematic above 9 to 12 meters (30 to 40 feet) with some supports. A practical maximum height of 9 to 11 meters (30 to 35 feet) is achievable utilizing existing luminaire supports. Testing indicates that 12 meters (40 feet) is better than 9 meters (30 feet), but the evidence is not as strong for increasing to 15 meters (50 feet).

4.7 Automatic Vehicle Identification

Automatic Vehicle Identification (AVI) provides the ability to uniquely identify a vehicle passing through the detection area. One common use of AVI technology is for collecting toll charges electronically from a driver’s account when they pass through the toll station without stopping. Another use of AVI technology is to measure elapsed travel times from point to point electronically in real-time.

The original AVI technology, which has been in use for several years, uses a radio frequency signal from the roadside to activate a tag (or transponder) located in the vehicle windshield. The tag answers this signal by sending a response that is encoded with specific information about the vehicle or driver. The response signal is then read by a roadside reader. This form of AVI technology requires the vehicles to be channeled through the detection area. The reader is typically located above the pavement, but it can also be embedded in the pavement.

The next generation of AVI technology is currently under development for use in Intelligent Transportation Systems. The new technology will provide the ability for high-speed, multilane, and two-way communication between the vehicle and roadside. Vehicle information such as speed, link time, vehicle pollutants, number of occupants, and toll collection account may be transmitted from the vehicle, and information such as route guidance, traffic information, and road conditions may be transmitted to the vehicle.

4.8 Acoustic Detection Systems

A recent addition to the list of non-intrusive detectors for highway detection is a passive acoustic device, developed in partnership with the U.S. Navy. The major components of this sensor system include a controller card, from one to four independent acoustic sensors (microphones), and interconnect cables. The device provides a detection zone size of 1.8 to 2.4 m (6 to 8 ft) in the direction of traffic. The processor in the controller card has the capability to compute traffic flow measurements such as vehicle volume, lane occupancy, and average speed for a selectable time period. In limited testing, its speed accuracy was ± 10 percent compared to inductive loop detectors. It does not currently classify vehicles, but this addition is being planned. Its power requirements are low, 5 to 6 watts, allowing the use of solar panels. The cost of this sensor is \$1,450 per unit, with one required per lane per detection location. This system also requires a controller card at a cost of \$800, which can accommodate four sensors. Mounting requirements are a minimum of 6 meters (20 feet) overhead and 7.6 meters (25 feet) horizontal distance from the travel lane. It can be mounted in a side fire or parallel direction. According to available information, there is no interference due to inclement weather, other than very dense fog.

5.0 Summary of Data Collection Equipment Characteristics

Table 7-1 provides a summary of the different types of equipment that can be used to collect data.

Table 7-1. Summary of Data Collection Equipment

Type	Location	Detection Mode	Detection Area	Cost	Life	Reliability	Technology
Loop Detectors	embedded, on-pavement	pulse, presence	size of loop	low	moderate	high	current
Magnetometers	embedded	pulse, presence	small	moderate	long	high	current
Magnetic	embedded	pulse, presence	large	moderate	long	moderate	current
Piezoelectric	embedded, on-pavement	mechanical stress	length of strip	low	moderate	high	current
Pneumatic Tubes	on-pavement	pulse	length of tube	low	short	low	current
Tapeswitches	on-pavement	pulse	length of switch	low	short	moderate	current
Cameras	above-pavement	optical	variable	high	long	high	current
Aircraft	airborne	visual	variable	high	long	high	current
Vehicle	roadway	visual, mechanical	variable	low	long	low	current
Plastic Loop	embedded	pulse, presence	size of loop	low	long	high	developing
Infrared	roadside, above-pavement	pulse, presence	small	high	long	high	developing
Ultrasonic	roadside, above-pavement	pulse, presence	moderate	high	moderate	high	developing
Microwave and Radar	roadside, above-pavement	pulse, presence	moderate	high	long	high	developing
Laser	roadside, above-pavement	pulse, presence	small	high	moderate	high	developing
Image Processing	above-pavement	presence	variable	high	moderate	moderate	developing
Automatic Vehicle Identification	in-vehicle with on- or above-pavement	presence, account number	variable	moderate	long	high	developing
Acoustic	roadside, above-pavement	presence	small	moderate	moderate	high	developing

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DATA COMMUNICATION EQUIPMENT

1.0 Function

Once the data is collected by the at-site detectors, it may be collected manually from the device or it may be sent via a communication system to a data collection hub. The path over which the information flows is called a transmission link, or channel, and the composition of the transmission link is called the communication medium. A modulator converts original information into a signal that can be efficiently transmitted over the channel, and a demodulator at the receiving end converts the information to its original form.

Communication systems have three major functions:

- ◆ the transmission of data on current operations and performance of traffic and the devices,
- ◆ the transmission of voice communications for applications such as: between field maintenance personnel and the control center, disabled motorists using the emergency roadside telephones or call boxes, and for the highway advisory radio systems (see Chapter 11, Section 3, Segment 2.0) for communication to drivers over the car radio, and
- ◆ the transmission of video images from closed-circuit television cameras.

The first two functions have communication loads and timing requirements that are well within the ranges of standard data transmission. However, video transmission requires a bandwidth (communication load) that greatly exceeds that of the data and voice functions.

The communication element of a traffic control system is critical for the successful implementation, operation, maintenance, and expansion of a system. It is also one of the most costly elements. The publication *Communications Handbook for Traffic Control Systems* provides information on how to plan, select, design, implement, operate, and maintain communications systems for traffic control. The report contains information on communications fundamentals, field equipment interfaces, communications requirements, communications architecture, land line alternatives, wireless alternatives, system and institutional concerns, and standards. Another publication, *Communications in Traffic Control Systems (Volume II: Final Report)*, provides information on communications in general and on specific communication technologies. The report includes a brief tutorial on communications technology and terminology; guidelines for conducting a thorough communications trade-off analysis; a detailed discussion of the types of communication media widely used in traffic control and the successful design and installation of these media; and a discussion of developing technologies. The National Cooperative Highway Research Program report on *Transportation Telecommunication* provides information on the fundamentals of telecommunications, the types of systems available, the current uses in state departments of transportation, and the implementation procedures and alternatives.

2.0 Concepts

In order to be able to discuss and understand the basics of communication technology for traffic surveillance and control, one must be familiar with the basic data communications components that make up a system. The sections that follow summarize those components that are required or exist naturally for each communication system.

2.1 Information Source

An information source is a unit capable of collecting and transmitting data. Inductive loop detectors, closed-circuit television cameras, and roadside mounted radar detectors are examples of information sources in the field, while a computer would be an information source at the TMC. Before data can be transmitted from the information source, it must first be modulated or converted to a signal for efficient transmission over a communication link.

2.2 Signal

Communication signals can be represented graphically by a sine wave that represents the variation of the magnitude of signal amplitude (signal strength or intensity) with respect to time. The rate at which this amplitude varies is the signal's frequency, which is defined as the reciprocal of the period or length of one cycle. Signal frequency is measured in units of hertz (Hz) or cycles per second.

Information can be transmitted in one of two signal forms: analog or digital. Analog transmissions are characterized by a continuously varying amplitude signal. Digital transmission, on the other hand, is characterized by a signal with a discretely varying amplitude. Traffic control communication systems typically make use of the digital signal form.

2.3 Modulation

To transfer data from the information source to the receiver, a carrier or continuous frequency is modulated and transmitted over a communication medium, e.g. phone line, radio, etc. This is accomplished by manipulating a property of the carrier line voltage, such as its amplitude or frequency, to be analogous with the information to be transmitted. Upon reaching the other end of the line, the signal must be demodulated to decode the transmitted information. The modulation and demodulation process is accomplished with the use of a *modulator* - *demodulator*, or *modem*.

2.4 Transmission Link or Channel

The path used to transmit the modulated signal is known as the transmission link or channel. The channel medium describes the type of communication link the signal travels over, such as copper cable, fiber optic line, voice grade line, and microwave. Several important characteristics of a channel medium are its bandwidth, attenuation, and power budget.

The bandwidth of a channel refers to the range of frequencies the channel is capable of transmitting without significant attenuation, or loss of signal strength. The usable bandwidth of a channel is determined by the physical and electrical properties of the channel medium. A channel with a larger bandwidth will be capable of transmitting information at a higher rate than a channel with a narrower bandwidth. The rate information transmitted over a channel medium is referred to as the baud rate, measured in bits per second (bps). A channel baud rate of 2400 bps transmits 2400 bits per second or approximately 240 characters per second.

Attenuation describes the loss of signal strength or amplitude as a signal is transmitted from one location to another. The sources and magnitude of attenuation are directly related to the channel medium. Regardless of channel medium, the result of attenuation is reduced signal strength, making the signal more susceptible to noise and interference. Amplifiers are often used on long cable lengths to counteract the effects of attenuation.

The power budget in a system refers to maximum allowable loss in signal strength to fall within the dynamic range of the receiver. Receivers have maximum and minimum input power levels between which signals can be received without distortion and increased error. The difference between the maximum and minimum limits of the receiver defines its dynamic range. Power budget calculations are performed by system engineers to determine whether or not a signal's strength will need to be reduced or amplified to fall within the dynamic range of the receiver. These calculations are a function of the transmitting power of the source, attenuation in the channel medium and connectors, and the dynamic range of the receiver.

2.5 Multiplexing

Multiplexing allows signals from two or more sources to be transmitted simultaneously over the same communication channel, greatly increasing the data-carrying capacity of the channel. The three types of multiplexing are:

- ◆ Frequency-division multiplexing (FDM),
- ◆ Time-division multiplexing (TDM), and
- ◆ Code-division multiplexing (CDM).

A system using FDM assigns each signal a subband of frequencies within the total channel bandwidth. Thus, signals can be transmitted simultaneously at different frequencies on a single channel. TDM assigns each signal a time interval within a polling cycle. The multiplexer sequentially samples and transmits each signal serially. In CDM, the signals are encoded with different binary sequences that allow them to simultaneously share the same frequency band.

2.6 Noise and Interference

After the signal has been transmitted and begins to travel down the communication channel, it becomes susceptible to outside noise and interference, potentially causing errors or incorrect output at the receiver. Noise is a signal disturbance caused by sources other than the signal being transmitted including:

- ◆ transmitter,
- ◆ receiver,
- ◆ lightning,
- ◆ power lines,
- ◆ car ignitions, or
- ◆ motors.

Interference is a signal disturbance caused by sources such as signals from other channels in the same network (crosstalk), interference from an unrelated channel (another transmitter broadcasting at the same frequency), or interference induced within the channel by the signal itself (echo).

2.7 Error Detection and Control

Error detection techniques are an important part of insuring that the transmitted data are reliable and accurate. Two approaches to detecting and correcting signal errors are the automatic repeat request and forward error control. Most commonly, if an error is detected using the automatic repeat request approach, then a request is sent to the transmitter to repeat the message transmission. The forward error control approach transmits error correcting codes, capable of correcting a limited number of errors, along with the signal. Forward error control has found little application with traffic control systems.

2.8 Data Transmission

Directional data flow on a channel can be described as simplex, half duplex, or full duplex. A simplex channel is only capable of transmitting data in one direction. A half duplex channel has the capability of sending information in both directions; however, the channel can only operate in one direction at a time. Full duplex allows for data flow in both directions at the same time. All three types of transmission are applicable to traffic control communication systems; however, critical links in the network which may require status checks or error handling should incorporate half duplex or full duplex capabilities.

Data transmissions can be classified as parallel or serial. Parallel transmission uses multiple channels to simultaneously transmit data from various sources. Because of the higher costs associated with parallel transmissions, most traffic control systems make use of serial transmissions. Serial transmissions utilize a multiplexer to transmit data from various sources on a single channel. Serial communication is simple in that only one bit of information is transferred at a time. This makes serial communication slower than parallel, but at a much lower cost.

2.9 Communication Architectures

Communication architectures refer to the organization of the system with respect to the way system elements are linked together. The communication architectures applicable for traffic control systems are as follows:

- ◆ central architecture,
- ◆ distributed architecture, or
- ◆ hybrid architecture.

Central architectures have been chosen for the development of many signal systems, freeway surveillance systems, and ramp metering systems. In a central architecture, only one level of computations occurs before a data signal reaches the field controller. In addition, only one data rate and protocol exist for communication between the field controller and the control center. With a distributed architecture, multiple levels of computation are possible in the field. In addition, a variable data rate may exist between the field controller and the central control. Distributed architectures have been used with closed loop signal systems. Two types of hybrid architectures are the backbone architecture and the multimedia architecture. Backbone architectures feature a high data transmission rate backbone channel that connects a series of communication hubs. Each hub is connected to multiple field controllers with low data rate channels. A multimedia architecture uses a multimedia channel that is capable of handling different types of signals, e.g., voice, data, and video, between the control center and field controller without altering the data rate or protocol.

3.0 Electronic Transmission Systems

The primary media considered for transmission of electronic traffic data are twisted wire pair cable, coaxial cable, fiber optic cable, microwave radio, narrow band radio, or spread spectrum radio. The systems can be used to transmit digital, voice, and/or video data. Technologies that should be considered for future applications are satellite communications and airborne lasers.

3.1 Twisted Wire Pair Cable (digital, voice)

Twisted wire pair cable is used for data and voice transmission. Transmission over distances of 16 to 25 kilometers (10 to 15 miles) are possible without repeaters. This medium is commonly found in surveillance systems, and is often used in area networks to interconnect devices. However, it is not typically used for the trunk line that carries information from several devices to a control center because of the greater capacity requirements.

3.2 Coaxial Cable (video, digital, voice)

Coaxial cable is the technology most commonly applied to cable television. As with twisted wire pair, it is easily applied to situations requiring connections with numerous field devices. Coaxial cable is suited for video, data, and voice transmission. One problem with this medium is the need for amplification and system maintenance with longer distances. The medium is also susceptible to outside interference from electrical sources.

3.3 Fiberoptic Cable (video, digital, voice)

Fiberoptics communication uses pulsating light waves to digitally transmit data. This can be used to transmit data, voice, and video and has proven to be reliable and free from electrical interference common to wire cable systems. The medium appears to be best suited for long distance trunk applications for digital data and for limited video data, although improvements in the area of short haul transmission and in the capacity of video transmission are expected. The cost of fiberoptic technology is also becoming more competitive with other technologies.

3.4 Microwave (video, digital, voice)

Microwave technology is best suited for the transmission of voice and digital data in a trunking capacity, although it is also used for video transmission. The system requires line of sight between transmitter and receiver, and approval by the Federal Communication Commission (FCC). An FCC license may be difficult to obtain in communication intense urban areas. Transmissions may be adversely affected by environmental factors for short periods of time. The costs are competitive with cable systems.

3.5 Radio (digital, voice)

Radio technology can be used for transmitting limited amounts of voice or digital information. Because of insufficient channel space to allow data transmission to and from many field devices, radio does not appear to be an appropriate medium for use in a traffic management system. It also does not provide the necessary capacity for the trunking function. A Federal Communication Commission (FCC) license is required and may be difficult to obtain in some urban areas.

Radio technology can also be used to communicate information to drivers in vehicles. An emerging technology for radio communications with drivers is Side Carrier Allocation (SCA) Networks, which are discussed in Chapter 11, Section 4, Segment 4.0.

3.6 Narrow Band Radio (digital, voice)

Narrow band radio technology can be used for transmitting limited amounts of voice or digital information. It does not appear to be appropriate as a major component of the surveillance design because of insufficient channel space to allow data transmission to and from many field devices, nor does it provide the necessary capacity for the trunking function. An FCC license is required and may be difficult to obtain in some urban areas.

3.7 Spread Spectrum Radio (digital, voice)

Spread spectrum radio spreads transmit power over a very wide bandwidth so that the power per unit bandwidth (watts per hertz) is minimized. This technology requires line-of-sight data links and can be adapted to handle surveillance and traffic control functions. It does not require individual user licensing from the FCC.

4.0 Closed-Circuit Television Transmission

Images from cameras are transmitted to a control center using one of the following three video transmission types:

4.1 Real-Time Motion

Real-time motion presents the visual images at 30 frames per second. At this rate no information is lost. It has the most limiting communication requirements of the three video transmission types.

4.2 Compressed Video

Compressed video collects and processes the video picture and transmits the information at rates of 1 frame per second or less. Because the picture is updated only once every second, some information is lost between the presentation of the picture frames. However, motion of the vehicles is discernable. An advantage of compressed video transmission is that the information can be transmitted over normal telephone lines and cellular channels. However, there are costly additional data processing equipment needs at the camera and at the monitor.

4.3 Slow Scan Video

Slow scan video collects and processes the data from one frame and then transmits the information over telephone lines at rates of 5 to 10 seconds per frame. Because of the considerable time lag between picture updates, motion of the vehicle is not discernable. As with compressed video, slow scan video information can be transmitted over normal telephone lines and cellular channels and requires additional data processing equipment at the camera and at the monitor. However, this equipment is less costly than that for a compressed video system.

The desired design for CCTV for traffic surveillance is the real-time motion transmission. If this transmission system is not available, then the compressed video is preferred. The slow scan television has limited applications, but can be used to monitor such operations as emergency call boxes, dynamic message sign operations, gates, and other control devices. Some traffic information, such as the presence of traffic queues, can be monitored with slow scan video, but the time required to transmit and evaluate the transmissions often are excessive for a traffic responsive system.

5.0 In-Vehicle Communication Equipment

Drivers in the traffic stream and individuals responding to an incident or an crash can report traffic conditions or incidents using in-vehicle communication devices such as cellular telephones or Citizen-Band radios.

5.1 Cellular Telephone

Increasingly, authorities are receiving information on traffic conditions and incidents from drivers with cellular phones. Some areas have established Freeway Telephone Trouble Numbers that can be used to notify or request aid for stranded motorists. A single toll free number is established that is tied to the dispatch centers of the police or other agencies responsible for responding to incidents. The number can be used from existing telephones along the freeway corridor or by mobile cellular telephone users. A number such as 999 or CALLMAP (225-5627) should be used since it can be easily remembered by motorists. Advantages of the system include low start-up cost and the two-way communication capability between an on-site observer and the response agency. However, the incident detection capability is limited by the number of cellular phones existing in an area and a driver's willingness to report an incident. A campaign to inform drivers of the existence of a Freeway Telephone Trouble Number and the benefits of reporting the incident may minimize this disadvantage. It is also important to have a way to inform motorists that an incident has been reported, so that the operating agency does not continue to be swamped with calls to report the same incident over and over.

5.2 Citizen-Band (CB) Radio

Drivers equipped with Citizen-Band (CB) radios in their vehicle can report traffic conditions or an observed incident to a central monitoring center which, in turn, transmits the information to the appropriate agency for dispatch of the required assistance. Signs informing motorists of the channels that are monitored are recommended. Local CB clubs or other citizen volunteer organizations can be used to staff the central monitoring center. Mobile CB monitors installed in incident response vehicles can reduce response time and eliminate the need for an extensive communications network.

Since two-way communication exists between motorists and the response agency, the nature of the traffic conditions and the type of response required by incidents can be more readily determined. This is the primary advantage of these methods. The primary disadvantage is that the detection capability of the system is dependent upon the number of cellular telephone and CB equipped vehicles on the freeway at any given time and the willingness of the operators to use their devices to report incidents. Few passenger cars are equipped with CB radios, although many of the large trucks use them. Weather effects, potential false reports, and interference from other electronic devices are other disadvantages of this system.

Chapter 11, Section 3, Segment 5.0 contains information on the use of CB radio to provide motorists with information about highway conditions.

6.0 Summary of Data Communication Equipment Characteristics

Table 7-2 provides a summary of the different types of equipment that can be used to communicate data.

Table 7-2. Summary of Data Communication Equipment

Equipment Type	Data Type	Data Capabilities	Cost	Distance Capabilities	FCC License Required	Technology
Twisted Wire	digital, voice	low	low	long	no	current
Coaxial	video, digital, voice	moderate	moderate	short	no	current
Fiber Optic	video, digital, voice	high	high	long	no	current
Microwave	video, digital, voice	high	moderate	line-of-sight	yes	current
Radio	digital, voice	low	low	long	yes	current
Narrow Band	digital, voice	low	low	long	yes	current
Spread Spectrum	digital, voice	low	moderate	line-of-sight	no	new
Cellular Telephone	digital, voice	low	low	moderate	no	current
Citizen-Band Radio	digital, voice	low	low	moderate	no	current

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USES OF DATA

The data collected by a data collection system can have several uses. It can be used to determine the system's characteristics and to evaluate the traffic operations on the system. Traffic data is also used to detect incidents and in making decisions on control strategies.

1.0 System Characteristics Determination

One of the principal uses of data in systems operation is for the determination of system characteristics. These include but are not limited to: total travel, total travel time, average speed, number of stops, fuel consumption, and vehicle emissions. Total travel for a specific length of roadway expresses the productivity of operations in terms of vehicle or person kilometers (miles) of travel. Total travel time is the summation of each vehicle's travel time during a specific time period for a specific length of road. The number of stops that vehicles are required to make while traveling through a freeway section or an arterial street network is a measure of the efficiency of signal systems or other traffic management strategies. Fuel consumption and vehicle emissions are frequently used to estimate the impacts of operational and design changes.

2.0 Evaluating Operations

The data from a collection system is also used to evaluate the operations of a management system. The data does not need to be in real-time; however, the data should reflect the conditions being evaluated. For example, if a ramp metering plan is being evaluated, data for both before and after the implementation of the plan may be necessary for the evaluation. Chapter 8 discusses various evaluation techniques for different elements of the system management program, for site specific controls, and for the quality of traffic operations in a corridor or area.

3.0 Detecting Incidents

Collected data can also be used to detect incidents in any part of the system under surveillance. Once an incident is detected, located, and verified, an appropriate response is determined and initiated. Real-time data is required if incident detection is to be used to manage operations in the system. Some of the techniques that can be used for incident detection are described in Chapter 7, Section 6. Chapter 9 addresses the response to and management of incidents.

4.0 Decisions on Control Strategies

Traffic data is also used to determine which types of control strategies should be implemented. Traffic counts, when compared to available capacity on a freeway, its ramps, and the parallel streets, assist in the decision on the method of ramp metering control and signal timing alterations needed. Those counts could also be used to determine if mainline control, freeway lane closure, ramp closure, or signal timing changes are necessary for improved traffic operations in the area. Chapter 10 discusses various control strategies available for traffic management.

5.0 Administrative Issues

The design of a traffic control communication system is based on a host of factors other than the state of the art of existing technologies. Administrative issues that impact system design include the agency's ability to maintain a given system, the possibility of future expansion, equipment compatibility standards, and local institutional issues.

5.1 Maintainability and Expandability

For a communication system to operate effectively with minimal down time, it must be designed with maintainability in mind. It is important that an agency have the ability to maintain the communication system, whether in-house or contracted. If the transportation agency is to maintain the system, it is important to develop a maintenance plan, purchase necessary communication testing equipment, and have maintenance technicians in place to receive training from the contractor while the system is being installed. The ease of maintaining a system will be increased if all system components use common standards. The use of non-standard equipment can lead to problems such as the potential inability to acquire specialized repair parts from the manufacturer in the future and limited future system expandability due to compatibility mismatches. All agencies with utility lines in a common right-of-way should coordinate any construction and maintenance to reduce the potential for damage to communication lines.

To provide for future expansion, designers should consider expansion of system functions at a given controller site, e.g., addition of lane control signals, addition of new controllers within the current project limits, expansion of the system to sites neighboring the current project limits, and expansion of the system to sites remote from the current project limits. Several techniques for providing future expansion requirement in a communication system include:

- ◆ Provision of spare function or bit capacity within current communication protocol,
- ◆ Provision of additional controller capacity in polling cycle,
- ◆ Provision of spare channel capacity in communication cable,
- ◆ Provision of trunked cable capacity in conduit,
- ◆ Addition of spare ports in central computer complex,
- ◆ Addition of communications server to central computer complex, and
- ◆ Acquisition of area radio channels from other agencies whose need has diminished or terminated.

5.2 Standards and Protocols

The use of communication equipment designed to commonly used standards greatly increases the reliability, maintainability, and expandability of the system. System elements that should be considered for standardized use in the project specifications include the serial data interface, modems, voice band channels, digital signals, fiberoptics, integrated services, compressed video, and local area network. Some of the benefits of standardization include greater ease of finding replacement parts, greater ease of finding compatible equipment for future expansion, greater availability of testing equipment, and availability of support manuals.

5.3 Institutional Issues

Institutional and local issues can often impact the final communication system design as much as the technical evaluation of alternative systems. Common issues include:

- ◆ Possible use of existing conduit, cable, and controllers for cost savings,
- ◆ User preference based on investment in existing system,
- ◆ Availability of franchises with power or telephone companies to obtain conduit or pole rights,
- ◆ Technical ability of agency to maintain a given communication system,
- ◆ System reliability to minimize down time, and
- ◆ Standardization to conform with existing components or for future expansion.

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INCIDENT DETECTION TECHNIQUES

Two methods frequently used to collect traffic data are electronic surveillance and closed-circuit television. Electronic surveillance utilizes detectors placed along the roadway. Closed-circuit televisions utilize cameras to view traffic. These methods are also frequently used to detect incidents.

Other methods are also used to survey the roadway for incidents. These other methods are not typically considered a part of a data collection system in the sense that traffic measurements are taken. Two such procedures that provide information on incidents are visual observations taken from stationary or moving patrol vehicles and aircraft and reports transmitted by motorists from telephones and roadside call boxes.

Frequently, a combination of detection methods is used so that the ability to detect and verify potential incidents is maximized. The best method or combination of methods depends upon the desired objectives of the incident management system.

1.0 Electronic Surveillance

Electronic surveillance provides real-time monitoring of traffic data through the use of detectors installed along the freeway. Sensors, usually loop detectors embedded in the pavement, are placed along the roadway and on ramps to automatically detect changes to traffic conditions. Some general guidelines indicate that detector spacings over 0.8 kilometer (0.5 mile) produce information which is inadequate for incident detection purposes. In contrast, decreasing spacings below 0.4 kilometer (0.25 mile) generally produces relatively little or no increase in effectiveness while increasing the cost.

Incidents are detected by logically evaluating the variations that occur in traffic flow. A signal is transmitted from the detector to a roadside terminal which is connected to a computer. An algorithm (Segment 1.1) in the computer interprets the signal. When measurements on the roadway exceed a predetermined threshold, an alarm is triggered signaling the operator of a potential incident.

1.1 Detection Algorithms

Traffic data is transmitted into a computer, and an algorithm is used to identify the presence of an incident. Although many detection algorithms and variations of algorithms have been developed and tested, no one algorithm has been found to be superior. The principal problems are the high number of false calls generated by the algorithms and the errors due to inaccurate detector information. The basis for incident detection algorithms is the detection of a disruption to a smooth, continuous flow of traffic. When the incident occurs in congested traffic, spacings between vehicles upstream of the incident decreases, and speeds drop; downstream of the incident, the spacing between vehicles increases and the speeds either remain high, or increase.

continued

1.1 Detection Algorithms (continued)

In general, there are two types of incident detection algorithms: pattern recognition and time series. Pattern-recognition algorithms deal with current traffic patterns and pay no attention to past traffic conditions. Time-series algorithms utilize short-term forecasting techniques to identify the sudden changes in traffic stream behavior which occur during incidents. In both types of algorithms, there is a trade-off in the relationship between the probabilities of detecting incidents and false alarms (signaling of an incident when no incident has occurred). In most cases, a high detection rate results in a high false alarm rate and a low false alarm rate may result in a low detection rate. Furthermore, as the sensitivity of the algorithm is adjusted to detect an incident more rapidly, the probability of generating false alarms increase.

Computer algorithms have been developed to detect incidents in freeway surveillance and control systems. Some of these algorithms compare direct measurements of traffic to preestablished thresholds. Others use statistical procedures to detect changes in traffic conditions over time. Still others use complex theoretical models to predict expected traffic conditions given current conditions and historical trends. The structure of an algorithm can greatly influence its performance in terms of detection rate, false alarm rate, and detection time. These three terms are typically used to assess the performance of incident detection algorithms.

Proper calibration of the algorithm also affects performance. Since geometric anomalies (i.e., lane drops, severe grades, etc.) affect traffic flow, algorithms must be calibrated on a zone-by-zone basis for them to be of use to the operators. Extensive amounts of data, effort, and time are required to properly calibrate an algorithm. In the comparison of algorithms, no single one appears to be superior in terms of its repeated performance, data requirements, ease of implementation, ease of calibration, and operational experience. Results from both on-line and off-line evaluations show that most algorithms achieve similar detection rates, false alarms, and detection times when they are properly calibrated.

2.0 Closed-Circuit Television

Closed-circuit television (CCTV) is used in control systems to detect and/or confirm the presence of an incident and quickly determine the nature and severity of the incident. The image from a CCTV image can also be used to provide an electronic input into an image processing system. Due to the extensive manpower required to constantly monitor the screens, CCTV as the sole detection system is limited to locations where delay-causing incidents occur with regular frequency and fast response is necessary. A primary value of CCTV is its ability to confirm and provide information about the cause of a specific congestion problem. Most CCTV systems are used in conjunction with electronic surveillance systems.

3.0 Motorist Assistance/Courtesy Patrols

Motorist assistance and/or courtesy patrols use vehicles circulating in the traffic stream with the primary purpose of identifying incidents, determining the nature and extent of the incident, providing motorists with assistance if needed, and dispatching the appropriate type of response. Systems for detecting incidents range from routine police patrols in which incident detection is only one of the normal law enforcement responsibilities of the unit, to specially equipped patrol vehicles dedicated to freeway incident detection and response. Some agencies also use special tow trucks, vans, and light-duty trucks as dedicated patrol vehicles. These vehicles are often equipped with gasoline transfer devices, push bumpers, roll-away dollies, multipurpose jacks, and other items necessary to provide routine or minor repairs to stalled vehicles or to remove the vehicle off the freeway. Motorist assistance/courtesy patrols are used to provide services ranging from basic assistance for stranded motorists (providing gasoline, water, air, jumper cables, etc.) to sophisticated management at incidents and emergencies (removing spilled loads, righting overturned vehicles, etc.).

The primary advantage of using motorist assistance/courtesy patrols for incident detection is that the detection and response mechanism can be one in the same. The police are usually the first agency to be dispatched to an incident in order to verify the incident and determine the necessary response; therefore, considerable time savings can be achieved by using the police. However, the availability of police for patrols is subject to other, more urgent demands of police work, including public safety needs. Also, many incidents do not require police assistance; therefore, freeway incident detection is not an efficient use of police time.

Patrols sponsored by local citizen groups, private organizations, or transportation agencies utilize the same concept of circulating through the traffic stream. They typically use specially equipped light-duty trucks or vans to detect and respond to incidents. Most patrols are equipped to provide routine assistance to stranded motorists by providing fuel, oil, water, tire changing services, and minor maintenance repairs. Often these vehicles are equipped with police department radios to improve communications and reduce response time.

The primary advantages of motorist assistance/courtesy patrols are that they provide rapid response to motorists' needs while freeing the police to respond to other public safety concerns. They are also cost-effective. A patrol system is costly to establish and operate. However, estimates of the benefit/cost ratio of existing programs range between 7:1 and 36:1.

The primary benefit of using motorist assistance/ courtesy patrols as an incident detection technique is that the time required to begin clearing the incident is greatly reduced. Since motorist assistance/courtesy patrols are equipped to handle most minor incidents, the response and clearance task can begin immediately once the patrol arrives on the scene. At major incidents, motorist assistance patrols can assist in the clearance functions by performing one or more of the following tasks:

continued

3.0 Motorist Assistance/Courtesy Patrols (continued)

- ◆ direct traffic at the incident scene,
- ◆ help plan and implement emergency detour routing,
- ◆ provide emergency medical assistance until additional help arrives,
- ◆ coordinate communications among various response agencies,
- ◆ provide traffic reports or other information to highway or enforcement personnel, local media, or the public, and
- ◆ provide emergency transportation to motorists and response to medical personnel.

Motorist assistance/courtesy patrols exist in the cities of Houston, Dallas, Fort Worth, Austin and San Antonio. Although TxDOT is involved in all of the programs, the degree of participation varies. The Dallas, Fort Worth, Austin and San Antonio patrols are all run and supported solely by TxDOT. The Houston patrol is operated by a unique combination of public and private agencies. *Incident Response and Clearance in the State of Texas: Case Studies of Four Motorist Assistance Patrols* provides descriptions of existing programs and useful insight into the various attributes that need to be considered when developing a motorist assistance program.

The time required for a patrol to detect an incident is directly related to the number and frequency of patrol vehicles. For example, the routes for the Houston program are such that a single patrol vehicle will pass at any given point on a freeway once per hour. Since patrols monitor both sides of the freeway at once, the effective headway between patrol vehicles is 30 minutes. As a result, the average detection time for incidents on a typical Houston freeway tends to be about 14 minutes.

4.0 Motorist Call Systems

Motorist call systems involve communication equipment located on the roadside. Typically, call devices are spaced at 0.4- to 0.8-kilometer (0.25- to 0.5-mile) intervals on both sides of a freeway. Motorists may have to stop at one of these devices in order to report traffic conditions or indicate a problem. There are three basic types of motorist call systems:

- ◆ Emergency Telephones,
- ◆ Emergency Call Boxes, and
- ◆ Cooperative Motorist-Aid Systems.

4.1 Emergency Telephones

With telephones, voice communication is used to transmit the details of the situation and the requests for assistance, if any. Emergency telephone systems typically experience fewer false alarms and provide greater certainty of dispatching the appropriate response than call box systems. They also allow more accurate reporting of traffic conditions and provide for two-way communication between the motorists and a dispatcher.

4.2 Emergency Call Boxes

With call boxes, the motorist presses one or more buttons that transmit pulse-coded messages to request various services (police, ambulance, wrecker services, etc.). Call box systems are generally less expensive to install than voice communication systems. With call boxes, confirmation that a distress call has been received is not typically displayed to the motorist; however, this can be remedied by placing a “message sent-message received” indicator in the call box.

4.3 Cooperative Motorist-Aid Systems

Cooperative motorist-aid systems utilize passing motorists or volunteer observers to report an incident. A system in which motorists flash their bright lights at light-sensitive sensors installed next to the roadway can be used to detect incidents. By monitoring each of the detectors, an indication that some sort of incident has occurred upstream of a particular detector location can be obtained. Drivers of transit vehicles can also provide a cooperative motorist-aid system. Another system uses volunteer observers located in buildings overlooking particular sections of freeway to detect incidents.

The cellular telephone has become the primary tool of a cooperative motorist-aid system. Chapter 11, Section 3, Segment 3.0 discusses the cellular telephone in more detail.

4.4 Advantages of Motorists Call Systems

- ◆ They are a relatively efficient method of signaling a potential interruption in the traffic stream, a motorist’s need for assistance, and can provide reassurance that aid is forthcoming.
- ◆ Cooperative motorist-aid systems have low installation and operating costs.
- ◆ Cooperative motorist-aid systems do not require the motorist to leave their vehicle in order to summon aid.

4.5 Disadvantages of Motorists Call Systems

- ◆ They rely upon individuals to provide a measure of traffic conditions.
- ◆ There is an inherent delay associated with the motorist deciding to use the system and making the appropriate report. This can result in significant detection times for incidents.
- ◆ There is a high initial installation cost associated with call boxes or telephones. As units must be installed at one or two locations per kilometer (two or three locations per mile) on both sides of a freeway, initial installation costs can be significant.
- ◆ They typically experience a large number of “gone-on-arrival” calls.
- ◆ Motorists may be exposed to passing traffic if they have to walk to the nearest call box or emergency telephone, increasing the potential for pedestrian/vehicle crashes.
- ◆ Call boxes may be subject to vandalism.

Due to the cost, vandalism, and response monitoring demands of motorists call systems, they are not normally used in Texas.

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OVERVIEW

Traffic operations analysis provides a mechanism for evaluating the movement of vehicles on a highway in order to obtain the maximum use of the facility. It can be used as an aid to help designers determine if the proposed geometrics will provide the needed service. It can also be used to evaluate improvements to existing highways in order to estimate the effectiveness of the improvements. Operations analysis can also be used to select components of a management system (Chapter 6).

This chapter provides an introduction to traffic operations characteristics, describes the philosophy of different analysis procedures, describes specific computer programs, and provides guidelines for the use of these computer programs. In a sense, the relationships and analysis procedures described in this chapter provide a miniature laboratory where experiments can be developed to estimate the effectiveness of design alternatives, improvements, or management strategies.

Most of the analysis procedures used to evaluate traffic operations can be performed on a computer, using various software programs. Several of these programs are discussed later in this chapter. However, these programs should not be used by individuals who do not have an understanding of the fundamentals upon which the procedures are based. Therefore, some basic fundamentals are presented in the first part of this chapter, followed by descriptions of specific computer programs used to perform an analysis.

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TRAFFIC OPERATIONS ANALYSIS

Traffic operations are analyzed in order to assure that driver expectancy and driver needs are being met and to provide a safe, effective, and efficient highway facility. The segments in this section describe the objective, benefits, and applications of traffic operations analysis.

1.0 Objective

The primary objective of traffic operations analysis is to provide a low-cost means of evaluating the effectiveness of highway designs, improvements, and management strategies that maximize traffic flow.

2.0 Benefits

There are many benefits of analyzing traffic operations. Primarily, operations analysis provides an opportunity to estimate changes in traffic flow without building or modifying the highway. As a result, the effectiveness of various design options can be determined with a fair amount of accuracy.

Another benefit of analyzing traffic operations includes the evaluation of potential improvements and traffic management strategies such as lane additions, ramp metering, or route diversions. Most analyses can be performed with readily available computer equipment, and the costs of performing an analysis is relatively low.

3.0 Applications

There are many different applications for traffic operations analysis. As previously mentioned, analyses can be used to evaluate a proposed highway design, highway improvements, or traffic management strategies. An analysis should also be conducted periodically after management strategies have been implemented in order to keep roadways or intersections operating efficiently. There are analysis procedures that can be used to analyze large areas such as a freeway corridor or small areas such as an interchange. Analyses can be used to evaluate the operation of weaving areas, the impacts of a work zone, the effectiveness of management strategies, and the capacity of a highway. Traffic operations analyses may also be used as part of a systemwide management program.

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TRAFFIC OPERATIONS CHARACTERISTICS

It is necessary to be familiar with traffic flow terminology before undertaking an analysis. The three basic traffic stream characteristics (flow, speed, and concentration) were introduced in Chapter 1, Section 5, Segment 3 and are summarized below:

- ◆ **Flow** - Number of vehicles passing a point during a given time period, typically measured in vehicles per day or vehicles per hour. Commonly referred to as volume.
- ◆ **Speed** - Motion of a vehicle, measured at a point (time-mean speed) or over a length of roadway (space-mean speed).
- ◆ **Concentration** - Measure of vehicle spacing, described as the density of traffic (vehicles per kilometer [mile]).

These three characteristics alone are not sufficient to describe traffic operations. A number of terms have been developed to describe specific aspects of traffic flow. The following sections define some of the terms which are most commonly used to describe traffic flow. The symbols used to represent these terms are also defined.

1.0 Flow and Movement

Traffic flow represents the use of the highway system and is often related to the capacity. Flow can be less than demand (the number desiring to use the facility) due to limited capacity. Flow is the number of vehicles which pass a point during a given time period. Various flow measures are described below.

- ◆ **Traffic Volumes.** Traffic volumes are used to represent generalized traffic flow. Units of measure for traffic volumes include vehicles per day and vehicles per hour. Common measures of traffic volume are Average Daily Traffic (ADT) and hour volume. Traffic volumes do not account for the peaking characteristics of traffic (see Traffic Volume Variations below). Volumes are represented by the symbol Q .
- ◆ **Flow Rate.** Short-term traffic flow is represented by a *flow rate*. Flow rates are based on traffic counts of less than an hour which are expressed as an equivalent hourly flow rate. The unit of measure for flow rates is vehicles per hour. The flow rate is represented in equations by a q . As an example of converting a traffic count to a flow rate, if 325 vehicles pass a point during a 10-minute period, the flow rate is:

$$(325 \text{ vehicles}/10 \text{ minutes}) \times (60 \text{ minutes}/1 \text{ hour}) = 1,950 \text{ vehicles}/\text{hour}.$$

continued

1.0 Flow and Movement (continued)

- ◆ **Traffic Volume Variations.** Due consideration should be given to the time period and data used in an operational analysis (see Chapter 1, Section 7). One-hour volumes may not adequately account for variations in flow which occur during an hour. Therefore, the peak hour factor (PHF, see Chapter 1, Section 7, Segment 2) should be applied to one-hour volumes to obtain a peak flow rate. In addition to variations within a given time period, traffic flow also varies by the month, the day, and the time of day. An indication of the variability of Texas traffic can be obtained from the *Permanent Automatic Traffic Recorder Annual Report* published by TxDOT. This document summarizes traffic volumes over a one-year period at over 150 permanent count stations located throughout the state. This document also identifies the 30th highest hour volume (or design hour volume, DHV) and the K factor (ratio of DHV to AADT) for use in highway design.

- ◆ **Capacity.** Capacity is the maximum flow rate at which vehicles can be reasonably expected to traverse a point under prevailing roadway, traffic, and control conditions. The symbol q_m is used to represent the capacity or maximum flow rate. Chapter 8, Section 3, Segment 7.0 describes capacity concepts in greater detail.

2.0 Speed

Speed describes how fast a vehicle is moving, and is normally measured in kilometers (miles) per hour. In some cases, speed is measured in meters (feet) per second. Although speed is the preferred term, it has also been referred to as velocity. In general, speed is represented in equations by a u . All measures of speed can be classified as a space-mean speed or a time-mean speed.

- ◆ **Space-Mean Speed.** Space-mean speed is the average speed of a traffic stream and is computed by dividing the length of the roadway segment by the average travel time of the vehicles traversing the segment. Space-mean speed is represented in equations by u_s . Space-mean speeds are typically computed from travel time studies. If delays are not included in the calculation of the space-mean speed, then it is known as the **average running speed**. When delays are included, space-mean speed is typically referred to as the **average travel speed**.
- ◆ **Time-Mean Speed.** Time-mean speed is the average of individual vehicle speeds at a point on the roadway and is represented in equations with u_t . Time-mean speeds are also referred to as spot speeds because the measurement is made at a specific location or point. Time-mean speeds are typically measured with radar detectors or speed traps using vehicle detectors.
- ◆ **Comparison of Space-Mean and Time-Mean Speeds.** Space-mean speed provides a better indication of the speed of the traffic stream and is the most statistically relevant measure in relationships with other variables. Space-mean speeds are lower than the corresponding time-mean speeds, generally by about 2 to 5 kmph (1 to 3 mph).
- ◆ **Free-Flow Speed.** The free-flow speed is the speed when traffic is flowing freely on the facility. The symbol used to represent free-flow speed is u_f .

3.0 Concentration

Concentration is one of the terms used to describe the spacing of vehicles within the traffic stream. Concentration is most commonly measured in terms of density or headway. Concentration is a difficult parameter to measure and, therefore, is not normally obtained directly.

- ◆ **Density.** Density is the most common measure of concentration and represents the total number of vehicles occupying a highway segment of a given length. The unit of measure for density is vehicles per kilometer (mile). The only direct method of measuring density is by using aerial photographs to identify the number of vehicles in a highway segment of known length. Density is represented in equations by k . Subscripts can be used to denote various measures of density.
- ◆ **Headway.** Headway is often used as a measure of the spacing of vehicles. Headway is a measure of the time interval between the same point on successive vehicles in the same lane. It is normally measured from the front bumper of the first vehicle to the front bumper of the second vehicle or from rear bumper to rear bumper. The symbol for headway is h .
- ◆ **Lane Occupancy.** Another indication of traffic density is lane occupancy. Lane occupancy represents the percentage of time that a vehicle is occupying a point in a lane.
- ◆ **Lane Distributions.** Lane distributions describe the distribution of vehicles among the lanes of a facility. It is normally described as the percentage in each lane of the total number of vehicles.

4.0 Vehicle Terminology

The vehicles in the traffic stream can be described by the percentage of various vehicle types, passenger car equivalents, and vehicle occupancy.

- ◆ **Vehicle Types.** Vehicle types have an impact on the interaction of vehicles on a highway. Vehicle classifications indicate the number and types of vehicles in the traffic stream so that traffic flow can be evaluated more accurately. The major interest of vehicle classifications is heavy vehicles. Heavy vehicles can be large trucks, buses, recreational vehicles, or any other vehicle with operating characteristics different than a passenger car. A simple working definition of heavy vehicles is those vehicles with more than two axles.
- ◆ **Passenger Car Equivalents (pce).** Heavy vehicles are usually present, and the size and operating characteristics of these vehicles impact operations more so than do passenger cars. Heavy vehicles are accounted for by converting them to an equivalent number of passenger cars. The passenger car equivalent is the number of passenger cars that are operationally equivalent to a single heavy vehicle of a particular type under prevailing roadway, traffic, and control conditions. The *1994 Highway Capacity Manual* contains a procedure for calculating the passenger car equivalents for freeway vehicles. In level terrain, the passenger car equivalent of trucks can be assumed to be two. As the grade and the length of the grade increases, the passenger car equivalent also increases.
- ◆ **Vehicle Occupancies.** Historically, the vehicle-carrying capacity of the highway was the primary concern of transportation officials; however, in recent years, more concern has been directed toward the people-carrying capacity of highways. In these cases, vehicle occupancy is used to define the people carrying capacity. Vehicle occupancy is the total number of persons in a vehicle. Average vehicle occupancy is normally used for a highway corridor and has wide application to high-occupancy vehicle operations.

5.0 Additional Terminology

Other terms commonly used in traffic operations analysis are described below.

- ◆ **Uninterrupted Flow.** Traffic flow where vehicles traversing a length of roadway are not required to stop as the result of causes external to the traffic stream, such as traffic control devices.
- ◆ **Interrupted Flow.** Traffic flow where vehicles traversing a length of roadway are delayed by external features, such as traffic control devices (e.g., traffic signals).
- ◆ **Recurrent Congestion.** Congestion which occurs repeatedly at the same time and place in subsequent weekdays.
- ◆ **Nonrecurrent Congestion.** Congestion which results from a random event such as a crash or road closure.

continued

5.0 Additional Terminology (continued)

- ◆ **Bottleneck.** A location where demand (the number of vehicles desiring to use a facility) exceeds capacity. Typical bottlenecks are geometric features such as a lane drop or an increase in grade or locations with high demand such as entrance ramps.
- ◆ **Queue.** An accumulation of vehicles upstream of a bottleneck.
- ◆ **Platoon.** A group of vehicles traveling together at the speed set by the lead vehicle, rather than at the speeds preferred by the following vehicles.
- ◆ **Shock Wave.** A boundary between different flow-density concentrations in the traffic stream.
- ◆ **Critical Gap.** The minimum time interval between vehicles in a major traffic stream that permits side-street vehicle at a stop-controlled approach to enter the intersection under prevailing traffic and roadway conditions.
- ◆ **v/c Ratio.** The ratio of demand flow rate to capacity for a traffic facility.
- ◆ **Average Stopped-Time Delay.** The total time vehicles are stopped in an intersection approach or lane group during a specified time interval divided by the volume departing from the approach or lane group during the same time period.
- ◆ **Average Total Delay.** The total additional travel time experienced by drivers, passengers, or pedestrians as a result of control measures and interaction from other users of the the facility, divided by the volume departing from the corresponding cross section of the facility.
- ◆ **Weaving Area.** A length of highway over which traffic streams cross each other's path without the aid of traffic signals, doing so through lane-changing maneuvers.

6.0 Traffic Flow Relationships and Analysis

Traffic operations analysis may be defined as the description of traffic behavior by the application of systematic procedures utilizing equations and established relationships. At the present time, there is no single theory which explains the movement of vehicles on a highway. Instead there are several different approaches. Figure 8-1 illustrates generalized relationships between flow, speed, and density. The solid dots represent traffic in free flow conditions, and the hollow dots represent forced flow traffic located upstream of a capacity restriction.

The exact shape of the curves used to represent the points in Figure 8-1 is subject to some debate. Research efforts continue to identify and understand the complex relationships that exist between various traffic parameters. Chapter 2 of the *1994 Highway Capacity Manual* provides more information on the relationships between flow, speed, and density.

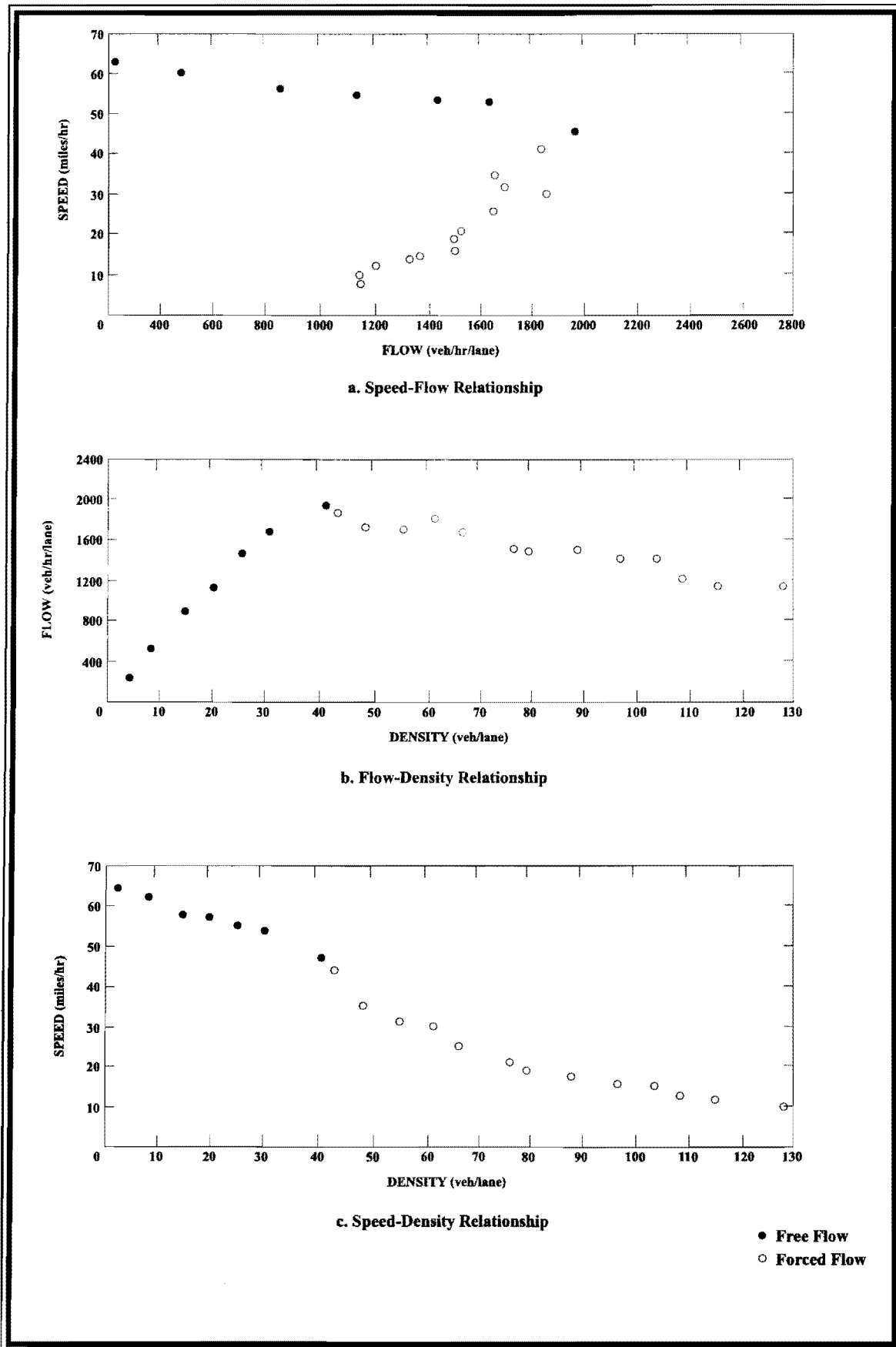


Figure 8-1. Flow, Speed, and Density Relationships

7.0 Capacity

A clear understanding of the concept of capacity is a fundamental requirement for operations analysis. The capacity of a section of highway is the maximum flow rate at which vehicles can be reasonably expected to traverse the section of highway under the prevailing roadway, traffic, and control conditions. While a highway can be divided into a number of sections, each with its own capacity, the capacity of the full length of the highway is determined by the section with the lowest capacity. When traffic demand is higher than the capacity of a section of highway, queues will form upstream of the point where the lower capacity section begins. The area limiting operations is known as a bottleneck.

7.1 Freeway Capacity

Traditionally, the ideal capacity for freeways has been assumed to be 2,000 passenger cars per hour per lane (pcphpl). However, recent research has shown that a more accurate representation of freeway capacity is 2,300 pcphpl. It should be noted that the 2,300 pcphpl represents the average capacity across all lanes. Actual traffic flow rates for individual lanes may be even higher. The higher flow rates are found on the inside (or median) lanes.

7.2 Capacity Restrictions

The most common factors which decrease the capacity of a roadway are stated below:

- ◆ The number of lanes are reduced due to a lane drop, an incident in a lane, or a lane closure in a work zone.
- ◆ Vehicles merge into the traffic stream from an entrance ramp.
- ◆ Vehicles enter and exit a section of highway within close proximity to each other (these areas are known as weaving sections).
- ◆ An incident that is located within the highway right-of-way (Chapter 9, Section 2, Segment 2.1 addresses the reduction in capacity due to incidents). An incident does not have to block a lane to reduce the capacity of the highway.
- ◆ Restrictive highway geometrics cause vehicles to slow down and cause turbulence in the traffic stream. Sharp horizontal curves or vertical upgrades are typical examples of geometrics which may cause a reduction in capacity.
- ◆ The presence of heavy vehicles may also create turbulence in the traffic stream, causing a reduction in capacity.

Exit ramps typically have little impact on capacity if the exit ramp is isolated from the affects of upstream or downstream ramps and adequate capacity exists on the ramp and its terminus.

A capacity restriction downstream of an entrance ramp may cause queues which extend upstream of the entrance ramp. Despite the fact that the entrance ramp vehicles are entering stop-and-go flow on the freeway, all the entrance ramp demand will be able to enter the freeway, up to a volume of about 1,000 vehicles per hour on the entrance ramp.

continued

7.2 Capacity Restrictions (continued)

Figure 8-2 illustrates traffic flow on a freeway with capacity restrictions. The freeway illustrated in Figure 8-2 consists of 5 sections of varying capacities. Sections A, C, and E are basic freeway segments with no capacity-reducing influences. Section B is a merging area located at an entrance ramp. The capacity of Section B is primarily a function of the freeway traffic volume and the entrance ramp volume. Even though there are four freeway lanes through Section B, the capacity of this section may be less than four lanes of traffic due to the turbulence created by high volumes entering the freeway or limitations in geometrics. Section D represents a lane closure or lane drop. The capacity of Section D may be less than three lanes of traffic because of the turbulence created when traffic redistributes itself from four lanes to three lanes. The overall capacity of this highway is determined by Section D, because that section controls the maximum number of vehicles which can travel through the highway.

The hypothetical speeds through this freeway are illustrated in the lower part of Figure 8-2. If the demand entering Section A is assumed to be equal to a little more than three lanes of capacity, free-flow speeds of 88 to 96 kmph (55 to 60 mph) are present because volumes are well below capacity. The speeds through Section B may decrease slightly due to the turbulence created by the entrance ramp. Although the figure does not illustrate the point, it is important to note that the entrance ramp has the greatest impact on freeway speeds on the outside lane and the least impact on the inside (or median) lane. Speeds will start to increase at the beginning of Section C, until free-flow speeds are reached. The traffic demand entering Section D is greater than the capacity of Section D, therefore, a queue will form. The queue will continue to increase in length until demand is reduced below capacity. The back of the queue forms a shock wave as it propagates back up the freeway. The speed of the traffic stream quickly drops from free-flow to stop-and-go conditions at the shock wave. Because the shock wave is moving upstream, the point of speed reduction is also moving upstream. The movement of the shock wave is shown by the cross-hatched area in Figure 8-2. Traffic between the leading edge of the shock wave and the bottleneck operates in stop-and-go conditions. As traffic enters the bottleneck at Section D and redistributes itself to three lanes, speeds begin to increase to the free-flow speed in Section E.

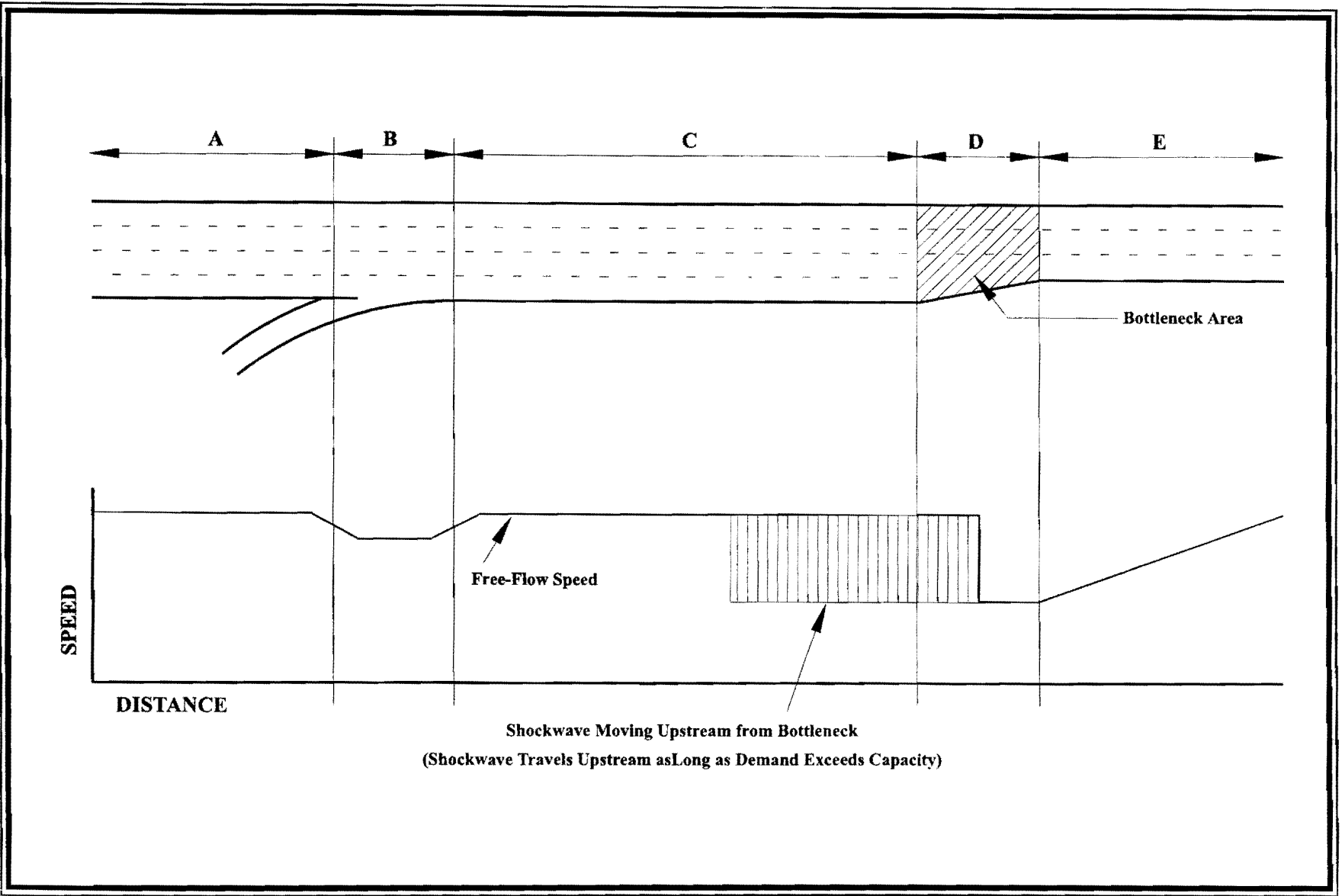


Figure 8-2. Traffic Flow Measurement

7.3 Capacity Measurement

The location where the capacity is measured must be carefully selected in order to provide an accurate representation of the capacity. Capacity, which can have a major influence on the results of an analysis, can be estimated using traffic counts downstream of existing bottlenecks along the freeway. The capacity of the highway is the volume discharging from the bottleneck. *It must be emphasized that traffic volumes measured in stop-and-go traffic upstream of a bottleneck do NOT represent capacity flows.*

Figure 8-3 illustrates the importance of location in the measurement of capacity. The freeway at the top of the figure includes four measurement stations as shown by A, B, C, and D. Speed, flow, and density are measured at each station. One section of the freeway has a lower capacity due to a lane drop. Station A is far enough upstream to be away from any influences of the lane drop, Station B is only a short distance upstream of the lane drop, Station C is the lane drop, and Station D is downstream of the lane drop.

When the demand increases from a very small flow to a flow equal to two lanes of capacity, the data collected at the measurement stations is represented in the speed-flow-density curves by the solid dots. Stations A, B, and D are operating at only two-thirds of capacity and at relatively high speeds and low densities. Station C has reached its capacity with significantly lower speeds and higher densities. As can be seen, the range in speed and density are relatively small for Stations A, B, and D. However, there is greater range in the values of the speed and density at Station C because demand is equal to capacity.

When the demand is equal to a flow equivalent to 2½ lanes of capacity, the resulting data measurements are represented by hollow dots. Station A is not influenced by the lane drop, therefore, the speeds are high since demand is less than capacity. Station B is identical to Station A until Station B is influenced by the lane drop. When this happens, flow at Station B will be equal to the flow at Station C. Speeds will decrease, densities will increase, and congestion will occur. There is a wide range in speed and density data measurements as traffic transitions from high speed, low density, to low speed, high density. At Station C, the flow will remain fairly uniform at the capacity because excess demand exists upstream of the bottleneck (lane drop). There is little range in speed and density. Although the capacity at Station D is three lanes and the demand is 2½ lanes, the flow at Station D will be the equivalent of two lanes, as that is all that can pass through Station C. Station D will exhibit high speeds and low densities.

Only Station C provides an accurate measurement of the capacity of the bottleneck. Some of the measurements at Station B represent the demand of 2½ lanes, while later measurements at Station B represent the flow of 2 lanes.

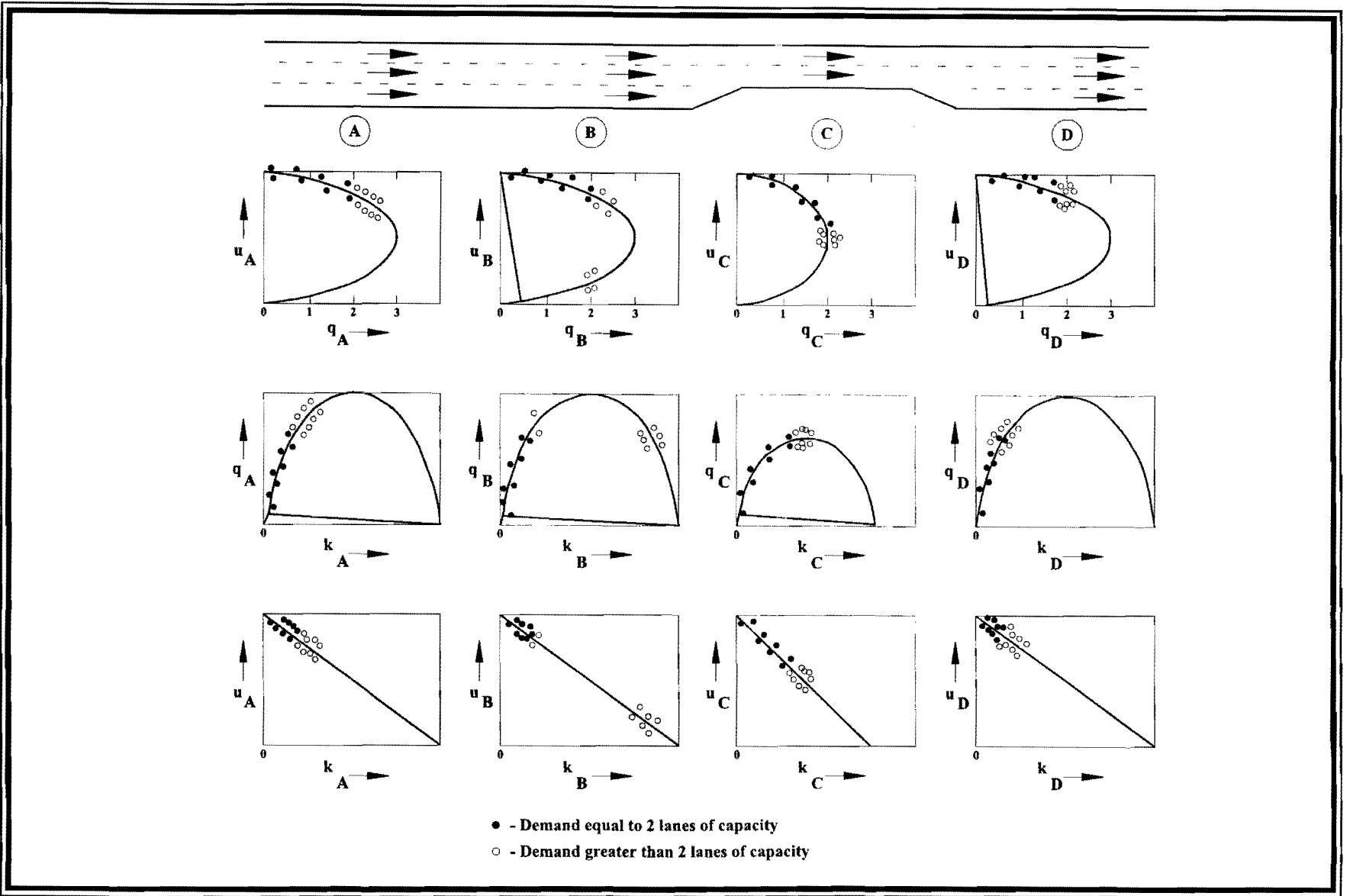


Figure 8-3. Importance of Location

7.4 Capacity Improvements

In some cases, a capacity improvement can be made to a section of highway which results in a higher level of service for the entire highway. In other cases, a capacity improvement to one section of highway will only reveal a previously unknown capacity restriction in another section. Therefore, a thorough understanding of the demand and capacity of individual sections of highway are needed before considering making capacity improvements to a highway.

Figure 8-4 illustrates how a capacity improvement to a freeway can reveal a hidden bottleneck. The freeway in Figure 8-4 consist of three lanes, one exit ramp, and two entrance ramps. Traffic volumes are measured at Stations 1, 2, 3, and 4. An auxiliary ramp is being considered as a capacity enhancing improvement downstream of the last entrance ramp. The demand for two different cases is shown in Table 1. The freeway demand (Demand A) for Case 1 is 200 vehicles per hour (vph) less than the freeway demand for Case 2. The entrance and exit ramp demands are identical for both cases.

Table 2 shows the capacity, demand, and flow for Cases 1 and 2 without a proposed auxiliary lane. The capacity at each measurement station is the same for both cases. The demand at each station is 200 vph higher for Case 2. The measured flow rates at each station are also identical, despite the different demands. In Case 1, demand does not exceed capacity until the last entrance ramp. A queue will begin at this entrance ramp and extend upstream. All of the demand at the entrance ramp will be accommodated; therefore, the flow at Station 3 is equal to the capacity at Station 4 minus Input D. In Case 2, demand exceeds capacity at Stations 3 and 4. However, the queue from Station 3 is contained within the queue from Station 4. As a result, Station 3 is a hidden bottleneck in Case 2.

Table 3 in Figure 8-4 shows the capacity, demand, and flow for each case if the auxiliary lane is provided. In Case 1, the additional capacity provided by the auxiliary at Station 4 results in the demand being less than capacity. No queues will form as a result. However, Case 2 reveals the hidden bottleneck. Although the Case 2 demand at Station 4 is less than capacity, the demand at Station 3 still exceeds the capacity at Station 3, causing a queue to form at Station 3 and extend upstream.

The example in Figure 8-4 illustrates that although the flow rates at Station 3 were well below capacity before the auxiliary lane was added, there was a hidden bottleneck at Station 3 in Case 2. Flow rates at a given location may not represent demand at that location. Demand must be considered in light of upstream and downstream demands and capacities.

Typical low cost improvements in bottlenecks include:

- ◆ using a short section of shoulder as an additional lane,
- ◆ restriping merge or diverge areas to better serve demand,
- ◆ reducing lane widths to add a lane,
- ◆ modifying weaving areas, and
- ◆ metering or closing entrance ramps.

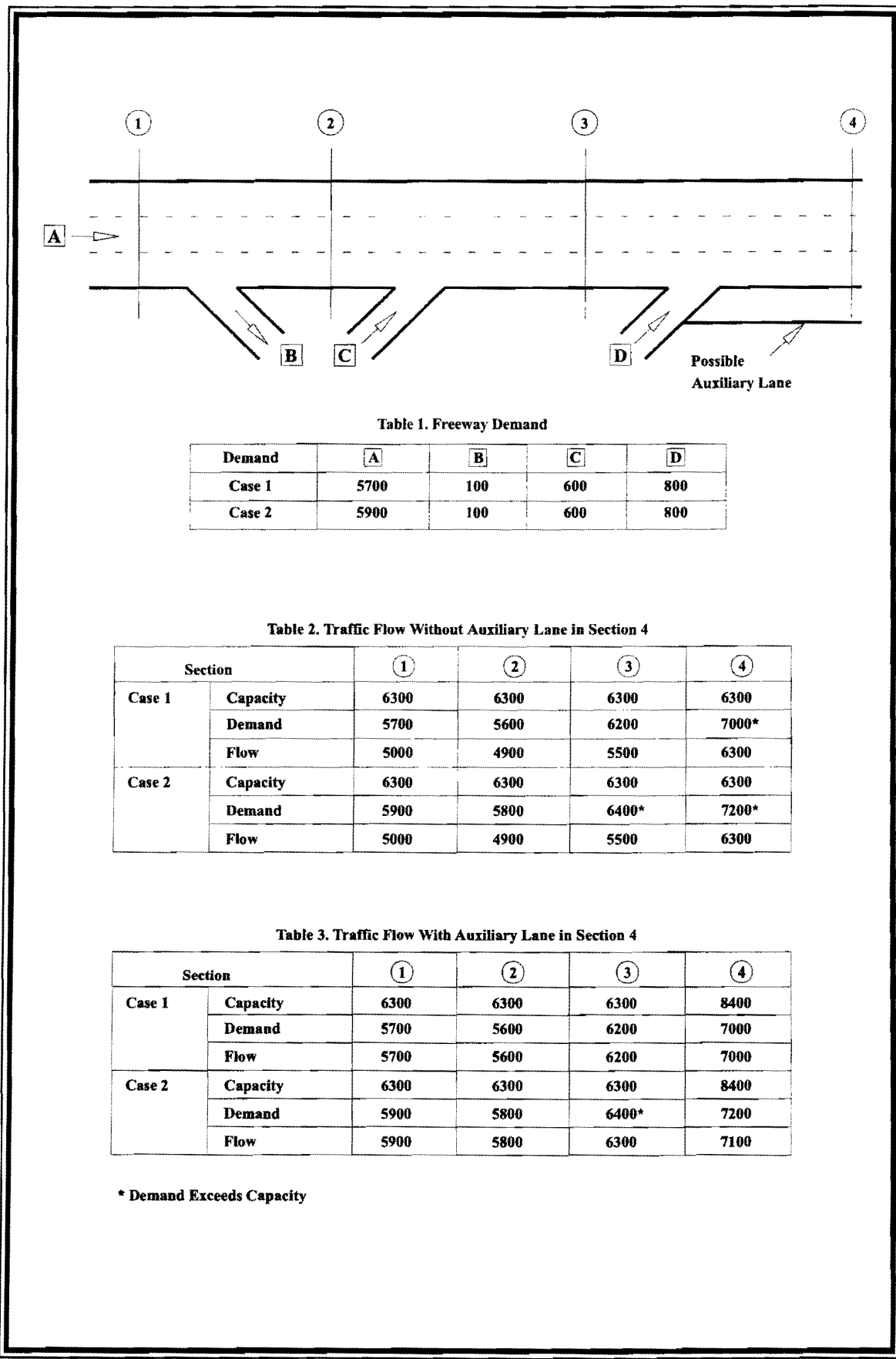


Figure 8-4. Capacity Improvement Example

8.0 Measures-of-Effectiveness

The results of a traffic operations analysis are described using measures-of-effectiveness (MOEs). MOEs give an indication of how traffic flows under a given set of circumstances or how much improvement results from an optimization. The most common MOE is level of service. Other MOEs include volume, speed, density, and delay.

Level of service provides a qualitative description of the traffic flow. Level of service is based on such factors as speed, density, delay, or other parameters. Level of service is described by the letters A through F, with A being the highest or most desirable level of service. Table 8-1 gives a qualitative description for each level of service.

Table 8-1. Level of Service Descriptions

Level of Service	Status	Description
A	Free Flow	Individual users are virtually unaffected by the presence of others in the traffic stream. Freedom to select desired speeds and to maneuver within the traffic stream is extremely high.
B	Stable Flow	Freedom to select desired speeds is relatively unaffected, but there is a slight decline in the freedom to maneuver within the traffic stream. The presence of others in the traffic stream begins to affect individual behavior.
C	Stable Flow	Marks the beginning of the range of flow in which the operation of individual users becomes significantly affected by interactions with others in the traffic stream. Selection of speed is affected by the presence of others and maneuvering within the traffic stream requires substantial vigilance on the part of the user.
D	High-Density Stable Flow	Speed and freedom to maneuver are severely restricted, and the driver experiences a generally poor level of comfort and convenience. Small increases in traffic flow will generally cause operational problems.
E	Unstable Capacity Flow	Operations are at or near capacity. All speeds are reduced to a low, but relatively uniform value. Freedom to maneuver within the traffic stream is extremely difficult, and it is generally accomplished by forcing a vehicle to give way. Operations are unstable because small increases in flow or turbulence within the traffic stream will cause breakdowns.
F	Forced or Breakdown Flow	The amount of traffic approaching a point exceeds the amount which can traverse the point and queues form behind the point. Operations within the queue are characterized by stop-and-go waves and are extremely unstable.

9.0 Highway Capacity Manual

The *1994 Highway Capacity Manual* (HCM) provides procedures for determining level of service on a variety of highway types. The *1994 Highway Capacity Manual* contains the most often utilized procedures for performing simple analyses at isolated locations. Computer programs are available that automate all HCM procedures. The HCM also provides information on traffic characteristics and basic principles of traffic flow.

ANALYSIS USING COMPUTER PROGRAMS

1.0 Analysis Concepts

A variety of procedures exists for the analysis of roadway operations. The differences between the analysis assumptions and strategies determine how a procedure is classified, and provides insight into its use and application. The different classifications for analysis procedures include:

- ◆ analysis approach (macroscopic/microscopic),
- ◆ analysis basis (empirical/analytical),
- ◆ analysis objective (simulation/optimization), and
- ◆ analysis outcome (deterministic/stochastic/probabilistic).

The various computer programs mentioned later in this chapter will be described using these classifications.

1.1 Analysis Approach

A fundamental difference between analysis procedures is the approach used to represent the traffic stream. The two options are **macroscopic**, where the traffic stream is represented as a homogeneous group; or **microscopic**, where the vehicles in the traffic stream are treated as individual units.

The macroscopic approach represents the three basic stream characteristics (flow, speed, density) with flow rates, average speeds, and traffic stream densities, respectively. Individual vehicles are not considered explicitly.

The microscopic approach analyzes the movement of individual vehicles using a car-following methodology.

1.2 Analysis Basis

The analysis procedure can be based on previous experience and direct observations of similar situations, or it can be based on mathematical techniques and physical laws. When the analysis procedure relies on previous experience and field observations, it is an **empirical** analysis. A procedure using numerical relationships is an **analytical** analysis.

Empirical procedures make use of tables, charts, nomographs, and other aids to provide a measure of traffic operations. Empirical analyses are most often used with macroscopic approaches. Statistics are often used in empirical analyses to estimate traffic stream relationships.

Analytical procedures utilize formulas and relationships based on theoretical models to provide a measure of traffic operations. Because of the complex relationships of the microscopic approach, its procedure is analytically based.

1.3 Analysis Objective

There are two possible objectives of traffic operations analysis -- to reproduce traffic operations for a given circumstance or to determine the modifications needed to improve traffic flow. When the procedure attempts to reproduce traffic flow, it is called **simulation**. When the procedure attempts to improve traffic flow, it is called **optimization**.

The results of a simulation indicate how traffic will operate under the conditions specified in the analysis. If a change in operations is desired, the input conditions must be changed.

An optimization analysis will produce the most efficient operating conditions for a given set of parameters. Typically, only one process variable can be optimized. An example of an optimization would be an analysis which determines the most effective timing for freeway ramp metering controls.

1.4 Analysis Outcome

The human element in the traffic stream introduces some level of randomness in traffic operations. There are also some variations in traffic stream characteristics such as flow, speed, and density. However, most analysis procedures utilize rigid methods which do not account for the randomness of traffic. When an analysis results in the same outcome every time the analysis is performed with a given data set, it is a **deterministic** analysis procedure. When randomness is introduced into the analysis procedure, a **stochastic** or probabilistic process results. The outcome of a stochastic or probabilistic analysis varies each time the analysis is performed.

2.0 Use of Computer Programs

Virtually all traffic operations analyses are now performed with the assistance of computers. The computer programs used to perform an analysis provide many advantages over manual evaluation. However, shortcomings which may limit the effective use of computer programs exists. Advantages and disadvantages of computer programs are described in Table 8-2.

Computer programs are not intended to serve as a "black box" into which some input data can be inserted and out of which comes the answer to a problem. Instead, computer programs are intended to assist the evaluation of complex relationships. A computer program used to represent a process which is not clearly understood by the user is certain to be of little value.

There are several steps involved in using a computer program to perform an analysis. The first step is the decision to use a computer program, followed by the selection of the specific program to be used. The input data and operating parameters are then entered into the program and the analysis is performed. However, before the results can be used, the program must be calibrated to provide accurate results. After calibration is achieved, the program can be used to analyze the impacts of the desired parameters.

Table 8-2. Advantages and Disadvantages of Computer Programs

Advantages	
Cost	Computer modeling can be done at much lower costs than manual evaluation or actual construction.
Speed	Computer programs can represent traffic movement in a compressed time frame.
Scope	Computer programs can be used to examine factors outside the scope of practical experimentation.
Controllability	Computer programs allow individual parameters to be constrained so that the impacts of each parameter can be determined.
Disadvantages	
Credibility	Modeling solutions are derived from an approximation of a real world process.
Personnel Requirements	Computer programs should be used by individuals with a general knowledge of the modeling process and detailed knowledge of the process being modeled.
Hardware Requirements	The proper computer hardware must be available to utilize the desired software.
Data Collection	Programs can require a significant amount of data.
Time	Time is required to collect and reduce data and to calibrate the program.

2.1 When to Use a Program

The decision to use a computer program for an operational analysis is based on the benefits which can be achieved over performing the analysis by manual means. When the analysis is simple, manual methods are often less time consuming than computer analysis. However, as the circumstances become more complicated, the computational speed of computers becomes important. Computer analysis should be used when there is a large number of calculations or when repeated analyses are performed with only minor changes in the input variables.

2.2 Selection of a Program

Important aspects which must be considered before selecting the most appropriate computer program for a task include: the alternative being evaluated, the analysis objective (simulation or optimization), the availability of computer hardware, the study limits of project, the level of detail desired for the results, and the desired MOEs. A description of each of these factors is as follows:

- ◆ **Alternatives Being Evaluated.** A program can be used to evaluate the differences between existing conditions (base case) and proposed geometric or demand-related alternatives. Geometric alternatives that may be evaluated include lane drop/additions, lane blockages, ramp re-configurations, and changes in roadway grade or curvature. The demand for the roadway may also be changed and the operational effects evaluated. Alternatives can include: entrance ramp metering, priority entry control, HOV lane addition, and vehicle lane restrictions.
- ◆ **Analysis Objective.** The evaluation of a roadway includes simulation and/or optimization. Simulation is a representation of operating conditions. A simulation model estimates operating characteristics, such as speed, volume, and density, based on a given set of input parameters. An optimization evaluation produces the optimal roadway control plan (e.g., a signal timing plan, ramp metering scheme) for a given set of parameters. Once an optimal plan is determined, a simulation is usually conducted to evaluate the operational effects of the control plan.
- ◆ **Computer Hardware Requirements.** Individuals may be restricted in their choice of computer programs because of the computer hardware requirements of the program. Some simulation programs are currently only available for mainframe computers, while the more recent programs are being developed for personal computers (PC). Some of the detailed simulation programs that operate on a PC require the PC to have extended internal memory (RAM), a math co-processor chip, high clock speed, and other hardware configurations.
- ◆ **Study Limits of Project.** The study limits should include all segments likely to experience changes in travel patterns or operations. The study site may be confined to only one direction of a roadway segment or, because an individual street is not an isolated entity (i.e., it is only a portion of the transportation network), the problem may require the simulation of a larger portion of the system. Congestion at an isolated location may appear to be curable by some geometric change, when in fact such a change will simply move the congestion to another location or identify a hidden bottleneck upstream. For this reason, it is advisable that the engineer or planner simulate not only the specific site that requires attention, but also the segments upstream and downstream of the geometric change.

continued

2.2 Selection of a Program (continued)

- ◆ **Level of Detail.** The level of detail necessary for an evaluation may limit the choice of the simulation program. If individual vehicle data is required or if a detailed analysis of a complex weaving segment is to be conducted, a microscopic program may be necessary. A microscopic program identifies, moves, and tracks each vehicle in a network. Vehicles are processed through the network using car-following and lane-changing algorithms. If a less detailed analysis is desired, a macroscopic program may be used. Macroscopic programs treat the traffic stream as a whole, and traffic flow and speed are based upon a speed flow/density relationship. Macroscopic programs require less computer time and memory to execute than microscopic programs.
- ◆ **Desired Measures-of-Effectiveness.** Depending upon the purpose of the simulation, the measures-of-effectiveness produced by the models may govern their application. For example, if level of service (LOS) is desired, a program that produces density values (which can be translated into an LOS value) needs to be selected. The selection of a program is influenced by the MOEs identified as needed for evaluating the proposed alternatives.

2.3 Collection and Input of Data

Typical data include roadway geometry (e.g., number of lanes and road grade) and traffic flow rates. Traffic composition by vehicle type and auto occupancy may also be needed. Certain programs require a capacity estimate of each segment. Chapter 8, Section 3, Segment 7 discusses the measurement of capacity.

2.4 Calibration of the Program

If the user is evaluating several alternatives, the results from an initial simulation run that used existing condition data are compared to existing field measurements of speed and volume. Input data, such as capacity and free-flow speed, can be modified to attempt to reproduce, as closely as possible or within a range set by the user, existing operations. It should be noted that if the calibration requires extensive “fine tuning,” the program being used or the section being studied may not have been properly selected (e.g., just upstream of a major bottleneck).

2.5 Analysis of Desired Conditions

Once the program is calibrated to existing conditions, the initial run is generally called the base case and is used as a comparison to the other alternative results. The next step in the process is to complete the computer simulations of each alternative and to compare the results from the different alternatives with each other and the base case.

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FREEWAY ANALYSIS PROGRAMS

There are four computer programs which are commonly used to evaluate traffic flow on freeways. These programs include the **Highway Capacity Software (HCS)**, **FREQ**, **FREFLO**, and **FRESIM**. Each of these programs is capable of simulating basic freeway sections and other aspects of freeway operations. The **QUEWZ** model can be used to evaluate road user costs and queue lengths associated with freeway work zones. The basics of each program are summarized in the following subsegments, and the differences among the programs are also noted.

The *1994 Highway Capacity Manual (HCM)* procedures, which are automated in the HCS, are useful in analyzing specific highway features. However, as traffic flow approaches capacity at a number of locations on a highway system, it is necessary to evaluate the roadways as a system. The reason for systemwide analysis is that the removal of a bottleneck may create another bottleneck either downstream due to increased traffic volume or reveal a bottleneck upstream that was hidden in the queue of the bottleneck that was removed. Although the analysis can be done manually, computer programs, such as FREQ, FREFLO, and FRESIM, allow for better quantification of systemwide effects of alternatives.

1.0 Highway Capacity Software (HCS)

The Highway Capacity Software uses a macroscopic, empiric, deterministic, simulation (see Chapter 8, Section 4, Segment 1 for discussions on these terms), approach to evaluate traffic flow at specific highway features. It is based on the *1994 Highway Capacity Manual* which contains widely accepted capacity analysis procedures. The analysis procedures used in the HCS are exactly the same as those of the HCM, but computer automation allows the calculations to be performed in a fraction of the time. References to the HCM or HCS should be construed as the same, unless noted otherwise.

Four chapters of the HCM specifically address freeways. There are also two chapters at the beginning of the HCM which address introductory material and traffic characteristics. The four freeway chapters describe the theory and methods for determining the level of service, capacity, and service flow rates for basic freeway sections, weaving areas, ramps and ramp junctions, and freeway systems. The HCS is more appropriate for relatively quick analyses at specific locations rather than a comprehensive analysis of a freeway system.

2.0 FREQ

FREQ can perform both simulation and optimization of traffic flow. The FREQ freeway program was developed to evaluate uni-directional freeway operations resulting from lane additions, lane blockages (construction or incidents), and various ramp configurations. FREQ may also be used to generate, evaluate, and select an entrance ramp metering scheme that will optimize freeway operations based on a user-specified objective function. Throughout its development, the FREQ program has been widely applied and has received widespread validation. The current version of FREQ is known as FREQ10PC, which can be executed on a microcomputer. FREQ also contains an interactive data input manager which simplifies data entry and coding.

continued

2.0 FREQ (continued)

The optimization component in FREQ is used in developing an optimal ramp metering scheme. Freeway operations may be optimized to maximize vehicle input, vehicle-miles of travel, passenger input, or passenger-miles of travel. The simulation component can be used to evaluate the before and after effect of some geometric or demand related alternative. It can also be used to evaluate traffic performance under the ramp metering strategy developed in an optimization analysis. Analysis options that may be invoked include a ramp merging analysis and a weaving analysis, both of which are based on procedures contained in the *1965 Highway Capacity Manual* (not the *1985 or 1994 Highway Capacity Manual*). The current version of FREQ will allow priority bypass at ramp meters for high-occupancy vehicles. An earlier version, FREQ7PL, can evaluate concurrent flow high-occupancy vehicle lanes.

The FREQ input is organized by dividing the freeway into discrete, homogeneous segments in terms of geometry, demands, and capacity. Segment boundaries are located at the entrance and exit ramps. The data requirements for each segment include segment length, number of lanes, grade, capacity, design speed, volumes, percent trucks, ramp configuration, and ramp capacity. Necessary volumes include the mainlane volume entering the first subsection, the mainlane volume leaving the last subsection, and all entrance and exit ramp volumes.

FREQ allows the user to specify the amount of information output. The output choices include freeway design features, distribution of vehicle occupancy by segment, freeway travel time, ramp/freeway delay, total travel time, total travel distance, contour maps of speed and density, queuing diagram, volume to capacity ratios, fuel consumption, hydrocarbon emissions, carbon monoxide emissions, nitrous emissions, and noise levels. A freeway performance table by segment can also be selected. It includes number of lanes, length, demand volume, serviced volume, capacity, weave efficiency, storage rate, v/c ratio, speed, and emission data. For optimization analysis, the output also include ramp metering rates.

3.0 FREFLO

FREFLO was designed to evaluate incidents and entrance ramp operations, and to provide standard measures of travel. The measures that are produced include flow rate, density, space-mean speed, and travel time. FREFLO is capable of simulating entire freeway networks in both directions. In addition to incidents and entrance ramp operations, FREFLO can analyze freeway-to-freeway connectors and vehicles can be distinguished by type. Special purpose lanes such as HOV lanes may also be simulated.

Freeway segments are represented as links and nodes, where links represent segments and nodes represent a change such as a lane drop or ramp. Required link data includes link length, number of lanes, capacity, free-flow speed, and entering and exiting volumes.

The FREFLO output includes the density for each link of the network. The level of service for each link is determined from the density using the *1994 Highway Capacity Manual* procedures. Other output includes link volumes and speeds for each time period of simulation, vehicle trips, vehicle kilometers (miles), vehicle minutes, vehicle average speed, person trips, person kilometers (miles) and person minutes.

4.0 FRESIM

FRESIM is a freeway corridor program that is an enhanced, user-friendly, and PC-compatible successor to INTRAS. FRESIM is capable of simulating freeway mainlanes, ramps, freeway-to-freeway connectors, variations in grade, curvature and superelevation, lane additions or drops, lane blockages, and acceleration or deceleration on auxiliary lanes. The model also provides simulation of operational features such as ramp metering, freeway surveillance, performance capabilities of six different vehicle types (two types of passenger cars and four truck types), restriction of heavy vehicles from certain lanes, differences in driving habits, and driver's reaction in terms of lane changing behavior to warning signs, incidents, or exits. Recently-released CORSIM combines the FRESIM and NETSIM models into an integrated, microscopic analysis package.

5.0 QUEWZ

QUEWZ (Queue and User Cost Evaluation of Work Zones) is designed to evaluate freeway work zones. An analysis capability of the program is estimating the queue lengths and additional road user costs resulting from freeway work zone lane closures. Another capability is identifying schedules for lane closures so that queuing will not exceed a user-specified queue length or delay. The data requirements include: configuration of the work zone, the schedule of work activities, traffic volumes, and alternative values for program defaults (percent trucks, maximum acceptable delay to motorists, etc.). The output from the program includes a summary of travel impacts and/or an acceptable lane closure schedule. The travel impacts include hourly estimates of diverted traffic, volume through the work zone, approach speed, work zone speed, average queue length, and additional road user costs.

6.0 CORFLO

CORFLO is a name given to the combination of the PC versions of FREFLO, NETFLO (Levels 1 and 2), and TRAFFIC macroscopic programs. CORFLO may be used to simulate freeways, ramps, frontage roads, and the surrounding urban street system. The CORFLO package was designed to enable the user to stimulate an entire urban network with a single model. CORFLO may be used to stimulate uni-directional or bi-directional freeway sections, freeway-to-freeway connectors, interchanges or complete freeway networks. The software can also simulate urban links to the freeway (i.e., frontage roads and arterial streets).

7.0 Comparison of Computer Programs

Tables 8-3 and 8-4 summarize the description, capabilities, and differences between the freeway programs discussed previously.

Table 8-3. Summary of Freeway Computer Programs

Model	Analysis Types ^a				Microcomputer Version
	Approach	Basis	Objective	Outcome	
HCS	Macroscopic	Empirical	Simulation	Deterministic	Yes
FREQ	Macroscopic	Analytical	Simulation or Optimization	Deterministic	Yes
FREFLO/ CORFLO	Macroscopic	Analytical	Simulation	Deterministic	Yes
FRESIM/ CORSIM	Microscopic	Analytical	Simulation or Optimization	Stochastic	Yes
QUEWZ	Macroscopic	Analytical	Simulation	Deterministic	Yes

^aChapter 8, Section 4, Segment 1 includes discussions on the various analysis types.

Table 8-4. Advantages and Disadvantages of Freeway Computer Programs

Advantages	
HCS	Widely accepted and easy to use.
FREQ	Easiest of the programs to use. Can optimize ramp meters. Considerable testing, validation, and use nationwide. Operates on a microcomputer. User friendly data input manager.
FREFLO/ CORFLO	Explicit treatment of freeway system. Can evaluate temporary changes in roadway characteristics. Compatible with TRAFFIC, an equilibrium traffic assignment program. Can simulate freeway to freeway connectors. Produces density as output MOE.
FRESIM/ CORSIM	Explicit treatment of freeway and surface street system. Can evaluate temporary changes in roadway characteristics. Can evaluate complex weaving sections. Can simulate freeway-to-freeway connectors. Can evaluate geometric changes and vehicle/driver characteristics
QUEWZ	Allows for the estimation of road user costs and queue lengths resulting from lane closures. User friendly, menu driven data input manager.
Disadvantages	
HCS	Empirically based, no systemwide analysis capabilities.
FREQ	Only one directional freeway segment can be evaluated. Only one simplified parallel alternative route can be simulated. Cannot simulate freeway-to-freeway connectors.
FREFLO/ CORFLO	Large CORFLO networks have large data requirements and require long computing times.
FRESIM/ CORSIM	No direct representation of HOV operations. No direct modeling of the effect of reduced lane widths.
QUEWZ	Limited to work zone analyses only.

OTHER ANALYSIS PROGRAMS

Several computer programs are available to analyze arterial streets and intersections. The **Highway Capacity Software** (described in the previous section) can be used for relatively quick analyses at specific locations or along arterial streets. **PASSER II** is capable of analyzing isolated signalized intersections as well as a series of signalized intersections. **PASSER III** is designed for signalized diamond interchange analyses. The **TEXAS** model is used to analyze single intersections. **TRANSYT-7F** and **NETSIM** are capable of evaluating the operations along a series of intersections with and without signals. **PASSER IV** is an arterial street timing optimization model for networks. Each model has unique qualities which are discussed below.

1.0 PASSER II

PASSER II is capable of optimizing timing for isolated signalized intersections, optimizing signal timing for progressive systems, and analyzing existing timing evaluations. The program is also capable of analyzing various complicated left-turn signal treatments either with or without left-turn lanes. The package provides the user with a menu driven, graphical input/output processor that is user-friendly. The most current version of PASSER II provides advanced analysis procedures. The output from the program includes optimum (within constraints) cycle length, phase sequences, phase durations, progression bandwidths, bandwidth efficiency and attainability, average progression speed, intersection level of service, saturation ratio, stops, delay, fuel consumption, and time-space diagrams. The performance of the system can be observed from an on-screen graphical representation of the traffic operations. The movements of individual vehicles are displayed along with measure-of-effectiveness values. This allows for a visual appreciation of where queues are forming and where excess capacity may exist.

2.0 PASSER III

PASSER III is designed to analyze pretimed or traffic-responsive, fixed sequence signalized diamond interchanges. The program allows the evaluation of existing or proposed signalization strategies for diamond interchanges. It determines which plan best minimizes the average delay per vehicle. It is capable of analyzing various complicated left turn signal treatments either with or without left-turn lanes. The program also calculates signal timing plans for interconnecting interchanges along continuous frontage roads. The current version, PASSER III-90, provides enhanced input/output functions and signal timing reports. It also has the capacity to evaluate multiple cycle lengths at isolated interchanges. In addition, it can analyze over-saturated conditions and cycle lengths up to 300 seconds in length. The microcomputer version of PASSER III provides the user with an interactive data entry that is user friendly. An assistant function is provided to expedite the assignment of traffic movements to optimize lane use assignments. This is a particularly important feature for maximizing frontage road utilization.

3.0 TEXAS

The TEXAS program can be used to evaluate the operational effects of various traffic demands, types of traffic control, and/or geometric configuration at single intersections. The program is a microscopic traffic simulation model for single intersections. It can be applied when evaluating existing or proposed intersection designs and for assessing the effects of changes in roadway geometry, driver and vehicle characteristics, flow conditions, intersection control, lane control, and signal timing plans upon traffic operations. It is a microscopic computer simulation designed to perform detailed evaluations of traffic operations at isolated intersections. It has recently been upgraded to allow the user to simulate and optimize two intersections only as a diamond interchange configuration. The TEXAS Model is comprised of three sub-models. GEOPRO is used to create the required geometry information. DVPRO is used to randomly generate individual driver pairs. Several driver types and vehicle classifications are used. SIMPRO examines sequentially each driver-vehicle unit in the system. Delay, speed, and volume statistics are accumulated throughout the simulation and reported at the end of user-selected time increments. Animated graphical output of vehicles moving through the intersection is also available using the TEXAS Model.

4.0 TRANSYT-7F

TRANSYT-7F is a traffic signal timing optimization program. Using standard traffic data and timing parameters as inputs, it can both evaluate existing or other predetermined timing plans and optimize new timing plans that minimize stops, delays, fuel consumption, or cost. A data input manager (DIM) program and a Platoon Progression Diagram (PPD) are included with the TRANSYT-7F program. The DIM is a full screen editor with prompts for each card type to facilitate data entry. The PPD combines the traditional time space diagrams and TRANSYT's "flow profile diagram." The most current public domain version (Release 6) has new algorithms for bandwidth constraint, improved actuated signal modeling, optimized splits for grouped nodes, additional reporting of route summaries, and more powerful objective functions. The program provides signal timing tables and traffic performance summary tables. The signal timing tables include the phase intervals and offsets while the traffic performance summary tables include degree of saturation, travel time, delays, stops, queue lengths, and fuel consumption by link and for the entire network. Optional outputs include flow profile plots and time-space diagrams.

5.0 NETSIM

NETSIM (NETwork SIMulation Model) is a simulation program which can evaluate a variety of proposed operational improvements prior to implementing the changes in the field. It is a microscopic simulation program that provides a detailed evaluation of proposed operational improvement in a signalized network. For example, it can evaluate the effects of converting a two-way street to one-way, adding lanes or turn pockets, moving the location of a bus stop, or installing a new signal (fixed-time or actuated). The output from the program includes information on travel, delay, stops, speeds, queues, link (roadway segments) occupancies, degree of saturation, cycle failures, fuel consumption, and vehicle emissions for each link and for the entire network. This information is provided at several points in time and for the entire simulation period. NETSIM also has the ability to display how the traffic is flowing on screen. Vehicles progressing along the arterial or through the intersections, signal indications, and other information are shown for a specified amount of the network. Using the graphics package, the user can visually appreciate how different improvements affect traffic operations.

6.0 PASSER IV

PASSER IV-94 has been developed to optimize signal timings for large multi-arterial networks based on maximizing platoon progression bandwidth on all arterials. The program can analyze both one-way arterials in closed networks as well as open networks. PASSER IV-94 can calculate green splits, optimum cycle length for the system, and offsets. The program selects optimum phasing sequences to maximize bandwidth along the arterials. The program can print multiple signal timing reports and generate input data files for the TRANSYT-7F program. Time-space diagrams are generated for each arterial in the network. PASSER IV-94 provides a network signal timing optimization capability that was previously available only for arterial problems through the combined use of PASSER II and the Arterial Analysis Package (AAP).

7.0 Comparison of Computer Programs

Tables 8-5 and 8-6 summarize the description, capabilities, and differences between the signalized intersection programs discussed previously.

Table 8-5. Summary of Signalized Intersection Computer Programs

Model	Analysis ^a			Microcomputer Version
	Approach	Objective	Outcome	
PASSER II	Macroscopic	Optimization	Deterministic	Yes
PASSER III	Macroscopic	Optimization	Deterministic	Yes
TRANSYT-7F	Macroscopic	Optimization	Deterministic	Yes
NETSIM	Microscopic	Simulation	Stochastic	Yes
TEXAS	Microscopic	Simulation & Optimization	Stochastic	Yes
PASSER IV	Macroscopic	Optimization	Deterministic	Yes

^aChapter 8, Section 3, Segment 1 includes discussions on the various analysis types.

Table 8-6. Advantages and Disadvantages of Signalized Intersection Programs

Advantages	
PASSER II	Widely accepted and used, can optimize a coordinated or simulate an existing signal system. Graphical output is available.
PASSER III	Widely accepted and used for simulating or optimizing the signals associated with the cross-street/frontage road intersections at a diamond interchange.
TRANSYT-7F	Widely accepted and used with continual upgrading. Allows use of stop-controlled approaches and permitted movements. May be used to stimulate or optimize any system of intersecting arterial streets.
NETSIM	Detailed simulation of arterial street intersection systems. High quality animated graphical representations of selected intersection operations.
TEXAS	Detailed simulation of an isolated intersection or diamond interchange signal system. Allows animated graphical representations of selected intersection operations.
PASSER IV	Simultaneously maximizes progression bandwidth on all arterials in an open or closed network. Extremely user friendly interface. Can be run in combination with TRANSYT-7F to minimize bandwidth-constrained delay.
Disadvantages	
PASSER II	Awkward data input manager, difficult to edit previously entered data.
PASSER III	Only applicable to diamond interchange signal systems.
TRANSYT-7F	Data input manager is not comprehensive, which makes the coding of specialized configurations difficult.
NETSIM	Extensive input data required, simulation capability only.
TEXAS	Extensive input data required, isolated intersection or diamond interchange signal system capability only.
PASSER IV	Cannot simulate existing signal timing offsets

ANALYSIS OF SPECIFIC CIRCUMSTANCES

In some cases, the area of concern may be limited to a certain aspect of freeway operation. The freeway programs previously mentioned provide several alternatives for analyzing common freeway situations. The following sections describe how these programs can be used to analyze weaving, ramp metering, work zones, incidents, and queues on freeways.

1.0 Weaving

Weaving sections impose significant impacts on highway operations. The impact of the weaving section depends on the spacing between interchanges, the traffic volumes of the weaving and non-weaving movements, the speed of the weaving and non-weaving movements, and the number and type of lane changes required.

Analyzing weaving areas is a complicated process. The *Highway Capacity Software (HCS)* procedures provide level of service on an empirical basis. The HCS procedure requires considerable judgement in its application. The weaving analysis in *FREQ* is based on the *1965 Highway Capacity Manual* (not the *1985 Highway Capacity Manual*). *FREFLO* contains no weaving analysis; instead, as vehicles are introduced at an entrance ramp gore, they are immediately merged into the freeway mainlanes. *FRESIM*, by virtue of its microscopic nature, provides the highest available level of detail possible in simulating traffic behavior. Specifically, individual entrance ramp vehicles are spaced on the ramp to minimize turbulence (adequate following distances). The program then searches for an empty slot of sufficient size in the adjacent freeway lane to accommodate the lead entrance vehicle. This highly detailed process is needed for merging and weaving studies to realistically simulate the vehicle interactions in those areas.

2.0 Ramp Metering

Optimizing freeway operations by varying ramp metering rates is a cumbersome process when done manually. Several freeway models provide a means for determining the desired metering rates in order to maximize various measures-of-effectiveness.

FREQ allows the user to create an optimal entrance ramp metering plan based on the maximization of any of four objectives: the number of vehicles on the freeway, the total number of vehicle kilometers (miles) of travel, the passenger inputs, or the passenger kilometers (miles) of travel. Maximum and minimum metering rates, as well as queue length limits, are options available for controlling the range of metering rates. *FRESIM* supports four different entrance ramp metering strategies. These are: clock time metering, demand-capacity metering, speed control metering, and gap acceptance metering.

3.0 Work Zones and Incidents

Work zones and incidents have a significant impact on freeway operations. This impact varies according to the nature and the location of the blockage. In terms of simulation, a work zone and an incident are modeled identically. Both are capacity restrictions for a specified period of time. While all of the programs will produce simulated freeway speeds, only *FREQ* and *QUEWZ* produce a queue length output, which is a measure-of-effectiveness most associated with work zones or incidents. *FREQ* allows the user to reduce the freeway capacity for each subsection for a given period of time to simulate a lane blockage due to either a work zone or incident. *QUEWZ* estimates the queue length and additional road user costs resulting from a work zone lane closure. The *Highway Capacity Software* provides total and lane capacity values for work zones. *FREFLO* provides for the representation of an incident or work zone by allowing the specification of a reduced number of lanes and/or a constrained flow rate past a certain point. *FRESIM* allows the user to simulate work zones, incidents, or lane closures over a subsection length for specific lanes for a given time period. Other features of *FRESIM* are that advanced warning signs may be placed for the approaching traffic to vacate the appropriate lane and a “rubbernecking” factor may also be applied to the adjacent lanes to simulate the resulting slow-down.

4.0 Queue Length

When demand exceeds capacity, a queue will form. Traffic speeds within the queue are reduced, and the length of the queue can increase rapidly. The *FREQ* and the *QUEWZ* programs allow the length of a queue to be determined.

5.0 Reduced Lane Widths

Reduced lane widths and/or reduced lateral clearance have been used on freeways in work zones and when adding one or more lanes to an existing freeway. Reduced lane widths can have an impact on operations; however, none of the freeway computer programs can specifically model this restriction. The lane capacity in *FREQ* and *FREFLO* and the driver sensitivity factor in *FRESIM* may be lowered to simulate a reduced lane width or lateral clearance. The *1994 Highway Capacity Manual* contains procedures for calculating the capacity of a freeway segment with reduced lane widths or lateral clearances, but they are not particularly accurate. Lane widths of 3.4 meters (11 feet) or more are unlikely to significantly affect capacity.

6.0 Computer Program Recommendations

In addition to the specific situations just described, the freeway programs mentioned in this chapter can be used to analyze other freeway conditions. Table 8-7 summarizes the freeway programs that can be used to analyze specific freeway operations. Table 8-7 also indicates which programs are recommended for analyzing a specific freeway condition. It should be noted that operational analysis is rarely concerned with only a single operational aspect. Therefore, the selection of a freeway computer program should be based on the available equipment, user experience, and the capability of the program to provide an accurate and total picture of freeway operations.

Table 8-7. Freeway Applications and Program Recommendations

APPLICATION	PROGRAMS WHICH ANALYZE	PROGRAMS WHICH DO NOT ANALYZE
Weaving LOS	FRESIM, FREFLO, FREQ, HCS	QUEWZ
Detailed analysis of weaving sections	FRESIM	HCS, FREQ, FREFLO, QUEWZ
Ramp metering optimization	FREQ, FRESIM	FREFLO, HCS, QUEWZ
Ramp metering simulation	FREQ, FRESIM	HCS, FREFLO, QUEWZ
Work zone capacity	HCS, QUEWZ	FREQ, FREFLO, FRESIM
Queue length	FREQ, QUEWZ	FREFLO, FRESIM, HCS
Reduced lane widths	---	HCS, FREQ, FREFLO, FRESIM, QUEWZ
Incidents	FREFLO, FREQ, FRESIM	HCS, QUEWZ
Lane addition/lane drop	FREFLO, FREQ, FRESIM, QUEWZ	HCS
Lane blockage	FREFLO, FREQ, FRESIM, QUEWZ	HCS
Auxiliary lanes (full or partial)	FRESIM	FREQ, FREFLO, HCS, QUEWZ
Ramp reconfiguration	FREFLO, FREQ, FRESIM, HCS	QUEWZ
Freeway segment with HOV lane	FREFLO, FREQ	FRESIM, HCS, QUEWZ
Lane restrictions by vehicle type	FRESIM	HCS, FREQ, FREFLO, QUEWZ
Freeway-to-freeway connectors	FREFLO, FRESIM	FREQ, HCS, QUEWZ
Entire freeway system	FREFLO, FRESIM	FREQ, HCS, QUEWZ
Changes in grade, curvature, or pavement	FRESIM	FREQ, FREFLO, HCS, QUEWZ
Changes in vehicle mix (classification)	FREFLO, FREQ, FRESIM, HCS	QUEWZ
Changes in driver behavior (aggressiveness)	FRESIM	HCS, FREQ, FREFLO, QUEWZ

Note: Models listed in order from most recommended to least recommended

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ANALYSIS OF INCIDENT MANAGEMENT PROGRAMS

The effectiveness of an incident management program can be evaluated based on an estimate of the total amount of annual delay caused by incidents in a given freeway segment. Chapter 9 discusses how delay caused by an incident can be represented graphically. A number of major factors affect the total amount of incident-caused delay, including:

- ◆ capacity of the freeway,
- ◆ demand flow rate,
- ◆ reduced flow rate through the incident,
- ◆ getaway capacity, and
- ◆ duration of the incident.

The two most important aspects in determining total delay are the reduced traffic flow rate and the duration of the incident. The duration of an incident is dependent upon the time needed to detect, respond, and remove the incident from the freeway.

A methodology for evaluating the effectiveness of an incident management system is provided in *Alternative Surveillance Concepts and Methods for Freeway Incident Management -- Volume 3: Computational Example for Selecting Low-Cost Alternatives*. It uses the estimated number of incidents, the distribution of incidents, the characteristics of the incident management program, and the prevailing traffic flow parameters to estimate the total number of vehicle-hours of delay incurred annually. A Delay Computation Worksheet, developed to assist in evaluations, can be used to evaluate existing or proposed incident management programs.

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ANALYSIS OF FRONTAGE ROAD LEVEL OF SERVICE

1.0 General Considerations

Frontage roads are an integral part of the Texas freeway system. They provide access to land development and connect the freeway with local streets. In addition, frontage roads can serve as alternate routes to the freeway during congestion, maintenance activities, or emergencies. Frontage roads contain characteristics of both freeways and arterial streets. Frontage roads are one-way or two-way, contain entrance and exit ramps servicing the freeway, and provide access to local driveways and low priority streets. In addition, the frontage road system is interconnected with the major streets intersecting the freeway, usually as signalized or stop-controlled intersections.

Procedures are available to evaluate the traffic operations and level-of-service along different frontage road scenarios (see Figure 8-5):

- ◆ a continuous frontage road section up to several kilometers in length,
- ◆ a one-sided weaving area formed by an exit ramp followed by an entrance ramp connected by an auxiliary lane, and
- ◆ a two-sided weaving area formed by an exit ramp followed by a downstream signalized intersection.

Guidelines are also available for exit ramp to entrance ramp spacings, exit ramp to downstream signalized intersection spacing, and signalized intersection to metered entrance ramp spacing.

Frontage road section analysis procedures are based on the arterial analysis chapter of the *Highway Capacity Manual* and include consideration of the delays that are incurred at ramp junctions. The procedures can be used to evaluate the operations on one-way and two-way frontage road sections which, in turn, can assist in prioritizing frontage road improvement projects and/or predicting future operations. Weaving volumes (i.e., the exit ramp and the entrance ramp volumes) are used to determine the level of service on one-sided weaving sections.

An exit ramp to intersection is a common frontage road geometric configuration in Texas. When an exiting vehicle weaves across all frontage road lanes to make a right turn at the downstream intersection, the maneuver is called a two-sided weave. The developed procedure to evaluate this maneuver uses roadway configuration, length of weaving section, exit ramp and frontage road volumes, and percentage of exiting vehicles desiring to make the two-sided weave. The procedures to estimate the level of service for two-sided weaving segments along with an example are given in the following section. (Additional information on this and other analysis procedures are contained in report FHWA/TX-95/1393-4F, *Procedures to Determine Frontage Road Level of Service and Ramp Spacing*. Texas Transportation Institute, College Station, Texas. August 1996.)

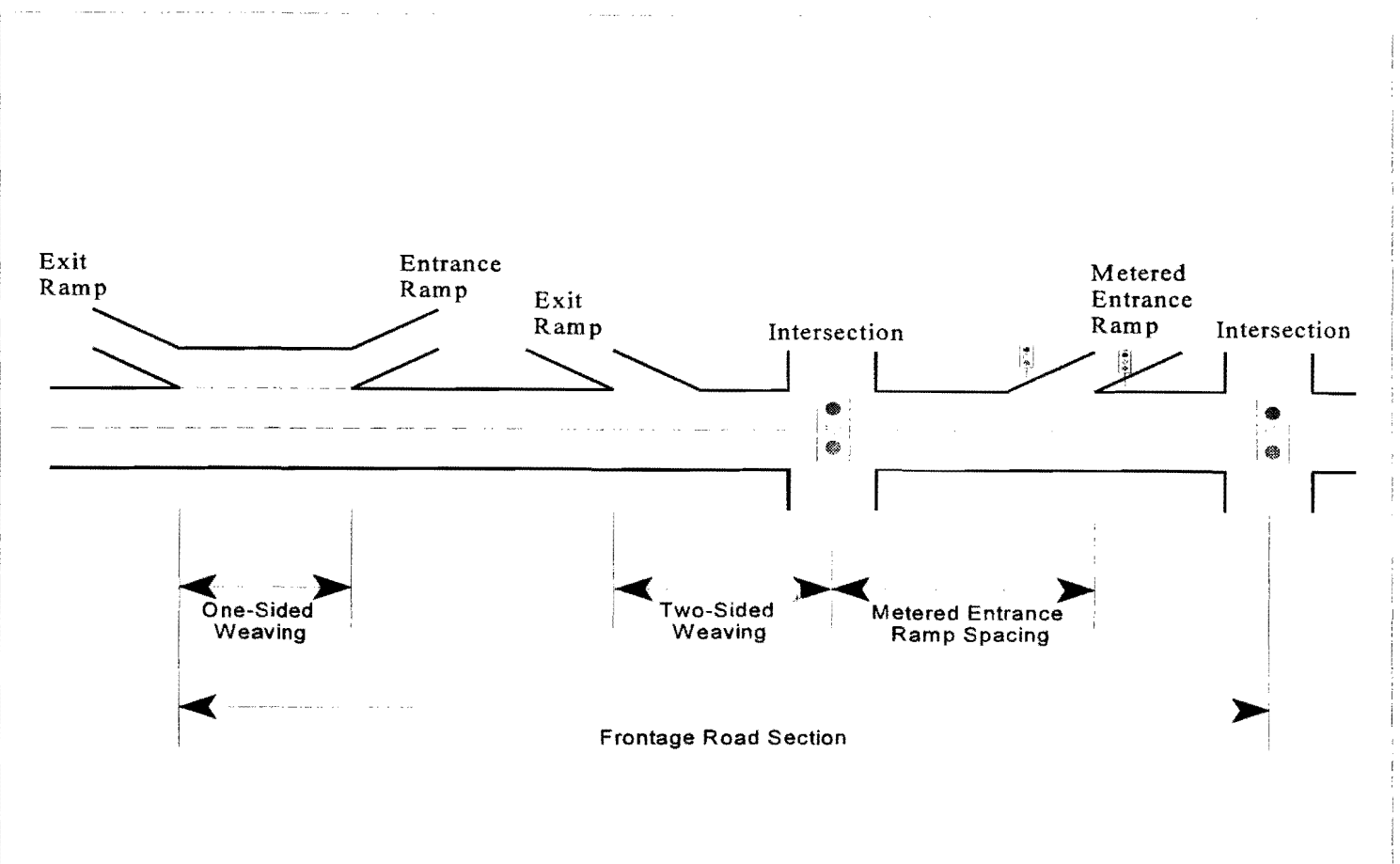


Figure 8-5. Frontage Road Analysis

2.0 Analysis of Two-Sided Weaving Segment

Analysis with the operations on a two-sided weaving segment on a one-way frontage road requires the following steps. Figure 8.6 is a worksheet that was developed to aid in the analysis.

- (1) Determine the configuration of the frontage road [i.e., two-lane frontage road (2LFR), three-lane frontage road (3LFR), or two-lane frontage road with an auxiliary lane extending from the exit ramp to the downstream intersection (2LFR+Aux)].
- (2) From the field, collect the following information: exit ramp hourly volume (vph); frontage road hourly volume (vph); spacing between exit ramp and downstream intersection (m); and an estimate of the percentage of exit ramp vehicles making a right turn at the downstream intersection (as either \leq less 50 percent or $>$ 50 percent).
- (3) Based on the frontage road configuration and the data collected in the field, compute density using the appropriate regression equation.
- (4) Estimate the level of service for the two-sided weaving section based on the computed density. Engineering judgement should be used for frontage road configurations with turn bays and situations in which a signalized intersection is causing high delays for the frontage road approach.

The worksheet in Figure 8-7 illustrates an example of a two-sided weaving analysis. The segment being analyzed is a two-lane frontage road (2LFR). The required frontage road data needed to perform the analysis is shown on the worksheet. Using the regression equation for a 2LFR configuration, the estimated density is 56 veh/km/ln. This value represents a level of service in the *constrained* region (40 - 100 veh/km/ln).

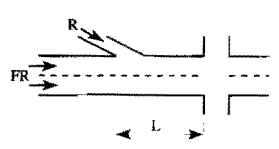
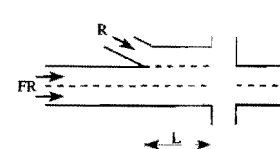
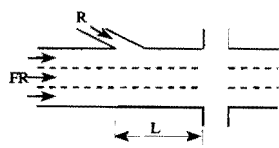
TWO-SIDED WEAVING ANALYSIS WORKSHEET									
Location: _____ Direction: _____ - bound									
Description: _____									
Date: _____ Prepared By: _____									
Exit Ramp Volume (R): _____ vph Ramp Spacing (L): _____ m									
Frontage Road Volume (FR): _____ vph Percent 2-Sided Weaving (T): _____ [T=0 for ≤ 50%, T= 1 for > 50%]									
 <p style="text-align: center;">2LFR</p> $D_L = 0.034(FR) + 0.098(R) - 0.132(L) + 9.51(T)$	 <p style="text-align: center;">2LFR+Aux</p> $D_L = 0.021(FR) + 0.077(R) - 0.150(L) + 23.4(T)$								
 <p style="text-align: center;">3LFR</p> $D_L = 0.055(FR) + 0.080(R) - 0.200(L) + 27.4(T)$	<p style="text-align: center;">Density (D_L): _____ veh/km/ln</p>								
<table style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th style="text-align: left; border-bottom: 1px solid black;">Density, veh/km/ln</th> <th style="text-align: left; border-bottom: 1px solid black;">Level of Service</th> </tr> </thead> <tbody> <tr> <td>< 40</td> <td>Unconstrained</td> </tr> <tr> <td>40 - 100</td> <td>Constrained</td> </tr> <tr> <td>> 100</td> <td>Undesirable</td> </tr> </tbody> </table>		Density, veh/km/ln	Level of Service	< 40	Unconstrained	40 - 100	Constrained	> 100	Undesirable
Density, veh/km/ln	Level of Service								
< 40	Unconstrained								
40 - 100	Constrained								
> 100	Undesirable								
Level of Service: _____									

Figure 8-6. Two-Sided Weaving Analysis Worksheet

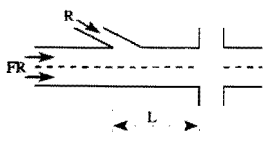
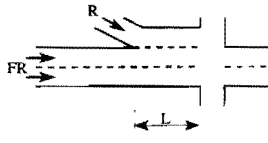
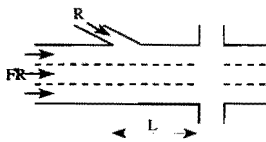
TWO-SIDED WEAVING ANALYSIS WORKSHEET									
Location: <u> IH-19 </u>	Direction: <u> South </u> - bound								
Description: <u> 2-Lane Frontage Road </u>									
Date: <u> 6/30/96 </u>	Prepared By: <u> </u>								
Exit Ramp Volume (R): <u> 500 </u> vph	Ramp Spacing (L): <u> 200 </u> m								
Frontage Road Volume (FR): <u> 1000 </u> vph	Percent 2-Sided Weaving (T): <u> 0 </u> [T=0 for ≤ 50%, T= 1 for > 50%]								
 <p>2LFR</p> $D_L = 0.034(\text{FR}) + 0.098(\text{R}) - 0.132(\text{L}) + 9.51(\text{T})$	 <p>2LFR+Aux</p> $D_L = 0.021(\text{FR}) + 0.077(\text{R}) - 0.150(\text{L}) + 23.4(\text{T})$								
 <p>3LFR</p> $D_L = 0.055(\text{FR}) + 0.080(\text{R}) - 0.200(\text{L}) + 27.4(\text{T})$	<p>Density (D_L): <u> 56 </u> veh/km/ln</p>								
<table style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th style="text-align: left; border-bottom: 1px solid black;">Density, veh/km/ln</th> <th style="text-align: left; border-bottom: 1px solid black;">Level of Service</th> </tr> </thead> <tbody> <tr> <td>< 40</td> <td>Unconstrained</td> </tr> <tr> <td>40 - 100</td> <td>Constrained</td> </tr> <tr> <td>> 100</td> <td>Undesirable</td> </tr> </tbody> </table>	Density, veh/km/ln	Level of Service	< 40	Unconstrained	40 - 100	Constrained	> 100	Undesirable	<p style="text-align: right;">Level of Service: <u> Constrained </u></p>
Density, veh/km/ln	Level of Service								
< 40	Unconstrained								
40 - 100	Constrained								
> 100	Undesirable								

Figure 8-7. Two-Sided Weaving Analysis Sample Calculation

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**CHAPTER 9
INCIDENT MANAGEMENT**

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OVERVIEW

Incidents are the major cause of nonrecurring congestion, and are a primary concern of traffic management agencies. A quick and appropriate response to an incident can do much to alleviate the resulting congestion. Actively responding to incidents is commonly known as incident management.

An understanding of incidents is necessary before incident management strategies can be implemented. This includes the causes of incidents and the impact of incidents on highway operations. Reducing the impacts of congestion caused by incidents is vital to successful operations on any facility. Reducing the congestion caused by incidents will result in vastly improved traffic operations.

This chapter addresses various aspects of an incident management program. It provides descriptions of the causes of incidents and the severity of congestion that can result from an incident. The frequency and impacts of incidents on highway capacity and motorist delay are described. A general process of responding to an incident is provided, along with specific techniques that can be used in responding to incidents.

An integral part of an effective incident management program is effective surveillance and control strategies, which are covered in Chapters 7 and 10, respectively. Analyzing the operational impacts of incidents and giving motorists vital information about highway conditions in the vicinity of incidents are also a part of an effective incident management program. These topics are covered in Chapters 8 and 11.

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INCIDENT CHARACTERISTICS

Analyzing the causes, magnitude, frequency, and impacts of incidents is important in gauging the magnitude of the problem and selecting appropriate, cost-effective techniques for incident management. A careful examination of incident data is required, as the potential for double counting and conflicting information is not unusual with incident data. Local incident data can be obtained by reviewing crash reports, towing reports, dispatch logs, and other sources from both public and private agencies. When local data is scarce or unreliable, typical values can be used to estimate the extent and nature of the problem for planning purposes. These values should be augmented whenever possible with sampling from local data bases.

1.0 Importance of Incident Management

Effective incident management can considerably reduce delay. It has been estimated that for each additional minute that a lane is blocked by an incident in off-peak, free-flow operations, two to three minutes is added to the time needed to restore the freeway to free-flow conditions. In other words, for each additional minute that the time to clear a blocked travel lane is reduced, at least two to three minutes can be cut from the delay that each motorist will experience. Therefore, a comprehensive system which includes measures for restoring full capacity as quickly as possible as well as reducing demand during an incident can reduce motorist delays and frustration. This, in turn, leads to improved safety.

2.0 Causes of Incidents

Incidents are events that impede traffic flow and reduce the capacity of a highway section. Incidents are occurrences such as traffic crashes, disabled or stalled vehicles, spilled cargo, failure of a highway component, emergency (or unscheduled) maintenance, traffic diversions, or adverse weather which reduce the capacity of the highway. By its very nature, the occurrence of an incident is not predictable; therefore, the congestion resulting from an incident is known as nonrecurring congestion. As incidents are random events which cannot be easily predicted, nonrecurring congestion cannot be dealt with in the same manner as recurrent congestion. Chapter 10 discusses the management of recurrent congestion.

Scheduled activities (Chapter 5) such as maintenance operations or special events are closely related to incidents because their occurrence is irregular and often unexpected by motorists. However, the impacts of scheduled activities can be anticipated in advance and appropriate measures can be taken to reduce these impacts.

3.0 Incident Magnitude

Incidents cause considerable delay and cost to the motoring public. It has been estimated that over one-half of the vehicular delay experienced nationwide is due to incidents. In Texas, the cost of delay due to incidents is over one billion dollars annually (based on a delay cost of \$8.50 per person-hour and a commercial vehicle operating cost of \$1.03 per kilometer (\$1.65 per mile) and the cost of wasted fuel consumption is one-fourth of a billion dollars (based on an average fuel cost of \$1.05 per gallon).

4.0 Incident Frequency

The primary factors in determining operating conditions are incident frequency and incident duration. Facilities that experience a high number of incidents are often congested more frequently. Also, as incident duration increases, the magnitude of the resulting congestion and delay increases. The time of day an incident occurs is also an important factor that influences the amount of congestion and delay. If an incident occurs at the beginning of the peak period, the delay will be much greater than if the same incident occurred at the end of the peak period or in the off-peak period.

Determining the frequency of delay-causing incidents is important in quantifying the magnitude of the problem. Prediction of incident occurrence is a function of the traffic volume, the time of day, the roadway design, and the environmental conditions that exist at any given time. These factors vary from section to section along a facility. Therefore, it is necessary to analyze incident occurrence on a section-by-section basis.

In the absence of site-specific data, an annual incident rate of 200 incidents per million vehicle-miles has been recommended as a starting point in developing an estimate of the effectiveness of an incident management program on freeways with shoulders. This rate includes both shoulder and lane-blocking incidents. Over 96 percent of these incidents can be assumed to be located on the shoulder. Shoulder incidents include those incidents where the vehicle is quickly moved to the shoulder after the incident occurs in the main lanes. Only 4 percent of the incidents, on the average, block the main lanes for an extended period.

5.0 Incident Impacts

The type, location, and severity of an incident determine the operational impacts of an incident. Congestion resulting from an incident can be classified as either a reduction in capacity and/or an increase in delay.

5.1 Reduction in Capacity

The impacts of an incident on the capacity of a freeway section are significant. As shown in Table 9-1, an incident that blocks one lane of a three-lane section reduces the capacity of the freeway by approximately 50 percent, even though the actual physical reduction in usable lanes is only 33 percent. Even when an incident is located on the shoulder, capacity is reduced due to motorists slowing to look at the problem or “rubbernecking.”

Table 9-1. Available Capacity During Incident Conditions On A Three-Lane Roadway

Conditions	Average Flow Rate (vph)	Capacity Reduction (percent)
Normal Flow (three lanes)	5,560	---
Crashes on Shoulder (no lanes blocked)	4,030	26
Stall (one lane blocked)	2,880	48
Non-injury Crash (one lane blocked)	2,750	50
Crash (two lanes blocked)	1,150	79

Source: M.E. Goolsby. Influence of Incidents on Freeway Quality of Service. In *Highway Research Record 349*. Highway Research Board, National Research Council, Washington, D.C., 1971.

5.2 Increase in Delay

Delays result when capacity is reduced to a level less than the demand. To quantify delay, the duration and magnitude of the capacity reduction is considered. A graphic technique for estimating total vehicle-hours of delay is shown in Figure 9-1. The horizontal axis is a time line indicating the occurrence of certain incident-related events and the overall duration of incident-caused impacts on traffic flow. The vertical axis is the cumulative traffic volume. The slope of a diagonal line defines the flow rate at that time.

Prior to an incident, the slope of the demand line (D_N) is less than the slope of the capacity line (C_N). When an incident occurs at time t_o , the slope of the capacity line drops from C_N to C_I , reflecting a reduction in capacity. However, the demand continues, resulting in the formation of a queue. Unless some technique is used to improve the capacity, the capacity reduction lasts for the duration of the incident. The slope of the capacity line returns to normal (C_N) when the incident is cleared at time t_{IC} . The queue is dissipated when the normal capacity line intersects with the demand line (D_N) at time t_{QC} . The total delay resulting from the incident is the area bounded by the demand line (D_N) and the two capacity lines (C_N and C_I). The time period between t_{IC} and t_{QC} is the time required for the freeway to return to normal operation after the incident is cleared. The queue (Q_N) at any point in time (t_N) is the vertical distance between the demand and the capacity lines. Figure 9-1 indicates why congestion lasts longer than the duration of the incident and that a significant amount of delay occurs after the incident is cleared.

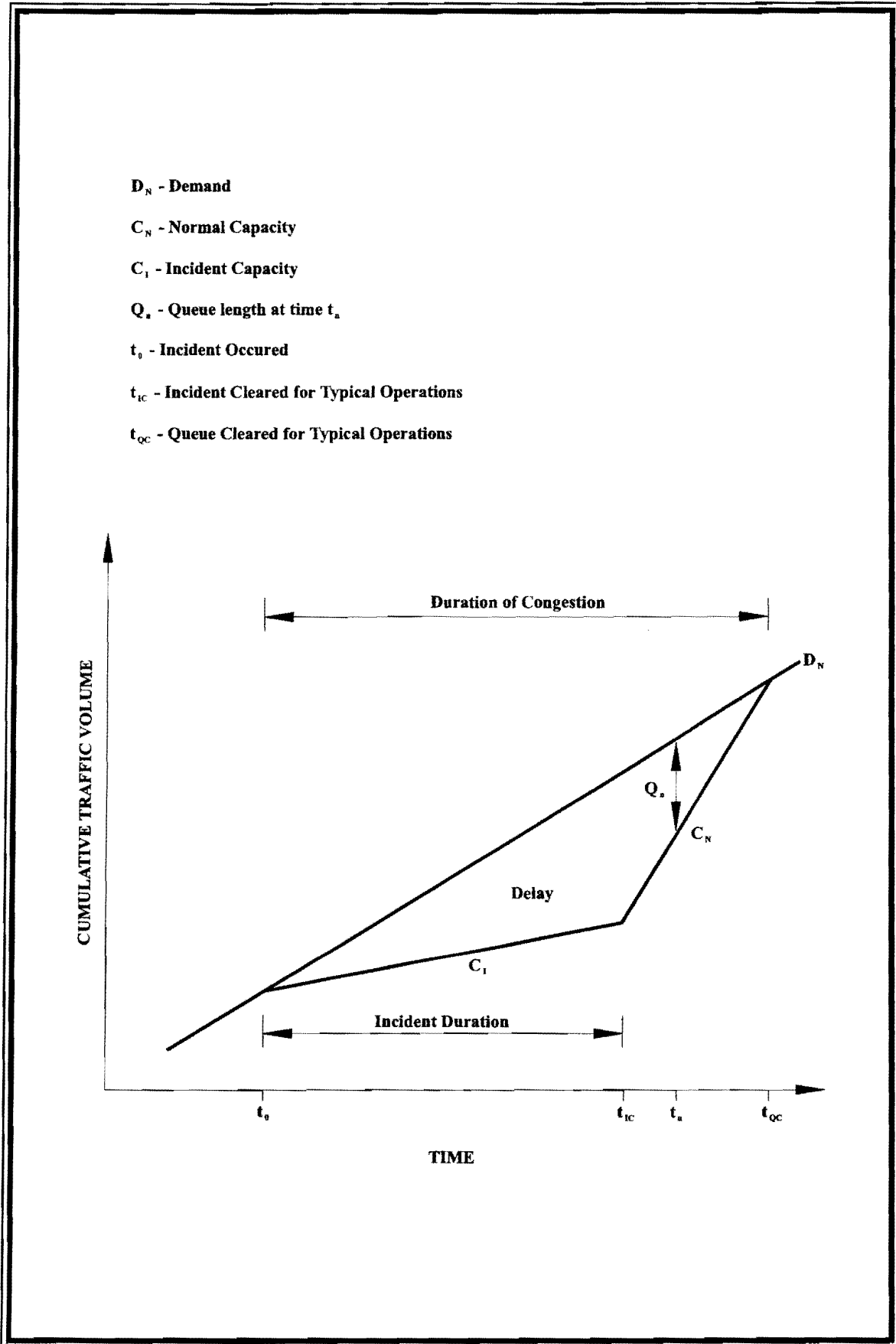


Figure 9-1. Incident Delay for Typical Operations

6.0 Legal Issues

There are two Texas laws which relate to moving vehicles involved in an incident off of the travel way. Section 550.022 of the Texas Transportation Code has been in place for a number of years. It states that when an crash occurs on or adjacent to a freeway, and the vehicles involved in the crash can be driven safely, then the drivers of those vehicles shall move them out of the freeway area in order to minimize interference with freeway traffic. In May 1991, legislation was enacted (Sections 474.011-472.014, Texas Transportation Code) authorizes the Texas Department of Transportation to remove spilled cargo or personal property from the roadway or right-of-way when TxDOT determines the spillage is blocking the roadway or endangering the public safety. The language for these laws are contained in the Appendix.

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INCIDENT RESPONSE AND MANAGEMENT

An effective process for responding to incidents is vital to a successful traffic management system. The management process involves several distinct steps, each of which has an impact on the speed and accuracy of the response. The components of the process are the detection, evaluation/response, and removal of an incident. The application of this process to roadway corridors can reduce the incident duration, increase the capacity, or reduce the traffic demand. The *Incident Response Guide* provides a description of the response steps and techniques appropriate under specific incident situations.

1.0 Components of Response

From an incident management standpoint, an incident can be viewed in terms of the different activities that contribute to the length of an incident. Figure 9-2 shows the activities and time elements associated with a typical response to an incident. The time required to perform each of the incident response activities can be grouped into three periods: detection time, evaluation/response time, and removal time. The sum total of these is equal to the total incident duration. Separating the incident duration into these components allows for a better calculation of the incident duration. Consideration of the factors affecting each component can help determine where the incident management process can be improved.

1.1 Detection Time

Detection time is measured from the moment an incident occurs until the time it has been detected by or reported to an official agency with incident management responsibilities. This includes any delay time associated with communicating the information to the proper response agency. Detection time is often the longest of the three components, especially for minor incidents. Chapter 7, "Data Collection," addresses incident detection.

1.2 Evaluation/Response Time

Evaluation/response time is measured from the moment the incident management system becomes aware of the occurrence of an incident until the time when all of the resources necessary to complete removal have arrived at the incident site. The components of the evaluation/response time include: the time required to determine the appropriate emergency equipment and personnel needed to remove the incident, the time needed to communicate these needs to the appropriate agencies, and the travel time of the emergency vehicles and personnel to the incident site. Improved coordination and communication within and between agencies is the primary means of reducing response time. Some of the factors that influence evaluation/response time include the following:

- ◆ the nature of the incident (this defines the resources necessary to effect removal),
- ◆ the method by which the incident is detected,
- ◆ the quality of the incident management communication network,
- ◆ the location of emergency resources,
- ◆ other demands on emergency resources, and
- ◆ the traffic conditions encountered by the response vehicles en route to the incident site.

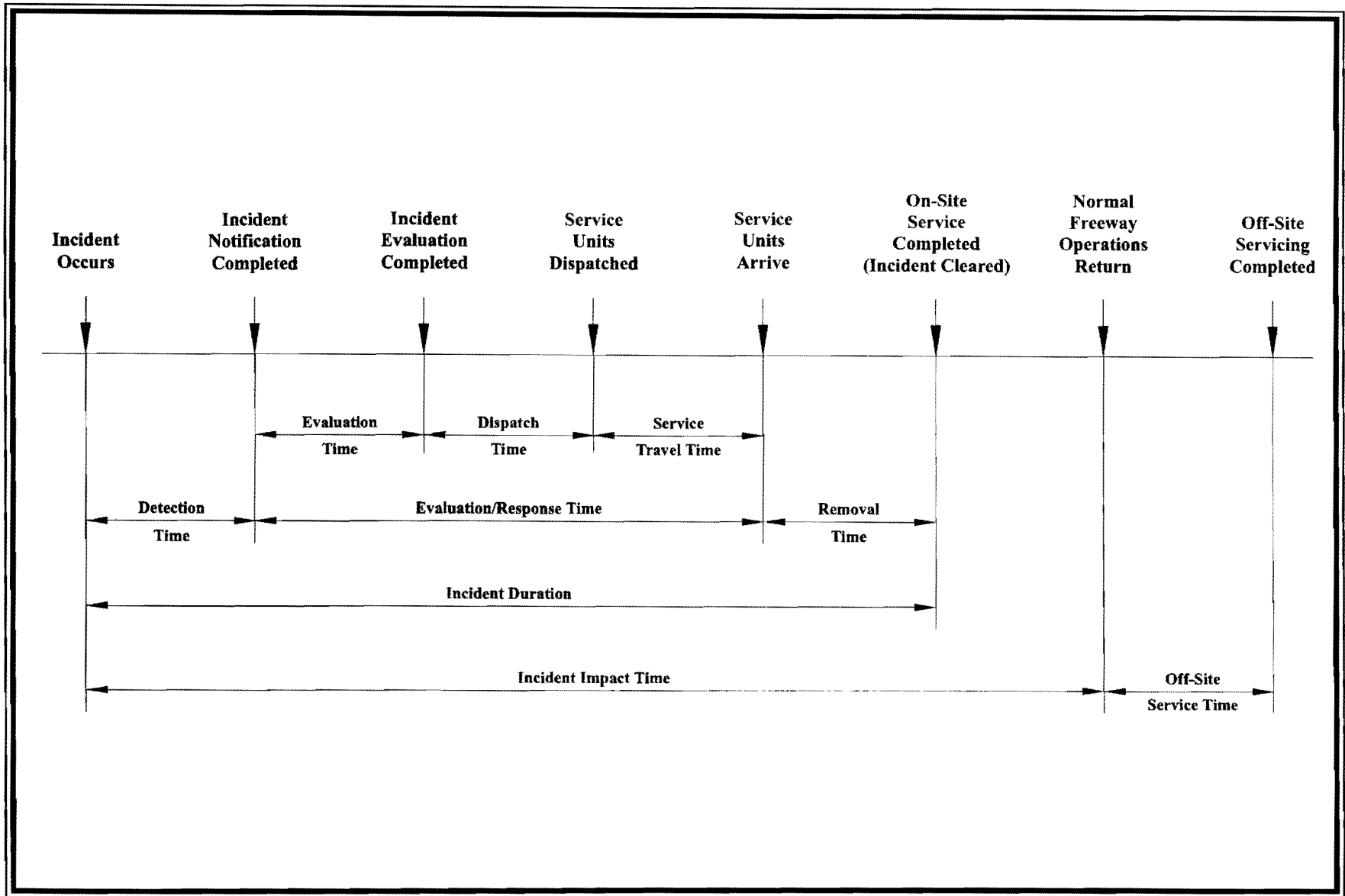


Figure 9-2. Incident Response Time

1.3 Removal Time

Removal or clearance time is defined as the time taken to remove an incident and restore full capacity. Even when an incident is removed to the shoulder, a reduction in capacity occurs due to rubbernecking. Removal time begins as soon as the first response unit arrives at the site and ends when the last unit leaves. Since removal time is dependent upon factors that are unique to each individual incident, it is the most difficult component to control. Typical activities performed during the removal time interval are:

- ◆ first aid,
- ◆ extraction of occupants from damaged vehicles,
- ◆ fire fighting,
- ◆ crash investigation,
- ◆ traffic control and diversion,
- ◆ vehicle removal,
- ◆ debris cleanup, and
- ◆ removal of temporary signing and traffic control devices.

2.0 Incident Management

Incident management refers to a coordinated and preplanned approach for restoring traffic to its normal operation as quickly as possible after an incident has occurred. The approach involves a systematic use of human, electronic, and mechanical processes for detecting the incident, assessing its magnitude, identifying what is needed to restore the facility to normal operation, and providing the appropriate response in the form of control, information, and aid. The primary goal of incident management is to minimize the impacts of incidents on traffic flow by reducing the duration of the incident and efficiently managing traffic during the incident. This is accomplished by:

- ◆ improving detection, response, and removal activities so as to reduce the duration of the incident;
- ◆ increasing the capacity past the incident by effective on-site management; and
- ◆ reducing the traffic demand by providing timely and accurate information to the public.

2.1 Incident Duration

Incident duration is the most significant factor affecting total delay that can be influenced by freeway incident management techniques. As shown in Figure 9-3, considerable delay savings can be produced by reducing the duration of an incident. Since incident duration is directly affected by the three incident management activities (detection, evaluation/response, and removal), any procedure or technique that reduces the time necessary to complete these activities will reduce the delay experienced by motorists.

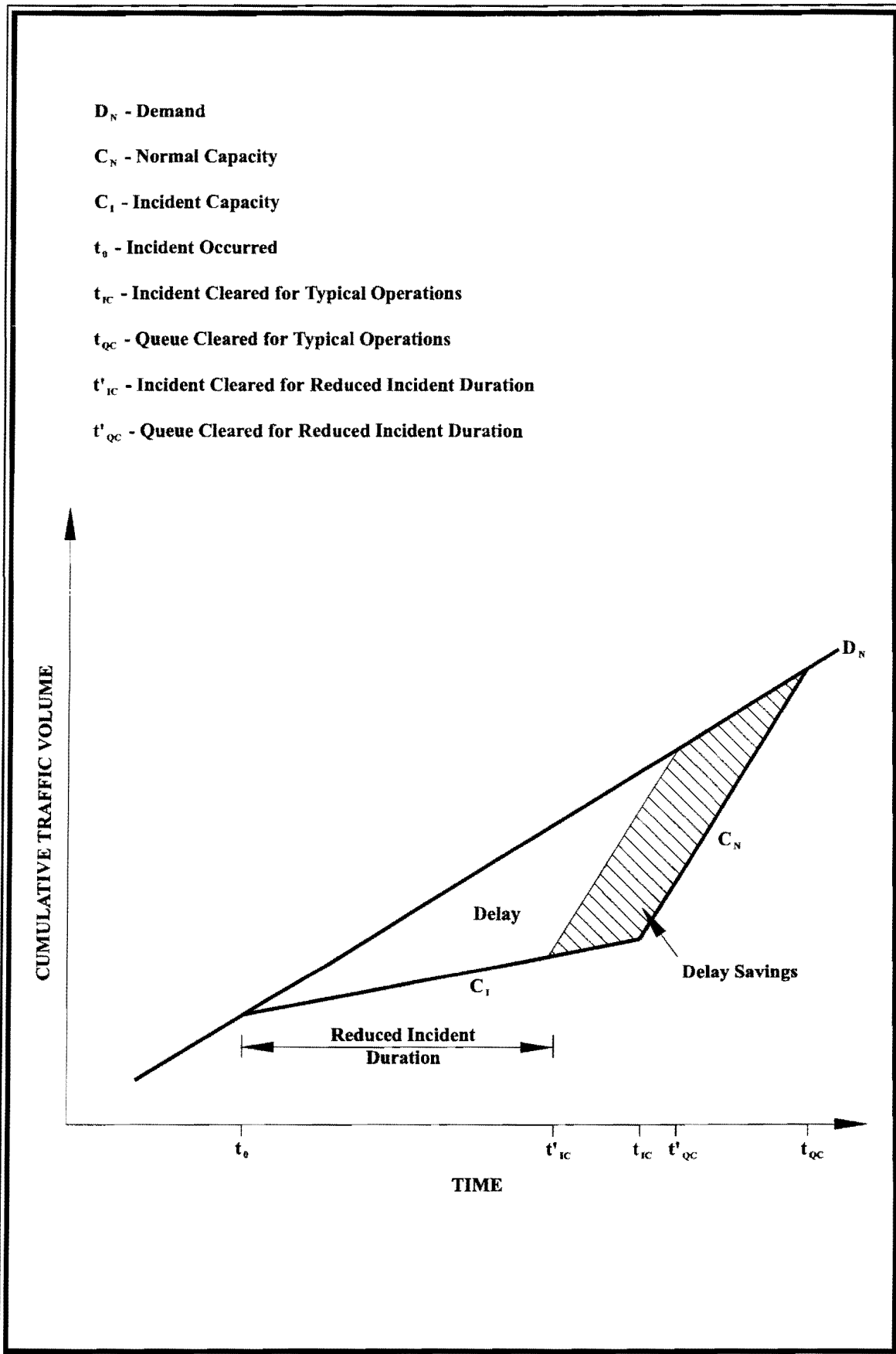


Figure 9-3. Incident Delay for Reduced Incident Duration

2.2 Capacity Utilization

An increase in the available incident capacity can reduce the amount of delay experienced by motorists. The result of an increase in incident capacity is graphically illustrated in Figure 9-4. Some of the procedures discussed in Chapter 5, "Operational Considerations for Scheduled Activities," can be used to increase capacity. Effective use of on-site traffic management techniques (Chapter 9, Section 4) will allow response personnel to make full use of whatever capacity remains and can significantly reduce the delays due to incidents.

2.3 Motorist Information

A reduction in traffic demand at the incident can also reduce the amount of delay experienced by motorists. Figure 9-5 illustrates how reducing the amount of traffic utilizing a freeway upstream of the congestion point can produce a delay savings. One method of reducing traffic demand at an incident is to provide motorists with information about the incident. If the information is accurate and timely, motorists may be encouraged to divert around or away from the incident site, change their departure time, or switch to an alternate mode of transportation.

The effectiveness of providing motorists with information about the incident depends on:

- ◆ the accuracy of the information,
- ◆ the timeliness of the information, and
- ◆ the location where the information is provided to motorists.

The various aspects associated with providing motorists with the necessary information are described in Section 3 of Chapter 11. The types of information techniques described in Chapter 11 include:

- ◆ Dynamic message signs (Segment 1.0),
- ◆ Highway Advisory Radio (Segment 2.0),
- ◆ Telephone "Hot Line"/Cellular Telephone (Segment 3.0),
- ◆ Commercial Radio and Television (Segment 4.0),
- ◆ Citizen-Band Radio (Segment 5.0), and
- ◆ Lane Control Signals (Segment 6.0).

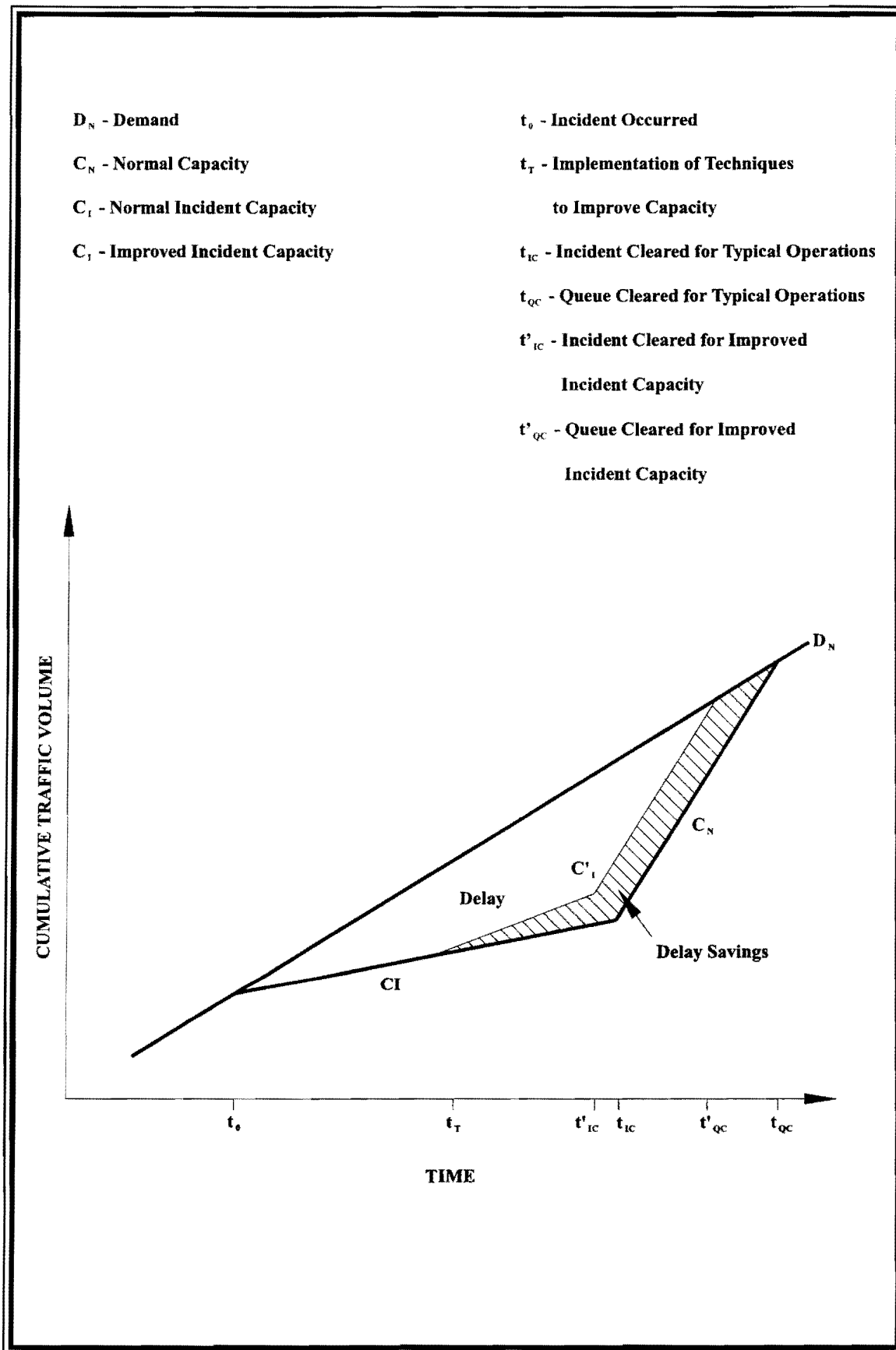


Figure 9-4. Incident Delay for Improved Incident Capacity

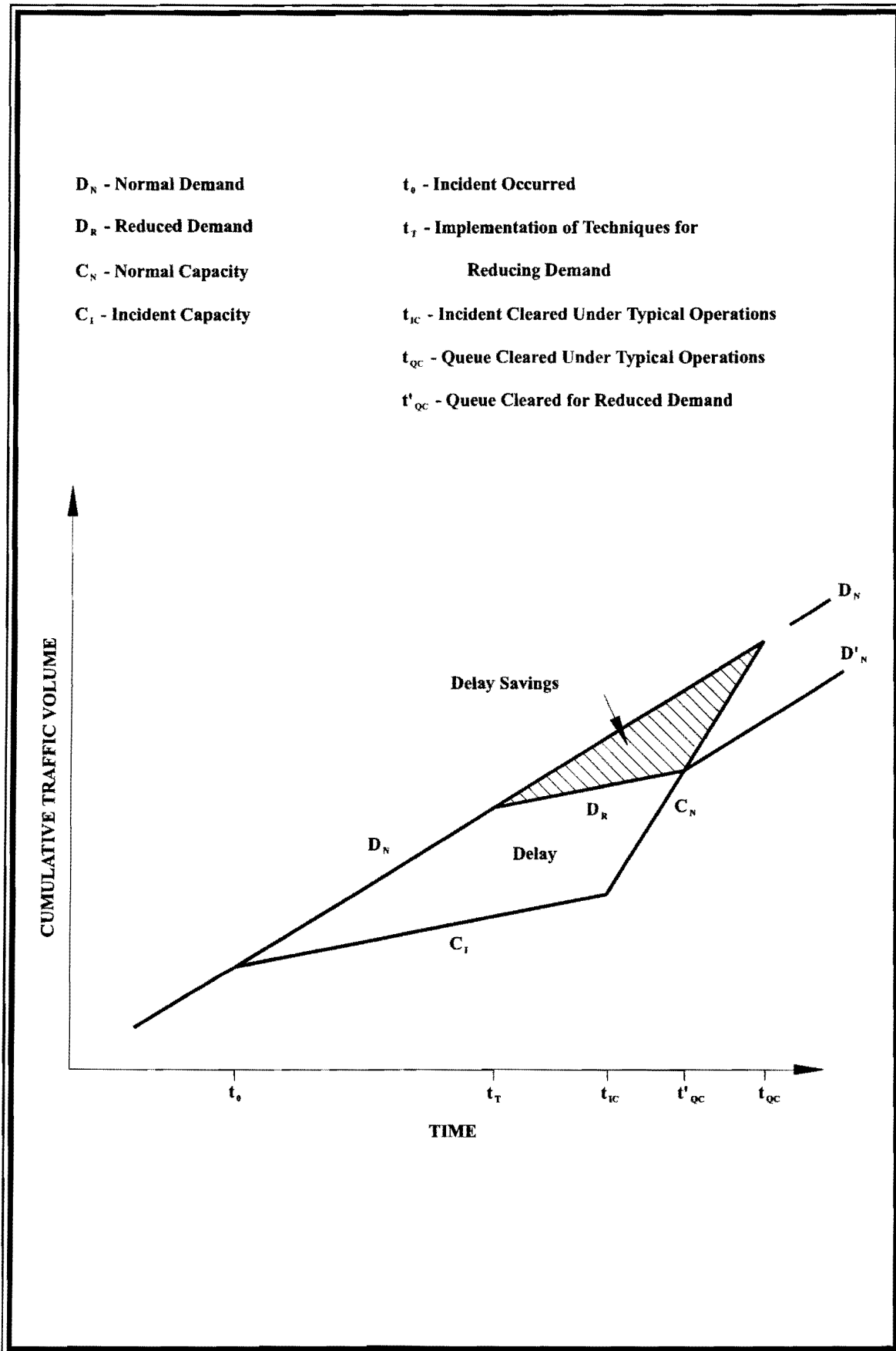


Figure 9-5. Incident Delay for Reduced Demand

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MANAGEMENT TECHNIQUES

The functional elements of an incident management system are incident detection, response, and removal. Demand management is also essential for mitigating the impacts of an incident.

1.0 Incident Detection

A variety of surveillance systems exist that can be used for detecting incidents. Some systems convey information concerning the type of response necessary to remove the incident. Other systems need on-site verification in order to determine the nature and extent of the incident and the appropriate type of response. Not all incident detection techniques require the use of sophisticated equipment. Some can be implemented quickly and inexpensively on both large and small roadway networks.

The most common techniques of detecting incidents are electronic surveillance, closed-circuit television, aerial surveillance, motorist call systems (which include emergency call boxes and emergency telephones), cooperative motorist aid systems, cellular telephone, Citizen-Band (CB) radio, and police and service patrol vehicles. Advantages and disadvantages exist for each type of detection method. Some methods provide for better detection while others allow more detailed analysis of the magnitude and nature of the incident. Frequently, a combination of detection methods is used so that the ability to detect and verify potential incidents is maximized. The best method, or combination of methods, depends upon the desired objectives of the incident management system. Chapter 7, Section 6, Segment 3.0 discusses surveillance techniques used to detect incidents.

2.0 Incident Evaluation and Response

Knowing the specific nature of the incident is critical when determining the type of response required. Figure 9-6 shows a typical decision-making process that is performed by an operator once an incident is detected. The first step in the process is to verify the occurrence of the incident either through visual inspection or by voice communications. Once the incident has been verified, it is then necessary to determine the nature of the incident in terms of its location, type, and severity. An evaluation is then performed to assess the capabilities of the organization in terms of personnel and equipment availability, status, and location. Estimates of the duration of the incident, the potential impacts on traffic flow, and the status of the primary and diversion routes are also performed.

The result of the evaluation leads to the determination of the type of response. This involves decisions related to the personnel and equipment needed and available to respond (who is at the scene, who else should be sent, who needs to be notified), the use of real-time motorist information systems, the type of traffic control needed and present at the scene, and the off-site traffic control needed to establish a diversion route, if necessary. Once the response has been implemented, conditions should be monitored to determine if adjustments are necessary.

continued

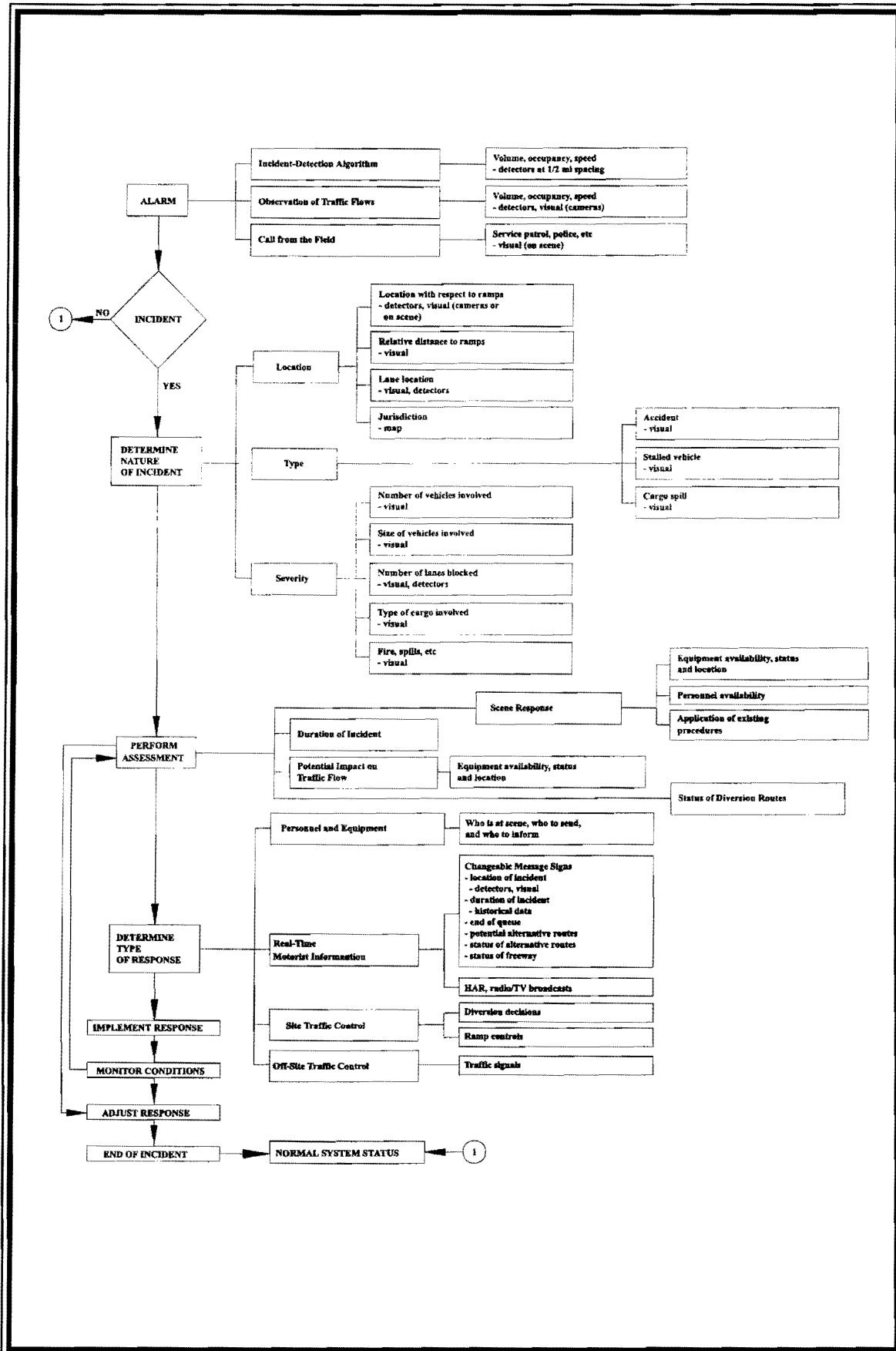


Figure 9-6. Decision-Making Process for Operator

2.0 Incident Evaluation and Response (continued)

The response time that an agency desires dictates the requirements of the system and consequently affects the cost of the system. A system which has the objective of removing all incidents 10 minutes after they occur will cost more than one which permits a 20-minute response time. Therefore, the relationship between response time and cost for alternative designs must be determined when developing an incident management system. Techniques for reducing response time include stationary response vehicles, increasing service or police patrol frequency, developing dispatch and hazardous material manuals, advance planning of alternate detour routes, dispatching assistance prior to verification, and response teams.

2.1 Stationary Response Vehicles

Strategically placing a response vehicle along a freeway where the driver can detect incidents and respond immediately is one technique for reducing response time. Response vehicles can be located near high-crash locations or at critical locations with the sole responsibility of responding to incidents that occur at these locations. An analysis of historical crash data is necessary to determine deployment location and optimal type of the response vehicles. Stationary response vehicles may be used either on a full-time basis at critical locations such as at bridges or tunnels or during peak periods along particular sections of freeway. Access routes and response procedures must be preplanned in order to ensure that all incidents can be reached by the response vehicles. Contract tow trucks, police, or agency response vehicles can be used as the response vehicles. However, the cost of contract tow trucks and police vehicles should be considered in the evaluation of this strategy.

2.2 Increased Service Patrol Frequency

Another method of improving response time is to increase the frequency of public or privately-owned service patrols circulating through the traffic stream. Reducing the time between each successive pass of a service patrol increases the probability that an incident will be detected and a response initiated in a shorter period of time. Implementation of this technique can be accomplished by acquiring new units, reassigning existing units, or reordering patrol priorities. Motorcycles, which have greater mobility than patrol vehicles traveling through congestion, can also reduce response time.

2.3 Dispatch Manual

A single, exhaustive manual which lists numerous system resources can reduce response time. The manual would include the names, addresses, and telephone numbers of various emergency resource providers. Other informational aids such as maps, diagrams of selected interchanges, milepost identifiers, and locations of utilities and other sensitive or hazardous off-freeway facilities are also contained in the manual. The information is organized in a manner which facilitates immediate access to specific informational aid or telephone numbers and minimizes the number of required entries. Examples of resource information that should be included in a dispatch manual are listed in Table 9-2.

2.4 Management of Hazardous Material Incidents

Response time can also be improved by the development of reference documents for use by field personnel and/or dispatchers in the event of an incident involving vehicles carrying hazardous materials. On-site personnel, especially police officers and highway department participants who are the first to arrive at the scene of a hazardous material spill, should be provided with a brief, portable guide to assist them in identifying the cargo and stabilizing the incident. Dispatchers require a more lengthy and detailed document in order to more accurately consult and advise on-site personnel of the procedures and actions to be taken in the presence of hazardous material.

The responsibility for immediate protection of public safety is vested with state and local governments. The federal government has a supporting role and does not become involved unless specifically requested by state or local officials. Exceptions to this general rule include situations involving nuclear weapons or weapon-related materials. In such situations, either the Department of Defense (DOD) or the Department of Energy (DOE) has the lead role, depending on which agency has custody of the weapon materials.

There are three basic phases to hazmat emergency response, involving three different response groups:

1. The initial phase is handled at the local level with local personnel.
2. The second phase involves the use of special hazmat response teams and experts, who are available throughout the country on a rapid response basis.
3. The third phase is handled by commercial firms with great expertise in that particular situation and usually involves only major emergencies of hazmat cargo spillage that are highly toxic or radioactive.

Personnel who initially respond to a hazardous materials crash are usually local firefighters or police. Local response personnel typically treat the crash initially as a transportation crash rather than as a hazardous incident. The hazard may be compounded for local authorities because of the sophistication of today's chemicals and other products. Local response personnel may not have adequate knowledge about correct stabilization and neutralization procedures and are less likely to have the resources, money, and trained personnel to respond to a hazardous material crash.

State-level response support is often varied, depending on whether the state is highly industrialized or has experienced a hazardous materials crash. The Texas Natural Resources Conservation Commission has been designated as the lead state agency in a hazardous material spill response. The Commission has established the Texas Emergency Response and Assessment Section, which operates 24 hours a day and can be reached at (512) 463-7727.

continued

2.4 Management of Hazardous Material Incidents (continued)

The Response and Assessment Section will provide technical assistance and expertise, by activating an emergency spill response team from the appropriate regional office. The section can also provide assistance in contracting additional expertise for containment and clean-up operations as necessary. In addition to the headquarters located in Austin, there are regional offices in the following cities: Amarillo, Lubbock, Abilene, Arlington, Tyler, El Paso, Odessa, San Angelo, Waco, Beaumont, Austin, Houston, San Antonio, Corpus Christi, and Harlingen. Each regional office is equipped to dispatch an emergency spill response team.

The primary function of initial response personnel to a hazardous material crash is the protection of the general public. During the first minutes after a crash, emergency action may be required for saving lives, attending the injured, preventing or putting out fires, identifying the hazards, and determining the actions required to prevent further threat to human life, property or the environment. Oftentimes, management and response procedures for hazardous materials incidents will be much more involved, requiring complete roadway closures, evacuations of the public from businesses and residences, and specialized clean-up equipment. If a local jurisdiction cannot handle a particular hazmat crash, the jurisdiction can request support from the previously discussed federal and state agencies. The DOT has published and distributed a *Hazardous Material Emergency Response Guidebook* and has funded demonstration projects at the state and local levels to examine prevention and emergency response.

2.5 Alternate Route Planning

The preplanning of alternate routes for diverting traffic is one of the cornerstones for building an effective incident management system. This involves developing pre-incident, detailed alternate route contingency plans for different levels of freeway incidents at any location on the freeway system. The advance alternate route planning process clarifies the responsibilities of each responding agency. Response time is reduced since the specific locations for the placement of signs, barriers, barricades, law enforcement personnel, and the personnel needed to implement a detour on any section of freeway have been identified prior to an incident occurring in that section of freeway. Alternate route planning must have involvement and support of local officials. It is also important that routes are checked prior to final selection to avoid "sensitive" locations (i.e. schools, hospitals, etc.).

2.6 Response Teams

The creation of a team of traffic engineers, technicians, and other necessary individuals capable of responding to major traffic incidents for the purpose of implementing a preplanned diversion route or other on-site management and traffic control activity is an effective technique for reducing response time for major incidents. Team members should be experienced traffic engineers and technicians with a working knowledge of the freeway and all secondary routes and should also be familiar with all of the traffic control requirements to implement various diversionary techniques. Familiarity with the handling of hazardous material is recommended for team members. Team members should play a major role in the alternate route planning process.

3.0 Incident Removal

A key to minimizing the adverse effects of nonrecurrent congestion is to reduce the time required to remove the incident from the freeway. The preplanning of operational procedures for the removal of disabled vehicles to a location off the freeway as rapidly as possible is necessary in order to mitigate the impacts of an incident. Cooperation between agencies is essential to the success of any incident removal scheme. Techniques for providing rapid incident removal and mitigating the impacts of incidents include: off-site crash investigation sites, push bumpers, inflatable air bag systems, policies restricting the use of emergency lights, fast vehicle removal policies, and wrecker contracts or agreements.

3.1 Crash Investigation Sites

Crash investigation sites are specially designated and signed areas off the roadway where damaged vehicles can be moved, motorists can exchange information, and police and motorists can complete the necessary crash report forms. A transportation agency often takes responsibility for designing, constructing, and maintaining these sites. They are typically located in areas that are out of view of the freeway, such as under freeway overpasses, on side streets or parallel frontage roads, and shopping center parking lots. By locating these facilities out of view of the roadway, the potential for continued capacity reduction and secondary crashes caused by “rubberneckers” or “gawkers” is reduced. They are typically designed to accommodate at least five vehicles: a police car, two disabled vehicles, and two wreckers. To ensure that the sites are used, a commitment from the police agency is required. Static signs located along the freeway can be used to direct motorists to the closest crash investigation site. Section 550.022 of the Texas Transportation Code supports the use of crash investigation sites and the fast removal of vehicles involved in minor, property damage-only crashes.

3.2 Push Bumpers

Patrol cars or small response vehicles can be equipped with a push bumper, which allows the response vehicle to move disabled vehicles off the traveled way without the use of a tow truck. Installation of such a device must be accompanied by a set of clearly defined guidelines describing when it is appropriate to remove a damaged or disabled vehicle.

3.3 Inflatable Air Bag Systems

Air bag systems, which can effectively right overturned vehicles, consist of several heavy rubber inflatable cylinders of various heights, lengthy air hoses, and an air pumping system. These systems work ideally in constrained areas, such as tunnels, bridges, or overpasses, where larger towing or response vehicles may have difficulty maneuvering. When deflated, the air bags can be positioned almost anywhere to begin the righting process. As the process continues, the cooperation of a wrecking vehicle may be required.

Limitations do exist on its use with some truck trailer types. Some trailers, depending on their size and shape, can puncture the air bags. However, air bag systems are ideal for fragile loads/tankers that may be damaged or punctured by other righting means.

3.4 Emergency Lights Procedure

The implementation of a procedure on the display of emergency lights is designed to reduce an emergency vehicle's natural tendency, by its mere presence, to cause a general traffic slowdown by eliminating the indiscriminate use of flashing lights, especially roof-mounted lights. Typically, emergency lights should be used as a warning signal to oncoming motorists when an incident obstructs a traffic lane. When the incident is located outside of the traffic lane (i.e., on the shoulder), the display of emergency lights is not recommended since they attract undue attention and may lead to "rubbernecking."

In certain agencies, a change in policy may be required to adopt or implement an emergency lights procedure. Prior to enacting a procedure, an evaluation of existing formal or informal emergency lights would demonstrate the trade-off between warning oncoming motorists and attracting undue attention to an incident.

3.5 Fast Vehicle Removal

Enactment of legislation or an administrative policy which promotes the fast removal of disabled, abandoned, or damaged vehicles that constitute a hazard to other motorists is one method of mitigating the impacts of an incident. A fast vehicle removal policy can take the form of a law (such as Sections 472.011-472.014 of the Texas Transportation Code) or local ordinance which requires motorists to move their vehicles off the freeway immediately after an incident, defines a maximum time limit for leaving unattended vehicles within the freeway right-of-way, or establishes an operating procedure which allows official vehicles to immediately remove disabled vehicles with a push bumper or tow truck. Implementation of a fast vehicle removal policy also requires publicity, translation of the policy into operating procedures, and enforcement to cite violators and effect removal.

3.6 Wrecker Contracts/Agreements

Wrecker contracts and agreements can be used to ensure that minimum response times are achieved in a specific section of freeway. Rotation lists and bid contracts are the most typical forms of wrecker contracts or agreements. The use of wrecker contracts or agreements may require legal action to ensure that existing wrecker services are not put out of business and yet are sufficiently regulated to obtain the desired wrecker response. An ordinance giving police the authority to establish wrecker contracts, to lay the ground rules for use of these contracts, and to determine the penalties for non-compliance by wrecking companies is essential. The establishment of wrecker contracts and agreements may receive considerable opposition from existing wrecker companies; therefore, it is recommended that this form of incident removal enhancement be carefully considered before being implemented.

4.0 Demand Management

Reducing the demand on a freeway is another method of mitigating the impacts of an incident on the traffic stream. This is accomplished by providing motorists with information which will enable them to select the best course of action. The information provided to motorists might include warnings of stopped or slow traffic conditions downstream, notification of the occurrence of an crash, and warnings and information about other unusual freeway conditions. Information systems may be used to advise drivers to travel in a specific lane or, in the case of heavy congestion, to leave the freeway and reroute around the congested area.

Providing motorists with accurate, reliable, up-to-date information is essential to maintaining the credibility of an information system. Information systems used for incident management must be flexible and have the capability to warn motorists far enough upstream of the incident so that they have sufficient time and opportunity to adjust their travel patterns. The information must be presented in a manner to be easily understood. Clear, concise messages that convey the essentials of the situation must be highly visible or clearly enunciated. Accurate information about alternate routes must also be provided.

An information system should provide the following information about a freeway incident and the actions to take:

- ◆ the location of the incident in relation to the device presenting the information,
- ◆ the anticipated duration of the incident,
- ◆ the severity of the incident and the extent of the resulting congestion,
- ◆ potential alternate routes to avoid the incident,
- ◆ the status of traffic conditions on the potential alternate routes, and
- ◆ the status of traffic conditions on the freeway where the incident occurred.

Motorists can be provided with this information through various types of devices. Examples of such devices include portable and permanent dynamic message signs, Highway Advisory Radio (HAR), commercial radio, television broadcasts, and cellular mobile telephone. A more detailed discussion of information devices and their use is provided in Sections 3 and 4 of Chapter 11 (Information Systems).

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MANAGEMENT FOR MAJOR EMERGENCIES

A major transportation emergency is considered to be an event which affects the transportation system in such fashion that the response measures required or the resulting traffic impacts are not typical of the normal day-to-day operations of the system. The response may be unusual in terms of the number and types of agencies involved, in the amount of personnel and equipment resources required, or in the actions required away from the emergency scene. Likewise, impacts upon traffic may be unusually severe, of especially long duration, or require very special reactions by the motorists. Examples of major transportation emergencies include hurricane evacuations, nuclear and chemical plant disasters, flooding, tornadoes, hazardous material spills, and damage to the transportation infrastructure.

1.0 Planning for Major Emergencies

Emergencies that affect the transportation system of an area can occur anywhere at anytime. Emergencies can result in major traffic delays and congestion as well as cause risk to life or property. Several categories of preparations have been found through past experiences to have a major effect upon how well an agency is able to cope with the various types of major emergencies:

- ◆ transportation system evaluation,
- ◆ interagency coordination,
- ◆ resource assessment and management, and
- ◆ public communication and notification.

Generally speaking, a detailed evaluation of the transportation system should be performed in preparation for those emergencies which afford an agency with some advance warning (i.e., ice storms, hurricanes) or which the location of the emergency can be pinpointed (such as near chemical plants, oil refineries, etc.). The evaluation may include such things as:

- ◆ traffic operations analysis at a specific signalized and unsignalized intersections,
- ◆ capacity analysis of key diversion and evacuation routes,
- ◆ identification of "sensitive" locations within the corridor from a transportation perspective (schools, hospitals, etc.), and
- ◆ assessment of manpower and traffic control device needs to accomplish real-time traffic management at key points.

The evaluation is an ongoing process in which the agency develops and maintains an awareness of the ability of the system to accommodate travel before, during, and after a major emergency. In this regard, knowledge of temporary conditions within the system (such as roadway construction and non-functioning traffic control devices) are as important in the process as the physical characteristics of the roadway (which do not change).

continued

1.0 Planning for Major Emergencies (continued)

Although each situation is different, experiences suggest that interagency coordination can be enhanced in many cases by establishing:

- ◆ interagency cooperation agreements,
- ◆ interagency communication networks, and
- ◆ personnel training programs.

Resource needs change constantly when responding to emergencies, and a mechanism is required for tracking and allocating resources in real-time to react to these changing needs. The importance of keeping up with resources must be stressed prior to an emergency, and agency personnel need to be designated to perform the updating and management function during an actual emergency. Events (i.e., personal crises, other volunteer commitments, etc.) during an emergency may keep some employees from contributing to agency emergency response and traffic management efforts. Consequently, agency response and traffic management plans for emergencies should not be dependent upon knowledge or capabilities of specific individuals participating in those activities. Rather, efforts should be taken to ensure that more than one person has the necessary expertise to accomplish agency activities.

The amount and type of information to be disseminated to the public by a transportation agency depends on the characteristics of an emergency. Therefore, an agency should always appoint a public information coordinator to handle the collection and dissemination of transportation information to the media and to the public directly.

2.0 Emergency Response and Management

A number of techniques have been implemented in past emergencies to increase transportation mobility during an emergency condition. These include:

- ◆ adjustments in traffic signal timings to favor diversions or evacuate traffic flows,
- ◆ left-turn and parking restrictions on emergency routes,
- ◆ use of high-occupancy vehicles and facilities to increase evacuation capabilities,
- ◆ conversion of two-way and/or freeway facilities to one-way flow away from the emergency,
- ◆ stationing tow-trucks along major routes to reduce capacity reductions caused by crashes and stalled vehicles and to promote continued roadway flow,
- ◆ suspension of tolls on bridges and toll facilities serving as evacuation or detour routes, and
- ◆ prohibiting unauthorized movement of oversize/overweight cargoes in the emergency area.

Certainly, interagency coordination and cooperation are essential components of the utilization of any of these techniques, which further emphasizes the need for advance planning and preparation in order to be able to implement these techniques.

The report, *Planning Guidelines for Major Transportation Emergencies*, presents guidelines for responding to major emergencies.

3.0 Recovery from an Emergency

Traffic control and management can pose special problems during emergency recovery operations. Existing traffic controls may be missing, damaged, or inoperable; roadway segments may be blocked with debris or structurally damaged, requiring extensive detouring; and traffic demands can be significantly different than normal due to residents returning to their home (in case of emergencies requiring evacuations). In addition, special signing may be needed to warn vehicular and pedestrian traffic of structures near collapse, or of rescue and repair work ongoing in the area.

Most of the traffic control and management techniques discussed in Segment 2.0 are relevant in emergency recovery phases as well. A common problem in past emergencies of a regional nature has been the shortage of normal traffic control devices. Lightweight temporary signs made out of fabric or paper have been used successfully on occasion to ease traffic control needs in major emergency recovery operations. Resource lists are important in this phase of an emergency and can greatly facilitate the procurement and implementation of needed traffic control.

Major traffic control components during emergency conditions are police officers, department of transportation and public works personnel, and even volunteers who provide active traffic control at critical intersections. In the recovery phase of an emergency, a top priority of transportation and public works agencies is to get power and repairs made to traffic signals and street lighting at major intersections so as to free up police and other personnel from this hazardous duty and allow them to focus their attention elsewhere.

Officials involved in past emergencies have identified a number of significant issues that have arisen regarding debris clean-up:

- ◆ Several agencies reported severe tire shortages during emergency clean-up and repair activities, as downed power lines and sharp objects in the roadway ruined tires almost as fast as they were changed.
- ◆ Coordination between transportation and public works agencies and the military, when they are involved, has been a point of difficulty in some past emergencies.
- ◆ A lack of knowledge about federal requirements for assistance (regarding bidding procedures, identification of roadway segments to be included, etc.) delayed the beginning of some clean-up activities.
- ◆ A lack of proper performance requirements (in terms of time) of private contractors for debris removal resulted in the awarding of contracts to firms unable to complete the job in a reasonable amount of time.

Transportation agencies need to coordinate and communicate with other agencies involved in an emergency to determine as soon as possible whether federal assistance is forthcoming (since documentation needs increase dramatically if that occurs) and have preexisting debris removal contracts in place or specifications prepared to implement in the event they are needed.

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**CHAPTER 10
CONTROL STRATEGIES**

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OVERVIEW

Several control strategies are available for managing congestion within an area. Some strategies focus on freeway traffic while others focus on surface street traffic. Other strategies manage the traffic throughout a system (surface streets, freeways, and connectors between the surface streets and the freeways). Management of traffic is concerned not only with providing additional capacity, it also uses demand reduction techniques, such as carpools and alternative work schedules, to provide all travelers with a higher quality of service. This chapter describes various control strategies used to manage traffic. Chapter 8, Sections 4 and 5, provides information on computer programs and operational analysis procedures to develop and evaluate control strategies.

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FREEWAY CONTROL STRATEGIES

There are a number of strategies that can be used to control freeway traffic. Most of these strategies are intended to limit the number of vehicles in the freeway system. Examples include ramp metering, ramp closure, mainlane metering, and freeway closure. Other strategies are intended to optimize the use of the freeway. Examples are freeway lane control, priority control, and reversible lane use control.

1.0 Ramp Metering

Ramp metering uses traffic signals to regulate the number of vehicles that can enter the freeway at the entrance ramps. The basic concept is to control the flow so that the combined freeway and ramp flow rates will not exceed the downstream capacity of the freeway. The use of ramp metering provides for maximum utilization of freeway capacity. When demand exceeds capacity, the resulting stop-and-go traffic creates turbulence that prevents the freeway from operating at its theoretical capacity. Figure 10-1 illustrates the capacity that can be gained by using ramp metering to maintain traffic flow just below the freeway capacity.

In addition to its primary purpose of maintaining traffic flow below the freeway's capacity, ramp metering has several other operational benefits. These include restoring the mobility priority of the freeway that is often lost during congested conditions, improving freeway operations in the vicinity of a ramp, and spreading out of platoons of arriving ramp vehicles.

When the speed of the freeway traffic drops to that of a ramp and there is no ramp metering, the freeway and ramp vehicles share equal access to the freeway. Freeway and ramp vehicles alternate as the two traffic streams merge. As a result, the freeway traffic loses its mobility function and ability to serve through traffic. Ramp metering limits the number of vehicles merging with the freeway traffic, thereby preserving the ability of the freeway to give priority to the through traffic.

When ramp metering is used to limit freeway access to one vehicle at a time, the freeway vehicles can more easily adjust their speed and positions in the outside freeway lane to accommodate the merge of the entering vehicle. Without ramp metering, queues can form in the ramp merging area, leading to difficult merging maneuvers. Ramp metering minimizes the occurrence of vehicles stopped in the merge area, and therefore, enhances traffic safety.

Entrance ramp traffic often arrives in platoons, resulting from the green indication of the upstream signal at a signalized diamond interchange. Ramp metering distributes the platoons and thereby reduces the short-term ramp flow rates of the entering traffic by increasing the time intervals between vehicles entering the freeway so that the total freeway demand does not exceed capacity.

continued

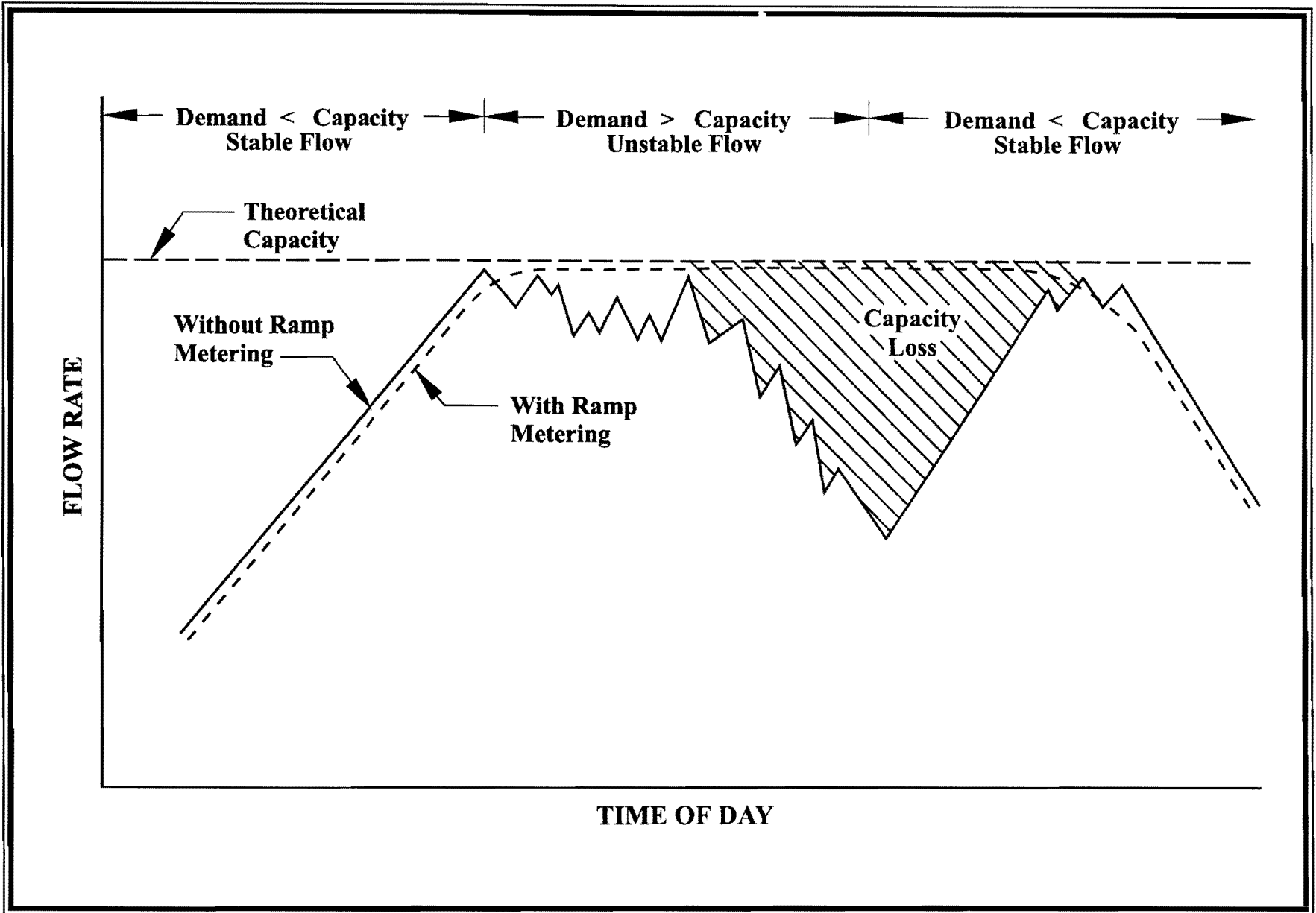


Figure 10-1. Capacity Gain from Ramp Metering

1.0 Ramp Metering (continued)

Even if the ramp traffic demand at a particular ramp does not exceed the capacity of a merging area, it may be necessary to reduce its entrance flow rate to maintain the balance between demand and capacity in a downstream freeway section. This would be necessary when the desired metering rate at one or more ramps cannot be implemented. For example, if a ramp does not have a suitable alternative route and if queues from the ramp signal block critical intersections and driveways, the flow rate on the ramp needs to be higher than that required to balance demand and capacity. Therefore, upstream ramps would have reduced rates to compensate for the lack of downstream control.

The primary function of ramp metering is to maintain the freeway's capacity to efficiently serve high-priority urban traffic demands. Additionally, it may be used to affect travel demand management actions, such as promoting HOV lane operations, congestion management strategies, and traffic safety problems.

Two ramp metering strategies are utilized by TxDOT: local metering and system metering. Local metering is used at ramps with no coordination between ramps. System metering is the operational coordination of a series of local meters along the freeway to provide maximum flow without allowing congestion to form. Software has been developed to aid in the development of ramp metering timing plans for both modes of operation. The software, named RAMBO (Real-time Adaptive Metering Bottleneck Optimization), also provides an evaluation of the metering plans and graphic plots of the results. RAMBO fully supports the TxDOT Freeway Traffic Management system. RAMBO I is the local ramp meter program and RAMBO II is the system program.

An important consideration in entrance ramp control is the availability of alternative routes. If the control strategy requires low metering rates at a time of high entrance ramp demands, the queue lengths and vehicle delays will become excessive. These conditions will encourage drivers to use the alternate routes, to enter the freeway at different ramps, or to use surface streets to avoid the freeway entirely.

A comprehensive discussion of ramp metering, including information on how to implement different metering rates, is presented in the *Traffic Control Systems Handbook* and *Advanced Freeway System Ramp Metering Strategies for Texas*.

2.0 Ramp Closure

There are two choices to consider when circumstances make it impractical to control an entrance ramp by metering:

- ◆ do not apply any control to the ramp or
- ◆ apply total control by closing the ramp to some or all traffic.

The first alternative is not attractive since it negates the benefits of the other parts of the control system. The second alternative is not attractive because it totally denies access to a public facility. However, this disadvantage can be alleviated by the provision of well-defined alternate routes.

The impacts on cross street, frontage road, and driveway operations must be considered if an entrance ramp does not have adequate storage distance for the expected queues that form at the ramp signal. In a similar manner, if the length of acceleration distance from the ramp signal to the freeway merge area is not adequate, then the installation of ramp metering may not improve the merging operations. Closure of the ramp and provisions for directing the traffic to other ramps and surface streets would be the preferred control method.

If the required metering rate for a ramp would result in long queues and delays, ramp closure may be a viable alternative, even if the geometrics of the designs are adequate. This is especially true if frontage roads and arterial streets in the area provide useful corridor capacity. The destination of entrance ramp traffic is another consideration in ramp closure. If a high percentage of ramp traffic is determined to have short trip lengths on the freeway, ramp closure control should be considered.

3.0 Mainlane Metering

Mainlane metering applies the concept of entrance ramp metering to freeway lanes. If the total traffic flow approaching a freeway section approaches or exceeds the capacity of that section, then congestion and lower levels of service can be expected. If ramp metering can not adequately adjust the entering flows, then some form of control could be applied to the mainlanes to achieve the desired balance. This concept has not been widely used. To date its applications have been successful on primarily on toll facilities and special control access facilities such as bridges and tunnels.

4.0 Freeway Lane Control

Control of freeway lanes is accomplished through closing freeway lanes or indicating preferred lanes for travel. There are two types of freeway lane closures. In an informal closure, one or more lanes are closed as the result of an object or objects blocking traffic flow. In a formal lane closure, one or more lanes are intentionally closed using traffic control devices or other official directions such as those given by a police officer. Informing road users of the preferred lanes of travel can be accomplished through the use of signing or lane control signals.

The formal closure of a freeway lane or lanes is often associated with roadway maintenance and construction activities. Chapter 5, Section 2 addresses methods for closing a lane. In these cases, channelizing devices, barrels, cones, and/or arrow panels may be used to close the lane. A formal freeway lane closure may also be implemented in response to an incident. In these cases, signs and cones which can be carried by response vehicles are used to close a lane or lanes. Police officers and/or flaggers can also close a lane.

An informal lane closure occurs when a vehicle or object blocks one or more freeway lanes. Most often, this occurs as the result of an crash, a vehicle breakdown, or a load which has fallen from a vehicle. Before a response team arrives at the scene, vehicles maneuver around the blockage without the aid of formal traffic control.

The assignment of a lane to a specified class of vehicles is another form of lane control. The designation of a lane for exclusive use by high-occupancy vehicles such as buses and carpools would be a typical strategy to provide preferential treatment for these vehicles. The restriction of large vehicles to one or more lanes, however with major differences in objectives (e.g., increased roadway capacity or pavement wear), is another application of this control.

Lane control signals can be used to provide advance notice of lane closures or to indicate preferred lanes of travel. The use of lane control signals for freeways is addressed in Chapter 11, Section 3, Segment 6.0.

5.0 Freeway Closure

The total closure of a freeway is applied only under extreme conditions, when other forms of traffic control are not effective. Reasons for considering the total closure of a freeway include:

- ◆ a major traffic crash blocks all lanes (where closure warnings are initiated prior to major interchanges to present best alternate route selection),
- ◆ a major crash or incident in the vicinity of the freeway involving hazardous materials which could result in the evacuation of the area,
- ◆ a major reconstruction project or maintenance operation that either would endanger the traffic or could not be completed with the presence of vehicular traffic, and
- ◆ severe weather conditions.

This type of control obviously requires a large amount of advance planning, coordination, and cooperation of many agencies and organizations. The diversion of freeway traffic to other freeways and onto city streets must be analyzed for its effects, and the traffic controls on these alternate routes adjusted accordingly. Updates of the operational status of city streets are essential for effective diversion as similar closure problems may occur on them as well. Signs to lead traffic along the designated routes and back to their original route must be provided. The coordination of closure activities for random events are most difficult, unless advanced planning has been conducted.

6.0 Priority Control

The concept of priority control for high-occupancy vehicles (HOV) is to provide preferential treatment for buses, vanpools, and carpools in the form of travel time advantage and reliability over single-occupancy vehicles. Preferential treatment is intended to relieve traffic congestion on freeways by encouraging better utilization of highway and vehicular resources. The objective is to better serve the people-demand for the freeway corridor and reduce the vehicle-demand by inducing more people to use HOVs during peak traffic hours. People in the regular lanes also benefit because of the diversion to high-occupancy vehicles and the more efficient use of the facility. In addition to reducing vehicular demand, higher vehicle occupancies contribute to reductions in air-pollution and fuel consumption. Different methods of priority control that have been used on freeways are separated facilities, reserved lanes (concurrent flow and contraflow), and priority access control.

6.1 Separated High-Occupancy Vehicle Facilities

Separate roadways or space reserved in median areas provide positive separation of HOV traffic from the rest of the traffic. These are among the most expensive HOV treatments because major construction is required. Separate HOV facilities do not have the same enforcement and safety problems encountered by the non-separated treatments. Separation techniques range from buffer zones without physical barriers to parallel physical barriers.

6.2 Reserved Freeway Lanes

Freeway lanes reserved for HOV use have been implemented in two basic configurations, concurrent flow and contraflow lanes. Reserved lanes in the same direction as peak flow and on the same side of the median are concurrent-flow HOV lanes, while reserved lanes on the off peak direction side of the median where HOV traffic moves against the flow of traffic are contraflow lanes.

Contraflow lanes have received limited application, with their use restricted to specific areas of extreme congestion where the imbalance in directional flows permit consideration. In general, they have been considered to be interim actions during the development and demonstration of long-range solutions. The concept of concurrent-flow reserved lanes designates a normal lane in the peak direction for HOV use. This preferential lane may be provided by adding a lane through construction or restriping, or by preempting an existing normal-use lane. The use of dedicated concurrent flow lanes is the preferred alternative.

Experience with converting an existing normal-use lane to HOV use has revealed significant public opposition. By contrast, public acceptance of adding a lane has been higher, even in cases where lane width standards have been compromised. The primary problem of concurrent-flow lanes is enforcement. Violating vehicles have virtually unrestricted access to the lane, and positioning enforcement officers at proper locations is difficult, creating the need for a special enforcement plan.

Moveable barriers provide a means of reserving a lane for HOVs while maintaining a safety barrier between opposing traffic. The moveable barriers are moved prior to the peak period in order to create an HOV lane on the off-peak side of the freeway.

6.3 Priority Access Control

Ramp bypass lanes for buses, vanpools, and carpools can be used with entrance ramp metering to reduce the delay to the HOVs caused by ramp queues, while still maintaining non-congested flow on the freeway. Typical applications of priority access control utilize a two-lane entrance ramp or two separate ramps in close proximity to one another. One lane or ramp can be used only by HOVs, while the other ramp is metered for non-HOV traffic. Dedicating ramps to exclusive HOV use without nearby provision for non-HOVs has generally been limited to special situations; for example, the direct connection between priority lanes and park-and-ride lots or in construction zones as a traffic management tool.

6.4 High-Occupancy Toll Lanes

High-occupancy toll (HOT) lanes are a new form of congestion pricing that is being tested in a few locations nationwide. HOT lanes use advanced technologies that allow agencies to charge single-occupant vehicles who wish to pay the toll to travel on the HOV lane (high occupancy vehicles continue to utilize the lane for free). The amount of the toll charged these single occupant vehicles is varied depending on the level of demand so that the lane volumes are kept below capacity, maintaining high-speed flow.

7.0 Reversible Lane Use Control

Reversible lanes provide a more economical and efficient use of road space and right-of-way by assigning the available freeway capacity according to the peak directional demand of traffic. In its ideal form, the lane assignment corresponds to the directional demand. For instance, if the directional split of traffic is 70/30 and the freeway has 10 lanes, then 7 of the lanes would be assigned to traffic moving in the peak direction.

Reversible freeway lanes are limited in application due to the desire to provide a barrier separating opposing traffic. Its most common form is an HOV contraflow lane. For reversible lanes to be warranted, peak period corridor traffic volumes (traffic on the freeway mainlanes and on parallel streets and frontage roads) must exhibit a significant directional imbalance (e.g., 70 percent to 30 percent) which will exist for a number of years.

URBAN STREET CONTROL STRATEGIES

There are numerous alternatives for controlling traffic on urban streets. Most of the alternatives consist of some form of traffic signal control. Signalized control of intersections can be divided into isolated, arterial, or network control. Special considerations for signalized control include diamond interchange operation, flashing operation, and right-turn-on-red. Other considerations for urban street control include dynamic lane use assignment, parking restrictions/prohibitions, and turn prohibitions.

1.0 Isolated Intersections

Signalized control at an isolated intersection operates independently of control at any adjacent intersections. Roadway characteristics, such as the number of approach lanes, traffic volumes, arrival patterns, and number of intersection approaches, are all factors used in determining the appropriate type of intersection control.

Full-actuated control is usually the most efficient type of operation at isolated intersections. When a decision is made to install a traffic signal, full-actuated control should be the first consideration. Pretimed control is best suited for locations where traffic is highly predictable and constant over a long period of time. However, predictable traffic flow does not usually exist at isolated intersections.

2.0 Arterial Street Control

Intersection control in an arterial system is comprised of two or more traffic signals whose operation is time-related. The major concern is the coordination of local controllers along an arterial street to ensure progressive traffic flow. The basic concept of arterial street control is that vehicles on the arterial are grouped in platoons and travel progressively from signal to signal with minimum impediment. Depending upon prevailing traffic demand, this progression may be oriented to one or both travel directions. The main objective is to establish and ensure a time relationship between the beginning of arterial greens at each of the locally controlled intersections, commensurate with progressive flow speed and desired direction, so that continuous traffic flow in defined platoons reduces the number of stops and delay along the arterial.

3.0 Network Control

In a network system, such as a typical central business district (CBD), crossing arterials form a grid pattern with virtually every intersection in the network requiring signal control. Because of the nature of this closely spaced arrangement of signals and a basic desire to provide arterial progression on all of the streets in each travel direction, the prevalent signal control is pretimed operation. Semi-actuated control is used in some network systems at midblock pedestrian signals and, less often, at lighter traveled intersections to provide left-turn protection on demand only.

The objective in the network system is to provide time relationships between the beginning of greens at each of the signalized intersections. The relationship is defined by a timing plan to optimize traffic performance for a given traffic pattern (e.g., inbound peak, balanced light flow, etc.). Provision of safe, orderly, and dependable flow with a minimum of stops and delays over a wide range of traffic volumes is the desired operational objective. Minimizing of queue spillback during high-volume conditions is also desired.

4.0 Special Controls for Diamond Interchanges

Special controls are defined as traffic control applications for other than the standard control of signalized diamond interchanges. There are many variations of diamond interchanges: conventional full diamonds, half diamonds, split diamonds, and others. Chapter 3, Section 3, Segment 5.3 contains additional information on the different types of diamond interchanges. Diamond interchanges may or may not have frontage roads. Several operational problems can occur when diamond interchanges are signalized. One problem occurs when there is a spillback from one of the adjacent ramps through one of the signalized intersections. Another spillback that can influence operation is when the left-turn pocket overflows and spills back into a through lane, thus reducing the capacity available for through traffic. A third type of spillback is exit-ramp spillback. This occurs when a long queue of vehicles on the exit ramp backs onto the freeway, thus creating potential conflicts between high-speed freeway vehicles and stopped vehicles. As a result of these factors, diamond interchanges are often controlled by diamond interchange controllers which are specifically designed for this purpose. Dynamic lane assignment (Chapter 10, Section 3, Segment 6.0) can also be used for controlling traffic at a diamond interchange.

5.0 Converting Frontage Roads to One-Way Flow

As development in certain areas and along certain freeway corridors occur, it sometimes become desirable to convert an existing two-way frontage road to one-way operation. Generally speaking, two-way frontage roads should be converted whenever the safety and operational benefits of one-way operation exceed those for existing two-way operation. Conversion is recommended if daily traffic volumes entering a frontage road/cross road interchange of various geometric configurations exceed the values shown in Table 10-1.

Frontage road conversion to one-way operation should also be considered if at least two critical turning movements at the signalized diamond interchanges meet or exceed 65 percent of their phase capacity during the peak 15-minute period (morning or afternoon). If considerable local opposition to frontage road conversion exists, this criteria may be increased to 80 percent of available phase capacity. These criteria assume that the interchange signal timings are operating at near optimum levels.

Although definitive criteria is not available, agencies must also consider the impact of frontage road conversion upon the number of contraflow trips that will be affected and the effect that diverting these trips will have upon local streets and businesses in the corridor. Frontage road interchange spacing must also be considered in conversion decisions to one-way operation. Conversion is favorable if spacing between interchanges is 3 kilometers (2 miles) or less.

Table 10-1. Average Daily Frontage Road Interchange Traffic Volumes Warranting Conversion to One-Way Operation

Description of Interchange		Warrant Conditions	
Cross Section	Frontage Road	Desirable	Minimum
two-lane	two-lane	20,000	25,000
two-lane + left-turn	two-lane + left-turn	27,500	35,000
four-lane + left-turn	two-lane	30,000	37,500
four-lane + left-turn	two-lane + left-turn	35,000	42,500

6.0 Dynamic Lane Assignment

Turning movement demand at a diamond interchange varies during the day. Where the variability in turning movements becomes substantial, maintaining uncongested traffic conditions throughout the day is a challenging problem because lane assignments for turning movements are made on a permanent basis. Dynamic lane assignment provides the ability to change the lanes assigned for turning movements according to variations in traffic demand caused by both recurrent and non-recurrent congestion. Dynamic lane assignment is a fairly new concept, but has been very successful in limited field applications to date.

Lane use information at intersections is presently conveyed to drivers via permanent traffic control devices such as pavement markings and lane control signs. The static nature of these traffic control devices results in the inefficient use of available capacity when wide variations in turning movements exist. This problem can become acute, especially on one-way frontage roads that serve as alternate routes during incidents and pavement maintenance activities.

The concept of dynamic lane assignment is to change the turning movement assignments for each lane according to the demand for the turning movements. Figure 10-2 illustrates this concept. The use of dynamic lane assignment signing provides a more efficient means of responding to cyclical variations in turning movements, allowing lane usage to be optimized based on traffic demand. Dynamic lane assignment can be defined as “space management.” When it is used in conjunction with “time management” (the use of demand responsive signal control), it can be a cost-effective alternative to the re-design of major intersections.

The design and operation of internally lighted displays depend on basic “rules-of-thumb” and experience. Design procedures for dynamic lane assignment signs are not yet well established, due largely to the rapid development of these types of signs. Design procedures and requirements should take into account the visual capabilities of drivers in both daytime and nighttime driving conditions. Liability issues further mandate that dynamic lane assignment signing conform as closely as possible to the requirements of the TMUTCD for signing. *Space Management: An Application of Dynamic Lane Assignment* describes some of the key issues and considerations associated with the use of dynamic lane assignment.

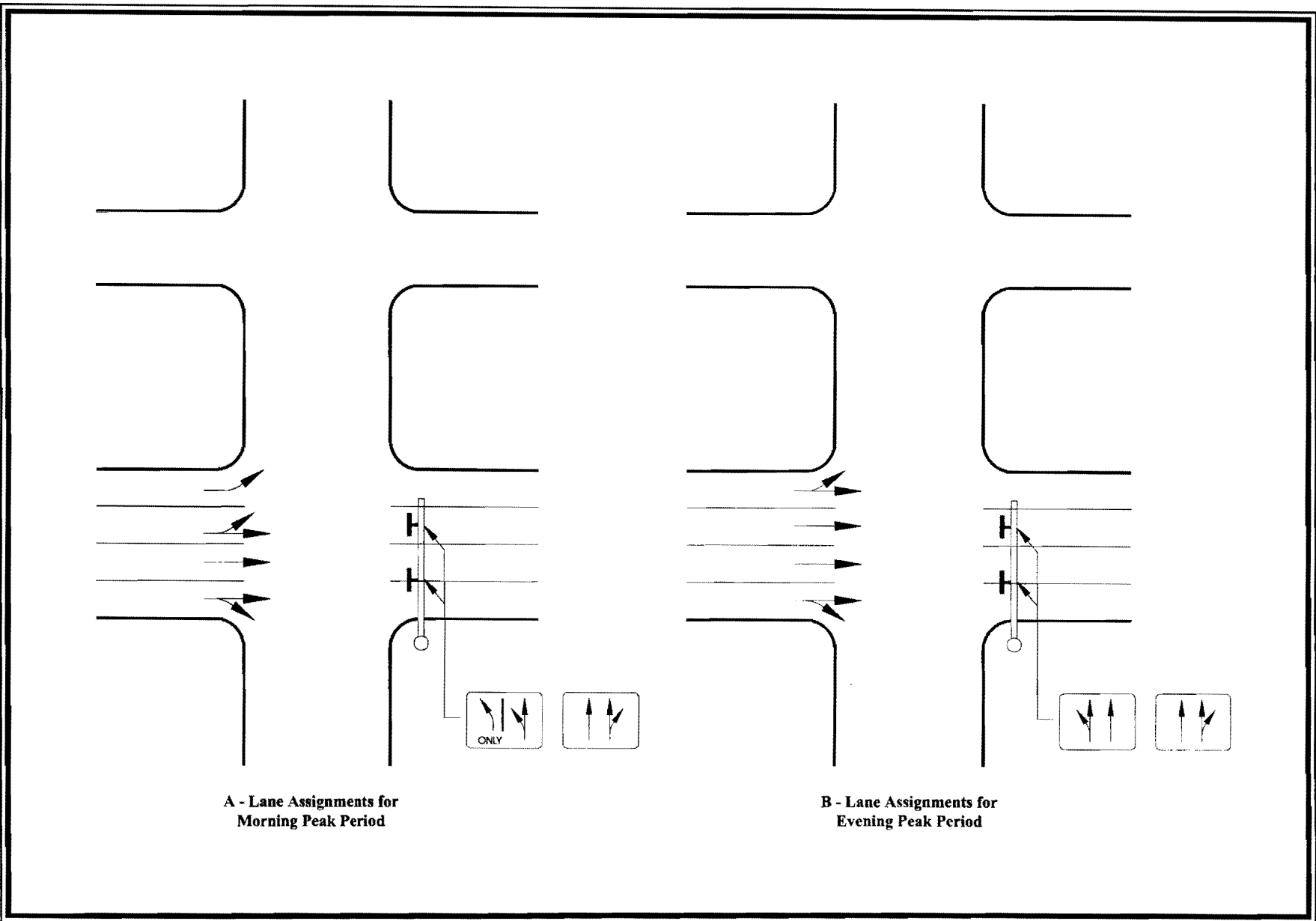


Figure 10-2. Dynamic Lane Assignment Concept

7.0 Flashing Signal Operation or Signal Removal

The traffic conditions which support the installation and operation of a traffic signal may not exist during all periods that the signal is operating, or the conditions may change over time as traffic patterns change. Two options available to address lower traffic volumes at signalized intersections are flashing operation or signal removal.

Signals may be placed in the flashing mode during temporary low-volume conditions. These conditions typically occur during late night or early morning periods. The *Texas Manual of Uniform Traffic Control Devices (TMUTCD)* states (section 4B-18) that pretimed traffic signals should be placed on flashing operation when traffic volumes drop to 50 percent of the warrant volumes for a period of four or more consecutive hours. This section of the *TMUTCD* also contains some guidance for placing signals in flashing operation.

In some cases, traffic demand at a signalized intersection decreases to a level where a traffic signal may not be the most effective means of controlling the intersection. There are no specific guidelines which address the traffic volume below which traffic signals are not appropriate. Instead, many factors must be considered before a traffic signal can be removed, including sight distance, site conditions, traffic volumes, crash impacts of removal, fuel savings, vehicular delay, and alternative improvements. The *TMUTCD* states (section 4C-2) that a traffic signal should not be continued in operation if the warrant requirements are not met. The *User Guide for Removal of Not Needed Traffic Signals* describes an analysis process for evaluating the impacts of removing a traffic signal at a specific intersection.

8.0 Right-Turn-On-Red

Texas law allows vehicles to turn right after coming to a stop when facing a red indication at a signalized intersection, if the turn can be completed in a safe manner and if there are no signs prohibiting a right turn during the red indication. The right-turn-on-red (RTOR) maneuver provides an opportunity to increase the operational efficiency of a traffic signal by reducing the demand for a green indication. The use of RTOR is especially effective at locations with an exclusive right-turn lane. Factors which impact the prohibition of the RTOR include sight distance, pedestrian traffic, bicycle traffic, conflicting traffic volumes, signal phasing, site conditions, and operational experience (i.e., safety problems). RTOR should also be restricted where dual right turn lanes exist, at least from the inside lane.

9.0 Parking Prohibition

Prohibiting on-street parking may result in improved traffic operations on urban arterials, particularly in the vicinity of intersections. The advantages of removing on-street parking include increased street capacity resulting from the additional lane or the presence of the wider lane, removal of parking maneuver conflicts, and elimination of potential sight distance restrictions. When on-street parking is removed, consideration should be given to alternate parking areas and how the relocation of parked vehicles will impact traffic operations

10.0 Turn Prohibitions/Restrictions

Traffic operations at an intersection may be improved by prohibiting some turning movements. These prohibitions may be on a part-time or full-time basis. Turn prohibitions may be utilized due to insufficient intersection capacity for all turning and through movements, insufficient sight distance, or other site restrictions. Turn prohibitions are most often utilized at signalized intersections. One of the most beneficial applications of turn prohibitions is prohibiting left turns at signalized intersections during peak hours. This prohibition reduces the number of signal phases, thus increasing the operational efficiency of the signal. The prohibition may be applied to the peak direction of travel, the off-peak direction, or both. However, prohibiting left turns does not remove the driver's desire to turn left. Consideration should be given to how the relocation of left turns will impact operations at other locations and to determine that the problem has not been shifted to another location.

SYSTEM CONTROL STRATEGIES

Control strategies for an entire system are aimed more at controlling the total system demand rather than controlling input to the system. Corridor control uses freeway and urban street control to manage the total demand for the system. System demand can also be managed through ridesharing, alternative work schedules, and diversion to alternative travel modes.

1.0 Corridor Control

A corridor is comprised of a freeway, its ramps, freeway frontage roads, parallel arterial streets that can be used as alternative routes, and cross streets that are links between the freeway ramps and the parallel alternatives. The purpose of corridor control is to provide optimum utilization of all available facilities in a corridor.

Implicit in the concept of corridor control is that it must be traffic-responsive to be meaningful. The underlying philosophy of corridor control is twofold: restriction and diversion. Restriction consists of limiting demand on corridor links to less than their individual capacities through the coordination of such regulatory controls as ramp, mainline, and arterial-street controls. Diversion of traffic from corridor links with excess demand to links with excess capacity is achieved through driver information systems (Chapter 11).

The purpose of corridor control is to integrate the operation of the various control and driver information systems in the corridor so that optimum utilization of corridor capacity is achieved. This integration entails application of the following techniques:

- ◆ coordination of traffic signals on frontage roads and on parallel arterials,
- ◆ coordination of ramp control and frontage road operations to provide alternative routes on frontage roads during congested periods on the freeway or during freeway incidents,
- ◆ coordination of the ramp metering control with the frontage-road/cross-street intersection control to prevent queuing across these intersections,
- ◆ provision of turning phases at parallel alternative route intersections with cross streets leading to freeway ramps, possibly in coordination with driver information displays, and
- ◆ coordination of traffic signals at freeway interchanges with arterial cross streets.

2.0 Ridesharing

Techniques available to reduce vehicle volume on streets and highways include increasing vehicle occupancy through ridesharing. Some methods of ridesharing are as follows:

- ◆ **Carpools** - Typically involve 2 to 4 persons who share driving to work, usually on a rotating basis.
- ◆ **Vanpools** - A van, usually owned by the employer, that is used by 8 to 15 persons who each pay a prorated share of vehicle and operating costs.
- ◆ **Subscription bus service** - Usually provided to prearranged groups of 30 to 40 persons who commute to work from the same general area.
- ◆ **Shared-ride taxi service** - Typically associated with prearranged trips to an airport or bus or train terminal.

continued

2.0 Ridesharing (continued)

The success of ridesharing depends on how well the proposed strategy compares with the single-occupant automobile in terms of travel time, cost, and convenience. Other strategies, such as reserved parking for ridesharing and separate lanes for high-occupancy vehicles, provide important additional incentives. Carpooling has perhaps the greatest potential because it is easily implemented, requiring very little in the way of organization or new vehicles.

3.0 Alternative Work Schedules

Another approach to relieve peak period congestion on streets and highways is to shift demand to less congested times when surplus capacity is available and to reduce the need to travel. At large places of employment, alternative work schedules can significantly reduce the number of employees arriving and departing during the peak periods. Alternatives include:

- ◆ **Staggered work hours**, by which groups of employees are assigned different starting times, for example, at 15-min intervals over a 2-hr period.
- ◆ **Flexible work hours**, where individual workers are allowed to have some control over their own working hours, but all employees are required to be present during a core time.
- ◆ **Compressed work weeks**, by which employees work fewer than 5 days per week but work more hours per day, for example, 4 days per week, 10 hr per day.
- ◆ **Telecommuting**, where telecommunication technologies are used to reduce the demand for travel to an office.

4.0 Encouraging Travel by Means Other Than Automobile

If motorists would leave the car at home and travel to work by bus, train, bike, or on foot, then the duration of congestion during the peak period might be reduced, and the total person-movement through the corridor could be increased. For this to occur, the service provided by the other modes must be perceived as comparable or better than driving alone. Buses are the most common alternative mode of transportation. The *Guidelines for Planning, Designing, and Operating Bus-Related Street Improvements* report provides information on incorporating provisions for buses into street planning, design, and operational processes.

Park-and-ride facilities have proven to be an effective means of encouraging transit use. The provision of parking lots at outlying locations is relatively easy to implement, because they can be built at low cost. For a park-and-ride facility to be successful, a high level of transit service must be provided, preferential treatment should be provided on part or all of the trip length, and the total cost to the motorist should be lower than the cost by auto. The parking lots should be constructed so as to be compatible with the neighborhood and should be located in an area where travel demand and traffic congestion are sufficient to warrant service. The *Revised Manual for Planning, Designing, and Operating Transitway Facilities in Texas* addresses transitways planning, design, and operational considerations.

CHAPTER 11
INFORMATION SYSTEMS

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OVERVIEW

One means of reducing congestion and improving the operations of a transportation system is to reduce or reallocate demand. Demand on the system can be reduced or reallocated by providing users with information about traffic conditions. With this information, users may decide to choose an alternate route to their destination, change their mode of transportation, alter their departure time, or cancel their trip. These actions help reduce the level of congestion and improve the efficiency of the transportation system. This chapter discusses not only the importance of information but also some of the existing and emerging technologies that can be used to provide travelers with information.

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IMPORTANCE OF REAL-TIME INFORMATION

Highway and transit users need current, accurate, and reliable information in order for them to make informed and intelligent mode, route, and departure time decisions. The type of information, the format in which it is presented, and the device used to present it depends upon the intended audience, the nature of the situation, and the action desired of the user. How users react to the information depends upon their destinations; their familiarity with the area; their trip purpose; and their willingness to change from their preferred route, mode, or departure time. The purpose of real-time information systems is to provide roadway and transit users with information about roadway and commuting conditions so that they can make informed decisions and take appropriate actions which best serve their needs.

1.0 Definition of Real-Time

The definition of real-time varies among the operators of information systems and transportation officials. To some, the definition of real-time means the information is received or provided at the same moment a situation occurs or as conditions change on a facility. In some situations, such as a major accident or hazardous materials spill, an almost instantaneous response is desirable or necessary. However, there are situations where considerable delays can be tolerated before action is needed. The key to any real-time system is to provide information in ample time to affect appropriate operational, control, and scheduling changes that improve the efficiency and safety of the transportation system as a whole. Therefore, how real-time information is defined depends on the circumstances of the situation and on the potential impacts that failing to communicate changing roadway, traffic, or weather conditions have on travelers.

2.0 Modes of Presentation

Roadway and transit users receive information from a variety of sources. Most sources present information in either a visual or auditory format.

2.1 Visual Mode

Most users are accustomed to receiving information through signs and displays. As a result, the visual mode of presentation is the primary means users obtain information. The visual mode of presentation is also favored by many system operators since the technology to provide information visually is readily available. However, there are several constraints to providing information visually. The amount of information provided users through visual means, especially motorists in their vehicles, is limited. Often, users can obtain only brief, interrupted glimpses of messages. For this reason, the visual mode of presentation relies heavily on coding and abbreviations that may not be readily understood by all users. Furthermore, most techniques for presenting visual information are confined to a fixed or specific location. The user must make an effort to see and read the device. If, for some reason, the user is unable to read the message as the device is passed, the user does not obtain the information.

2.2 Auditory Mode

With auditory messages, users can be provided with more detailed information. The information can be in a free flowing and continuous format, thereby permitting lengthier messages. Because of the range of some auditory systems, users can be provided with the same information at numerous locations along a facility. However, it is more difficult for users to process and retain complex auditory information. Long, complicated auditory messages must be repeated often to be understood by users. Furthermore, the number of devices for providing auditory information are limited. With some devices, message transmissions are susceptible to interruptions due to environmental conditions.

3.0 Design Considerations

Regardless of whether visual or auditory devices are used to provide users with information, there are several important issues to be considered when designing a real-time information system.

3.1 Maintaining Credibility

Roadway and transit users rely on information systems to provide them with reliable, accurate, and current information. Care must be taken to ensure that users are provided with the correct information in a timely manner. The credibility of the system is damaged when users are provided with information that is contrary to current conditions, erroneous, or not easily understood or interpreted. The credibility of the system suffers even if good information is used, but is provided without ample time to react, not significantly better than their current course of action, or already known by the users. Listed below are several factors which will help to ensure that credibility is maintained:

- ◆ The information provided should not exceed the surveillance capabilities of the system.
- ◆ The information should be updated as conditions change.
- ◆ Users should not be placed in a worse situation than they are currently experiencing.

3.2 System Objectives

The objectives of an operational information system should be determined prior to designing the system. Specific questions that help define the objectives of a system are listed below:

- ◆ **What** is the problem to be addressed with the system?
- ◆ **Who** will be receiving the information?
- ◆ **What type** of response is required of the users?
- ◆ **Where** should the response take place?
- ◆ **How** will the system be operated?
- ◆ **When** will the information be provided?

The answers to these questions not only help define the type and placement of the devices to be used in a system but also influence the type, format, length, and redundancy of the information provided.

3.3 When to Provide Information

There are two schools of thought as to when information should be provided. The first believes some type of information should always be provided by the system, regardless of whether or not there is any new information to be reported. The other school of thought believes information systems should be used only when users need to be notified of unusual or changing conditions.

By always providing some type of information, users are assured that the system is operational and that they will be informed when something occurs. The argument against this philosophy is that users will become complacent if no new information is provided, thereby limiting the effectiveness of the system when new information is provided.

The other school of thought believes information systems should be used only when users need to be notified of unusual or changing conditions. The philosophy of using information systems only when there is a need is based on human factor principles recommending against providing trivial or irrelevant information. The argument against this philosophy is that users do not know if the system is operational unless information is provided. However, both schools of thought agree it is better to display less or no information if the operator is unsure about the conditions on a facility.

3.4 User Reactions

Users may react differently to the same information depending upon their destination, their preferred mode or route choice, their familiarity with the potential options, and their trip purpose. How individual users react to information also depends upon the type, location, and magnitude of the changing conditions. Some of the reasons motorists react differently to information are:

- ◆ unfavorable experiences encountered when responding to past information,
- ◆ anticipated unsatisfactory conditions on alternate routes or modes,
- ◆ failure to receive or understand the information,
- ◆ importance of arriving on time at the current destination,
- ◆ time of day,
- ◆ unfamiliarity with recommended alternate routes or modes, and
- ◆ a lack of confidence in the information.

Research has shown that as much as 10 to 15 minutes of travel time savings must be perceived by motorists before they will divert to an alternate route during peak periods. Motorists may be less sensitive to time savings information during peak travel periods than during the off-peak periods.

Also, some users, such as heavy truck operators or hazardous materials haulers, may be prohibited by law or regulation from responding to the information. Whatever the reasons, some portion of the user population will not react to the information. However, many situations can be improved if only a portion of the users react to the information. The different ways in which users react to information is a valuable asset of the information system.

3.5 Jurisdictional Information

Specific areas which will need to be addressed by transportation agencies in the future are:

- ◆ how inter-jurisdictional cooperation and integration of traffic data should be handled,
- ◆ what involvement transportation agencies should have in the dissemination and control of traffic information, and
- ◆ how information will be best distributed to motorists.

Inter-jurisdictional coordination is a requirement in any effective corridor or regional traffic management system to prevent data collection redundancies and to establish cooperative traffic management strategies among all of the various roadway facilities.

INFORMATION TECHNIQUES

Information can be presented either through static or dynamic devices. Static devices, such as regular traffic control signs and pavement markings, convey the same message to all users, regardless of the conditions. They are most commonly used at locations where the conditions are well-defined and the same response is desired all the time. The *Texas Manual on Uniform Traffic Control Devices* should be consulted for information dealing with static information devices.

With dynamic or variable systems, information can be altered to reflect changing roadway, traffic, or weather conditions. Dynamic systems are generally used to advise highway and transit users of unusual conditions and to provide recommendations on a course of action that not only benefits individual users but also enhances the safety and operation of the transportation system as a whole. This section describes some of the existing techniques for providing travelers with information using dynamic systems.

1.0 Dynamic Message Signs

Dynamic message signs (DMSs) (also called variable message signs [VMS] or changeable message signs [CMS]) are perhaps the most commonly used technique for providing highway users with current roadway, traffic, and weather information. DMS use visual words, numbers, or symbolic displays that can be electronically or mechanically varied to inform motorists of changing traffic conditions. Dynamic message signing systems offer tremendous flexibility in types of messages that can be displayed to motorists. For this reason, DMSs are used in freeway and arterial traffic management systems. They are also used in traffic control systems for construction and maintenance work zones, and for special events. They may be either permanent or portable depending upon the type of service they are intended to provide, and can be operated either on a fixed time basis with on-site control or interconnected with a traffic management surveillance system to provide remote automatic control. The signs can be used to perform the following functions:

- ◆ Inform motorists of varying traffic, roadway, and environmental conditions.
- ◆ Provide more specific information relative to the location and delays associated with incidents.
- ◆ Advise motorists on ways to obtain additional information.
- ◆ Suggest alternate routes to avoid freeway congestion.
- ◆ Reassure drivers on unfamiliar alternate routes.
- ◆ Redirect diverted drivers back to freeways.

There are three basic types of DMSs: light-reflecting, light-emitting, and hybrid. Each type has its own set of characteristics, advantages, and limitations. Table 11-1 lists some of the DMS systems currently available. The *Traffic Control Systems Handbook, Manual on Real-Time Motorist Information Displays, Guidelines on the Use and Operation of Changeable Message Signs*, and *Guidelines on the Selection and Design of Messages for Changeable Message Signs* should be consulted for more information about the design and operating characteristics of each type of DMS.

Table 11-1. Types of Dynamic Message Signs

LIGHT REFLECTING
Foldout - conventional sign with a hinged viewing face that is closed when not needed
Scroll - flexible cloth or plastic material stretched between rollers
Rotating Drum - 1 to 4 multifaced rotating drums with each face having a fixed message
Electromagnetic Disk Matrix - legend characters formed by array of reflective disks
Electromechanical Flap Matrix - matrix of electromechanically actuated flaps
Electrostatic Vane Matrix - matrix of closely spaced iridium-coated aluminum vanes
Tri-color Sign - matrix of rotating element with each face having one of three colors
LIGHT EMITTING
Neon or Blank-out - uses neon tubing to form the legend characters
Fiberoptics - message formed by light energy dispersed through fiber bundles
Lamp (Bulb) Matrix - message formed by an array of incandescent lamps
Light Emitting Diode (LED) Matrix - similar to bulb matrix except uses LED lamps
HYBRID
Fiberoptic/Reflective Disk - fiberoptic pixels shine through the reflective disks
LED/Reflective Disk - LED pixels shine through the reflective disks

2.0 Highway Advisory Radio

Although not as widely used as dynamic message signs, Highway Advisory Radio (HAR) is another means of providing highway users with information. Information is relayed to highway users through their existing AM radio receiver in their vehicle. Users are instructed to tune their vehicle radio to a specific frequency via roadside or overhead signs. Usually, the information is relayed to the users by a pre-recorded message, although live messages can also be broadcast. Message transmissions can be controlled either on-site or from a remote location through telephone or radio interconnects. Most HAR systems operate at the 530 or 1610 kHz frequency level; however, any available frequency can be used as long as a low enough power level is used. A license from the Federal Communication Commission is required to operate a HAR system at high power levels (10 watts or greater). There are two types of HAR systems: vertical “whip” antenna systems and induction cable antenna systems.

2.1 Vertical Antenna Systems

Vertical “whip” antenna systems use individual antennas or a series of antennas electronically connected together to transmit information. The signal radiates from the antenna in all directions providing a circular area of transmission. Vertical antenna systems are small, easy to install, and can be placed within several hundred meters (feet) of the roadway. They are also less costly to purchase and install than induction cable systems. However, they are subject to damage by weather, crashes, and vandalism. They often require special equipment to ensure that the signal is stable, reliable, and easily tuneable. Also, because the information is broadcast in a circular zone of coverage, the signal may interfere with other coverage zones on the same or adjacent roadways.

2.2 Induction Cable Antenna Systems

Induction cable antenna systems use a cable installed either under the pavement or adjacent to the roadway. This type of antenna design produces a strong but highly localized signal within a short lateral distance (30 to 45 meters [100 to 150 feet] from the cable). With this type of antenna design, the signal is strong enough to provide full coverage of a multilane facility without causing interference to other HAR systems. Also, with this system, messages can be individualized by direction of travel. Information is received by the motorists within range of the cable. As a result, interference to other radio systems in the area is minimized. Since the cable must extend the full length of the desired coverage area, induction cable systems are more costly to purchase, install, and maintain. Furthermore, they are not easy to install, especially in built-up areas or on existing facilities, and once installed, they cannot be transported from one location to another.

3.0 Telephone “Hot Lines”/Cellular Telephone

Telephone call-in services or “hot lines” are means of providing both highway and transit users with pre-trip information. By providing direct access to a traffic information database, callers can obtain traffic and roadway conditions reports, transit route or scheduling information, or incident information before beginning their trip. The information can then be used to adjust departure times or to select alternate routes or modes to their destination. Information can be provided using recorded messages, synthesized voice messages, or human operators. A touch-tone menu system can be used to provide individual callers with route or corridor specific information.

The primary advantage of a telephone call-in service is that highway and transit users can be provided with the information they may need to assist them in making departure time, route, and mode selection decisions prior to beginning their trip. Until recently, the main disadvantage of telephone call-in services is that information could not be directly accessed from within the vehicle. However, improvements to cellular telephone technology have made telephone call-in services a viable option for traffic management and transit agencies to provide users with both pre-trip and during-trip information. Because cellular telephones permit individuals to turn their commute time or travel time between appointments into productive time, the number of cellular telephone users has increased dramatically in recent times. Private traffic reporting services have long recognized the potentials of cellular telephones and have begun to rely heavily on cellular telephone “traffic tipsters” to provide them with traffic information. Traffic reporting services have found the information provided by repeat informers to be accurate, credible, and reliable.

continued

3.0 Telephone “Hot Lines”/Cellular Telephone (continued)

Many public agencies are also beginning to capitalize on the increased number of cellular telephone users in the traffic stream by establishing numbers that cellular telephone users can call to receive traffic information or to report changes in traffic conditions and incidents. Many of the incident calls are “good Samaritan” calls in which cellular telephone users are reporting the troubles of others. In addition to providing information that can be used for pre-trip and alternate route planning purposes, cellular telephones have the potential for providing traffic management agencies with a means of obtaining real-time travel information and early identification of traffic incidents. Recommendations for establishing telephone “hot-lines” and cellular telephone call-in systems are summarized below.

- ◆ The call must be toll free to users.
- ◆ The telephone number must be easy to remember and dial.
- ◆ The information must be concise. Long messages should be avoided. If a menu system is used, a long and tedious menu selection process should be avoided also.
- ◆ A sufficient number of lines should be provided to prevent the majority of users from receiving a busy signal.
- ◆ If a system is going to be used to gather information from users, there must be a method of ensuring the accuracy of the incoming information. Information should be considered valid only if more than one call reporting the same incident is received.
- ◆ “Official” use of tipster information requires judgement on the behalf of the traffic management agency. Procedures for verifying tipster information should be established.
- ◆ If incident information is to be received, a human operator is recommended so that secondary questions can be asked to clarify confusing or unclear reports.

4.0 Commercial Radio and Television

The public has learned to depend upon the media to provide them with “almost” real-time traffic information. Both commercial radio and television are excellent means of providing travelers with pre-trip information. Traffic and roadway condition reports have become standard programming items on many commercial radio and television stations. Commercial radio has the best potential of reaching the greatest number of commuters since most of them have radios in the vehicle they drive to and from work. In addition to pre-trip information, commercial radio reports can be used by motorists to make route choice decisions once they have initiated their trip. Television offers the added advantage of being able to provide a visual representation of the location of traffic problems or incidents, and alternative routes around congestion on a map.

The primary disadvantage to using both commercial radio and television is the accuracy of the information. Traffic reports are transmitted only when scheduling permits. This may cause considerable time delays from when an incident occurs to when it is reported by the media. Often, many incidents go unreported or are cleared by the time they are reported by the media. The accuracy of the information provided by commercial radio and television is a function of the time between the broadcaster's last communication with the incident reporting source and the number of incidents that have occurred and/or have been cleared during that time.

continued

4.0 Commercial Radio and Television (continued)

Public access television is a means of overcoming many of the disadvantages of privately owned media stations. Many city governments are responsible for franchising cable television service within the corporate limits of the city. As part of awarding the franchise to a company, many city governments stipulate that the cable company dedicate channels to be used solely by the public. Many city governments offer their own programming on one or more of these dedicated channels. Public access channels can be used by traffic management agencies to broadcast continuous traffic information during peak hours. Either "crawl" messages across the bottom of the screen or map displays accompanied by voice messages can be used to provide users with information. Traffic reports can also be provided by interrupting normal programming. The primary disadvantage of using public access television is that the information would be available only to cable subscribers. Travelers living outside the service area or not subscribing to the particular cable company would not have access to the information.

5.0 Citizen-Band Radio

Even though it was once considered an excellent means of providing motorists with two-way communications from their vehicle, Citizen-Band (CB) radio has declined in popularity in recent times. However, there are still a significant number of vehicles, particularly commercial vehicles and trucks, equipped with CB radios. In the past, CB radios have been used primarily in motorist-aid systems. A disabled or passing traveler broadcasts a request for assistance on Channel 9. The channel is monitored 24 hours a day, 7 days a week by a police or volunteer organization which dispatches aid to the stranded traveler. The primary advantage of a CB radio system is it permits two-way communication between the traveler and the response agency. Since the effective range of many CB radios is approximately 32 kilometers (20 miles) (depending upon geographic conditions), CB radio systems are particularly well-suited for rural, less populated areas. Signs should indicate an active CB monitoring area. Chapter 7, Section 4, Segment 4.2 contains information about CB radio as a data communication tool.

6.0 Lane Control Signals

Lane control signals (LCSs) are typically used to control traffic on reversible-flow facilities. However, they are also used on freeways to provide an advance indication of the status of freeway lanes and as a traffic management tool. In freeway applications, the LCSs are placed above the individual lanes to indicate whether the use of a specific lane or lanes is permitted or prohibited, or to indicate the impending prohibition of use. When one or more lanes are blocked, the LCSs provide advanced warning of slow traffic conditions ahead and advise the motorists which lanes are blocked. Although this does not prevent motorists from using the affected lanes on the approach to the scene, it can provide information on how many lanes are blocked which the motorist can use to determine if alternative routes should be taken. Other conditions, such as lost loads, debris, high water, or pavement failures also warrant the use of LCSs. LCSs should not be used unless the conditions can be verified.

continued

6.0 Lane Control Signals (continued)

Some of the LCS applications described in the Texas MUTCD with respect to freeway operations include the following:

- ◆ on a freeway, where it is desired to keep traffic out of certain lanes at certain hours to facilitate the merging of traffic from a ramp or other freeway;
- ◆ on a freeway near its terminus, to indicate a lane that ends; and
- ◆ on a freeway or long bridge to indicate a lane which may be temporarily blocked by an crash, breakdown, etc.

The Texas MUTCD currently defines the following three LCS symbols for use in freeway traffic management applications:

- ◆ *Steady Red X* - Indicates that the lane below the indication is closed to traffic.
- ◆ *Green Down Arrow* - Indicates that the lane below the indication is open to traffic.
- ◆ *Steady Yellow X* - Indicates that the lane below the indication is about to close (steady red X display) or is experiencing congestion ahead.

In addition to these symbols, TxDOT has received permission to experiment with downward diagonal yellow arrows in advance of a red X for freeway lane blockages. Research has shown this symbol to have superior understanding by motorists in comparison to a yellow X in some applications. A request has been submitted to change the TMUTCD to include this symbol for use in freeway applications.

When LCSs are used to indicate a complete freeway closure, a green arrow should be displayed over the shoulder lane and red Xs over the remaining lanes. This arrow display proved to be less confusing to drivers as it indicates that they should move to the right side of the freeway, from which police can direct them onto the frontage road. An array with only red Xs does not provide drivers an option regarding the correct travel lane to be in.

The mounting location of the LCS over travel lanes can create parallax problems for drivers when viewing them on a curve (LCS will appear displaced over one or more travel lanes). To avoid this confusion, LCS should be mounted on tangent freeway sections to facilitate correct association of LCS displays with the lane for which they are intended.

Part of the traffic control plan for a freeway work zone may include the operation of lane control signals (LCS) in advance of the site. The advanced warning provided by these signals can be helpful in establishing the work zone, as well as providing information during maintenance and construction activities.

EMERGING TECHNOLOGIES

There have been tremendous advances in communication technology in recent times. This section provides a brief description of some of the emerging technologies that may be suitable for use as traveler information systems.

1.0 Teletext

Teletext is a means of providing visual and up-to-date pre-trip information to travelers. Using the Vertical Blanking Interval of a television video signal, text information can be transmitted with a normal television signal. It is then displayed in a black horizontal space located in the lower portion of the television screen. A device similar to that used to make closed caption features available for the hearing impaired is required to make the text appear on the screen. Although the device currently must be added to television sets, the trend in television manufacturing is to include teletext reception as a standard feature, thereby increasing the general availability of teletext information.

2.0 Video Text

Video text is a variation of the dial-in or bulletin board information services currently available to many personal computer users having modems. Using a combination of text and graphics, information services such as news, weather, entertainment, financial reports, etc., can be accessed via a personal computer. It is being developed as a major marketing service where products and services (such as grocery shopping, banking, etc.) can be purchased directly at home or place of employment. Several major department stores are exploring the use of video text to increase and supplement their mail order business.

Video text is particularly well-suited to provide pre-trip information to travelers. A video text service could be used to provide traffic, transit, and roadway information to commuters. The type of information that could be provided includes reports on the status of the freeways, transit stop and schedule information, information about construction activities, and incident reports. Commuters would have the flexibility of accessing the information before leaving their home or office. Multiple screens can be used to allow commuters to select the type of information they desire. Some of the current limitations of video text technology are listed below.

- ◆ A personal computer and a modem are required to access the service.
- ◆ The availability of video text services is limited.
- ◆ Some video text services are complex and difficult to operate.
- ◆ A commuter is not likely to purchase or subscribe to a video text service as a primary means of obtaining traffic information.
- ◆ Because most video text services market in wide geographic areas, it would be difficult to provide facility or corridor specific information.

3.0 Side Carrier Allocation Networks

One method of broadcasting information digitally is to use an FM Side Carrier Allocation (SCA) network. SCA uses the empty space that acts as a buffer between commercial radio stations to provide control information to a network of receivers or users. It is common to broadcast control information that eliminates the advertisements from commercial radio stations played in office buildings.

From a traffic management standpoint, SCA can be used to develop a radio-based system “dedicated” to providing continuous information to motorists and commuters. By using a synthesized voice format, detailed verbal instructions can be provided to motorists either at their work or in their vehicle. Information can be tailored to specific corridors or locations by using different frequencies.

Some of the limitations of SCA technology are listed below.

- ◆ SCA requires a special receiver to receive and process control information.
- ◆ Most SCA systems are privately owned and operated (although a public agency could fund and operate its own SCA system as a public service).
- ◆ Although unnoticeable to most listeners, SCA degrades the quality of voice transmissions on adjacent radio stations. This problem is more pronounced when used with low powered radio stations.

4.0 Advanced Traveler Information Systems (ATIS)

Advanced traveler information systems (ATISs) were one of the components of an Intelligent Transportation System (ITS). ATISs use visual or auditory techniques to provide travelers with dynamic, or real-time information about traffic, route, and roadway conditions directly in their vehicles. Through in-vehicle display devices, information about traffic congestion, transit schedules and routes, safety advisories, parking lot status reports, and hazardous environmental conditions would be made available to travelers not only prior to initiating their trip but also during their trip. In addition to providing travelers with condition information, traffic management agencies can use specially equipped vehicles as dynamic traffic sensors to provide them with information about current traffic and roadway conditions. With this information, traffic management agencies can anticipate congestion and implement operational measures to provide relief in a real-time manner.

continued

4.0 Advanced Traveler Information Systems (ATIS) (continued)

ATISs being developed include systems that would provide in-vehicle replication of roadway maps and signs, electronic pre-trip route planning systems where travelers can be provided with detailed instructions or a map to reach a specific destination either prior to beginning on their trip or in their vehicle, and in-vehicle navigational devices that provide travelers with location and guidance information. The following lists some of the specific advance traveler information systems currently being developed:

- ◆ vehicle location and navigation systems;
- ◆ traffic information receivers;
- ◆ color video displays for maps, traffic information, and route guidance;
- ◆ on-board database systems with detailed maps, business directories, specific locations of services, hospitals, and tourist-related information;
- ◆ electronic vehicle identification systems; and
- ◆ safety advisory systems.

These systems are being designed to provide travelers with a wide range of services. Some of the services that ATIS will provide are:

- ◆ the transmittal of information from traffic management centers on congestion, incidents, and other traffic problems to travelers in their vehicle;
- ◆ the transmittal of weather or low visibility conditions;
- ◆ route-planning assistance to minimize travel distance or time;
- ◆ the automatic collection of tolls and fees without requiring the vehicle to stop;
- ◆ assistance for aged or impaired drivers; and
- ◆ the signaling of motorist aid services.

Even though ATISs are beginning to be implemented in many major metropolitan areas, there are a number of human factors, safety, and traffic management issues that remain to be resolved before the full benefits of ATIS can be achieved. Some of the questions that need to be addressed are listed below.

- ◆ What information do drivers need to navigate and how do they obtain it?
- ◆ How should route guidance and navigation information be presented to drivers (i.e., moving map displays, simplified turn-by-turn instructions, highlighted routes, etc.)?
- ◆ Should route guidance information be presented using visual (i.e., maps and simplified schematics) or auditory (i.e., voice) displays?
- ◆ How well will in-vehicle communications devices be accepted by drivers?
- ◆ What are the safety implications of providing route guidance and navigation information directly to drivers in their vehicles?
- ◆ What kind of intergovernmental and interjurisdictional agreements will need to be formed in order to integrate traffic information from multiple agencies and jurisdictions?
- ◆ How should the public agency be involved in the collection, dissemination, and control of travel information?
- ◆ What is the best way to distribute travel information to motorists through an overall information system which utilizes both available and emerging technology?

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CHAPTER 12
CONTROL CENTERS

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2.0	User-Centered Design Process	12-6
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OVERVIEW

At the center of a freeway, transit, or arterial street management system is the control center. The control center is where information about the highway system is collected, processed, and fused with other operational and control data. It is also the location where decisions about what control strategies to implement are made, where the coordination with other agencies occurs, and where operational measures are implemented and monitored. Information dissemination to motorists and the media is also typically coordinated and implemented from the control center.

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CONTROL CENTER DESIGN AND OPERATIONS

1.0 Need for a User-Centered Design

Because every control center being implemented today relies on human operators to make decisions and implement appropriate strategies in response to changing traffic conditions (albeit to varying degrees), the success of most freeway, transit, and arterial management systems ultimately depends on how the human operator interacts with the system devices. The capabilities and limitations of the personnel operating the system must be considered and integrated in the design of the control center.

A user-centered approach is one way of ensuring that many of the human factors requirements are addressed in the design or upgrade of a control center. Unlike other approaches that focus primarily on technologies, a user-centered design has as its focus the user of the system: the operator. The *Human Factors Handbook for Advanced Traffic Management Center Design* identifies the following to be major distinguishing factors of a user-centered design:

- ◆ **The design focus is on the operator, not the designer.** In the user-centered design, the user (i.e., the operator) is viewed as a critical system component whose characteristics, capabilities, and limitations need to be defined and considered during the requirements analysis and design of the system. Ideally, the user should be involved in the design process at its earliest stages, and this involvement should continue throughout the design and testing phases.
- ◆ **The selection and acquisition of system components is based on validated functional requirements.** Many control centers have been designed adhering to a *technology-centered design approach* where the focus in designing the system has been on hardware and software. The user-centered design focuses on *what* needs to be accomplished by the system, not *how*. Therefore, system components are selected based on an analysis of the functional requirements of the system. A *validated requirement* is a functional capability (e.g., identify sensor locations at which occupancy exceeds 30 percent during a running 2-minute period) that has been formally stated and objectively evaluated.
- ◆ **The process is iterative.** Systems are best developed through an *iterative* process, in which a design is tested and validated in a series of stages. This is particularly important in control center design, where the multiple iterations can uncover problems -- and opportunities -- that are not apparent until they are viewed in the context of the total system.
- ◆ **The process extends throughout the life cycle of the control center.** The fact that a new control center has been built and put into operation does not mean that it is "complete." As the managers and operators of the control center become familiar with the system, they will likely make recommendations for many excellent design feature and procedural changes to improve their abilities to control traffic on the freeway.

2.0 User-Centered Design Process

As stated earlier, the term *user-centered design* refers to a design philosophy in which the user is viewed as a critical system component whose characteristics, capabilities, and limitations need to be defined and considered during the design process. Figure 12-1 illustrates the principle of a user-centered design approach. The user-centered design approach focuses first on the overall goals and objectives of the system (*Mission Analysis*). The mission analysis defines what the system is supposed to do. A *Functional Analysis* is then used to identify what functions the operator of the system will perform. Once the functions of the operator have been determined, the tasks that the operator must accomplish in performing a function are identified (*Task Analysis*). A task analysis involves breaking a task down into its individual elements including a detailed description of both manual and mental activities, duration, frequency, complexity, etc. The results of this process define many of the critical elements of the operations control center including the number of operators required to operate the system, the design of the informational displays, etc.

An eleven-step process has been developed for conducting a user-centered design analysis. The steps applied in the analysis are as follows:

- ◆ conduct a mission analysis,
- ◆ prepare a design concept,
- ◆ conduct a function analysis and allocation procedure,
- ◆ conduct an operator task analysis,
- ◆ identify sources of human operator error,
- ◆ identify human performance constraints,
- ◆ design jobs,
- ◆ design the physical environment,
- ◆ design and specify workstations,
- ◆ design and specify controls and displays, and
- ◆ design and specify user interfaces.

The *Human Factors Handbook for Advance Traffic Management Center Design* provides a detailed description of this eleven-step process.

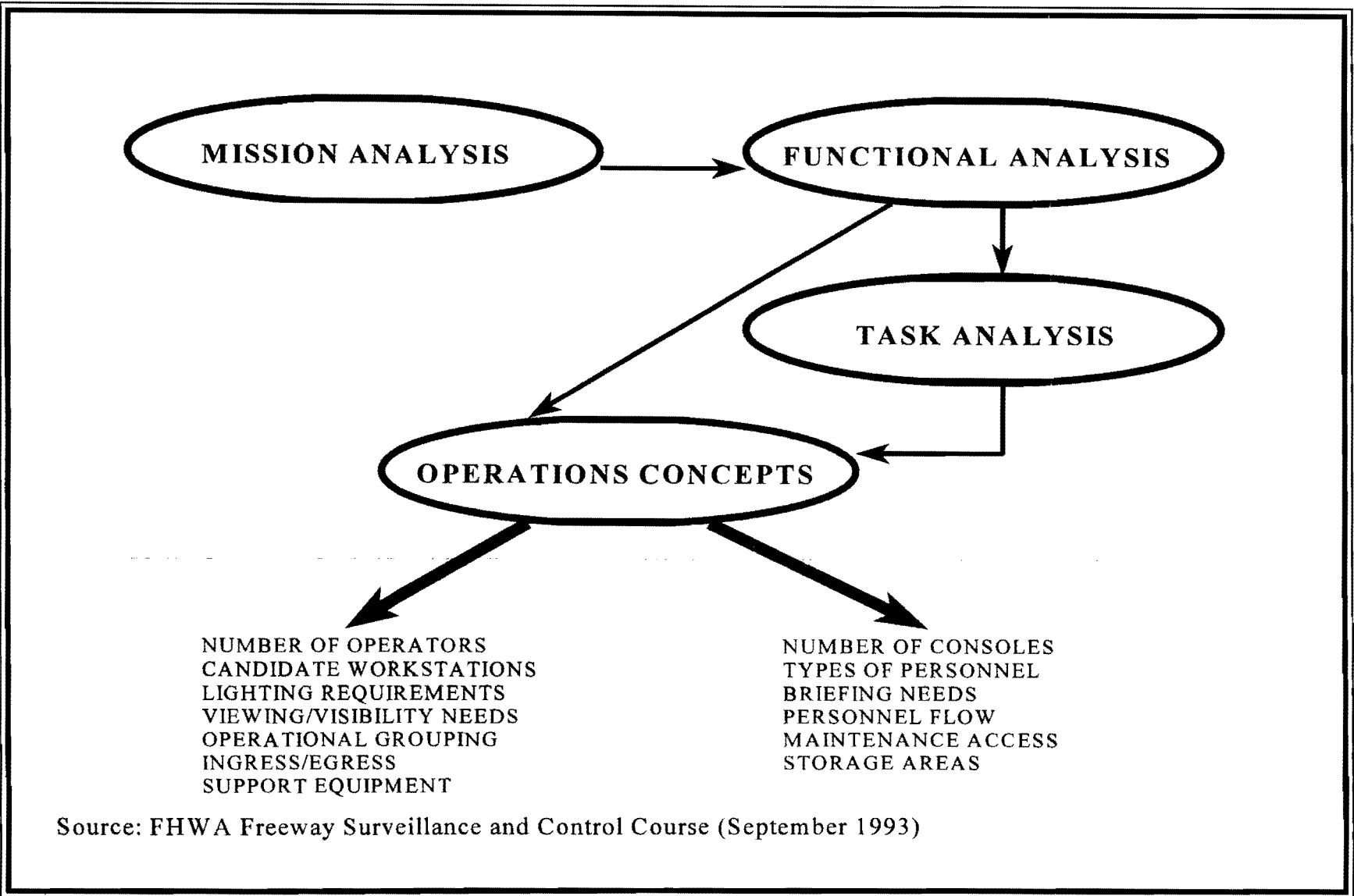


Figure 12-1. Concept of User-Centered Design Approach

3.0 Staffing

Unfortunately, there are no hard and fast rules for the number of operators in a control center. The number of operators in a control center depends primarily on the functions that are being performed, the number of facilities covered, and the operating objectives and philosophy of the center. The qualifications for control center operators also tend to vary considerably from center to center. For example, some locations employ part-time students as operators. These students are under the supervision of a manager or a senior operator. At other centers, operators come from the agencies' technical staff of traffic engineers or computer scientists who have other assigned technical duties or who may be given special projects to work on as well as their duties in the control center. A small number of centers require their operators to have college engineering or technical degrees.

In general, the level of qualifications for control center operators should be directly related to the design of and function allocation within the center. If the operators' functions are relatively repetitive, predictable, and non-critical, operators with low qualifications can be employed; however, if unique problems are frequent, rapid reaction is needed, and/or criticality is high, operators need to have higher levels of training and expertise. As a general rule, operators must possess good verbal skills, a degree of computer literacy, and good reasoning skills. Some agencies also require operators to have a good working knowledge of the freeway system and some dispatching experience.

Also as a general rule, those centers whose functions include significant interaction with police officers in the field should consider including a police liaison officer on their staff. A police liaison officer fosters stronger interagency cooperation and can aid in dispatching appropriate police responses to incident scenes.

4.0 Spacing Requirements

The size of control centers varies considerably, depending on the design objectives and functions performed by the system. A functional analysis is needed to determine the design of the control center. Factors that impact the design of the system include:

- ◆ the hours and days of operation,
- ◆ the types of information displays that will be used in the center,
- ◆ the type of monitoring and control strategies included in the system,
- ◆ the desire to have interagency staffing,
- ◆ the need for media and public access to the control center,
- ◆ whether the control center will function as a communications or dispatching center, and
- ◆ whether the control center will also function as an emergency operations center.

continued

4.0 Spacing Requirements (continued)

Generally, most traffic control centers occupy between 1,600 to 2,300 square meters (18,000 to 25,000 square feet). Some control centers, such as TransGuide in San Antonio, Texas, and TransStar in Houston, Texas, occupy as much as 4,800 square meters (52,000 square feet). A typical traffic control center has the following work areas within the building:

- ◆ operations room,
- ◆ computer and peripheral area,
- ◆ communications area,
- ◆ gallery for viewing and training,
- ◆ conference room,
- ◆ system support offices,
- ◆ break room, and
- ◆ media room.

The operations room is the hub of the control center. It houses the operator work stations and display boards/video terminals that are used to display information about conditions in the network to the operators. The number of operator work stations that will ultimately be located in the control center and the type and location of the information displays dictates the size of the operations room. Figure 12-2 illustrates the layout of the TransGuide control center in San Antonio.

The computer/peripheral area houses the computers needed to run the freeway operations center. The size of the computer room depends upon system design decisions regarding how much computer capability will be based at the control center as compared to that installed at hub locations in the field. Often these rooms require strict environmental controls (in terms of heating and air-conditioning). Many locations also have strict access control to this area.

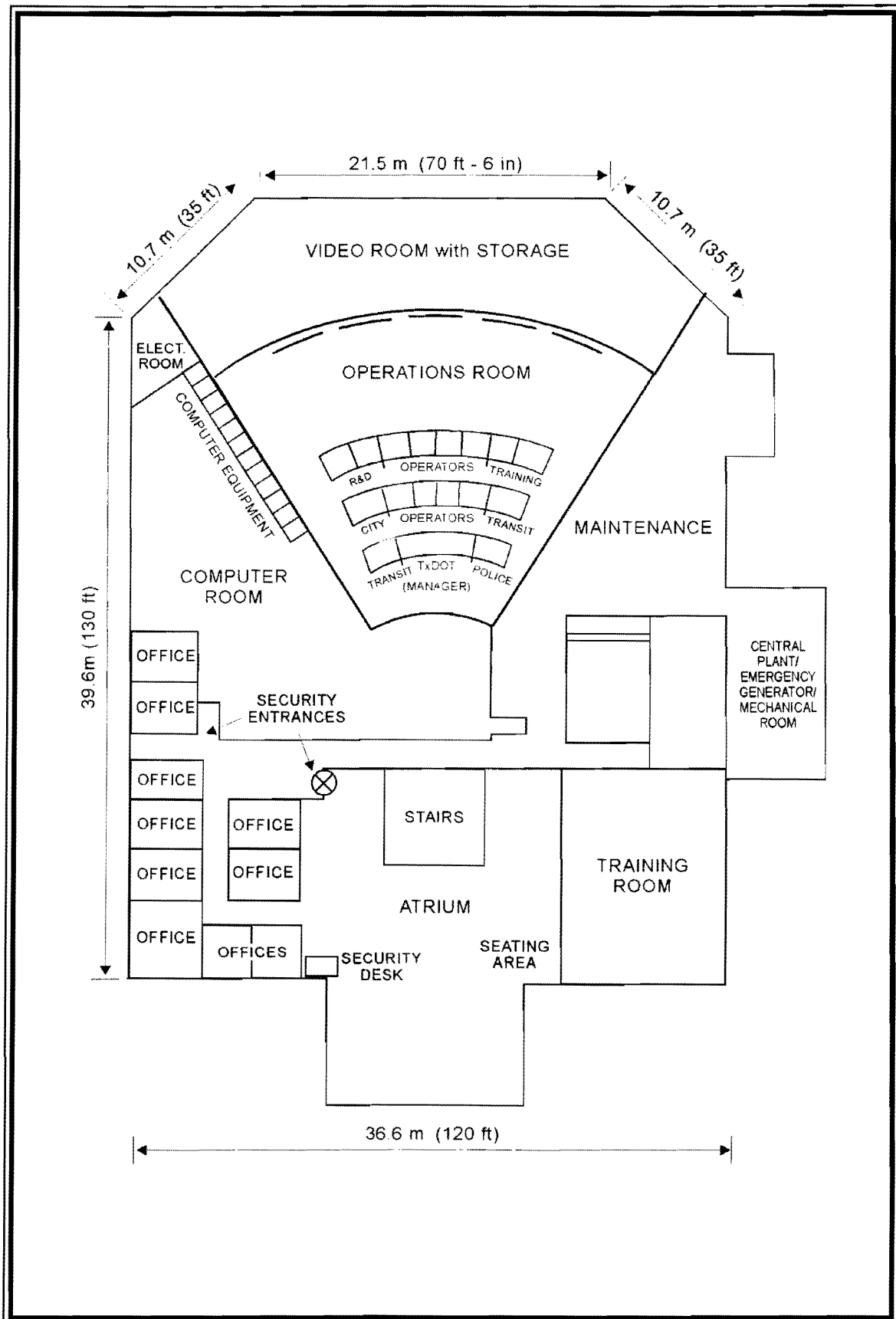


Figure 12-2. TransGuide Control Center in San Antonio

CHAPTER 13
APPENDIX

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**APPENDIX A
TRAFFIC LAWS ON VEHICLE REMOVAL**

TRC 550.022 ACCIDENT INVOLVING DAMAGE TO VEHICLE

(a) The operator of a vehicle involved in an accident resulting only in damage to a vehicle that is driven or attended by a person shall:

(1) immediately stop the vehicle at the scene of the accident or as close as possible to the scene of the accident without obstructing traffic more than is necessary;

(2) immediately return to the scene of the accident if the vehicle is not stopped at the scene of the accident; and

(3) remain at the scene of the accident until the operator complies with the requirements of Section 550.023 (Duty to give information and render aid).

(b) If an accident occurs on a main lane, ramp, shoulder, median, or adjacent area of a freeway in a metropolitan area and each vehicle involved can be normally and safely driven, each operator shall move the operator's vehicle as soon as possible to a designated accident investigation site, if available, a location on the frontage road, the nearest suitable cross street, or other suitable location to complete the requirements of Section 550.023 and minimize interference with freeway traffic.

(c) A person commits an offense if the person does not stop or does not comply with the requirements of the section. An offense under this section is:

(1) A Class C misdemeanor, if the damage to all vehicles is less than \$200; or

(2) A Class B misdemeanor, if the damage to all vehicles is \$200 or more.

TRC 472.011 DEFINITION. In this subchapter, "personal property" includes spilled cargo, a hazardous material as defined by 49 U.S.C. App. Section 1802, and a hazardous substance as defined by Section 26.263, Water code.

TRC 472.012 DEPARTMENT AUTHORITY GENERALLY.

(a) The department [TxDOT] may remove personal property from the right-of-way or roadway of the state highway system if the department determines the property blocks the roadway or endangers public safety.

(b) The department may remove the personal property without the consent of the owner or carrier of the property.

TRC 472.013 OWNER AND CARRIER RESPONSIBLE FOR COSTS OF REMOVAL AND DISPOSITION The owner and the carrier of personal property removed under this subchapter shall reimburse the department for the costs of removal and disposition.

TRC 472.014 DEPARTMENT NOT LIABLE FOR DAMAGES The department and its officers and employees are not liable for:

- (1) any damage to personal property resulting from its removal or disposal by the department unless the removal or disposal is carried out recklessly or in a grossly negligent manner; or
- (2) any damage resulting from the failure to exercise authority granted under this subchapter.

APPENDIX B
DOUBLE-FINE LAW IN WORK ZONES

TRC 472.022 OBEYING WARNING SIGNS

(d) An offense under this section is a misdemeanor punishable by a fine of not less than \$1 or more than \$200, except that if the offense is committed in a construction or maintenance work zone when workers are present, the offense is a misdemeanor punishable by a fine of not less than \$2 or more than \$400.

(e) In this section:

(1) "Barricade" means an obstruction:

(A) placed on or across a road, street, or highway of this state by the department, a political subdivision of this state, or a contractor or subcontractor constructing or repairing the road, street, or highway under authorization of the department or a political subdivision of this state; and

(B) placed to prevent the passage of motor vehicles over the road, street, or highway during construction or repair.

(2) "Construction or maintenance work zone" means a portion of a highway or street:

(A) where highway construction or maintenance is being undertaken, other than mobile operations as defined by the Texas Manual on Uniform Traffic Control Devices; and

(B) that is marked by one or more signs indicating that it is a construction or maintenance work zone.

(3) "Warning sign" means a signal, marking, or device placed on a barricade or on a road, street, or highway under construction or repair by the department, a political subdivision of this state, or a contractor or subcontractor to warn or regulate motor vehicular traffic. The term includes a flagger deployed on a road, street, or highway by the department, a political subdivision of this state, or a contractor or subcontractor to direct traffic around or on the road, street, or highway under construction or repair.

TRC 542.404 FINE FOR OFFENSE IN CONSTRUCTION OR MAINTENANCE WORK ZONE

(a) If an offense under this subtitle, other than an offense under Chapter 548 or 552 or Section 545.412 or 545.413, is committed in a construction or maintenance work zone when workers are present:

(1) the minimum fine applicable to the offense is twice the minimum fine that would be applicable to the offense if it were committed outside a construction or maintenance work zone; and

(2) the maximum fine applicable to the offense is twice the maximum fine that would be applicable to the offense if it were committed outside a construction or maintenance work zone.

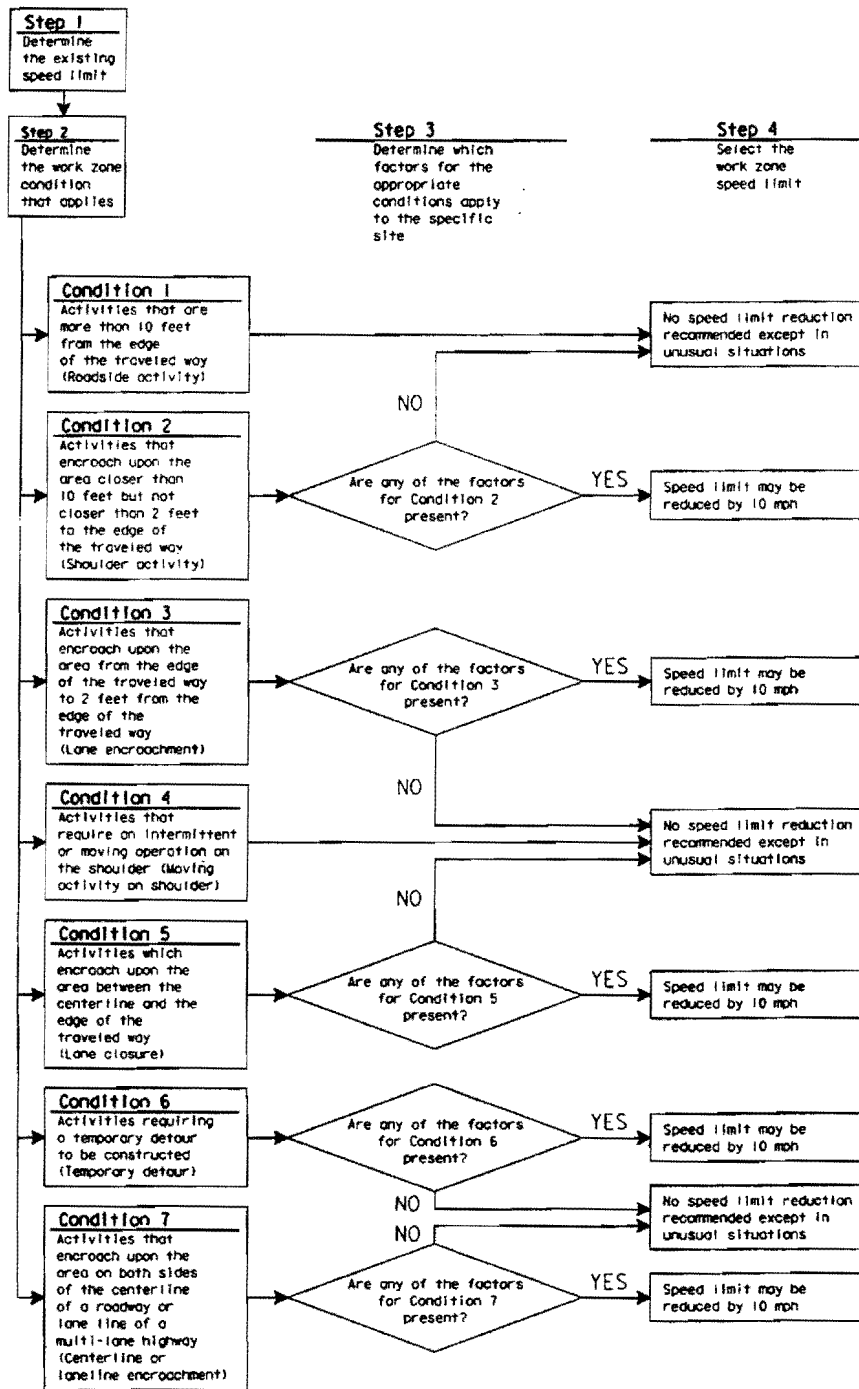
(b) In this section, "construction or maintenance work zone" has the meaning assigned by Section 472.022.

TRC. 729.004. FINE FOR OFFENSE IN CONSTRUCTION OR MAINTENANCE WORK ZONE

- (a) This section applies to an offense under Section 729.001 for a violation of Subtitle C, other than Chapter 548 or 552 or Section 545.412 or 545.413.
- (b) If an offense to which this section applies is committed in a construction or maintenance work zone when workers are present:
 - (1) the minimum fine applicable to the offense is twice the minimum fine that would be applicable to the offense if it were committed outside a construction or maintenance work zone; and
 - (2) the maximum fine applicable to the offense is twice the maximum fine that would be applicable to the offense if it were committed outside a construction or maintenance work zone.
- (c) In this section, "construction or maintenance work zone" has the meaning assigned by Section 472.022.

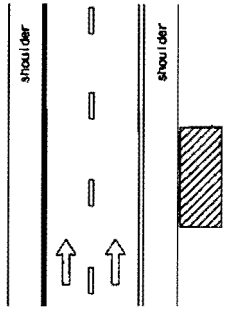
APPENDIX C SETTING WORK ZONE SPEED LIMITS

REGULATORY SPEED LIMIT DETERMINATION GUIDELINES



Note: Where work zone geometrics with reduced design speeds cannot be avoided, the work zone speed limit should not exceed the design speed, even if this requires a speed limit reduction greater than 10 mph.

WORK ZONE CONDITIONS



Condition 1:
Roadside Activity

Condition 1:
Activities that are more than 10 feet from the edge of the traveled way (roadside activity)

Typical Applications
Roadway construction
Cleaning drainage
Landscaping work
Structural work
Utility work
Reworking ditches
Fencing work

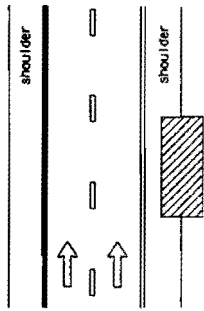
Reductions of Existing Regulatory Speed Limit
Should not be used

Maximum Amount of Speed Reduction
None

Factors
None

The regulatory speed limit shall meet all requirements of the MUTCD.

*There should not be a reduction to the existing regulatory speed limit unless unusual situations create hazardous conditions for motorists, pedestrians, or workers.



Condition 2:
Shoulder Activity

Condition 2:
Activities that encroach upon the area closer than 10 feet but not closer than 2 feet to the edge of the traveled way (shoulder activity)

Typical Applications
Roadway construction
Culvert extensions
Guardrail installation
Cleaning drainage
Reworking ditches
Shoulder work
Utility work
Side slope work
Landscaping work
Structural work
Sign installation

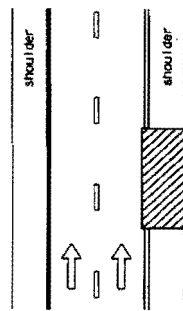
Reduction of Existing Regulatory Speed Limit
May be used where Factors exist

Maximum Amount of Speed Reduction
10 mph

Factors

- Workers present for extended periods within 10 feet of traveled way unprotected by barriers
- Horizontal curvature that might increase vehicle encroachment rate (could include mainline curves, ramps, and turning roadways)

The regulatory speed limit shall meet all requirements of the MUTCD.



Condition 3:
Lane Encroachment

Condition 3:
Activities that encroach upon the area from the edge of the traveled way to 2 feet from the edge of the traveled way (lane encroachment)

Typical Applications
Roadway construction Utility work
Guardrail installation Shoulder work

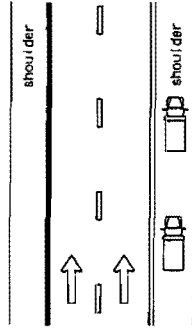
Reductions of Existing Regulatory Speed Limit
May be used where Factors exist

Maximum Amount of Speed Reduction
10 mph

Factors

- Workers present for extended periods within 2 feet of traveled way unprotected by barrier
- Horizontal curvature that might increase vehicle encroachment rate (could include mainline curves, ramps, and turning roadways)
- Barrier or pavement edge drop off within 2 feet of traveled way
- Reduced design speed for stopping sight distance
- Unexpected conditions

The regulatory speed limit shall meet all requirements of the MUTCD. Where work zone geometrics with reduced design speeds cannot be avoided, the work zone speed limit should not exceed the design speed, even if this requires a work zone speed limit reduction greater than 10 mph.



Condition 4:
Moving Activity on Shoulder

Condition 4
Activities that require an intermittent or moving operation on the shoulder (moving activity on shoulder)

Typical Applications
Roadway construction
Widening
Delineator installation
Shoulder and slope work
Utility work
Guardrail installation
Landscape work

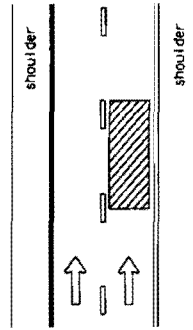
Reductions of Existing Regulatory Speed Limit
Should not be used*

Maximum Amount of Speed Reduction
None

Factors
None

The regulatory speed limit shall meet all requirements of the MUTCD.

*There should not be a reduction to the existing regulatory speed limit unless unusual situations create hazardous conditions for motorists, pedestrians, or workers.



Condition 5:
Lane Closure

Condition 5
Activities that encroach upon the area between the centerline and the edge of the traveled way (lane closure)

Typical Applications
Roadway construction
Pavement repair
Utility work
Widening
Pavement resurfacing
Pavement marking
Bridge repair

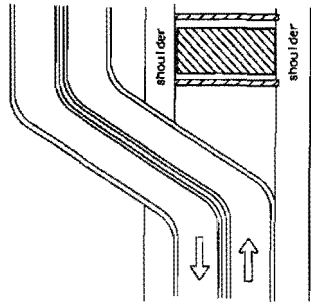
Reductions of Existing Regulatory Speed Limit
May be used where Factors exist

Maximum Amount of Speed Reduction
10 mph

Factors

- Workers present for extended periods in the closed lane unprotected by barrier
- Lane width reduction of 1 foot or more with a resulting lane width less than 11 feet
- Traffic control devices encroaching on a lane open to traffic or within a closed lane but within 2 feet of the edge of the open lane
- Reduced design speed for taper length or speed change lane length
- Barrier or pavement edge dropoff within 2 feet of the traveled way
- Reduced design speed of horizontal curve
- Reduced design speed for stopping sight distance
- Traffic congestion created by a lane closure
- Unexpected conditions

The regulatory speed limit shall meet all requirements of the MUTCD. Where work zone geometrics with reduced design speeds cannot be avoided, the work zone speed limit should not exceed the design speed, even if this requires a work zone speed limit reduction greater than 10 mph.



Condition 6:
Temporary Diversion

Condition 6
Activities requiring a temporary diversion to be constructed (temporary diversion)**

Typical Applications
Roadway construction
Subgrade restoration
Bridge construction
Culvert repair

Reductions of Existing Regulatory Speed Limit
May be used where factors exist

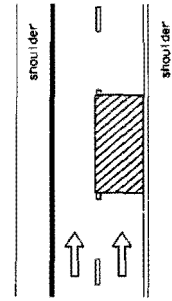
Maximum Amount of Speed Reduction
10 mph

Factors

- Lane width reduction of 1 foot or more with a resulting lane width less than 11 feet
- Reduced design speed for detour roadway or transitions (radius of curvature, superelevation, and sight distance)
- Unexpected conditions

The regulatory speed limit shall meet all requirements of the MUTCD. Where work zone geometrics with reduced design speeds cannot be avoided, the work zone speed limit should not exceed the design speed, even if this requires a work zone speed limit reduction greater than 10 mph.

**Detour and transition geometry with a design speed equal to or greater than the existing regulatory speed limit should be provided whenever possible.



Condition 7:
Centerline or Lane Line Encroachment

Condition 7
Activities that encroach upon the area on both sides of the centerline of a roadway or lane line of a multilane highway (centerline or lane line encroachment)

Typical Applications

Roadway construction	Widening
Pavement marking	Crack sealing
Pavement resurfacing	Bridge repair
Pavement repair	

Reductions of Existing Regulatory Speed Limit
May be used where factors exist

Maximum Amount of Speed Reduction
10 mph

Factors

- Workers present on foot in the traveled way or in the closed lane unprotected by barrier for extended periods
- Remaining lane plus shoulder width is less than 11 feet
- Reduced design speed for taper length or speed change lane length
- Barrier or pavement edge drop off within 2 feet of the traveled way
- Reduced design speed of horizontal curve
- Reduced design speed for stopping sight distance
- Traffic congestion created by lane closure
- Unexpected conditions

The regulatory speed limit shall meet all requirements of the MUTCD. Where work zone geometrics with reduced design speeds cannot be avoided, the work zone speed limit should not exceed the design speed, even if this requires a work zone speed limit reduction greater than 10 mph.

APPENDIX D LOOP DETECTOR INDUCTANCE

A loop detector consists of turns of wire embedded in or below the pavement. This loop is connected to the detector unit with the lead-in cable. The loop wire, lead wire, and detector unit comprise a tuned radio frequency circuit. When an electrical current is passed through the circuit, an electromagnetic field is created. A vehicle passing through this electromagnetic field absorbs some of the energy of the loop, resulting in a change in the frequency of the loop circuit. If the change in frequency is above a threshold value, then the vehicle is detected.

Inductance is the electrical property which defines the operating parameters of a loop detector system (the loop plus the lead-in cable). The typical range of inductance for commercially available detector units is 20 to 2,000 microhenries. Operating loop systems normally fall in the 50 to 300 microhenry range. The total inductance of the loop system is a function of the loop size, the number of turns of loop wire, and the length of the lead-in cable. Equations B-1 through B-8 identify some of the key relationships for a loop system.

$$L_C = l_C \times L_U \quad \text{Equation B-1}$$

$$L_L = \frac{P}{4} (N^2 + N) \quad \text{Equation B-2a}$$

$$L_L = \frac{5PN^2}{10 + N} \quad \text{Equation B-2b}$$

For loops in series

$$L_T = L_1 + L_2 + \dots + L_N \quad \text{Equation B-3}$$

For loops in parallel

$$\frac{1}{L_T} = \frac{1}{L_1} + \frac{1}{L_2} + \dots + \frac{1}{L_N} \quad \text{Equation B-4}$$

$$L_D = L_T + L_C \quad \text{Equation B-5}$$

$$\text{Efficiency} = \frac{L_T}{L_D} \times 100 \quad \text{Equation B-6}$$

$$\Delta L_2 = \Delta L_1 \frac{(L_T)}{L_D} \quad \text{Equation B-7}$$

$$\text{Sensitivity} = \frac{\Delta L_2}{L_T} \quad \text{Equation B-8}$$

Appendix B (continued)

where	L_C	=	Inductance of lead-in cable (μh)
	l_C	=	Length of lead-in cable (m [ft])
	L_U	=	Unit inductance of lead-in cable (μh)
	L_L	=	Inductance of loop (μh)
	L_T	=	Total inductance of one or more loops (μh)
	L_N	=	Inductance of highest number loop involved (μh)
	L_D	=	Total inductance at the input to the detector unit (μh)
	ΔL_1	=	Inductance change at the loop
	ΔL_2	=	Inductance change at the detector

NOTES:

The unit inductance of lead-in cable (L_U) is $0.72 \mu\text{h/m}$ ($0.22 \mu\text{h/ft}$).

Either Equation B-2a or Equation B-2b can be used to calculate the inductance of a single loop. Both equations yield similar inductance values.

Use Equation B-3 for loops connected in series and Equation B-4 for loops connected in parallel.

If the loop system contains only one loop, L_T is equal to L_L .

CHAPTER 14
ABBREVIATIONS AND DEFINITIONS

PART A - ABBREVIATIONS

<i>AADT</i>	Annual Average Daily Traffic
<i>AASHTO</i>	American Association of State Highway and Transportation Officials
<i>ATIS</i>	Advanced Traveler Information Systems
<i>ADT</i>	Average Daily Traffic
<i>ATMS</i>	Advanced Traffic Management Systems
<i>AVCS</i>	Advanced Vehicle Control Systems
<i>AVI</i>	Automatic Vehicle Identification
<i>B/C</i>	Benefit/Cost ratio
<i>CB</i>	Citizen-Band Radio
<i>CBD</i>	Central Business District
<i>CCTV</i>	Closed Circuit Television
<i>DMS</i>	Dynamic Message Signs
<i>CVO</i>	Commercial Vehicle Operations
<i>DIM</i>	Data Input Manager
<i>DHV</i>	Design Hour Volume
<i>DSD</i>	Decision Sight Distance
<i>FCC</i>	Federal Communication Commission
<i>FHWA</i>	Federal Highway Administration
<i>f</i>	Friction Factor of Pavement
<i>G</i>	Grade, in percent
<i>HAR</i>	Highway Advisory Radio
<i>HCM</i>	Highway Capacity Manual
<i>HCS</i>	Highway Capacity Software
<i>HOV</i>	High-Occupancy Vehicle
<i>h</i>	headway
<i>ITE</i>	Institute of Transportation Engineers
<i>ITS</i>	Intelligent Transportation Systems
<i>K</i>	K factor, DHV/AADT
<i>k</i>	Density
<i>LCS</i>	Lane Control Signal
<i>LED</i>	Light Emitting Diode
<i>LOS</i>	Level of Service
<i>MOE</i>	Measure of Effectiveness
<i>MUTCD</i>	Manual on Uniform Traffic Control Devices
<i>mph</i>	Miles per Hour
<i>PHF</i>	Peak Hour Factor
<i>PSD</i>	Passing Sight Distance
<i>PC</i>	Personal Computer
<i>pce</i>	Passenger Car Equivalents
<i>pcphpl</i>	Passenger Cars per Hour per Lane
<i>PPD</i>	Platoon Progression Diagram

<i>PVDF</i>	Polyvinylidene Fluoride
<i>q</i>	Flow Rate
<i>RF</i>	Radio Frequency
<i>RPM</i>	Raised Pavement Marker
<i>RTOR</i>	Right-Turn-on-Red
<i>SC&C</i>	Surveillance, Communication, and Control
<i>SCA</i>	Side Carrier Allocation
<i>SSD</i>	Stopping Sight Distance
<i>sec</i>	Seconds
<i>TCP</i>	Traffic Control Plan
<i>THOM</i>	Texas Highway Operations Manual
<i>TMT</i>	Traffic Management Team
<i>TMUTCD</i>	Texas Manual on Uniform Traffic Control Devices
<i>TRB</i>	Transportation Research Board
<i>TRR</i>	Transportation Research Record
<i>TTI</i>	Texas Transportation Institute
<i>TxDOT</i>	Texas Department of Transportation
<i>u</i>	Speed
<i>u_f</i>	Free-Flow Speed
<i>u_s</i>	Space-Mean Speed
<i>u_t</i>	Time-Mean Speed
<i>V</i>	Speed, mph
<i>vph</i>	Vehicles per Hour
<i>vphpl</i>	Vehicles per Hour per Lane

PART B - DEFINITIONS

<i>acuity</i>	A clinical measure of vision describing a person's ability to discern fine detail.
<i>auxiliary lane</i>	A lane added to accommodate demands supplementary to through traffic movement.
<i>Average Annual Daily Traffic</i>	The total volume passing a point on a highway, in both directions, for one year, divided by the number of days in the year.
<i>Average Daily Traffic</i>	The average 24-hour volume, being the total volume during a stated period divided by the number of days in that period.
<i>average running time</i>	The average time vehicles are in motion while traversing a highway segment of given length; excludes stopped-time delay.
<i>average travel time</i>	The average time spent by vehicles traversing a highway segment of given length, including all stopped-time delay.
<i>basic freeway segment</i>	A section of freeway facility on which operations are unaffected by weaving, diverging, or merging maneuvers.
<i>capacity</i>	The maximum flow rate at which vehicles can be reasonably expected to traverse a point under prevailing roadway, traffic, and control conditions. Measured in vehicles per hour (vph).
<i>critical density</i>	The density at which capacity occurs for a given facility.
<i>critical speed</i>	The speed at which capacity occurs for a given facility.
<i>cone of vision</i>	The area where a person focuses their visual attention.
<i>concentration</i>	The number of vehicles occupying a road lane per unit length at a given instant. Usually measured as density.
<i>congestion</i>	A reduction in the level of service resulting from an increase in demand or a decrease in capacity.
<i>nonrecurring congestion</i>	Congestion which cannot be anticipated in advance. Normally occurs as the result of a capacity reducing incident.
<i>recurring congestion</i>	Congestion which occurs on a regular basis and can be predicted in advance. Normally the result of daily peaks in demand.
<i>construction activities</i>	Projects on or near a highway facility which are stationary in nature (or related to a specified section of highway) and lasting more than a few hours.
<i>density</i>	The number of vehicles occupying a road lane per unit length at a given instant. Measured in vehicles per kilometer (mile) per lane (veh/km[mi]/ln).
<i>Design Hour Volume</i>	A volume determined for use in design, representing traffic expected to use the highway, and represented by the 30th highest hourly volume during a one year period.

<i>design speed</i>	A speed determined for design and correlation of the physical features of a highway that influence vehicle operation. It is the maximum safe speed that can be maintained over a specified section of highway when conditions are so favorable that the design features of the highway govern.
<i>diverge</i>	Separation of a single lane of traffic separates into two separate lanes without the aid of traffic control devices.
<i>driver expectancy</i>	A roadway or traffic condition which produces an inclination to respond in a predetermined manner, based on previous experiences.
<i>flow</i>	The number of vehicles passing a point per unit of time.
<i>flow rate</i>	The equivalent hourly rate at which vehicles pass a point on a lane or roadway during time intervals of less than one hour. Measured in vehicles per hour (vph).
<i>forced flow</i>	Traffic demand in excess of capacity.
<i>fork</i>	A highway which divides into two separate highways without the aid of traffic control devices.
<i>freeway</i>	A highway with full control of access and egress.
<i>gap</i>	The time interval between passage of consecutive vehicles moving in the same stream, measured between the rear of one vehicle and the front of the next. Measured in seconds.
<i>glare</i>	Vision interference or reduction resulting from bright lights or light reflection.
<i>headway</i>	The time interval between passage of consecutive vehicles moving in the same stream, measured between corresponding points on the vehicles. Measured in seconds.
<i>high-occupancy vehicle</i>	A motor vehicle carrying a sufficient number of passengers to qualify for occupying a lane which is reserved for movement of a large number of people.
<i>inside merge</i>	Merging conditions with lanes on the outside of each merging lane so that merging vehicles have no escape or recovery area.
<i>ITS</i>	A range of technologies and ideas that can improve mobility and transportation productivity, enhance safety, maximize existing transportation facilities and energy resources, and protect the environment. It is based on modern communications, computer, control, and electronic technologies.
<i>ATIS</i>	Lets drivers know their location and how to find desired services.
<i>ATMS</i>	Permits real-time adjustment of traffic control systems and variable signing for driver advice.

<i>APTS</i>	Applies advanced electronic technologies of communications, navigation, and advanced information systems to the operation of high-occupancy, shared-ride vehicles, including buses, rail, and para-transit vehicles.
<i>AVCS</i>	Applies additional technology to vehicles to identify obstacles and adjacent vehicles, thus assisting in the prevention of collisions in safer operation at high speeds.
<i>CVO</i>	Selects from ATIS those features critical to commercial and emergency vehicles. They expedite deliveries, improve operational efficiency, and increase safety.
<i>K factor</i>	A ratio of the DHV to AADT.
<i>level of service</i>	A qualitative measure describing operational conditions within a traffic stream; generally described in terms of such factors as speed and travel time, freedom to maneuver, traffic interruptions, comfort and convenience, and safety.
<i>maintenance activities</i>	Moving or short duration projects intended to improve the condition of a portion of a highway facility.
<i>merge</i>	A movement in which two separate lanes of traffic combine to form a single lane without the aid of traffic signals or other right-of-way controls.
<i>optional lane</i>	A lane from which the driver may take more than one path without merging into another lane.
<i>peak hour factor</i>	The hourly volume during the maximum volume hour of the day divided by the peak 15-minute flow rate within the peak hour; a measure of traffic demand fluctuation within the peak hour.
<i>peripheral vision</i>	The area outside the cone-of-vision in which a person can discern movement, but not detail.
<i>performance</i>	A measure of a vehicle's ability to perform work. Normally described by a horsepower to vehicle weight ratio.
<i>power</i>	The rate at which a vehicle performs work such as accelerating, maintaining speed, and climbing grades. Normally measured in horsepower.
<i>sight distance</i>	The portion of the highway environment visible to the driver.
<i>decision sight distance</i>	The distance required for a driver to detect and perceive a difficult information source or hazard in a complex driving environment, determine the proper course of action, and perform the appropriate maneuver. Its application is based on a driver's eye height of 3.50 feet and an object height of 0.5 feet.
<i>passing sight distance</i>	The distance required for a vehicle to pass a slower moving vehicle without conflicting with the overtaken vehicle or the oncoming vehicle from the opposing direction. Its application is based on a driver's eye height of 3.50 feet and an object height of 4.25 feet.

<i>stopping sight distance</i>	The distance required for a driver to bring a vehicle to a stop after seeing an object. Includes the distance traveled while reacting to the object and the distance required to bring the vehicle to a stop.
<i>special event</i>	A planned activity not related to construction or maintenance which has an impact on highway traffic flow.
<i>speed</i>	A rate of motion expressed as distance per unit time. Measured in miles per hour (mph) or feet per second (fps).
<i>average running speed</i>	The average speed of a traffic stream computed as the length of a highway segment divided by the average running time of vehicles traversing the segment.
<i>average travel speed</i>	The average speed of a traffic stream computed as the length of a highway segment divided by the average travel time of vehicles traversing the segment.
<i>space-mean speed</i>	The arithmetic mean of speeds of vehicles occupying a given length of road lane at a given instant. Measured in miles per hour (mph). Can also be determined by the average travel time of vehicles to traverse a segment of roadway. Same as the average travel speed.
<i>time-mean speed</i>	The arithmetic average of individual vehicle speeds passing a point on a roadway or lane. Measured in miles per hour (mph). Normally measured with a radar gun.
<i>traffic control plan</i>	A plan for handling traffic through a work zone. The TCP may range in scope depending on the complexity of a project and resulting traffic interference.
<i>volume</i>	The number of vehicle passing a point in a given time period. Typically measured in vehicles per second (vps), vehicles per hour (vph), or vehicles per day (ADT).
<i>weaving area</i>	A length of highway over which traffic streams cross each other's path without the aid of traffic signals over a length of highway, doing so through lane-changing maneuvers.
<i>work zone</i>	An area of a highway in which maintenance and construction operations are taking place which impinge on the number of lanes available to moving traffic or affect the operational characteristics of traffic flowing through the area.

CHAPTER 15

ANNOTATED BIBLIOGRAPHY

The publications described below are sources of information that the engineer may consult to obtain more detailed material about specific subjects. These publications are listed in alphabetical order by title. They may be purchased from the organization at the appropriate address (addresses are at the end of the annotated bibliography) or they may be borrowed from the RTT Library.

Texas guidelines or standards may be different than those contained in the publications described below. Therefore, the following publications should be used for informational purposes only. In the case of conflicts between Texas guidelines or standards and those found in the following publications, the Texas guidelines or standards should be used. Consult the appropriate TxDOT Division if appropriate guidelines or standards cannot be found.

A Policy on Geometric Design for Highways and Streets. American Association of State Highway and Transportation Officials, Washington, D.C. 1990.

Addresses the geometric features of rural and urban highway design. Contains design practices in universal use as the standard for highway geometric design. Also known as the "Green Book."

Advanced Freeway System Ramp Metering Strategies for Texas. Research Report 1232-23. Texas Transportation Institute, College Station, Texas, October 1993.

This report identifies and examines a microcomputer-based optimization scheme that can assist in developing efficient freeway control strategies for on-line freeway surveillance and control. A multi-level freeway control structure is employed for which ramp metering control algorithms are developed for each level of control. Flow-based and lane occupancy-based system algorithms are presented. Detailed data file requirements are provided for each control level

Alternative Surveillance Concepts and Methods for Freeway Incident Management: Volume 3 - Computational Example for Selecting Low-Cost Alternatives. FHWA-RD-77-060. Federal Highway Administration, Washington, D.C. March 1978.

This report is the third of six volumes describing a research study which identified low-cost incident management systems for responding to freeway disturbances. Volume 3 gives police, highway, and traffic engineering personnel an easy to follow example of the methodology used to conduct freeway incident management analysis.

Communications Handbook for Traffic Control Systems. FHWA-SA-93-052. Federal Highway Administration, Washington, D.C., April 1993.

This handbook was written to enable transportation engineers to plan, select, design, implement, operate, maintain communications systems for traffic control. The handbook provides information on communications media, system architecture, decision-making processes, and trade-off analyses. The handbook will serve as a guide for agencies wishing to initiate a traffic control system that incorporates functional, effective, reliable, and economical communications, and to update and modernize an existing communication system for traffic control.

Communications in Traffic Control Systems: Volume 2 - Final Report. FHWA-RD-88-012. Federal Highway Administration, Washington, D.C. August 1988.

This report provides understandable information on communications in general and on specific communications technologies to those persons involved in the planning, design, and implementation of computer-based traffic control systems.

Decision Sight Distance for Highway Design and Traffic Control Requirements. FHWA-RD-78-078. Federal Highway Administration, Washington, D.C. February 1978.

This report describes a research project intended to relate the decision sight distance concept to specific road types, design speeds, traffic operating conditions, geometric features, and driver attributes. Recommendations are presented on the decision sight distance criteria, and its application for design and traffic operations.

Driver Interpretation of Existing and Potential Lane Control Signal Symbols for Freeway Traffic Management. Research Report 1298-1. Texas Transportation Institute, College Station, Texas, November 1993.

This report documents the results of laboratory studies to assess motorist interpretations of the following symbols used or initially viewed as potential freeway lane control signals: red X, yellow X, green down arrow, yellow diagonal arrow, yellow down arrow, circle with a slash, and a red X superimposed on a green arrow. The effects of flashing indications on motorist interpretation were also evaluation.

Formulation of Guidelines for Locating Freeway Sensors. FHWA-RD-78-137. Federal Highway Administration, Washington, D.C. December 1979.

This report develops guidelines and procedures for specifying the optimum location and spacing of sensors for detecting freeway incidents. Major emphasis is placed upon assessing the tradeoffs between costs and effectiveness of a variety of candidate sensor configurations.

Framework for Developing Incident Management Systems. WA-RD 224.1. Washington State Department of Transportation, Olympia, Washington. August 1991.

This document serves to provide guidance for managing incidents by discussing the process of developing and implementing an incident management system. Specific information, including technique description, relative costs and benefits, operational requirements, and funding variations, is given for each incident management technique described in this report.

Freeway Management Handbook. FHWA-SA-97-064. Federal Highway Administration, Washington, D.C. August 1997.

This document, organized in a modular format, provides information and guidance on the various technologies and tasks pertaining to freeway management. Each module discusses the decision process, techniques and technologies, and lessons learned regarding a particular area of freeway management.

Guide for the Design of High-Occupancy Vehicle Facilities. American Association of State Highway and Transportation Officials, Washington, D.C. 1991.

The information contained in this guide will be useful for location and design of high-occupancy vehicle lanes. It will also serve as a basis for further refinement as operational experience dictates.

Guidelines for Planning, Designing, and Operating Bus-Related Street Improvements. Research Report 1225-2F. Texas Transportation Institute, College Station, Texas. August 1990.

The guidelines in this report address the following aspects of bus-related street improvements: 1) bus service planning, 2) bus facility design, and 3) bus service operations.

Guidelines on the Use and Operation of Changeable Message Signs. Research Report 1232-9. Texas Transportation Institute, College Station, Texas, November 1992.

This report is a primer on the characteristics that affect the design, use, and operations of changeable message signs, and provides guidance on the selection of the appropriate type of display. This report is an update and consolidation of *Manual on Real-Time Motorist Information Displays* (FHWA-IP-86-016), *Guidelines on the Use of Changeable Message Signs* (FHWA-TS-90-043), and *Portable Changeable Message Signs at Work Zones* (TTI 292-4).

Guidelines on the Selection and Design of Messages for Changeable Message Signs. Research Report 1232-10. Texas Transportation Institute, College Station, Texas, November 1992.

This report presents guidelines on the design of changeable message sign messages for use in freeway corridors for incident management and route diversion. It is a companion to *Guidelines on the Use and Operation of Changeable Message Signs* (TTI 1232-9).

Highway Capacity Manual, Special Report 209. Transportation Research Board, Washington, D.C. 1994.

This manual is a collection of techniques for estimating highway capacity as the capacity relates to a particular quality or level of service. Portions of the manual address capacity principles, freeways, rural highways, and urban streets. This is the 3rd edition of the *Highway Capacity Manual*, and reflects a level of sophistication and understanding that will allow more precise and accurate analysis of highway facilities and operating conditions thereon. Some of its procedures are radically different than the 1965 edition.

Highway Design Division Operations and Procedures Manual. Texas Department of Transportation, Austin, Texas. revised to 1987.

This manual, also known as the *Design Manual*, contains the procedures and standards for the geometric design of Texas highways.

Human Factors Handbook for Advance Traffic Management Center Design. Prepared by the Georgia Institute of Technology, Georgia Tech Research Institute for the U.S. Department of Transportation, Federal Highway Administration, October 1995.

This handbook provides human factors design guidelines and recommendations that were selected from existing standards and documentation and, where necessary, tailored for applicability to the traffic management center environment. It includes design implications of recent human factors research covering a broad range of areas including automation and user-computer interface design, as well as human factors lessons and observations gleaned during visits by the program staff to various advanced traffic control centers in the United States, Canada, and Europe.

Incident Response and Clearance in the State of Texas: Case Studies of Four Motorist Assistance Patrols. Research Report 1232-15. Texas Transportation Institute, College Station, Texas, October 1992.

This report contains case study analyses of four motorist assistance patrol programs in Texas. It also contains discussions of the four incident response and clearance strategies most often pursued by various agencies in the state. This report provides useful insight into the various political and organizational attributes that need to be considered when developing a motorist assistance program.

Incident Response Guide: Office Reference. WA-RD 225.1. Washington State Department of Transportation, Olympia, Washington, D.C. September 1991.

Incident Response Guide: Field Reference. Washington State Department of Transportation, Olympia, Washington, D.C. September 1991.

This guide is a resource document for use by departments of transportation, state patrol offices, and other agencies that respond to incidents. It describes response steps and techniques appropriate under specific situations and lists the procedures for requesting additional equipment and staff, as well as resources and contacts. The guide was developed for use in the Puget Sound area, but it can be adapted to other urban and rural areas if the resource information is changed to be appropriate for those locations.

Improving Truck Safety at Interchanges. FHWA-IP-89-024. Federal Highway Administration, Washington, D.C. September 1989.

This report offers highway engineers guidance in designing interchanges so as to reduce the likelihood of truck crashes on highway interchanges by showing that the interaction between truck dynamics and interchange geometry can contribute to rollovers, jackknives, and other loss-of-control crashes.

Manual of Traffic Engineering Studies, 4th Edition. Institute of Transportation Engineers, Washington, D.C. 1976.

Presents techniques and practices of transportation studies, including inventories for traffic studies, traffic volume, traffic crash studies, travel times and delays, and street lighting.

Manual on Real-Time Motorist Information Displays. FHWA-IP-86-016. Federal Highway Administration, Washington, D.C. August 1986.

This manual provides practical guidelines for the development, design, and operation of real-time driver displays, both visual and auditory, for freeway corridor traffic management. The emphasis is on the recommended content of the messages to be displayed, the manner in which messages are to be displayed, and where messages should be placed.

Overhead Guide Sign Visibility Factors: Volume 1 - Final Report. FHWA-RD-88-196. Federal Highway Administration, Washington, D.C. May 1989.

Overhead Guide Sign Visibility Factors: Volume 2 - Appendices. FHWA-RD-88-197. Federal Highway Administration, Washington, D.C. May 1989.

This report describes a research project concerning the night use of overhead guide signs. The project included the investigation of current signing practices throughout the country, development of a set of in-use luminance values for current overhead guide sign materials, development of life cycle costs for current signing materials and practices, and determination of driver response characteristics for these overhead guide sign systems.

Permanent Automatic Traffic Recorder Annual Report. Texas Department of Transportation, Austin, Texas, published yearly.

This report summarizes the results of traffic counts at TxDOT's permanent count stations in Texas. Count information includes AADT, directional splits, high hourly volumes, and average day and month volumes.

Planning and Scheduling Work Zone Traffic Control. FHWA-IP-81-006. Federal Highway Administration, Washington, D.C. October 1981.

This report documents a planning process that can be used to select the most effective work zone traffic control strategy for a particular project.

Planning Guidelines for Major Transportation Emergencies. Research Report 1231-3F. Texas Transportation Institute, College Station, Texas, November 1991.

This report presents guidelines as to how transportation agencies can better prepare to handle major transportation emergencies. It is a planning document which will facilitate an agency's ability to maintain and even enhance mobility before, during, and after an emergency. Topics addressed include transportation system evaluation, intra agency and interagency coordination, resource assessment and management, and public communication and notification.

Procedures for Establishing Speed Zones. Texas Department of Transportation, Austin, Texas, August 1996.

This publication contains information on conducting an engineering study to determine the lawful maximum speed limits for public streets and highways. 50 pages.

Revised Manual for Planning, Designing, and Operating Transitway Facilities in Texas. Research Report 339-14. Texas Transportation Institute, College Station, Texas, August 1988.

This manual provides guidelines and standards for the planning, design, and operation of high-occupancy vehicle facilities in Texas.

Roadside Design Guide. American Association of State Highway and Transportation Officials, Washington, D.C. 1988.

This guide is a synthesis of current information and operating practices related to roadside safety. It focuses on safety treatments that can minimize the likelihood of serious injuries when a motorist leaves the roadway.

Roadway Delineation Practices Handbook. FHWA-SA-93-001. Federal Highway Administration, Washington, D.C. August 1994.

This handbook is intended to assist the practicing engineer in determining the appropriate roadway delineation system for a particular situation. The contents cover current and newly developed devices, materials, and installation equipment in terms of demonstrated or anticipated performance based on actual experience or field/laboratory tests.

Roadway Lighting Handbook. FHWA-IP-78-015. Federal Highway Administration, Washington, D.C. December 1979.

Addendum to Chapter 6 of the Roadway Lighting Handbook. FHWA-IP-78-015.1. Federal Highway Administration, Washington, D.C. September 1983.

This handbook assists the engineer in responding to lighting needs. It presents the basic principles for the design, installation, operation, and maintenance of lighting systems for streets and highways.

Space Management: An Application of Dynamic Lane Assignment. Research Report 1232-18. Texas Transportation Institute, College Station, Texas, March 1993.

This report presents the findings of research on dynamic lane assignment. Issues addressed in the research include testing the sign for human factor measures such as legibility and target value, operational parameters such as sign brightness and light output, and sign placement relative to traffic signals. The report also describes the results of field tests of dynamic lane assignments.

Standard Highway Sign Designs for Texas. Texas Department of Transportation, Austin, Texas. revised to 1991.

This manual is a supplement to the Texas MUTCD and contains drawings showing dimensions, shapes, colors, and other information necessary for laying out signs described in the Texas MUTCD.

Texas Manual on Uniform Traffic Control Devices. Texas Department of Transportation, Austin, Texas. revised to 1988.

This manual provides a uniform system of traffic control devices for all public streets, roads, and highways in the State of Texas. The Texas MUTCD (TMUTCD) basically follows the National MUTCD with some modifications to meet State laws or more closely fit conditions in Texas.

Texas Traffic Signal Detector Manual. Research Report 1163-1. Texas Transportation Institute, College Station, Texas. February 1991.

This manual is a guide to the design and installation of detectors for long life and high reliability and contains many suggestions for more rapidly installing loop detectors. It reports on the testing of innovative loop designs and gives special emphasis to detector sealants, high speed saw blades, and loop wire.

The National Architecture for ITS: A Framework for Integrated Transportation into the 21st Century. Federal Highway Administration, Washington, D.C. 1997.

This series of documents, available on both CD-ROM and hard copy, presents the framework that defines the rules of information management necessary to achieve a seamless, multimodal national ITS system.

Trade-Off Between Delineation and Lighting on Freeway Interchanges. FHWA-RD-88-223. Federal Highway Administration, Washington, D.C. August 1989.

Report describes two field studies conducted to determine whether performance at partially lighted interchanges with improved delineation can approach performance under full lighting, particularly in rain.

Traffic Control Devices Handbook. Federal Highway Administration, Washington, D.C. 1983.

Supplements the *U.S. Manual on Uniform Traffic Control Devices (MUTCD)*. Contains recommended practices and guidelines for uniform application of traffic control devices, in accordance with national standards in the *MUTCD*.

Traffic Control Systems Handbook. FHWA-SA-95-032. Federal Highway Administration, Washington, D.C. 1996.

A compendium of traffic control systems technology. Reflects current state of the art and is focused toward the needs of the experienced user. Provides assistance to traffic engineers in planning, design, implementation, and operation of effective traffic control systems.

Traffic Detector Handbook. FHWA-IP-90-002. Federal Highway Administration, Washington, D.C. July 1990. (available from the Institute of Transportation Engineers)

The handbook provides information to enable the engineer and technician to make practical use of traffic detectors. Presents information for the three most widely used traffic detectors: the magnetic detector, the magnetometer, and the loop detector.

Traffic Flow Theory, Special Report 165. Transportation Research Board, Washington, D.C. 1975.

This report serves as a reference for anyone wishing an introduction to traffic flow theory. It addresses various theoretical approaches to models of traffic flow. Individual chapters address measurement of traffic, statistical distributions, traffic models, driver information processing, car following, queuing models, and simulation of traffic flow.

Traffic Engineering Handbook, 4th Edition. Institute of Transportation Engineers, Washington, D.C. 1992.

Authoritative reference text to assist transportation professionals in planning, design, and operation of surface transportation facilities. Includes 28 chapters by noted international experts. Chapters cover: urban transit, urban travel characteristics, statewide and regional transportation planning, urban transportation planning, economic considerations, traffic flow theory, highway capacity and levels of service, traffic studies, transportation safety, lighting of traffic facilities, traffic regulations, legal liability, and more.

Transportation Telecommunication. NCHRP Synthesis of Highway Practice 165. Transportation Research Board, Washington, D.C. October 1990.

This document provides information on the fundamentals of telecommunications, types of systems available, current uses in state DOTs, and implementation procedures and alternatives.

User Guide for Removal of Not Needed Traffic Signals. FHWA-IP-80-012. Federal Highway Administration, Washington, D.C. November 1980.

This guide discusses the criteria that may be applied to determine if an existing traffic signal should be removed. The signal removal criteria apply only to signals on normal green, yellow, red operation, not to flashing signals or beacons.

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**CHAPTER 16
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